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FAA Technical Center  
Atlantic City International Airport  
New Jersey 08405

# Proceedings of the International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials

Trump Taj Mahal Casino • Resort  
Atlantic City, New Jersey USA

February 9 - 11, 1993

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THE INTERNATIONAL CONFERENCE FOR  
THE PROMOTION OF ADVANCED FIRE  
RESISTANT AIRCRAFT INTERIOR  
MATERIALS (FAA) 372 P



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DOT/FAA/CT-93/3

FAA TECHNICAL CENTER

Atlantic City International Airport NJ. 08405

# International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials

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International Conference sponsored by the  
Federal Aviation Administration Technical Center,  
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in Atlantic City, New Jersey USA  
on February 9 - 11, 1993

April 1993

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**Advanced Fire Resistant Materials**  
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Boeing Commercial Airplane Group

**Session II**  
**Advanced Technology**  
Dr. Richard Lyon  
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Technical Center

**Session III**  
**Test Methods and Modeling**  
Dr. Jack Snell  
National Institute of Standards & Technology (NIST)

**Session IV**  
**Future Needs and Requirements**  
Mr. Denis Warren  
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**Congressman Tom Lewis**  
United States House of Representatives

\* Paper included in proceedings



## **PREFACE**

The International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials was conceived as a vehicle for characterizing the state-of-the-art for low flammability materials used in aircraft cabins. This characterization provided a baseline for future advances in material fire resistance. The impetus for long-term research leading to more fire-resistant materials was provided by the Aviation Safety Research Act of 1988. One of the goals of research associated with this legislation is the development of a totally fire-resistant aircraft cabin.

A parallel activity to the planning and organization of this conference was the development of a long-range strategy for future improvements in aircraft cabin fire safety (FAA Fire Research Plan, FAA Technical Center, January 1993). This strategy will emphasize material research with additional thrusts in the areas of fire modeling, vulnerability analysis, improved systems, advanced fire suppression, and fuel safety.

The conference organizers would like to thank all the participants for making this event not only an excellent technology exchange forum but also a solid foundation for fire safety improvements in the future.



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**ADDRESS BY**

**RONALD ASHFORD**

**European Joint Aviation Authorities (JAA)**

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# EUROPEAN/US COLLABORATION AND HARMONISATION ON CABIN SAFETY REQUIREMENTS

*Ronald Ashford*  
*European Joint Aviation Authorities (JAA)*

## Summary

The aviation safety authorities of twenty European countries (the Joint Aviation Authorities) have signed "Arrangements" to collaborate on safety regulation. The JAA have developed common requirement codes for the certification, operation and maintenance of aircraft and flight crew licensing, together with related procedures. The JAA's requirements (Joint Aviation Requirements - JAR) are therefore applied by those countries representing the majority of aviation manufacturing and operation in the Western world outside the USA. As co-operative manufacturing, cross-border leasing, liberalised and truly competitive air transport progressively become more common, and the public expectations for air safety create the need for improving safety standards, harmonised European/US regulations providing higher levels of safety become an essential objective. My paper briefly explains the JAA system, the JAA/FAA efforts for harmonisation and co-operation on research and the achievements and aims for cabin fire safety in particular.

### **1. The JAA and JAR's**

The European Civil Aviation Conference was started in 1955 and now comprises 31 countries. ECAC was conceived by the Council of Europe and was aimed at achieving the greatest possible degree of co-ordination in inter-European air transport; ICAO was asked to undertake the task of arranging the original conference. ECAC still works in close liaison with ICAO but has an autonomous status.

Membership of JAA (or Eurocontrol, which is concerned with collaboration on Air Traffic Control) is restricted to ECAC members, 14 countries of the 31 ECAC countries are members of Eurocontrol and 20 of JAA. Though all European Community (EC) and European Free Trade Area (EFTA) countries are members of JAA, JAA has no direct association or origins stemming from these political/economic groupings. The position is summarised in figure 1.

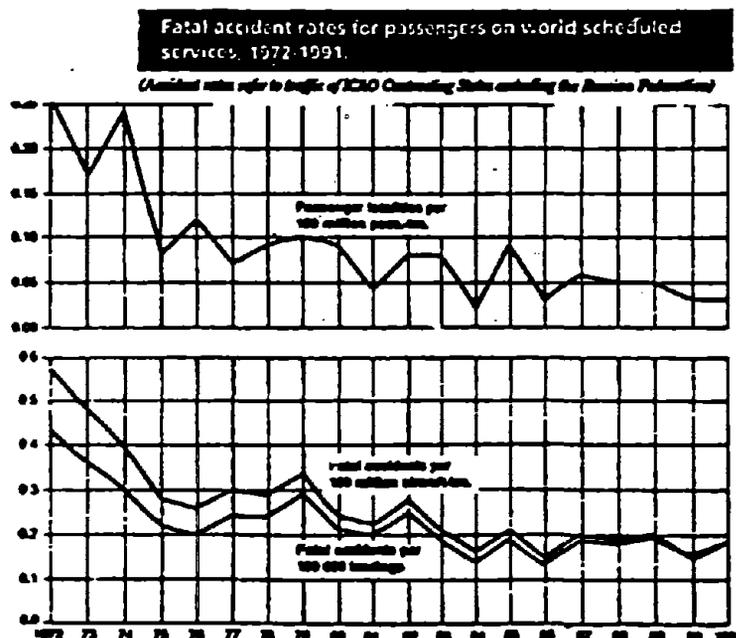


In the case of the small aeroplane and helicopter requirements (JAR 23, 27 and 29), all of which are due to be published this year, major efforts have been made to achieve harmonisation with the FAR's before publication (and publication has been delayed to achieve this). Changes have been made to the draft JAR'S and FAA has a programme of NPRM's to achieve a reasonably high degree of harmonisation. From the point of view of US and European industry, the harmonisation of JAR'S and FAR'S is of the highest importance. Both the FAA and JAA treat this as a matter of highest priority and a satisfactory conclusion as an essential goal.

## 2. The Need for Improving Safety Standards

Air transport activity has achieved extraordinary growth since the second world war. For example, the ICAO world data (excluding the People's Republic of China and the former USSR) shows that the number of passengers carried annually has increased from 46 million in 1952 to 1159 million in 1990 - growth by a factor of over 25. Passenger kilometres have increased even more dramatically, by a factor of over 47. Over the same period, the number of fatal accidents has actually reduced overall and the number of fatalities remained reasonably constant. Obviously, this can only be achieved by an appropriate and continuing reduction in the fatal accident rate - accidents per million hours, flights or aircraft kilometres or fatalities per 100 million passengers km. This has occurred, as can be seen in Figure 2.

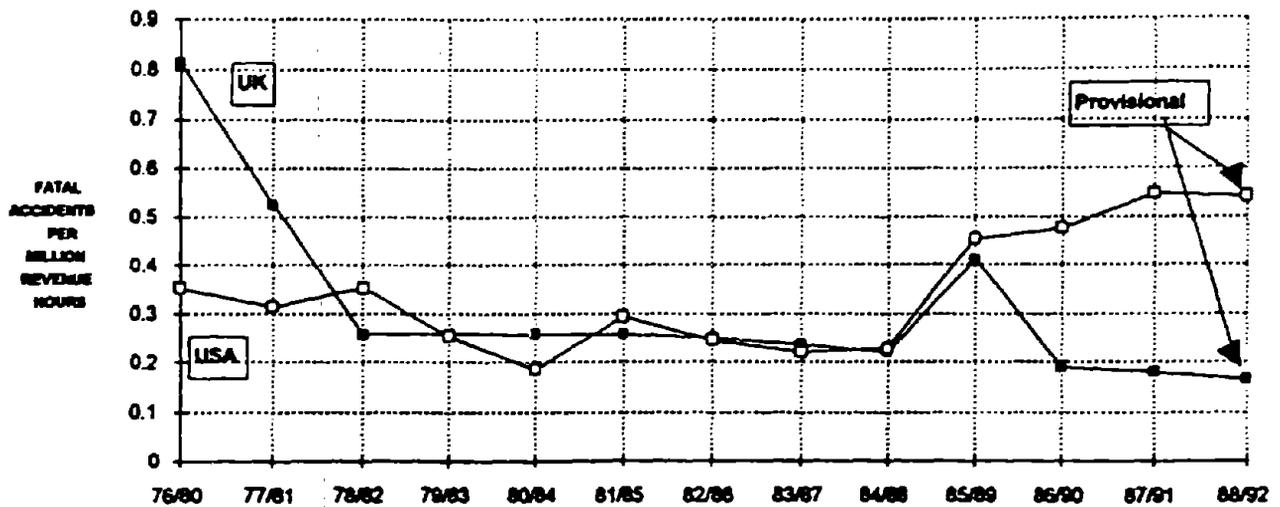
Figure 2



The ultimate driving force for safety is, in my opinion, public expectation. When the public is not satisfied, or is concerned, pressure will be put on politicians and governments and by them on the safety regulators and industry. I believe that the public will not accept a significant increase in the annual number of fatal accidents or fatalities. As the industry continues to expand (and Major growth will surely return) there is a need to continue to reduce the accident rate such as to prevent the number of accidents or fatalities rising. This has generally been achieved, but there is a tendency in recent years for the accident rate curve to flatten or even rise (eg in the US and UK - See Figure 3) and this could be a cause for concern in the near future.

Figure 3

**UK v USA FATAL JET ACCIDENT RATE**  
**UK - JET AEROPLANES (OVER 40 SEATS): PUBLIC TRANSPORT\***  
**USA - JET AIR CARRIERS (14 CFR 121): PUBLIC TRANSPORT**  
 \* (excludes terrorism and third-party fatalities)



5 YEAR MOVING AVERAGE - JET ONLY

	YEAR	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
UK	ACCIDENTS	1	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0
	MILLION HOURS	.88	.88	.74	.79	.82	.78	.74	.74	.81	.82	.88	.87	1.08	1.18	1.21	1.17	1.28
USA	ACCIDENTS	2	3	4	2	0	1	4	1	0	4	0	4	2	11	0	4	4
	MILLION HOURS	6.78	8	8.57	8.88	8.8	8.27	8.43	8.89	7.8	8.21	8.84	8.64	8.78	8.88	10.14	10.88	10.1

### 3. The Improvement in Cabin Fire Safety

The cabin fire safety measures introduced in the last decade have already dramatically improved safety. A study of potentially survivable accidents involving commercial passenger flights of turbine-powered aircraft with 30 or more seats and where both fire and fatalities occurred, showed a major reduction in accident numbers and fire fatalities in spite of the very large growth in aircraft movements (sabotage and Eastern bloc accidents were excluded). This can be clearly seen in the table on the Cabin Fire Safety in Europe

**Figure 4**

**Fire Accidents and Fatalities**

Period	Number of Fire accidents	Average no of fire fatalities/ accidents	Fire fatalities per year (average)
1972 to 1981	40	36	145
1982 to 1991	28	21	60

As an illustration of the benefits of the recent fire safety improvements, the NTSB Accident Report on the Delta Airlines Boeing 727 accident at Dallas-Fort Worth on August 31, 1988 concludes that "a number of lives were saved by the use of a fire blocking layer on the passenger seats". The progressive retroactive introduction of the latest standard of fire hardening for cabin wall liner materials, etc. when refurbishment takes place, the delivery of new aircraft fitted to the latest standard, and the retirement of older aircraft not fitted with the new materials should all help to ensure that this progress continues.

**4. Cabin Fire Safety in Europe**

Survivable accidents in Europe involving fire, such as that to a British Airtours Boeing 737 at Manchester in 1985 and the Airbus A-320 at Mulhouse in 1989, caused fire safety to take on a higher profile in Europe. The UK, France and the Netherlands carried out a large amount of work with FAA and Transport Canada to study the feasibility and net benefit of passenger smoke hoods. The unanimous conclusion was that there was no overall safety benefit to be gained by requiring their introduction - in some circumstances lives would be saved, in others probable delays in evacuation could be expected to cause some increase in the loss of life. Work by the SAVE company in the UK on cabin water sprays indicated that such systems had real potential for reducing fire risks, with the obvious benefit of requiring no special actions from passengers. The original systems were too heavy to be acceptable on the basis of a cost-benefit analysis. Subsequent work by FAA at their Technical Center has, however, produced dramatic improvements which suggest that far less water may be needed such that this could make the concept practicable. Interesting developments and testing of a "fire curtain" concept using small amounts of water to limit fire spread are also being conducted by BP in the UK, who have also developed an advanced portable air-water fire extinguisher.

In the area of cabin materials, the requirements for much more fire resistant seat cushions and other cabin furnishing materials were led by the FAA. Application to new aircraft types, through FAR 25 and JAR 25 presented little problem. However, the JAA

countries have no joint procedure - and very different national practices for retrospective requirements and this is one of the weaknesses in the present JAA system that is now being addressed.

One JAA country is also working on means of fire-hardening the aircraft structure to delay fuselage burn-through.

The JAA believed in a "global" approach to cabin fire safety:

- 1) Measures to prevent accidents
- 2) Measures to improve fire hardening and fire suppression when an accident occurs
- 3) Measures to improve survivability and evacuation

#### **5. FAA/TC/JAA Cabin Safety Working Group**

A cabin safety working group involving FAA, Transport Canada and the European Joint Aviation Authorities was established in 1988. This is a particular example of international airworthiness harmonisation. The Working Group has had ten meetings, alternating between Europe and North America and has, to date, addressed 46 cabin safety issues. Some of the more important subjects are illustrated below.

##### **FAA/TC/JAA Cabin Safety Working Group**

- Agreement on a number of interpretation policies on cabin safety
- "Round-robin" tests for comparison of OSU chambers
- Drafting of joint rule changes
- Development of a joint Advisory Circular on crew rest compartments
- Participation in joint research on type III exit requirements
- Agreement on ditching exit policy

The Working Group has provided an invaluable forum for open review of proposed rule changes. As a recent example, I believe that the FAA and JAA views on space adjacent to Type III exits have been brought closer together through discussion in the Group.

## **6. JAA Cabin Safety Study Group**

In order to more satisfactorily handle the Cabin Safety issues that were previously handled by a "systems" Study Group, the JAA decided to set up a Cabin Safety Study Group in October 1991.

The Study Group is responsible for Cabin Safety issues for large aeroplanes (both airworthiness and operational aspects) and report to the Regulation Director.

Its membership comprises representatives from Authorities, Manufacturers, Operators and Pilot Unions. The Authorities members briefly report on the discussions being held during the JAA/FAATC meetings.

The Chairman of the Study Group is the JAA focal point for harmonisation of Cabin Safety issues between JAA and FAA.

## **7. JAA Research Committee**

JAA has a small Research Committee which aims to co-ordinate research work in the member countries and to seek funding where this may be available, eg from the European Commission. The members of the Committee are from the United Kingdom, France, Germany, Italy and the Netherlands plus a representative from the European Commission. At present the Committee is preparing a summary document of European Aviation Safety Research projects which will become a JAA Information Leaflet; this is now planned for issue in April 1993. The Committee has also outlined a large aviation safety research programme which has been put forward to the European Commission with a view to obtaining funding.

Both FAA and JAA have expressed interest in extending their co-operation by closer liaison and integration of their research work. It is planned that the FAA Technical Center will present an overview of its research programme to the JAA before the summer of 1993 as a step in this direction.

## **8. Concluding Remarks**

- 1) The European Joint Aviation Authorities (JAA), an association of the safety regulation authorities of 20 states, have agreed to work together in:-
  - setting common standards;
  - collaborating on their common application; and
  - having a system of mutual recognition of approvals.
- 2) Both FAA and JAA are committed to harmonisation of their requirements to the maximum degree possible. This is not just a long-term goal but an essential and urgent objective.

- 3) **FAA and JAA are now undoubtedly the two bodies with the largest influence on the development and application of safety standards world-wide. It is clear that harmonisation and co-operation is necessary for industry and for the travelling public.**
- 4) **Most JAA cabin fire safety regulations have been adopted unchanged from the FAA.**
- 5) **There has been a major improvement in fire safety in the last decade, with fire fatalities in potentially survivable accidents reduced to less than a half of those of the previous decade, in spite of major growth in traffic.**
- 6) **Excellent co-operation and integrated analysis and research has been carried out between some JAA Authorities and FAA on passenger smoke hoods and cabin water spray systems. Much progress has been made on common rules and interpretation, through the joint Cabin Safety Working Group (FAA/J AA/Transport Canada).**
- 6) **Closer research liaison is needed, and is planned.**

**SESSION I**  
**ADVANCED FIRE RESISTANT MATERIALS**

Tuesday, February 9, 1993

Session Chairman  
**Dr. James Peterson**  
Boeing Commercial Airplane Group



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P. 8  
New Thermoplastic Laminating Adhesives for the Aircraft Industry  
with Low Heat Release and Low Smoke Emission

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ABSTRACT

In Aeroplas '90 and Fire Safety '91, we discussed the flammability behavior of several aircraft substrates with different types of decorative laminates. We concluded that due to the substrate's own fire characteristics, aircraft decorative laminate manufacturers have substantial problems meeting current Heat Release and Smoke Emission requirements.

To solve this problem, we decided to develop new thermoplastic adhesives which will help decorative laminates manufacturers meet current Federal Aviation Administration (FAA) flammability requirements on virtually all substrates. These adhesive films are tested on commercially available thermoplastic decorative laminate with a PVF surface, after bonding to crushed core substrate.

All flammability tests are carried out in FAA-approved OSU Heat Release and NBS Smoke Emission Chambers. Toxicity tests are also carried out using the same NBS Smoke Chamber. The flammability test data of these new adhesives will be discussed in this paper.

## INTRODUCTION

A manufacturer of the decorative laminates should meet:

- (i) Current US Federal Aviation Administration (FAA) Regulations (also know as Federal Air Regulation FAR) and
- (ii) Manufacturer's individual requirements.

From August 20, 1990, FAA has Heat Release requirements of 65 KW/m<sup>2</sup> peak and 65 KW.min/m<sup>2</sup> for 2 min. (also known as 65/65) and Smoke Emission requirements of 'D<sub>200</sub> (for 4 min.). But individual manufacturer requirements may be 55 KW/m<sup>2</sup> for peak and 55 KW.min/m<sup>2</sup> for 2 min. value, and 'D<sub>150</sub> for smoke emissions when the laminated product is bonded to the specified substrate.

Some manufactures also require that their laminated products should be bonded to substrates using a specified primer and which will further effect the Heat Release and Smoke Emission values. To meet FAA and manufacturer's individual specifications for OSU (Heat Release) and NBS (Smoke Emission), individual fire characteristics of a substrate and also decorative laminate (with adhesive) play a very important role. In Aeroplas '90 we discussed the flammability behavior of the substrates listed in Table I by themselves (Siddiqui, 1990).

In Fire Safety '91, we also presented the behavior of the substrates (listed in Table II) when bonded on the following two types of decorative laminates (Siddiqui, et al, 1991):

Product A: Light weight thermoplastic laminate with a PVF surface.

Product B: Rigid thermoset composite laminate with PVF surface.

Table I

Aerospatiale crushed core  
20 Gauge Aluminum  
Boeing crushed core  
British Aerospace panel  
Deutsche Airbus sandwich  
Deutsche Airbus monolith  
Fliteform GN-7 panel  
Heath Techna crushed core  
McDonnell Douglas C&D panel

Table II

Aerospatiale crushed core  
20 Gauge Aluminum  
Deutsche Airbus monolith  
Deutsche Airbus sandwich  
Diathelm panel  
Fliteform GN-7 panel  
Heath Techna crushed core  
Hexcel DP-200 panel  
Soceman sandwich  
Strativer sandwich

From these studies we concluded that, when any new decorative laminate product is bonded on these panels to meet FAA(1990) and manufacturer's individual specified requirements for OSU Heat Release and NBS Smoke Emission values, due to the panels own fire characteristics, it is sometimes not possible to meet both FAA and OEM(original equipment manufacturer) specified requirements.

To solve this problem of aircraft decorative laminates product manufacturers in meeting the OSU and NBS requirements for the customers, we decided to develop new thermoplastic adhesives which will help in meeting customer flammability requirements.

## NEW HEAT ACTIVATED ADHESIVES

Three new thermoplastic heat activated adhesives were designed for this study. These new heat activated adhesives are coded as following:

ATI 786-3

ATI 786-5

ATI 786-9

## TESTING EQUIPMENTS

The FAA approved OSU Heat Release Chamber and NBS Smoke Emission Chamber located at Mount Vernon, Indiana, USA, were used.

Airbus/Boeing Toxicity tests are also carried out using the same NBS Smoke Chamber. Mr. Herb L. Curry, a FAA Designated Engineering Representative(DER), witnessed all these tests.

## SUBSTRATE USED

The following one substrate was used for this study:

Aerocore 65, thickness 0.494 inch

## RESULTS & DISCUSSION

The weight of these heat activated adhesives ATI 786 Series are given in Table III.

Table III

	<u>Typical Values</u>	<u>Standard Requirements</u>
Weight of Adhesive Film:	.78 g/m <sup>2</sup> .23 oz/yd <sup>2</sup>	80±10 g/m <sup>2</sup> 2.36±0.29 oz/yd <sup>2</sup>

The OSU and NBS test results presented in Fire Safety '91 conference with and without Product A on the substrates listed in Table II are summarized in Table IV.

Table IV  
Product A on Substrates from Table II

Substrate Code #	Control (Substrate only)			Product A on same Substrate		
	OSU		NBS	OSU		NBS
	Peak	2 Min.	4 Min.	Peak	2 Min.	4 Min.
	KW/m <sup>2</sup>	KW.min/m <sup>2</sup>	'D <sub>n</sub>	KW/m <sup>2</sup>	KW.min/m <sup>2</sup>	'D <sub>n</sub>
1	36	23	4	72	52	87
2	25	26	20	65	63	132
3	48	35	34	81	80	156
4	63	51	19	70	66	122
5	66	45	258	80	86	352
6	54	44	9	63	67	94
7	2.3(0)	-3.7(0)	0.4(0)	60	64	238
8	0	0	0	59	46	54
9	50	44	31	65	65	156
10	40	40	16	57	80	145

Notes:

- 1.) Product A is not a commercially available product.
- 2.) Substrate coded #8 is an aluminum panel.
- 3.) Substrate coded #7 is a honeycomb panel.  
(In OSU Chamber a peak of 2.3 KW/m<sup>2</sup> and 2 min. value -3.7 KW.min/m<sup>2</sup> is considered no value and similarly in NBS Chamber a 0.4 'D<sub>n</sub> is also considered no value.)
- 4.) The above test data is obtained from the paper presented in Fire Safety '91 (see reference #2).

It can be observed from Table IV that all substrates are no-identical or even similar in properties when tested in OSU Heat Release Chamber. The similar statement is also true in the case of smoke emissions. There are only two substrates (coded #7 & #8) which have no heat release and no smoke generating properties.

Table V shows the OSU and NBS test data of currently available light weight decorative laminates using new heat activated adhesives (ATI Series ;786). These test data are on one of the similar composite panels used in the study reported in Table IV. It can be observed from the data in Table V that by using newly formulated adhesives (ie; ATI 786-3, ATI 786-5 and ATI 786-9) it will lower the heat release and smoke emission values. We believe that these newly designed heat activated adhesives will help the manufacturer of decorative laminates meet the FAA and customer own specified requirements on almost all composite panels.

Table V

<u>Construction</u> <u>Substrate/Adhesive/Laminate</u>	<u>OSU</u>		<u>NBS</u>
	<u>Peak</u> <u>KW/m<sup>2</sup></u>	<u>2 Min.</u> <u>KW.min/m<sup>2</sup></u>	<u>4 Min.</u> <u>'D</u>
X / - / -	28	27	10
X /ATI 786-3/ C	51	50	145
X /ATI 786-5/ C	45	51	118
X /ATI 786-9/ C	41	41	97

X = Substrate Aerocore 65, thickness 0.494 inch.  
C = Commercially available light weight decorative laminate without adhesive.

## TOXICITY FOR SMOKE GASES

The samples used for NBS Smoke Emission test are also used for this test. The toxicity for smoke gases is determined only in flaming mode. The average concentration (ppm) of three toxic gases is shown in Table VI.

Table VI

### Toxicity (Flaming Mode)

<u>Toxic Gases</u> <u>After 4 min.</u>	<u>Using ATI</u> <u>Series 786</u>		<u>Standard</u> <u>Requirement</u>
	<u>before</u>	<u>after</u>	<u>ATS 1000.001 issue 5</u>
Nitrous Gases (NO+NO <sub>2</sub> )	2-3	2-3	100 ppm
Hydrogen Fluoride (HF)	70-75	70-75	100 ppm
Hydrogen Chloride (HCL)	35-40	35-40	150 ppm

From the above data it can be concluded that ATI Series 786 do not generate any toxic gases when burned.

### ACKNOWLEDGEMENTS

The author wishes to express his appreciation to FAA Designated Engineering Representative(DER) Mr. Herb L. Curry, President of Herb Curry, Inc. and to Mr. John(Jack) J. Kolatosz for their contributions in processing, finishing and testing the decorative laminates and adhesives. The author extends his gratitude to all others who assisted in finalizing this presentation.

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**A New Low Smoke, Low Heat Release Structural Foam**

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**ABSTRACT**

Gillfoam™ was developed specifically to be a structural phenolic foam capable of providing increased cabin safety during a fire in an aircraft. This product meets current Federal Airworthiness Regulations pertaining to peak and total heat release, vertical and 45° flammability, smoke density, and toxic gas release. The NIST smoke density ( $D_p$ ) for the highest density foam (20 lbs/ft<sup>3</sup>) is less than 50 when the product is tested in the flaming mode.

Foams having densities ranging between 4.0 and 20.0 lbs/ft<sup>3</sup> are currently being evaluated for a variety of potential applications. Some of these applications include: environmental control system (ECS) ducting; cores for partitions, bulkheads, and galley panels; and for close-outs in laminated honeycomb sidewall panels. Gillfoam, as sheet stock, is also conformable in crushed core applications so it can be laminated to produce contoured profiles. When fabricated into a duct, the low smoke foam product is lighter in weight than either a multi-layer prepreg duct or an aluminum duct of comparable size. Moreover, Gillfoam ducts may require no additional thermal insulation, depending on specific applications. This paper describes development issues, performance properties, and several applications of this state-of-the-art structural foam.

**INTRODUCTION**

Rigid polyisocyanurate (polyurethane) and polyvinyl chloride/urea-amide alloy foams have been used widely in the aircraft industry for a number of years. Typical applications include ECS ducting, edge closeouts in thin sidewall panels and overhead stowage bins, and as a close-outs in galley and lavatory sandwich panels, food carts and other applications.

These foams are used to prevent moisture penetration into the sandwich panel and degrading the properties of the Nomex® honeycomb used as the majority of the core of the panel. Foam close-outs having densities greater than 10 lbs/ft<sup>3</sup> have inserts installed and are used as points of attachment to the framework of the aircraft. Both the polyurethane and polyvinyl chloride/urea amide alloy foams provide some sound attenuation and thermal insulation.

Potting using two-part epoxy and other polymeric systems is also used for closing out panel edges, but this is both costly and labor intensive. Each panel must be prepared for the potting operation by cutting the Nomex® honeycomb back from the edges, leaving both facings intact. This operation requires sophisticated programming of capital intensive, high

\*Patent Pending

speed routing equipment (usually a CNC machine) or manual routing by highly skilled personnel. Potting compounds must then be mixed prior to use. These have a finite shelf life and once mixed, they have a limited pot life. Any residual material and the mixing utensils are subject to the laws of hazardous waste disposal. The potting itself is done manually and the uniformity is applicator dependent.

Current methods of supplying conditioned air to aircraft passenger compartments employ main ducts composed of aluminum or polyurethane foam. Aluminum ducts are costly to fabricate. Moreover, they are relatively heavy, must be insulated and are subject to a high damage rate during installation. Repairs are difficult and cut edges are sharp. Polyurethane foam ducts offer significant weight savings, but have high OSU (Ohio State University) heat release and NIST (National Institute of Standards and Technology)\* smoke density values.

A major concern to the airframe manufacturers is smoke generation and OSU heat release values of components used in the cabin interior. The flammability characteristics of wall panels, stowage compartment exteriors, galley faces and other visible items in the crew and passenger cabins are governed by FAR 25.853 (CFR, 1992) and must meet the requirements of Appendix F, Parts I through V plus the stringent specifications for burn and smoke values established by the aircraft manufacturers themselves. FAR 25.853 limits the smoke density (Appendix F, Part V) (D<sub>s</sub>) to 200 in the NIST smoke chamber. In Part IV, the OSU heat release on the same items must not exceed an average peak rate of 65 kilowatts per square meter (KW/M<sup>2</sup>) and an average total heat release of 65 kilowatt-minutes per square meter (KW·MIN/M<sup>2</sup>).

## DEVELOPMENT ISSUES

The development of a structural phenolic foam has been a difficult and frustrating challenge. Gilfoam is the result of a major multi-year research and development effort. One key objective for developing this product line was to take advantage of the exceptionally low flammability and smoke evolution characteristics offered by polymers based phenolic resole chemistry. Another key objective was to develop a low smoke foam that would also offer structural capabilities suitable for a variety of aircraft applications. Moreover, manufacturing a structural foam material whose characteristics are consistent from lot to lot was an especially important development task for complying with contemporary quality systems.

The development of Gilfoam required the evaluation of many interdependent material and process variables. The formulated phenolic resin is a complex mixture of ingredients that gives a foam that not only has low smoke, but generates minimal toxics when burned in the NIST smoke chamber. The following is a list of the criteria and properties chosen for a viable low smoke foam:

- Little or no shrinkage during the foam process
- Density controllable from 4.0 - 20.0 lbs/ft<sup>3</sup>
- Uniform cell size and distribution resulting in uniform foam density from top to bottom, regardless of foam thickness
- Non-corrosive in contact with treated aluminum
- Rigid, yet somewhat conformable in thin slices and low densities
- Processing latitude or robust design

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\*Formerly National Bureau of Standards (NBS)

The formulations used to produce various density phenolic foams contain no chlorofluorocarbons or other potentially ozone-depleting chemicals. Ingredients and process conditions were chosen carefully to provide a balance of selected characteristics. Small, closed and uniformly shaped cells, sufficient speed of cure to prevent foam collapse, even distribution of phenolic resin and low friability were among the primary characteristics chosen for monitoring. Mold geometry, size and position of vents, mold temperature and heat profile are important process considerations. Throughout the research and process development phase, utmost consideration was given to meeting customers' performance requirements, the cost of the phenolic foam products, manufacturability in a production environment and safety of the operation.

## RESULTS

This section compares flammability, mechanical properties and thermal conductivity of Gillfoam with those of commercial polyurethane and polyvinyl-alloy products. Properties of shaped phenolic foam products follow the presentation of data for flat (or sheet) Gillfoam. OSU heat release and thermal conductivity tests were performed by independent, certified laboratories. All other flammability and mechanical tests were conducted at the M.C. Gill product development laboratory except as noted in the accompanying tables and figures.

Polyurethane sheet stock (18.0 pcf density, .5 inch thick) was found to have an average NIST smoke density ( $D_p$ ) of more than 300 and average OSU heat release values of 144 Kw/m<sup>2</sup> average peak heat release rate and 164 Kw-min/m<sup>2</sup> total heat release. These values far exceed the limitations of FAR 25.853, Appendix F, Part V, ¶ b and Part IV, ¶ g, respectively.

This polyurethane product is used by a major aircraft builder to form edge close-outs for honeycomb/phenolic fiberglass sandwich panels. Due to the high smoke generation and heat release values, that airframe manufacturer currently limits polyurethane foam close-outs to .5 inch wide strips. In lighter density (about 5 lbs/ft<sup>3</sup>) a sandwich of polyurethane foam and fiberglass is used as the main air handling (ECS) duct of a major airframe manufacturer. Although the polyurethane ECS duct does not have to meet the requirements for OSU heat release values of FAR 25.853, this airframe manufacturer is screening alternate materials and designs to reduce smoke generation, OSU heat release and toxic gas evolution of all cabin components.

Polyvinyl alloy foam is used typically in densities of 7.0 lbs/ft<sup>3</sup> and lower in aircraft components. Its flexibility as a thin sheet allows it to be used in contoured shape close-outs. Besides its relatively high cost, this foam also exhibits high optical smoke density generation and OSU heat release values. The data in Table I compare the flammability, smoke density and OSU heat release values of Gillfoam with results for typical aerospace grades of polyurethane and polyvinyl chloride/urea-amide alloy foams at similar densities.

The data in Table II compare the mechanical properties of Gillfoam versus the same materials as in Table I.

**Table I**  
**Flammability Characteristics of Gilfoam,**  
**Polyurethane and Polyvinyl Chloride/Urea-Amide Alloy Foams**

Property	Unit	Gilfoam™		Polyurethane	Polyvinyl Chloride Urea-Amide
Nominal Density	lbs/ft <sup>3</sup>	7.0	18.0	18.0	7.0
Smoke Density	D <sub>s</sub>	18.3	17.0	319.9 <sup>1</sup>	555.0
OSU @ .5" Thickness Average Peak Release Rate Average Total Heat Release	KW/M <sup>2</sup> KW-MIN/M <sup>2</sup>	38.6 53.9	54.4 64.6	144.9 164.2	50.2 80.2
Flammability - Vertical @ .5" Thickness Burn Length Extinguishing Time Flaming Drops	inches Seconds Seconds	1.3 .7 0	2.3 1.2 0	3.3 1.7 0	4.3 3.6 0

1. General Plastics Company.

**Table II**  
**Mechanical Properties of Gilfoam,**  
**Polyurethane and Polyvinyl Chloride/Urea-Amide Alloy Foams**

Property	Unit	Gilfoam™		Polyurethane	Polyvinyl Chloride/ Urea-Amide Alloy
Nominal Density	lbs/ft <sup>3</sup>	7.0	18.0	18.0	7.0
Thickness	inch	.5	1	1	.5
Compressive Strength	psi	190	1257	877	128
Compressive Modulus	psi	3,799	22,935	8,750	2,591
Shear Strength	psi	83	428	548	199
Shear Modulus	psi	3,414	7,899	16,322	8,553

Thermal conductivity values were determined according to the heat meter method outlined in ASTM C-518. Gillfoam from 4.5-18.0 pcf density was evaluated at two elevated temperature ranges. A plot of thermal conductivity values versus foam density is shown below in Figure 1. The graph shows a good fit for a linear correlation of thermal conductivity with the foam density.

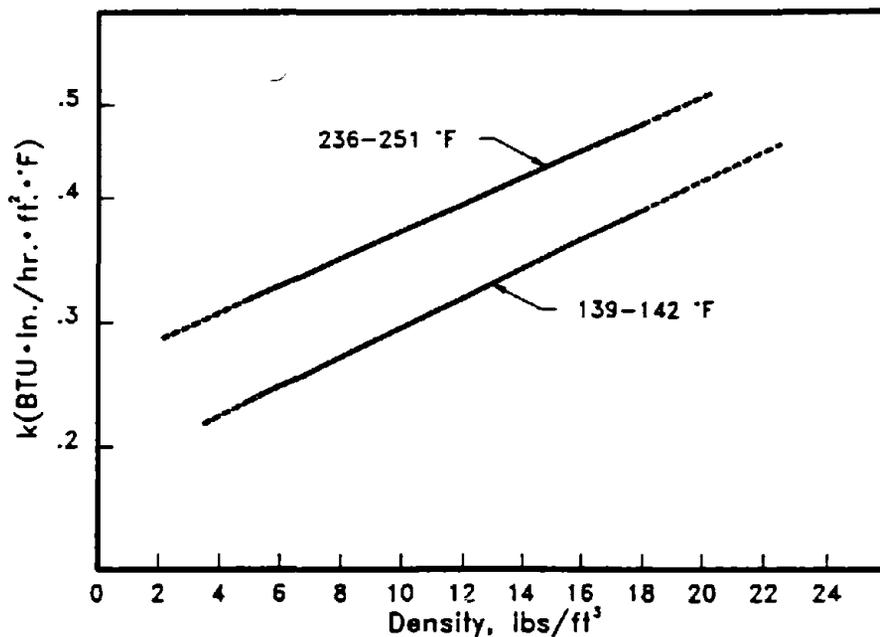


Figure 1 - Thermal Conductivity of Gillfoam

The data in Table III compare the thermal conductivity of the phenolic foams at various densities versus common insulating materials used in the construction industry. The values for the latter products were obtained from the ASHRAE Handbook (ASHRAE, 1981). This shows that the phenolic foam has good insulating properties which lead to other potential applications where low flammability and low smoke generation are also considerations.

**Table III**  
**Thermal Conductivity of Phenolic Foam Versus**  
**Common Insulating Products**

Material	Density (lbs/ft <sup>3</sup> )	BTUIN/HR-FT <sup>2</sup> -F
Asbestos-Cement Board	120	4.0 <sup>1</sup>
Cellular Glass	8.5	.35 <sup>1</sup>
Expanded Perlite	1.0	.36 <sup>1</sup>
Cellular Polyurethane	2.0	.14 <sup>1</sup>
Mineral Fiber w/binder	15.0	.29 <sup>1</sup>
Expanded Polystyrene	1.8	.25 <sup>1</sup>
Phenolic Foam	4.5	.22 <sup>2</sup>
Phenolic Foam	7.0	.26 <sup>2</sup>
Phenolic Foam	10.0	.29 <sup>2</sup>

1. Determined at 75°F
2. Determined at 139-142°F

Phenolic foam can be used as the core of a sandwich panel with a variety of facings including phenolic/fiberglass or phenolic/carbon. The facings may be composed of unidirectional tows or woven fabric. Depending upon the density of the foam, the end products can be used for fire resistant walls or ceilings of buildings, aircraft, marine or other areas where a low smoke, light weight, insulating product may be useful.

Light weight polyurethane foam (4.0 pcf nominal density) is foamed in place between faces of fiberglass cloth in predefined shaped molds for various end uses. In particular there is an oval foam ECS duct used for supplying conditioned air in the main cabin area which runs the length of the aircraft in a number of models of a major manufacturer's aircraft. Brackets, diffusers and outlets are cemented in place. The M.C. Gill Corporation has developed a low smoke, phenolic foam duct which can be used in this application. This duct duplicates the low weight of the polyurethane duct, but exhibits very low flammability and smoke values. Moreover, the phenolic foam duct does not cause pitting when in contact with an anodized aluminum plate at 95% relative humidity and 160°F in a humidity chamber for 10 days.

The data in Table IV compare the flammability properties of Gillfoam foamed in place between fiberglass facings to a similar construction using polyurethane foam.

**Table IV**  
**Flammability Characteristics of Gillfoam<sup>®</sup>/Fiberglass Skins and**  
**Polyurethane Foam/Fiberglass Skins**

Property	Unit	Gillfoam	Polyurethane
Smoke Density	D <sub>s</sub>	14.0	256.0
OSU @ .5" Thickness Average Peak Release Rate Average Total Heat Release	KW/M <sup>2</sup> KW-MIN/M <sup>2</sup>	40.7 32.6	121.6 148.9
Flammability - Vertical @ .5" Thickness Burn Length Extinguishing Time Flaming Drops	Inches Seconds Seconds	2.0 .5 0	2.6 1.7 0

Depending on the type of service, Gillfoam ducts may be useable without additional insulation to prevent heat loss. The following provides an example based on standard calculations. Aluminum has a thermal conductivity (k) of 1532.3 BTUin/hrft<sup>2</sup>°F. Assuming a linear relationship with thickness, a .020 inch thick aluminum sheet would have a thermal conductance (C) of 78115 BTU/hrft<sup>2</sup>°F. Such a conductance would require that the aluminum duct be wrapped with an a .8 inch thick layer of a 2 lb/ft<sup>3</sup> density mineral fiber batt to obtain an equivalent thermal conductance of a .5 inch thick 4.5 lb/ft<sup>3</sup> density phenolic foam duct. Thus, aircraft safety is also being supplemented with weight savings and overall size reduction by the availability of low smoke phenolic foam ducts.

In addition to the low smoke and low flammability properties, the phenolic foam also exhibits low toxic gas emission, good insulation properties and good structural properties. At higher densities (15.0 lbs/ft<sup>3</sup>) the foam can easily be machined into various shapes on most types of milling equipment. Patterns can be embossed into the foam to allow volatiles and excess resin to escape during manufacture of any product which incorporates a composite skin on one or both sides.

## **SUMMARY**

The continued desire of airframe manufacturers to reduce the OSU heat release and smoke density values of components used in the cabin area of commercial aircraft was the impetus for the M.C. Gill Corporation to develop a low smoke phenolic foam. This product is available in sheet stock in densities of 4.5 to 20.0 lbs/ft<sup>3</sup> in various sizes up to 18"x100" and in thicknesses from .25 inch. All foamed to shape products (such as ducts) are produced to customer requirements for density, size and wall thickness.

Sandwich panels using Nomex honeycomb core and the low smoke foam as the edge closeouts can be produced to customer requirements. Either phenolic/fiberglass or phenolic/carbon skins can be utilized to give an overall panel construction of light weight, easy installation and low smoke and low OSU heat release values. Flat panels using this foam as the entire core material could find use as walls in galley areas, food carts and other areas where additional insulation properties might be advantageous. The availability of a high quality, structural, low smoke phenolic foam gives rise to other potential products which previously could not be made from other types of foam owing to their excessive flammability and smoke generation.

## **ACKNOWLEDGEMENTS**

We wish to thank Rose Verdon and Daisy Qiu for their efforts in the preparation and testing of all of the phenolic foam products discussed in this paper. We also wish to thank Andrea Foelsch for her patience and expertise in preparing this manuscript.

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**"Polyimide Foam Insulation Systems"**

**A Major Weight Reduction and Improvement in  
Fire Resistance of Sidewall Systems**

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## INTRODUCTION

As a result of the 1967 Apollo fire, NASA started the Fireman Program. NASA's requirements for materials were for the lowest possible smoke, flame spread, toxicity, off-gassing and out-gassing. The final NASA requirement was that weight should not exceed that of the existing materials. This resulted in the full development of polyimide foam. Solimide® polyimide foam exceeds all of the stated requirements including weight, which is up to five times lighter in some applications than the materials it replaces.

Commercial aircraft is a different situation. Today there are very limited fire requirements on insulation materials, or any material outside those requiring the C.S.U. Heat Release and Furnace Burners. However, there are several potential changes in requirements that would effect insulation in the future:

1. In the future, expansion of the fire test requirements such as O.S.U. Heat Release, Smoke Generation, etc. to include all non-metallic materials, structures and systems from the skin in-board throughout the entire interior.
2. Burn-through requirements as discussed by the CAA on Thursday and their proposed test and fire hardening of aircraft being developed by Darchem Engineering, Ltd. Darchem's presentation is tomorrow.

Additional testing or improved fire hardening has usually been considered as costly and unnecessary relative to benefits derived.

Weight is of definite concern to the aircraft manufacturer. Polyimide foams offer a 20 to 40% reduction in weight when compared to fiberglass .42 lb./ft<sup>3</sup> aircraft grade insulation. In addition, the burn-through resistance is improved with little or no loss in thermal or acoustical properties.

Since the Manchester, England crash, burn-through has become an issue and the British CAA is addressing the issue aggressively. Many survivable crashes and ramp fires have exhibited burn-through as a problem. Rapid smoke development and toxic gases are also very prevalent in these fires. Older aircraft are being upgraded to meet 1990's noise standard. However, these same aircraft are still certified under 1940's flammability standards and are not required to upgrade unless, for all intents and purposes, a totally new interior is installed.

## REQUIREMENTS

As previously mentioned, the fire requirements for commercial aircraft are very lenient. The only non-metallic systems or materials requiring more than a bunsen burner test are cargo liners and seats requiring the kerosene burner tests, and interior passenger cabin surface panels requiring the O.S.U. Heat Release and N.B.S. smoke chamber. All of these tests require only a pass/fail and none are tested to destruction. Today, the kerosene burner test is the only one that could be called a severe test. Insulations fall under 25.853a(ii) vertical bunsen burner with a 12 sec. exposure to the flame, average burn length of no more than 8", and the flame must self-extinguish in 15 sec. If there are drips they must self-extinguish in 5 sec. or less.

As these areas of concern, such as burn-through are identified, new tests will be developed and requirements established and enforced. These tests and requirements will be regulated by authorities to meet today's needs as well as tomorrow's. The O.S.U. rate of heat release took from the early 1980's to August 20, 1988 to be implemented as a FAR. In the U.S.A. the FAA is hampered by a long legislative process since FAR's are laws, which are passed by Congress. Other countries can regulate new requirements much more expeditiously. All public forms of transportation: rail, bus, ship and air regulations are being upgraded in safety and survivability, internationally. Just as burn-through is being investigated by the CAA, smoke, toxicity, heat release, etc. are being considered as part of the requirements for all modes of public transportation in many countries. Both manufacturers and suppliers must be aware of this fact and work to improve their products from all aspects of a fire safety standpoint. The question is not what the FAA requires today, but what is going to be required by the FAA and also by the international community.

## POLYIMIDE FOAMS

Polyimide foams are used in a variety of specialty applications in aircraft. Some of these are duct insulation, bulkhead cushioning foam, fire barriers, void fillers, floor insulators, etc. In these applications the foam is either modified by specialty fabricators or combined with other products or systems, to meet specific needs of the airframe manufacturer. Amelia De Baggis of Illbruck, Inc. will be discussing some of these areas in the next presentation. My discussion will center on the thermal and acoustical fuselage insulation.

Today, both polyimide foams and the more traditional fiberglass insulation, meet all of current regulatory requirements. For all practical purposes, fiberglass and polyimide foams are comparable thermally and acoustically on a weight/performance basis. The installed performance does vary as the fiberglass compresses much more readily than polyimide foams, thus degrading the installed performance. The covering materials are polyester or polyvinyl fluoride films. These films are acceptable only because of the test method, as I will show later.

The primary reason polyimide foams are being designed into the fuselage insulation systems is weight reduction. This weight reduction can be significant, as polyimide foams can be made much lighter than the traditional fiberglass aircraft insulation products. Due to the difference in the compression resistance of the two systems, the polyimide is generally equal in performance at a reduced weight. This weight difference is typically 20 to 25%, but can be as high as 40% depending on the overall thermal and acoustical requirements. To meet the needs, Imi-Tech has introduced a new series of foams for aircraft applications. The Solimide AC-400 series polyimide foams have all the traditional fire properties of polyimide foams plus very good thermal and acoustical properties for their weight. These foams can be produced as low as 3.2 kg/m<sup>3</sup> with a typical range requested by the airframe manufacturer in the 4 to 5 kg/m<sup>3</sup> range.

## BURN-THROUGH

As mentioned in the introduction, a burn-through test is being developed for consideration by Darchem Engineering, Ltd. of England for the British CAA. This test will subject the fuselage construction and the system in-board from the skin, such as the insulation system, to high heat flux. The test is designed to simulate pool fire scenarios on a small scale basis.

NASA-Houston investigated the use of the furnace burner in the early 1980's. This demonstrated rapid burn-through of the aluminum skin in approximately 30 seconds, and also the fiberglass system in 30 seconds. It took several additional minutes to burn through the polyimide insulation in their test scenario. In a full-scale test both insulation systems fell into the pool fire. Work stopped at that time but the furnace burner concept carried onto the seats and cargo liner tests.

As the new CAA test was not available for testing prior to this meeting, we asked Darchem to try and simulate the heat flux of the new CAA test. They constructed a 1m<sup>2</sup> test fixture with burners which operated at 2200° F. The test samples consisted of an aluminum skin of 1.6mm with three frames. Between the frames (21" on center) were placed a series of 6 sample sets. There were five configurations of .42 lbs./ft.<sup>3</sup> aircraft grade fiberglass and Solimide AC-403 polyimide foam tested, and one set of .6 lbs./ft.<sup>3</sup> fiberglass and Solimide AC-406 polyimide foam.

TABLE I  
INSULATION SYSTEMS CONFIGURATIONS

	FRAME BAY 1	FRAME BAY 2
TEST 1	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
TEST 2	3" .42 lbs./cu.ft. fiberglass	3" Solimide AC-403
TEST 3	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
	1" Solimide AC-403	1" .42 lbs./cu.ft. fiberglass
	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
TEST 4	3" .60 lbs./cu.ft. fiberglass	3" Solimide AC-406 (nominal density .5)
TEST 5	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
	1" Solimide AC-403	1" .42 lbs./cu.ft. fiberglass
	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
	1" Solimide AC-403	1" .42 lbs./cu.ft. fiberglass
	1" .42 lbs./cu.ft. fiberglass	1" Solimide AC-403
TEST 6	5" .42 lbs./cu.ft. fiberglass	5" Solimide AC-403

These test configurations represent thickness commonly found in fuselage insulation systems today. The systems are primarily .42 lbs./cu. ft. fiberglass, however, the .6 lb./cu.ft. fiberglass is used in some narrow body aircraft.

The combination of fiberglass and polyimide is being used and being considered in new designs, due to unique acoustical properties and a considerable weight reduction.

**TABLE II**  
**BURN-THROUGH RESULTS**

	FRAME BAY 1	FRAME BAY 2
<b>TEST 1</b>		
Aluminum	Not reported	Not reported
System	1 min. 46 sec.	----
Test stopped before Solimide frames.	had burn-through. Both samples	were falling from between the
<b>TEST 2</b>		
Aluminum	No reported	Not reported
System	2 min. 20 sec.	2 min. 55 sec.
Delta		+ 35 sec.
<b>TEST 3</b>		
Aluminum	1 min. 57 sec.	1 min. 57 sec.
System	3 min. 0 sec.	3 min. 20 sec.
Delta		+ 20 sec.
<b>TEST 4</b>		
Aluminum	1 min. 36 sec.	1 min. 36 sec.
System	2 min. 20 sec.	2 min. 40 sec.
Delta		+ 20 sec.
<b>TEST 5</b>		
Aluminum	2 min. 0 sec.	2 min. 0 sec.
System	6 min. 0 sec.	8 min. 5 sec.
Delta		+ 125 sec.
<b>TEST 6</b>		
Aluminum	1 min. 48 sec.	1 min. 48 sec.
System	2 min. 47 sec.	3 min. 11 sec.
Delta		+ 33 sec.

Please note this is not a standardized test. It was strictly run as a screening test as the CAA Burn-Through Test was not available. Burn-through was reported when flames were observed, and there were no stringers to position the insulation 1' from the skin or to block the vertical flame path.

## **SUMMARY**

As indicated in the preliminary burn-through testing the amount of insulation, the type, and the configuration, all have an influence. The combination of polyimide foam and fiberglass insulation is of particular interest as it has a positive influence on burn-through, weight, and on thermal/acoustical performance of the more traditional all-fiberglass systems. The reduction in weight by the use of polyimide also allows the redesign of the systems to incorporate flame barriers to improve burn-through time with little or no weight penalty. Imi-Tech is continuing to develop new systems and materials to meet the fire hardening requirements of the transportation industry while controlling weight, improving the installed cost, life-cycle cost, and safety for the ultimate-end customer--the passenger.

I would like to thank Harriet Ashworth of Darchem Engineering, Ltd., the Darchem Fire Test Laboratory and Bob Nali, of the Imi-Tech Research Laboratory for their support in the gathering, testing and reporting of the sample results on burn-through. We hope to have full-scale results on the CAA test in the near future.



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A POLYIMIDE FOAM FOR ADVANCED FIRE  
RESISTANT AIRCRAFT APPLICATIONS

Amelia DeBaggis

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ABSTRACT

A fire-proof, non-toxic and lightweight modified polyimide foam, has been designed for advanced fire-resistant aircraft construction. The fire-resistant, thermal, mechanical and water-repellency performance shows the insulation meets the needs of aerospace applications.

INTRODUCTION

The focus of this paper is the material performance characteristics and the potential aircraft application uses of willmid®FM.

willmid®FM has been determined to be a fire-proof polyimide foam insulation based on the results of some key aircraft material tests. Material performance tests have been conducted according to aircraft and marine standards.

The base foam insulation used to make willmid®FM is Solimide®AC406 or TA301. The polyimide is modified according to patent additives and processing. Because willmid®FM is made from Solimide and the willmid®FM additives are non-burning, the non-toxic off-gassing and low smoke properties are maintained, and its fire resistance dramatically improved. willmid®FM shows no flame penetration or burn-through when exposed to 2000°F flame per "FAA Firewall Penetration Testing," while the base polyimide under the same conditions burns through in less than one minute.

The performance testing of willmid®FM is not complete at this time. The material performance tests that have been conducted show that willmid®FM's fire, thermal, water repellency and mechanical properties can satisfy the FAA requirements for aircraft interiors, engine, auxiliary power unit (APU) and adjacent fire zone applications.

## FIRE PERFORMANCE

Evaluation of willmid®FM's fire and combined material tests show it can perform equally or better than metal, ceramic and composite plastic-type material fire shields used in aircraft engines and accessory areas.

A fifteen minute 2000°F, fire proof testing was conducted on willmid®FM without facings at 0.5 inch and 1.0 inch thicknesses. This test was performed in accordance to "FAA Firewall Penetration Test" (1). The flame did not penetrate or burn through the insulation and maintained integrity with a slight surface char and discoloration observed. The firewall penetration test is intended to determine the capability of the insulation to control the passage of fire to prevent additional hazards to the aircraft in cases of fire. 2 x 2 foot panels were placed horizontally at a maximum four inch distance to the 2000°F flame source with a minimum heat transfer rate of 4,500 British Thermal Units per hour (Btu/hr.). The insulation is exposed to the flame for 5 minutes to determine if it is fire-resistant and continued for a total of 15 minutes for fire-proof determination.

Another type of 2000°F burn-through fire test in accordance with MIL-STD-2031 (2) was conducted on willmid®FM. This test is used to evaluate fire penetration and insulating performance of firezone insulation for marine applications. Three variations of polyimide foam laminates with fiberglass facings were exposed to a 2000°F flame for 30 to 45 minutes. The specimen size is 2 x 2 foot panels placed vertical to the flame source at a distance of 18 inches with the flame providing 500,000 Btu/hr.

The insulation is observed for fire containment, material integrity and insulating characteristics. The temperature of the non-flame side or backside is monitored by three thermocouples placed on the insulation surface. The thermocouples are located at the top, middle and bottom sections of the insulation's backside. (Non-fireside).

None of the specimens burned through and the material maintained integrity with little to no disintegration. There was only a discoloration caused by a carbonization or char formation.

A 2 inch thick willmid®FM averaged 164°F at 5 minutes and 249°F after 15 minutes of fire exposure. A 2.0 laminate of 1.0 inch willmid®FM to 1.0 inch of Solimide®, (willmid®SF/FM) averaged, 219°F at five minutes and 332°F after 15 minutes exposure. All of the 2.0 inch constructions are laminations of 1.0 inch thick insulation, laminated with the same material used to make the 1.0 inch thick willmid®FM. The one inch thick willmid®FM averaged 317°F at 5 minutes and 328°F after 15 minutes. Both the 2.0 inch

willmid®FM and the willmid®SF/FM composites showed stabilization of the backside temperature in approximately 15 minutes of fire exposure. But, with the 1.0 inch thick willmid®FM, the backside temperature continued to rise to 470°F in 17 minutes before stabilizing. This temperature stabilization may indicate a protective carbonization formation. The fire exposure was run for 45 minutes on the 2.0 inch willmid®FM showing no additional appearance or backside temperature changes from the 15 minutes time period. Graphic examination of MIL-STD-2031 backside temperatures are shown in Figure 1.

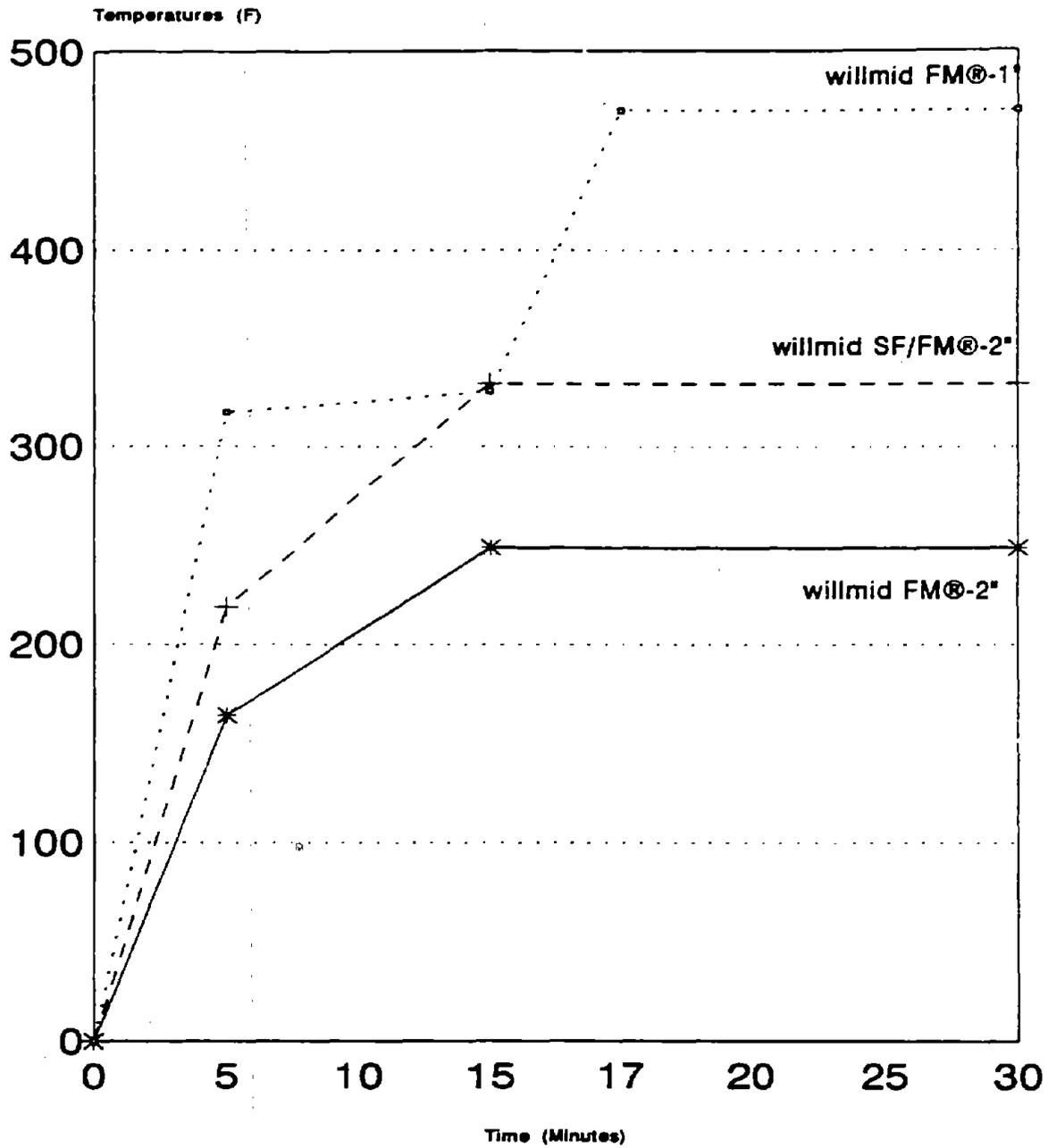


Figure 1: MIL-STD-2031  
Back Side Temperatures

## WEIGHT CONTROL

willmid®FM's density averages 2.70 pounds per cubic foot (PCF). The addition of facing laminates only slightly increases the total composite weight. By comparing areal weights based on one inch total thickness, the weight variations can be observed. (The addition of light weight 8.5 oz./yd<sup>2</sup> fiberglass increases willmid®FM's areal weight from 0.23 to 0.29 (pound per square foot) PSF. A laminate of heavy weight, 12.8 oz./yd.<sup>2</sup> fiberglass, gives a 0.32 PSF composite weight.) Other laminate composite weights can be determined from published data on Tedlar®, Kapton®, Hypalon®, and aluminized fiberglass.

Conversely, the addition of the base polyimide foam laminated to willmid®FM will significantly lower the composite weight. By comparing the areal weight of a 0.5 inch Solimide®AC406, laminated to 0.5 inch of willmid®FM, the composite weight is decreased to 0.14 PCF based on 1.0 inch total thickness. Table I shows the composite and laminate weight comparisons.

Table I: Areal Weight Comparison Based on 1.0" Total Thickness

Description	Weight (PSF)
Solimide®AC406	0.05
willmid®FM	0.23
willmid®FM/8.5 oz./yd. <sup>2</sup> Fiberglass laminate	0.29
willmid®FM/12.8 oz./yd. <sup>2</sup> Fiberglass laminate	0.32
willmid®SF/FM	0.14

## THERMAL PERFORMANCE

More foam is used for thermal insulation than for any other purpose. Several factors combine to limit heat flow in foams: the low volume fraction of the solid phase; the small cell size which virtually suppresses convection and reduces radiation through repeated absorption and reflection at the cell walls; and the poor conductivity of the enclosed gas (5). Polyimide foam is also included in this ideal structure because it is a light weight foam, and it has a high density of small cells contributing to the reduction of heat radiation. The thermal conductivity (K) of Solimide®AC406 and willmid®FM as measured per American Standard Test Method (ASTM) C518 "Steady State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus" at 75°F is 0.30 and 0.32 Btu-in-hr.<sup>-1</sup> ft.<sup>-2</sup> OF<sup>-1</sup> respectively. Both of these values are still very low in comparison to conventional insulating foams such as polyethylene and polyurethane which have typical thermal conductivity values of 0.30 and 0.35 respectively. These thermal K values are compared graphically in Figure 2.

## WEIGHT CONTROL

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willmid®SF/FM	0.14

## MECHANICAL PERFORMANCE

The mechanical properties of non-structural foams do not have a significant impact on fire and thermal insulation usage. Some mechanical tests have been conducted to compare willmid®FM with Solimide®AC406 (base polyimide foam). These tests were conducted according to the ASTM E-3574 "Methods of Testing Flexible Cellular Materials". The results are an average of five or greater specimens. The willmid®FM specimens were made from the same lot of Solimide®AC406. The tensile-elongation of willmid®FM shows that the strength and elasticity are not significantly changed, but with a trend to a less elastic and more rigid material.

The compression set of willmid®FM shows a loss of 49% of its original 1.0 inch thickness when compressed 50% in accordance with the ASTM E 3574 Method D. The same lot of Solimide® AC406 showed a 43% thickness loss. Even though the material usage is non-structural, a compression set is not a desirable feature due to potential thickness inconsistency that could occur when exposed to compression during installation or application usage. Potential compression set due to point loading is minimized by using protective facings, such as fiberglass, laminated to the exposed side. Material damage is reduced by increased handling experience.

There are numerous water absorption and immersion tests that measure percent weight gain or tensile loss after various moisture, heat and time conditioning. The actual requirements needed for each specific application should be conducted on a case by case basis. The ASTM E3574 Steam Autoclave J test, extending to eight days, at 120°F and at 95% relative humidity (RH) was conducted on willmid®FM and Solimide® AC406. The weight gain measured after a 1.0 hour (hr.) ambient drying condition showed willmid®FM at 0.7% and Solimide®AC406 at 7.0% and tensile values of 1.6 and 0.86 pounds per square inch (PSI) respectively, after the J2 Steam Autoclave testing (5 hours, 95% RH @ 125°C.) Even though willmid®FM's water weight gain is low compared to the base Solimide® polyimide, water is absorbed and diffused through the porous cell structure. For this reason, it is recommended that if the insulation is to be directly immersed, water protective laminations or coatings should be incorporated. A protective lamination of Hypalon® is currently in use to provide water repellency in aircraft heating and ventilation polyimide insulation duct wrap. Most plastic and elastomeric films and coatings have sufficiently low enough surface energy to give excellent water repellency and protect the foam surface from water exposure. These films and coatings should be screen tested to meet the Federal Aviation Regulation (FAR) requirements of smoke density, toxic gas and heat release rate. Table II shows the mechanical performance results per ASTM E-3574.

TABLE II: Mechanical Tests per ASTM E-3574

Property	Test Method	Solimide®AC406	Willmid®FM	Units
Tensile	E	6.0	9.4	PSI
Elongation	E	12.4	6.9	%
Compression Set	D	43.0	49.0	% loss
Steam Autoclave Aging (8 days, 120°F @ 95% RH)	J	7.0	0.7	% gain

## RECOMMENDATION AND CONCLUSIONS

Because of willmid®FM's balance of fire-proof, lightweight, thermal insulation and non-toxic properties, it can provide the solution to many aircraft material needs. Some potential applications are: firewalls, engine accessory areas, duct fire insulation blankets, cargo compartment liners and any aircraft components that need to show compliance to the "FAA Firewall Penetration Test".

Not all property testing has been completed on willmid®FM because it is a newly developed fire-proof polyimide foam insulation. But key fire performance tests that have been completed show the insulation is resistant to 2000°F flame without burn through for exposure times of 15 to as much as 45 minutes.

In addition to its fire performance, willmid®FM can be supplied in various forms and shapes. Molded saw cut tubes can be produced for duct wrap and die cut shapes to fit complex spacings. Various combinations of plastics, fiberglass and elastomeric films can be laminated to the insulation's surface to enhance its thermal, mechanical, water repellency, durability, electrical, acoustical and esthetic properties. Laminations of Scilmide® with willmid®FM can be incorporated to balance mechanical, thermal, and fire-proof properties. The mechanical and thermal properties show little to no detriment from the base polyimide foam properties, testing is ongoing. willmid®FM is being considered for tests in actual application constructions and configurations. Testing will be conducted to verify that the insulation meets all the durability, mechanical, thermal and fireworthiness aircraft requirements.

## **ACKNOWLEDGEMENTS**

The author is thankful to illbruck, incorporated for the opportunity to work with its patented, fire-resistant, high temperature, and non-toxic foams as an Applications Engineer.

illbruck, incorporated is an international foam fabricator of engineered thermal and acoustical foam insulation for aerospace, marine, automotive, construction and industrial applications.

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**A Repair Patching System for Aircraft Cargo Liners**

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**ABSTRACT**

With the FAA's mandate that cargo liner repair patches must meet flame penetration requirements described in FAR 25, Appendix F, Part III, several new repair systems were introduced to the airlines to meet this demanding application. Previously available patches consisted of liner material with a pressure sensitive adhesive. While easy to use, the adhesive could not withstand temperatures to 1800°F, as required by the flame penetration test. Consequently, the patch fell from the liner, allowing the flame to penetrate the damaged area. The currently available repair systems were developed to meet the flame penetration requirements; however, the patches are difficult and time-consuming to apply. Moreover, they are expensive.

A new patching system was developed which can be applied in less than 5 minutes, depending on the extent of the damage. This system is designated Gillpatch II and meets all flammability and flame penetration resistance tests described in FAR 25.855. The patch and adhesive combinations will be available in kits for rapid, on-the-spot repairs. This paper describes the installation criteria and technical approach to solving the repair patch needs of the airlines and maintenance stations.

**INTRODUCTION**

Cargo and baggage compartment lining materials for commercial aircraft are designed to provide physical protection for the fuselage and the electrical, hydraulic, and mechanical control systems routed through these compartments. Additionally, the liners are required to serve as a fire containment system by preventing flames from penetrating the cargo compartment for a period of up to five minutes, during which time extinguishing or other emergency procedures can be effected. The earliest liners were required to be self extinguishing when tested by relatively conventional gas burner methods; but, the concept of fire containment imposed a new criterion which further restricted the choices of materials from which cargo liners and repair systems could be constructed. Since flame penetration testing is performed at a temperature of  $1700 \pm 100^\circ\text{F}$ , organic polymeric reinforcing fibers could no longer be used; even aluminum melts at the test temperature.

The flame penetration test apparatus, as described in 14 CFR Chapter 1, Part 25, Appendix F, Part III, (1.) is shown in Figure 1. A high intensity flame, provided by an oil burner, is directed forcefully at the cargo liner, producing the  $1700^\circ\text{F}$  temperature at the liner's surface. The thermal output of the flame is calibrated at  $9.1 \pm 0.6$  watts/cm<sup>2</sup>. A

thermocouple is placed four inches above the back surface of the cargo liner under test, and the indicated temperature must be no higher than 400°F at any time during the test period of five minutes. Cargo liners containing woven fiberglass fabric reinforcement have been successful, generally, in meeting flame penetration resistance requirements. The resin/binder systems in these liners are major contributors to physical and mechanical properties, but are short-lived at 1700°F.

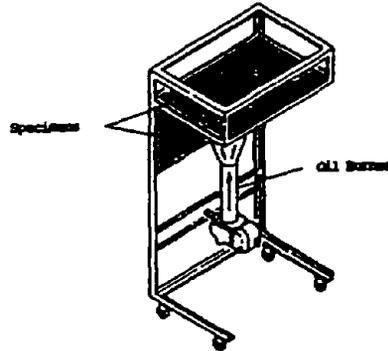


Figure 1 - Flame Penetration Resistance Test Apparatus

#### REPAIR PATCH BACKGROUND

Cargo liners are subject to physical abuse from the rigors of loading and unloading baggage and cargo, shifting loads, and handling equipment. Punctures and tears compromise the mechanical and fire containment integrity of the liner. Total replacement of a damaged liner is not always possible, or practical, since it is time consuming, expensive, and liner availability at remote locations can be a problem. The types of damage encountered most often are relatively minor punctures and tears, and the damage could be repaired quickly and inexpensively with suitable repair patch systems. The early patches were simply cargo liner materials, one side of which was coated with a pressure sensitive adhesive, and repairing a damaged liner entailed removing the protective covering from the adhesive and pressing the patch in place over the damage. The patch restored the mechanical properties of the liner. As the liner, the patch was self extinguishing and resistant to flame penetration by the small-scale gas burner test methods. However, such patches could not survive the rigors of the larger scale oil burner test because the adhesive melted and decomposed at the test temperatures, causing the patch to fall off, thereby allowing the flame to penetrate the damaged liner.

Two types of repair patch systems were developed to meet the flame penetration requirements:

- a) a mechanically fastened liner section which utilized a number of rivets to attach it to the damaged liner and,
- b) a multiple layer epoxy/glass fabric system.

The mechanically attached patch has been criticized by the airlines because of its cost and difficulty of application. A large number of holes must be drilled around the damaged area, and the patch fastened by blind rivets. The epoxy patching systems avoid the problems of drilling through the liner, but they, too, have proven costly because of the one-half hour or more required for installation.

The M.C. Gill Corporation currently supplies cargo liner for a riveted patch system (under license by Douglas Aircraft Company). However, the airlines, in general, and the Air Transport Association have expressed dissatisfaction with currently available repair patches. To continue its commitment as a full service supplier to cargo liner customers, the company undertook a major program to develop an acceptable patching system.

#### **INSTALLATION - TARGETED CRITERIA**

Potential customers for liner repair patches were queried, and a "wish list" of desirable properties emerged. These properties became the objectives of the development project -- in addition to the prime requirement of flame penetration resistance. Cost reduction, of course, was the ultimate goal, but this overall objective comprises many different attributes:

- **Rapid Installation**
  - Eliminate the need to remove liner for repairs
  - Eliminate time consuming surface preparation of liner
  - No special tools needed -- patch kit is self contained, i.e., nothing else needed for installation
  - Patch kit readily available, can be carried in cargo compartment for easy accessibility
- **Permanent repair, not necessary to replace liner if damage is within allowable limits**
- **No risk of damage to systems behind the liner**
- **No need for high skill or knowledge level of adhesive systems**
- **Maintain integrity of cargo liner mechanical properties**
- **Light colored, reflective surface**
- **Resistant to commonly used cleaning materials**
- **No solvents or noxious fumes**
- **Residual adhesive and mixing paraphernalia easily disposed of after use**
- **Shelf life of patch kit greater than one year**

## REPAIR PATCH DEVELOPMENT

The ease of application of the "stick-on" patch prompted an initial investigation into improved, heat resistant pressure sensitive adhesives. During fire testing, temperatures of the patch/liner interface reach 1000-1200°F with a nominal 0.030 inch thick patch, and no adhesive was found which could withstand such temperatures. Even with so-called improved adhesives, patches remained in place only 20-30 seconds longer than with the standard pressure sensitive adhesive. Additives to the patch resin/binder system to improve thermal barrier properties provided a slight improvement in patch life, but performance was still far short of specification requirements.

Replacement of the pressure sensitive adhesive with two-part epoxy adhesives showed further improvement in patch stability under the flaming conditions, but, again, this approach failed to meet FAA burn through requirements. Throughout the development program, the design philosophy was a total system concept; i.e., all of the property goals were considered in the experimental design, rather than a sequential, one-at-a-time investigative process. A major consequence of systems development was the incorporation of a laminate, similar in construction and properties to the cargo liner, to serve as the actual patch, thus focusing emphasis on the patch adhesive and technique for providing a thermal barrier to delay the decomposition process.

As noted earlier, the addition of materials to reduce thermal conductivity of the patch were unsuccessful and the introduction of intumescent materials was investigated. Intumescence or swelling under the influence of elevated temperatures can be caused by the generation of gases resulting in the expansion of the material, producing a cellular or foam-like structure. The expanded substance shows greatly enhanced insulating properties, which can be sufficient to protect material underneath from further damage. The combination of organic polymers and the high temperatures of the fire penetration test cause rapid decomposition and formation of gases, but these conditions do not necessarily result in a self-supporting intumescent structure. However, the presence of gas-forming, fire retardant additives can aid the foaming mechanism before complete decomposition occurs, leading to the formation of a carbonaceous char. The integrity of the remaining intumesced layer is dependent on the type of polymer and the char-producing additives used. In the worst case, only an inorganic ash remains, which drops off or is easily blown away by the force of the flame.

Early experimentation with intumescent polymer systems showed the effectiveness of the concept by doubling patch life, i.e., to 3-4 minutes from the previous 1-2 minute flame exposure times. With sufficient insulation of the pressure sensitive adhesive, it was surmised that the frequently-used cargo liner top surface of Tedlar® film could also be prevented from melting or decomposing. If this thermoplastic film remained stable, the patching system could be applied directly to the liner without the burdensome and time consuming task of removing the surface film.

The incorporation of an intumescent layer on the patch surface caused another mechanism of failure to become apparent; namely, the application of the flame and rapid decomposition of the resin binder systems induced voluminous outgassing resulting in distortion and blistering of the cargo liner. This severe mechanical stress leads to gap formation around the unprotected edges of the patch. Consequently, the adhesive system was exposed directly to the flames which caused melting and decomposition, followed rapidly

by repair patch failure. The application of an intumescent adhesive around the edges of the patch, and overlapping the patch and liner by about  $\frac{1}{2}$  inch appeared to be a viable technique without seriously compromising any of the stated ease-of-application goals. The configuration of the repair patch is shown in Figure 2.

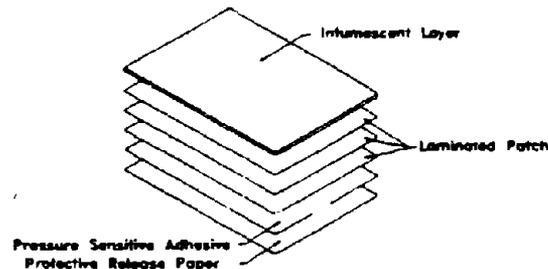


Figure 2 - Gillpatch II Construction

Efforts were focused on developing an adhesive/edge seal with intumescent properties similar to the layer on the patch. The materials which appeared to meet the ease of application criteria were the two-part epoxy adhesives. A flame retardant system with a gelling time of 4-6 minutes at room temperature, and containing intumescent additives has been found to provide adequate thermal protection for the edges. During the application of the flame, both the surface layer and edge seal expand to form a char structure 4-6 times thicker than the original thickness of these materials. In addition to forming a thermal barrier, the char around the edge retains sufficient integrity to prevent its destruction from the warping and swelling mechanisms induced during exposure to the flame.

#### REPAIR PATCH INSTALLATION

Because it was not necessary to remove the Tedlar surface film as supplied with many cargo liner systems, installation time was easily held to under five minutes, depending on the extent of the damage and condition of the liner surface. For optimum adhesive bonding, the surfaces to be joined must be free of grease or oil, and they must be dry and reasonably free of solid debris or contamination. Surfaces of Tedlar are cleaned easily by wiping with a clean dry cloth, or for more stubborn contamination, using an approved cleaning solution/solvent. After preparing the surface around the damaged area, the protective paper covering the pressure sensitive adhesive is removed, and the patch pressed in place by hand pressure. The two-part edge seal is supplied in a ratio-pack container which allows convenient mixing in a closed system. After mixing for about one minute, a corner is torn from the pack, and the adhesive is squeezed out (much as toothpaste from a tube) around the edges of the patch, using all of the material in the container. The adhesive is then spread evenly around the edges, overlapping on the patch about  $\frac{1}{4}$  inch, and on the liner about one inch. The adhesive hardens to the touch in 4-6 minutes at 70°F, and is sufficiently cured after 10-15 minutes to meet the flame penetration requirement. At a temperature of 40°F, the hardening time is 30-45 minutes and the adhesive is functional after 10-15 additional minutes.

## REPAIRABLE DAMAGE

Assessments of cargo liner damage which is repairable vary considerably among the airlines and the aircraft manufacturers. The overriding criterion, of course, is that the integrity of the liner be maintained both as a mechanical protection and as a fire containment system. This consideration implies that the extent of a repair must be capable of being tested to insure compliance with the 14A requirements. Because the flame penetration test specimen size is 16 inches x 24 inches, any damage and repair must be contained in an area no larger than 12 inches x 20 inches to accommodate a 2 inch margin surrounding the damage (2.). The nature of the damage must also be considered, and, for cargo liner laminates, two types of minor damage usually occur: tears, either straight or L-shaped; and holes, which, in effect, remove liner material from the immediate area of the damage. Sandwich panel liners can suffer punctures, flexural damage, skins broken on one or both sides, core damage, and delamination - all of which pose difficult or non-repairable situations. The FAA has recommended limitations on the extent of damage which is repairable (2.). Damage outside of those limits require the cargo liner section to be replaced. These limits were used for the patch system described in this paper, and are as follows:

- a) Slits up to 12 inches long
- b) L-shaped tears up to 9 inches by 5 inches
- c) Holes up to 1.5 inches in diameter

## SUMMARY

A cargo liner repair patch system was developed which meets the flammability and flame penetration requirements of FAR 25.855 (CFR 14, Chapter 1, as of 01/01/92). The patch does not use mechanical fasteners, eliminating the need for drilling or removing the liners for repair, and it can be applied in under 5 minutes. Different size patches will be available in kits for ease of storage and availability for rapid repairs at remote locations. FAA certification and compliance testing programs are in progress, and patches are expected to be introduced for sale before the end of March 1993.

## ACKNOWLEDGEMENTS

The authors wish to thank Nha-Hanh Nguyen and Mike Schoepke for their invaluable work in the patch development program and many thanks are due also to Andrea Foelsch for her preparation of this paper.

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PRIMASET™: A SAFER MATERIAL FOR AIRCRAFT INTERIOR APPLICATIONS

Sajal Das

AlliedSignal, Inc., Morristown, NJ 07962

Aircraft interior designers favor plastics for their low weight, decorative effect and functional strength. However, many plastics tend to emit smoke and toxic gases when they burn. Organic compounds such as hydrogen cyanide, hydrochloric acid, sulfur dioxide, carbon monoxide and various oxides of nitrogen can be part of the lethal gaseous cocktail that modern laminates produce on combustion. Following a number of highly publicized accidents in which fatalities were primarily caused by fire on the ground, the Federal Aviation Administration (FAA) has moved to upgrade the fire performance of aircraft interiors, focusing on flammability. Faced with public horror and outrage over the years, airworthiness authorities have sought to make cabin interiors safer in fire. The underlying philosophy is simple: all concerned accept that, once established, a fire is likely to destroy the aircraft, but if the fire can be contained for a brief period, the occupants will be given time to evacuate. The realistic brief period has been determined to be two to five minutes in most of the Fire, Smoke and Toxicity (FST) tests.

It was recognized that the 60 second vertical Bunsen burner test was not fully representative of cabin fires, so a special apparatus was developed by Ohio State University (OSU) to inject more realism by introducing radiant heat into the tests and measuring the rate at which the burning material releases heat. This test became highly influential in the aircraft materials business. Having established test procedures for FST, the next task was to set actual numbers for screening materials. Some of the FST numbers mandated by the FAA under current aircraft cabin interiors are tabulated below:

Table 1: FST Requirements for Aircraft Interiors

Fire Test	Allowed
Burn	
Exting. time (sec)	5
Burn length (in)	4.5
Drip exting. time (sec)	0
OSU	65/65
Smoke (DS) 4 min	< 200
Toxicity (Limit), ppm	
HF	100
HCl	100 after 4 min
HCN	100 after 4 min
(SO <sub>2</sub> + H <sub>2</sub> S)	100 after 4 min
CO	3500 after 4 min
(NO + NO <sub>2</sub> )	100 after 4 min

The toxicity values are measured in an NBS chamber. The toxicity limits of gaseous products are taken from ATS 1000.001 issue 5 (AirBus Industries).

The once widely used acrylonitrile-butadiene-styrene (ABS) and polyvinyl chloride (PVC) materials are a menace in fires and have given way to epoxy or phenolic/fiberglass epoxy or phenolic/Kevlar and carbon/phenolic. Even some of these do not meet the very latest requirements. Some are good in authenticity, low color shift, surface finish and reproducibility (epoxy and unsaturated polyester) but are high in FST. On the other hand, other materials (phenolic) are fair in FST but exhibit problems in authenticity and reproducibility. Some compromises were made in arriving at the requirements shown in Table 1.

Besides the performance requirements, the material must also meet the manufacturing requirements set by aircraft panel manufacturing companies. The primary manufacturing requirement is to utilize existing tooling and press capabilities to produce acceptable parts with minimal cost impact. For honeycomb core sandwich panels made from glass resin prepreg, a typical molding condition (vacuum bag) is 260°F/one hour. This low temperature (using steam temperature) and low pressure molding (vacuum bag) obviously eliminates many thermoplastic candidates with good FST, such as polyether ether ketone (PEEK), polyether imide (PEI) and polyether sulfone (PES).

The best candidates found so far which by and large meet the performance as well as the manufacturing criteria are phenolic prepregs. However, a major problem with phenolic resins is their high release of volatiles (free phenol, formaldehyde, ammonia and water) during molding and handling. Some of the volatile products are health hazards. These pose a serious threat in the workplace where the actual molding and handling of the aircraft interior takes place. In addition to condensation products release from phenolic resin during its curing, other volatiles such as methyl ethyl ketone, acetone and ethanol are frequently found in phenolic prepregs. These solvent related volatiles come from prepreg manufacturing. Most of the time these volatiles are removed to meet the aircraft manufacturing companies' specifications. However, for complex part fabrication, a tacky prepreg is desirable, and tackiness in phenolic prepreg is driven by the amount of residual solvent present. These solvents provide artificial tack but release their vapor in the workplace.

There is another element to be considered in phenolic based prepregs. Although phenolic resin is good in FST compared to epoxy and polyester, to meet the latest OSU numbers (65/65) some fire retardant additive must be added to the base resin. Some of these additives are toxic in nature (for example, antimony trioxide), and there is growing concern about handling phenolic prepreg for laminate manufacture.

The toxicity of pyrolysis products is yet another concern. Considering the complexity of aircraft panels (honeycomb panel/adhesive/decorative panel), the aircraft industries set limits for certain lethal gaseous products. These limits are becoming tighter, especially in Europe, and clean burning of aircraft interior material poses an additional challenge to material suppliers.

In this paper a new non-volatile cure thermoset (Primaset™) resin and some of its inherently good FST characteristics will be discussed. In addition, a comparative study of cure characteristics of phenolic-triazine (PT) resin and phenol-formaldehyde (PF) resin will be discussed.

## Comparative Phenol-Formaldehyde and Phenolic-Triazine Chemistry

### Synthesis Chemistry

Phenolic resin is prepared by phenol and formaldehyde condensation polymerization reaction. It is prepared either with acid catalyst (novolac resin) or with base catalyst (Resole). Melt polymerization is used to prepare phenolic resin from low cost raw materials. This makes phenolic resin one of the most economically attractive polymers. The down side of melt polymerization is the lack of complete elimination of phenol and formaldehyde from the phenolic product. New manufacturing techniques have reduced the phenol and formaldehyde levels, but despite these new techniques these two chemicals are present in phenolic resin.

Phenolic-triazine (PT) resin is derived from novolac (phenolic) resin with very low phenol and formaldehyde content. Furthermore, PT resin is produced in such a way that after the cyanation reaction with cyanogen halide and organic base, all free phenol and formaldehyde is removed by the resin purification method. The details of the synthesis of PT resin are explained in several U.S. patents.<sup>1-6</sup>

### Cure Chemistry

The typical cure temperature for aircraft interior applications is 250 to 275°F. At these temperatures "hexa" cure phenolic resin (novolac) generates ammonia and water, while "self" cure phenolic resin (Resole) generates water and formaldehyde. The cure chemistries of PF resins are illustrated below.<sup>7</sup>

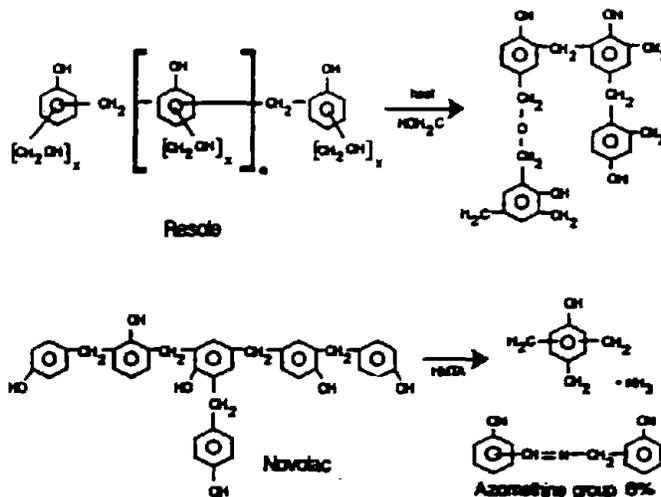
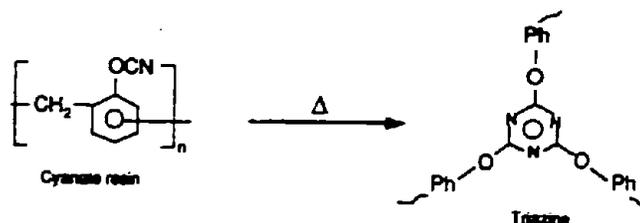


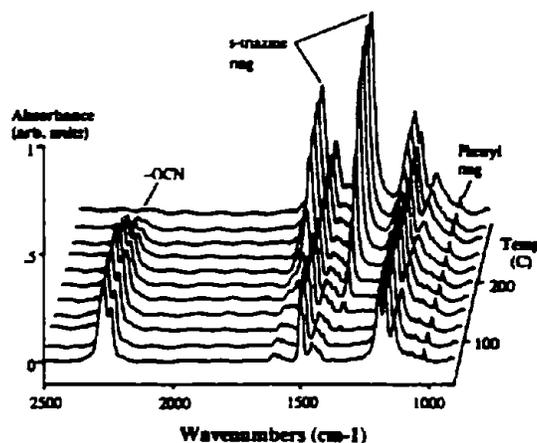
Figure 1: Cure Chemistries of PF Resins

The cure chemistry of cyanated esters is mainly governed by the cyclotrimerization of the nitrile group. The major reaction product of this reaction is a highly crosslinked polytriazine network<sup>8</sup> (Figure 2).



**Figure 2: Chemistry of PT Resin Cure**

The cyclotrimerization was monitored by FTIR and solid state  $C^{13}NMR$ . Cyanate absorption ( $2220\text{ cm}^{-1}$ ) and triazine ring formation ( $1385\text{ cm}^{-1}$ ) were measured to monitor the extent of cure. The aromatic band at  $800\text{ cm}^{-1}$  was chosen as an internal standard. It is assumed that the intensity of this band remained constant during cure (Figure 3).

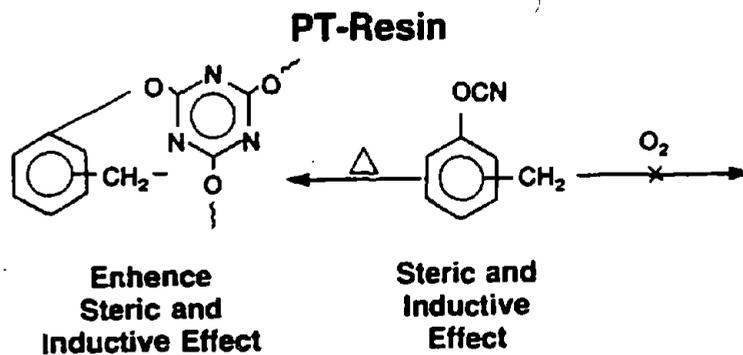


**Figure 3: Curing of Low MW PT Resin (FTIR)**

The cyclotrimerization of nitriles may be accelerated by many catalysts. In commercial applications, coordination metal catalysts are used extensively to cure cyanated esters. Depending on the type and amount of catalyst, the cyclotrimerization reaction can be initiated even at room temperature. For aircraft interior applications the low temperature ( $125^{\circ}\text{C}/250^{\circ}\text{F}$ ) cure under autoclave is easily achieved with good peel strength and flame properties. Some of the most effective catalysts for the  $250^{\circ}\text{F}$  cure conditions for PT resin are cobalt acetylacetonate, zinc octoate and manganese octoate.

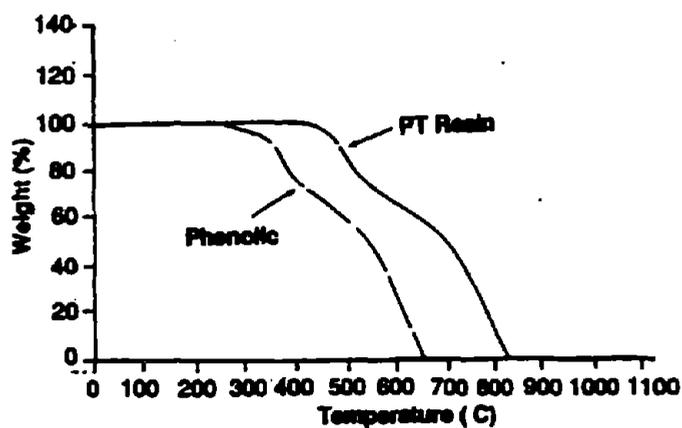
#### Mechanical and Thermal Properties of PT Resin and Phenolic Formaldehyde (PF) Resin

The rigid triazine moiety in the PT resin backbone contributes to the superior oxidative characteristics. The methylene bridge in PT resin is stabilized by the bulky triazine ring through steric hindrance (Figure 4). Thus the susceptibility of the methylene bridges to oxidation is minimized in PT resin as compared to standard phenolics.



**Figure 4: Oxidative Stabilization of PT Resin**

The thermogram (Figure 5) indicates that the thermo-oxidative stability of PT resin is much superior to that of standard phenolics.



**Figure 5: Thermal Stability of PT Resin in Air Compared to Phenolic (Heating Rate 20° C/min)**

The highly crosslinked and aromatic structure of PT resin also provides high compressive strength and modulus. Table 2 shows the comparative mechanical and thermal properties of PT and PF resins.

**Table 2: Mechanical and Thermal Properties of Neat Resin**

Property	PT Resin	PF Resin (control)*
Thermal decomposition temperature, °C (TAG)	450	350 - 380
Tg, °C (DMA)	400	121 (unfilled)
Char yield, % at 1100°C	66 - 68	55
Ultimate elongation, %	2	0.3 (very brittle)
Flexural strength, psi	14,000	7,000**
Flexural modulus, psi, x 10 <sup>6</sup>	0.68	0.37**
Compressive strength, psi	45,000	15,000**
Thermal coefficient of expansion, x 10 <sup>-3</sup> in/in/°C	22	65**
Rockwell hardness (M Scale)	125	93

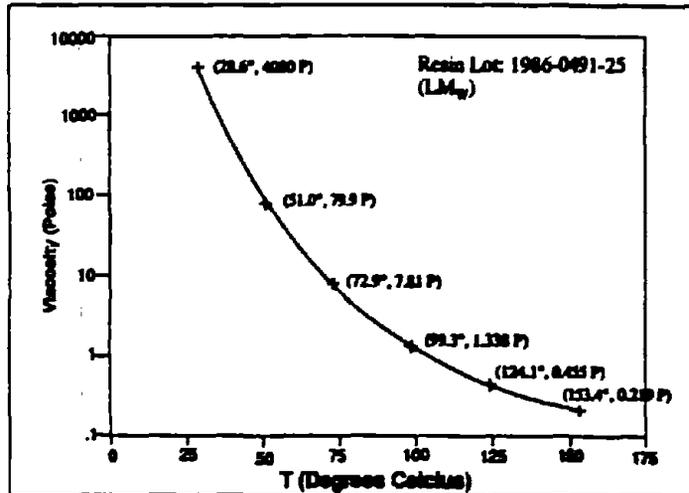
\*hexacured phenol-formaldehyde resin

\*\*Literature value (21st Century Phenolic, SPE, 1987)

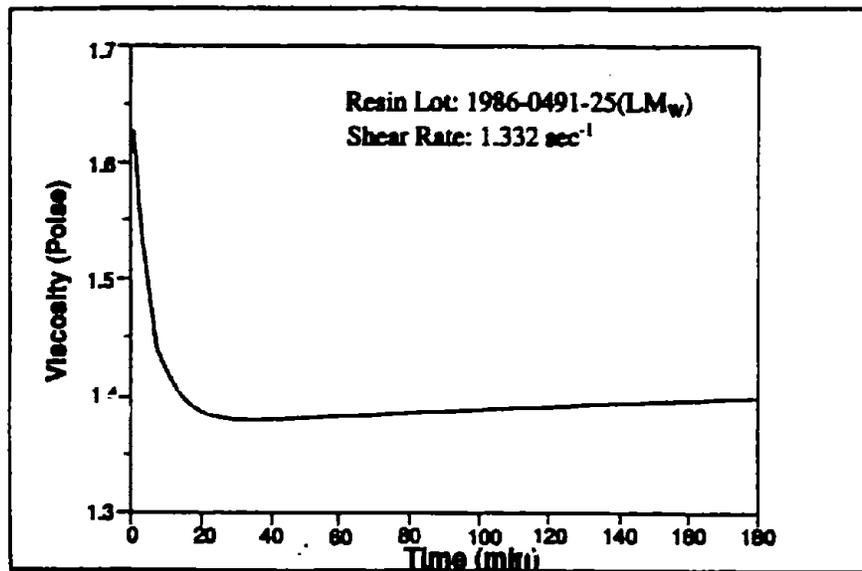
**Hot/Melt Prepreg of PT Resin**

PT resin is compatible with a variety of substrates such as glass, carbon fiber and Kevlar fiber. As the resin is soluble in several low boiling solvents (acetone, MEK, methylene chloride), it is easy to make a solution prepreg with industrial solvents. But interestingly, the viscosity of PT resins very low at reasonable temperatures (80 - 100°C), so it is also easy to prepare prepreg using hot/melt techniques (without solvent).

The effect of viscosity (Figure 6) and the stability of viscosity at 100°C (Figure 7) are shown below:



**Figure 6: Temperature vs. Viscosity of PT Resin**



**Figure 7: Change of Viscosity of PT Resin with Time at  $99 \pm 1^\circ\text{C}$**

#### Tacky Characteristics of PT Prepreg

PT resin is available in three grades: solid, semisolid and liquid. With these different grades it is easy to adjust the tack characteristics of PT prepreg from high to low to none.

#### Fire, Smoke and Toxicity (FST) Performance of PT Resin

##### Fire Performance

Two tests were conducted to demonstrate the fire performance of PT resin:

- 1) 60 seconds vertical burn test
- 2) Ohio State University (OSU) radiant heat test

PT resin is highly aromatic in structure and upon burning it quickly forms char (65 - 70%). This char is exceptionally heat and mechanically stable (Figure 8) and acts as a protective heat barrier (insulator) in an actual fire situation. The limited oxygen index of PT resin is 45 (neat resin) and this high limited oxygen index is an indicator of good ant flame characteristics (Figure 9).

THEORY/METRIC ANALYSIS IN AIR

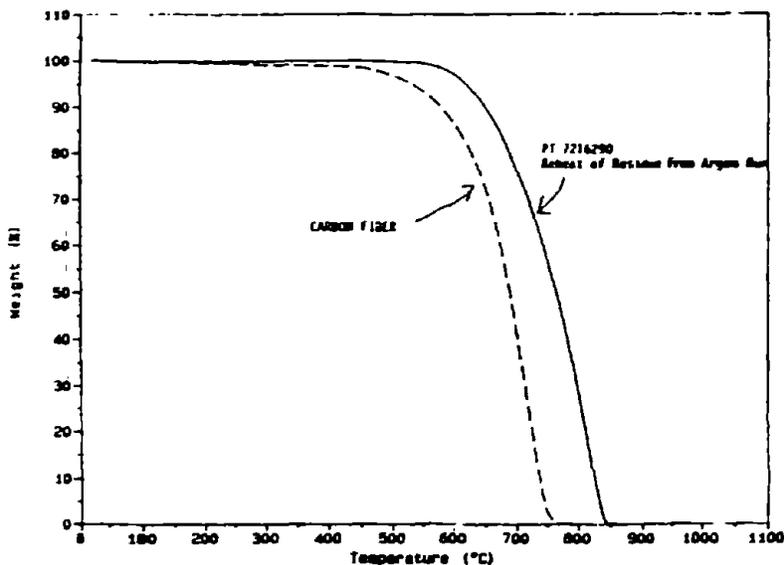


Figure 8: Char Stability of PT Resin

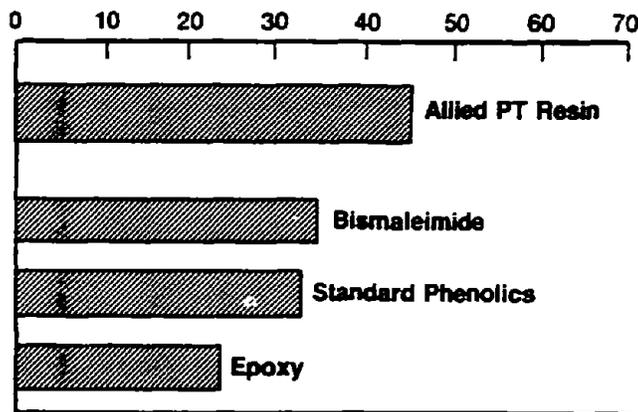


Figure 9: Oxygen Index of PT Resin vs. Other Thermosets

The 60 second vertical burn test of PT resin was conducted on the following configuration:



Figure 10: PT Composite Configuration for Flammability/Burn Characteristics

The lamination was performed according to Boeing BMS-226 (vacuum bag cure at 250°F for one hour). The PT resin was formulated with zinc octoate or cobalt octoate (ppm level) for low temperature cure. The results of the burn tests are tabulated below:

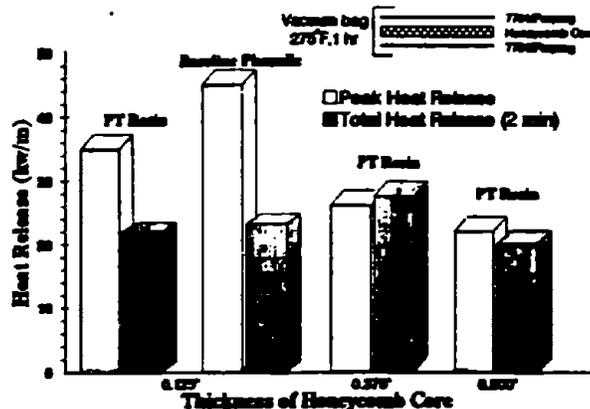
**Table 3: 60 Second Vertical Burn Test of PT Composites**

Composite Type:	PT-Carbon*	PT-Glass**
Number of Plys:	6	7
Self-extinguish Time (sec):	0	0
Burn Length:	0	1.25
Drip Extinguishing Time (sec):	No drip	No drip

\* Fiber volume  $V_f$  65%, W-322 woven cloth (Fiberite), cure conditions: 375°F/one hour

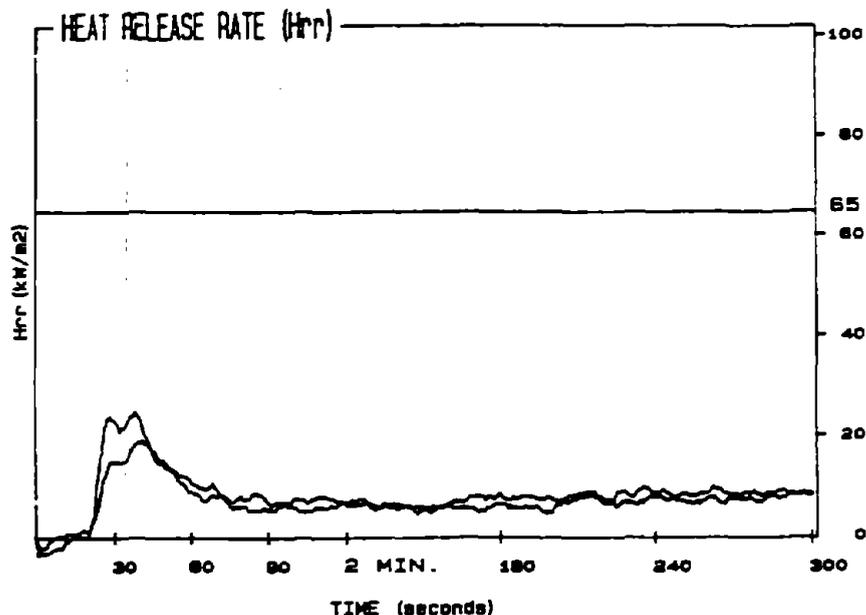
\*\* 7781 glass cloth (Volan finish), wt % resin in laminate: 32. cure conditions: 260°F/one hour, vacuum bag cure

Since the introduction of the OSU test in aircraft interiors, a great deal of frustration has been experienced by manufacturers, the FAA, material suppliers and testing laboratories. The reproducibility of OSU results has become a major problem. A great deal of modification was conducted on equipment parts, as well as setting the right heat flux (3.5 w/cm<sup>2</sup>). However, very little attention was paid to the material aspect of reproducibility. In general, thermoplastic materials (PEI, polysulfone, etc.) are better than condensation type materials (phenolic resin for example). This is because volatiles release from condensation polymerization products during measurement that upset reproducibility. The OSU reproducibility of PT resin is excellent. PT resin cures via a cycloaddition mechanism and there are no volatile products during curing. The OSU graph of PT resin is represented below (Figure 11). A representative aircraft resole based (tacky prepreg) material is also included in this graph.



**Figure 11: OSU Heat Release of Composite Panels**

The OSU number of PT resin laminates is significantly reduced by an antflammable formulation (Figure 12).



**Figure 12: Formulated OSU of PT Glass/Honeycomb (1/8") Core Panel**

Toxicity of PT Resin

Uncured PT resin is nontoxic. The gaseous products released upon burning are found to be below the limits of Boeing Aircraft as well as the standards of AirBus. Table 4 shows the gaseous products of PT laminates.

**Table 4: Pyrolysis Products on PT/7781 Lot No. E-9001301-2 Derived Structures**

<u>Component</u>	<u>Observed Level (4 min. ppm)</u>	<u>Release Limits (ppm)</u>
HCN	3	150
NO <sub>x</sub>	3	100
HCl	3	500
SO <sub>2</sub>	0	100
CO	60	3,500

### Acknowledgements

Some of the experimental work in this document were conducted by C. Calderone, G. Su and L. Townsend. The Author acknowledges their technical contributions.

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A NEW FR WATER RESISTANT ACOUSTIC INSULATION MATERIAL FOR AIRCRAFT

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ABSTRACT

A new lightweight fire resistant thermal and acoustical insulation material has been developed for weight critical applications such as aircraft. This new insulation is based on non melting microfibers of heat treated oxidized polyacrylonitrile fiber(OPF). The insulation material is in the form of light weight battings in the range of 0.2 to 0.4 lbs/ft<sup>3</sup>. This material (Curlon<sup>r</sup>) has outstanding fire blocking properties with an LOI of 58, nonconducting, high emissivity, and nonmelting. The flame burn through resistance of these battings significantly exceeds that of glass and polyimide insulation materials at 2000° F. The thermal, acoustical and FR properties of this new insulation will be presented.

INTRODUCTION

RK Technologies, Ltd. (RK Carbon Fibers is the U.S. subsidiary) has been producing specialized heat treated fibers derived from PAN (polyacrylonitrile fiber) including carbon fiber, preox(Panox) and partially heated carbonaceous fibers for over 20 years. Over the past two years, RK has been developing a relatively low cost fire resistant carbonaceous microfiber for use in insulation and fire blocking applications. (RK holds the exclusive world wide license from Dow Chemical-U.S.A. for the many patents covering these materials.) This development work has been carried out both at our fiber manufacturing plant in Scotland and our nonwovens plant in Auburn, AL. Although there is a wide range of applications for this new insulation material, RK has focused on aircraft insulation, fire blocking panels, and fire resistant batting blends. For these high loft applications RK has developed Curlon<sup>r</sup> fiber and insulation which is based on a permanently crimped FR microfiber. RK has also developed Lineon<sup>r</sup> which is a straight version of the same fiber. Figure 1 represents a schematic of these two fibers based on heat treated PAN.

LINEON AND CURLON

FIGURE 1

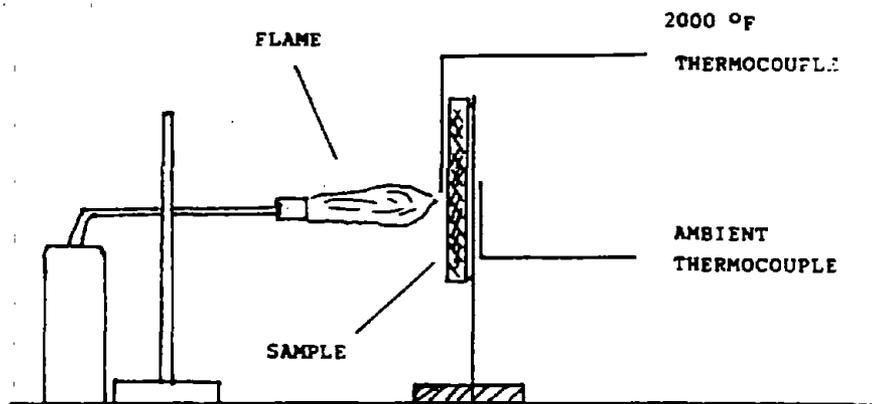
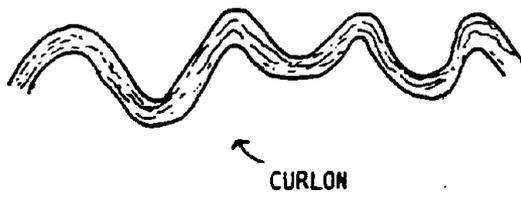
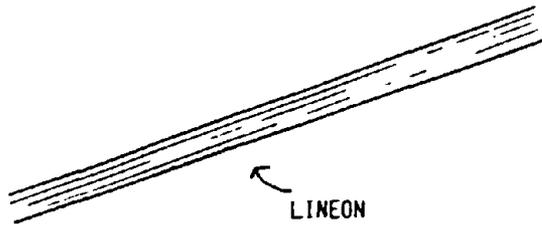


FIGURE 2

TEST STAND FOR BURN THROUGH TIME

TABLE 1  
CURLON FIBER PROPERTIES

FILAMENT DIAMETER (microns)	6
TENSILE STRENGTH (Gpa)	0.6 (86,000psi)
TENSILE MODULUS (Gpa)	20 (2.9X10 <sup>4</sup> psi)
ELONGATION AT BREAK (%)	3
DENSITY (g/cm <sup>3</sup> )	1.55
THERMAL CONDUCTIVITY (W.m <sup>-1</sup> °C <sup>-1</sup> )	1.0
ELECTRICAL RESISTIVITY (Ohm-m)	400 (nonconducting)

TABLE 2  
CURLON ELEMENTAL ANALYSIS

	%
CARBON	67
HYDROGEN	3
NITROGEN	20
OXYGEN	10

TABLE 3  
CURLON FLAME RESISTANCE PROPERTIES

<u>FIBER COMPOSITION</u>	<u>WT. % BLEND</u>	<u>PASS/FAIL</u>
CURLON/POLYESTER	15/85	PASS
CURLON/POLYESTER/POLYPROPYLENE	20/10/70	PASS
CURLON/POLYESTER/COTTON	10/10/90	PASS
CARBON FIBER/POLYESTER	40/60	FAIL
para-ARAMID/POLYESTER	40/60	FAIL
meta-ARAMID/POLYESTER	40/60	FAIL
OPF/POLYESTER	40/60	FAIL

(OPF = OXIDIZED POLYACRYLONITRILE FIBER)

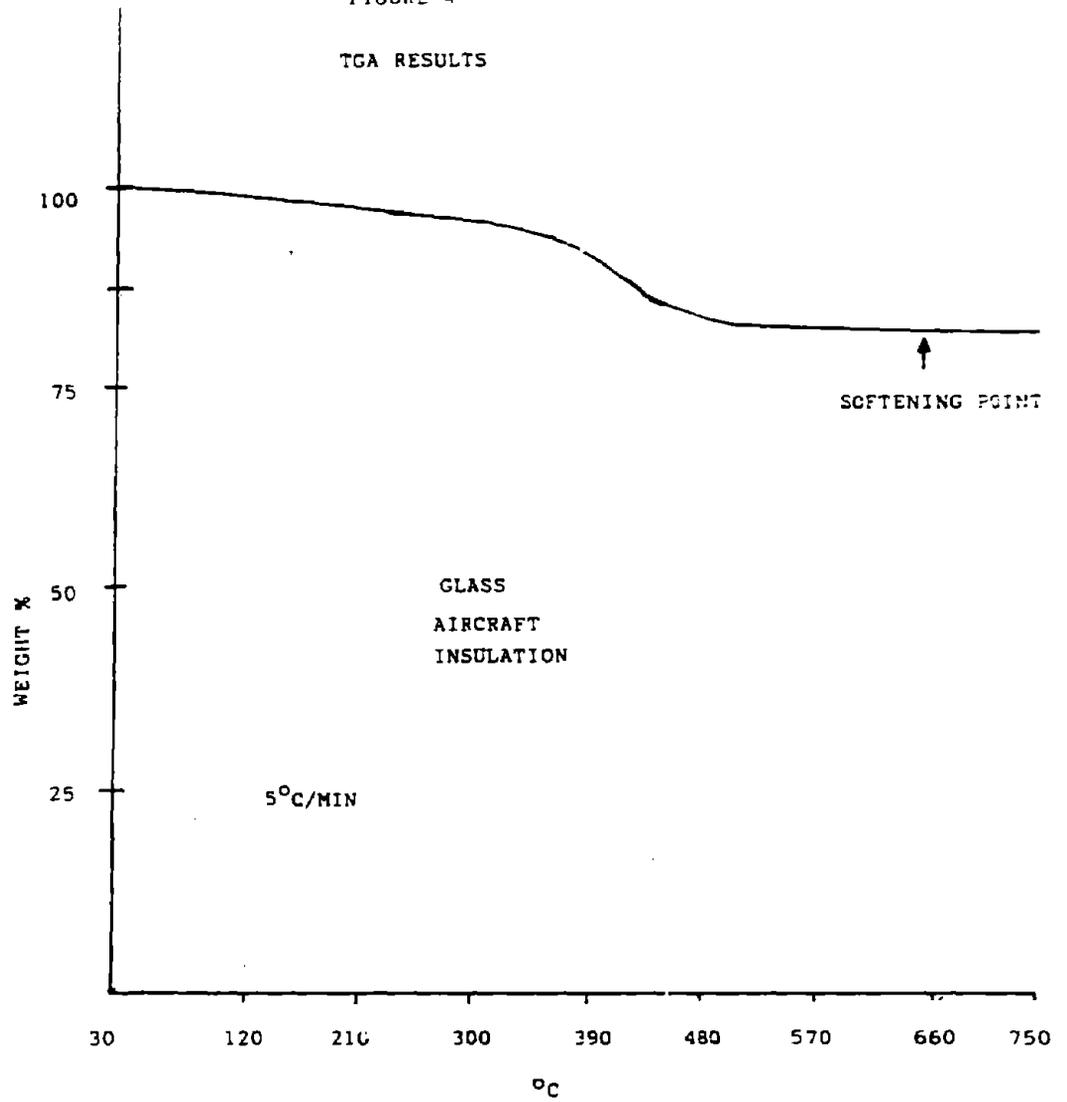
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TEST CONDITIONS FOR FELTS:

THICKNESS---- 2.54 CM  
 DENSITY----- 6.7 TO 9.6 kg/m<sup>3</sup> (0.4 TO 0.6 lb/ft<sup>3</sup>)  
 VERTICAL BURN --- 90 DEGREES  
 FTM 5903; FAR 25.853b

TABLE 4  
LOI OF FLAME RESISTANT FIBERS

<u>FIBER</u>	<u>LOI</u>
LINEON/CURLON	58
CARBON FIBERS	55
OPF (PANOX)	55
PBI	42
POLYIMIDE	38
KEVLAR/NOMEX	30
PHENOLIC (KYNOL)	28
FR POLYESTER	28
POLYESTER	22

FIGURE 4  
TGA RESULTS



## PROPERTIES

### Physical

Table 1 lists the typical physical properties for Curlon<sup>®</sup> fiber used for lightweight aircraft insulation and other high loft battings. With a diameter of less than 12 microns, Curlon<sup>®</sup> readily qualifies as a microfiber which partly explains its excellent insulation properties. In addition, it is a non-conductor with a resistance of 400 ohm-meters. It also has a relatively low density compared to ceramic materials but only slightly higher than aramids and polyimides which are about 1.4. The elemental analyses listed in Table 2 show that the carbon content of this fiber is less than 70% even though it has exceptional FR properties.

### Fire Resistance

One of the most unusual and most outstanding properties of Curlon<sup>®</sup> and its battings is its ability to protect materials or surfaces behind it from flame and heat. This property is even more dramatic when small amounts of Curlon<sup>®</sup>, 8 to 10 %, are intimately blended with polyester staple in battings with densities of one lb/ft<sup>3</sup> or greater. The resultant batting is self extinguishing. Table 3 lists the vertical burn test results for some of these polyester blends with various fibers.

A comparison of the LOI (limiting oxygen index) for a variety of fibers is given in Table 4. It can be seen that Curlon<sup>®</sup> has the highest LOI rating of any fiber other than ceramic fibers. However, an explanation of the remarkable properties of Curlon<sup>®</sup> in comparison with standard carbon fibers (80%+ carbon) and OPF (preox or Panox<sup>®</sup>) can not be based entirely on the high LOI value. It is likely that Curlon<sup>®</sup> gives an optimum combination of high thermal resistance (insulation) and high emissivity to produce a synergism which is not usually found in one fiber. This is shown in Table 5.

A summary of the key properties of Curlon<sup>®</sup> and Lineon<sup>®</sup> is given in Table 6.

Two in-house flame resistance tests were also applied to the standard aircraft insulation product batting which has been developed with Curlon<sup>®</sup>. In the first test, a comparison is made for burn through times for lightweight battings of the order of 0.4 lbs/ft<sup>3</sup> normally used for aircraft insulation. Figure 2 shows the simple test stand. These results are listed in Table 7 and show the relative difference between glass insulation and various densities of Curlon<sup>®</sup> insulation. There is no question of the extended flame resistance and potential increase in fuselage burn through time that this new insulation offers.

TABLE 5

MECHANISM FOR FLAME RESISTANCE IN CURLON/POLYESTER FELTS

- \* CURLON IS A NONCONDUCTOR
- \* CURLON IS AN EFFICIENT BLACK BODY RADIATOR WITH HIGH EMISSIVITY. CURLON ABSORBS ENERGY FROM THE FLAME AND RE-RADIATES IT AT DIFFERENT WAVELENGTHS AWAY FROM THE HOT SPOT.

<u>FIBER</u>	<u>EMISSIVITY</u>	<u>THERMAL RESISTANCE</u>	<u>RESULT OF BURN TEST</u>
OPF	LOW (X)	HIGH (V)	FAIL
CURLON/LINEON	HIGH (V)	HIGH (V)	PASS
CARBON FIBERS	HIGH (V)	LOW (X)	FAIL

NEED AT LEAST TWO OF THESE PROPERTIES TO BE A HIGHLY EFFICIENT FIRE RESISTANT FIBER.

TABLE 6

SUMMARY OF PRIMARY FR PROPERTIES OF CURLON/LINEON

- \* FLAME RESISTANCE
- \* LOW THERMAL CONDUCTIVITY
- \* HIGH THERMAL INSULATION
- \* HIGH EMISSIVITY (BLACK BODY RADIATOR)
- \* LOW SMOKE EMISSION
- \* LOW ELECTRICAL CONDUCTIVITY
- \* CHEMICAL RESISTANCE NON-MELTING
- \* LOW SHRINKAGE

Additional testing at 1100°C (2000°F) which is shown in Table 8 demonstrates that one-inch Curlon<sup>f</sup> insulation can keep the temperature behind it from rising above 180°F for more than 60 seconds. This may become an important feature of any "aircraft shell" material in the future.

In the second test, a 1400°C (2300°F flame) was applied to the surface of high density batting and the burn through time measured. These results are listed in Table 9 and demonstrate the effective protection afforded by a relatively small amount of a lightweight batting.

#### Thermal Stability

Figure 3 shows the greater thermal stability of Curlon at 600° C compared with alternative low density polyimide foam. Glass fiber is thermally very stable (Figure 4), but it melts at about 650°C.

#### Thermal Insulation

Since Curlon<sup>f</sup> is a nonconducting microfiber, it does show exceptional thermal insulation capability. Table 10 lists a comparison of Curlon<sup>f</sup> with other known insulation materials. It significantly out performs goose down. Current glass aircraft insulation has 0.42 lbs/ft<sup>3</sup> as it is the lightest available qualified density and is listed in Table 11 along with Curlon<sup>f</sup> properties for light weight aircraft insulation battings. The Curlon<sup>f</sup> batting at 0.25 lbs/ft<sup>3</sup> is equivalent in thermal insulation properties to the heavier glass insulation. For thermal insulation alone, Curlon could reduce current weights of aircraft insulation by up to 40%. Table 12 shows the approximate weight saving for various aircraft based on thermal insulation requirements.

#### Water Repellency

One of the features of an aircraft insulation which is not widely discussed is the need to reject water condensate which accumulates in the insulation due to the frequent temperature and relative humidity cycles which aircraft encounter everyday. This water absorption causes both an additional weight penalty and a potential corrosion problem on the inner aluminum skin of an aircraft. Curlon<sup>f</sup> battings have been treated to enhance water repellency. A comparison with current glass aircraft insulation is listed in Table 13. The water repellency behavior of Curlon<sup>f</sup> is outstanding with this treatment.

#### Acoustical Properties

The acoustical performance of an aircraft insulation is one of the key performance features for selection. The critical acoustical range for sound absorption performance is between 250 and 2000 Hz although some testing also incorporates the response to frequencies up to 3000 Hz.

FIGURE 3  
COMPARISON OF FIBER THERMAL STABILITY  
CURLON AND POLYIMIDE AT 600°C IN AIR

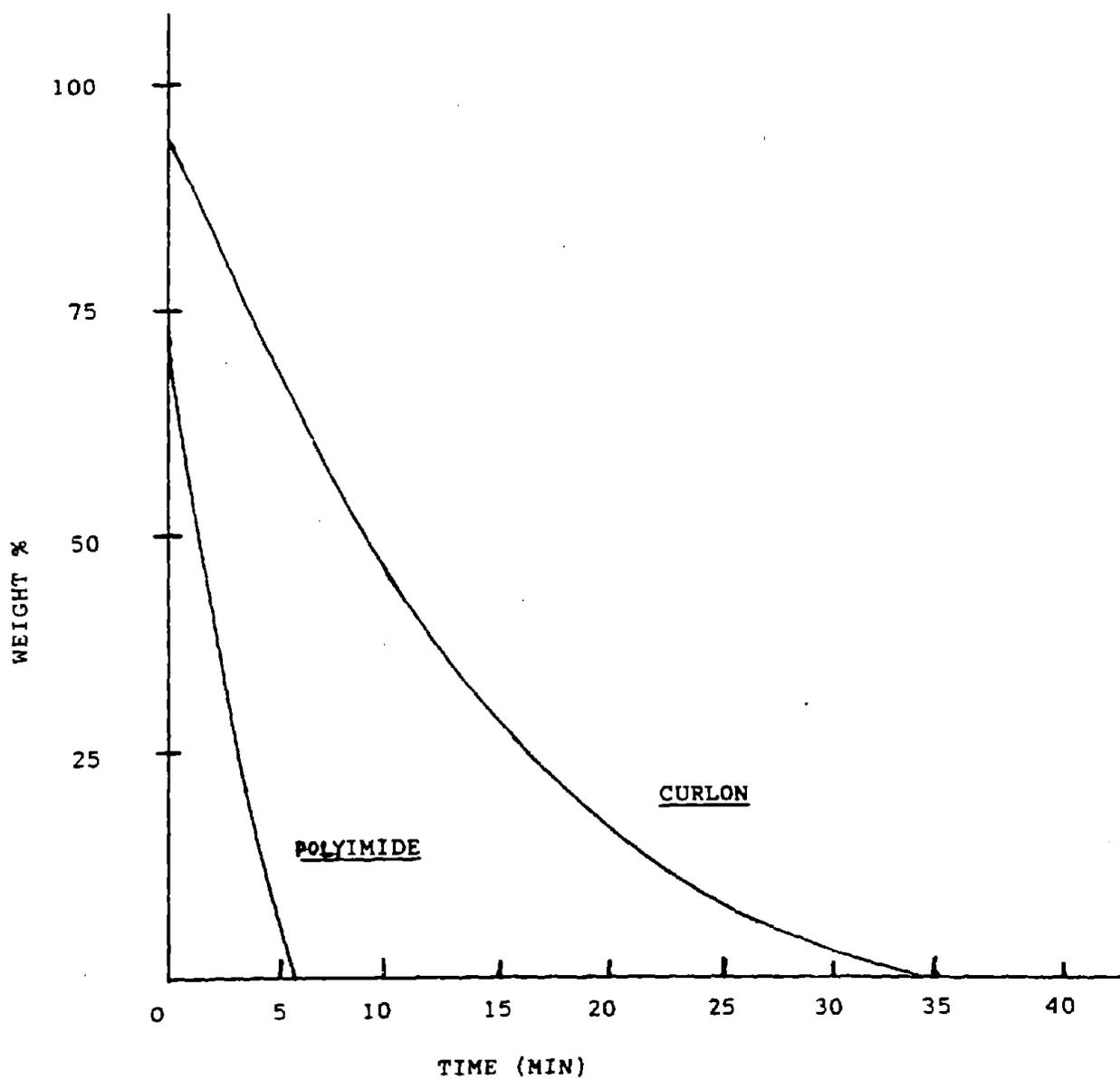


TABLE 7

CURLON BURN THROUGH PERFORMANCE  
AT 2300°F

<u>PRODUCT</u>	<u>DENSITY(LB/FT<sup>3</sup>)</u>	<u>BURN THROUGH TIME (SECONDS)</u>
CURLON	0.25	65
CURLON	0.30	80
CURLON	0.40	85
GLASS	0.42	5

CURLON - 75% CURLON/25% POLYESTER

TEST----- ALL SPECIMENS WERE 30 CM X 30 CM X 2.5 CM.  
PROPANE FLAME AT 2300° F APPLIED TO CENTER OF TEST PIECE.  
TIME TAKEN WHEN TEMPERATURE AT BACK FACE ROSE OVER 120°F

TABLE 8

CURLON BURN THROUGH PERFORMANCE  
AT 2000°F

<u>PRODUCT</u>	<u>DENSITY(lb/ft<sup>3</sup>)</u>	<u>BURN THROUGH TIME (SECONDS)</u>
CURLON	0.25	194
GLASS	0.42	6

CURLON - 75% CURLON/ 25% POLYESTER

TEST - ALL SPECIMENS WERE 30 CM X 30 CM X 2.5 CM (1 INCH)  
- FLAME AT 2000°F APPLIED TO CENTER OF TEST PIECE  
- TIME TAKEN WHEN REAR FACE TEMPERATURE ROSE OVER 120° F

TABLE 9  
 CURLON FIRE BLOCKING PERFORMANCE  
 AT 2300°F

<u>CURLON INSULATION</u>		<u>BURN THROUGH</u>	<u>REAR FACE</u>
<u>DENSITY(lb/ft<sup>3</sup>)</u>	<u>THICKNESS(in.)</u>	<u>TIME (min.)</u>	<u>TEMPERATURE,(°C)</u>
0.8	1.00	4.75	124
1.0	1.00	5.10	74
1.2	1.25	6.25	66
3.0	0.75	9.75	67
5.5	1.50	24.50	65

CURLON - 75% CURLON/ 25% POLYESTER

TEST - PROPANE FLAME AT 2300°F APPLIED TO CENTER OF TEST PIECE  
 - REAR FACE TEMPERATURE IMMEDIATELY BEFORE BURN THROUGH

TABLE 10  
 CURLON COMPARED TO OTHER COMMERCIALY AVAILABLE INSULATIONS

<u>INSULATION</u>	<u>THERMAL RESISTIVITY</u> <u>(INVERSE K VALUE)</u>	<u>THERMABESISTIVITY</u> <u>PER UNIT WEIGHT</u> <u>(DOWN = 1)</u>
CURLON	4.00	3.09
DOWN	2.94	1.00
HOLLOWFIL (DUPONT)	2.51	0.51
QUALLOFIL (DUPONT)	3.16	0.33
THINSULATE (3M)	3.70	0.38
POLARGUARD (3M)	2.68	0.55

TABLE 11

PROPERTIES OF GLASS AND CURLON INSULATION

	<u>GLASS</u>	<u>GLASS</u>	<u>CURLON</u>
FELT THICKNESS (cm)	2.54	2.54	2.54
FELT DENSITY (lbs/ft <sup>3</sup> )	0.60	0.42	0.25
(kg/m <sup>3</sup> )	9.6	6.7	3.2
FIBER DIAMETER (microns)	1.5	1.5	6
K VALUE (BTU in. °F <sup>-1</sup> hr <sup>-1</sup> ft <sup>-2</sup> )	0.24	0.27	0.25

TABLE 12

POTENTIAL THERMAL WEIGHT INSULATION WEIGHT SAVINGS  
BY COMMERCIAL AIRCRAFT TYPE

ESTIMATE BASED ON THERMALLY EQUIVALENCY OF:

CURLON 0.24 LB/FT<sup>3</sup>, 1 INCH; AND GLASS 0.42 LB/FT<sup>3</sup>, 1 INCH

<u>AIRCRAFT</u>	<u>WEIGHT SAVINGS (LBS)</u>
<b>BOEING</b>	
B737 - 200	530
B737 - 400	344
B747 - 400	1810
B757 - 200	450
B767 - 300	602
B767 - 400	766
<b>MCDONNELL DOUGLAS</b>	
MD 80/90	230
MD 11	775

Figure 5 shows the performance of glass insulation in comparison with two types of Curlon<sup>f</sup> insulation batting. The first type is equivalent in density to the glass insulation and is comprised of 9 micron diameter Curlon<sup>f</sup> at the same thickness although the Curlon<sup>f</sup> fiber. The second type is only 75% of the density of the glass insulation and is comprised of 6 micron Curlon<sup>f</sup> fiber. All battings are one inch thick and are tested bagged in Orcon film bags.

Overall, the Noise Reduction Coefficients are similar for all three materials. However, each Curlon<sup>f</sup> batting exhibits a different absorption response to the frequency range. For the same density batting, Curlon<sup>f</sup> (9 micron) is superior to glass below 650 HZ indicating that it would be a more efficient sound absorber in propeller driven aircraft. Alternatively, current noise levels could be maintained with a corresponding reduction in insulation weight.

The lower density insulation with Curlon<sup>f</sup> (6 micron) absorbs less sound at lower frequencies but is more efficient than glass above 1500 Hz despite the lower weight. It is expected that blended Curlon<sup>f</sup> battings will provide a favorable and targeted absorption response combined with a weight reduction.

#### CERTIFICATION TESTING

A series of certification tests were performed at British Aerospace under the various FAR and ATS test protocols as required by FAA. The results for the following tests are given in Tables 14 through 18.

- 1) Flammability-FAR 25.853b
- 2) Smoke emission-ATS 1000.001, Issue 5 Para 4.1 App A
- 3) Toxic Gas Emission-ATS 1000.001, Issue 5 Para 4.2
- 4) Heat Release-FAR 25.853 App F Part IV

This new insulation material has passed all required test criteria. Earlier versions of this material have been flying on Falcon Jets for over three years. The priority development effort for the past two years has been to reduce the price of this material to be cost competitive with currently used aircraft insulation and to improve the acoustic absorption while maintaining weight savings. Based on the results presented in this paper, Curlon<sup>f</sup> insulation material is now ready for the commercial aircraft market.

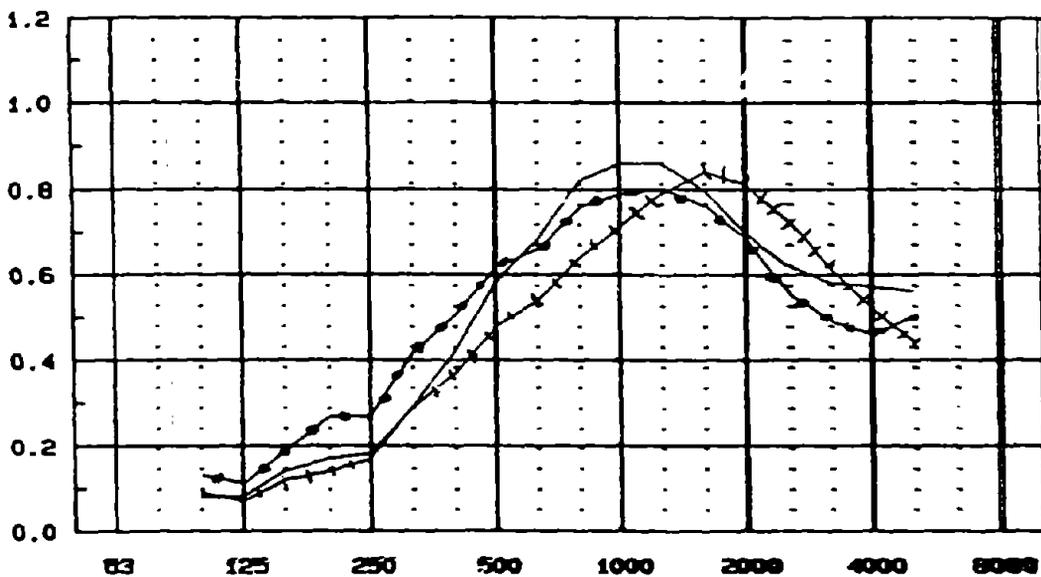
FIGURE 5

ACOUSTICAL PERFORMANCE OF GLASS AND CURLON INSULATION  
RANDOM INCIDENCE SOUND ABSORPTION ASTM C423-84a

Temperature 22°C

Relative Humidity 57%

1/3 OCT ABSORPTION COEFFICIENT



Frequency (Hz)

Noise Reduction

Coefficient (250 - 2000 Hz)

—●— Curlon 0.42lb/ft<sup>3</sup> (9 micron)

0.59

—▲— Curlon 0.30lb/ft<sup>3</sup> (6 micron)

0.55

—◆— Glass 0.42lb/ft<sup>3</sup>

0.58

TABLE 13

WATER REPELLENCY OF INSULATION FELTS

<u>PRODUCT</u>	<u>DENSITY</u>	<u>WATER ABSORPTION (%)</u>	<u>RELATIVE WEIGHT GAIN PER UNIT SURFACE AREA</u>
CURLON	0.25 lb/ft <sup>3</sup>	20	1.0
GLASS	0.42 lb/ft <sup>3</sup>	45	3.8

TEST: STATIC ABSORPTION TEST/ ASTM D 583 - 63  
 MODIFIED FROM 15 MINUTES TO 5 MINUTE SOAK

BRITISH AEROSPACE  
 REGIONAL AIRCRAFT LTD  
 TEST FACILITIES DEPARTMENT, WOODFORD

Bae-FST-GEN-4679

FLAMMABILITY TEST REPORT

TEST SPECIFICATION : ATS 1000.001  
 LAB REFERENCE No. : 3085  
 JOB No. : 005520006015301  
 DATE OF TEST : 20-08-1992  
 MATERIAL / CONSTRUCTION : CURLON CARBON FIBRE AIRCRAFT INSULATION  
 BATTING.  
 MANUFACTURER / SUPPLIER : R.K. TEXTILES COMPOSITE FIBRES LTD.

TEST METHOD : FAR 25.853 b

	RUN 1	RUN 2	RUN 3	MEAN	LIMIT
BURN LENGTH (mm)	0	0	0	0	200
AFTER FLAME (sec)	0	0	0	0	15

DRIP FLAME TIME (sec) 0 0 0 0 5

FLAME EXPOSURE TIME FOR TEST METHOD : 12 Seconds

OBSERVATIONS : SPECIMEN GLOWED.

RESULTS

PASSED TEST REQUIREMENTS OF FAR 25.853 b

TESTED BY : *REB*

APPROVED BY : *[Signature]*

TABLE 14

SMOKE EMISSION TEST REPORT

TEST SPECIFICATION :ATS 1000.001 Issue 5 para 4.1 app A

LAB REFERENCE No. :8131  
DATE OF TEST :10-09-1992  
WORKS ORDER No. :05520008016301  
THERMAL EXPOSURE :2.5 Watts/cm.sq FLAMING  
MATERIAL / CONSTRUCTION :CURLON CARBON FIBRE AIRCRAFT INSULATION  
BATTING REF :- CURLON/COATED/NOT BAGGED

NOMINAL THICKNESS :25mm  
MANUFACTURER / SUPPLIER :R.K.TEXTILE COMPOSITE FIBRES

	RUN1	RUN2	RUN3	RUN4	MEAN
WEIGHT (g)	0.6	0.6	0.6	0.6	0.6
DS AT 1 MIN	6	5	4	5	5
DS AT 1.5 MIN	6	6	5	6	6
DS AT 2 MIN	7	6	6	6	6
DS AT 3 MIN	7	7	6	6	7
DS AT 4 MIN	6	6	7	6	7
TIME TO DS=150 (min)					
TIME TO DS=200 (min)					
DM CORRECTED					
TIME TO DM (min)					
DM IN 1.5 MIN	6	6	5	6	6
DM IN 4 MIN	6	6	7	6	7

STANDARD DEVIATION OF 4 MINUTE DM :1.0  
COEFFICIENT OF VARIANCE OF 4 MINUTE DM :13.2

DM=Maximum Specific Optical Density DS=Specific Optical Density

OBSERVATIONS : SPECIMENS GLOW IN AREA OF FLAME  
IMPINGEMENT

TEST CRITERIA : DS<200 WITHIN 4 MINUTES

RESULTS

PASSED TEST REQUIREMENTS OF ATS 1000.001 Issue 5 para 4.1 app A

TESTED BY : *V. R. R. R.*

APPROVED BY : *A. J. R. R.*

TABLE 15

TOXIC GAS EMISSION TEST REPORT

TEST SPECIFICATION :ATS 1000.001 ISSUE 5 PARAGRAPH 4.2

LAB REFERENCE No. :6130  
WORKS ORDER No. :05520008016301  
DATE OF TEST :10-09-1992  
THERMAL EXPOSURE :2.5 Watts/cm.sq NON-FLAMING  
MATERIAL / CONSTRUCTION :CURLON CARBON FIBRE AIRCRAFT INSULATION  
BATTING REF :- CURLON/COATED/NOT BAGGED

NOMINAL THICKNESS :25mm  
MANUFACTURER / SUPPLIER :R.K.TEXTILE COMPOSITE FIBRES

		RUN1	RUN2	RUN3	RUN4	MEAN	LIMIT
WEIGHT (g)		0.6	0.5	0.6	0.6	.6	
HYDROGEN CYANIDE (HCN)by Draeger	90sec	<2	<2	<2	<2		100
	4min	<2	<2	<2	<2		150
CARBON MONOXIDE (CO)by Draeger	90sec	<10	<10	<10	<10		3000
	4min	<10	<10	<10	<10		3500
NITROUS GASES (NOx) by I.C.	90sec	0	0	0	0		50
	4min	0	0	0	0		100
SULPHUR DIOXIDE (SO2+H2S)by I.C.	90sec	0	0	0	0		50
	4min	0	0	0	0		100
HYDROGEN CHLORIDE (HCl) by I.C.	90sec	8	7	7	4	7	50
	4min	11	12	7	6	10	150
HYDROGEN FLUORIDE (HF) by I.C.	90sec	1	2	1	0	1	50
	4min	1	1	0	1	1	100
HYDROGEN BROMIDE (HBr) by I.C.	90sec	0	0	0	0		
	4min	0	0	0	0		

All concentrations in PPM : I.C.=Ion Chromatography  
Draeger=Colourimetric Tube : I.S.E.=Ion-Specific Electrode

OBSERVATIONS :

RESULTS

PASSED TEST REQUIREMENTS OF ATS 1000.001 ISSUE 5 PARAGRAPH 4.2

TESTED BY : *V. R. R. R.*

APPROVED BY : *A. J. R. R.*

BRITISH AEROSPACE  
CIVIL AIRCRAFT DIVISION  
REGIONAL AIRCRAFT LTD. WOODFORD

BAe-FST GEN-4680  
PAGE 1 OF 2

TABLE 17

HEAT RELEASE TEST REPORT

TEST METHOD : FAR 25.853 Appendix F part IV  
LAB. REF. NO. : 1918  
JOB NO. : 005520006015301  
DATE OF TEST : 28/08/92  
THERMAL EXPOSURE : 3.5 Watts/cm.sq  
Kh VALUE : .2486 KW/mV  
MATERIAL/CONSTRUCTION : CURLON COATED FIBRE AIRCRAFT INSULATION BATTING  
REF :- CURLON/COATED/NOT BAGGED

MANUFACTURER/SUPPLIER : R.F. TEXTILES COMPOSITES

	RUN1	RUN2	RUN3	RUN4	RUN5	MEAN	LIMIT
WEIGHT (g)	2.25	2.16	1.98				2
NOM. THICKNESS (mm)	25	25	25				25
TOTAL HEAT RELEASE IN 2 MIN. (kW.min/eq.m)	2	3	6				65
TOTAL HEAT RELEASE IN 5 MIN. (kW.min/eq.m)	13	14	22				16
PEAK HEAT RELEASE * IN 5 MINS (kW/eq.m)	9	10	9				10 65
TIME TO PEAK RELEASE (s)	283	6	8				92
TIME TO TOTAL FIRE INVOLVEMENT (s)	300	300	300				300

\* DATA GIVING RELEASE RATES OF HEAT (in kW/eq.m) AS A FUNCTION OF TIME ARE DETAILED ON PAGE 2

OBSERVATIONS

SURFACE GLOWED INITIALLY. MATERIAL UNCHANGED EXCEPT FOR LIGHTENING IN SHADE OF SURFACE FIBRES.

RESULTS

PASSED THE 65/65 TEST LIMITS

TESTED BY : *K. Red*  
APPROVED BY : *A. J. B*

TABLE 18

BRITISH AEROSPACE P.L.C.  
REGIONAL AIRCRAFT  
WOODFORD SITE TEST FACILITIES

CERTIFICATE OF TEST No. BAe-MSM-CT-0343  
Issued under CAA authority reference No. DAU1011/55

Customer: R K TEXTILES  
COMPOSITE FIBRES LIMITED  
CRAIG COURT  
25 HALE ROAD  
ALTRINCHAM  
CHESHIRE WA14 2EY  
Contract No. 21944  
Work Order No. 005520006015301

Item: Drawing/Part/Type No. Serial No.

CURLON COATED CARBON FIBRE AIRCRAFT INSULATION BATTING  
REFERENCE - CURLON/COATED/NOT BAGGED

Customer Release Note/Advice Note No.

Test Standard/Specification No. Issue/Amend. List  
ATS 1000 001 5

Summary of results:

- 1) The above material PASSED the test requirements of FAR 25.853 b (FLAMMABILITY)
- 2) The above material PASSED the test requirements of FAR 25.853 Appendix F part IV (HEAT RELEASE)
- 3) The above material PASSED the test requirements of ATS 1000 001 ISSUE 5 paragraph 4.1 appendix A (SMOKE EMISSION)
- 4) The above material PASSED the test requirements of ATS 1000 001 ISSUE 5 paragraph 4.2 (TOXICITY)

For detailed results see Test Report No. BAe-FST-GEN-4679-4682 Inc.

"CERTIFIED that the above mentioned specimens/part/material/systems have been tested/checked in accordance with the contract and applicable standards and the requirements of the Civil Aviation Authority relating to the testing of such air material systems. This certificate does not relate to the standard or quality of the manufacture of the item/material except specified in the test contract."

Signed: *A. J. B* Date: 21-9-92

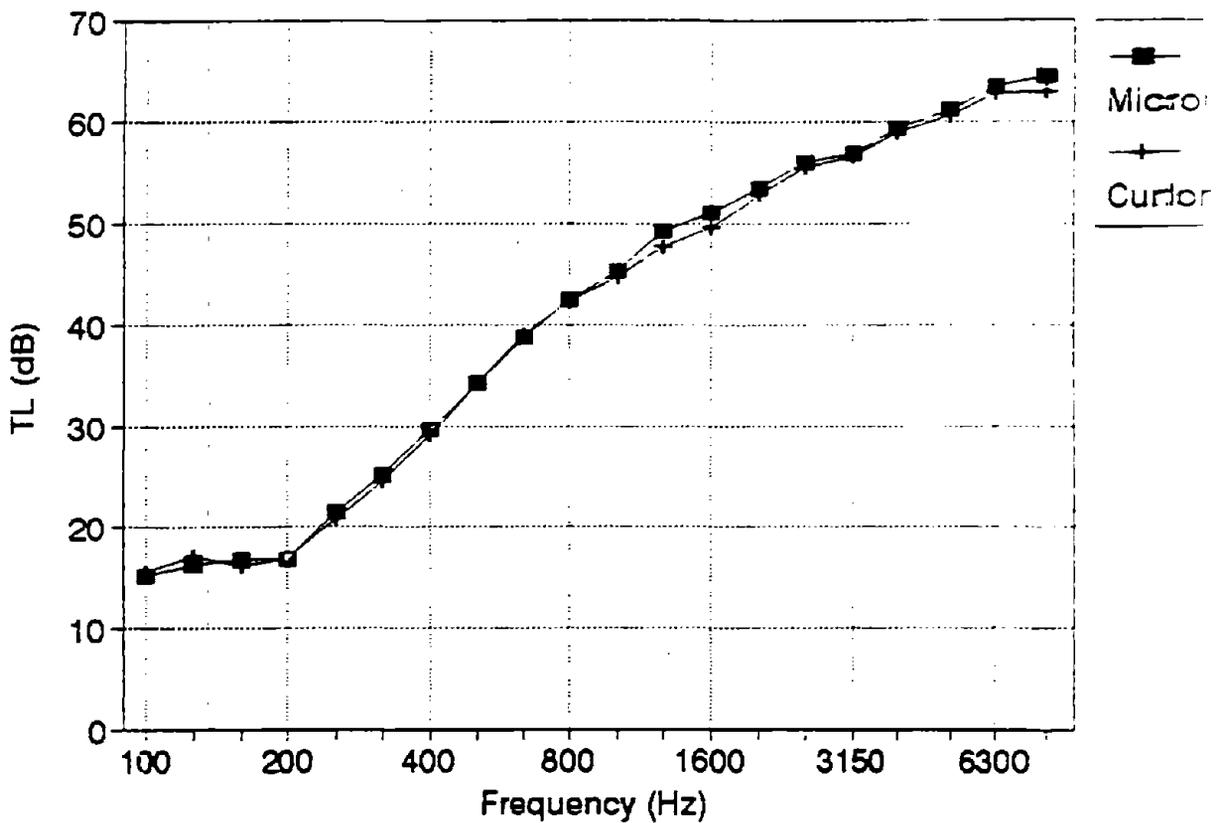
for and on behalf of British Aerospace.

Dept: Engineering Test Facilities

Chester Road, Woodford, Stockport, Cheshire. SK7 1QR

# AIRBORNE SOUND TRANSMISSION LOSS

RK Textiles Ltd



Microlite  $0.42 \text{ lb/ft}^3$

Curlon  $0.30 \text{ lb/ft}^3$

N94-

10774

INCLAS



**N94-10774**

58-27

163244

P. 11

**\*NEW TECHNOLOGY FOR EFFECTIVE CONTROL  
OF FLAMMABILITY IN POLYOLEFIN FIBER/TEXTILES\***

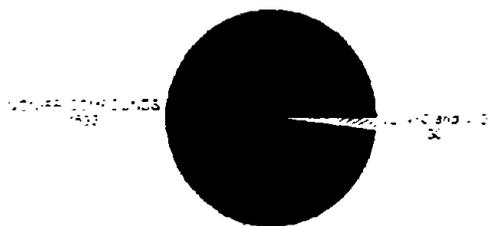
Charles W. Yacomeni, Ph.D.  
Great Lakes Chemical Corporation

**INTERNATIONAL CONFERENCE FOR THE PROMOTION  
OF ADVANCED FIRE RESISTANT AIRCRAFT INTERIOR MATERIALS**

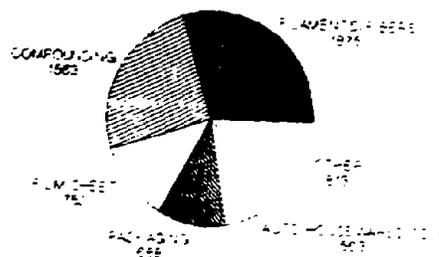
February 9 - 11, 1993  
Trump Taj Mahal Casino•Resort  
Atlantic City, NJ USA

There is a substantial demand for polypropylene with the largest market segments being fibers and compounding. There has also been a historical demand for flame retardant (FR) polypropylene for molding applications. This demand is growing (although small in relation to the total market) and the following estimate of market size gives an idea of the relative importance of FR polypropylene as a segment of the overall polypropylene market.

COMPOUNDED POLYPROPYLENE  
NON-FR vs FR



POLYPROPYLENE MARKET SEGMENTS



CHEM PROG SYNOPSIS JUNE 82

Flame retardants used to effectively meet UL 94 V-0 and V-2 ratings have been based on halogen chemistry synergized with antimony trioxide. Examples of such products can be Decabromodiphenyl oxide, Tetrabromobisphenol A Bis (2,3 Dibromopropylether), Ethylenebistetrahydrophthalimide, Ethylenebis(dibromonorbornane dicarboximide), Dodecachlorododecahydrodimethanodibenzocyclooctene, and some other brominated aromatics have also been shown to provide flame retardancy to molded polyolefins. Similarly there are effective non-halogen flame retardant products for polyolefins that require no antimony synergist but do require much higher loading levels than typical halogenated FR systems.

The title of this paper and its subject matter concerns the hitherto unsolved issue of how to effectively flame retard polyolefin (in particular polypropylene) fiber in order to impart inherent flame resistance to a finished textile. One of the previously mentioned products is used in substantial quantities world-wide to flame retard textiles (e.g. automotive and commercial upholstery) traditionally made from polyamide or polyester fiber; this product is applied in the form of a compounded latex back-coating. Polypropylene is difficult to flame retard. Substantial efforts have been made to incorporate some of the previously mentioned products into polypropylene fiber during the fiber extrusion process with some limited success<sup>11</sup>. However most of these products are not melt blendable with polypropylene and therefore particle size of the flame retardant becomes a critical issue at the lower fiber deniers. There is also the necessity of antimony trioxide as a synergist which represents yet another incompatible particle present in the fiber cross section. Migration of an incompatible flame retardant to the fiber surface is also a possibility which could cause build-up on fiber processing equipment.

There is potential in the following market segments for a flame retardant polypropylene fiber:

<u>Market Segment</u>	<u>Flammability Standard</u>
● Commercial carpet	● ASTM E-648
● Automotive	● MVSS-302
● Commercial upholstery	● CAL-133
● Office divider panels	● ASTM E-84
● Wallcoverings	● NFPA-701; UBC 42-2

Great Lakes has developed novel technology which can impart flame resistance to polypropylene fiber. Hence a new product was formed which is melt-blendable and compatible with polypropylene and requires no antimony trioxide as synergist. Textiles derived therefrom have been shown to pass appropriate flammability tests.

Before discussion of flammability test results, it is appropriate to review the technical barriers that had to be overcome in order to offer a commercially viable product. The following issues had to be evaluated:

- SPINNABILITY
- UV STABILITY
- CORROSION
- ODOR
- COLORATION
- FLAMMABILITY

Each of these issues will be addressed separately later in this presentation.

Raw material strength in Bromine has afforded Great Lakes the opportunity to develop derivatives businesses, one of the most important of which is our flame retardants business. A recently commercialized monomer is DIBROMOSTYRENE (Great Lakes DBS™). This product is manufactured in a multi-million pound capacity plant in Eldorado, AR. The first derivative of DBS was its homopolymer which we call PDBS™; this product is commercially available from Great Lakes and is used as an additive flame retardant in certain engineering plastics.

The next step in derivitization of DBS led us to graft technology which is well established for styrenic modified polyols<sup>[2-5]</sup> and for modification of polypropylene with maleic anhydride and acrylic acid<sup>[6-8]</sup>. Thus the product GPP-36™ was born. GPP-36™ is a graft copolymer of polypropylene and dibromostyrene (USP 5,077,337 and foreign filings). It has the following properties:

- Appearance . . . . . Off-white plastic pellets
- Bromine Content . . . . . 36%
- Density @ 25C, g/ml . . . . 1.24 - 1.28
- Softening Range . . . . . 160 - 175° C

- TGA Data:
  - 1% - 339° C
  - 5% - 383° C
  - 10% - 398° C
  - 25% - 416° C
  - 50% - 431° C
- Toxicology:
  - Rat acute oral LD<sub>50</sub> > 5000mg/kg
  - Rat dermal LD<sub>50</sub> > 2000 mg/kg

GPP-36™ is listed on the TCSA Inventory and can be manufactured in unlimited quantities in the U.S. Its components are also EINECS listed and therefore it can be imported into, or manufactured in, the EEC.

As previously mentioned, the practical issues involved in the production of a flame retarded polypropylene fiber required study.

**SPINNABILITY**

The following deniers were produced initially on pilot equipment:

- 2 dpf; 5 dpf; 20 dpf

The equipment used is manufactured by Hills Inc, Melbourne, FL. Yarn was manufactured repetitively to demonstrate that each denier can be produced. Subsequent fiber extrusion evaluations on commercial production equipment have confirmed that GPP-36™ can be successfully used in the production of an inherently FR polypropylene fiber in this denier range. Fiber containing up to 33% GPP-36™ has been extruded; as expected, at the upper loading levels, fiber tenacity suffers due to ever increasing polystyrenic character. However examples of fiber tenacity at different Bromine content are seen to be within the range of acceptability.

**GPP-36™**

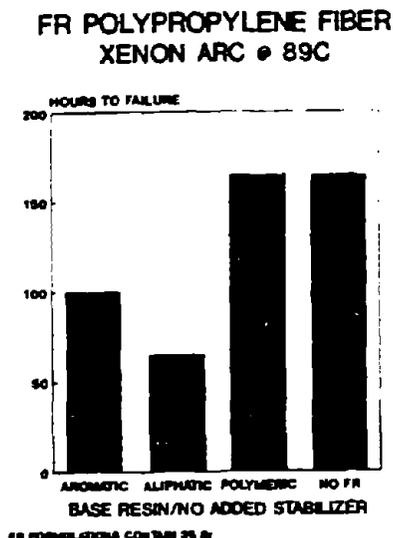
**Tenacity vs. FR Content**

<u>Bromine Content %</u>	<u>Tenacity g/Denier</u>
0	3.5
6	3.0
12	2.5

**UV STABILITY**

The question arises as to how the FR fiber is going to behave towards UV radiation.

Traditional halogenated flame retardants are known to detract from the effectiveness of Hindered Amine Light Stabilizers (HALS) in polypropylene fiber<sup>[9-11]</sup>. In cooperation with Ciba-Geigy<sup>[12]</sup> data were developed confirming the antagonism mentioned a moment ago, and also offering a solution to the problem.



An effective solution to the issue of UV stability in combination with flame retardancy is available. The most efficacious combinations of UV stabilizers and/or HALS needs to be studied with reference to the actual flammability and UV ratings of any particular finished textile.

### CORROSION

A question we have been asked many times is, "What is a brominated flame retardant going to do to my extruder and fiber processing equipment?" FR polypropylene fiber containing GPP-36™ has been extruded at 200-250°C without any problem. Looking at the TGA data for GPP-36™, its exceptional thermal stability is obvious:

### THERMAL STABILITY

GPP-36™  
 1% — 339 C  
 5% — 383 C  
 10% — 398 C  
 25% — 416 C  
 50% — 431 C

Great Lakes has also developed its own method for evaluating whether a flame retardant is corrosive towards mild steel. This involves exposing molded plaques of flame retarded polypropylene to 250° C; no evidence of corrosion has been found. It is also a fact that during the reactive extrusion process used to manufacture GPP-36™, we see zero evidence of corrosion of the extruder elements.

### ODOR

During the fiber extrusion process the use of GPP-36™ will impart a different odor to the immediate working area. GPP-36™ is not virgin polypropylene and it does smell different than polypropylene during processing. The major odor components are under investigation and preliminary analytical results indicate that these are derived from residual initiator present in GPP-36™. An effective ventilation system is recommended where the fiber exits the spin pack.

### COLORATION

It is a property of GPP-36™ that it will deluster polypropylene fiber. The obvious issue is that direct shade matching is probably not possible. A flame retardant fiber, yarn, or staple will need to be presented to interested parties as having its own shade range and not necessarily that of any non-FR counterparts. Additional data is also being developed on the interaction of pigments with stabilizers.

### FLAMMABILITY

Does GPP-36™ work?

Flammability requirements are specific to a particular textile end-use. Flammability of a particular textile is dependent on the fiber and yarn denier, the fabric construction (woven; knitted; tufted; needle-punched; spun-bonded etc) and of course bromine content. We have certified flammability passes <sup>[13]</sup> for knitted fabric under NFPA-701 and FAR 25.853. Carpet manufactured with FR polypropylene face fiber and FR back-coating has passed ASTM E-648 (flooring radiant panel test). Upholstery using 100% FR polypropylene fiber has also been evaluated under the California Technical Bulletin 133 protocol and found to pass the criteria set in this test.

### CONCLUSION

GPP-36™ offers access to inherently flame retardant polypropylene fiber. It requires no heavy metal synergist. It is melt-blendable and totally compatible with polypropylene allowing for full range of fiber/yarn denier production.

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12

**Applications of Continuous Fiber Reinforced Thermoplastics in Aircraft Interiors**

Robert G. Diehl

Design and Integration Dept.  
Fokker Aircraft B.V.  
Amsterdam, The Netherlands

**ABSTRACT**

As part of a technology development program, actual aircraft interior parts have been manufactured from polyetherimide (PEI) resin reinforced with woven glass fiber in the form of composite solid laminates and sandwich materials. These parts are evaluated against an aircraft manufacturer's design criteria, highlighting critical areas. The status of a number of the parts is given - technology proving, flying prototype part, serial production etc. The materials have good fire safety properties, some unexpected mechanical properties and an above average contribution to parts cost.

The state of the art is such that the present interior applications for this material are restricted to areas with highly specific requirements. Further development to improve some mechanical properties and process control could quickly open up the field because of substantial savings in manufacturing costs.

**Keywords:** thermoplastic composite components, aircraft, interior, fire.

**INTRODUCTION**

The material under review (PEI/glass) has been available for some years though not appearing in the catalogs of the major suppliers of semi-finished sandwich panels for reasons which should soon become clear. A few smaller companies in the Netherlands have developed modest research and production facilities using their own resources pooled with those of national aerospace interests with the aim of exploiting the, at first sight, attractive material properties by manufacturing finished and semi-finished goods for the commercial aircraft OEM market. Some exterior applications are described in refs. 1 and 2. This paper focusses on interiors with their particular blend of requirements for materials.

The airframe manufacturer's technical contribution has been to establish product performance specifications, to suggest candidate products for development and production and to assist in the design of prototypes. In some cases the semi-finished product specifications have been revised. The parts manufacturers have responded by developing new and existing processes with which to make these candidate parts. Some of these parts are now flying. The results to date are presented here from the point of view of one airframe manufacturer.

92  
~~CONFIDENTIAL~~

## MOTIVATION

Thermoset composites form about 90% of the interior furnishings<sup>1</sup> in today's commercial transport aircraft. Clearly any serious candidate for replacing these materials needs to be carefully investigated because of the size of the potential gains and penalties. The latest flammability regulations have resulted in less than optimum design solutions in many of these large area parts. These factors have prompted Fokker to consider new technology for future interiors. Any change has to offer a comfortable margin of fire safety in the final product but at an affordable price and without degrading the other qualities desired of modern interiors.

So what is the airframe manufacturer looking for that cannot be fully satisfied by the traditional thermoset composites and metals? Why thermoplastic composites? The shopping list of desirables is of course not new. Potentially, thermoplastic composites offer the following (shortlisted) benefits:

- Cheaper tooling, especially for short production runs (< 100)
- More versatile production methods
- Short process cycles
- Elimination of hand finishing
- More durable parts without weight penalty
- Integral color, pattern and texture
- Recyclable materials usage (environment protection)
- Better specific fire behavior without loss of durability or appearance

A development program tries to answer the question: how much of the above can be achieved in interiors with the current thermoplastic composites fabrication techniques, with what kind of trade-offs and what needs to be developed further to make the technology competitive? In an orderly world, once the technical feasibility is proven, the choice between thermoplastics and traditional materials will finally depend on the commercial considerations. So how far have we got towards a commercial proposition?

## REVIEW OF PRODUCT DEVELOPMENT

### Base Material Considerations

The regulations affecting aircraft interiors, primarily concerned with the health and safety of the public and of the work-force, form a starting point for material selection. Fire safety regulations were receiving much attention worldwide at the beginning of the program. Of the thermoplastics available which promised to fulfil all the fireworthiness requirements (PEI, PEEK, PES, PI, PPS, PPSU), PEEK was too expensive, PES and PPSU are not available

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<sup>1</sup> Excluding "soft" items such as seats and carpeting.

in woven prepreg form,<sup>2</sup> leaving PEI as the only serious candidate at this stage in the program.

Continuous fiber reinforced PEI is available in prepreg form or as consolidated laminated sheet. Semi-finished board materials can be made by bonding laminates to a suitable core such as aramid fiber reinforced phenolic honeycomb. A patented solvent process exists to generate a (PEI) foam core between two laminates or single plies without the need for adhesives. In all products discussed the reinforcement is woven glass and the starting point for manufacture is a semi-finished product.

The choice of glass versus carbon depends on the actual product requirements. Interior parts which are subject to localized impact loading are generally more cost-effective in glass than carbon. Carbon is more favorable when pure stiffness in a small space is required. Hybrids tend to fall between two stools and aramid reinforced PEI burns through. Technology readiness can be demonstrated with either material, so glass has been chosen for the largest potential area of application.

Woven cloth has a number of advantages over unidirectional (UD) fiber reinforcement. One of the attractive features of thermoplastics is the potential for integral decor. In the absence of a decorative film, virtual elimination of slivers (fiber breakout) is an important consideration in product liability, injury to own personnel etc. where the frequency of human contact is high. Burn through and wear through requirements are easier to meet with woven materials. It was also thought that thermofolding with UD would be more difficult to obtain cosmetically pleasing fold lines. These considerations outweigh the higher nominal strength and stiffness of UD reinforcement. Combinations of UD and cloth have not been considered. The latter and the carbon versus glass trade-off is seen as a follow-up activity along with new polymers and knitted fabrics.

#### Candidate Aircraft Interior Parts

There is no better way to gain practical experience in applying new materials than to try to make simple, real parts. A number of candidate interior parts - 7 thermoset and 2 metal - have been selected from a preliminary feasibility study in which existing parts were considered for "conversion" to an interchangeable thermoplastic equivalent. Each candidate was designed to meet current part-specific requirements<sup>3</sup> so as to enable a valid cost comparison. The thermoplastic parts are reviewed here in turn per semi-finished material type.

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<sup>2</sup> Material development is not Fokker core business. The developers of PI and PPS did not meet the selection criteria for partners in this program.

<sup>3</sup> Interior panel design requirements (available from airframe manufacturers) are typically selected from: weight, decorative finish, flatness, interchangeability, impact tolerance, flexural stiffness, peel strength, insert pull-out/ torque-out, abrasion resistance, edge quality, temperature range, chemical resistance, UV yellowing, antistatic, noise transmission and fireworthiness.

### Sandwich with foam core

- stowage cabinet shelf
- ceiling panel
- waste bin door
- air duct

### Sandwich with aramid honeycomb

- cargo floor panels
- cabin floor panels
- electrical power center

### Solid laminate

- covers and caps in cargo lining
- kickplates (dado panels)

### Sandwich With Foam Core

Potentially, this solvent process offers double-curved sandwich parts having gradual and stepwise variations in thickness, integral coloring and edge finishing and molded-in features such as hardpoints. Flat stock boards can be thermofolded using a hot knife process to produce prismatic parts on cheap tools. Edge closing and finishing is a similar hot process. Material recycling potential is good (for composites). The lighter constructions comply easily with the latest FAA and industry requirements for fireworthiness. Critical aspects include core rigidity at competitive weights, surface finish for painted applications, scatter in performance parameters, solvent health hazard and high price<sup>4</sup>.

Control and understanding of the solvent process for the manufacture of flat stock boards is considered to be too limited at present to risk further investment in product development. Unfortunately the necessary venture capital to develop the material processing technology further is not available in the Netherlands today. Products from this material are included in the review for the sake of completeness.

Stowage cabinet shelf. This part is a medium sized low volume flat component without thickness variations, having a single folded up edge. It is finish painted. Impact tolerance and stiffness requirements are both relatively high for an interior part. Fireworthiness requirements are smoke and toxic gas emission and flammability. Status: design study.

Ceiling panel. Cabin outer ceiling panels are small size, medium volume, single-curved prismatic components having a thickness step and are finished with a decorative film. Fireworthiness requirements are smoke and toxic gas emission and flammability. This part was selected because it has a simple shape and is lightly loaded. Elimination of

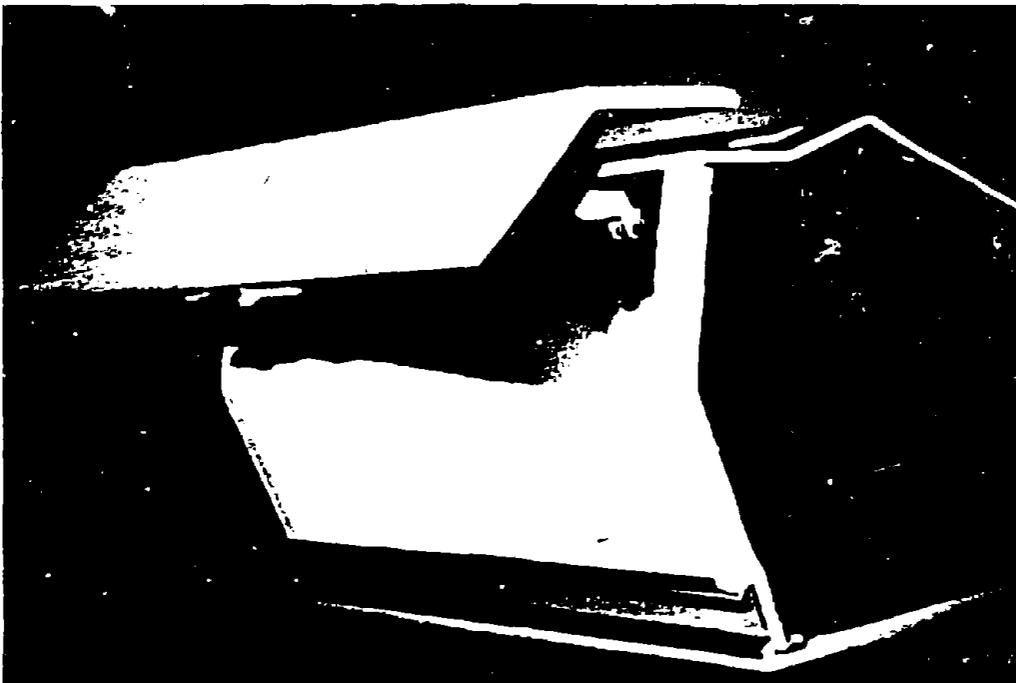
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<sup>4</sup> about 5 times the price of equivalent thermoset flat stock.

edge filler, with its weight and undesirable fire properties, and of labour intensive finishing is an attractive target. Status: production feasibility study.

Waste bin door. Lavatory waste receptacles, up to three per aircraft, are provided with this small, finish painted, flat sandwich product. Fireworthiness requirements are smoke and toxic gas emission, fire containment and flammability. This application was chosen for the same reasons as the ceiling plus the need to determine the robustness of the edge finishing technique. Status: production feasibility study. The conclusion was that this simple product is very cost-effective (expected net cost savings 60% of existing thermoset design) through eliminating hand finishing.

Air duct. This is a large, low volume, undecorated part which, because of its location, has a complex prismatic shape. Fireworthiness requirements are smoke and toxic gas emission, burn through and flammability. This kind of "technical" product (no cosmetic requirements) is particularly suited to initial evaluation of a new technology because it allows development to be broken down into manageable steps. Status: production feasibility study. This part would probably not achieve the initially expected savings because of its large size and lack of hand finishing required.



**Figure 1. FOAM CORE STOWAGE BIN**

Overhead Stowage Bin. This assembly was developed outside the main program. Manufacture of this part in glass/phenolics using autoclave techniques involves considerable hand finishing. Potential savings in manufacturing costs are the main driver in selecting this part. No weight savings are achievable at a parts level because of stiffness and impact damage requirements. Status: a complete bin section has been produced as a

technology demonstrator based on part-for-part replacement of thermoset panels. Existing joint techniques are retained. See figure 1.

Sandwich with Aramid Honeycomb

Flat stock boards are made in an autoclave or press and can be thermofolded using a hot knife process to produce prismatic parts on cheap tools. Edge closing and finishing is a similar hot process. Present consolidation techniques produce typically near mirror finish panels, flat, free of pinholes and most of the visual defects associated with thermoset boards. The consolidated sheet supplier and the parts manufacturer are qualified to aerospace standards. The semi-finished product is undergoing qualification having been screened earlier this year.

Critical areas discovered so far concern the mechanical properties, particularly impact behavior and the effects of stress concentrations. Skydrol resistance is a qualification requirement which, just as for thermoset panels, cannot be met without sealing the edges. An extensive qualification test program is required to obtain reliable data. The standard floor panel qualification program is likely to be sufficient for most interior

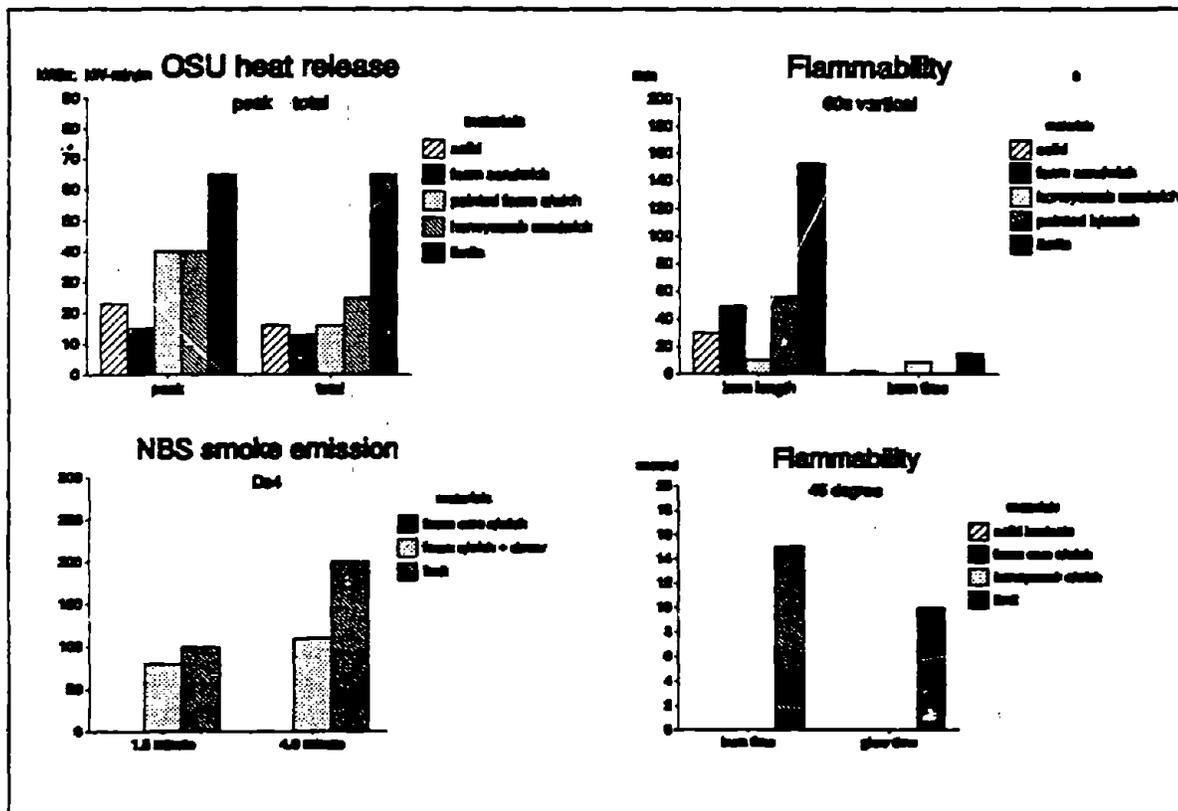


Figure 2. TYPICAL FIRE TEST VALUES FOR THERMOPLASTIC COMPOSITE PANELS

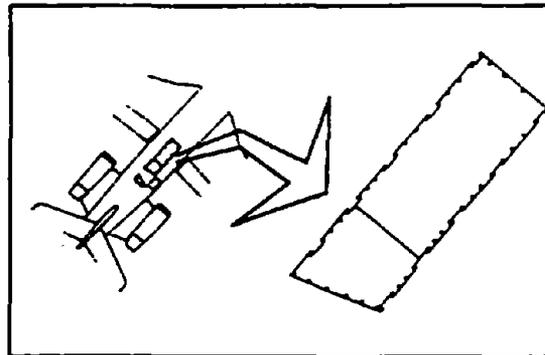
requirements. This material meets FAA and industry fire safety requirements by a comfortable margin. See figure 2.

Behaviour under impact loading is unexpectedly poor, probably and paradoxically as a result of good consolidation of the faces. Energy absorption takes place either via the adhesive layer or in localised brittle tensile fiber fracture in the upper face. The delaminations normally observed in the top skins of impact damaged thermoset panels are entirely absent. This makes visual assessment of the panel's residual load carrying capability after impact damage unreliable.

Stress concentrations such as induced in an open-hole bending test can reduce the tensile strength by over 50% (thermosets around 30%). The failure mechanism is localized brittle tensile fiber fracture in the lower skin with little ductile energy absorption in the resin matrix. This mechanism is more severe than that found in the "brittle" thermosets.

A classic solution for both these drawbacks is to add a  $\pm 45^\circ$  layer to the face sheet though this is not usually adopted in interiors for the usual cost/strength/weight reasons. It is interesting to note that foam cored sandwich panels do not exhibit this impact behavior as energy is absorbed by local deformation of the core.

Cargo floor panels. See figure 3. These parts are large, medium volume flat stock components for which the main consideration is strength - particularly impact, bending and wear, chemical and corrosion resistance. Cargo compartment floors traditionally have a short, hard life. Fireworthiness requirements are smoke and toxic gas emission, burn through and flammability. The upper surface is colored white.



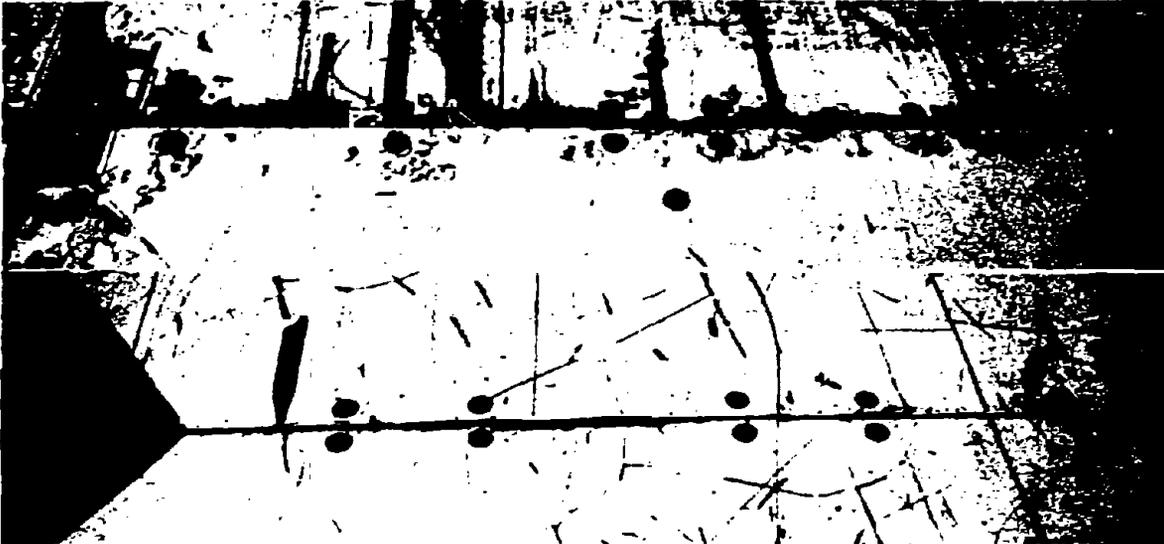
**Figure 3. THERMOPLASTIC CARGO HOLD FLOOR PANELS.**

At first sight the design parameters and the material properties do not make a good match and the material costs alone are not competitive enough to justify a change. When the wear mechanism of traditional (phenolic) thermosets was investigated, however, it was found that the edge construction plays a critical role in preventing the initiation of the pot-hole effect. Traditional thermoset panels are discarded in service when either (the risk of) injury from splinters is too high, the panels contain too much visible damage or they feel "soft". The higher material price could be justified if the service life were to be sufficiently lengthened.

A robust edge is easily and neatly produced in thermoplastic material. The top face sheet of the thermoplastic panels cut from stock board is thermofolded down along the product edges to meet the bottom face<sup>5</sup>. A shipset of these panels is in trial service with a

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<sup>5</sup> See ref. 1. Note that this edge feature can be molded in thermoset panels as cured. Many airlines prefer to make their own panels from stock board, however.



**Figure 4. COMPARATIVE WEAR OF CARGO FLOOR PANELS IN SERVICE (1900 FLIGHTS)  
TOP: PHENOLIC UD PLYS ON HONEYCOMB CORE. BOTTOM: PEI/FABRIC ON H/COMB**

major European airline to determine the suitability for serial production which, depending on the outcome, is scheduled for airline introduction this summer (1993). These panels have realized 2 500 flights to date without replacement. The target is 6 000. See figure 4. Development continues to introduce integral coloring, improved bonding of face sheets to honeycomb, and reinforcing of holes. An improved thermoset version, or metal<sup>6</sup> may yet prove to be the best choice.

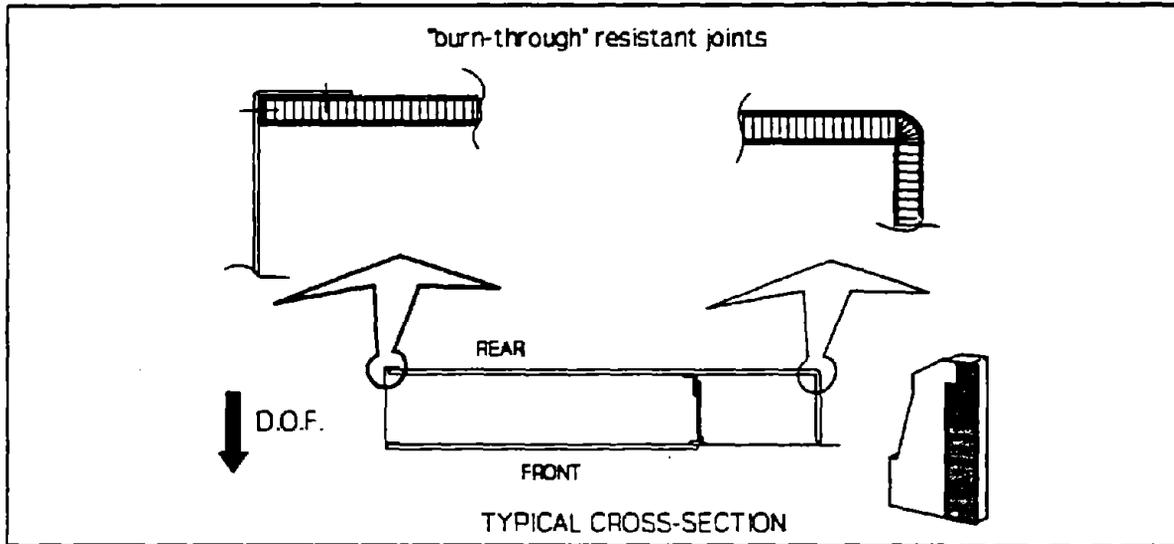
Cabin floor panels. Initial attention was focused on underseat flooring where the impact loading is lower than in entrance and main aisle applications. An internal review of crashworthiness strategy, however, advised not to allow brittle behavior in these parts. The application has been dropped pending material improvements.

Ceiling panel. The same outer ceiling mentioned above was made as a comparative exercise. These single-curved parts are formed during the bonding process. Status: demonstration prototype.

Electrical Power Center. Following an inflight fire incident in 1989 when an electrical fire spread from the EPC to an adjoining galley and filled the flight compartment with smoke, a fire containment requirement has been voluntarily added over and above the means of compliance recommended in AC25-16 for a new modular design. The ability to thermofold this material to avoid elaborate fireworthy joints made PEI/glass sandwich an attractive candidate. The weight saving target compared with the existing metal design was achieved on paper. Status: commercial tender. See figure 5.

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<sup>6</sup> GLARE, aluminium laminated with fiberglass in a patented process, looks interesting for cargo floors because of good impact and burn-through properties.

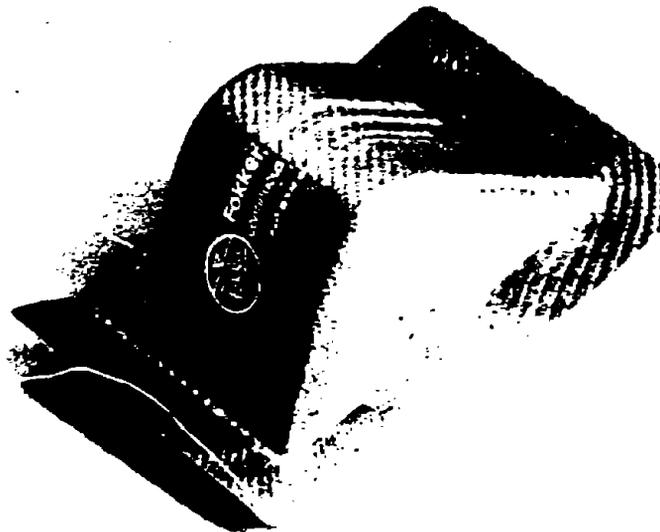


**Figure 5. MODULAR E.P.C HOUSING.**

#### Solid Laminates

The earliest trials were carried out using solid laminates and preregs. The fabrication techniques considered were deep-drawing, creep forming, membrane forming, rubber press forming and welding. Hot knife thermofolding and hot dimpling were later added in parallel with sandwich panel processing.

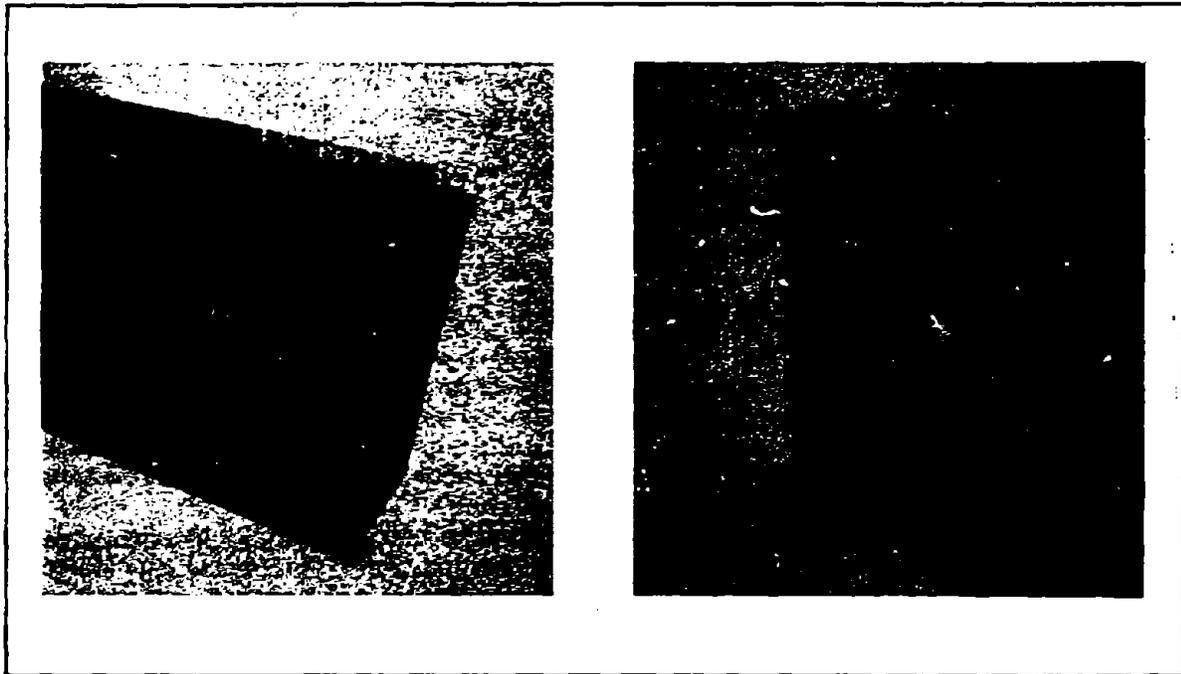
Covers and caps in cargo lining. These are small, non-structural, roughly hat shaped shells used to close off openings in the cargo compartment ceiling and sidewall lining and provide a recess. They were introduced in 1987 to replace vacuum formed PC parts to comply with the FAA burn through requirement. Cosmetic requirements are not as strict as for cabin furnishings so that deep-drawing and painting produce an acceptable finish. Final part cost is significantly less than for similar glass/phenolic hand laminated parts. Status: Serial production. See figure 6.



**Figure 6. DEEP-DRAWN CAP (CARGO LINING)**

Kickplates. Kickplates, or dado panels, are flat prismatic parts, some over 2 meters long. Design constraints include (propeller) noise transmission, subjective stiffness and residual strength after the warp fibers are damaged during thermo-

folding. Fireworthiness requirements are heat release, smoke and toxic gas emission, burn through and flammability.



**Figure 7. PROTOTYPE SOLID LAMINATE KICK PLATES**

Weight saving of 13 kg per aircraft compared with existing metal design has been realised. Integral color and texture are envisaged in further development to save more weight and the cost of carpeting. Status: a prototype shipset will undergo in-service trials with a large regional European airline from February 1993. This application was also adopted for foam core solutions which offer an even greater weight saving but discontinued before production prototype stage for the reasons given earlier.

## DISCUSSION

The small-scale approach illustrated here seems to have achieved moderate success. There is a better understanding of the limitations of the material and of its ability to be shaped and worked. A factor often forgotten in the haste of achieving "technology readiness" is the learning process required to design and manufacture in new materials efficiently. We do not yet know how much of these new materials' apparent shortcomings to accept and to design around, and which properties, strong or weak, to ask the materials developers and suppliers to improve on. Something clearly needs to be done about the apparent brittleness of the current honeycomb sandwich materials. Advances in joining/fastening techniques, integral decoration and finishing would increase the applications available without adding to the basic material price. Obviously a part like a sidewall panel, with its strongly double-curved surfaces, is not technically feasible from flat stock. In the short

term one can expect a modest expansion in the prismatic applications as the materials become more familiar.

In discussions with material suppliers the question often comes up of how to steer materials development in the right direction. Will thermoplastic composites remain small-scale or can a gradual take-over of thermoset territory be expected? The limited front money to fund material and related process development is dependent on a projected return from more or less widespread application and it is not yet certain that the larger parts are going to pay off. The accurate calculations necessary for a go-ahead cannot yet be made because of uncertain data on scale effects. These calculations will need to include external factors such as the environmental lobby, making it even less desirable for an operator to consign an interior to the scrap-heap, the work-force demanding healthier surroundings, and the economics of deregulated operation, maintenance and passenger appeal in a transport medium which is becoming steadily more commonplace worldwide.

## CONCLUSIONS

Progress to date is modest. There are no thermoplastic composite sidewalls, ceilings or stow bins yet in serial production to indicate a breakthrough. Cost savings and quality improvements are more elusive than at first expected even in the smaller parts. Since the demise of the foam core technique there is no prospect of double-curved products in the short term. The "technology proving" step in applied materials development requires sound appraisal and adequate funding throughout. New materials usually mean new or adapted manufacturing processes involving substantial investment in new - and the writing off of old - processing machinery, tooling and technology. This presents an obstacle to further development of thermoplastic technology no less than elsewhere.

When fully developed, these materials are likely to find a niche where designers can offset the much higher material cost with either cost/weight savings through design and manufacturing benefits or with qualitative improvements leading to a lower life cycle cost. We should see thermoplastic composites as a welcome addition to our small armory of interior materials but also bear in mind that thermosets and metals are likely to provide most optimum solutions to large interior parts for some years. In order to progress to the main parts it is necessary to pursue a long-term, cooperative, new materials program while the optimum designs are still being provided by the more fully developed traditional materials.

## ACKNOWLEDGEMENTS

The information presented here has become available thanks to the cooperation of members of the Aircraft Technology Program team at Fokker Aircraft B.V. and of Arnt Offringa and colleagues at Fokker Special Products B.V.

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Advanced Phenolic Systems For Aircraft Interiors

H. Gupta and M. McCabe

SP Systems

ABSTRACT

Recent advances in the phenolic prepreg systems suitable for aircraft interior's applications are described. The current state of the art phenolic systems achieve a balance of properties and comfortably meet heat release and smoke emission requirements of various regulatory agencies such as FAR 25.853 and ATS 1000.001. A recent commercially available phenol formaldehyde resin based prepreg product SPH 2400 is reviewed. A single ply SPH 2400 sandwich laminates fabricated from Nomex honeycomb core and 7781 style fiberglass show Ohio State University (OSU) test peak heat release characteristics as low as 18 KW/M<sup>2</sup> and an average OSU heat release of 15 KW-Min/M<sup>2</sup> over a period of two minutes. The optical density of smoke emission measured by NBS method in flaming mode was found to be only 6 when measured over four minutes. The product SPH 2400 can be processed by using a variety of techniques such as vacuum bag molding, multiple opening press (MOP) molding and crushed core (CC) press molding. The prepreg system possesses outstanding self adhesive characteristics to a variety of core substrate and does not require an additional adhesive layer for core bonding. A proprietary latent catalysis technology enables rapid cures at temperature as low as 132°C (270°F) while maintaining excellent out time at room temperature.

INTRODUCTION

In the recent past, composite materials have gained acceptance as materials of choice for many aircraft interior applications including side walls, partitions, ceiling panels, floor panels, seat backs and overhead stowage bins. Besides their light weight advantage, current composites meet or exceed stringent regulatory requirements of FST (Fire, Smoke and Toxicity) [1,2] and offer strength, excellent aesthetics and serviceability.

In the United States, the Federal Aviation Agency (FAA) and its predecessor, the Civil Aeronautics Administration (CAA), have had the statutory responsibility to establish minimum safety standards for aircraft design and safety. The federally mandated requirements for aircraft are contained in the part 14 of the Code of Federal Regulations commonly known as FAR's (Federal Air Regulation). The FAR PART's 25 covers the design of large transport category aircraft. The relevant section is paragraph 25.853 which describe regulatory statutes for compartment interiors.

The current FST regulatory requirements have evolved over the last three decades, however, major changes have taken place only in the past five years or so. During this period, the FAA has adopted an unprecedented series of new standards designated to improve transport aircraft fire safety [3,4]. The most stringent FAA requirements apply to large area cabin liners such as sidewalls, ceilings, partitions, stowage bins, etc. These requirements are discussed in details in references 3 and 4. New regulatory requirements are typically released by FAA through amendments to FAR PART 25. A summary of various amendments [3] in the recent past is shown in table 1. The present standards have been internationally

Rule	Final Rule Published	Compliance Date	Parts Affected	Am't'l No.
1. Seat Fire Blocking Layers	26 Oct. 84	26 Nov. 87	25, 29, 121	25 - 29
2. Floor Proximity Lighting	26 Oct. 84	26 Nov. 86	25, 121	25 - 58
3. Cabin Fire Protection A. Lavatory Smoke Detectors B. Lavatory Auto. Fire Extinguishers C. Halon 1211 Hand Extinguishers D. Hand Extinguishers	29 Mar. 85	29 Oct. 86 29 Apr. 87 29 Apr. 86 29 Apr. 85	121	121 - 185
4. Cargo Compartment Fire Protection	16 May 86	16 Jun. 86	25	25 - 60
5. Cabin Material Flammability A. 100/100 Heat B. 65/65 Heat, 200 Smoke	21 Jul. 86 & 25 Aug. 88	20 Aug. 88 20 Aug. 90	25, 121	25 - 61 & 25 - 66
6. Crew Protective Breathing	03 Jun. 87	06 Jul. 89	121	121 - 193
7. Cargo Compartment Fire Protection	17 Feb. 89	20 Mar. 91	121, 135	121 - 202

TABLE 1: TRANSPORT AIRCRAFT SAFETY RULEMAKING | 3 |

anchored in specifications such as Airbus Technical Specifications (ATS) 1000.001.

The earliest requirement was that cabin materials had to pass the horizontal burn Bunsen burner test. A vertical Bunsen burner test was introduced in 1967 which involved a 12 second exposure to the flame. The exposure time was increased to 60 seconds in 1972. Materials such as polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS) copolymers met these requirements and were widely used. High performance applications also involved phenolics, epoxy on glass and Kevlar and polycarbonates. It was later recognized that a direct flammability test was not fully representative of cabin fire. A more realistic simulation would involve the introduction of a radiant heat source into the test. A new test developed at Ohio State University (OSU) was introduced in 1986 and new standards were adopted in 1988. All aircraft certified from 1988 had to meet the "100/100" requirements for the 2 minutes average heat release and the peak heat release respectively which became progressively stringent to the "65/65" for aircraft certified from 1990. These standards were further tightened by incorporating the smoke density and toxicity standards. The underlying philosophy was simple. In a cabin fire scenario, more often occupants die through

TEST TYPE	MINIMUM PASS CRITERIA
IGNITABILITY FAR 25 Appendix F, Part I 60 - SEC BUNSEN BURNER includes flooring part	< 6 - INCH BURN LENGTH < 15 SEC EXTINGUISHING TIME FOR SPECIMENS < 3 SEC EXTINGUISHING TIME FOR DRIPS
HEAT RELEASE FAR 25 Appendix F, Part IV OSU CALORIMETER above floor parts only OSU CALORIMETER above floor parts only	< 65 Kw/MP PEAK RATE DURING 4 - MIN. TEST < 65 Kw - MIN/MP TOTAL DURING FIRST 2 MIN.
SMOKE RELEASE FAR 25 Appendix F, Part V NBS SMOKE CHAMBER above floor parts only	< 200 SPECIFIC OPTICAL DENSITY DURING 4 - MIN. TEST

TABLE 2: THE FAA FLAMMABILITY REQUIREMENTS FOR AIRPLANE CABIN LINERS [4].

asphyxiation by smoke or breathing toxic smoke. If cabin materials could resist spread of fire along with emission of low smoke during a post crash fire scenario, the occupants will have additional time to evacuate. The current FAA requirements for airplane cabin liner are listed in table 2. Among all the regulatory requirements, incorporation of quantitative limits on heat release, smoke density and toxicity in a simulated combustion scenario [5 - 9] has influenced the material selection process in perhaps the most notable way. Even though the majority of older technologies fell short in conforming to these strict standards, phenol formaldehyde resin technology emerged as a technology of choice. Today, a proper selection of resin and flame retardants enables many commercial systems to far exceed these requirements.

Besides meeting safety criteria, the interior parts must be functional. From the part manufacturer's perspective, the parts should be rapidly processable, cost competitive and reproducible in sufficient quantities. From the airlines perspective, cabin furnishing in the aircraft interior must be sturdy, durable with pleasant and comfortable architecture. These usually translate in enhanced performance and design standards for the materials of construction. For example, comfortable and pleasing interior designs often involve complex contours for which lay-up techniques often require specific handling characteristics of the prepreg such as tack. The prepreg product, then, must be able to be manufactured at different desired tack levels while maintaining processability.

A widely used composite panel design for aircraft interiors involves Nomex honeycomb core based sandwich structures. Good adhesion of the composite skin is necessary to the honeycomb core for secondary operations. In general, phenolic have poor adhesion to Nomex honeycomb and other core materials frequently used for aircraft interiors. This can be overcome by employing an additional adhesive layer to facilitate better bonding. Current prepreg composites, however, are self adhesive and may not require additional adhesive layer to improve the peel strengths. This translates into material and process cost savings. However, improvement in peel strength may be accompanied by a compromise in flame, heat release and smoke release characteristics. Achieving a balance of desirable properties in a composite material system is still practiced as a proprietary art. In this presentation we describe a commercial prepreg system SPH 2400 that achieves this balance.

## EXPERIMENTAL

### A) MATERIALS

The commercial prepreg products SPH 2400 is a fire retardant prepreg product manufactured by SP Systems. The product consists of a proprietary resin system based on phenol formaldehyde resin technology on a woven reinforcement. The prepreg material is obtained by impregnation and subsequent B-staging of the impregnated reinforcement in a tower. The conditions of impregnation are kept as proprietary. The product SPH 2400 is extremely amenable to customization. There are two types of custom variations that are normally introduced for a given basic product chemistry. The first variation involves changes in the handling characteristics such as tack of the prepreg. This usually results from changing conditions of drying or B-staging subsequent to impregnation. As a standard nomenclature, up to two letters following SPH 2400 describe the custom variations in the handling characteristics of the prepreg. A moderate tack version of the prepreg is designated as SPH 2400M. A lower tack version results with increasing the degree of drying and/or B-staging. This prepreg product is named as SPH 2400L. A very low tack version is produced by further

staging the product and is designated as SPH 2400LC.

A complete product designation involves a description of the reinforcement. The designation of the reinforcement style follows the matrix description after a slash. Depending on the application, various styles of fiberglass or graphite may be used. As an example, the product nomenclature SPH 2400L/7781 reflects the L version of SPH 2400 prepreg product on fiberglass style 7781.

An experimental variation of the product SPH 2400 was prepared in a laboratory simulated impregnation tower with the objective to optimize peel strengths in Nomex honeycomb core and fiberglass sandwich structures. This experimental variation is designated as XSPH 2400B4/7781. The prepreg physical properties of this product are considered as proprietary and an X before normal product assignment reflects its experimental product status.

Nomex honeycomb core of 3 lb density with 1/8" cell size was obtained from Ciba Geigy Corporation. For OSU data thickness of the Nomex honeycomb core used was 1/8" while the core used for peel strength panels was 1/2" thick.

## B) PANEL FABRICATION

### Configuration

Different configurations were standardized for different test evaluations. For peel strength evaluations a 2 ply of 7781 glass prepreg, 1/2" Nomex honeycomb core and 2 plies of 7781 glass prepreg was utilized. For OSU data 1 ply of 7781 glass, 1/8" of Nomex honeycomb core and 1 ply of 7781 fiberglass configuration. For NBS smoke density determination the configuration used involved 1 ply of 7781 fiberglass, 1/8" Nomex honeycomb and 1 ply of 7781 fiberglass. For all the configurations, the fill side faced the core and the direction of the fill yarn was parallel to the ribbon direction.

### Cure

For panels cured by press molding process, 12" by 12" specimens of the desired configurations were loaded in a preheated press at 127°C (260°F) in between two 1/4" thick release coated caul sheets and kept there for 45 minutes under 50 psi pressure. Subsequently the press was opened and the panels were removed hot.

For panels cured by crushed core press molding process, 12" by 12" specimens in the desired configurations were loaded in a preheated press at 160°C (320°F) in between two 1/4" thick release coated caul sheets. The platens were closed to the press using a set of crush rails. The panels were isothermally kept for 8 minutes and subsequently removed hot.

## C) PREPREG PHYSICALS, CHEMICAL CHARACTERIZATION & MECHANICAL TESTING

Various methods of chemical characterization, heat release and mechanical testing were employed to understand chemical, thermal and mechanical behavior of the new SPH 2400 system.

### Prepreg Physicals

The percent volatile (Vols) in the prepreg was measured by evaluating the weight loss in the prepreg after curing at 121°C (250°F) for 10 minutes in an air circulating oven. The volatile were calculated as follows:

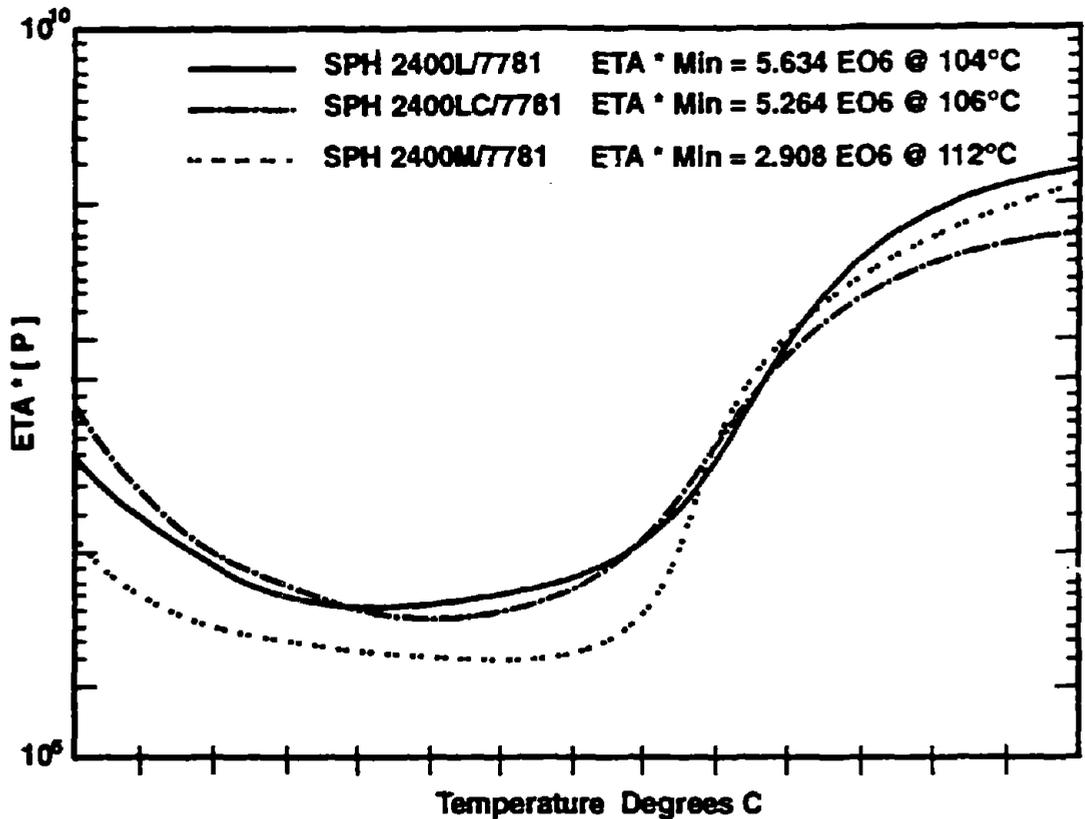


FIGURE 1: DYNAMIC COMPLEX VISCOSITY OF SPH 2400 PRODUCT M, L & LC VERSIONS ON 7781 STYLE WOVEN FIBERGLASS REINFORCEMENT.

$$\text{Vols} = 100 \times (W1 - W2) / W1 \quad (1)$$

where

W1 Weight of the prepreg

W2 Weight of the cured prepreg

Resin content (RC) of the prepreg samples was evaluated by using a burn off technique. A known weight of a cured prepreg ply 4" by 4" in dimensions was kept in the muffled furnace at 593°C (1100°F) for 60 minutes. The resin content was evaluated by using the following formula:

$$\text{RC} = 100 \times (W2 - W3) / W2 \quad (2)$$

where

W2 Weight of the cured prepreg

W3 Weight of the prepreg after burn off

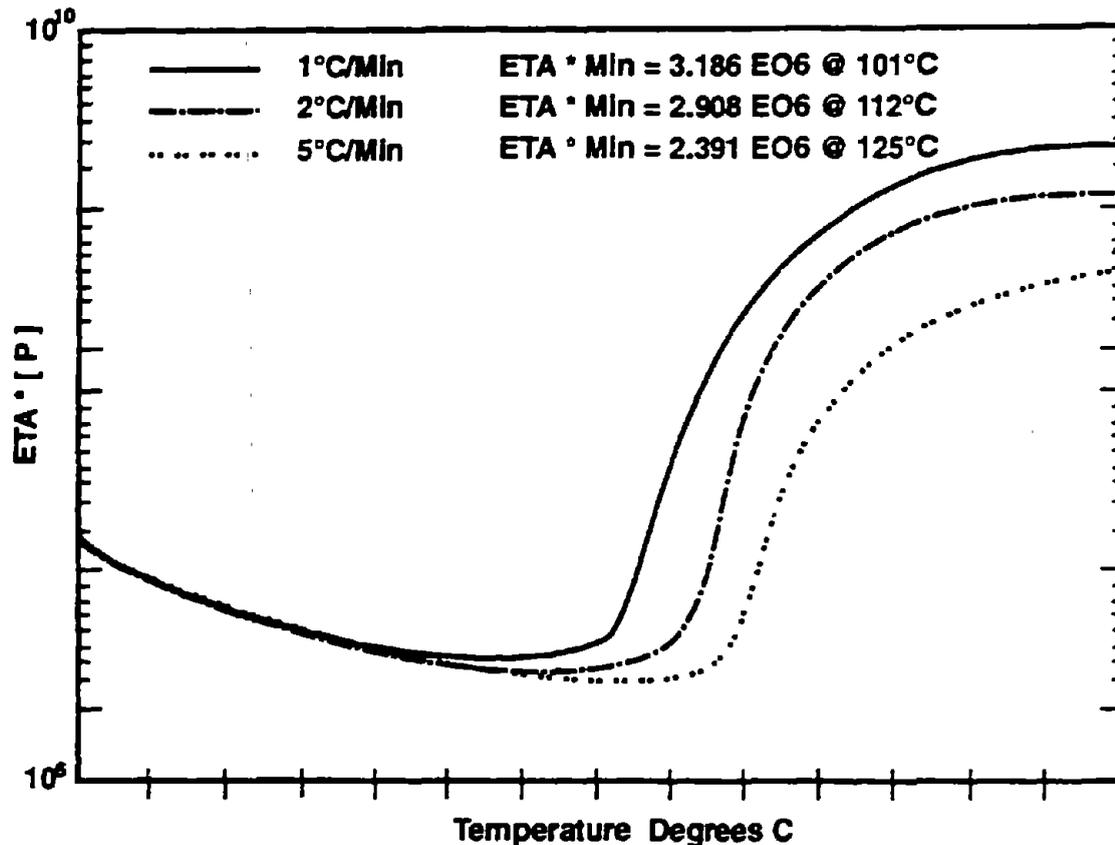


FIGURE 2: DYNAMIC COMPLEX VISCOSITY OF SPH 2400M/7781 AS A FUNCTION OF HEAT RATE.

The percent flow in the prepreg was measured as the amount of resin flowed out of a stack of four plies of 4" by 4" prepreg when kept at 121°C (250°F) for 10 minutes in a preheated press at 50 psi pressure.

The gel time was measured as the time required for the sneezed prepreg resin to undergo gelation at 121°C (250°F). The gelation was measured by an event when stringiness of the resin ceases to exist.

Tack of the prepreg was measured only qualitatively under ambient conditions of 25°C (77°F) and relative humidity of 65%. A low tack prepreg showed no adherence to itself whereas a moderate tack prepreg showed self adherence.

#### Thermal Analysis (TA)

A Dupont Thermogravimetric Analyzer TGA model 951 and thermal analysis work station (model TA 9900), has been used throughout this study. All the experiments were performed under isothermal conditions in a nitrogen environment with the gas flowing at 40 cc/Min.

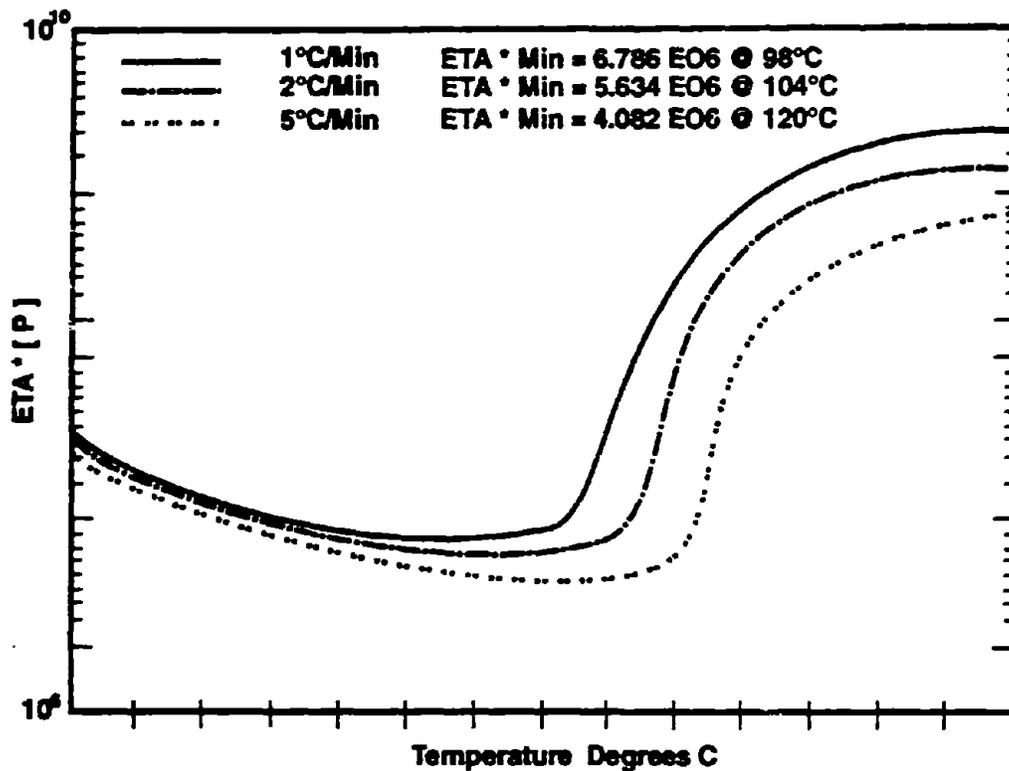


FIGURE 3: DYNAMIC COMPLEX VISCOSITY OF SPH 2400L/7781 AS A FUNCTION OF HEAT.

#### Chemorheology

Dynamic mechanical testing was performed on an RDS II. Rheometrics dynamic spectrometer, using a rectangular torsion accessory. All the experiments were conducted with 'auto tension on'. This feature is necessary to prevent samples from buckling under compression due to the thermal expansion. Dynamic mechanical parameters such as  $G'$ ,  $G''$  and  $\eta^*$  were calculated from equations 3 to 5.

$$G' = K \cdot \text{Real}(\tau/\theta) \quad (3)$$

$$G'' = K \cdot \text{Imag}(\tau/\theta) \quad (4)$$

$$\eta^* = (G'^2 + G''^2)^{1/2} / \omega \quad (5)$$

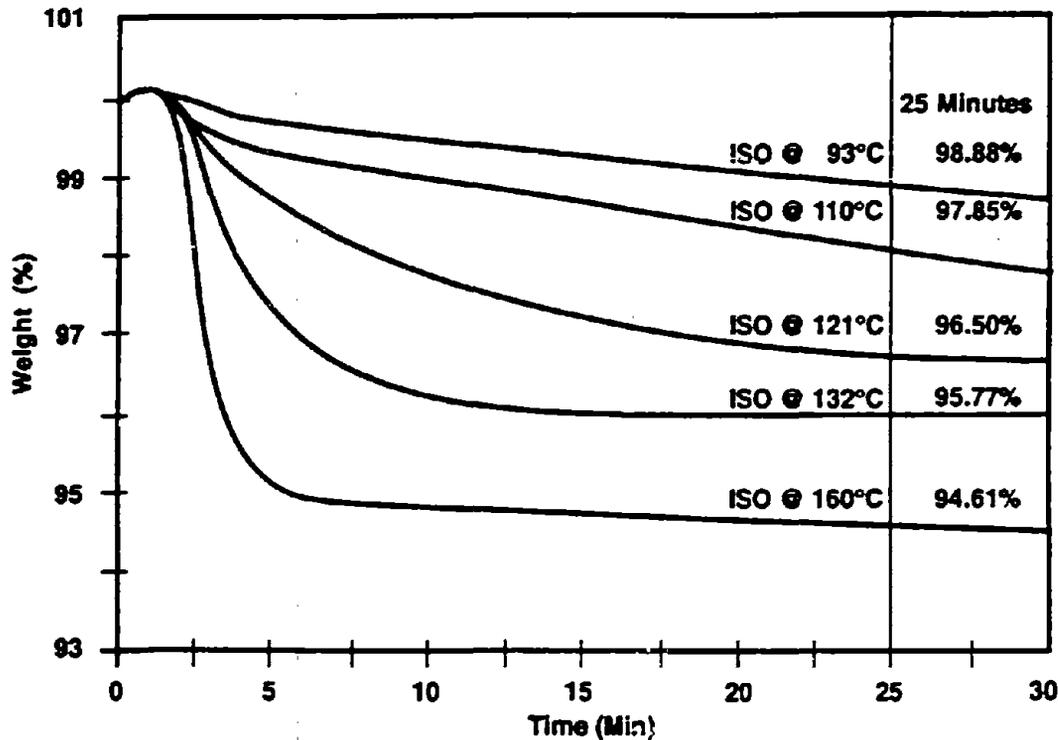


FIGURE 4: ISOTHERMAL THERMOGRAVAMETRIC ANALYSIS OF SPH 2400M/7781 AT VARIOUS TEMPERATURES.

For rectangular torsion accessory

$$K = L \cdot 980.7 / [ (T / 10)^3 \cdot W \cdot (1/3 - .21 \cdot (T/W)) ] \quad (6)$$

T : Sample thickness  
 L : Sample length  
 $\theta$  : Shearing angle  
 $\tau$  : Shearing Torque  
 w : Test frequency

Two plies prepreg samples were cut at 45° orientation w.r.t warp axis for all products. A frequency of 40 Rads / sec was used along with a 0.4% strain rate. The samples were heated at specified heat rate from room temperature to 180°C (356°F).

#### Peel Strength

A United Calibration Smart-1 mechanical tester was used throughout the study. All the mechanical testing was performed in accordance with Climbing Drum peel test method outlined in MIL-STD-401.

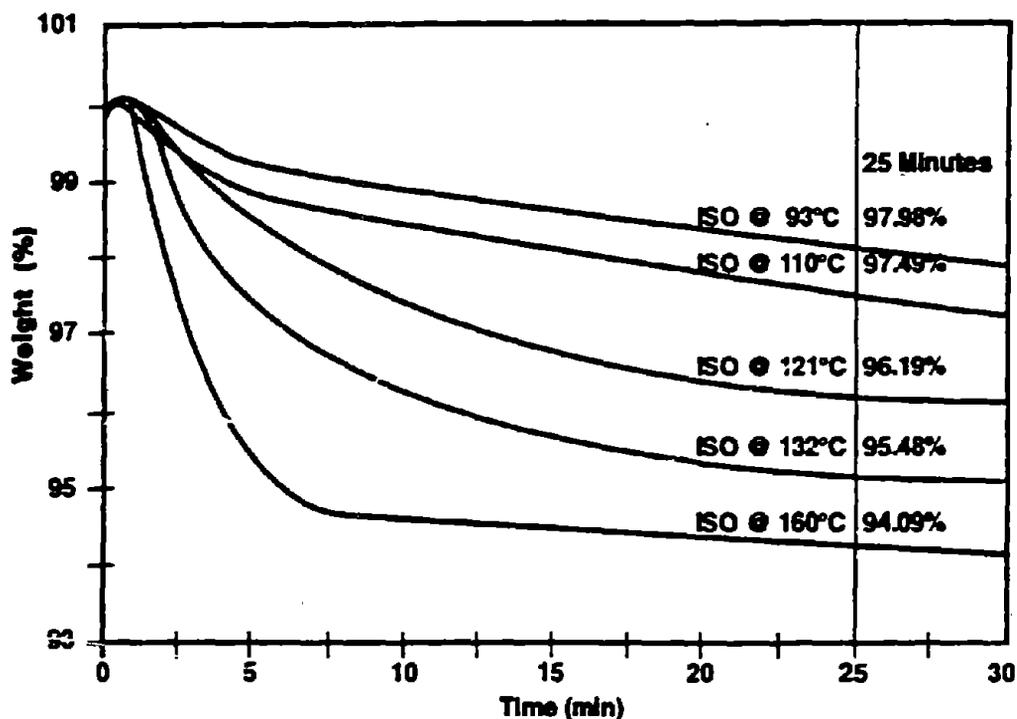


FIGURE 5: ISOTHERMAL THERMOGRAVAMETRIC ANALYSIS OF SPH 2400L/7781 AT VARIOUS TEMPERATURES.

OSU Heat Release & NBS Smoke Testing

Samples were sent to Delsen laboratory for evaluation. The heat release characteristics were evaluated based on Ohio State University (OSU) test method in accordance with requirements of FAR 25.853. The optical density of the smoke emission was measured as per the National Bureau of Standard (NBS) specification adopted by FAR 25.853.

RESULTS AND DISCUSSION

The physical characteristics of three commercial versions of the product SPH 2400 are shown in table 3. Resin content of the L and the M version is targeted to be around 40%, however, flow and volatile in the L version are targeted to be lower than the M version. Resin content of the LC version, in contrast, is targeted to be only 32% and the prepreg has low flow characteristics. These differences in prepreg physical properties manifest significant differences in the handling performance of the prepreg product. The M version has moderate tack in comparison to the L version which has low tack and the LC version has even lighter tack. In general, prepreg physicals are controlled by regulating various operational

	Resin Content		Flow %		Volatile %		Gel Time (Minutes)
	Specification	Actual	Specification	Actual	Specification	Actual	
SPH 2400L/7781	35 - 43	39	8 - 18	15.5	3.2 max	2.9	6'
SPH 2400 L C/7781	29 - 35	33	10 - 20	12.9	6 max*	4.7	2'
SPH 2400 M/7781	38 - 43	40	15 - 25	22.5	5 max	3.8	9'
X SPH 2400 (B4)/7781	-	P**	-	P	-	P	P

\* Volatile % was measured at 180° C for 18 minutes P\*\* Proprietary Data

TABLE 3: THE PHYSICAL CHARACTERISTICS OF VARIOUS VERSIONS OF SPH 2400 PREPREG PRODUCT

parameters of the impregnation tower. For a given reinforcement, resin content of the prepreg is a function of line speed, gap setting of metering bars and resin dilution. Flow characteristics and residual volatile percents are complex quantities and usually depend on resin content as well as the extent of drying and B-staging subsequent to impregnation. In the impregnation tower, drying and B-staging are mainly controlled by a combination of tower temperatures and the line speed. With increasing temperature and residence time in the tower, prepreg is drier, less tackier and more B-staged. The tack characteristics may be quite important from the application stand point. By virtue of moderate tack levels, the M version is more suitable for lay-ups involving complex contours where tackiness of the prepreg is desired. The product version L, on the other hand, is suitable for flat laminates and sandwich structure. The LC version is most suitable for crushed core or high pressure press molding processes.

Thermal history of the impregnated reinforcement in the tower affects chemorheology of the SPH 2400 products. The influence is seen both on minimum dynamic viscosity as well as initial dynamic viscosity. Figure 1 compares dynamic complex viscosity of the three commercial versions on 7781 style fiberglass reinforcement as a function of temperature. Lower minimum and initial viscosity attained by the M version are attributed to lower degree of B-staging during impregnation operation. The LC version attains the highest initial viscosity and minimum viscosity among the three commercial grades. This reduced ability to flow limits the LC grade to be processable only under high pressures. The flow behavior of the SPH 2400 products is also affected by the rate at which the heat is applied. Figure 2 and 3 show the effects of heat rate on the dynamic viscosity of the M and L versions of the prepreg. As the heat rate increases, the minimum viscosity reduces irrespective of the initial viscosity of different versions of SPH 2400 products. Temperatures at which the minimum viscosity is achieved, on the other hand, increasing the rate of heating. This is important in designing a cure cycle specially for processes where resin flow is a critical parameter.

The sequence of chemorheological changes that take place on heating phenol formaldehyde resin based prepreg systems are in general complicated by evaluation of volatile. This volatile may further affect the fabrication of honeycomb type sandwich structures by exerting internal pressure on the face skin. This is especially critical for press molding processes where placing a lay-up in a hot press and removing hot, results in a considerable time saving. For a system to be suitable for this process variation, the bondline needs to be strong enough at the process temperature, at the time of removal, to withstand the internal pressure of the volatile, or the skin will peel off the core. The rate of volatile liberation is a strong function

of the resin content of the prepreg and the temperature of the final cure. The effect of temperature on volatile generation was investigated on SPH 2400 products using TGA analysis. Figure 4 summarizes the weight loss characteristics of the M version as a function of the cure time at various temperatures. It is clear that the rate of volatile generation significantly change as the temperature increases. At lower temperatures of 93°C (200°F) and

	LYING ON THE TABLE WITHOUT COVER					ROLLED AND SEALED IN POLY BAGS				
	FRESH	8 DAYS	12 DAYS	15 DAYS	19 DAYS	FRESH	8 DAYS	12 DAYS	15 DAYS	19 DAYS
Resin Solid (Dry) %	40.0	39.5	39.3	39.7	39.4	41.7	40.0	39.4	39.5	39.5
Volatiles @ 121° C 18 %	4.6	4.7	4.0	4.3	4.0	4.6	4.7	4.0	4.3	4.3
Flow @ 121° C 68 P61 %	23.1	21.0	18.5	19.9	19.9	23.1	21.0	18.0	19.9	20.2
Gel Time @ 121° C	4' 58"	4' 41"	4' 36"	4' 32"	4' 24"	4' 58"	4' 41"	4' 36"	4' 32"	4' 19"
Tack & Drops	Med.	Med.	Med.	Med.	Med.	Med.	Med.	Med.	Med.	Med.

TABLE 4: ROOM TEMPERATURE AGING OF SPH 2400M/7781 PRODUCT

110°C (230°F), the loss of weight is gradual and does not achieve an equilibrium within 30 minutes of observation. At temperatures of 121°C (250°F) or higher, volatile evolve rapidly during the initial isothermal phase and then asymptotically approach to an equilibrium level. Noteworthy is the equilibrium amount of volatile that the system finally approaches to at various temperatures. The equilibrium weight loss at 160°C (320°F) is 94.61% in comparison to 95.77% at 132°C (270°F) and 96.5% at 121°C (250°F). This remarkable difference may be due to different temperature dependent mechanisms that the system may follow [10]. The L version shows similar weight loss profile as a function of time at different temperatures as shown in figure 5. The two products, however, show a marginal difference between the absolute magnitude of the weight loss characteristics. A lower weight loss by the L version may be attributed to higher degree of B-staging during the manufacturing process. From the weight loss curves, it is clear that SPH 2400 prepregs can be cured at temperatures as low as 93°C (200°F) and temperatures as high as 160°C (320°F) by varying the isothermal cure time [11]. At temperatures of 160°C (320°F) the system requires as little as 12 minutes for complete cure whereas at 93°C (200°F) time required for complete cure is 180 minutes. Despite their fast reactivity, SPH 2400 systems show excellent outlife. A roll of SPH 2400M/7781 prepreg was laid out at room temperature with and without the polyfilm and the prepreg physical characteristics were monitored for 18 days. The results are compiled in table 4. It is clear that no appreciable changes in the physical properties of the prepreg were noted over 18 days of observations.

In general, unmodified phenol formaldehyde resins do not bond very well to the core materials. This may be because of the condensation volatile that may stay trapped in the resin as flaws and weaken the bondline. If honeycomb core is used, the bonding is even more difficult due to the low area of adhesion. The peel strengths of a Nomex sandwich panel with self adhesive SPH 2400/7781 face sheet was investigated using a climbing drum technique

for the three commercial versions of the product. Table 5 lists the peel strengths of the selected configurations. Clearly SPH 2400 systems show excellent peel strengths to the honeycomb core. It is evident that peel strengths are a strong function of prepreg physicals, panel configuration and process conditions. Depending on the panel configuration and process conditions, the peel strengths vary from 12 in-lb/3 in width to 56 in-lb/3 in width. Panels fabricated with cores crushed from 0.5" to 0.08" thick showed peel strengths as high as 56 in-lb/3 in width. As the degree of crush reduced, as in case of panel crushed from .125" to 0.08", the peel strength dropped to 35 in-lb/3 in width. The flat panels process by the press molding process under 50 psi show a modest peel strength of 12 to 13 in-lb/3 in width. The outstanding peel strengths obtained using a crushed core process may be attributed to the additional core surface available for bonding due to the crush. As the degree of crush

Product	Molding Conditions		Configuration	Peel Strength in-lb/3 in Width
	Press (PSI)	Crushed Core (degree of crush)		
SPH 2400M/7781	50 PSI		2/H/2	12
SPH 2400L/7781	50 PSI		2/H/2	13
SPH 2400LC/7781		0.5" to 0.08"	1/H/1	56
SPH 2400LC/7781		0.125 to 0.08"	1/H/1	35

TABLE 5: CLIMBING DRUM PEEL STRENGTHS OF SPH 2400 PRODUCT

reduces, core surface available for bonding may be less resulting in lower peel strengths.

The commercial utility of a prepreg system used for manufacturing aircraft interior's parts depends on it's ability to meet the current "65/65/200" requirements for average heat release, peak heat release and the smoke density respectively [3,4]. Achieving lower heat and smoke release (LHSR) characteristics are extremely desirable for a variety of reasons. First is the safety consideration. Composite structures made from LHSR prepregs will be superior in fire worthiness. Secondly, lower heat release and smoke release may translate into easier compliance with the regulation. This may be critical for two reasons. First, it is now recognized that a substantial scatter is inherent in the determination of the OSU heat release results. The materials that perform marginally in OSU heat release testing may not sometimes meet the specifications simply because of inherent scatter in the test results. Secondly, a final decorative panel in general requires a number of operations that may involve materials such as paints, adhesives or decorative plies. These materials may adversely contribute to heat release and smoke release characteristics. Therefore, LHSR prepregs may translate into easier compliance of the overall panel. In fact, many fabricators frequently lower their internal acceptance specifications for qualified prepreg products. Fire worthy characteristics of SPH 2400 systems far exceed the current requirements of FAR 25.853. Table 6 lists the heat release characteristics and the smoke density of M and L version of SPH 2400 product on 7781 style fiberglass. These values represent an average of three specimen. For one ply Nomex honeycomb sandwich panels, the average heat release for the L and M version was only 15 and 20 KW-MIN/M<sup>2</sup> respectively and the peak heat release for

these versions was 18 and 17 KW/M<sup>2</sup> respectively. The optical density in flaming mode, in both these cases was less than 10.

The heat release and smoke release characteristics determined for 6 ply laminate of SPH 2400L system were similar to the one ply sandwich panel. The average heat release marginally increased to 19 KW-Min/M<sup>2</sup> and peak heat release characteristics actually reduced to 12 KW/M<sup>2</sup>.

An experimental version of SPH 2400 product designated as XSPH 2400B4/7781, created by altering prepreg physical characteristics, shows interesting combination of properties. In general, for a given system it has been noted that higher peel strength values are observed with a compromise in heat release and smoke release characteristics [12].

Table 7 shows the peel strengths, heat release and the smoke characteristics of this product. The climbing drum peel strength on Nomex honeycomb averages to 21 in-lb/3 in width. The average heat release rate is 15 KW-Min/M<sup>2</sup> and the peak heat release rate was 17KW/M<sup>2</sup>.

	Configuration	Molding	Property
Average Heat Release, 2 Min. HRR, 2 M KW-Min/M <sup>2</sup>	1/H/1	50 psi	15
Peak Heat Release, 4 Min. HP, KW/M <sup>2</sup>	1/H/1	50 psi	17
Dr. 4 Min. NBS Smoke Density	1/H/1	50 psi	9
Climbing Drum Peel Strength in-lb/3 in width	2/H/2	50 psi	21

TABLE 7: PEEL STRENGTHS & HEAT RELEASE CHARACTERISTICS OF EXPERIMENTAL X SPH 2400 (B4) / 7781 PREPREG PRODUCT.

It is clear that peel strengths are substantially increased over the L version by almost 62%. However, it is remarkable that it is achieved without sacrificing the heat release and the smoke release characteristics.

#### CONCLUSIONS

A new commercial SPH 2400 fire worthy composite prepreg system is introduced. The system represents an optimum of processing, FST and peel strengths. The system has been customized for variety processes like vacuum bag molding, press curing and crushed core processes.

#### ACKNOWLEDGMENTS

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URALANE<sup>®</sup> 5774-A/B:

CIBA-GEIGY'S ADVANCED URETHANE ADHESIVE FOR THE AIRCRAFT INDUSTRY

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Abstract:

In the aircraft industry, several trends in the fabrication of aircraft interiors have been observed in recent years. One development has been the application of new, flame resistant thermoplastics (i.e. Declar-T<sup>®</sup>, Ultem<sup>®</sup>, Kydex<sup>®</sup>, Europlex<sup>®</sup>, Radel<sup>®</sup>, etc.) to the construction of aircraft interiors. Use of these advanced materials by aircraft manufacturers has created an accompanying need for new adhesives that can effectively bond the tough-to-join thermoplastics and also provide the required flame, smoke and toxicity (FST) performance. In addition to these materials trends, is a heightened industry awareness of worker safety and the importance of minimizing worker exposure to chemicals.

In response to industry demands generated by the above-mentioned factors, CIBA-GEIGY Corporation's Furane Aerospace Product Group initiated a new product development effort several years ago. The program was aimed at formulating an effective thermoplastic-bonding adhesive that could be supplied in an environmentally improved package. The result was the creation of Uralane 5774-A/B urethane adhesive.

Uralane 5774-A/B is a two-component urethane adhesive designed to bond the advanced thermoplastics used in fabricating aircraft interior components. The adhesive complies with the FST requirements of FAR 25.853 a. And, it is formulated with a 2 to 1 mix ratio by volume, permitting packaging in Accumix<sup>™</sup> dual barrel cartridge kits. The kits are designed to accurately store, mix and dispense Uralane 5774-A/B without the need for direct worker exposure to the adhesive. An additional safety benefit of Uralane 5774-A/B is that it can be applied to unabraded substrates and requires only minimal surface preparation, thereby reducing worker exposure to dust and harsh solvents. Several major airframe manufacturers, aircraft interior fabricators and airlines have now specified this new adhesive for use in their shops. It is the intent of this paper to highlight the features and benefits of Uralane 5774-A/B as they apply to the aircraft industry.

### Introduction:

During the last ten years, the commercial aircraft industry has made a substantial effort to improve the flame and smoke resistant characteristics of aircraft interior components. The driving force behind this effort was the realization that many aircraft crashes would be survivable if impact were the only factor. However, if the situation involved fire, the rate of fatalities would increase dramatically.

To help improve aircraft safety, the CAA, FAA and other aviation industry regulatory groups have instituted a series of new tests and standards governing acceptable flame, smoke and toxic-gas emission levels for materials used in the construction of aircraft interiors. The tests are designed to determine a materials ability to self extinguish within 15 seconds (FAR 25.853 a and b, Appendix F), to burn without generating excessive smoke, NBS (FAR 25.853, a-1, Appendix F, Part V), and to satisfy acceptable heat-release rates, OSU (FAR 25.853, Appendix F, Part IV). By establishing these specific FST performance standards, regulating authorities have provided the commercial aircraft industry with a set of guidelines to improve fire safety. However, this accomplishment has put extreme pressure on materials suppliers to provide products that can comply with the new regulations.

Beyond meeting FST standards, materials used to fabricate aircraft cabin interiors must be adaptable for use on limited production runs and must be easy to fabricate and repair. Moreover, the materials must afford design engineers the luxury of creating interiors that are aesthetically pleasing and also exhibit the mechanical strength to support lightweight construction. In use, the products selected for these applications must be color fast and extremely durable to withstand the rigors of passenger service.

The aircraft industry has responded to the need for materials that satisfy this diverse range of physical and performance criteria by using new high-performance thermoplastics. The advanced thermoplastics now favored for fabrication of aircraft interiors generally have high glass transition temperatures (T<sub>g</sub>). These high T<sub>g</sub>'s are achieved through the establishment of a very rigid polymer matrix. This rigid matrix produces plastics with good thermal stability, excellent chemical resistance, and superior FST properties. The thermoplastics can also be processed easily by either thermoforming or injection molding; parts can be reprocessed and the plastic used again if desired.

With this combination of desirable characteristics, the latest generation thermoplastics appear to meet all of the material requirements of the aircraft industry. The drawback has been that, because of their resistance to chemicals, thermoplastics

are very difficult to adhesively bond. These plastics are chemically inert so they will not react with conventional adhesives to form durable bonds. As a result, adhesion must be accomplished either through mechanical interlocking (in which the adhesive cures inside a porous polymer surface) or surface affinity (in which similar chemistries of the adhesive and the polymer promote their bonding). Because many of the aircraft applications for high performance thermoplastics require extremely smooth, nonporous surfaces, the preferred method of obtaining adhesion is through surface affinity. This presents a major problem for most conventional adhesives because they typically rely on more than one mechanism to achieve optimum bond strength.

Compounding the adhesive selection dilemma is the fact that the products the industry used in the past had extremely poor FST properties. If these adhesives were used to assemble thermoplastic parts, the FST characteristics of the finished components would be adversely affected.

CIBA-GEIGY, therefore, initiated research to create an easy-to-handle, room temperature cure adhesive that could bond a broad variety of high performance thermoplastics, demonstrate good FST properties, and support the high-productivity demands of the industry. The product resulting from this program is Uralane 5774-A/B. The remainder of this paper will focus on the performance capabilities of this new urethane adhesive for aircraft applications.

#### Physical Properties:

Uralane 5774-A/B, a two-component urethane adhesive, is based on the reaction of a polyol with an isocyanate. The reaction generates an isocyanate-terminated urethane prepolymer. This prepolymer is then reacted with an amine curing agent resulting in a fully crosslinked polymer matrix. It is this matrix, blended with various additives, that produces the outstanding combination of physical and performance characteristics exhibited by Uralane 5774-A/B. Typical physical properties of the new CIBA-GEIGY urethane are shown in Table 1.

In addition to its excellent physical characteristics, Uralane 5774-A/B is designed to meet the handling requirements of the aircraft industry. It is formulated as a fast-setting adhesive with a work life of 15-25 minutes. It has a convenient 2:1 mix ratio to facilitate mixing by hand and also permits packaging in Accumix™ dual barrel cartridges. The adhesive is easy-to-apply with a paste-like consistency and demonstrates good sag resistance on vertical surfaces. Uralane 5774-A/B also provides excellent surface wet-out; it can be applied to most thermoplastic substrates after an isopropyl alcohol (IPA) wipe. Parts joined with the room temperature curing urethane can be handled after only four hours. For compatibility with the

variety of colored plastics used in aircraft interior components, Uralane 5774-A/B is colored beige. This neutral color is relatively non-contrasting when bonded to thin plastic films and helps minimize color bleed-through in assembled parts.

As a urethane, Uralane 5774-A/B features additional performance benefits common to this class of adhesives. These include good flexibility that can produce strong bonds between dissimilar substrates. Urethanes also perform well in vibrating environments such as aircraft interiors and are capable of sustaining high bond strength during thermal cycling.

#### **Mechanical Properties:**

Uralane 5774-A/B exhibits excellent mechanical properties, including good tensile lap shear and excellent T-peel even after aging under hot and humid conditions.

Tensile Lap Shear Strength. The tensile lap shear of Uralane 5774-A/B was measured according to the standard ASTM D-1002 test method. Bonded specimens were prepared from a broad variety of thermoplastic substrates using bond line thicknesses from 3 mils - 5 mils. The bonded samples were tested at temperatures of -40°F, 77°F, and 180°F. This temperature range was selected to reflect the typical operating conditions to which aircraft interior components are exposed. Table 2 describes the substrates that were tested, their chemical composition, and the surface preparation used prior to bonding.

Results of the tensile lap shear strength testing are shown in Graph 1. At -40°F, all of the substrates (with the exception of aluminum, stainless steel, Lexan, and PEEK) broke before bond failure occurred. At 77°F, the Europlex and ABS substrates failed. At 180°F, the ABS and Kydex 6565 substrates failed. A review of the data shows that Uralane 5774-A/B, in many cases, produces bond strengths that rival the strength of the plastic itself. This finding was substantiated during testing when many samples were observed to either fail or deform under load.

Thermoplastic specimens used for the tensile lap shear tests were prepared by lightly sanding the surfaces and then wiping them with isopropyl alcohol (IPA). Additional laboratory testing on selected thermoplastics prepared using only an IPA wipe showed only slight reductions in bond strength. Based on this testing, it appears that an IPA wipe may be sufficient to prepare surfaces for use with Uralane 5774-A/B in some applications.

Aged Tensile Lap Shear. A second series of tensile lap shear tests was conducted on specimens aged for 14 days at 120°F and 95% relative humidity (hot and humid). After aging, the samples were removed from the environmental test chamber and their lap shear strengths were measured at 77°F. These tests were

performed because, in the past, urethane adhesives have come under tremendous scrutiny because of their lack of hydrolytic stability. However, as urethane chemistry has evolved, great improvements in environmental stability have been achieved.

The results of this second series of tensile lap shear tests are shown in Graph 2. (For comparison purposes, the original 77°F tensile lap shear strengths [non-aged] are displayed next to the aged values.) As the aging tests indicate, Uralane 5774-A/B is not adversely affected by hot and humid environments. In fact, in many cases, mechanical strengths improved after aging. These test values demonstrate that thermoplastics bonded with Uralane 5774-A/B will remain stable in the most aggressive environments an aircraft interior is likely to encounter.

T-peel Strength. Tensile lap shear strength is a measure of an adhesive's ability to bond in a two-dimensional plane. In order to determine Uralane 5774-A/B's capabilities in three-dimensional bonding applications, T-peel tests were performed at 77°F according to standard ASTM test method D-1876. Graph 3 displays the T-peel strength results for substrates prepared using a bond-line thickness of 9 mils - 11 mils. (For this test the number of substrates tested was limited because some thermoplastics are too inflexible to generate meaningful data.)

An examination of the results shows that Uralane 5774-A/B can provide very good bond strength in the peel mode. The only exception to this is Radel 7700. However, in this case, the substrate was thicker than desired and that may have contributed to the lower values obtained during the test.

Additional T-peel tests were performed on aluminum and stainless steel specimens at -40°F, 77°F, and 180°F. This test series was restricted to metals because of the inflexibility of thermoplastics at -40°F. The results in Graph 4 show that metal samples bonded with Uralane 5774-A/B have excellent peel strengths at -40°F and 77°F. This good low temperature performance can be explained by the fact that Uralane 5774-A/B has a glass transition temperature of -70°F. At -40°F, the adhesive is still flexible and able to provide high bond strength. At 180°F, however, Uralane 5774-A/B's performance drops by approximately 50%. Even with this reduction, the T-peel strengths continue to be higher than those of many conventional adhesives.

Aged T-peel. The final T-peel tests were conducted on specimens exposed to hot and humid conditions. Graph 5 shows the results of the hot and humid aging as it affects T-peel performance. As before, this data is presented as a comparison between non-aged and aged samples. The results compare favorably with those generated for the tensile lap shear strength aging study. In both cases, Uralane 5774-A/B exhibits little or no reduction in mechanical performance.

### **Flame, Smoke and Toxicity:**

Uralane 5774-A/B was formulated specifically to satisfy the aircraft industry's need for a flame retardant adhesive that can produce bonded thermoplastic components that meet stringent CAA and FAA FST standards.

To confirm the FST characteristics of Uralane 5774-A/B, three different tests were run on the adhesive: a 60-second vertical burn test per FAR 25.853 a, Appendix F; a NBS smoke density test per FAR 25.853, a-1, Appendix F, Part V; and an Ohio State University (OSU) heat release rate test per FAR 25.853, Appendix F, Part IV. Both the NBS smoke density and OSU heat release rate tests were performed by the FAA-certified United States Testing Laboratory located in Los Angeles, California.

60-Second Vertical Burn Test. For this test, each specimen was prepared by coating 181 glass fabric with 15 mils of adhesive. After the adhesive cured, the specimen was cut to a standard 12 inch by 3 inch size. The coated fabric was then placed in a picture frame assembly to help support the specimen during testing. This test configuration was chosen based on its acceptance at a major aircraft manufacturer.

During this test, Uralane 5774-A/B coated samples exhibited a 60-second vertical burn length of 6.9 inches, as shown in Table 3. This burn length is well within the manufacturer's FST guidelines. During additional testing, samples with thicker adhesive coatings were prepared for evaluation. As the thickness reached 19 mils, the burn length fell below 5.5 inches.

NBS Smoke Density. For this test, Uralane 5774-A/B was used to bond a 25 mils Declar T face sheet to a 500 mils thick phenolic/Nomex honeycomb sandwich panel. The bond line thickness was held at 25 mils. The objective was to evaluate the adhesive on materials and under conditions that closely duplicated an actual aircraft interior.

Table 3 illustrates that, with a smoke density (Ds) at 4 minutes of 96, the assembly bonded with Uralane 5774-A/B easily meets the industry standard which is set at smoke density (Ds) of 150.

OSU Heat Release. The Ohio State University (OSU) heat release test on Uralane 5774-A/B was done in a similar fashion to the NBS test. Peak and average heat release rates were determined for the Declar T, the phenolic sandwich panel and the assembled part.

The test findings are shown in Table 3 with a graphical representation of the five-minute test for all three specimens offered in Graph 6. For the Declar T and the phenolic sandwich panel, the peak heat release rates of 24 and 35 KW/sq.m.

respectively were well within the 65 KW/sq.m. industry standard. When Uralane 5774-A/B was used to bond the assembly, the peak heat release rate increased to 56 KW/sq.m., which is still comfortably below the standard. The total heat release values on the test specimens were also substantially below the 65 KW-min./sq.m limit.

#### **Safety and Handling:**

The safety and handling of chemicals in the aircraft industry has received a significant amount of attention in recent years. Workers, fabricators, and regulators are becoming increasingly aware of the precautions that must be taken when handling aerospace-grade materials. This has forced aircraft manufacturers to carefully examine all Material Safety Data Sheets, chemical handling procedures and conditions as well as equipment made available to workers. To support the safety programs of customers, material suppliers have increased efforts to reduce use of potentially hazardous substances in their formulations and to supply products in packages that minimize worker exposure. As part of this commitment to safety, Uralane 5774-A/B was formulated for application with minimal substrate surface preparation and dispensing from Accumix dual barrel cartridges.

Minimal surface preparation of the thermoplastic substrates can eliminate worker exposure to harsh and flammable cleaning solvents. Additionally, surface abrading can result in release of plastic particulates into the air. Either one of these situations can be eliminated or modified by using an isopropyl alcohol surface wipe as a suitable surface preparation for Uralane 5774-A/B.

Traditional adhesive components are packaged separately in bulky metal containers that require users to pour the desired amounts of resin and hardener into a secondary container for accurate weighing and mixing. As part of this process, workers have considerable contact with the materials when opening/closing containers, pouring and weighing. In addition, the hand-mixing procedure demands accurate weighing skills, close attention to thorough blending, and a focus on properly re-sealing and storing unused portions of the adhesive to prevent moisture incursion.

The Accumix cartridges in which Uralane 5774-A/B is packaged, reduce worker exposure and eliminate the need for manual weighing and mixing. With the cartridge kit, shown in Figure 1, the resin and hardener components of Uralane 5774-A/B are packaged in separate chambers. In preparation for use, the cartridge containing both the resin and hardener chambers is placed in a manual or pneumatic dispensing gun. A static mix nozzle is then attached to the front of the cartridge. At this point, the adhesive is ready to be dispensed by simply pulling the handle on

the gun. The result is an easy-to-handle and dispense adhesive that almost totally eliminates worker contact with the material.

Use of the cartridge optimizes quality by ensuring proper mixing at the right ratio of resin to hardener because the chambers of the Accumix cartridge kit contain a fixed volume of adhesive. This reduces the potential for bond failure resulting from improper ratio control. The Uralane 5774 A and B components are also formulated in distinctly different colors that permit workers to visually monitor material blending as the adhesive is dispensed through the static mixing nozzle.

If adhesive remains in the cartridge after a bonding project is complete, the mixing nozzle can be simply removed and discarded and a cap replaced on the cartridge. The remainder of the adhesive can be safely stored in the cartridge until needed. With the reuseable cartridges, material waste is greatly minimized providing users with substantial cost savings.

#### **Conclusion:**

Uralane 5774-A/B urethane adhesive is a superior adhesive for bonding most high performance thermoplastics favored for the fabrication of aircraft interior components. With its excellent FST properties, Uralane 5774-A/B can be effectively used to bond thermoplastic assemblies so that they meet CAA/FAA regulatory standards. The material maintains its mechanical and physical properties on tough-to-join thermoplastics even after aging under hot and humid conditions. Because the adhesive can be applied to substrates after minimal surface preparation and is packaged in Accumix™ dual barrel cartridges, it minimizes worker exposure to chemical substances like uncured adhesive, solvents and plastic particulates. This combination of properties makes Uralane 5774-A/B a natural choice for use in aircraft interior construction.



**Table 2**

**Uralane 5774-A/B**

**Substrate Description and Preparation**

<u>Substrate</u>	<u>Chemical Description</u>	<u>Surface Preparation</u>
Aluminum	2024, T3, Clad	Etch per ASTM D 2651
Stainless Steel	-	IPA Wipe
Lexan®	polycarbonate	Sand and IPA Wipe
Declar T®	polyetherketoneketone	Sand and IPA Wipe
Ultem® 2100	polyetherimide	Sand and IPA Wipe
Plexiglas®	polymethylmethacrylate	Sand and IPA Wipe
ABS	acrylonitrile-butadiene -styrene	Sand and IPA Wipe
Radel® 7700	polyphenylsulfone	Sand and IPA Wipe
Kydex® 6565	acrylic/PVC alloy	Sand And IPA Wipe
PEEK	polyetheretherketone	Sand and IPA Wipe
Europlex®	polyethersulfone	Sand and IPA Wipe

Lexan®: Registered Trademark of General Electric Company  
 Declar-T®: Registered Trademark of E.I. DuPont DeNemours & Co.  
 Ultem®: Registered Trademark of General Electric Company  
 Kydex®: Registered Trademark of Kleerdex Company  
 Europlex®: Registered Trademark of BASF  
 Radel®: Registered Trademark of Amoco  
 Plexiglas®: Registered Trademark of Rohm & Haas

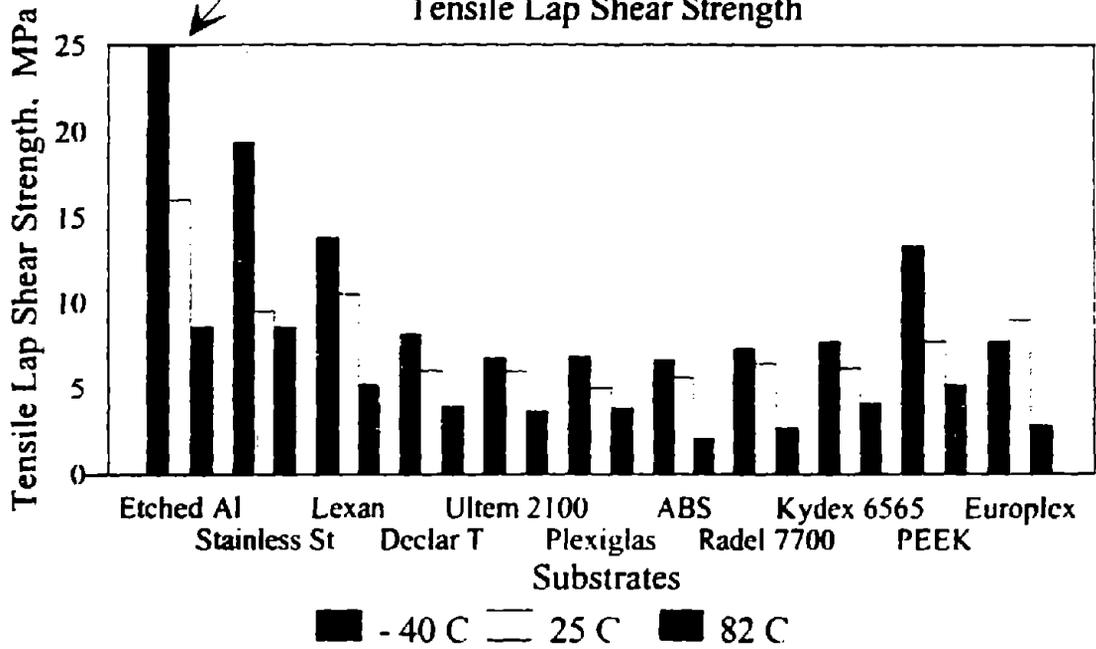
**Table 3**  
**Uralane 5774-A/B**  
**Flame, Smoke and Toxicity Data**

<u>Test</u>	<u>Results</u>
60 sec. Vertical Burn, FAR 25.853, Appendix F	
Burn Length, cm	< 17.5
Extinguish Time, sec.	< 2
Drip Extinguish Time, sec.	< 1
NBS Smoke Density, FAR 25.853, a-1, Appendix F, Part V	
Flaming Mode, Ds @ 4	
Declar T/Phenolic/Uralane 5774-A/B	96
OSU Haet Release, FAR 25.853, Appendix F, Part IV	
Peak Heat, KW/sq.m	
Declar T	24
Phenolic Sandwich Panel	35
Declar T/Phenolic/Uralane 5774-A/B	56

Graph 1

# Uralane 5774-A/B

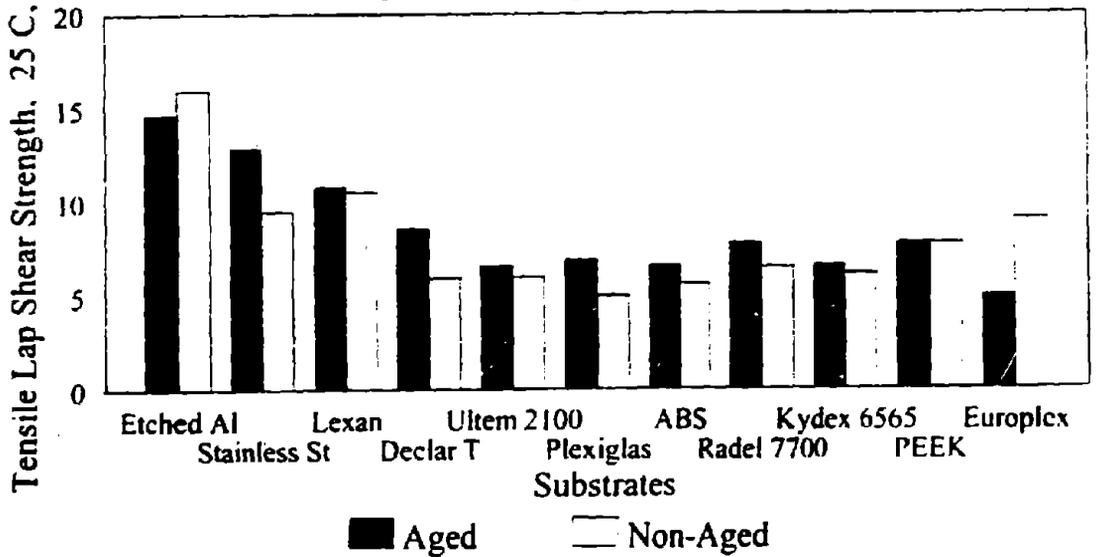
Tensile Lap Shear Strength



Graph 2

# Uralane 5774-A/B

Tensile Lap Shear Strength, Aged Versus Non-Aged

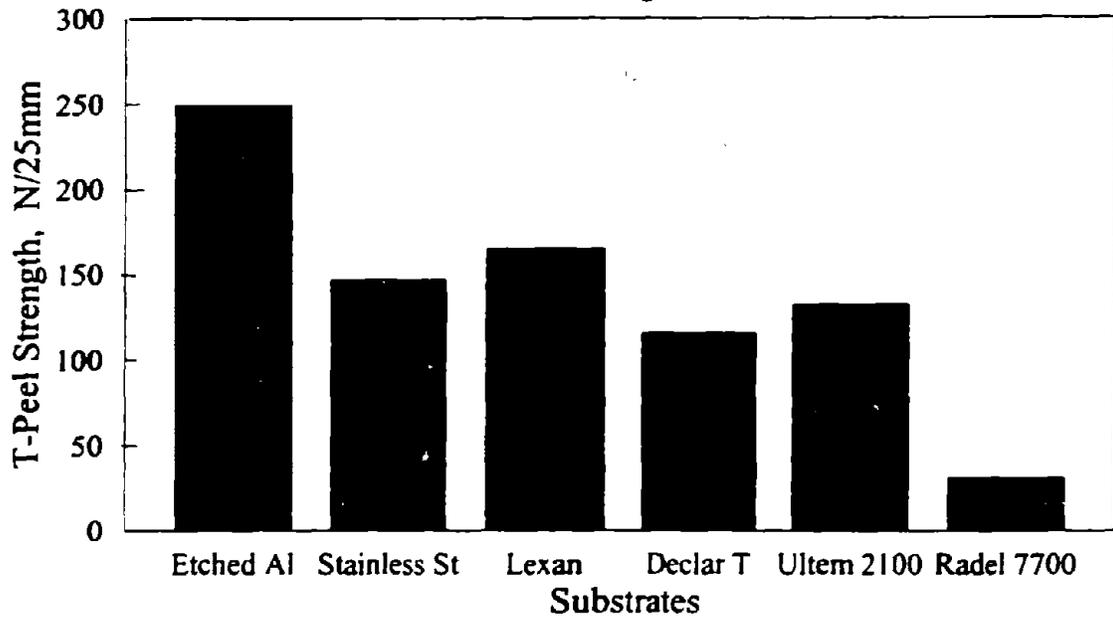


Aged 14 days at 48 C/95% RH

Graph 3

# Uralane 5774-A/B

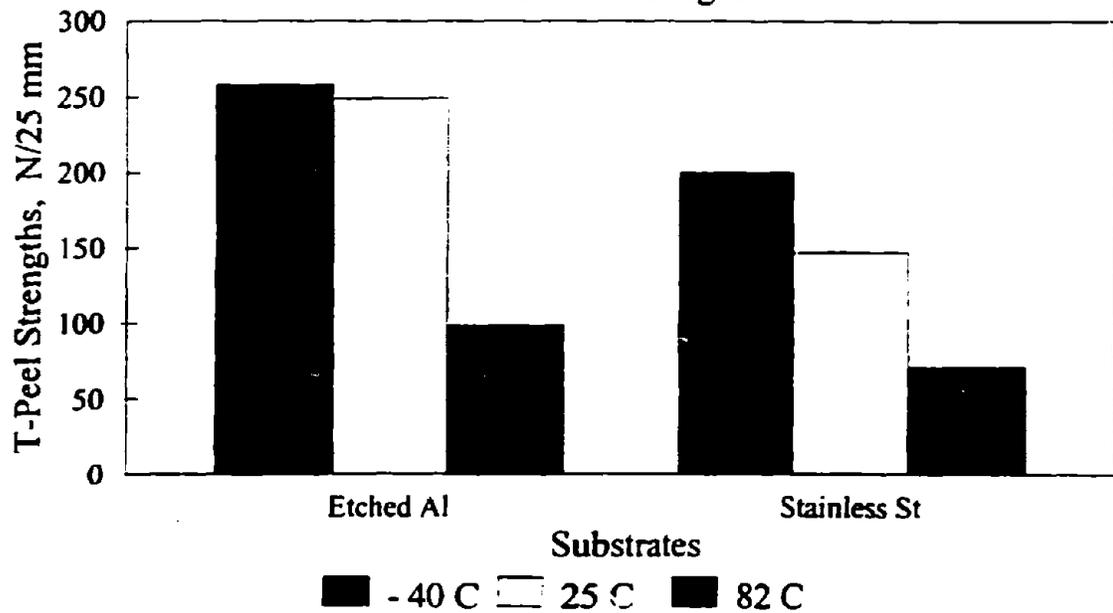
T-Peel Strength at 25 C



Graph 4

# Uralane 5774-A/B

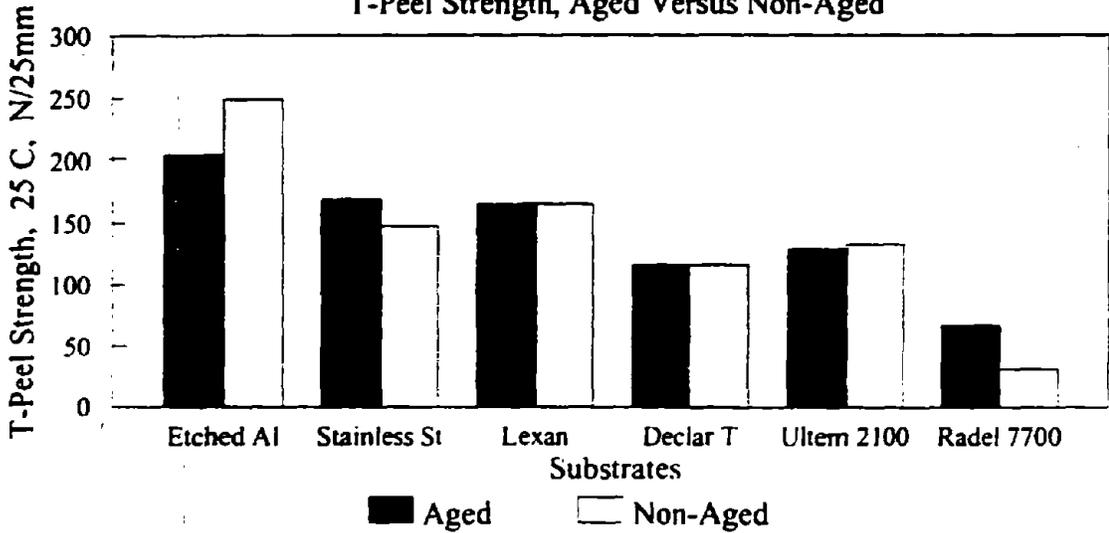
T-Peel Strength



Graph 5

# Uralane 5774-A/B

T-Peel Strength, Aged Versus Non-Aged

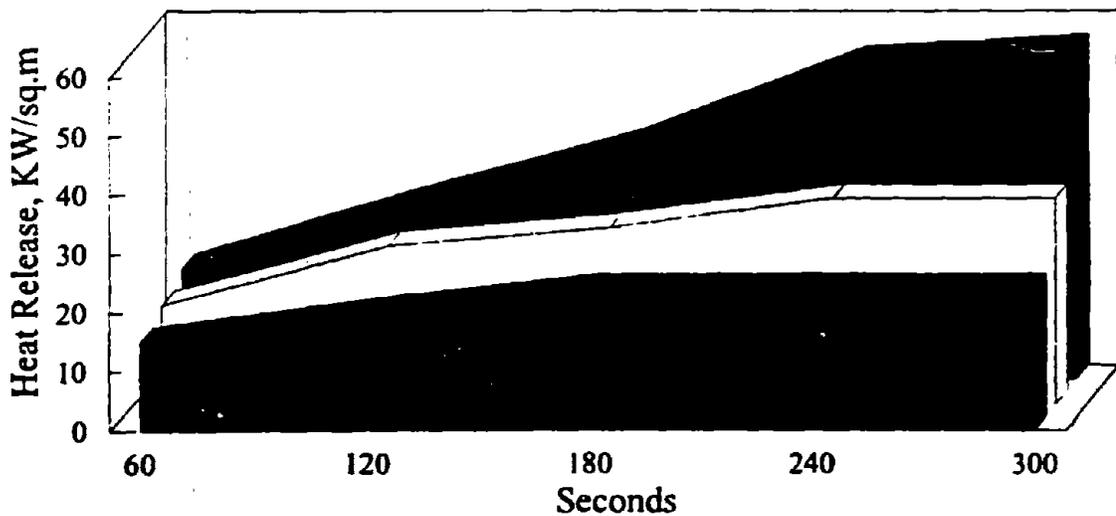


Aged 14 days at 48 C/95% RH

Graph 6

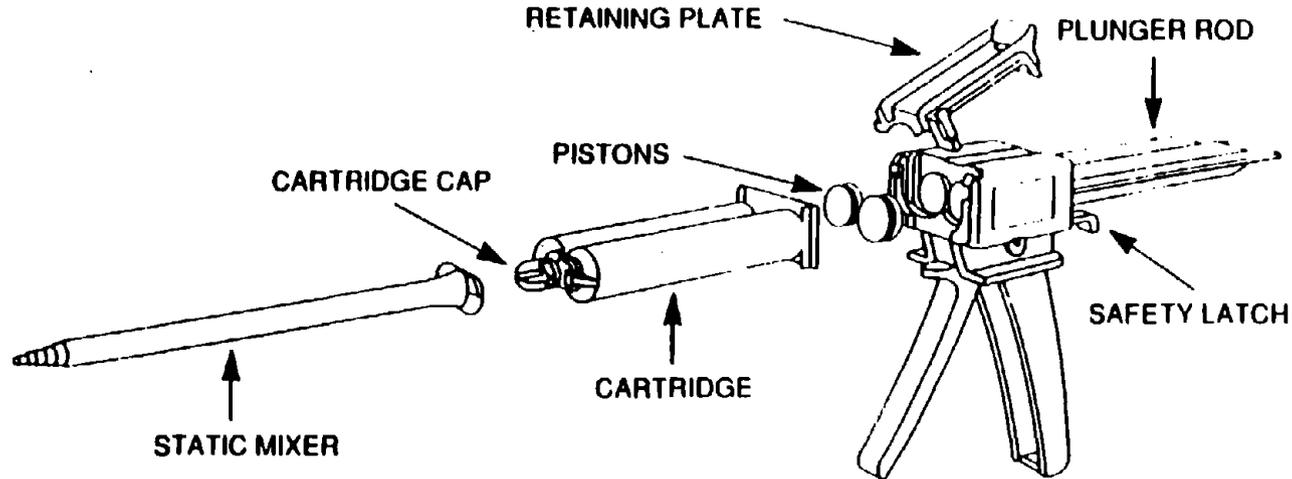
# Uralane 5774-A/B

OSU Heat Release Test Values



■ Declar T  
■ Declar T/Phenolic/Bonded with Uralane 5774-A/B  
□ Phenolic Sandwich

**Figure 1**  
**Accumix Cartridge and Dispensing System**





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THE FIRE PROPERTIES OF INSULATION BAGS, AS INSTALLED AND  
AFTER AIRCRAFT OPERATIONS

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TOMARK INDUSTRIES, INC.

FEBRUARY 9, 1993

ABSTRACT

Polymeric films and insulation bag materials made from these films were exposed to hydrolysis conditions and subjected to the 12 second Vertical Bunsen Burner Test. Despite a major weakening in mechanical strength of the polyester film samples, all the samples passed the test, by shrinking away from the flame, immediately. Only by testing the samples in multiple layers were slight differences observed. Instead of developing a suitable accelerated aging program, it is recommended that the industry test used insulation bags when they are replaced during maintenance schedules, because the instability of polyester based materials may still be of concern.

INTRODUCTION

The largest volume of non-metallic material inside an aircraft is the insulation system which covers the entire pressurized section. The insulation media is fiberglass of about 0.5 lbs./ft<sup>3</sup>, which is held together with a phenolic binder (FAA Fire Test Handbook, Sept. 1990). The primary mission of the insulation is acoustical with thermal characteristics playing a secondary role.

To protect the insulation from contamination, to hold it in place, and to reduce moisture absorption, the insulation is covered with a plastic film, which has been reinforced with synthetic yarn to improve its mechanical properties (Davis, 1991).

The insulation bags, as installed, must pass the FAA 12 second "Vertical Bunsen Burner Test for Cabin and Cargo Compartment Materials". (Some aircraft manufacturers use more stringent requirements, such as Boeing. Their BMS 8-142 involves placing lighted sticks in the fold of a right-angle creased insulation bag.) This requirement is covered in FAR 25.853. By reference, the materials must continue to meet the requirements of FAR 25.853 in FAR 121.312, which covers operating standards of aircraft.

The question can then be asked, are the materials in the insulation bag sufficiently stable that they would continue to meet FAR 121.312? What can occur over time which may degrade the insulation bag and cause it to become more of a fuel? Should the aircraft manufacturers and the maintenance centers use the most stable constructions available, especially if there is no undue economic hardship?

In this paper, we will report on some tests made with both commercial insulation bag materials and developmental material.

GENERAL COMPOSITION OF INSULATION BAGS

Insulation bags used in commercial aircraft are comprised of several layers of thin material. Common to all bag materials are a thin plastic film and a reinforcing yarn. The films and yarns most commonly used are:

Polyester film of a thickness between 0.20 and 0.48 mil.  
Polyvinyl fluoride film at a thickness of 0.5 mil.  
High tenacity industrial grade nylon yarn  
Industrial grade polyester yarn

To combine film and yarn and to achieve other property goals, manufacturers of insulation bag material apply a variety of coatings to the films. Some of them are:

Aluminum, vacuum deposited for lower moisture vapor transmission  
Heat seal coatings  
Coatings to lower the gloss of the film  
Flame retardant coatings  
Adhesive, to bond the yarn to the film

Whenever a coating is used, a check must be made to insure compliance with the 12 Second Vertical Burn Test.

In this paper, polyester film, polyvinyl fluoride film, and an 0.30 mil thick ethylene/tetrafluorethylene film, all reinforced with nylon yarn will be evaluated for stability. No attempt was made to evaluate the effect of coatings, although, where they seemed to affect the performance, it will be mentioned.

#### FACTORS WHICH CAN CAUSE DEGRADATION

Known to the industry for years are localized factors in specific areas of the aircraft. They include the following:

"Blue water", primarily the result of "over-service"  
Skydrol, the result of contamination during maintenance  
Coffee, tea and other liquids in the gallery  
Salt water from seafood shipments that leak

Because the chemical resistance of polyester film is poorer than polyvinyl fluoride film, the latter material is usually employed in those areas where the insulation bag is likely to be contacted by the chemical agent.

Two other more universal exposures of the insulation bag are:

Corrosion inhibiting compound, known as "goop"  
Heat and moisture

Aircraft manufacturers and maintenance centers apply varying quantities of anti-corrosion compounds to the interior of the fuselage and these compounds smear one side of the insulation bag. The effect on insulation bags, be they made from polyester film or any other film, is not known.

Certain plastics, on exposure to heat and moisture undergo a degradation known as hydrolysis. The higher the temperature the faster the hydrolysis. What occurs is polymeric chain scission, which reduces the molecular weight of the polymer. Chain scission causes a reduction in virtually all physical properties. The film becomes brittle. The chain scission may also result in loss of the effects of orientation with a resultant loss of thermal shrinkage built in the film by the biaxial stretching process. The combination of molecular weight reduction and loss of orientation may cause a deterioration in the fire properties of the film (Davis, 1992).

While conditions inside the fuselage of an aircraft are much milder than those normally associated with hydrolysis, degradation will still occur. It will simply take longer.

Of all the films used in insulation bags of all the plastics used in aircrafts, for that matter), the one most subject to hydrolysis is polyester. Figures 1 and 2 show the effects hydrolysis conditions have on polyester film (Mylar® Technical Bulletin).

## SAMPLE PREPARATION AND GROSS MECHANICAL PROPERTIES

Films and insulation bag materials were exposed to hydrolysis conditions as shown in Table 1. Noteworthy is the fact that only two samples came out of the exposure with significantly reduced strength; polyester film and polyester insulation bag material. Yellowing was observed on some insulation bag samples, but they appeared to be associated with adhesives and/or coatings applied by the manufacturers.

## 12 SECOND VERTICAL BUNSEN BURNER TEST RESULTS

The test results are shown in Table 2. There is a paucity of any significant data. All the samples pass with virtually no differences among them. Some samples exhibited some edge flaming and the polyester bag material smoked somewhat after hydrolyzing, but these effects could be due to coatings and not to the films.

To gain some differentiation, some of the remaining samples were tested by folding the samples to create multiple layers. These were then exposed to the Bunsen burner with the results shown in Table 3. Generally, without reinforcing yarn, adding layers of material has no effect. They all shrink away from the flame. With the insulation bag material, however, considerable edge flaming occurs in all the samples tested. The worst sample appeared to be 4 layers of hydrolyzed polyester in terms of burn rate, but what that means is not known.

## CONCLUSIONS

The data presented does not support the hypothesis that polyester film based insulation bags are unstable to the point where compliance with FAR 121.312 is placed in jeopardy. While there is some scant evidence that hydrolyzed polyester is worse in abnormal fire tests, it is insufficient to conclude that polyester insulation bags must be replaced.

The samples were exposed to unrealistic conditions versus aircraft operations. Perhaps it was also unrealistic to expect to be able to obtain a correlation between accelerated aging and actual exposure.

Several attempts were made to secure aged insulation bags from aircraft during their heavy maintenance checks. Only one such sample was made available from a charter airline company. It was a bag from a Boeing 747. The bag was produced in 1970. It didn't burn at all. The film in the bag was still quite strong and stretchy, while some of the reinforcing yarn had separated from the film. We have no positive identification as to the bag's composition.

## RECOMMENDATION

The stability of polyester film in insulation bags, despite the results and conclusions shown here, should still be a concern to the aircraft industry. The insulation bag manufacturers, aircraft

manufacturers, airlines, and the FAA should initiate a program of testing a representative selection of used bags to see if, indeed, degradation and loss of fire properties have occurred.

#### ACKNOWLEDGMENTS

The author expresses his appreciation to the following people and organizations:

Julie Hough and Marvin Young of the Circleville, Ohio plant of the Du Pont Company, for organizing and running the hydrolysis chamber.

Orcon Corporation and Facile Company for supplying insulation bag material.

Pat Cahill of the FAA Technical Center, Fire Safety Branch for testing the samples in the Vertical Bunsen Burner Test.

#### REFERENCES

Davis, R.F., "A Comparison of Insulation Blanket Films for Commerical Airframes." 1991 Fire Safety Conference, Pinelass Park, FL, 11/4-11/7 1991.

Davis, R., 1992, "On the Degradation of Polyester Film," 8/28/92.

FAA Fire Test Handbook, Sept. 1990, "Materials Used in Aircraft".

Technical Bulletin, Mylar® Polyester Film, "Hydrolytic Stability", (No date).

TABLE 1  
 HYDROLYSIS EXPOSURE & GROSS MECHANICAL PROPERTIES  
 OF FILMS AND INSULATION BAG MATERIALS  
 (4 WEEKS AT 100°C, 100% RH)

FILM/YARN	DIMENSIONAL CHANGE	DISCOLORATION	GROSS TENSILE STRENGTH (%) RETAINED
0.30 ETFE/-	NC	NONE	>90
0.50 PVF/-	NC	NONE	>90
0.20 PET/-	NC	NONE	<10
0.40 ETFE/NYLON	SOME CURLING	MODERATE YELLOWING	>90
0.50 PVF/NYLON	SOME CURLING	MODERATE YELLOWING ONE SIDE ONLY	>90
0.20 PET/NYLON	CRINKLING	NONE	-50

TABLE 2  
 12 SECOND VERTICAL BUNSEN BURNER TEST RESULTS

FILM/YARN	EXPOSURE °C / % RH	VERTICAL BURN TEST DATA			
		FLAME OUT TIME (sec.)	DRIP FLAME TIME (sec.)	BURN LENGTH (inches)	SHRINKAGE (inches)
0.3 ETFE/-	NONE	0	0	0	7.5
0.3 ETFE/-	100°C/100	0	0	0	7.0
0.5 PVF/-	NONE	0	0	0	7.0
0.5 PVF/-	100°C/100	0	0	0	7.0
0.2 PET/-	NONE	0	0	0	12.0
0.2 PET/-	100°C/100	0	0	0	MAX
0.4 ETFE/NYLON	NONE	0	0*	0	7.0
0.4 ETFE/NYLON	100°C/100	0	0*	0	7.5
0.5 PVF/NYLON	NONE	0	0*	0	7.0
0.5 PVF/NYLON	100°C/100	0	0	0	7.5
0.2 PET/NYLON	NONE	0	0	0	7.0
0.2 PET/NYLON	100°C/100	0**	0*	0	7.5

\* SOME FLAMING NEAR SPECIMEN HOLDER  
 \*\* SOME SMOKE

TABLE 3

12 SECOND VERTICAL BUNSEN BURNER TEST RESULTS, ABNORMAL PIORIDINE

FILM/YARN	EXPOSURE °C / % RH	NO. OF LAYERS BURNED	TEST DATA	
			EDGE BURNING (%)	FLAME OUT TIME SEC.
0.3 ETFE/-	NONE	2, 3, & 4	NONE	0
0.5 PVF/-	NONE	2, 3, & 4	NONE	0
0.2 PET/-	NONE	2, 3, & 4	NONE	0
0.4 ETFE/NYLON	NONE	2	NONE	0
0.4 ETFE/NYLON	NONE	3	60	15
0.4 ETFE/NYLON	NONE	4	>90	21
0.5 PVF/NYLON	NONE	2	<30	7
0.5 PVF/NYLON	NONE	3	<30	2
0.5 PVF/NYLON	NONE	4	>90	55
0.5 PVF/NYLON	100, 100	2	NONE	0
0.5 PVF/NYLON	100, 100	4	NONE	0
0.2 PET/NYLON	NONE	2	NONE	0
0.2 PET/NYLON	NONE	3	>90	NOT RECORDED
0.2 PET/NYLON	NONE	4	>90*	NOT RECORDED
0.2 PET/NYLON	100, 100	4	>90**	NOT RECORDED

\*BURNED A FASTER RATE THAN 3 LAYERS

\*\*BURNED AT FASTER RATE THAN UNEXPOSED 4 LAYERS

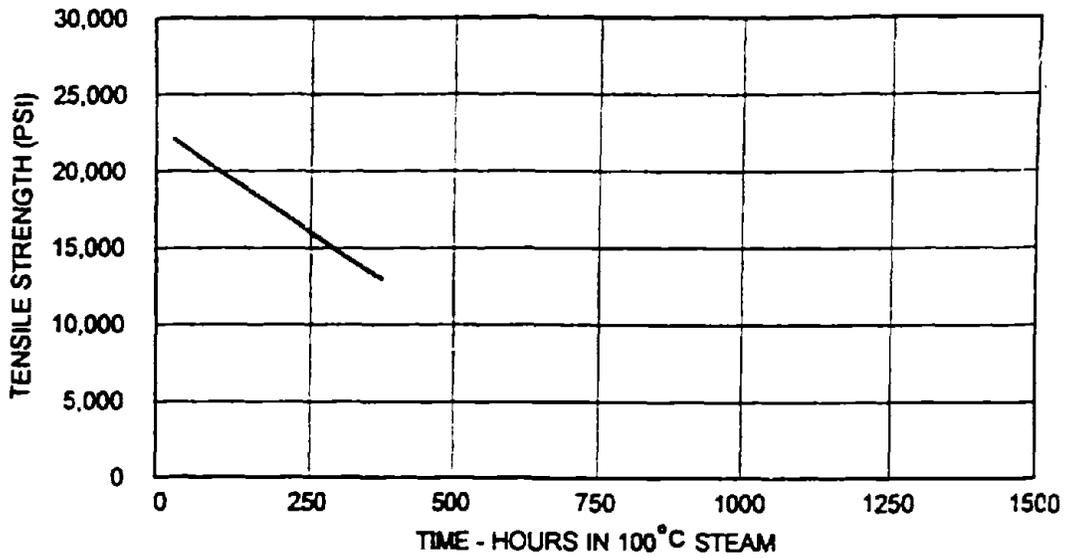


FIGURE 1: TENSILE STRENGTH OF POLYESTER FILM  
AFTER EXPOSURE TO STEAM

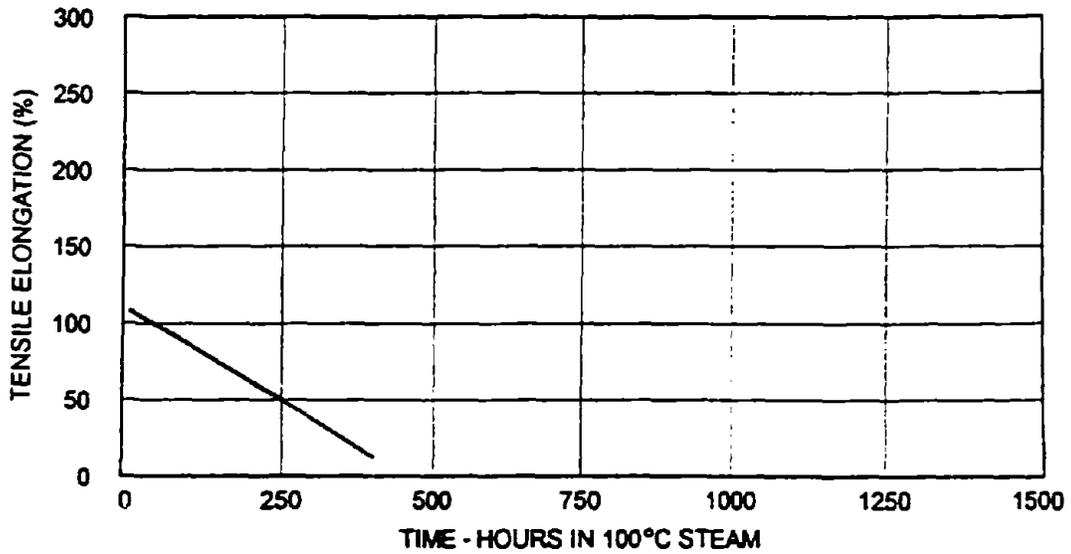


FIGURE 2: TENSILE ELONGATION OF POLYESTER FILM  
AFTER EXPOSURE TO STEAM



**SESSION II**  
**ADVANCED TECHNOLOGY**

Wednesday, February 10, 1993

Session Chairman  
**Dr. Richard Lyon**  
Federal Aviation Administration (FAA)  
Technical Center



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Computer-Aided Molecular Design of Fire Resistant Aircraft Materials

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ABSTRACT

Molecular dynamic simulations and Cone Calorimeter measurements were used to assess the effects of electron beam irradiation and heat treatments on the flammability of the honeycomb composites used in the sidewalls, ceilings and stowage bins of commercial aircraft. The irradiation of this material did not result in any measureable changes. A dramatic reduction in the peak rate of heat release, however, was observed in samples that had been heated overnight at 250 °C.

INTRODUCTION

Synthetic polymers comprise a significant fraction of the fire load borne by commercial aircraft interiors. The flammability, smoke and toxicity characteristics of these materials may impact passenger survivability in the event of an in-flight or postcrash fire. In recent years, the FAA has issued improved fire test standards for aircraft seat cushions, panels, cargo liners and evacuation slides. The goal of an "all-fire resistant aircraft cabin interior," however, will require significant breakthroughs in fire retardant chemistry and materials design.

In previous studies, molecular dynamics modeling was used to identify factors which contribute to the flammability of polymeric materials. This research focussed on the mechanistic aspects of char formation during thermal degradation [1-4]. Charring increases the fraction of the fuel retained in the condensed phase so that less combustible gases are evolved. The presence of a surface char also insulates the unburnt polymer from the external heat source, while at the same time, obstructing the outward flow of combustible products from the degradation of the interior. Computer movies based on molecular dynamics simulations indicate that cross-linked polymers tend to undergo further cross-linking when burned eventually forming high molecular weight, thermally stable chars. This prediction has been confirmed in Cone Calorimeter flammability measurements made on both radiation and chemically cross-linked polymers.

The scope of this research has now been expanded to include the study of materials used in aircraft cabin interiors. Cone Calorimeter measurements were made to assess the effects of electron beam irradiation and heat treatments on the flammability of the honeycomb composites used in the sidewalls, ceilings and stowage bins of

commercial aircraft. The purpose of this paper is to communicate preliminary results and to set forth a plan for future research.

## BACKGROUND

### Description of the Computer Model

Molecular dynamics modeling is a useful tool for exploring mechanisms of thermal degradation in polymers [1-3]. The model developed at BFRL consist of 7 chains arranged in accordance with the experimentally determined crystal structure of polyethylene (PE). Each chain is made up of 50 carbon and 100 hydrogen atoms (Figure 1). Hamilton's equations of motion

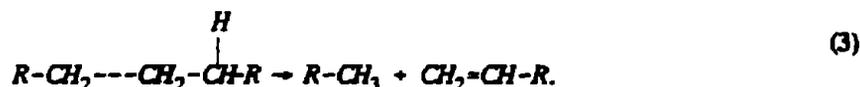
$$\frac{\partial H}{\partial p_i} = \frac{dq_i}{dt}, \quad \frac{\partial H}{\partial q_i} = -\frac{dp_i}{dt} \quad (i=1,2,\dots,3N), \quad (1)$$

are solved for the coordinates ( $q_i$ ) and momentum ( $p_i$ ) of the  $N$  atoms which constitute the model polymers. The Hamiltonian has the form

$$H = \sum_{i=1}^{3N} \frac{p_i^2}{2m_i} + \sum_{i=1}^{N-1} V_s(r_{i,j+1}) + \sum_{i=1}^{N_C-2} V_b(\theta_{i,j+1,j+2}) + \sum_{i=1}^{N_C-3} V_t(\phi_{i,j+1,j+2,j+3}) \\ + \sum_{i=1}^{N_C-3} \sum_{j=i+3}^{N_C} V_{nb}(r_{i,j}) + \sum_{i=1}^{N_C} \sum_{j=1}^{N_s} V_{ext}(r_{i,j}), \quad (2)$$

where  $N_C$  denotes the number of carbon and  $N_H$  the number of hydrogen atoms. The first term on the right hand side of Eq.(2) represents the kinetic energy of the  $N = N_C + N_H$  atoms. The next terms are the potential energies for bond stretching ( $V_s$ ) and bending ( $V_b$ ) and a torsional potential ( $V_t$ ) which restricts internal rotation around the C-C bonds. These are followed by non-bonded potential energy ( $V_{nb}$ ) interactions between the atoms in the dynamic polymer chains, as well as their interactions with an additional  $N_s$  atoms which constitute the bulk material or an external surface ( $V_{ext}$ ). The explicit forms for these potential energy functions have been reported elsewhere [3].

The thermal degradation of polymers involves a complex sequence of chemical reactions. Two reactions which are thought to play a major role are hydrogen transfer and depolymerization. An example of intramolecular hydrogen transfer is depicted in the following scheme:



The resulting fragments can react again and again in recursive fashion producing a broad spectrum of volatile

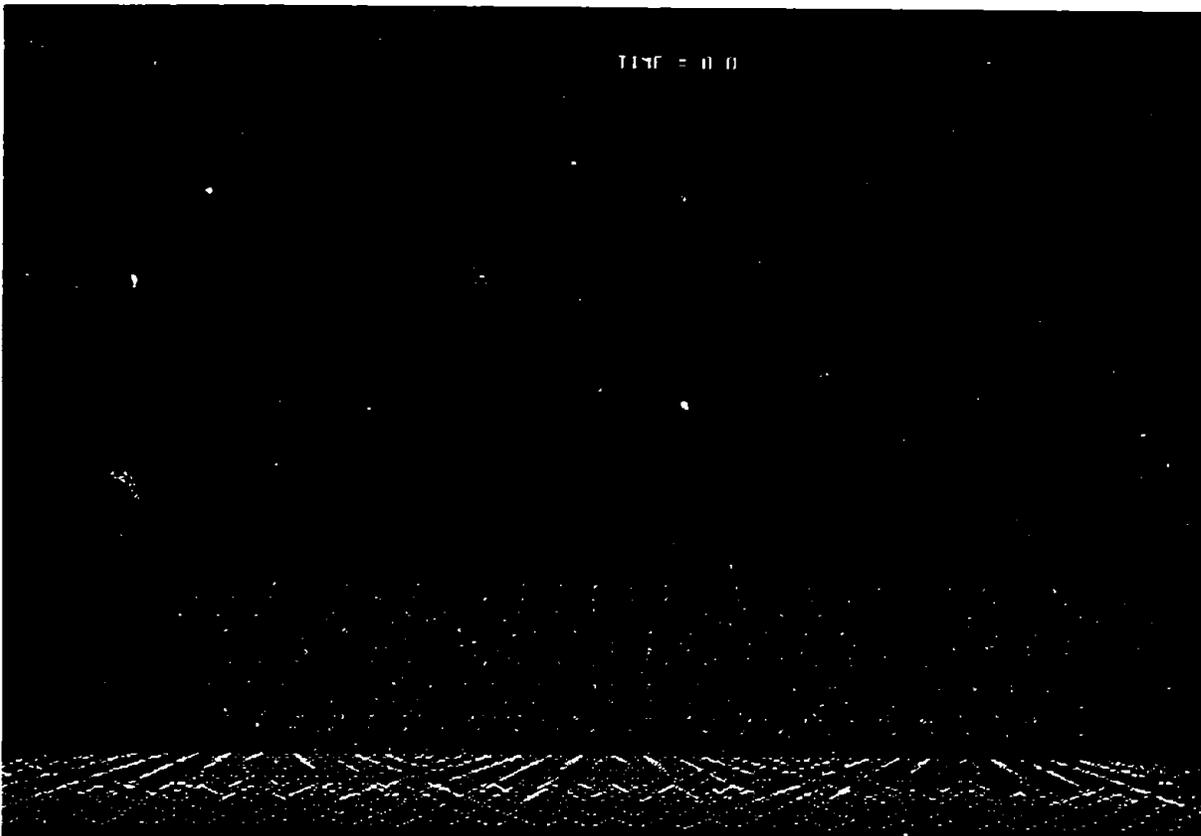
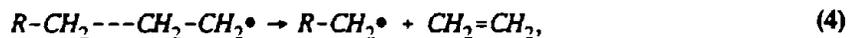


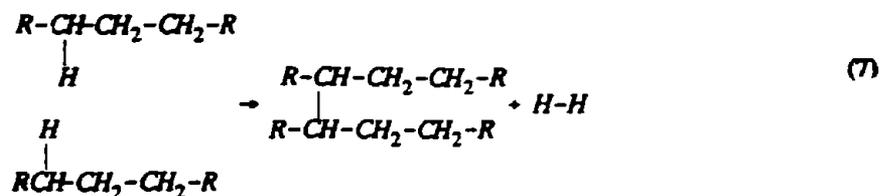
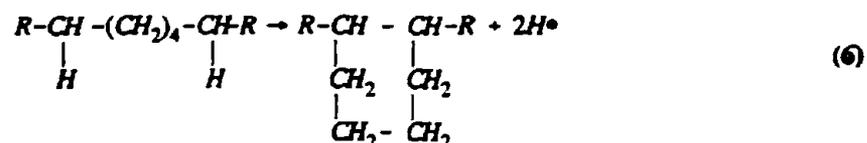
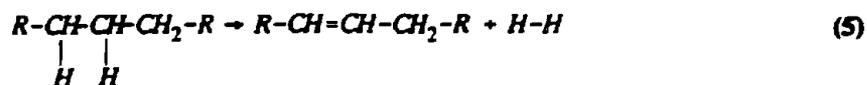
Figure 1. At time  $t=0$ , the 7 dynamic polymer chains are arranged in a planar zig-zag conformation. The static surface is indicated by white lines.

hydrocarbons which are readily combusted. In the depolymerization reaction,

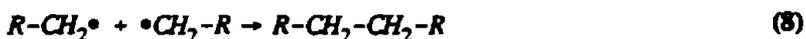


the monomer splits off from a free radical fragment generated by the random scission of a C-C bond. These reaction channels, as well as the additional possibility of intermolecular hydrogen transfer between free radical fragments, are accounted for in the computer program. Both hydrogen transfer and depolymerization are modeled as concerted processes so that bond making occurs simultaneously with bond breaking.

We also allow for a number of other reaction channels which, although inactive in the thermal degradation of PE, are thought to be critical to the formation of char. Included in this list are the chain stripping, cyclization and intermolecular cross-linking reactions illustrated in Eqs.(5)-(7).



The degradation process terminates when reactive fragments combine to form stable products. The mechanism incorporated in our computer model is the radical recombination reaction illustrated in Eq.(8).



### Computer Simulations

The chains were in a planar zig-zag conformation at the onset of the simulations (Figure 1). Thermal motion was initiated by giving each atom a three dimensional velocity chosen at random from a uniform distribution. Once the atoms in the model polymers were set in motion, they quickly adopted a Maxwell-Boltzmann velocity distribution [2]. The equations of motion were integrated using the differential equation solver ODE [5]. This routine is based on a predictor-corrector algorithm and uses a variable step-size. All forces were evaluated analytically. Simulations were carried out for 5 to 10 picoseconds at temperatures ranging from about 500 K, which is typical of the pyrolysis of PE, up to about 2000 K. These calculations required about 1 hour of CPU time on NIST's Cray Y-MP<sup>1</sup> computer. Trajectories were downloaded to a Silicon Graphics Crimson/GTX workstation where they were viewed

<sup>1</sup> Certain commercial equipment and materials are identified in this paper in order to adequately specify procedures. Such identification does not imply recommendation or endorsement, nor does it imply that they are the best available for the purpose.

in the form of movies.

The progression depicted in Figures 2 and 3 is representative of what happens in simulated thermal degradations of PE and other linear polymers. The chains fragment into fuel for gas phase combustion before a significant number of inter-molecular cross-links (highlighted in white) can form. In contrast, an incipient char was produced when a significant number of hydrogens (exceeding 20% of the total) was removed from the model polymers at the onset of the simulations. This gives cross-linking reactions a head start so that they can compete with fragmentation (Figures 4 and 5). The strength of the cross-links which form between polymer chains increases with the magnitude of the surface interaction ( $V_{\text{ext}}$ ). Presumably, this is because the chains are brought closer together as a result of their mutual attraction to the surface. This observation suggests that a filler, particularly one that has a strong affinity for the polymer, will facilitate the formation of heat resistant chars.

## RESULTS AND DISCUSSION

### Polyethylene

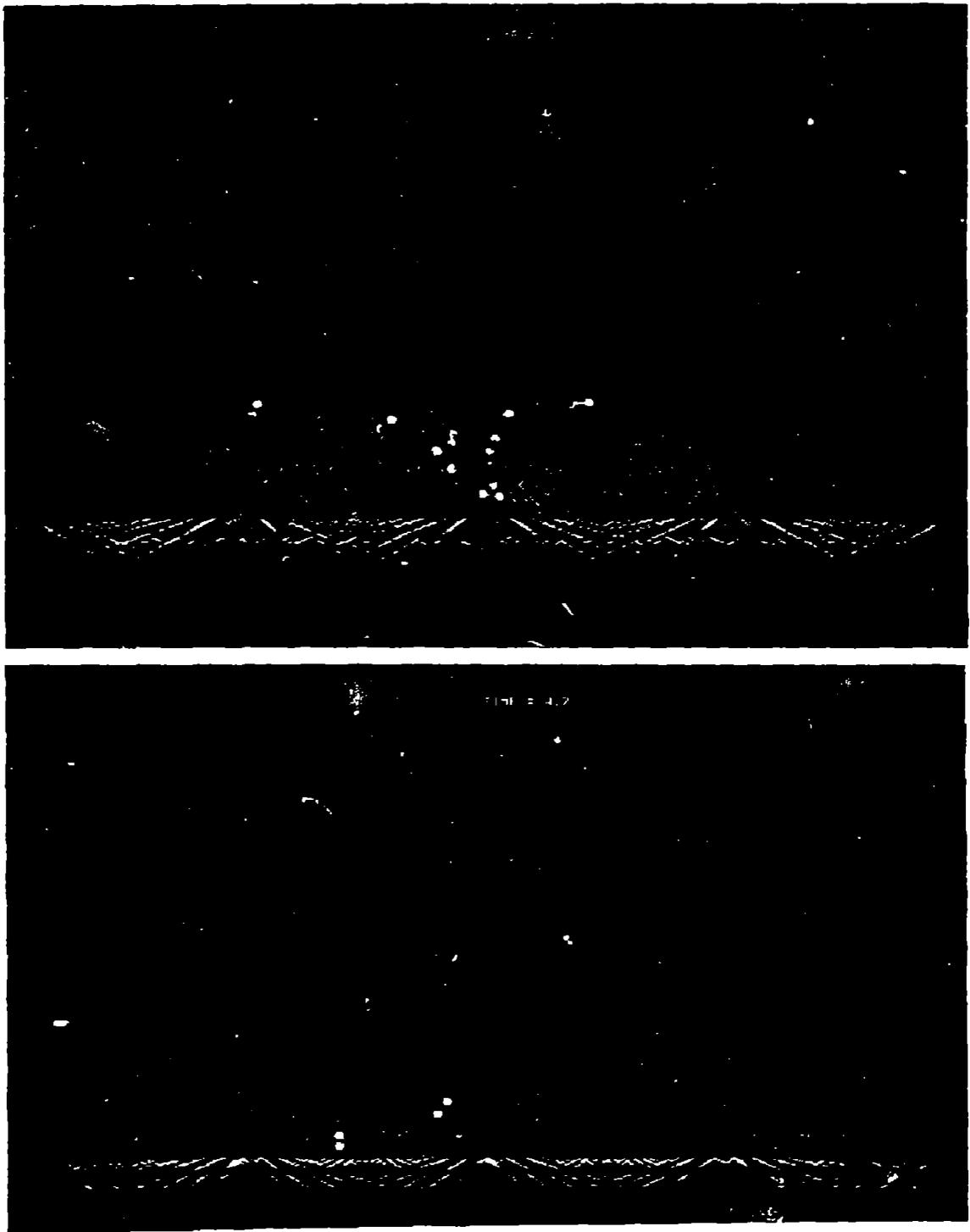
Under normal circumstances, linear PE does not char when it is burned. This was confirmed in experiments using the NIST Cone Calorimeter [6]. The cross-linked polymers, which were prepared by  $\gamma$  and (1 Mev) electron beam irradiations of linear PE, however, did leave measurable amounts of char. Indeed, glowing combustion, as indicated by the formation of red-hot embers, was observed when the cross-linked polymers were burned. The effectiveness of electron beam irradiation on delaying the time to ignition of PE is depicted in Figure 6. The performance of the irradiated samples during these experiments was particularly striking. The more highly cross-linked layer on the top formed a thin char which retained the gases generated by the decomposition of the polymer in the interior of the sample. Eventually, the gases broke through and the sample ignited leaving behind a thin skin of carbonaceous material when the flame self-extinguished. This behavior suggests that it may be possible to achieve a significant reduction in flammability by grafting a fire resistant shell to the surface of the plastic.

### Honeycomb Composite

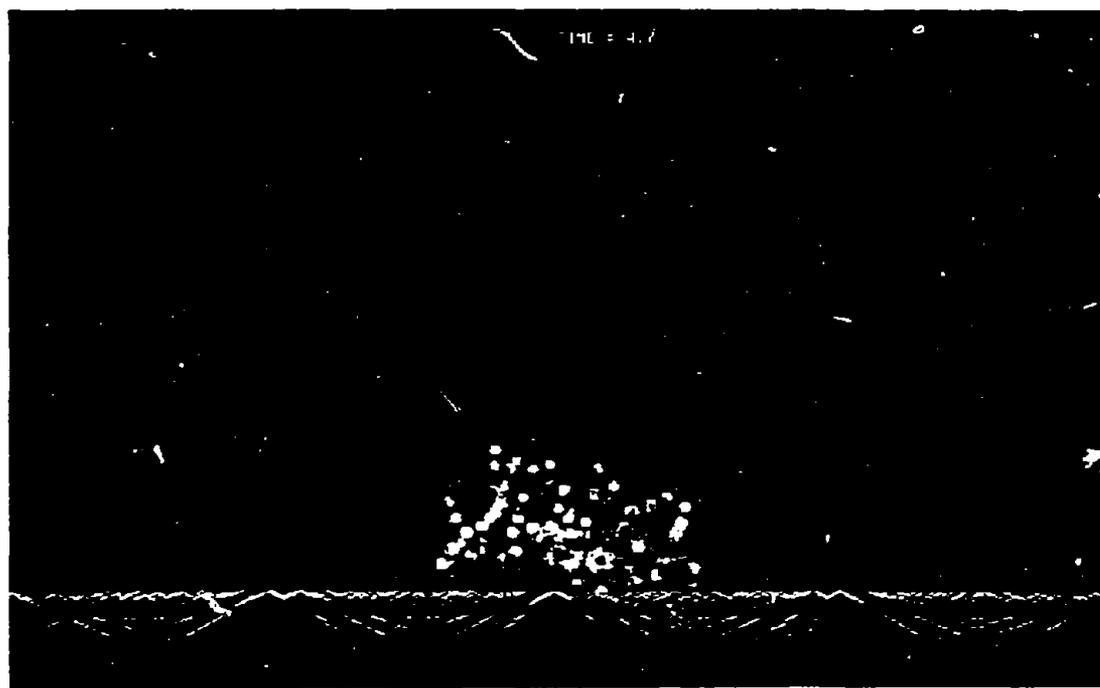
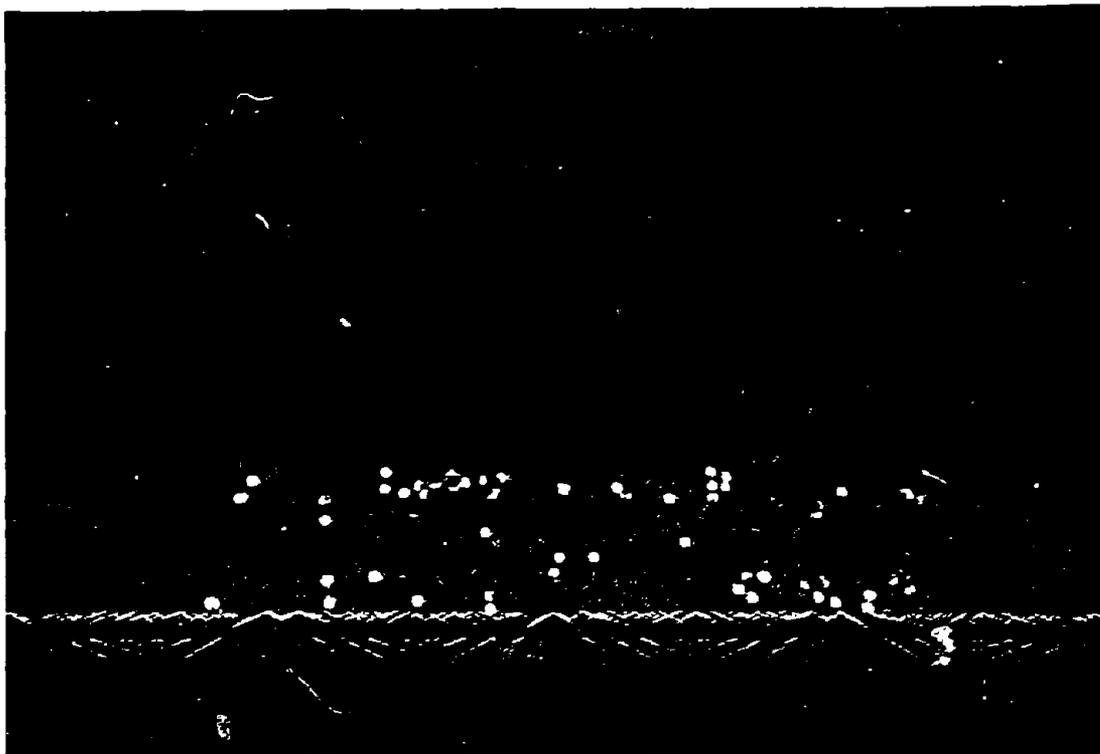
Honeycomb composite material was obtained from the FAA Technical Center. Samples were prepared by cutting the original panels into disks with an outer diameter of 7.5 cm. The rate of heat release (rhr) and ignition times were measured on the Cone Calorimeter for incident fluxes ranging from 30 to 60 kW/m<sup>2</sup>. The critical flux of the honeycomb composite is 34.4 ( $\pm$  0.6) kW/m<sup>2</sup>. This was determined from a series of measurements on independent samples which were subjected to increasing levels of incident flux.

The measured rhr curves indicate that there are two stages involved in the burning process (Figure 7). Initially, these materials burn with a yellow luminous flame which is typical of the combustion of complex hydrocarbons. This appears as a distinct peak in the rhr centered at about 1.25 minutes. The luminosity, which is indicative of the presence of soot, disappears after about 20 seconds giving way to an unstable blue flame which characterizes the remainder of the burn (tail in the rhr curve extending beyond 1.5 minutes). The flame usually extinguishes on the order of a minute later even though the material continues to smolder. The blue flame is most likely due to fluorescence associated with the oxidation of CO emanating from the charred Nomex.

It is clear that any attempt to improve the fire resistance of this material must focus on reducing the rate of heat released during the first stage of the combustion process. In fact, we found that a dramatic reduction in the peak rhr ( $\approx$  50%) could be achieved by heat treating the samples. Figure 8 is the rhr curve for a sample which was heated overnight at a temperature of 250 °C. It was measured at the same incident flux (40 kW/m<sup>2</sup>) as the rhr of the untreated composite displayed in Figure 7 (note change in the Y-axis scale). Although we have not yet



Figures 2 and 3. The chains fragment before strong cross-links (indicated by white spheres) can form.



Figures 4 and 5. An incipient char forms when hydrogens are removed at the onset of the simulations.

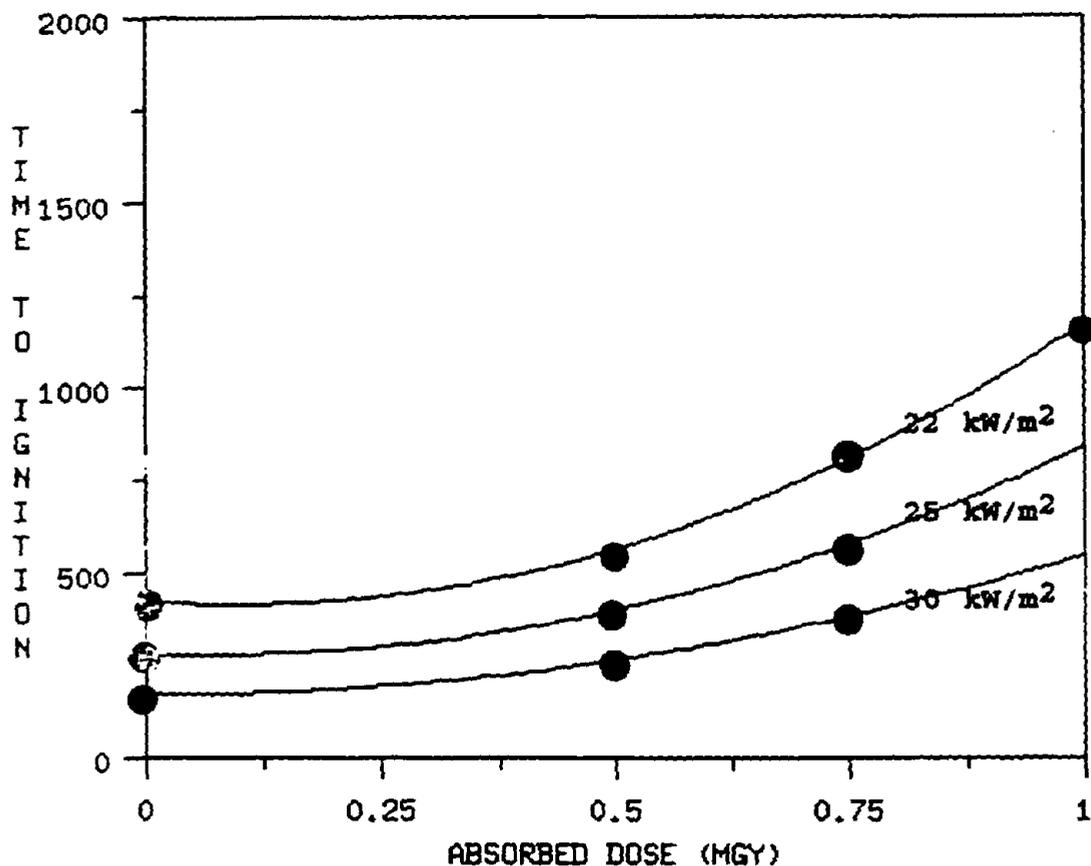
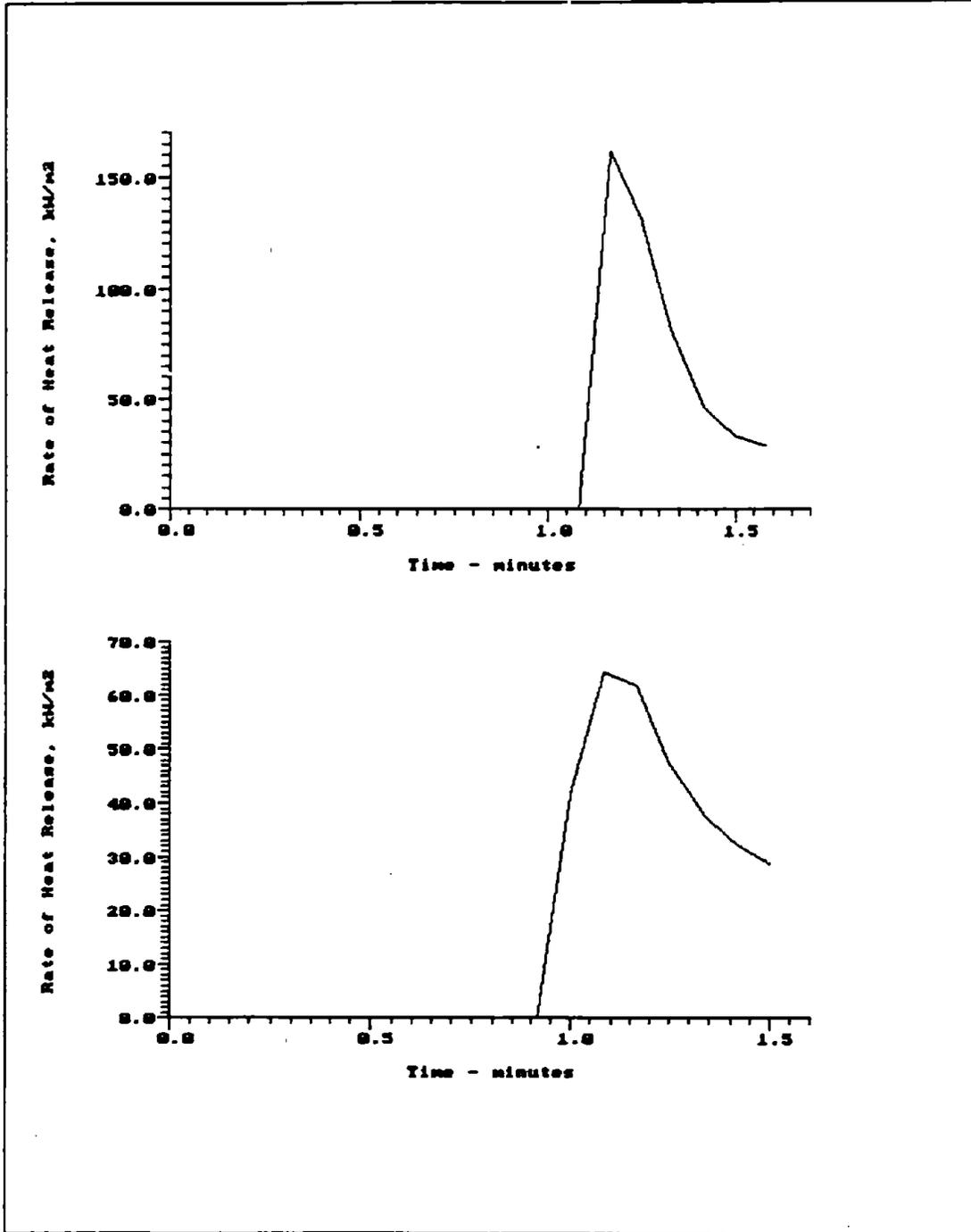


Figure 6. Times to ignition for electron beam irradiated PE as a function of absorbed dose.

identified the offending component(s), we suspect that it is associated with the surface laminate. The observation that the flammable components are so easily removed suggests that it should be possible to affect an improvement in fire resistance by enhancing the bonding between the constituent layers. Our work with PE indicated that this might be accomplished by exposing the material to ionizing radiation. We have begun to explore this possibility by irradiating the honeycomb disks with 1 Mev electrons from a Van der Graaf accelerator. Unfortunately, this did not have a measurable effect on ignition times (Figure 9) or rhr (Figure 10). During the next phase of this project we will explore the efficacy of using ionizing radiation to graft a fire resistant shell to the surface of the composite.

## CONCLUSIONS

Flammability measurements on the honeycomb composite panels used in the sidewalls, ceilings and stowage bins of commercial aircraft indicate that this material burns in two stages. Only the initial stage is associated with a significant release of heat. A dramatic reduction in the peak rhr was observed in flammability measurements of



Figures 7 and 8. Measured rhr at  $40 \text{ kW/m}^2$  for honeycomb panels before and after heat treatments. The tail extending beyond 1.5 minutes indicates a second stage in the combustion of these materials.

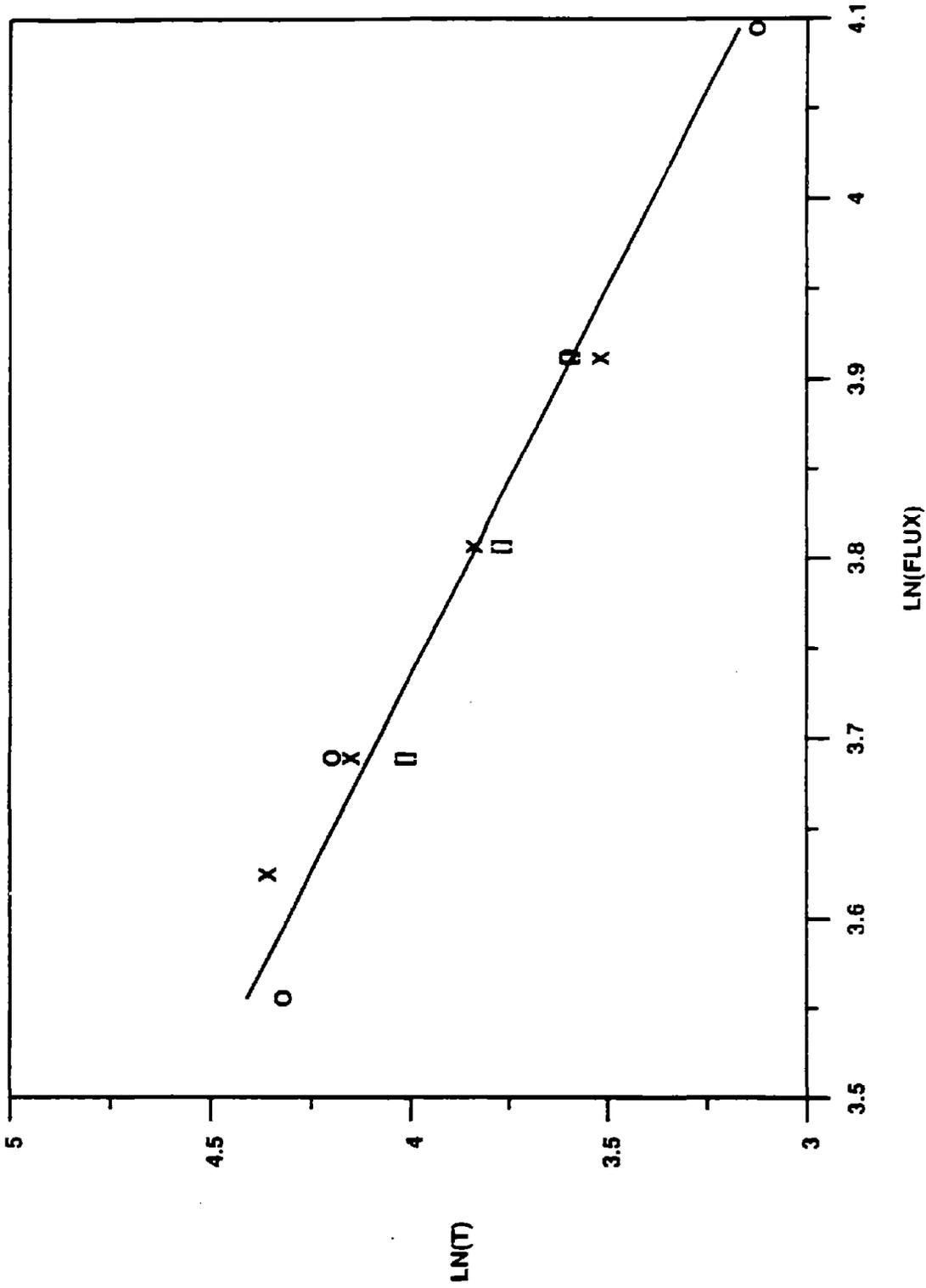


FIGURE 9. IGNITION TIMES CORRESPONDING TO DOSES OF 0 (O), 1.0 (X) AND 1.5 (I.)

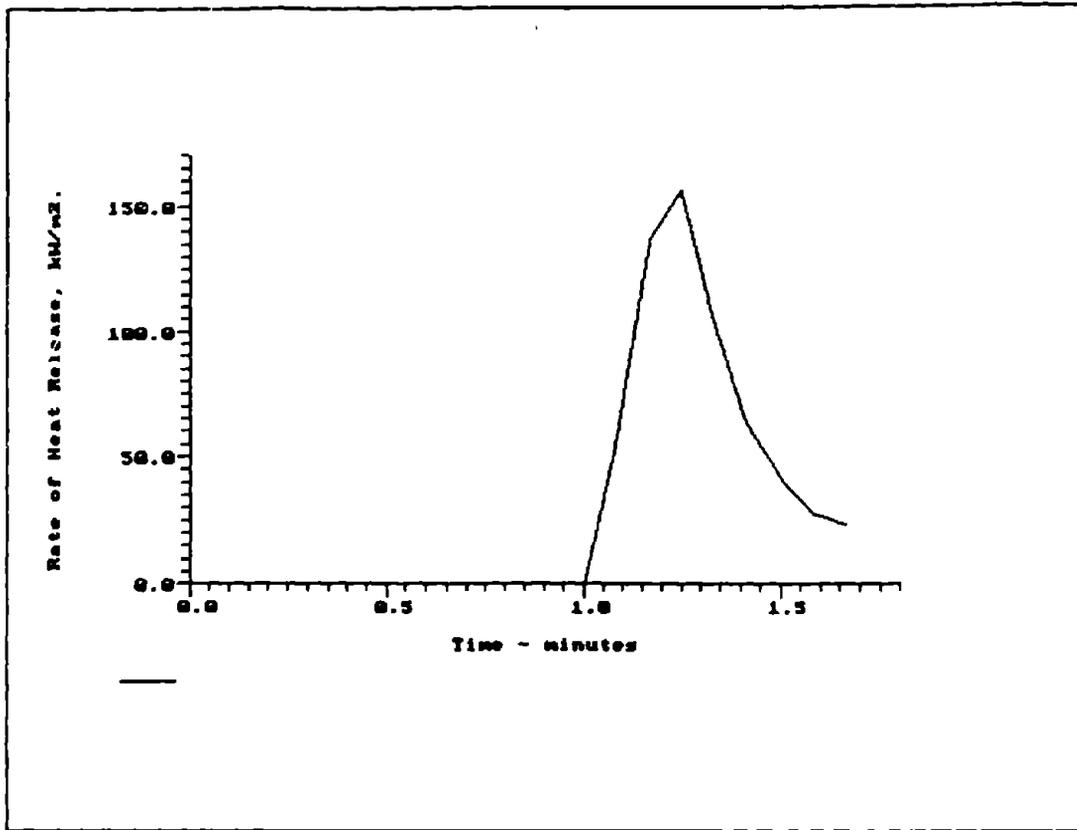


Figure 10. The rhr at  $40 \text{ kW/m}^2$  for honeycomb panels which had absorbed a dose of 1.0 MGy.

material which had been heated overnight at  $250^\circ\text{C}$ . This suggests that significant reductions in flammability may be achieved by improving the bonding between components. Future research will focus on the possibility of using radiative grafting to accomplish this objective.

#### ACKNOWLEDGEMENTS

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**Fire-Resistant Hydrolytically Stable  
Poly (Arylene Phosphine Oxide) Material Systems**

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**SUMMARY**

Arylene ether phosphine oxide homopolymers were prepared via nucleophilic aromatic substitution step polymerization of bis (4-fluorophenyl)phenyl phosphine oxide **1** with various aromatic bisphenols in the presence of a weak base and an aprotic dipolar solvent. These thermoplastic materials with  $T_g$  values in the range of about 200-285°C showed 5% weight loss in air around 500°C with substantial amounts (40-70%) of char yield at 700°C, in air, which suggests excellent self-extinguishing characteristics relative to other engineering thermoplastics. Additionally, the presence of high content phosphorus in the char after such high heating further implied a possible condensed phase mechanism. Nucleophilic substitution of **1** with *m*-aminophenyl oxide afforded the diamine, which was a key intermediate for thermoplastic polyimides, epoxy- and bismaleimide networks. These systems also showed extremely low amounts of etching in oxygen plasma when compared to other engineering polymers. The presence of phosphorus residues after either burning or etching with oxygen plasma suggests applications of commercial importance, including fire resistant materials. Qualitative burning experiments supports these conclusions.

**1. INTRODUCTION**

High performance engineering thermoplastics are becoming increasingly important in applications traditionally filled by metallic materials; moreover, their use in the field of high strength lightweight composite resins has already found many applications in the aerospace, automotive and related industries. Presently included in these industrially important thermoplastics are the poly(arylene ether ketone)s (PEKs) and poly(arylene ether sulfone)s (PESs). Poly(arylene ether)s of high molecular weight were first reported in the literature about twenty five years ago and the major success was with the amorphous class of PESs [1]. These materials were found to be soluble, tough, rigid thermoplastics with high glass transition temperatures ( $T_g$ ) depending on

the bisphenols incorporated. Many variations on this general theme have been introduced [2,3] and several reviews are available [4,5]. The group of PEKs has been successfully synthesized in only about the past ten years or so [6,7]. Recent developments and reviews can be found in the literature, covering most of the variations possible on the types of monomers which can be incorporated and the resulting material characteristics of the polymers [4, 8-10].

Our research has focused on many topics covering both the synthetic procedures necessary for poly(arylene ether) (PAE) preparation and novel poly(arylene ether) homo- and copolymers from new monomers and new functionalized oligomers. For example, new synthetic procedures were developed utilizing dipolar aprotic solvents with potassium carbonate as the weak base for phenate formation in a one pot procedure instead of the more complex sodium hydroxide route first developed by Johnson, et al. [ 11]. Also, Mohanty, et al. found a new solvent suitable for the nucleophilic aromatic polycondensation reactions, N-methylpyrrolidone [12]. New copolymer compositions were investigated for radiation-resistant PAEs [13], for PAE-polycarbonates [14,15], PAE-polyimides [16] and PAE-poly(aryl ester)s [17]. Functionalized PAEs of controlled molecular weight were synthesized for incorporation into block copolymers [18] and for the development of new toughened thermosetting networks [19-20]. Finally, we found a novel method for the synthesis of semicrystalline PEKs via an amorphous PEK precursor, namely poly(arylene ether ketimine)s [21,22] .

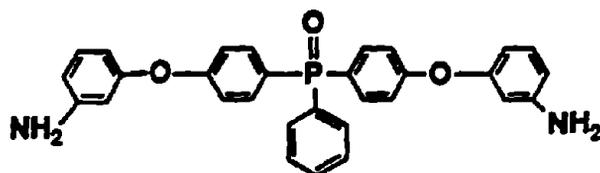
Other novel research in the field of nucleophilic aromatic substitution reactions yielding high molecular weight engineering polymers include the preparation of heterocyclic group containing PAS with moieties such as phenylquinoxaline [23], imidazole [24] and benzoxazole [25] by synthesizing either novel bisphenols or activated dihalides containing the units of choice. Incorporation of arylene ether units into the heterocyclic containing polymer chains improved the solubility without sacrificing thermal stability or mechanical properties.

A relatively new class of engineering thermoplastics, poly(arylene ether phosphine oxide)s (PEPOs), was introduced in the literature in 1977 [26]; however, only low molecular weight PEPOs were reported by the reaction of bis(4-chlorophenyl)phenyl phosphine oxide with bisphenols in various aprotic dipolar solvents utilizing sodium hydroxide as the base. More recently [27,28], German researchers have had success synthesizing these PAEs by the polycondensation of bis(4-fluorophenyl)phenyl phosphine oxide with various bisphenols in N-methylpyrrolidone using potassium carbonate as the weak base; however, physical properties resulting from the incorporation of phosphorus into these macromolecules were not given. Also, Hirose, *et al.* [29,30], synthesized two PEPOs by various methods and characterized these materials by thermal and viscosity measurements. We were interested to find the role the bulky

phenyl phosphine oxide unit played on the physical properties when incorporated in the polymer main chain, and also to compare the properties of the phenyl and methyl pendant groups attached to the phosphorus atom along the polymer chain. Some of our initial studies have been presented elsewhere [31-35], but this work compiles many of the unique aspects derived from the presence of phosphorus in the backbone of these polymers.

Phosphorus containing polymers have been shown in the chemical literature as being fire-resistant materials [36,37]; however, most of these systems were hydrolytically unstable, only gave low molecular weight and were principally vinyl-like in nature. Additionally, in most cases, the bonding around phosphorus in these polymers has been to oxygen or nitrogen, such as phosphonates or phosphazenes. Therefore, oligomeric forms of these hydrolytically unstable molecules have been incorporated in almost all cases as flame-retardant additives and not utilized as homopolymer systems. Our goals were to investigate the incorporation of carbon-phosphorus bonds in the backbone on the thermal, oxidative and other aggressive environment stabilities of these materials.

Aromatic polyimides are of high interest for engineering and microelectronic applications due to their unique property combinations. Exceptional thermal and oxidative stability and solvent resistance are complemented by excellent mechanical and electrical performance and dimensional stability over a wide temperature range. However, insolubility in common and/or environmentally acceptable solvents and high transition temperatures make these systems difficult to process. Therefore, much effort has been spent on synthesizing processable, tractable polyimides without compromising desired properties. To accomplish this goal, the incorporation of flexible bridging units into the rigid polyimide backbone has been widely used. Some polyimides meet processing, thermal and flammability requirements for many applications, but recent research and development has been concentrated on new and improved polyimide systems with respect to high temperature and humidity and/or low smoke and non-flammability properties. Since polymers containing phosphorus as an integral part of the backbone are known to be thermally stable and flame-retardant, efforts have been made to synthesize phosphorus containing polyimides. To accomplish this goal, a new diamine precursor, bis(3-aminophenoxy-4-phenyl) phenylphosphine oxide (m-BAPPO), was synthesized in our laboratories by utilizing the nucleophilic aromatic substitution reaction which contains m-amino groups and phosphorus.



This novel monomer was then used in the preparation of homo- and copolyimides of controlled molecular weight by a solution imidization technique. It was also employed for the generation of epoxy and bismaleimide networks and this will be reported later [46,47].

## 2. EXPERIMENTAL

### 2.1 Solvents and General Reagents

The dipolar aprotic solvents utilized in this research, N-methylpyrrolidone (NMP) or N,N'-dimethylacetamide (DMAC), were vacuum distilled over calcium hydride and stored in an anhydrous environment prior to use. Anhydrous potassium carbonate (Fisher) was dried at 100°C and stored in a desiccator. Toluene (Fisher) was used as received. Dry tetrahydrofuran (THF) was obtained through distillation over a sodium/benzophenone complex.

### 2.2 Monomers

Bisphenol A (BIS A), kindly supplied by Dow Chemical, was recrystallized from toluene and dried *in vacuo* overnight. Hydroquinone (HQ) (Aldrich ≥ 99%) was used as received. Biphenol (BP) (97%, Aldrich) was recrystallized from deoxygenated acetone and dried *in vacuo*. High purity 9,9-bis(4-hydroxyphenyl)fluorene (FL) samples were supplied by NASA, Langley Research Center.

Bis(4-fluorophenyl)phenyl phosphine oxide (BFPPPO) was prepared and purified by a variation of known Grignard techniques [29]. For example, to a flame dried four-neck 5 l round-bottom flask fitted with an overhead mechanical stirrer, an addition funnel and a nitrogen inlet, were added 85.1g (3.5 mol) magnesium turnings and 3.5 l dry THF. To this stirred solution was added dropwise, at 5°C, 618.7g (3.5 mol) 4-bromofluorobenzene (Aldrich, 99%) over 3-4 hours. This solution was stirred at room temperature overnight to give a gray, slightly cloudy mixture. Next, 351.8g (1.75 mol) phenylphosphonic dichloride (97%, Aldrich) was added dropwise at 5°C over 3-4 hours and this solution was allowed to stir at room temperature overnight to give a clear yellow mixture. Enough 10% aqueous sulfuric acid was added to make the solution acidic to litmus, and about 1 liter of water was added. If this mixture did not separate into organic and aqueous layers, diethyl ether was added to induce phase separation. The aqueous layer was washed well with

ether/THF mixtures and all organic phases were combined. The ether solvents were stripped off to give a wet product, which was dissolved in toluene and azeotroped for several hours over activated charcoal. Filtration through celite gave a clear orange solution. Toluene was then stripped off and the crude product was twice subjected to short path distillation under reduced pressure at 160-70°C, typically yielding 70-80% white crystalline polymer grade BFPPPO (m.p. 124-126°C).

Bis(4-fluorophenyl)methyl phosphine oxide (BFMPO) was synthesized in an analogous manner from methylphosphonic dichloride and 4-bromofluorobenzene. Purification procedures were similar to those above with the additional benefit of the ability to sublime the BFMPO. Yields again were excellent for monomer grade material in the range of 70-80% (m.p. 112-114°C).

### 2.3 Polymerization

The preparation of a high molecular weight BIS A poly(arylene ether phosphine oxide) (PEPO) will be used to illustrate representative procedures employed. A 250 ml 4-neck round bottom flask, equipped with an overhead stirrer, a nitrogen inlet, a Dean-Stark trap with condenser, and a thermometer was charged with 5.707g (0.025 mol) BIS A and 7.856g (0.025 mol) BFPPPO. The teflon coated pans from which the monomers were transferred were rinsed well into the flask with NMP, for a total volume of 90 ml NMP. A 5% excess of K<sub>2</sub>CO<sub>3</sub> (4.15g, 0.03 mol) and 45 ml toluene were added to the reaction mixture. A constant purge of nitrogen was maintained, and the temperature was controlled by a high temperature silicone oil bath. The water and toluene azeotrope formed at approximately 150-155°C and the system was allowed to dehydrate for about four hours. Next, the temperature of the mixture was raised to 165-170°C and maintained for about sixteen hours. The solution was a dark brown viscous mixture with a white inorganic salt suspension. Finally, the mixture was allowed to cool to room temperature, diluted with chloroform, and filtered. Glacial acetic acid was utilized to neutralize the solution to afford a clear brown to amber mixture. This solution was precipitated in a 80:20 methanol:water mixture in a high speed blender to yield a nearly white highly fibrous material. The polymer was dried overnight at 100°C under vacuum, redissolved in chloroform, filtered, neutralized, reprecipitated in methanol and dried again under the same conditions.

The poly(amic acid) preparations were performed in a four-necked flask equipped with a mechanical stirrer, nitrogen inlet, thermocouple and condenser fixed to a Dean-Stark trap. A calculated amount of phthalic anhydride was added to the prepared diamine solution to afford non-reactive end groups and controlled molecular weight. Dianhydrides were added in small increments, while the reaction flask was cooled to 5-10°C under nitrogen flow. The reaction mixture was stirred at room temperature for at least 8 hours to reach high molecular weight

distribution. The imidization was conducted at 15-20% (w/w) solid concentration with a co-solvent system of NMP (80%) and CHP (20%). The reaction was carried at 165°C for 24 hours to complete the cyclization as judged by FT-IR analysis (4). The solution was then cooled to room temperature, filtered through a 5µm filter and precipitated in methanol in a high speed blender. The polymer was collected by filtration and dried for 24 hours at 160°C.

## 2.4 Polymer Characterization

Differential scanning calorimetry (DSC) and thermogravimetric analyses (TGA) were carried out on a DuPont model 912 instrument, both at a heating rate of 10°C/min<sup>-1</sup>. The reported T<sub>g</sub> values from DSC were obtained on the samples which had been cold pressed and secured in crimped aluminium pans. Scans were run at 10°C min<sup>-1</sup> and the reported values were taken from the second run, after a quench cool from the first run unless otherwise noted. TGA was carried out in flowing air at a 10°C min<sup>-1</sup> heating rate and values reported are for the temperatures at 5% weight loss. Intrinsic viscosity measurements on the materials were performed in the indicated solvents at room temperature using Cannon Ubbelohde viscometers. Dynamic mechanical and dielectric thermal analyses (DMTA and DETA, respectively) were performed on Polymer Laboratories instruments. DMTA experiments were carried out at 1 Hz at 5°C min<sup>-1</sup> on compressed bars of the desired material 0.0508 mm thick. The pressed bars were obtained by compressing the samples 50°C above their T<sub>g</sub> values for 15 min, then quenched cool. Storage moduli (e') and loss tangent (tan δ) values were recorded.

## 2.5 Resin Origins

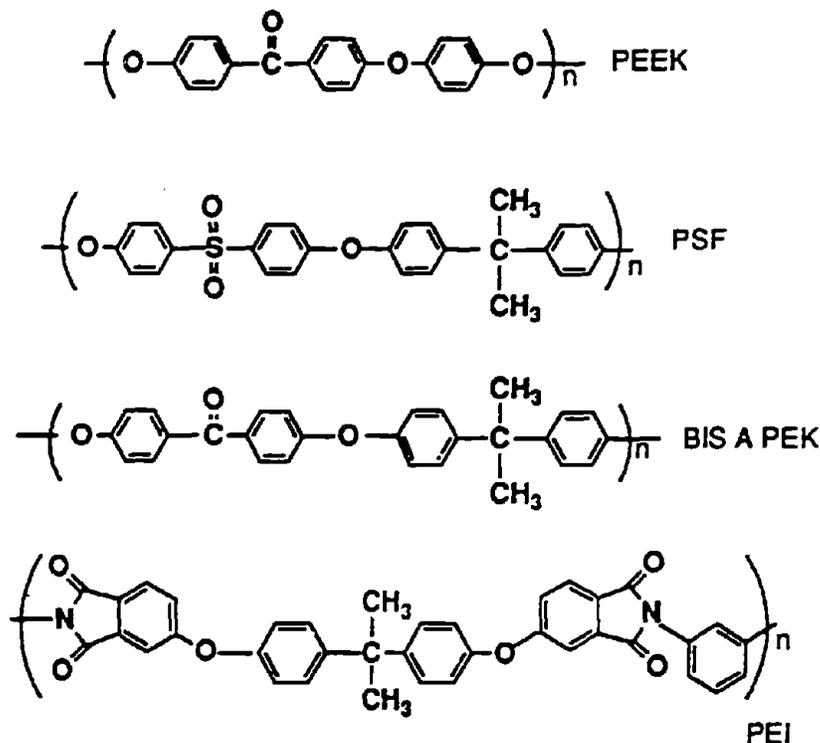
Acronyms used throughout this paper along with their respective chemical structures are illustrated in Figure 1. UDEL polysulfone (PSF) was supplied by Amoco Chemical Co. (Naperville, IL) and PEEK was provided by ICI (Tempe, AZ). BIS A PEK was synthesized in our laboratory by standard methods. Ultem poly(ether imide) was generously donated by General Electric Company (Evansville, IN). The materials are essentially free of additives.

## 3. RESULTS AND DISCUSSION

### 3.1 High Molecular Weight PEPO Synthesis

The nucleophilic aromatic substitution polymerization of aromatic bisphenols with the phosphorus containing activated dihalides was carried out under conditions developed in this laboratory [12], as shown in Scheme 1, to yield poly(arylene ether phosphine oxide)s (PEPOs).

**FIGURE 1: Engineering Thermoplastics Utilized Throughout This Study**



In the presence of a weak base, potassium carbonate, and an aprotic dipolar solvent (NMP) and at temperatures around 145°C, phenate formation was accomplished quantitatively and driven toward completion via removal of the water byproduct by azeotrope with toluene. Next, the temperature of the solution was raised to 165°C and maintained overnight to drive the polymerization to a high extent of conversion. After workup of the amber or red solutions with inorganic salt suspensions, nearly white highly fibrous materials were obtained. High molecular weight was obvious from intrinsic viscosity measurements (Table 1), which were in almost all cases above 0.60 dl g<sup>-1</sup>. Also, the ability to form tough clear slightly amber films from solution or by compression was an indication of acceptable molecular weight formation. Stirring these materials in boiling water for extended periods of time showed no effect on the viscosity, typical of poly(arylene ether)s. Investigations of the T<sub>g</sub> values of these PEPO materials by DSC identified their similarity in transition temperatures to the class of PESs, giving typically a 5-10°C increase in T<sub>g</sub> of the PEPO thermoplastics over the PES (Table 1). Additionally, when comparing the phenyl and methyl substituents bonded to phosphorus along the polymer backbones, only a slight decrease (about

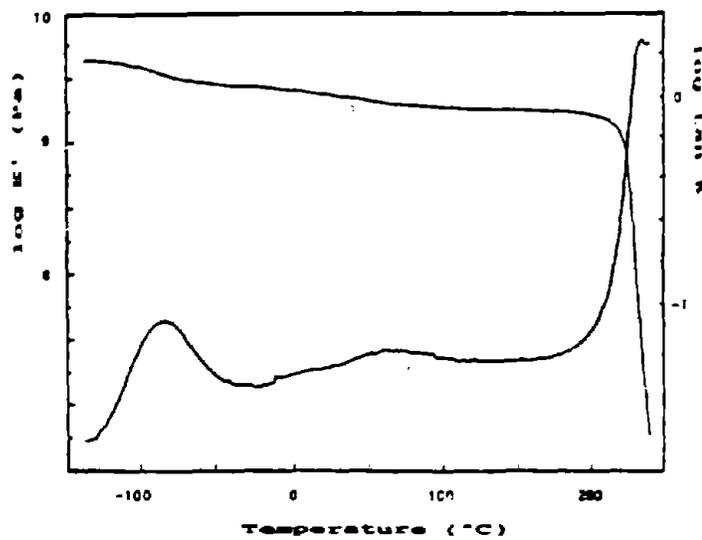


Figure 2: DMTA Thermogram of BP PEPO

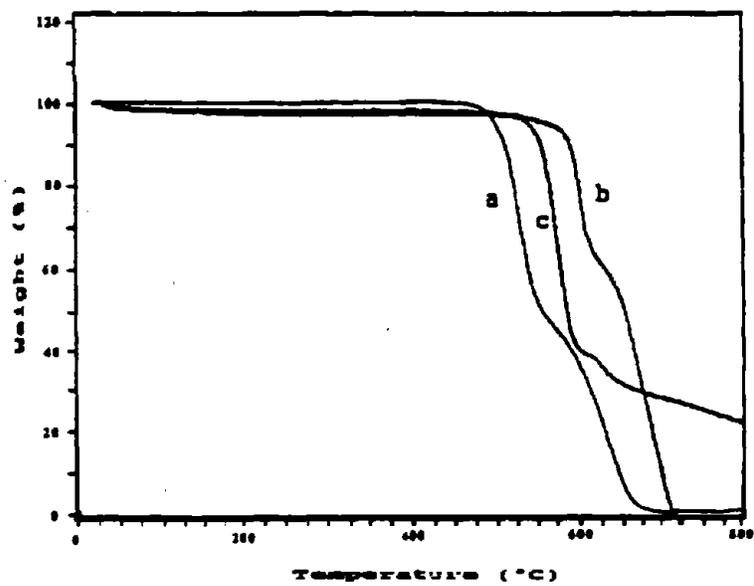


Figure 3: Dynamic TGA Scans in Air for (a) UDEL PSF, (b) PEEK and (c) BP PEPO

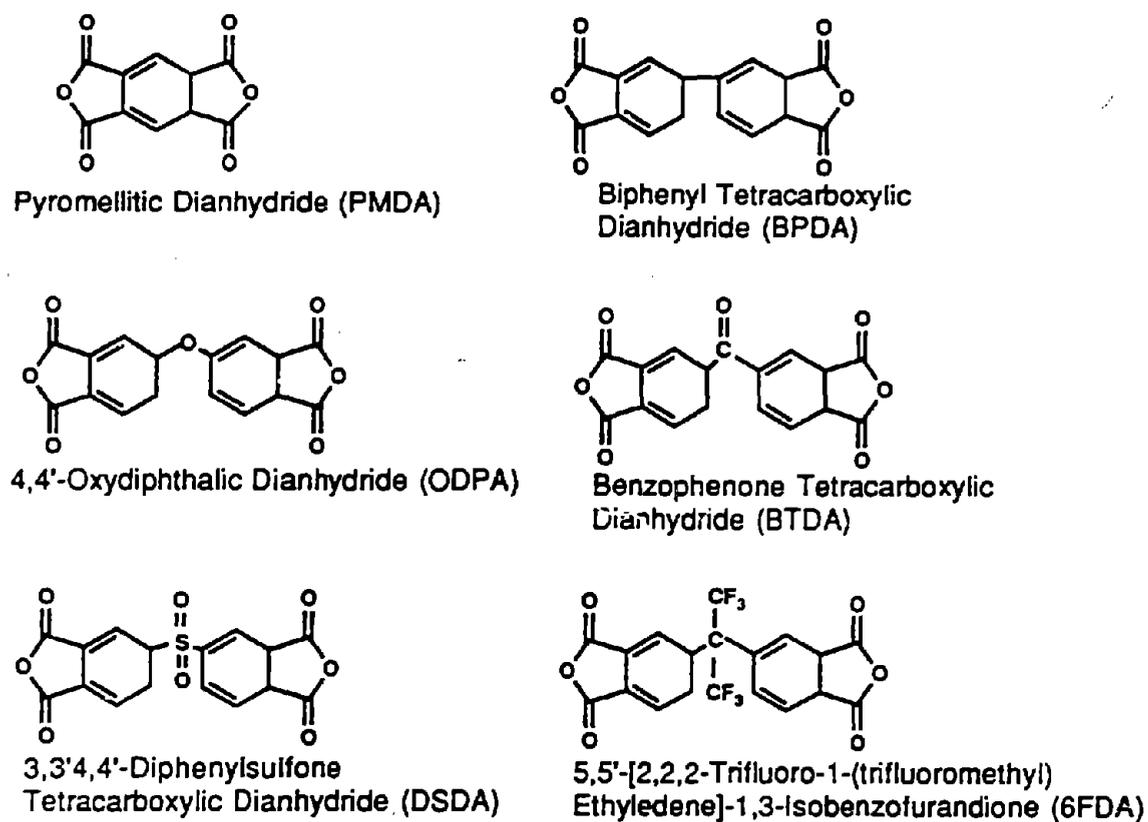
Formation of char appears to play an important role in the self-extinguishing properties of engineering thermoplastics and char yields have previously been correlated with the limiting oxygen index (LOI) of many polymers [40]. The LOI has been the most quoted measure of polymers' resistance to flame environments, but it seems to be dependent on such a long list of variables that it appears a single number cannot possibly describe the behavior of a polymer when burned. We developed a qualitative test in which films on the order on 0.5-1 mm thick were exposed to a Bunsen burner flame in air for constant amounts of time, then removed after a predetermined period in the flame. In all cases, non-phosphorus containing engineering thermoplastics (PEEK, UDEL, Ultem polyimide, etc.) with very high literature LOI values appeared to completely volatilize; on the other hand, all phosphorus containing PEPO systems immediately extinguished upon removal from the flame. This test could be repeated several times for any single PEPO sample.

The presence of phosphorus in polymeric systems has been known for some time to generically impart flame-retardance to materials. Indeed, molecules such as triphenyl phosphine oxide (TPPO) have been known to be thermally stable at temperatures of 700°C [41]. However, the study of polymeric materials containing the triphenyl phosphine oxide moiety chemically bound within the polymer chain as flame retardant polymers has been limited. On the other hand, poly(arylene ether sulfone)s and poly(arylene ether ketone)s have been explored in terms of thermogravimetry or pyrolysis in order to obtain a more detailed analysis of the degradation process [40, 42-45]. Typically, these materials begin to degrade by chain scission at the sulfone or ketone group to give sulfur dioxide or carbon monoxide, respectively. The radicals formed from this initial reaction go on to initiate further chemistry, finally totally volatilizing the polymer at sufficiently high temperatures. Using pyrolysis/gas chromatography/mass spectrometry techniques, along with neutron activation analysis, we were able to determine the fate of phosphorus in the burning process, as well as observing the degradation products of PEPO compared to other engineering thermoplastics.

Polyimides were prepared from dianhydrides with m-BAPPO. Solution imidization of the amic acid was performed in a cosolvent system of NMP and CHP at 165°C for 24 hours. Addition of CHP into poly(amic acid) solution as a azeotroping solvent in a 8:2 ratio was sufficient for the efficient removal of water which is formed upon the conversion of the amic acid to the imide. Complete imidization was confirmed by observation of an appearance of characteristic imide related infrared absorption bands in the range 1770-1780  $\text{cm}^{-1}$  (asymmetrical imide I), 1710-1735  $\text{cm}^{-1}$  (symmetrical imide I) and disappearance of amic acid band at 1535  $\text{cm}^{-1}$ . Strong bands in the range 1325-1390  $\text{cm}^{-1}$  (imide II), 1105-1120  $\text{cm}^{-1}$  (imide III) and 710-720  $\text{cm}^{-1}$  (imide IV) were

observed in the spectrum of all the polyimides. Along with these absorption, other absorption arising because of P=O at  $1175\text{ cm}^{-1}$ , P-C<sub>6</sub>H<sub>5</sub> at  $1425\text{ cm}^{-1}$ , and C<sub>6</sub>H<sub>5</sub> at  $1590$  and  $1490\text{ cm}^{-1}$  were also observed. Characteristics of the materials are provided in Tables 2-4.

**Figure 4**  
**DIANHYDRIDES**



**Table 2**  
**Intrinsic Viscosities and Upper Glass Transition Temperatures**  
**of Solution Imidized m-BAPPO Based Polyimide Homopolymers**

POLYIMIDE SYSTEM	THEORETICAL L <Mn>	[ $\eta$ ] (dL/g) 25°C NMP	Tg (DSC) °C
PDMA/m-BAPPO	30K	0.59	254
BPDA/m-BAPPO	30K	0.46	241
DSPA/m-BAPPO	30K	0.38	240
6FDA/m-BAPPO	30K	0.38	239
BTDA/m-BAPPO	30K	0.43	232
ODPA/m-BAPPO	30K	0.37	220

**Table 3**  
**Solubilities of Solution Imidized**  
**m-BAPPO Based Polyimides Homopolymers**

POLYIMIDE SYSTEM	TEMP OF 5% WT LOSS	TMWL*	Yc**
PDMA/m-BAPPO	523	570	18
BPDA/m-BAPPO	557	600	35
ODPA/m-BAPPO	518	560	12
DSPA/m-BAPPO	496	550	12
BTDA/m-BAPPO	513	540	10
6FDA/m-BAPPO	521	560	>5
KAPTON™	550	600	

\*TMWL: Temp of maximum weight loss;

\*\*Yc: Char yield %, at 750°C

**Table 4**  
**Thermogravimetric Analysis of m-BAPPO Based**  
**Polyimide Homopolymers in Air**

POLYIMIDE SYSTEM	NMP	ChCl <sub>3</sub>	CB	THF
PDMA/m-BAPPO	S	S	I	I
BPDA/m-BAPPO	S	S	I	I
ODPA/m-BAPPO	S	S	I	I
DSPA/m-BAPPO	S	S	I	I
BTDA/m-BAPPO	S	S	I	I
6FDA/m-BAPPO	S	S	GELS	S

NOTE: S=Soluble; I=Insoluble; CB=Chlorobenzene

The glass transition temperatures for homopolyimides are given in Table 1. These values are very important for identification of optimum processing temperatures at which polymer remains processable while introducing minimal thermal degradation during processing procedures. T<sub>g</sub> ranged from 220°C to 254°C depending on the structural composition. An increase in T<sub>g</sub> was observed according to the following series:



The dynamic thermogravimetric analysis results of these polyimides in air given in Table 3. The temperature of 5 percent weight loss for the polyimides ranged from 496°C to 557°C. One striking point is that all m-BAPPO based polyimides yielding substantial amounts of char at their temperature of maximum weight loss compared to commercially available polyimide KAPTON™ (PMDA/ODA). Furthermore, the BPDA/m-BAPPO polyimide system gave 35% char even at 750°C under air flow. However, these dynamic TGA analyses do not fully indicate the thermal performance of a polymer at a given temperature, isothermal TGA data were obtained at 300°C in air. All polyimides showed exceptionally good thermooxidative stability at this temperature, giving less than 0.2% weight loss over 15 hours. Both dynamic and static TGA analyses indicated that phosphorus containing polyimides have excellent thermal stability. The intrinsic viscosities of the resulting homopolyimides are also given in Table 1. The solubility of the polyimides are given in

**Table 4. They were very soluble in polar aprotic solvents as well as CHCl<sub>3</sub>. The 6FDA/m-BAPPO polyimide system showed great solubility even in THF.**

#### **4. CONCLUSIONS**

PEPOs were successfully prepared by the nucleophilic aromatic substitution polycondensation of aromatic bisphenols with bis(4-fluorophenyl)phenyl phosphine oxide or bis (4-fluorophenyl)methyl phosphine oxide in the presence of potassium carbonate and an aprotic dipolar solvent. In addition to offering hydrolytic, thermal and oxidative stability, with T<sub>g</sub> ranging from about 190°C to 280°C, these materials were more self-extinguishing than any other engineering thermoplastics tested when burned, due to the presence of phosphorus in the substantial amount of char. Moreover, phosphorus presence played the major role in forming a highly oxidized, non-volatile phosphorus-containing surface layer. These characteristics were all unique to all phosphorus-containing PAEs, with important implications for flammability.

The synthesis of phosphine oxide group containing diamine monomer and its incorporation into polyimide structures has been demonstrated. The resulting polyimides have T<sub>g</sub>'s from 220°C to 254°C and exhibit excellent thermooxidative stability and high char yields in air. Future studies are needed to quantify the apparent fire resistant characteristics.

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**A NON-HALOGENATED, FLAME RETARDED POLYCARBONATE**

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**ABSTRACT**

Various flammability properties of a siloxane-containing bisphenol-A polycarbonate sample, with the siloxane as an additive or as a copolymer, were measured and compared with those of a pure polycarbonate sample. The results show that the peak heat release rate for the siloxane-containing polycarbonate sample is significantly reduced (less than half) compared to that for the pure polycarbonate sample with two different sizes of sample, 10cmx10cm and 40cmx40cm. However, the ignition delay time for the siloxane-containing sample is shorter than that for the pure polycarbonate sample. Also, the flame spread rate under an external radiant flux becomes faster for the siloxane-containing sample than that for the pure polycarbonate sample. The observed char behavior, such as char depth, physical nature and apparent combustibility, and its impact on flammability properties are discussed.

**INTRODUCTION**

After the implementation of the stringent new FAA low heat release rate regulation (two minute heat release of 65 kW-min/m<sup>2</sup> and peak heat release rate of 65 kW/m<sup>2</sup>)[1], enhanced fire resistance of aircraft interior materials has become a challenge to the aircraft industry. Furthermore, two important recent trends which have started to affect the fire aspects of materials are non-halogenated flame retardant treatments and polymer recycling. Due to negative publicity about dioxin and furan as possible degradation products, some brominated flame retardants have received a negative public perception in Europe[2]. Regulations on the use of certain types of these flame retardants have been proposed in Germany. Although the use of halogenated flame retardants is still showing an upward trend, some concerns have been raised, and there is a definite trend to seek alternatives. Also, the huge waste volume of plastics is becoming a problem to modern societies. A popular solution is the recycling of waste plastics. In Germany, even now, plastic products for packaging have to be taken back by the producer or retailer for recycling or disposal. This will be extended to include electronic scrap, such as old computers, with an obligation to recycle as far as possible. Corresponding to these requirements, the labeling of all plastic components of computers to identify their material and manufacturers has already been implemented by IBM [3]. The emphasis on recycling might affect the selection of the base polymer and flame retardant treatment on the basis of ease of recycling and also on durability. It could be possible that material selections will be more limited than in the past.

Therefore, some U.S. plastics companies are interested in developing new non-halogenated retardants. As an example, the Corporate Research and Development Center of General Electric Co. and NIST are collaborating to do so. One of their basic polymers is bisphenol-A polycarbonate. Although roughly 25% of the initial sample weight is left as a residual char when a polycarbonate sample is burned at an external radiant flux of 40 kW/m<sup>2</sup> in the Cone Calorimeter, the peak heat release rate measured in the Cone Calorimeter is as high as 800 kW/m<sup>2</sup>; and GE is quite interested in hearing how to reduce the peak heat release rate without using any halogenated compounds.

## RESULTS MEASURED BY CONE CALORIMETER (SMALL SAMPLES)

Various amounts of a siloxane-containing compound were added to bisphenol-A polycarbonate as an additive. The sample size was about 10 cm x 10 cm x 0.3 cm thick. Since it is not clear what sample mounting configuration is the most appropriate to measure flammability properties of intumescent polymers in the Cone Calorimeter, the tests were conducted in two different mounting configurations[4]. One configuration is designated as "WG" in which a standard metal frame container and a grid were used. Initially, the sample was mounted such that the sample surface was 0.5 cm below the grid. In this configuration, intumesced char was prevented from swelling fully by the grid. The other configuration is designated as "NF" which means no grid or metal frame container around the sample. This configuration allows the char to intumesce and not lose any heat to a metal frame. Typical heat release rate curves for polycarbonate samples with the siloxane-containing additive measured by the Cone Calorimeter at an external radiant flux of 40 kW/m<sup>2</sup> are shown in Fig.1 for the "WG" configuration and in Fig.2 for the "NF" configuration, respectively. In Fig.1, the addition of small amounts of siloxane, even 0.25 wt%, significantly reduces the heat release rate. However, it increases the burnout time and also tends to yield two peaks in the curve instead of one large peak as for the sample without any siloxane. The incremental effectiveness of additional siloxane in reducing the heat release rate decreases with an increase in siloxane percentage. In Fig.2, the heat release rate initially increases sharply with time, compared to the results shown in Fig.1. The freely rising, intumesced char reduces the distance between the char surface and the Cone heater. This had two effects on heat release rate measured in the "NF" configuration: one was an increase in the sample surface area (heat release rate was calculated with the initial sample surface area) and the other was an apparent increase in the incident radiant flux to the sample. These two effects tend to an increase heat release rate. However, after the char is well intumesced, it protects the original polymer layer more than the suppressed intumesced char in the "WG" configuration. This reduces the gasification rate of the sample. Poor heat insulation by the suppressed, dense intumesced char does not reduce the gasification rate nearly as much. Therefore, the heat release rate remained nearly constant with time in the "WG" configuration as shown in Fig.1.

The results shown in the two figures indicate that an increase in the amount of the siloxane-containing additive decreases an ignition delay time. Thermogravimetric analysis of these samples shows a reduction in thermal stability from the original polycarbonate sample with an increase in the amount of the siloxane-containing additive. This indicates that the thermal stability of the siloxane-containing additive is less than that for the pure polycarbonate sample. Since piloted ignition is controlled by the supply of fuel gases[5], less thermally stable samples tend to ignite at an earlier time. Therefore, ignition delay time becomes less with an increase in the amount of the siloxane-containing additive. The effects of the amount of siloxane on piloted ignition delay time are shown in Fig.3. The results show that ignition delay time decreases rapidly with the addition of a small amount of siloxane and this decrease becomes more gradual above 1% of siloxane. Ignition delay time measured in the "WG" configuration tends to be slightly longer than that measured in the "NF" configuration presumably due to an apparent increase in the incident radiant flux on the rising polymer surface.

The effects of the amount of siloxane on peak heat release rate are shown in Fig.4. An addition of a small amount of siloxane, up to 1%, significantly decreases the peak heat release rate and a gradual decrease is observed above 1% of siloxane. The peak heat release rate measured in the "NF" configuration is significantly higher than that measured in the "WG" configuration due to the above-described reasons. Although peak heat release rate is significantly reduced by the addition of the siloxane-containing additive, the total heat release is not significantly affected by the addition, as shown in Fig.5. Since the total heat release is the integral of the heat release rate curve shown in Figs. 1 and 2, the trend of nearly constant total heat release can be explained from the results shown in these figures. The samples with the siloxane-containing additive generate lower peak heat release rates but tend to burn much longer than the pure polycarbonate sample. Therefore, the area under the heat release rate curve is about the same for all samples shown in Fig.5 except the sample with 5% of siloxane measured in the "WG" configuration. At present it is not clear whether a large percentage of siloxane might generate more heat release due to a significant decrease in thermal stability of the sample. On the other hand, there are clearer trends for the effects of the addition of siloxane on the sample mass loss, as shown in Fig.6, than those on the total heat release. The mass loss gradually decreases with the addition of siloxane when the sample was measured in the "NF" configuration. However, in the "WG" configuration, mass loss decreases up to 1% of siloxane and it remains nearly the same up to 4%. The sudden increase in mass loss at 5% of siloxane is similar to that for the total heat release.

It appears that there are some differences between the residual char formed from the samples with and without the siloxane-containing additive. The polycarbonate sample generates a brittle, thin shell-like char layer. The samples with the siloxane-containing additive tend to generate foamy, less brittle char. In the latter part of this paper, the results of an elemental analysis of these char layers will be presented to indicate whether there are significant differences in chemical structure between the samples with and without siloxane. It is also planned to analyze their heat insulation characteristics in the future.

Soot yields were obtained by measurement of the weight of collected particulates on a filter divided by the total sample weight loss. The effects of the addition of the siloxane-containing additive on soot yields are shown in Fig.7. Although there is significant scatter in the results, it appears that the addition of the siloxane-containing additive does not increase soot yield. Since soot yield is normalized by weight loss rate, soot generation rate could be significantly reduced for the polycarbonate samples with the siloxane-containing additive due to much lower weight loss rate (nearly proportional to heat release rate curve as shown in Figs. 1 and 2). This trend will be seen for the large size sample discussed later.

The above results are encouraging with regard to the goal of a reduction in peak heat release rate without using any halogenated-compounds. Furthermore, a significant reduction in peak heat release rate can be achieved with a relatively small quantity of siloxane, typically much less than 5%. The addition of such a small quantity of the compounds to the polycarbonate assures that the addition does not significantly affect the physical properties of the polycarbonate compared to that with the addition of a generally large quantity of metal hydrates needed for effective flame retardancy. However, one must be careful not to jump to conclusions regarding the flame retardant performance of the siloxane-containing polycarbonate sample. Two further studies were conducted: one to determine the effects of the addition of the siloxane on flame spread characteristics and the other to determine the effects of the sample size on flame retardant performance. As discussed above, the piloted ignition delay time for the siloxane-containing polycarbonate sample becomes less than that for the original polycarbonate sample at the same external radiant flux due to the former sample becoming less thermally stable. Since the process of flame spread can be considered as successive piloted ignitions, it is important to examine the effects on flame spread characteristics of the addition of siloxane to polycarbonate. In order to conduct the above two studies, a relatively large size sample was needed. Since such a large sample with the siloxane-containing compounds was available only as a copolymer,

a relatively high content of the siloxane-polycarbonate copolymer sample (about 4.2 wt%) was used for the next two studies.

## FLAME SPREAD

The HIFT (horizontal ignition and flame spread test) device was used to measure flame spread characteristics.\* The sample size was about 15 cm width x 80 cm length x 0.3 cm thickness for this experiment. The sample was preheated for 180 s and then a small pilot flame was rapidly inserted about 7 cm above the one end of the sample surface where the external flux was highest, at 40 kW/m<sup>2</sup>. The history of the flame front position for the two samples is shown in Fig.8 (Two tests were repeated for each sample). Time zero in the figure corresponds to the initiation of the preheating. The external flux initially decreases rapidly from 40 kW/m<sup>2</sup> with the movement of the flame front position and it decreases more slowly beyond 300 mm. The results show more rapid flame spread shortly after ignition for the polycarbonate-siloxane copolymer sample than for the pure polycarbonate sample. Beyond 400 mm, there is no significant difference between the two samples, which might be caused by a reduction in the external flux for the polycarbonate-siloxane copolymer sample due to a partial blockage of external radiation from the panel surface to the unburned sample surface by the large, intumesced char mound, shaped like a loaf of a bread. It is important to point out that the intumesced char mound was formed behind the flame front and its top nearly reached the panel surface. However, there was no loaf-shaped char mound for the pure polycarbonate sample. Its char was localized, small ragged/curled shape, scattered over the insulation board surface and its height was less than 5 cm. Also, the char was formed behind the flame front. Therefore, the char does not prevent or even slow down flame spread and does not have any significant effects on the flame spread process for both polycarbonate samples (apart from the possible shadowing of the panel, just mentioned), with and without siloxane. Furthermore, the chars formed from the two samples continued to burn during the test.

When flame spread over a polyetherimide sample was measured, char was formed before ignition and also before the arrival of the flame front. Furthermore, the char appeared to be very resistive to burning and only small, localized, scattered flames were observed over the surface exposed to high external fluxes. Heat release rate (peak heat release rate was 120 kW/m<sup>2</sup> measured in the "WG" configuration) and mass loss (about 30%) for the polyetherimide sample were much less than those of the polycarbonate sample. Since the principal difference in the chemical structure between the two polymers is a carbonate link vs an imide link, the nature of the imide link appears to control the structure and thermal stability of the char formed. A more detailed analysis of the residual char is needed to understand how char is formed for the two different polymers. Such information would be quite important for use as a guideline to improve fire performance of polymeric materials to form more and better fire resistant char.

## RESULTS MEASURED IN A FURNITURE CALORIMETER (LARGE SAMPLES)

When heat release rate is measured in the Cone Calorimeter, the sample size is about 10 cm x 10 cm. The height of the intumesced char mound was about 2 - 3 cm for the siloxane-polycarbonate sample. It appeared that this height might be determined by the sample size. Since the intumesced char height might be related to the heat insulation performance of the char, it is important to determine whether the above-observed flame retardancy of the siloxane-containing polycarbonate sample depends on the sample size or

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\* Since polycarbonate is a thermoplastic, it flows when it reaches its melt temperature range. If the conventional LIFT (lateral ignition and flame spread test) configuration is used, the polycarbonate sample melts down during the pre-heating period and meaningful data cannot be obtained. However, the HIFT configuration has one disadvantage compared to the LIFT configuration: there is an interaction of the sample flame and the gas panel so that the external flux from the panel changes during a test [4].

not. For this reason, larger burn tests were conducted using the NIST Furniture Calorimeter with a new electrically-heated radiant source which consists of two large panels as shown in Fig.9. Two different sample sizes were used; 40 cm x 40 cm and 61 cm x 61 cm. Since the estimated peak heat release rate for the pure polycarbonate sample was close to the maximum capability for the Furniture Calorimeter, only the smaller size was used. The polycarbonate-siloxane copolymer sample was used, due to the reason described above, instead of the siloxane-containing additive sample.

The comparison of heat release rate curves between the two samples is shown in Fig.10. Two tests were repeated for each sample. Although the ignition delay time for the pure polycarbonate samples was different between the two tests, the trend is very clear. Heat release rate of the polycarbonate-siloxane copolymer sample is much lower (about one third) than that for the pure polycarbonate sample; also the ignition delay time for the former sample is much less than that for the latter sample. These trends are consistent with those measured in the Cone Calorimeter. Therefore, the size of the sample does not significantly affect the flame retardant performance of the siloxane-containing polycarbonate sample. The only significant differences between the small sample and the large sample are in the total mass loss from the sample and also in the total heat release. Both samples lost about 90% of the initial weight for the large size experiment compared to about 70% for the small size experiment in the "NF" configuration. (The difference becomes much larger if the results measured in the "WB" configuration are used.) Correspondingly, total heat release per unit surface area for the larger sample is about 90 MJ/m<sup>2</sup> compared to about 60 MJ/m<sup>2</sup> for the smaller sample. The height of the intumesced char mound for the large siloxane-containing copolymer polycarbonate sample reached about 15 cm, but it continued to burn. The residual char after the test is quite porous and fragile. There was no char mound formed for the pure polycarbonate sample and its residual char was ragged/curled and scattered around.

Extinction area was calculated from the measured He-Ne laser beam transmission through the exhaust duct of the Furniture Calorimeter divided by the exhaust duct diameter multiplied by the exhaust volume flow rate. Thus, extinction area is related to the amount of particulates; higher extinction area means more mass of particulates. The comparison of the measured extinction area curve between the polycarbonate-siloxane copolymer sample and the pure polycarbonate sample is shown in Fig.11. The results show clearly that the peak extinction area for the polycarbonate-siloxane copolymer sample is roughly one sixth of that for the pure polycarbonate sample. This is mainly due to more vigorous burning of the pure polycarbonate sample and is not due to a reduction in soot yield because soot yield measured by the Cone Calorimeter is about the same for the two samples and also for the polycarbonate sample with the siloxane-containing additive sample, as shown in Fig.7.

As discussed above, two different siloxane-containing treatments were used for polycarbonate; one was as an additive and the other as a copolymer. Although the former sample was tested at 40 kW/m<sup>2</sup> and the latter sample at 30 kW/m<sup>2</sup> in the Cone Calorimeter and the Furniture Calorimeter, the results show very similar trends such as: much lower peak heat release rate, nearly same heat release and sample loss compared to the pure polycarbonate sample. The difference in flammability properties between the two treatments is not significant.

## DISCUSSION

Although the addition of siloxane significantly reduced peak heat release rate for polycarbonate, it is not clear how it is that siloxane affects heat release rate. It is particularly important to notice that the addition of siloxane not only slightly increases char yield and but also produces some physical differences in the char, as discussed above. Therefore, there might be chemical or physical differences or both in the char structure with and without siloxane in polycarbonate. In order to help discern such differences, elemental analysis of the char was conducted, as a first step. The char samples were generated at an external flux of

50 kW/m<sup>2</sup>, simulating flaming conditions under an external flux. The sample was heated in a nearly inert atmosphere of nitrogen (with 1 - 2% oxygen due to leaks in the system) using the second Cone Calorimeter at NIST. Samples were heated for 2, 4, and 6 minutes without any gas phase combustion and char was collected from different parts of the intumesced char mound. In this paper, B denotes the char collected from the bottom part of the mound just above the virgin polymer, T is from the top part and BT is from the middle part. The collected char was well ground using a ceramic mortar and pestle and fine-powdered char samples were sent to a commercial analytical laboratory for the elemental analysis. The preliminary results are shown in Fig.12 for pure polycarbonate and Fig.13 for the polycarbonate-siloxane copolymer samples. In these figures, normalized C/H is calculated from the carbon weight percentage divided by hydrogen weight percentage and normalized by the C/H value of the original sample; normalized C/O is calculated from carbon weight percentage divided by oxygen weight percentage and normalized by the C/O value of the original sample. The calculated ratios of the number of carbon atoms to the number of hydrogen atoms and of the number of carbon atoms to the number of oxygen atoms for the original polycarbonate are 1.21 and 5.38 obtained by accounting for the degree of polymerization and for the two end groups at the polymer chain ends. These values are reasonably close to the measured results of 1.1 and 5.5.

The results in Figs.12 and 13 show that oxygen is lost from the sample faster than carbon and hydrogen. This indicates that carbonate in the polycarbonate structure is lost at the fastest rate and is probably followed by the two methyls in the bisphenol. The relatively high amount of hydrogen after 6 minutes exposure time at the top part of char mound implies that hydrogens in the rings are not lost. This is confirmed by the ratio of the number of carbon atoms to the number of hydrogen atoms in the char is roughly two to one which implies the structure of C<sub>8</sub>H<sub>4</sub> which is a ring at backbone locations of polymer chains. The high number for normalized C/O indicates that there is only one oxygen for every 23 carbons in the char after 6 minutes exposure. Since there are not enough data for comparison between the results for polycarbonate and the copolymer sample, at present it is not clear whether the addition of siloxane causes significant difference in the chemical structure of the char. However, the preliminary results indicate that the rate of loss of silicon from the sample tends to be slower than total mass loss rate for the sample (normalized silicon weight percentage is larger than that in Fig.13). More silicon tends to stay in the sample but it is not clear as to what form is. Further continuation of the elemental analysis and more detailed analysis of the char are planned to find how siloxane reduces heat release rate.

## SUMMARY

The above results show that the peak heat release rate of the siloxane-containing polycarbonate sample is significantly reduced (less than half) from that for the pure polycarbonate sample. However, total heat release per unit surface area is about the same for both samples. In addition, piloted ignition delay time for the siloxane-containing polycarbonate sample is much shorter than that for the pure polycarbonate sample and the flame spread rate under an external radiant flux for the siloxane-containing sample is higher than that for the pure polycarbonate sample. This is caused by the reduction in thermal stability for the siloxane-containing sample.

Overall, the siloxane-containing sample appears to generate char at an early stage and also to create a thicker intumesced char layer. However, the formation rate of char is still not fast enough to interfere in the flame spread process. Although a thick intumesced char layer is formed for the siloxane-containing sample, the char appears to be relatively easily combustible and does not have strong flame resistance like the char from polyetherimide.

## ACKNOWLEDGEMENT

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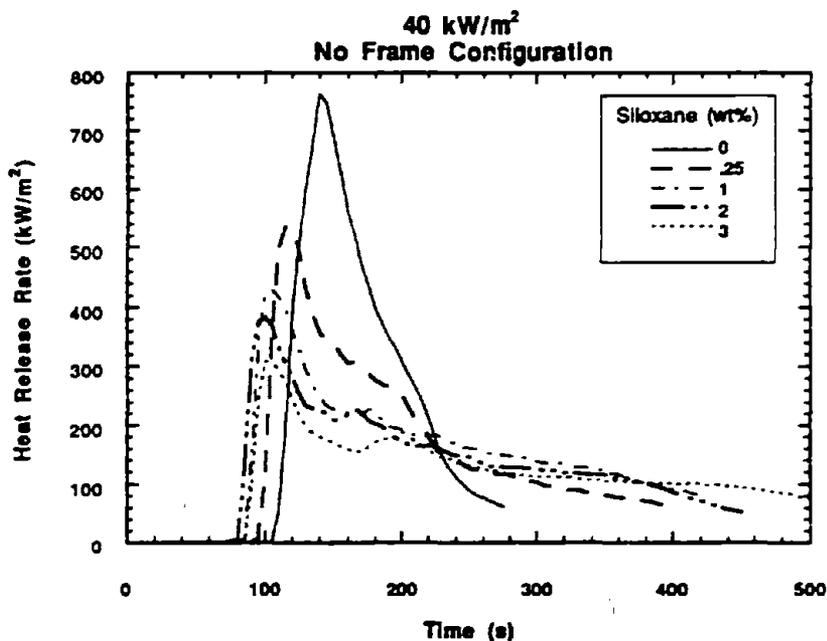


Figure 1. The effects of amount of siloxane on heat release rate curve of polycarbonate measured in the no frame configuration at external radiant flux of 40 kW/m<sup>2</sup>.

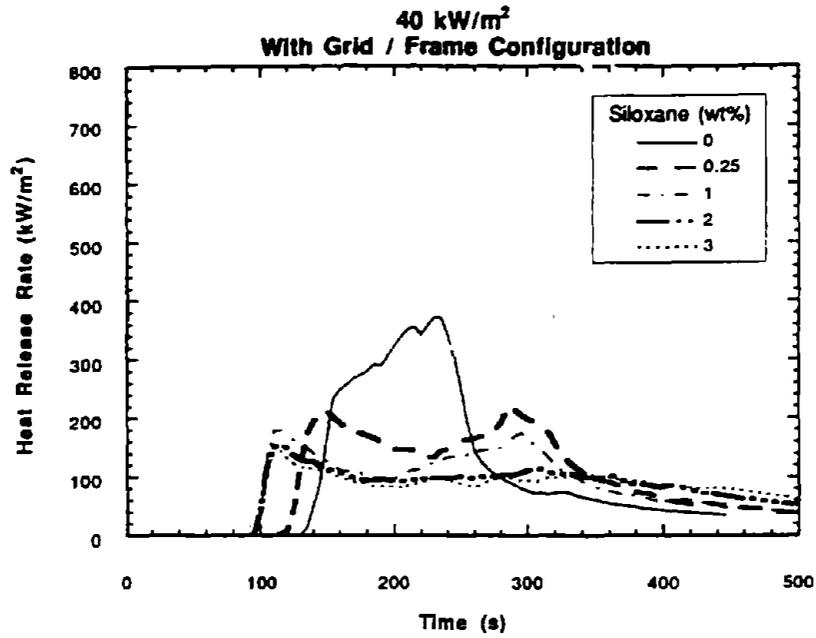


Figure 2. The effects of amount of siloxane on heat release rate of polycarbonate in the frame/grid configuration at external radiant flux of 40 kW/m<sup>2</sup>.

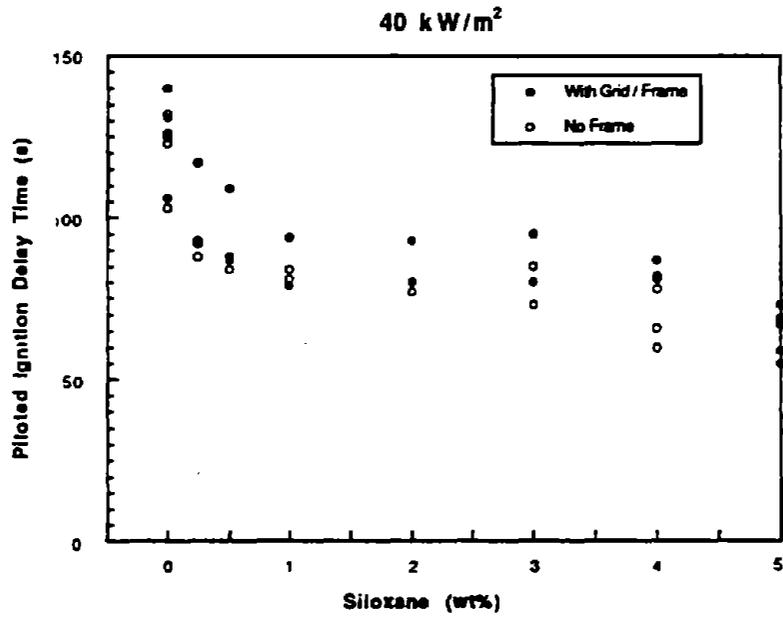


Figure 3. The effects of amount of siloxane on piloted ignition delay time of polycarbonate at external radiant flux 40 kW/m<sup>2</sup>.

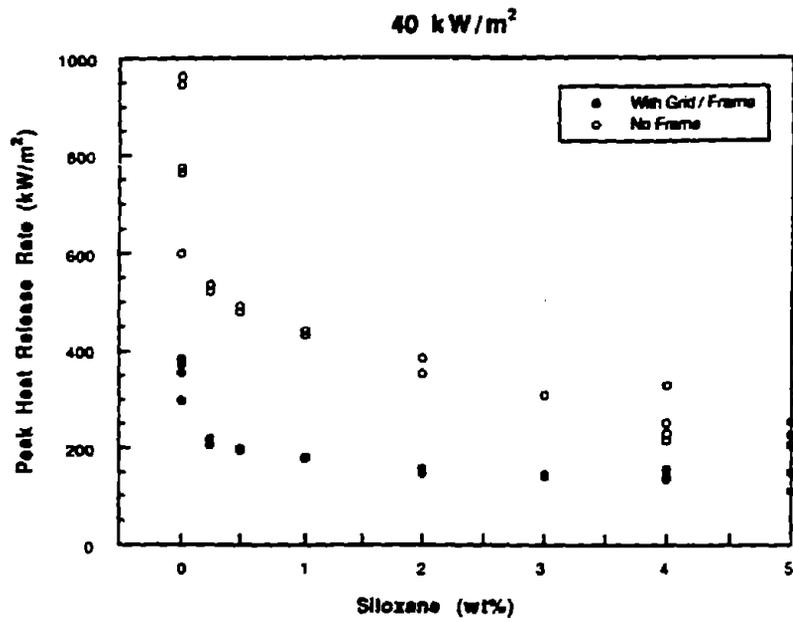


Figure 4. The effects of amount of siloxane on peak heat release rate of polycarbonate at external radiant flux of 40 kW/m<sup>2</sup>.

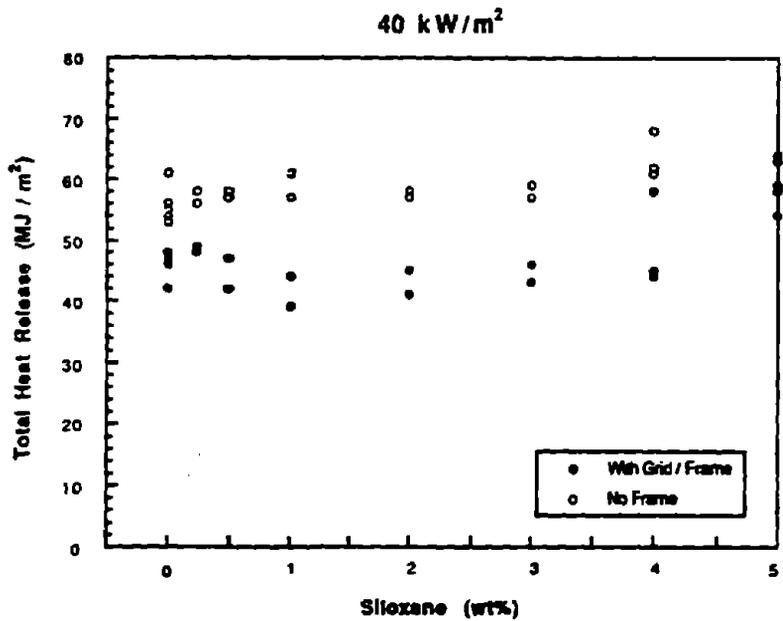


Figure 5. The effects of amount of siloxane on total heat release of polycarbonate at external radiant flux 40 kW/m<sup>2</sup>.

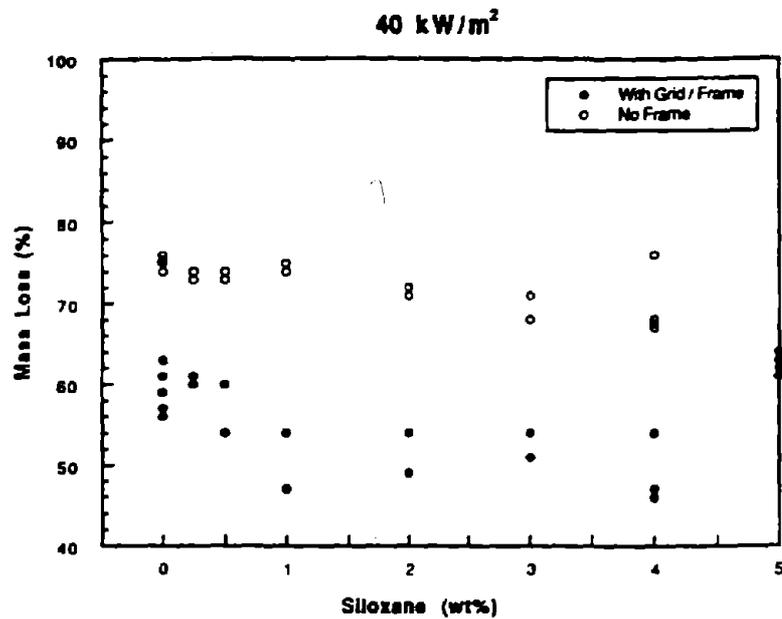


Figure 6. The effects of amount of siloxane on total mass loss of polycarbonate at external radiant flux of 40 kW/m<sup>2</sup>.

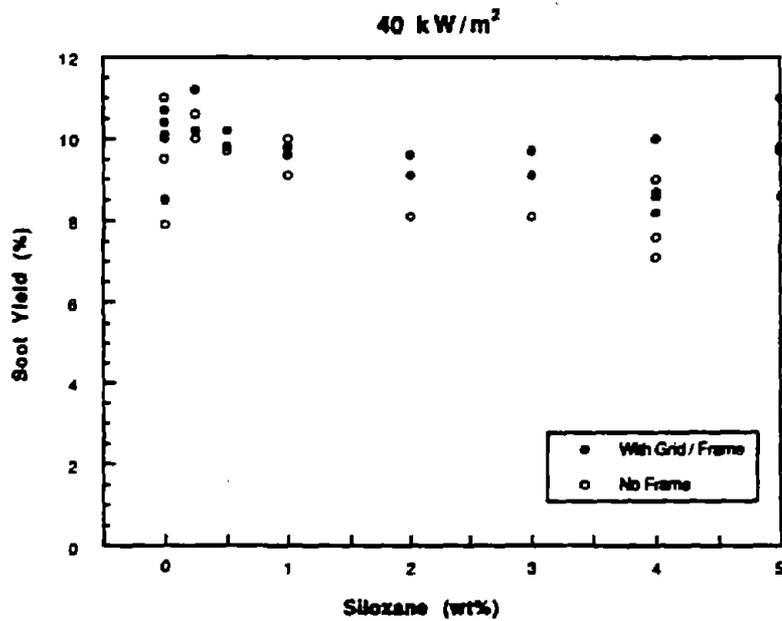


Figure 7. The effects of amount of siloxane on soot yield of polycarbonate at external radiant flux 40 kW/m<sup>2</sup>.

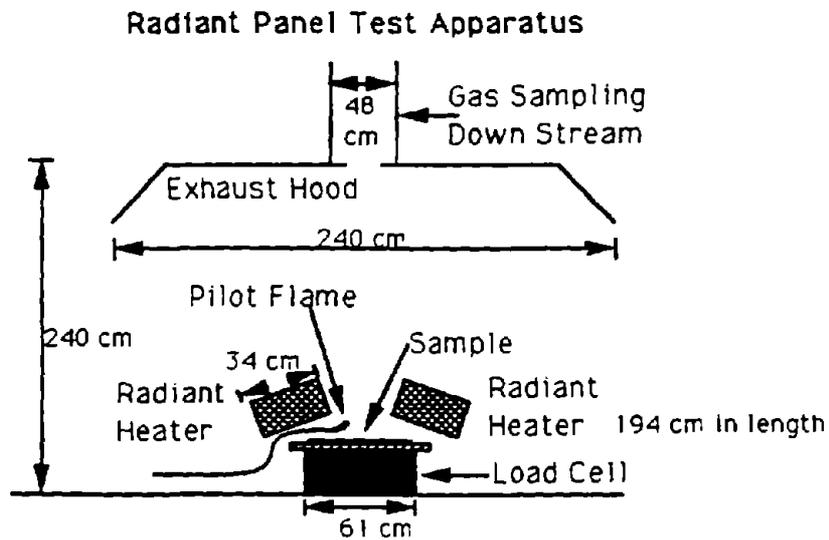


Figure 8. Schematic illustration of the large radiant panel test apparatus.

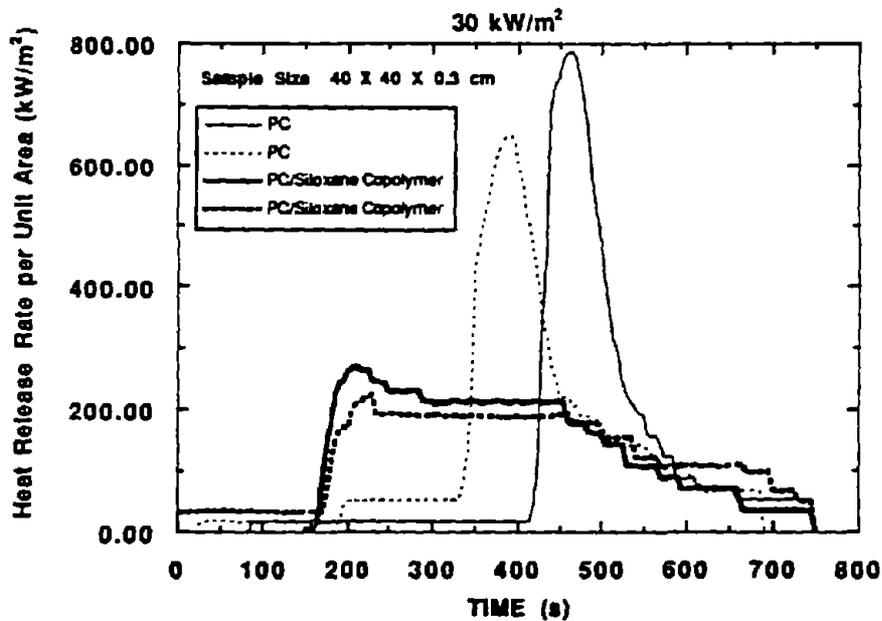


Figure 9. Comparison of heat release rate curve between the two large sample sizes at external radiant flux of 30 kW/m<sup>2</sup> (two repeated tests for each sample).

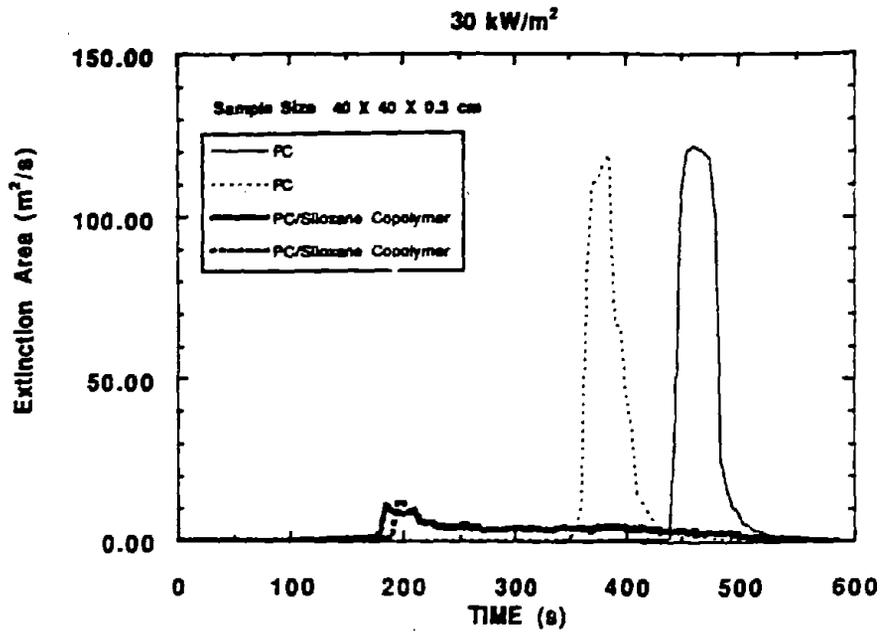


Figure 10. Comparison of extinction area between the two large size samples at external radiant flux of 30 kW/m<sup>2</sup> (two repeated tests for each sample).

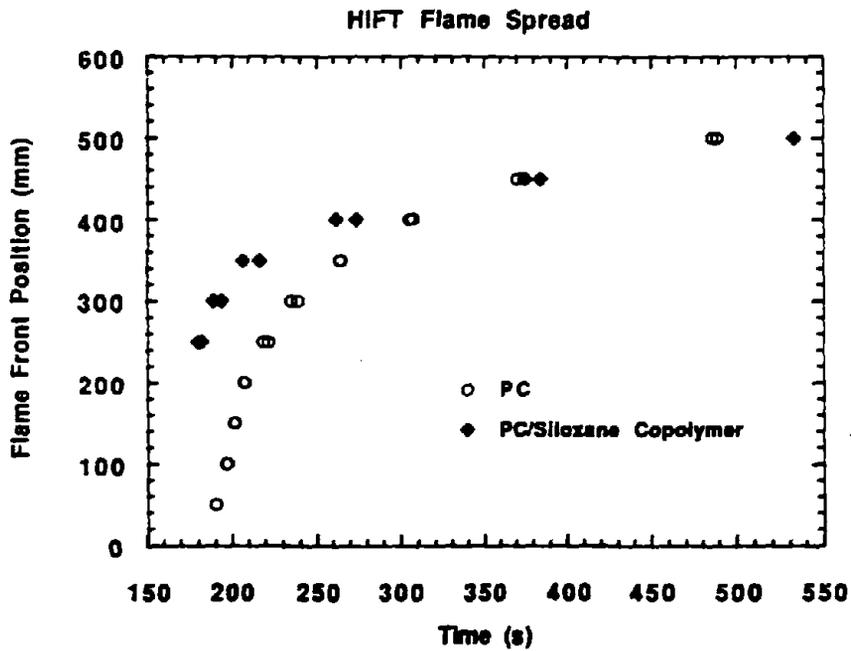


Figure 11. Comparison of history of flame front position between the pure polycarbonate sample and the polycarbonate-siloxane copolymer (two repeated tests for each sample).

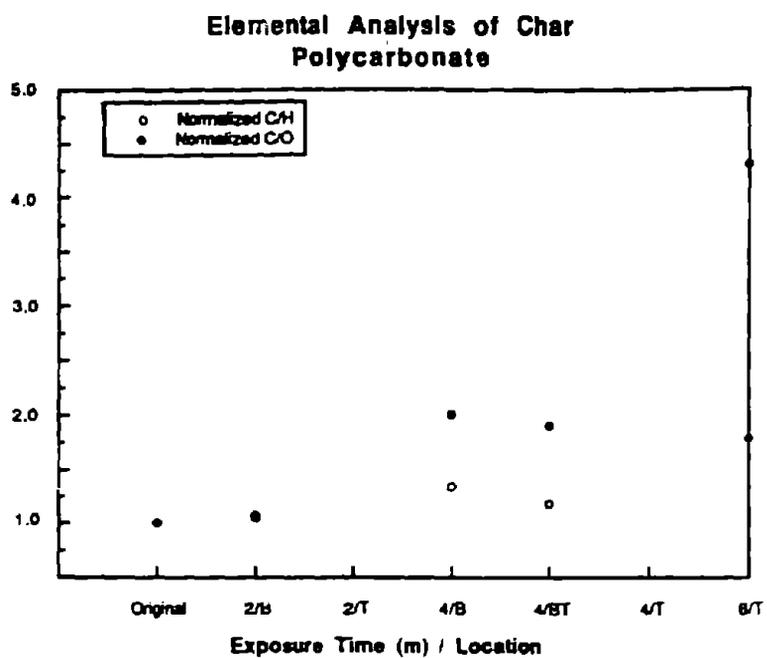


Figure 12. The effect of exposure time/location on normalized C/H ratio and normalized C/O ratio in char from pure polycarbonate.

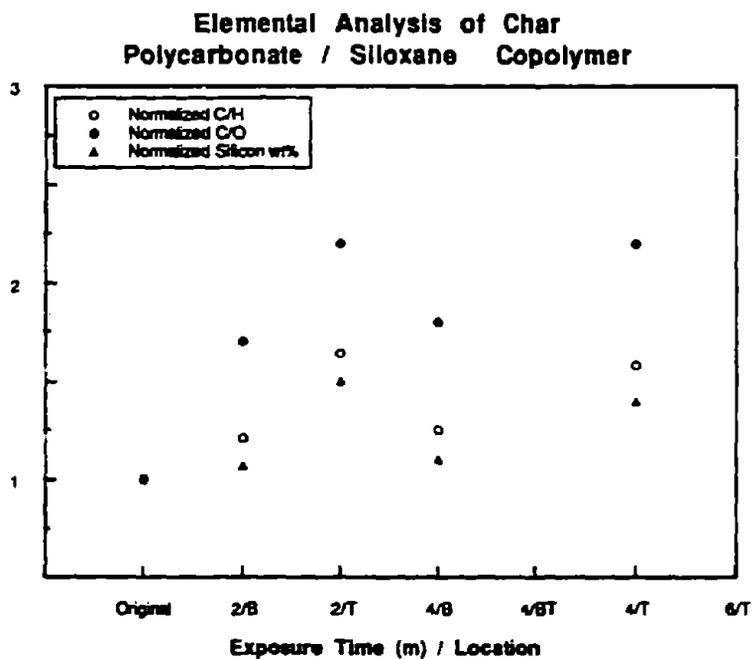


Figure 13. The effect of exposure time/location on normalized C/H , and C/O ratio and normalized silicon weight percentage in char from the polycarbonate-siloxane copolymer.



**SESSION III**  
**TEST METHODS AND MODELING**

Wednesday, February 10, 1993

Session Chairman  
**Dr. Jack Snell**  
National Institute of Standards and Technology (NIST)

*JES 1/8*



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**AN INVESTIGATION INTO AIRCRAFT FUSELAGE FIRE HARDENING**

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**ABSTRACT**

The paper outlines the current investigation into the development of a new test facility which can reproduce in a controlled manner the fire conditions that would be experienced by an aircraft fuselage following a fuel spillage incident.

The early investigation work has led to the definition of a fire source based upon previous test work in the aircraft industry and industrial pool fires in general. This definition was then used to design a test facility which has been built and commissioned. It can create a reproducible thermal insult of up to 1150°C and 210 Kw/m<sup>2</sup>.

The commissioning programme is now complete however one particular aspect proved to be of great interest. That is the increased burnthrough rate due to soot deposition during the first few seconds of a pool fire.

This phenomena will prove to be very critical as the ultimate aim of the project is to enhance the burnthrough capabilities of aircraft fuselages.

The programme will look at the determination of burnthrough times of existing fuselages before moving onto investigating the burnthrough capabilities of both improved materials and systems.

**INTRODUCTION**

The request to investigate fuselage fire hardening had been made by the United Kingdom Civil Aviation Authority (CAA) as part of its on-going research to identify methods of improving the fire resistance of civil aircraft.

Experience from both accidents and full scale tests have shown that, for a typical aircraft fuselage, that it could be fire hardened to possibly delay the penetration of an external fire into the passenger compartment. In the Manchester air crash the Accident Investigation Board report speculated that the burnthrough occurred within 60 seconds of the aircraft coming to a stop. If the mechanical integrity of the fuselage could be prolonged, then the passengers would have an increased level of protection from high temperatures, limited oxygen supply and toxic combustion products, thereby increasing the time available for the passengers to escape.

## DEFINITION OF FIRE SOURCE

### Literature Survey

The definition of the fire source was based upon analysis of previous published test work. The brevity of the programme and the difficulty of identifying the exact specification of a post-crash fire from the resulting wreckage led us to concentrating primarily on previous test work.

The resultant literature survey assisted by the CAA and the FAA produced 26 articles (ref 1 to 26) that related to the fire testing of aircraft or hydrocarbon pool fires. This literature could be further sub-divided into the following groups:

- (i) Full-scale pool tests on full aircraft
- (ii) Full-scale pool tests on aircraft sections
- (iii) Small-scale kerosene burner tests on small sections
- (iv) Pool fires of defined sizes engulfing simulated test equipment eg rail cars
- (v) General pool fire data

### Analysis Of Previous Experimental Data

The aim of analysing the experimental data was to collate information to assist in the definition of an external heat source. Reviewing the data also produced a number of conclusions that are relevant to the designing and operation of a standardised fire testing facility.

Details of the various aspects analysed are given below.

### Variability

The major difficulty to emerge from test work carried out using pool fires is the chaotic nature of the burning process. In any test there are always large variations with time of both temperature and heat flux measurements. There will also be additional variations between tests which can be due to geometric and atmospheric differences, for example the local wind speed and its direction with respect to the test article.

### Timescales

The aspects that we considered important when considering the fire hardening of an aircraft fuselage or indeed any structure are:

- i) rise time - the time for a pool fire to reach a defined temperature or heat flux
- ii) the time period over which the defined temperature or heat flux is maintained
- iii) the duration of the test sequence

### Rise Time

Pool fire test work is generally conducted over long time scales, typically 30 minutes or longer. Whereas the test work simulating aircraft fires has typically been conducted for periods of less than 5 minutes. Ref 16 indicates that flame propagation is approximately 10 seconds before any significant flame temperatures are reached. The fire then takes a further 10 seconds before temperatures are indistinguishable from a fully developed fire. In Ref 14, their analysis has resulted in taking a delay of 13 seconds into account where nothing happens until a step-change to a fully developed fire condition occurs.

It is therefore important to achieve a representative output from the proposed test configuration in which full temperatures and heat fluxes are available within a short time period of the test beginning. As burnthrough times of aluminium fuselage skins have been measured at 30 to 60 seconds in a fully developed fire Ref 21, 22 and 23.

### Test Duration

The test duration can be governed by several factors. The higher temperature tests would tend to last for the shortest periods as they would be more likely to affect a burnthrough in a relatively short period of say 30 to 60 seconds. Whereas at the other extent, lower temperatures from fires at a greater distance from the test article would not cause burnthrough for longer periods when smoke emission or cabin temperature may be the deciding factor.

### Temperature

As previously commented there is a large variability of temperature and heat fluxes during a pool fire. There will be periods when the aircraft skin is totally engulfed and at others when the flames are absent which results in the surface losing heat. Work conducted in Ref 13 and 17, included a statistical analysis of measured temperatures. They found there to be a bi-modal probability density function. The lower mode being at lower temperatures corresponding with data when there were strong wind effects. The other mode at higher temperatures corresponding to the case where the instrumentation was fully engulfed with flames.

The periods which the flames are present are typically in excess of 3 minutes, during which time the temperatures are higher than the overall average. This implies that for pool fires of less than 3 minutes, the flame profile could be one of many, and the temperature measured at a station could correspond to the higher or lower mode.

We therefore concluded that the higher measured temperatures and heat fluxes reported in the test work should be used as the basis for defining test conditions.

Table 1 shows a summary of the measured maximum flame temperatures from a range of JP4 and JP5 liquid pool fires. The results as expected show a wide variation. The datum we set for defining the representative pool fire temperature was 1120°C, the average of the maximum temperatures.

#### Heat Flux

The analysed heat fluxes demonstrated a large variation. This variation was especially marked in the cases where the heat flux had been calculated from thermocouple derived temperatures. The reason being that the temperatures demonstrated large fluctuations.

The heat transfer to a surface engulfed in a large optically thick pool fire is made up of the radiative and convective components. Since the net heat flux received is dependent upon the temperature of the receiving surface as well as the flame temperature. It is the usual practice to correct the net heat flux values to a constant cold wall temperature (this is not quoted in the reviewed literature). The average of the maximum quoted heat fluxes in Table 1 is 158 Kw/m<sup>2</sup>.

This representative value of total heat flux corresponds to the case when flames are covering and engulfing a fuselage surface. It falls within the bounds we would anticipate from other large industrial pool fires we have analysed, including power generation, offshore, chemical and mass transit.

#### Radiative Heat Flux

Attempts at separating the radiative and convective components of heat flux (Reference 2 and 13) indicate as anticipated that radiation is by far the largest part, being on average 80 - 90% of the total flux in a large pool fire.

### Convective Heat Flux

Convective heating in a large pool fire is due to gas movements over the cooler surface and is dependent upon gas properties and gas velocity. There is a wide reported range of results from pool fires though this is in part due to wind gusting. Tests conducted by the FAA technical centre on narrow bodied aircraft in their in-door facility have shown a plume velocity of approximately 2 M/S.

Given the relatively low proportion of heat fluxes due to convection (10 - 20%) we decided to base the gas velocity upon a nominal 2 M/S.

### Definition Of The Heat Source

The review of the previous experimental work has demonstrated a wide range of results. The selection of a representative fire is difficult though as expected from previous Darchem Engineering work the data tends towards an upper ceiling value for a hydrocarbon pool fire in terms of temperature and heat flux.

Taking this into consideration, the proposed upper values to represent the external heat source are the averages of the highest temperatures and fluxes derived from the previous test work.

The values decided upon are:

Temperature	1120°C
Heat Flux	160 Kw/m <sup>2</sup>
Gas Velocity	2 M/S
Rise Time	Instantaneous
Test Duration	5 Minutes

The definition of a lower bound for the heat source parameters is also of importance as it will assist in the design of the test facility in terms of the required furnace turn-down rates.

The test duration was based on the consideration that in the majority of survivable accidents occurring on airfields, the fire fighting would have normally commenced within 5 minutes during which time the passengers capable of self-evacuation would have left the aircraft. Whilst the lower temperature is based upon a typical aluminium melting temperature of 650°C.

Therefore the lower bound parameters are:

Temperature	650°C
Heat Flux	42 Kw/m <sup>2</sup>
Rise Time	Instantaneous
Test Duration	5 Minutes

## DESIGN OF FACILITY

After considering the previous test data and based upon our previous testing experience it was decided that the best method of producing a controlled and repeatable heat source was to design and build a dedicated gas fired test unit. The photograph (in Figure 1) demonstrates the basic system which consists of a mild steel box (2.0M x 2.0M x 1.5M internally) lined with ceramic fibre and powered by four 300 Kw propane burners. The burners fire tangentially into the furnace to ensure that energy is transferred efficiently to the furnace wall.

The floor of the furnace is brick-lined to provide a suitable thermal inertia to compensate for heat loss when the furnace lid is pulled back. The sample is supported over the sliding lid in the roof section. When the furnace is heated up to temperature and sealed, the insulated lid is then rolled back and the furnace presents an instantaneous thermal input to the test piece which is then maintained for the duration of the test. The results show that this method of storing energy and then releasing it provides the rise in a repeatable form (Figures 2 and 3).

## COMMISSIONING

Prior to the commissioning we had agreed at the request of the CAA to work with the FAA who were planning to embark upon a programme of full-scale burnthrough trials. Before they started this work they kindly offered to conduct a small series of full-scale burnthrough tests of 6061 aluminium at 3 thicknesses to provide a benchmark for our test work.

These trials produced burnthrough times of less than one minute for typical flame/age thicknesses, though the early results available from these pool fires demonstrated wide fluctuations in the heat flux and temperature values associated with pool fires.

The results produced during the commissioning trials have shown (Figures 2 and 3) that temperatures, heat fluxes and gas velocities can be produced both instantaneously and repeatable between the upper and lower ranges set during the first phase of this test programme. These values can be maintained for the full 5 minute duration of the test with the maximum deviation of results being 10%.

This figure is acceptable when compared to the deviations reported during previous test work which would fluctuate by up to 80% from the nominal value.

In the planning phase of the work, a limited number of sample burnthrough's were initially programmed however several were subsequently tested.

During the commissioning one feature of the samples tested appeared to be puzzling. In our test facility both measured temperatures and heat fluxes were higher than the FAA testing and the test pieces were lasting 2 to 3 times longer than the panels tested by the FAA. After re-checking our system we realised that although the sample started off with a low surface emittance of 0.1 to 0.15 it must rapidly scot in the first few seconds of the fire and hence increase its surface emittance. In conventional pool fire testing the test pieces are destroyed before the test ends so the level of sooting can not be determined.

The CAA agreed to further fund a small series of tests to look at soot deposition. The test consisted of a pool fire burning in a metal tray and then being rapidly extinguished by dropping a lid onto the fire.

Table 2 : Soot thickness during the early stages of a small pool fire

Time after Fire Start (sec)	0	5	10	15	20	25	30
Average Soot Thickness (mm)	0.00	0.01	0.011	0.015	0.016	0.026	0.026

Results showed that within 30 seconds of the fire developing up to 0.03 mm of soot had been deposited onto the surface of the sample (Table 2). By use of a thermal imaging camera we also determined that the surface emittance had increased from 0.10 to 0.45 in 30 seconds (Table 3).

Table 3 : Surface emittance during the early stages of a small pool fire

Time after Fire Start (sec)	0	5	10	15	20	25	30
Emittance	0.10	0.11	0.13	0.28	0.30	0.36	0.45

Armed with this information we sooted up a sample of 6061 aluminium and compared this with a clean 6061 sample.

The burnthrough time had dropped from 66 seconds to 8 seconds (Figure 4).

So besides the pool fire protecting fluctuating thermal values the transfer of this energy is dependent upon the variability of the soot deposition thickness. This phenomena does not appear to have been studied as most industrial fire protection systems have a performance life of 1, 2 or 4 hours and therefore the time to achieve a high surface emittance is relatively small. However in the case of aircraft fuselage burnthrough the time to achieve a high surface emittance can be a large proportion of the burnthrough time.

After discussions, we have concluded that it would be best to investigate this phenomena before proceeding onto the later phases of the test programme.

#### FUTURE WORK

##### Short Term Future Work

When the effect of soot deposition is fully understood we will then pass on to investigating the burnthrough of existing fuselages including typical features such as skin thickness, joint finish, insulation systems, stiffeners, 'doublets', rivet details etc.

##### Medium Term Future Work

When the investigation into the burnthrough of existing fuselages is complete it is anticipated that we will move on to investigate new materials or developments. We are currently in discussion with several manufacturers who are keen to invade their materials in the test programme.

It is proposed that as part of the agreed complementary collaboration with the FAA, promising candidate techniques and materials will be tested full-scale by the FAA. If significant improvements to cabin safety are perceived and good correlation between the test facility and full-scale testing has been shown, then requirement action and the adoption of the test facility as a certification tool may be considered.

#### **SUMMARY**

The analysis of previous test work (aerospace and general fire engineering) led us to identifying a typical pool fire as having of a flame temperature of 1120°C and a heat flux of 160 Kw/m<sup>2</sup>.

The gas fired test facility designed to reproduce the representative fire source is capable of producing temperatures of up to 1150°C and heat fluxes of 210 Kw/m<sup>2</sup>. The measured values are within  $\pm 10\%$  of the nominal values which compares extremely favourably with the expected variations in a pool fire.

Fuselage burnthrough times have been shown to be very dependent upon the soot deposited in the early stage of a fire.

This investigation will now move onto study in depth the burnthrough of typical aircraft fuselage sections before assessing improved fire-hardening designs.

#### **ACKNOWLEDGEMENTS**

The work was performed by Faverdale Technology Centre Ltd, a company within Darchem Engineering Ltd. The work is sponsored by the UK Civil Aviation Authority under contract 7D/S/922.

We would also like to thank the FAA Technical Centre for their co-operation and assistance throughout the project.

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SOURCE	REF NO	POOL SIZE	TEMP °C		HEAT FLUX KW/M <sup>2</sup>				COMMENTS
			MAX	AV	MAX		AV		
					TOTAL	RADIAT	TOTAL	RADIAT	
Nakos & Kaltner	2	9m x 18m	1100	-	180	-	132	117	Values vary with measurement position and calorimeter size
Heltner & Kent	5	3m x 3m	1000 - 1250	-	130	-	-	-	
Don W Conley	6	Variable	980	-	160	-	120	-	Full scale test
Kaltner & Moya	7	-	1050	-	-	-	150	-	Review article
RS Alger Et Al	11	.305 dia	-	-	125	-	115	-	
Don W Conley	12	Variable	-	-	-	216	-	120	Full scale range of tests
George B Oeyer	14	10m x 3m	1150	980	-	148	-	90	Full scale test
CP Sarkos	16	6m x 6m	1150	930	210	-	180	-	Full scale test
Gregory Et Al	17	9m x 18m	1170*	998	170	148	-	-	* Av of upper Bi-modal set of reading
Harry Webster Et Al	21	-	-	870 - 1150	-	-	57-260	-	Full scale tests
Hill, Johnson & Sarkos	22	Variable	-	-	170	-	-	-	Full scale tests
Schneider & Kent	13	9m x 18m	1111*	850	120	-	-	-	* Av of upper Bi-modal set of readings

Darchem  
Engineering  
Limited

DATA SUMMARY FROM PREVIOUS EXPERIMENTAL WORK TABLE 1

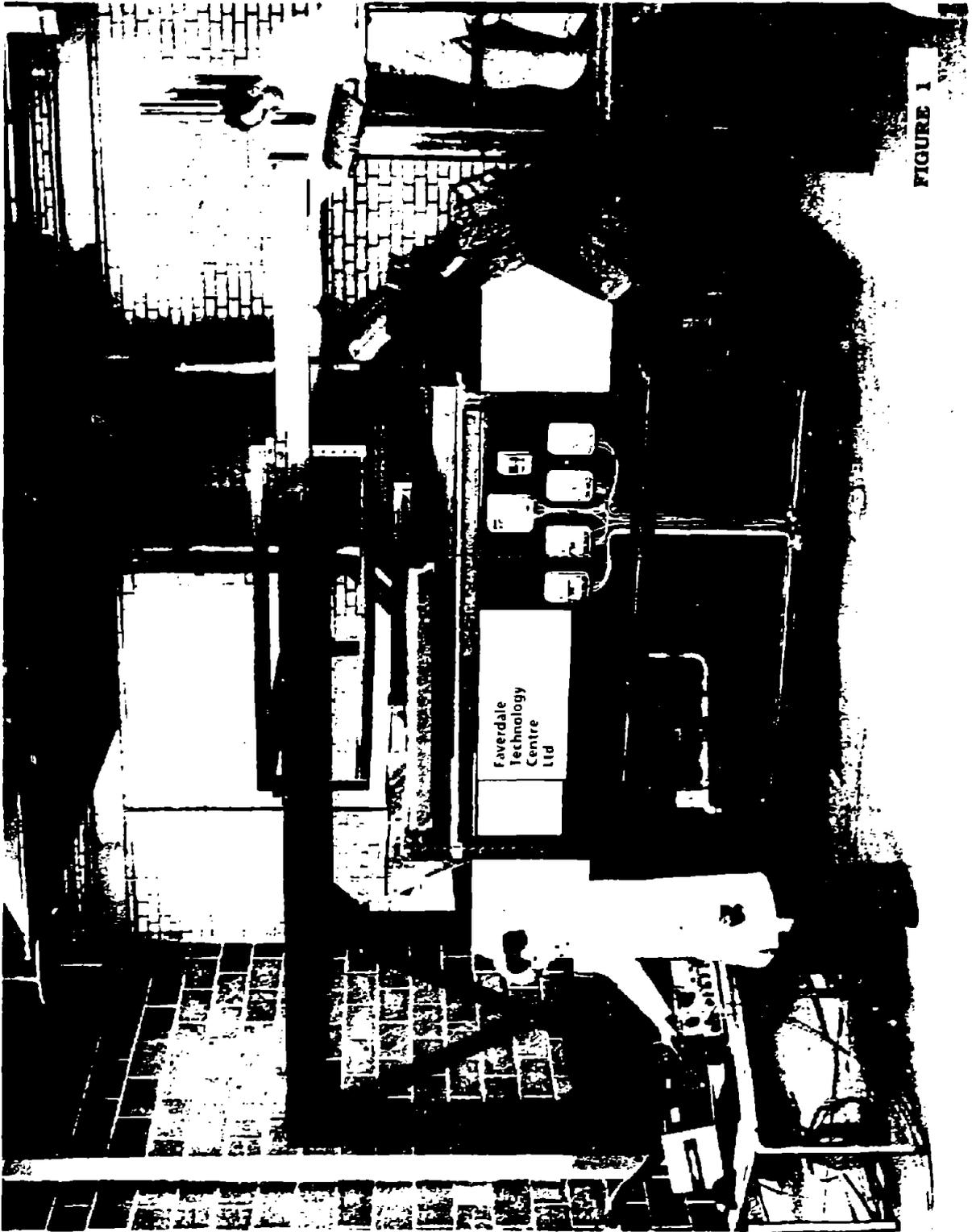


FIGURE 1

CAA Fuselage Fire Hardening  
Phase B Test 5 & 6

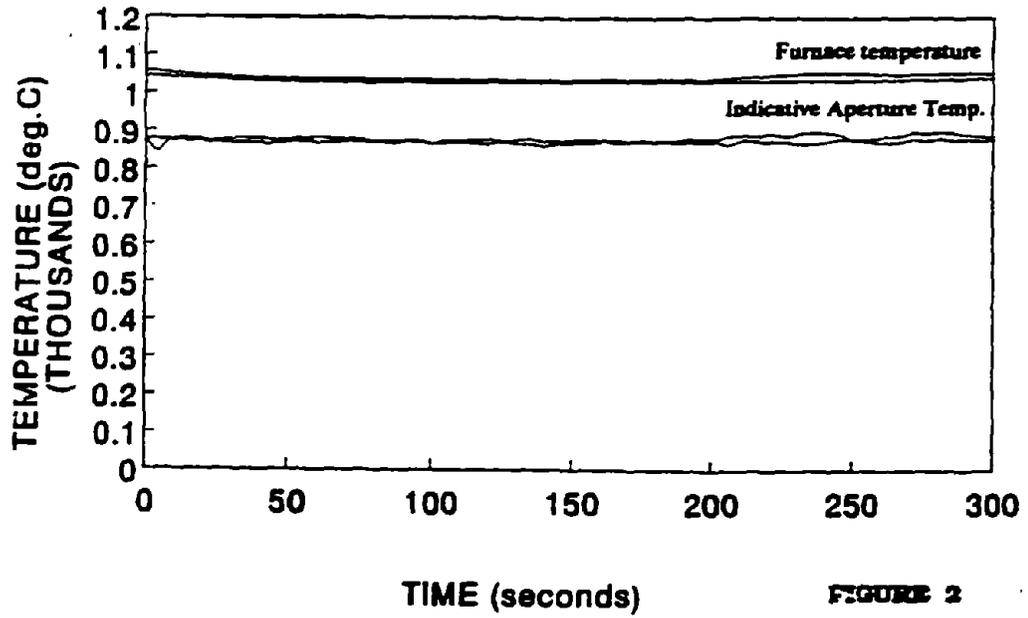


FIGURE 2

CAA Fuselage Fire Hardening  
Phase B Test 5 & 6

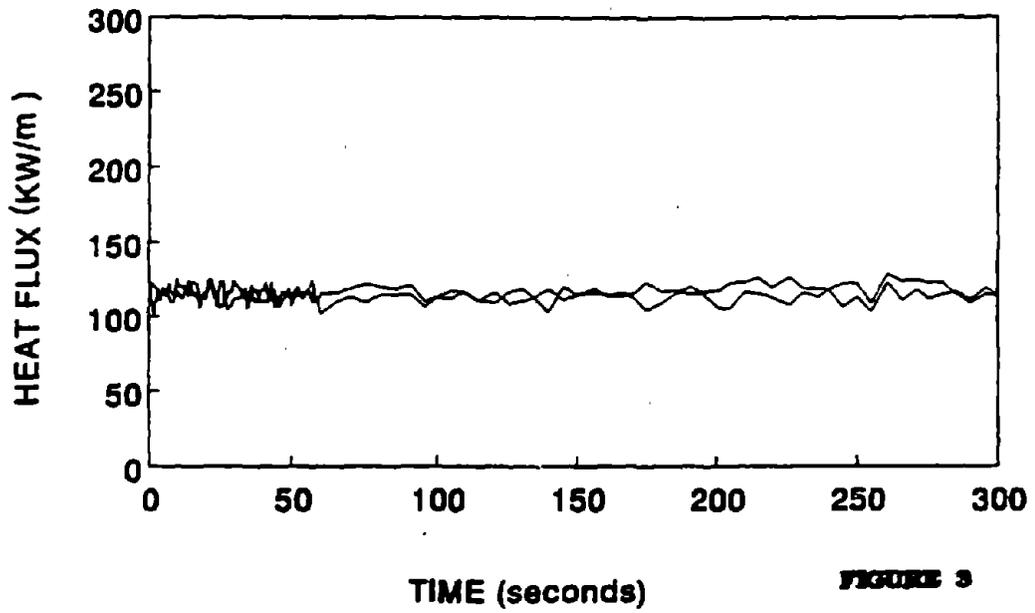


FIGURE 3

# FUSELAGE BURNTHROUGH

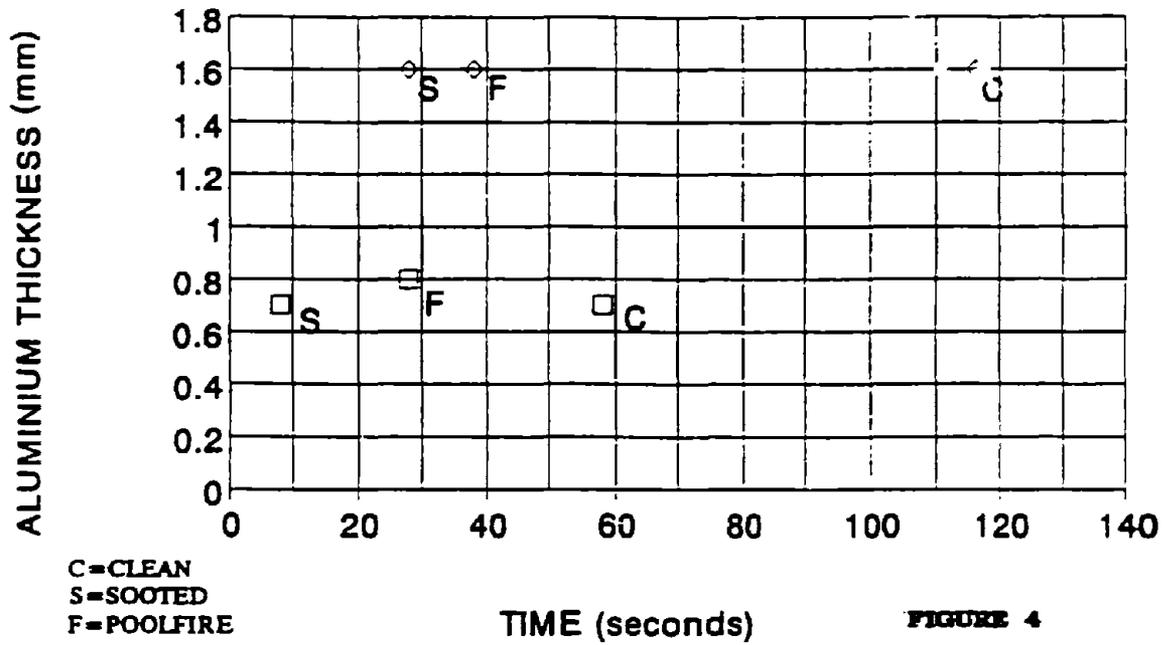


FIGURE 4



N94.

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7-25  
1000-3  
18

APPLICATIONS OF A MODEL TO PREDICT FLAME SPREAD OVER  
INTERIOR FINISH MATERIALS IN A COMPARTMENT

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ABSTRACT

Results from a mathematical model are investigated for fire growth on wall and ceiling combustible interior finish material in a compartment. A corner fire ignition source is maintained for 10 minutes at 100 kW and subsequently increased to 300 kW. For this scenario experimental results are available from the EURIFIC program, and are compared to the model. The time for the total rate of energy release rate to reach 1 MW is examined. In addition to the 11 EURIFIC materials, eight other materials are examined in this scenario by using the model. These materials represent the type of materials formerly and currently used as cabin interior finish materials in commercial aircraft. The model yields good results in most cases; in other cases, the model can be made to yield better agreement with the experimental results by making small changes in the property data. These changes are within the range of uncertainty of the property data.

INTRODUCTION

The purpose of this study is to investigate the accuracy of a mathematical model to predict the fire growth on combustible wall and ceiling interior finish materials in a compartment. The fire scenario is the room corner test as described in the Nordic standard NT Fire 025, or ISO DP 9705. This is similar to the "Proposed Method for Room Fire Test of Wall and Ceiling Materials and Assemblies" considered by ASTM. In the Nordic standard a square propane burner supplies fuel at the base of the corner with an energy release rate of 100 kW for 10 minutes. At 10 minutes, if the total energy release rate from the room does not exceed 1 MW, the burner fire is increased to 300 kW. Although other data are recorded, the principal criterion for the evaluation of the interior finish material is if or when the room energy release rate achieves 1 MW.

The mathematical model has been previously described (Quintiere, 1992), and compared to room corner test results for 13 materials tested in Sweden (Sunstrom, 1986). It was found in most cases that the model was reasonably accurate in predicting the outcome of the test to reach 1 MW. Other models have also been successful at predicting these test results. Wickstrom and Goransson (1992) have developed an empirical model, and Karlsson (1992) has developed a model similar to the model employed herein. The forerunner to the present model was also used successfully by Cleary and Quintiere (1991).

All of these models require material data from the Cone Calorimeter (ASTM E-1354-90, "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter"). Wickstrom and Goransson (1992) use data evaluated at an irradiance of 25 kW/m<sup>2</sup>, while Karlsson (1992) uses data at 50 kW/m<sup>2</sup>. The model by Cleary and Quintiere (1991)

obtained equally good results with Cone data selected at both 25 and 50 kW/m<sup>2</sup>. The current model attempts to be less arbitrary. It uses derived material property data from the Cone Calorimeter to calculate the needed information at the heat flux experienced by the material in the room-corner test. Also the current model and Karlsson's model require data from the LIFT apparatus (ASTM E1321-90, "Standard Method for Determining Material Ignition and Flame Spread Properties").

In the current study, the model will be compared to results from a cooperative program in the Nordic countries known as EURIFIC. In this program 11 widely different materials were tested in the room-corner test, and material data were derived from the Cone Calorimeter and the LIFT apparatuses.

In addition, the model was run for eight materials representative of past and current commercial aircraft cabin interior linings. Although full-scale post-crash cabin fire experiments exist for some of these materials, no room-corner tests are available. Hence, these results will only show the hypothetical performance of the aircraft materials relative to the Nordic studies.

#### SUMMARY OF MODEL

The model has been previously described by Quintiere (1992), and therefore will only be summarized here. The model simulates the ignition by the burner, flame spread, burn-out, and burning rate of wall and ceiling materials.

The flame pyrolysis and burn-out fronts are computed with respect to two modes of flame spread. One mode includes upward spread, spread along the ceiling, and spread along the wall-ceiling jet region. This is shown in Figure 1 where the dashed lines enclose the region of wind-aided flame spread due to the burner, and the ceiling jet.

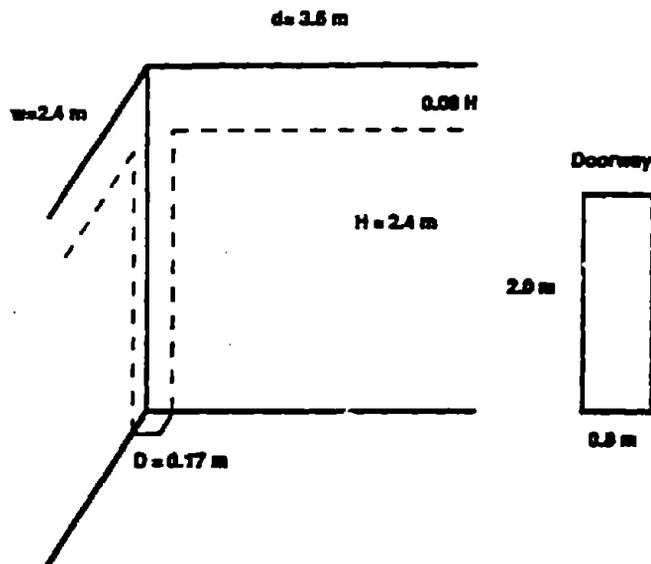


FIGURE 1. ROOM AND BURNER CONFIGURATION

At this time, no distinction for wall and ceiling wind-aided flame spread is made in the model and they are universally treated as governed by upward flame spread.

The second mode of spread is composed of lateral spread along the wall and subsequent downward spread from the ceiling jet. Again, the same relationship will be considered for both. In this fashion, the pyrolysis and burn-out areas are computed. An illustration of the pyrolysis ( $y_p$ ,  $x_p$ , and  $z_p$ ) and burn-out ( $y_b$  and  $x_b$ ) fronts is shown in Figure 2.

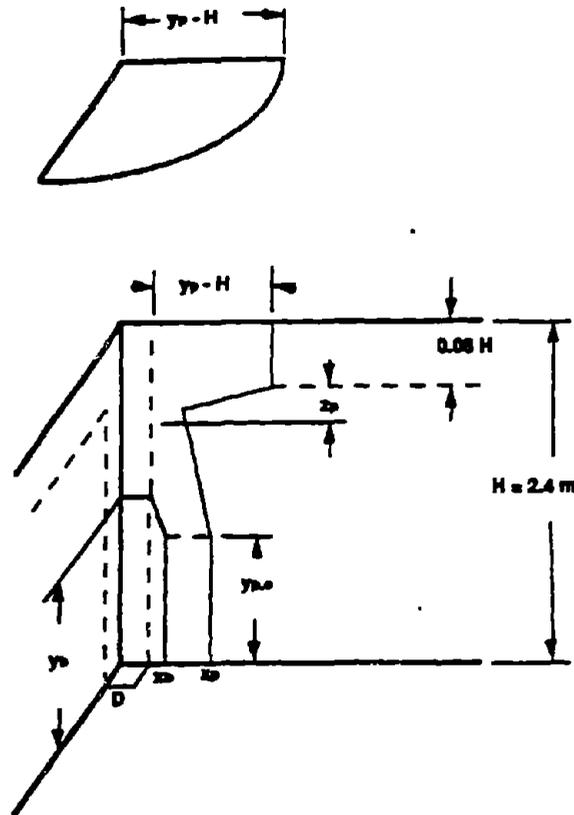


FIGURE 2. ILLUSTRATION OF PYROLYSIS AND BURN-OUT FRONTS

The energy release rate per unit area is computed from the net heat flux in the pyrolysis region. It is considered constant over the pyrolysis area which is computed from the front configuration as a function of time. The energy release rate per unit area is governed by both the flame heat flux and the radiative feedback from the heated room.

Flame heat flux is considered constant over the pyrolysis area, and constant over the extended flame length. Two values are selected: 60 kW/m<sup>2</sup> over the pyrolysis area and for the square burner corner ignition flame which governs burning rate and ignition, respectively; and 30 kW/m<sup>2</sup> for the extended flame region beyond the pyrolysis region which governs upward flame spread.

The room thermal feedback controls both the rate of spread through a computation of the material surface temperature ahead of the flame, and the rate of energy release per unit area through radiative heat transfer from the gas layer in the room. Global models are considered for average room surface and gas layer temperatures. The radiative effects are considered to be maximized to give an upper limit for its effect.

The details for each component of the analysis is summarized below. The symbols are completely defined in the NOMENCLATURE.

### Ignition by the Burner Flame

The time for ignition is computed when the propane burner flame heats the wall material to its ignition temperature, i. e. when  $T_{s,o} = T_{ig}$ . The surface temperature is given by

$$T_{s,o} - T_{\infty} = \frac{1}{\sqrt{\pi k \rho c}} \int_0^t \frac{q(\tau)}{\sqrt{t-\tau}} d\tau \quad (1)$$

where  $q(\tau) = \dot{q}_{ig} + \sigma (T^4 - T_{s,o}^4)$ ,

$\dot{q}_{ig}$  is the ignitor flame heat flux assumed at 60 kW/m<sup>2</sup>  
and  $T$  is the temperature of the upper gas layer in the room.

### Average Upper Gas Layer Temperature, T

$$T = T_{\infty} \left\{ 1 + C \left[ \frac{\dot{Q}}{\rho_{\infty} c_p \sqrt{g} T_{\infty} A_o \sqrt{H_o}} \right]^{2/3} \left[ \frac{\sqrt{k \rho c / i} A_s}{\rho_{\infty} c_p \sqrt{g} A_o \sqrt{H_o}} \right]^{-1/3} \right\} \quad (2)$$

where

$\dot{Q}$  is the total energy release rate,

$A_s$  is the room surface area,

$A_o$  is the area of the opening,

$H_o$  is the height of the opening,

$k \rho c$  is the thermal inertia of the room lining materials,

$\rho_{\infty} c_p \sqrt{g}$  is 3.44 kW/m<sup>5/2</sup> - K,

and

$C$  is the coefficient taken as 2.2 for these corner fires (compared to 1.63 for room-centered fires).

### Room Energy Release Rate, $\dot{Q}(t)$

$$\dot{Q}(t) = \dot{Q}_{ig} + \dot{Q}'' A_p(t) \quad (3)$$

where

$\dot{Q}_{ig}$  is the ignition burner energy release rate,

$\dot{Q}''(t)$  is the energy release per unit area of the material,

and

$A_p$  is the pyrolysis area.

### Material Energy Release Rate per Unit Area, $\dot{Q}''$

$$\dot{Q}'' = \frac{\Delta H_c}{L} (\dot{q}_r'' - \sigma T_{ig}^4 + \sigma T^4) \quad (4)$$

where  $\dot{q}_f''$  is the incident flame heat flux over the pyrolysis region (60 kW/m<sup>2</sup>),  
 $\sigma T_{ig}^4$  is the re-radiation flux loss,  
and  $\sigma T^4$  is the incident heat flux from the room.

### Pyrolysis Area, $A_p$

The pyrolysis area is computed from the configuration of the pyrolysis and burn-out fronts as illustrated in Figure 2. Specific formulas for all possible cases are given by Quintiere(1992), which are symbolically represented here as

$$A_p = A_p(y_p, y_b, x_p, x_b, z_p, z_b). \quad (5)$$

The initial area ignited is defined by the burner dimension along the intersecting walls (0.17 m), and by the height of the 100 kW fire which is taken as 1.3 m.

### Upward Spread Pyrolysis Front, $y_p$

The upward fronts are measured from the floor and are taken as continuous distances up the wall and along the ceiling and ceiling jet regions. The upward pyrolysis front is computed from the following differential equation involving the flame length,  $y_f$ , and an ignition time based on the average room surface temperature and the flame heat flux:

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \quad (6)$$

where

$$t_{ig} = \frac{\pi}{4} k\rho c \left[ \frac{T_{ig} - T_s}{\dot{q}_f''} \right]^2,$$

and

$$y_f = y_b + \begin{cases} k_f \left[ \dot{Q}_{ig}' + \dot{Q}''(y_p - y_b) \right]^n, & y_b \leq k_f \dot{Q}_{ig}'^n \\ k_f \left[ \dot{Q}''(y_p - y_b) \right]^n, & y_b \geq k_f \dot{Q}_{ig}'^n \end{cases} \quad (7)$$

where  $k_f = 0.01 \text{ m}^2/\text{kW}$  and  $n = 1$ .

$T_s$  is computed by Eq.(1) with

$$q(t) = \sigma(T^4 - T_s^4) + h_c(T - T_s). \quad (8)$$

and  $h_c = 0.01 \text{ kW/m}^2 \text{ K}$  as the convective heat transfer coefficient.

$\dot{q}_f''$  is taken as 30 kW/m<sup>2</sup> in the simulation.

$\dot{Q}_{ig}'$  is the energy release rate for the burner which is equivalent to a line-source. It is determined, based on flame length, such that the burner flame length corresponding to  $\dot{Q}_{ig}'$  is equal to  $k_f \dot{Q}_{ig}'^n$ . It is this flame extension due the burner fire that can cause the pyrolysis front to propagate in spite of sufficient energy release rate by the material alone. However, when the pyrolysis front extends beyond the burner flame length, it then no longer has any influence on the spread. Hence it is critical to specify the correct burner flame length. For the 300 kW burner fire, 3.6 m is taken in the model; however, a correlation suggested by Karlsson (1992) yields 4.4 m.

### Upward Burn-out Front, $y_b$

$$\frac{dy_b}{dt} = \frac{y_p(t) - y_b(t)}{t_b} \quad (9)$$

gives the differential equation for the burn-out front where

$$t_b = Q^*/\dot{Q}^*$$

and  $Q^*$  is the total available energy per unit area which is assumed constant for a given material.

### Lateral or Downward Pyrolysis Fronts, $x_p$ or $z_p$

$$\frac{dx_p}{dt} = \frac{\Phi}{k\rho c(T_{ig} - T_s)^2} \text{ for } T_s \geq T_{s,min} \quad (10)$$

where  $\Phi$  and  $T_{s,min}$  are material dependent properties derived from the test procedure of ASTM E-1321. The downward pyrolysis position is given for  $t > t_H$ , the time when  $y_p = H$  as

$$z_p = x_p(t) - x_p(t_H). \quad (11)$$

### Lateral or Downward Burn-out Fronts, $x_b$ or $z_b$

$$\frac{dx_b}{dt} = \frac{x_p - x_b}{t_b} \quad (12)$$

And the downward burn-out front is given by

$$z_b = x_b(t) - x_b(t_H'). \quad (13)$$

where  $t_H'$  is the time when  $y_b = H$ .

### Numerical Solution

Ignition time is determined from the solution of Eq. (1), an integral equation for the  $T_s$ . A Trapezoidal Rule, and a Gauss-Siedel iterative process is employed. In addition, a Regula Falsi iterative method is used to solve Eq.(2), an algebraic equation, to obtain  $T$ .

Once ignition occurs the differential equations for the fronts are integrated by a second order Runge-Kutta method, and the entire set are simultaneously solved advancing in time.

### MATERIALS AND THEIR PROPERTIES

The properties required by the model are determined from available data derived from the Cone and LIFT apparatuses. These properties are listed below:

- |  |                   |
|--|-------------------|
| 1. Ignition Temperature, $T_{ig}$                      | from Cone or LIFT |
| 2. Thermal Inertia, $k\rho c$                          | "                 |
| 3. Lateral Flame Spread Parameter, $\Phi$              | from LIFT         |
| 4. Minimum Temperature for Lateral Spread, $T_{s,min}$ | "                 |
| 5. Heat of Combustion, $\Delta H_c$                    | from Cone         |
| 6. Effective Heat of Gasification, $L$                 | "                 |

## 7. Total Energy per Unit Area, $Q^*$

Three sets of materials will be discussed. The first set consists of 13 materials originally tested in Sweden in the room-corner test. These materials (S-series) are listed in Table 1. The properties were assembled by Cleary and Quintiere (1991) from Cone and LIFT data available from several sources. These materials are between 10 and 43 mm thick. A more complete description of the materials, and the results in the room-corner tests are given by Sundstrom (1986).

Table 1. Flame Spread and Heat Release Properties of Swedish Fire Test Materials

Material	$T_{ig}$ (°C)	$k_{pc}$ (kW/m <sup>2</sup> K) <sup>2s</sup>	$\Phi$ (kW <sup>2</sup> /m <sup>3</sup> )	$T_{a, min}$ (°C)	$\Delta H_c$ (kJ/g)	L (kJ/g)	$Q^*$ (MJ/m <sup>2</sup> )
S1 Insulating Fiberboard	381	0.229	14	90	14	4.2	≥68.
S2 Medium Density Fiberboard	361	0.732	11	80	14	4.2	≥100.
S3 Particle Board	405	0.626	8	180	14	5.4	≥120.
S4 Gypsum Board	469	0.515	14	380	7	4.8	2.8
S5 PVC Covered Gypsum Board	410	0.208	25	300	13	3.7	4.6
S6 Paper Covered Gypsum Board	388	0.593	0.5	300	10	4.8	7.2
S7 Textile Covered Gypsum Board	406	0.570	9	270	13	1.5	8.3
S8 Textile Covered Mineral Wool	391	0.183	6	174	25	2.8	9.3
S9 Melamine Covered Particle Board	483	0.804	<1	435	11	4.8	≥60.
S10 Expanded Polystyrene (PS)	482	0.464	31	130	28	1.5	32.
S11 Polyurethane Foam (rigid)	393	0.031	3	105	13	3.1	14.
S12 Wood Panel (Spruce)	389	0.569	24	155	15	6.3	≥120.
S13 Paper Covered Particle Board	426	0.680	13	250	13	6.5	≥100.

The second set of materials come from the EURIFIC program. These materials (E-series) and their derived properties are given in Table 2. These materials are between 12 and 80 mm thick. The Cone data were taken from Thureson (1991), and the LIFT data were taken from Nisted (1991). In the latter case, the raw data were reprocessed since there appeared to be some discrepancies in that report. Also ignition data from the Cone were examined together with LIFT data in an attempt to derive more accurate values for  $T_{ig}$  and  $k_{pc}$ . In some cases this did not appear to improve accuracy since greater variations resulted. Hence we used our values that were more consistent with values used by Karlsson (1992) for these two properties.

Table 2. Flame Spread and Heat Release Properties of the EURIFIC Materials

Material	$T_{ig}$ (°C)	$k_{pc}$ (kW/m <sup>2</sup> K) <sup>2s</sup>	$\Phi$ (kW <sup>2</sup> /m <sup>3</sup> )	$T_{a, min}$ (°C)	$\Delta H_c$ (kJ/g)	L (kJ/g)	$Q''$ (MJ/m <sup>2</sup> )
E1 Painted Gypsum Paper Plaster Board	551	0.73	3.3	478.	4.1	3.6	3.3
E2 Ordinary Birch Plywood	392	0.99	13	164	11.9	6.2	75.5
E3 Textile Covering on Gypsum Board	387	0.97	7.7	189	7.5	3.1	9.5
E4 Melamine faced High Density Non- Combustible Board	631	0.32	12.7	527	8.5	3.5	7.0
E5 Plastic faced Steel Sheet on Mineral Wool	582	0.60	44	472	11.0	34.	2.5
E6 FR Particle Board Type B1	482	0.29	--	482	3.9	1.4	5.5
E7 Combustible faced Mineral Wool	354	0.11	0.86	263	11.0	9.2	1.7
E8 FR Particle Board	678	1.8	--	678	6.0	4.0	6.0
E9 Plastic faced Steel Sheet on Polyurethane Foam	494	0.60	22.	326	12.0	5.1	17.0
E10 PVC Wallcarpet on Gypsum Board	391	0.69	8.2	367	6.5	3.3	11.0
E11 Extruded Poly- styrene Foam	482	0.44	11.5	354	27.0	2.7	20.0

The third set of materials represent aircraft cabin lining materials studied by the FAA several years ago in their program to improve the survivability in post-crash fires. The property data were obtained by Harkleroad (1988) and Quintiere et al. (1985). These properties are given for the F-series materials in Table 3.

In the current model an important input property is  $\Delta H_c/L$ . This is derived from the slope of the peak energy release rate per unit area versus the irradiance level in the Cone Calorimeter. This will only yield appropriate results if the flame heat flux in the Cone does not vary with irradiance. Since  $\Delta H_c$  is derived from the Cone data separately and is usually fairly constant, the uncertainty then arises in deriving L. Hence although the current model attempts to evaluate the energy release rate at the heat flux in the room-corner test, the uncertainty in this ratio can lead to problems. In the third set of materials,  $\Delta H_c$  was not directly recorded for materials F6-8, but  $\Delta H_c/L$  could be evaluated which allowed the model to be run without any deficiency of input data.

#### ROOM-CORNER TEST SCENARIO

A sketch of the room-corner test based on NT FIRE 025 is shown in Figure

Table 3. Flame Spread and Heat Release Properties for the FAA Materials

Material	$T_{ig}$ (°C)	kpc (kW/m <sup>2</sup> K) <sup>2s</sup>	$\Phi$ (kW <sup>2</sup> /m <sup>3</sup> )	$T_{a, min}$ (°C)	$\Delta H_c$ (kJ/g)	L (kJ/g)	$Q^*$ (MJ/m <sup>2</sup> )
F1 Epoxy Fiberglass faced Nomex 1/4 in. Honeycomb Core	438	0.174	1.17	425	11.3	4.9	10.
F2 Phenolic Fiberglass faced Nomex 1/4 in. Honeycomb Core	570	0.107	6.23	490	23.	12.1	8.0
F3 Epoxy Kevlar faced Nomex 1/4 in. Honeycomb Core	465	0.188	4.86	400	11.4	5.7	9.0
F4 Phenolic Kevlar faced Nomex 1/4 in. Honeycomb Core	558	0.133	2.47	510	18.6	4.8	9.0
F5 Phenolic Graphite faced Nomex 1/4 in. Honeycomb Core	570	0.186	4.58	510	24.6	8.8	7.0
ABS with 20 % PVC 1/16 in. Sheet	388	0.76	6.63	282	15*	3.4+	27.0
Polycarbonate 1/16 in. Sheet	518	0.84	--	518	15*	1.6+	24.0
ULTEM 1/16 in. Sheet	585	0.91	--	585	15*	4.8+	11.0

\* Estimated value

+ Computed from estimated value of  $\Delta H_c$

3. The corner floor burner is maintained at 100 kW for 10 minutes and then increased to 300 kW. In the model this corresponds to a corner flame length of 1.3 m, followed by a flame which extends 1.2 m from the corner and along the ceiling (or an effective flame length of 3.6 m). The test is run to determine if and when the total energy release rate reaches 1 MW. The room-corner test results are available from Sundstrom (1986) for the S-series, and from Söderbom (1991) and Karlsson (1992) for the E-series. Also computer files are available from Lönvik and Opstad (1991). However, we were not always able to identify the correct channel. Also the times to reach 1 MW appear to differ by 20 s at most between those of Söderbom (1991) and Karlsson (1992). We used the latter. The FAA F-series materials will be run by the model, and no experimental results exist to check the calculations. However, full-scale experiments were run for four of the materials (F1, F2, F4, and F5) in a post-crash wide-body aircraft fire scenario ( Hill, Eklund and Sarkos, 1985). Hence, relative comparisons can be made for the FAA materials.

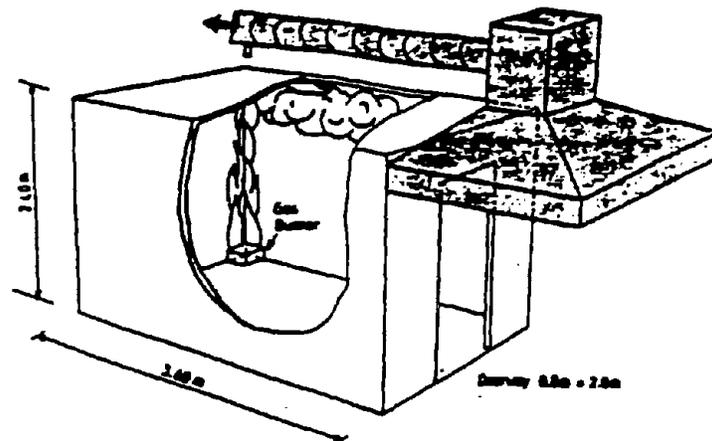


FIGURE 3. ROOM-CORNER TEST CONFIGURATION FROM SUNDSTROM (1986)

## RESULTS

The time to reach 1 MW will be compared to the experimental results for the S and E-series. In some cases variations in the input property data will be examined to see its effect on the time calculated. The time to reach 1 MW in hypothetical room-corner fire tests for the FAA materials will also be reported. In all of the cases, lateral flame spread was insignificant because the minimum surface temperature for spread was not reached until at least 1 MW was reached. This characteristic was not reported on in the experiments, so the appropriateness of the model calculations can not be addressed in this regard. Also radiation feedback from the room only becomes a significant factor as the energy release rate approaches 1 MW. From the experimental results reported by Karlsson (1992) at 1 MW the room gas temperature corresponds to approximately 500 °C. This corresponds to a radiant heat flux of 20 kW/m<sup>2</sup>.

### S and E-Series

Results for the S and E-series are reported in Table 4. The principal differences between the experimental and calculated times occur for cases that reach 1 MW after 10 minutes. Also This predominately occurs for thin materials on a noncombustible substrate. For example, S4 is unpainted gypsum wall board and E1 is painted gypsum wall board. The primary differences in these two materials is their  $\Delta H_c/L$  values, i.e. 1.5 for S4 and 1.1 for E1. By increasing L by 25 % and reducing  $Q^*$  by 50 % for S4 gives calculated results that are in agreement with the experiment. For the thin materials, the burn-out front can be initiated; and if it catches up to the pyrolysis front, the fire will die out. This is illustrated in Figures 4A and 4B for E1 where the energy release rates are compared, and the computed upward pyrolysis and burn-out fronts are shown as a function of time. The energy release rate of the painted gypsum board reaches a maximum of approximately 300 kW while the experimental results are about 100 kW over the 300 kW burner contribution. The pyrolysis front is initiated as E1 ignites due to the 100 kW burner fire at about 90 s. The burn-out front commences at about 180 s as the

Table 4. Time (s) to Reach 1 MW

	<u>Exp.</u>	<u>Calc.</u>	<u>Variation</u>	<u>Comment on Variation</u>
S1	59	29	36	1.25L
S2	131	91	120	1.25L
S3	157	121	167	1.25L
S4	∞	642	∞	1.25L & 0.5Q <sup>+</sup>
S5	611	30	602	1.25L & 0.5Q <sup>+</sup>
S6	640	613		
S7	639	41	606	1.25L & 0.5Q <sup>+</sup>
S8	43	12		
S10	115	44		
S11	6	4		
S12	131	110	156	1.25L
S13	143	222	148	0.75L
E1	∞	∞		
E2	160	265		
E3	670	∞	608	1.2(300 kW flame length)
E4	∞	646		
E5	∞	∞		
E6	630	∞		
E7	75	601		
E8	∞	∞		
E9	215	504	71	0.28kpc
E10	650	614		
E11	80	47		

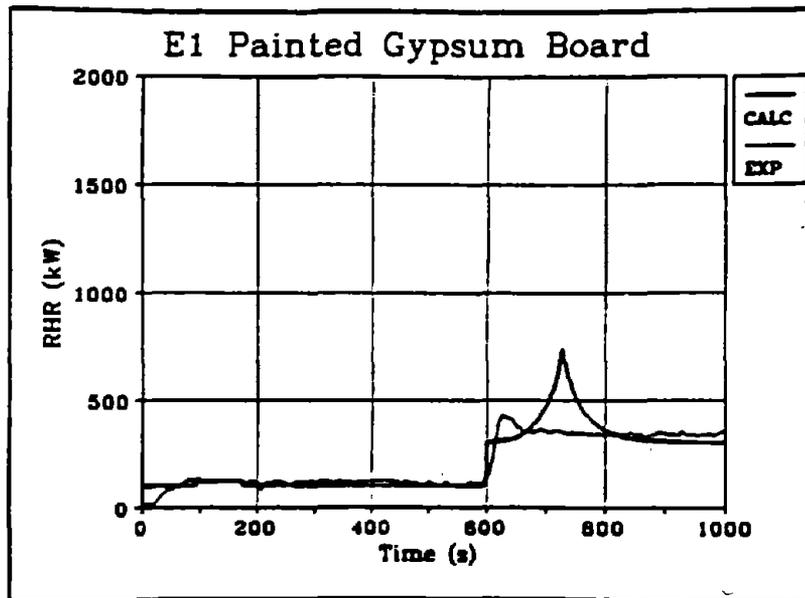


FIGURE 4A. A COMPARISON OF THE ENERGY RELEASE RATE (RHR) FOR MATERIAL E1: EXPERIMENT AND CALCULATION

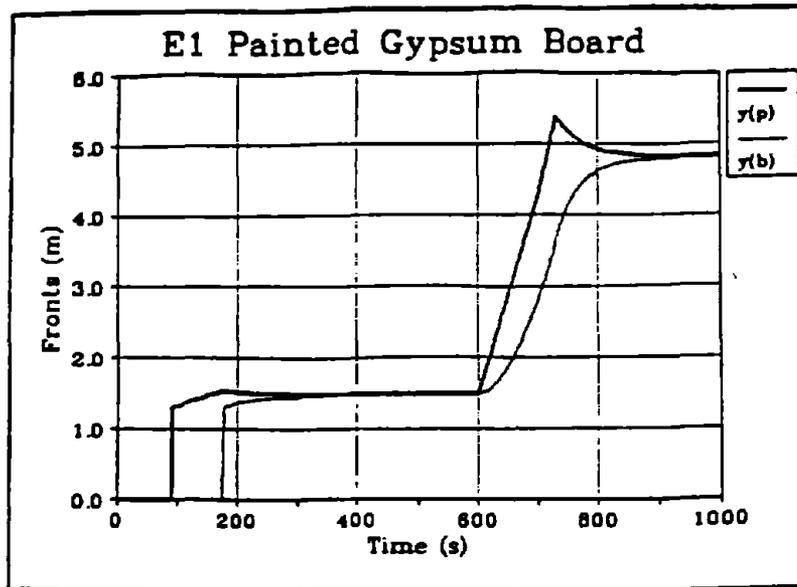


FIGURE 4B. THE CALCULATED UPWARD PYROLYSIS AND BURN-OUT FRONTS FOR MATERIAL E1

Painted paper burns away in the ignition region. Shortly after, the fronts coincide. But when the burner energy release rate is increased to 300 kW at 600 s, the pyrolysis front accelerates initially faster than the burn-out front due to the flame extension caused by the burner. Once the pyrolysis front gets beyond the region of influence of the burner flame, the fire again dies out. This is governed by the length of the burner flames and by the dimensionless quantity,

$$b = k_f \dot{Q}'' - 1 - t_{ig}/t_b \quad (14)$$

according to Cleary and Quintiere (1991). If  $b > 0$  acceleration is possible, and if  $b < 0$  the fire can die out. In the calculations,  $b$  varies with time so it is not obvious how to deduce a criterion for this behavior from the properties alone.

In Table 4 it should be noted that comparable variations in  $L$  for thick combustible materials (25 %) do not cause the same degree of differences in the times to reach 1 MW as the thin materials. Also for material E3, better agreement of the calculated result with the experiment was achieved by increasing the burner flame length at 300 kW by 20 %. This flame length is more consistent with the correlation given by Karlsson (1992). For material E9, a wide variation in  $k_{pc}$  occurred, and reducing the selected value by nearly 75 % gave calculated results that bracketed the experimental time. In all of the variations considered, the variation was within the bounds of the uncertainty for the deduced properties. It is not clear whether more careful and complete data can reduce this uncertainty, or whether the materials themselves may have significant property variations due to their construction. In some cases the method of bonding the components of the composite materials could be a factor.

Since it may be difficult to assess the overall accuracy of the calculated results listed in Table 4, a graph is plotted in Figure 5. In 8 of the 24 cases, poor agreement is seen. However, in 5 of these cases, relatively small changes in the

input properties brought the calculations into more consistent agreement with the experimental results. Four of these five materials were thin combustibles on an inert substrate.

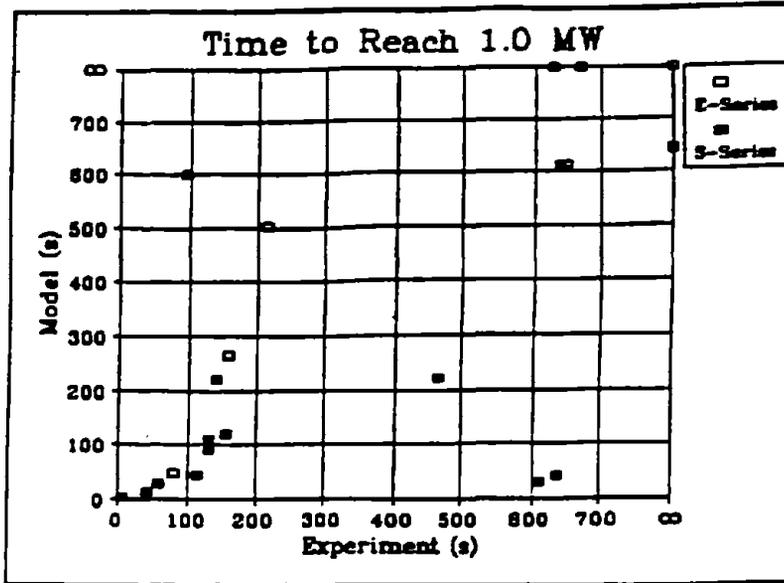


FIGURE 5. MODEL CALCULATED TIMES TO REACH 1 MW COMPARED TO THE EXPERIMENTAL RESULTS FOR THE S AND E-SERIES

Other results are shown for illustration in Figures 6 and 7 for materials E2, plywood, and E3, textile wall covering on gypsum board.

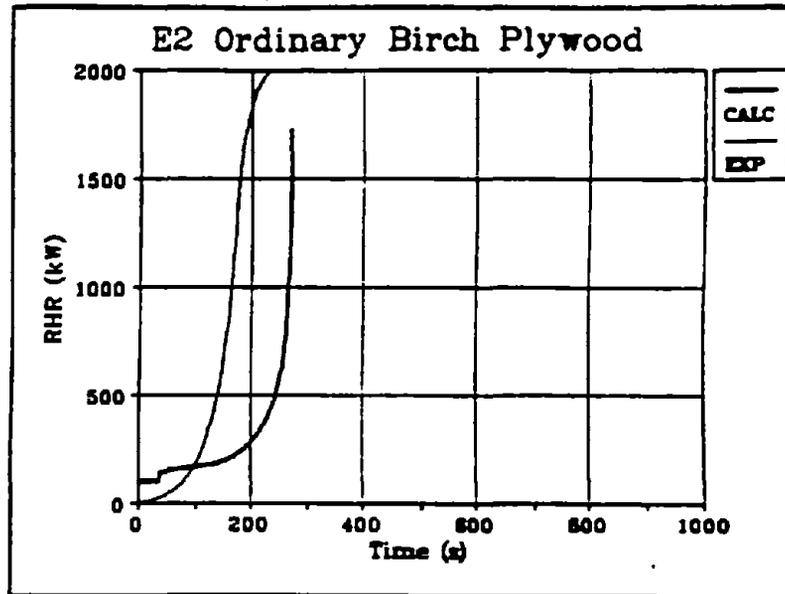


FIGURE 6. A COMPARISON OF THE ENERGY RELEASE RATE (RHR) FOR MATERIAL E2: EXPERIMENT AND CALCULATION.

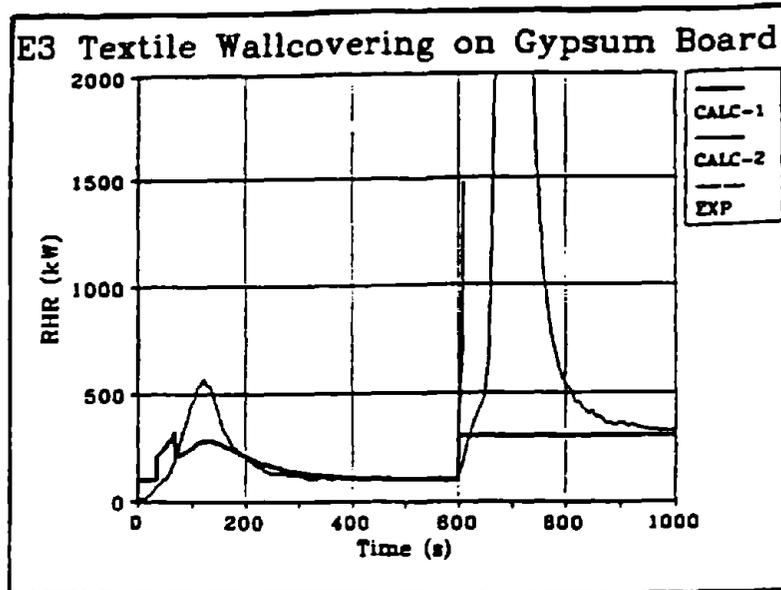


FIGURE 7. A COMPARISON OF THE ENERGY RELEASE RATE (RHR) FOR MATERIAL E3: EXPERIMENT AND CALCULATION.

**FAA Materials, F-Series**

Figure 8 shows the simulated room-corner results for the aircraft materials. The materials F1, Epoxy Fiberglass, and F3, Epoxy Kevlar, are the worst; and F5, Phenolic Graphite, is the best. Table 5 lists the times to reach 1 MW along with the times for the materials to ignite due to the 60 kW/m<sup>2</sup> burner heat flux. Also listed in Table 5 are the approximate times to flashover found in the post-panic fire experiments conducted by Hill, Eklund and Sarkos (1985) which contained seats

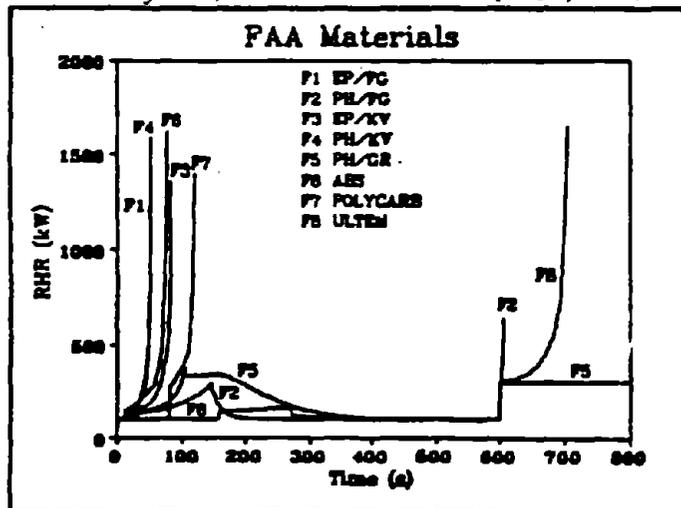


FIGURE 8. CALCULATED RATE OF ENERGY RELEASE (RHR) FOR THE AIRCRAFT MATERIALS IN THE ROOM-CORNER TEST

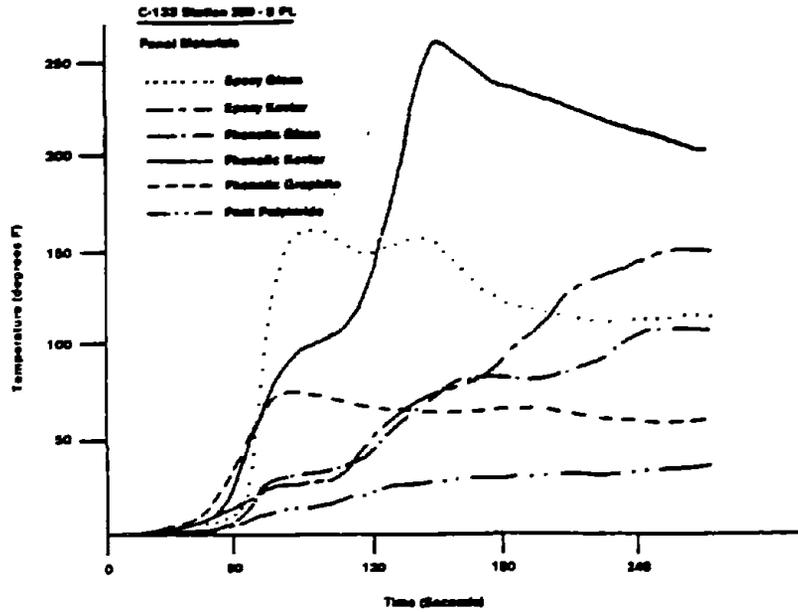


FIGURE 9. C-133 CABIN GAS TEMPERATURE FOR THE PANEL TESTS WITHOUT SEATS FROM HILL, EKLUND AND SARKOS (1985)

Table 5. Calculated Room-corner Test Results for Aircraft Materials, F-Series, and Comparison to the Post-Crash C-133 Tests by Hill, et al. (1985)

	Room -Corner Test Results		C-133 Post-Crash Fire Tests
	Ignition Time (s)	Time to 1 MW (s)	Flashover Time with Seats (s)
F1 Epoxy Fiberglass faced Nomex 1/4 in. Honeycomb Core	10	50	70
F2 Phenolic Fiberglass faced Nomex 1/4 in. Honeycomb Core	16	606	230
F3 Epoxy Kevlar faced Nomex 1/4 in. Honeycomb Core	12	81	--
F4 Phenolic Kevlar faced Nomex 1/4 in. Honeycomb Core	18	49	70
F5 Phenolic Graphite faced Nomex 1/4 in. Honeycomb Core	28	--	190
F6 ABS with 20 % PVC 1/16 in. Sheet	29	73	--
F7 Polycarbonate 1/16 in. Sheet	80	119	--
F8 ULTEM 1/16 in. Sheet	158	699	--

as well as the lining materials considered. Only four of the materials were tested with seats. The results are somewhat consistent except that the tests reverse the order of F2 and F5, making the Phenolic Fiberglass panel better than the Phenolic Graphite panel.

Figure 9 shows the cabin temperature response to the post-crash fire experiments for the case of the cabin tests with the panels only. Flashover conditions were not produced in these tests due to the lack of influence by the seats. Also ignition of the panel materials would depend on the interaction of the external fuel fire which could be spurious. If one interprets the area under the temperature curves as a measure of the performance of the panel materials, then this order of performance (F4, F1, F3, F2, F5, worst to best) is consistent with the calculated times to reach 1 MW in the room-corner test simulations.

## CONCLUSIONS

The model appears to predict consistent results with the experiments for the time to reach 1 MW in 2 out of every 3 of the 24 tests. It was found that some reasonable changes in either the input properties or the phenomenological specifications can improve the accuracy. It is not clear that the uncertainty in the property data could be reduced by more careful and complete experiments using the Cone and the LIFT apparatuses. However, this should be explored. It is felt that the areas needed for improvement in the model include the computation of the energy release rate per unit area, the heat fluxes, and the flame lengths specified for the burner flame. The extension of the upward spread equations to the ceiling and ceiling jet regions can only be regarded as a crude estimate, but must suffice until results for these phenomena are forthcoming from research.

The application of the model to the aircraft materials could be viewed as reasonably successful in terms of the apparent consistency with the limited results of the post-crash fire tests. It should be noted that the current model is not limited to the simulation of the room-corner test scenario, and could be modified with its current scope to address aspects of aircraft cabin fires or other room fire configurations.

## NOMENCLATURE

A	area
b	parameter defined in Eq. (14)
c	specific heat
d	depth of room
D	side of square burner
g	acceleration due to gravity
h	convective heat transfer coefficient
H	height of room, vent
k	thermal conductivity
$k_f$	empirical constant, Eq.(7)
L	effective heat of gasification
n	empirical power, Eq. (7)
q	heat

Q	energy release
t	time
T	temperature
w	width of room
x	lateral position
y	upward position
z	downward position
$\rho$	density
t	fictitious variable for time, Eq. (1)
$\Delta H$	heat of combustion

### Subscripts

b	burn-out
f	flame
ig	ignitor, ignition
min	minimum
p	pyrolysis
s	surface
s.o	surface responding to ignitor flame heat flux
o	initial
$\infty$	ambient

### Superscripts

( )	per unit time
( )'	per unit width
( )''	per unit area

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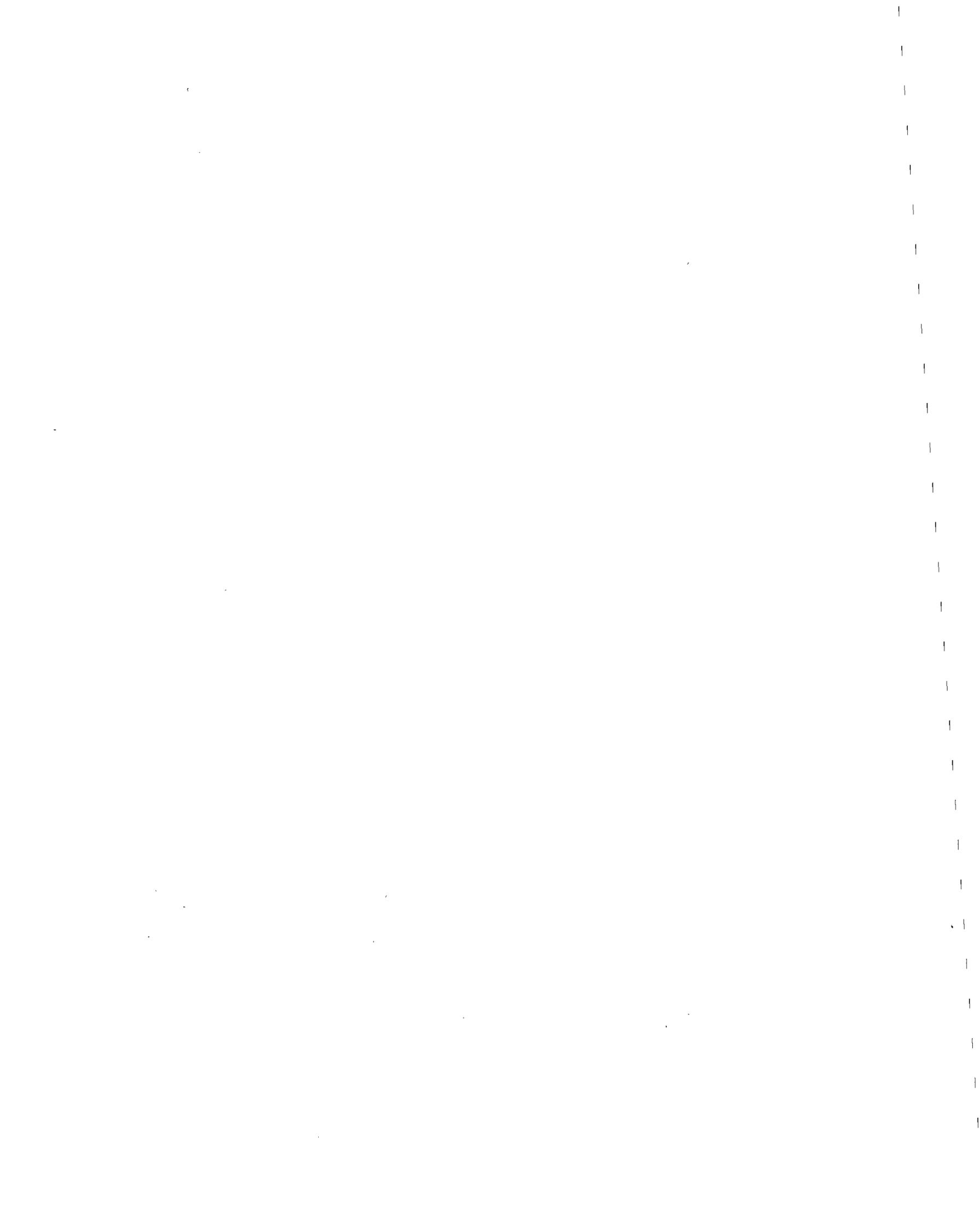
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THE OSU HEAT RELEASE RATE TEST USING THE OXYGEN CONSUMPTION PRINCIPLE

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ABSTRACT

The FAA Heat Release Rate (HRR) Test using the Ohio State University (OSU) apparatus can be improved by adopting the oxygen consumption principle. Using the present thermal method, the large heat input from the electrically-heated source of the radiative heat flux causes high baseline values in the output signals. The baseline value is easily and significantly changed by the thermal history of the apparatus and thermal disturbances. The heat absorbed by the apparatus and heat lost to the surroundings also cause errors. By using the oxygen consumption principle, these thermal errors can be eliminated. In Canada, a standard test method for measuring the HRR of low heat-releasing materials has been developed. The method uses the OSU apparatus with the oxygen consumption principle. This method is useful for testing the heat release rate of airplane cabin materials. Only the addition of an oxygen analyzer is required for the present OSU apparatus and, thus, costs are minimized.

INTRODUCTION

The FAA flammability test for passenger airplane cabin materials (FAA 1986, 1987, 1988) measures the HRR of cabin materials in combustion. In measuring HRR, there have been two generic types of measurements: the thermal method and the oxygen consumption method. The thermal method measures the increase in the temperature of the exhaust air by a thermopile. The oxygen consumption method, developed by Huggett (1980), measures the oxygen content in the exhaust air, and calculates the HRR based on the fact that a constant amount of heat is generated per unit quantity of oxygen consumed.

The current FAA HRR Test uses the OSU apparatus with the thermal method and is not free from some technical problems associated with the thermal measurement. In this paper the thermal method and the oxygen consumption method are comparably discussed based on the published information and new experimental data.

In Canada, there has been a demand from the code-writing committees for a test capable of quantitatively measuring low degrees of combustibility of materials to be used in non-combustible construction. Responding to this demand, the Institute for Research in Construction has developed an HRR test using the OSU apparatus with the oxygen consumption method and that method has been standardized (ULC, 1992). This test method, which was developed for construction materials can also be used for measuring the HRR of airplane cabin materials that are expected to release relatively small amounts of heat during combustion.

THERMAL METHOD VS. OXYGEN CONSUMPTION METHOD

HRR measurement with the thermal method started in the late 1950's and various methods were devised. Development of the oxygen consumption method started in the late 1970's. Several comparative studies of the thermal and oxygen consumption methods have been undertaken since then, some of which will be discussed below. At the present time, most HRR measurements in small-scale, as well as large-scale fire experiments, use the oxygen consumption method for the reasons discussed below.

1. One of the disadvantages of the thermal method is the slow response of thermal measurement. The heat generated

in the combustion of a sample is partially absorbed and desorbed by the walls of the apparatus. This process causes the thermal inertia and the peak value of the HRR to be significantly reduced. This effect was studied by several groups in the early 1980's and collectively discussed in a previous paper (Tsuchiya, 1982). Blomqvist (1983) demonstrated this effect using an ASTM E906 apparatus with a compensated thermopile. In those tests on a polyvinyl chloride (PVC) wall covering, which gave an HRR rapidly changed with time, the thermal method gave only 60% of the peak HRR value of that obtained using the oxygen method.

2. A thermopile, the temperature sensor used in the thermal method, measures the convective heat release but may not measure the radiative heat release, while the oxygen consumption method measures both heat releases without bias. According to Tewerson (1976), the ratio, radiative/convective heat, is 0.53/1 for PMMA and 0.84/1 for polystyrene. Thus, a significant portion of the HRR may not be measured in the thermal method. This effect was demonstrated by Kraus and Gann (1980) using an ASTM OSU apparatus with a reduced air flow (1/3 of that used in the standard). For particleboard and polystyrene, both of which produce bright flames, the thermal method of HRR measurement produced a significantly lower peak and a longer tailing than the oxygen consumption method.

3. The radiative/convective heat release ratio also causes error in the use of the calibration constant of the apparatus. In the FAA HRR and ASTM E906 tests, the apparatus is calibrated by burning methane. A methane flame is less bright, having a smaller radiative/convective ratio than a propane flame or wood flame. When a test sample has a flame of higher emissivity than the methane flame, the measured HRR value is biased and is recorded as smaller than it actually is. This effect of calibration gas bias was demonstrated in a previous paper (Tsuchiya, 1989) and the results summarized in Table 1. The effect of calibration gas bias was significant in the thermal method, but insignificant in the oxygen consumption method.

Table 1 Effect of calibration gas, HRR values of a control sample

Calibration gas	Thermal method		Oxygen consumption method	
	Methane	Propane	Methane	Propane
Peak HRR, kW/m <sup>2</sup>	78.3	102.7	123.9	128.1
Accum. HR, MJ/m <sup>2</sup>	3.05	4.00	3.53	3.65

4. The oxygen consumption method also produced more reproducible HRR data than the thermal method. In the study shown in Table 1, the calibration constants were measured in duplicate for each of the calibration gases. The averaged relative standard deviations were 1.01% for the oxygen consumption method and 1.67% for the thermal method (Tsuchiya, 1989).

## RECOMMENDED TEST APPARATUS AND TEST PROCEDURES

In the oxygen consumption method, oxygen concentrations in the combustion gases are measured. In order to sample the combustion gases, a three-hole L-shaped sampling probe is positioned 50 mm below the upper edge of the combustion chamber walls in the Canadian standard for Degrees of Combustibility. This is located below the convergence point of the chamber air flow and the by-pass air flow to ensure that no by-pass air is taken into the probe. Tests showed that the positioning was not critical; 10 mm up or down had no effect. The probe position is shown in Fig. 1.

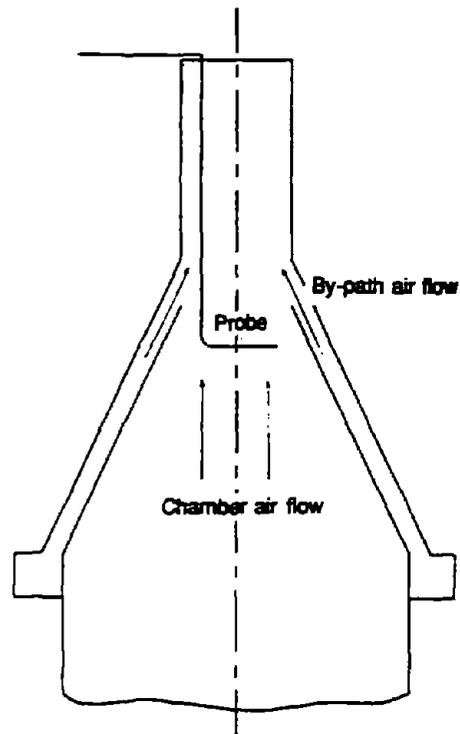


Fig. 1 Position of the gas sampling probe

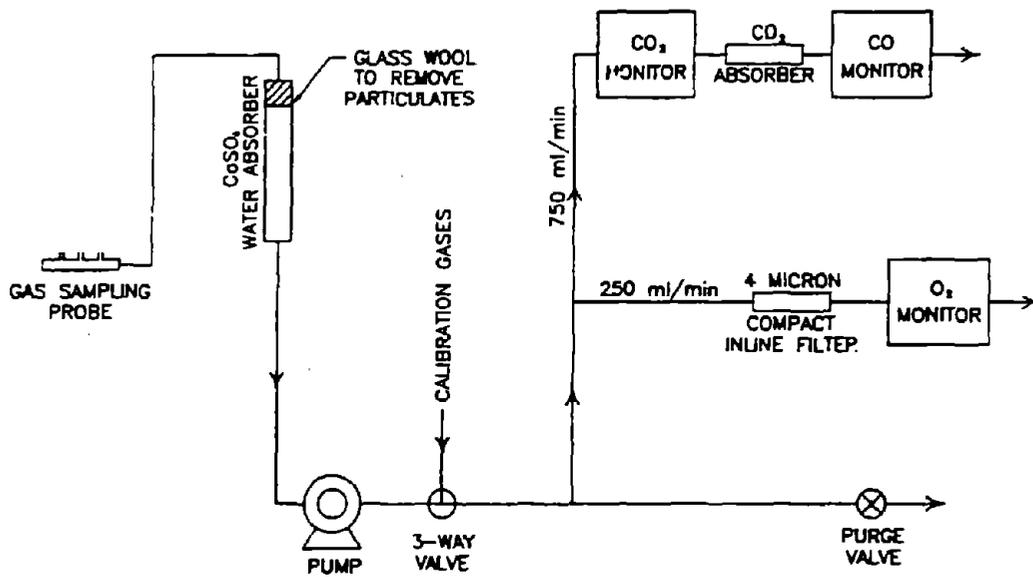


Fig. 2 Schematic diagram of gas analysis system

An oxygen monitor using the paramagnetic principle (which has a faster response time than the chemical cell type monitor) is used for measuring oxygen concentrations in the exhaust gases from the combustion chamber. That monitor is calibrated using atmospheric air. The particular type of oxygen monitor used in the author's laboratory has multiple measuring ranges of 20-21, 19-21, 16-21, and 11-21% oxygen. The 19-21% range is appropriate for the FAA HRR test. This range corresponds to an HRR measurement range of 0-150 kW/m<sup>2</sup> (approximate), taking into account oxygen consumption by the pilot flames.

In the FAA HRR test standard procedures, the apparatus is calibrated by a square wave heat input from burning a prescribed flow of methane. The methane gas flow rates are set in the sequence of 1, 4, 1, 6, 1, 8, 1, 6, 1, and 4 L/min for a duration of two minutes each. The calibration constant, in kW/mV, is calculated. The kW value in the calibration constant is calculated as the product of the methane flow rate, at standard temperature and pressure, and the net heat of combustion of methane. The mV value is the output from the oxygen analyzer in the oxygen consumption method as the thermopile mV output in the thermal method. The 8 L/min flow of methane in the calibration results in readings beyond the oxygen monitor range of 19-21%. If this procedure is employed the 16-21% oxygen range has to be used. In the Canadian Degrees of Combustibility standard, the calibration procedure has been modified to 1, 4, 1, and 4 L/min flows of methane for a duration of 2 minutes each.

When the combustion chamber air flow is reduced, the percentage of oxygen depletion increases, resulting in higher sensitivity of the HRR measurement. In the Canadian Degrees of Combustibility Test method, the air flow rate is 0.02 m<sup>3</sup>/sec, 1/2 the rate used in the FAA HRR Test or the ASTM test.

With the author's apparatus, concentrations of CO and CO<sub>2</sub> are also measured. These measurements are to obtain data such as the extent of incomplete combustion, which reduces HRR; the split ratio of chamber flow and by-pass flow; and the over-all accuracy of the experiments. These details are contained in a previous paper (Tsuchiya, 1991). A schematic diagram of the complete gas analysis system is shown in Fig. 2.

In the Canadian Degrees of Combustibility Test, the general construction of the apparatus, including the injection mechanism, is the same as the FAA HRR Test.

## EXPERIMENTAL STUDIES AND DISCUSSION

Experimental studies have been performed using the Canadian Degrees of Combustibility Test apparatus described above, with the addition of the FAA HRR Test thermopile, so that both the oxygen consumption measurement and the thermal measurement can be performed simultaneously. The methane calibration has been performed using the FAA HRR standard procedures. The results are shown in Fig. 3 in which three curves are shown: oxygen, thermal and CO<sub>2</sub>. The oxygen curve is the output of the oxygen analyzer using the 16-21% range. The CO<sub>2</sub> curve is the output of a CO<sub>2</sub> analyzer using the 0-5% range for comparison. The oxygen and CO<sub>2</sub> curves are almost identical except they are in the inverse position. The detailed patterns seen in the Oxygen and CO<sub>2</sub> curves are lost in the thermal curve because of the thermal inertia. Heat release rates can be measured using CO<sub>2</sub> measurement, however this is not discussed in this paper.

Millivolt outputs from the thermopile and oxygen monitor in testing an airplane cabin material are shown in Fig. 4. In the thermal method, it is notable that a large baseline value is subtracted from the mV signal values in calculating the HRR and accumulated HR. A variation in the baseline value may have relatively large effect on the HRR measurement. The accumulated HR, as defined in the FAA HRR test, is shown by the area surrounded by the mV curve, baseline and a vertical line at 120 s (Fig.4). In this particular example, the peak HRR value was about 70% higher than the acceptable 65 kW/m<sup>2</sup>. Most materials that pass the FAA HRR test have peak values (peak of mV curve minus baseline) much smaller than this example.

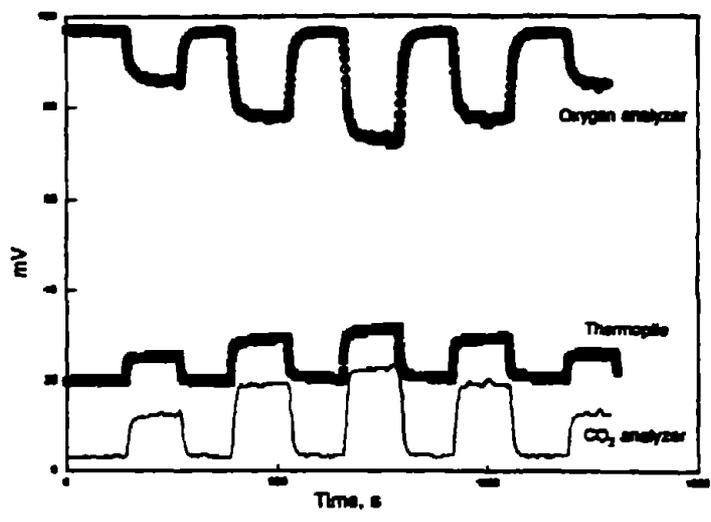


Fig. 3 Calibration using methane

HRR's have been calculated from the measured mV in Fig. 4 and are shown in Fig. 5. In this particular case, the peak value determined by the thermal method was only 60% of that by the oxygen consumption method. It is notable that the heights of the broad 2nd peak (between 100 s and 200 s) in the thermal and oxygen curves are about the same. The difference in the sharp 1st peaks is attributed to the slow response of the thermal measurement. The HRR curves are shown only to 300 s into the tests as required in the FAA HRR standard procedures. Continued measurement beyond 300 s showed a longer tailing in the thermal curve.

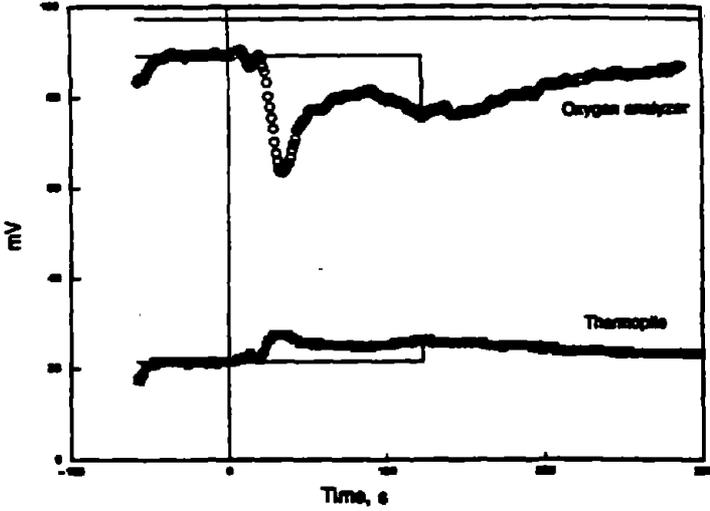


Fig. 4 Oxygen and thermal curves in an HRR measurement

If the oxygen consumption method is adopted for measuring the HRR of airplane cabin materials, the pass/fail criteria will have to be changed, for example, a peak HRR of  $100 \text{ kW/m}^2$  instead of  $65 \text{ kW/m}^2$ , and an accumulated HR of  $80 \text{ kW-min/m}^2$  ( $4.8 \text{ MJ/m}^2$ ) instead of  $65 \text{ kW-min/m}^2$  ( $3.9 \text{ MJ/m}^2$ ). More comparative data using both methods on existing airplane materials are required before deciding on the new criteria.

Modelling of a compartment fire using a computer is quite common today. The HRR of materials is often used as an input. If the lower-than-real peak HRR values obtained by the thermal method are used in such modelling, the predictions from the models could give questionable results that could lead to unsafe conditions.

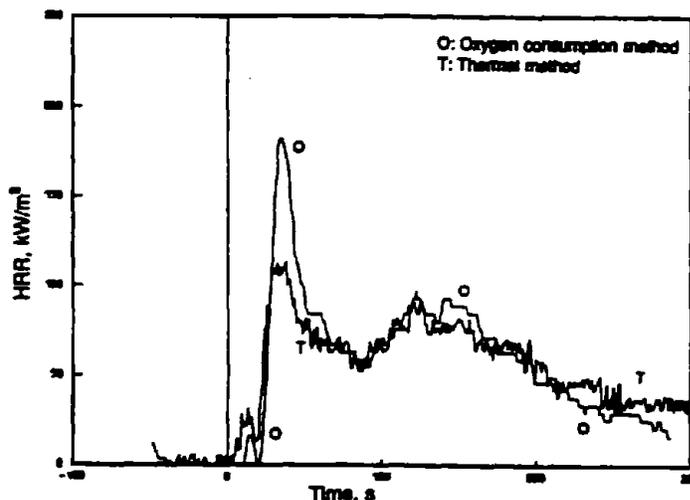


Fig. 5 HRR measured by the thermal method and oxygen consumption method

The concentration of CO, the production of which causes errors in HRR measurement, was checked because the reduction of chamber air flow may increase CO production. Tests showed CO production was insignificant. The highest concentration of CO observed was 0.2% in tests with flame-retardant treated plywood. The reduction of HRR caused by this amount of CO was calculated as 3%. This is considered insignificant and thus no correction of HRR, based on CO concentration, would be necessary.

Both the present method and the cone calorimeter (ASTM 1990) test method use  $\text{O}_2$  depletion as the basis for measuring HRR. When a material has a small HRR,  $\text{O}_2$  depletion is small. For more accurate HRR measurements, larger oxygen depletions are desirable. Two parameters are directly related to  $\text{O}_2$  depletion: the surface area of the specimen and the combustion air flow. The surface area of the specimen exposed to radiant heat is  $0.01 \text{ m}^2$  in the cone calorimeter and  $0.0225 \text{ m}^2$  in the OSU apparatus. A larger area consumes more oxygen in combustion. In the OSU apparatus, in which the specimen burns in an enclosure, the supply of air can be reduced. The present Degrees of Combustibility Test method uses 1/2 the air flow of the FAA HRR Test. A further reduction of air flow to 1/6 of the FAA HRR Test was tried without problems in measuring an HRR of  $10 \text{ kW/m}^2$ . In the cone calorimeter, the specimen burns in an open space and the exhaust air flow is set to collect all of the combustion gases into the exhaust system. A reduction of combustion air for the purposes of increasing oxygen depletion is not possible. There are presently some trials to enclose the cone calorimeter for the purpose of studying combustion under reduced oxygen atmospheres. Some reduction of air flow may be possible using this apparatus, but to date it is not documented and the apparatus is fairly complicated in construction. Considering these, the OSU apparatus

using the oxygen consumption method is preferable to the cone calorimeter for measuring small values of HRR.

## CONCLUSION

The thermal method and oxygen consumption method of HRR measurements were compared using an OSU apparatus. The oxygen consumption method was considered superior because:

- (1) it was free from thermal inertia which resulted in low HRR values in the thermal method
- (2) it was free from thermal disturbances which produced unreliable results in the thermal method
- (3) it measured both radiative and convective heat release without bias
- (4) it produced more reproducible data

The Canadian Degrees of Combustibility Test method using oxygen consumption has been developed in order to measure small values of HRR and was modified from the FAA HRR Test. This method is recommended as an improved test method for the flammability of airplane cabin materials.

The cone calorimeter is not recommended for testing these materials. The Degrees of Combustibility Test is superior in that a larger oxygen depletion is attained because of the smaller rate of combustion air flow and a larger specimen surface.

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**Practical Hazard Assessment An Approach to the Fire Safety**

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**James R. Hoover  
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**Abstract**

Fire hazard assessment, although a powerful technique, is usually complex and elaborate. A simplified approach for practical use is presented, which relies on simple, closed-form relationships to allow potential regulators and product designers to estimate the effects which material product fire and smoke properties would have on the developing fire hazard in aircraft interiors. The four steps in the process, scenario analysis, setting objectives, formulating a fire protection strategy, test method selection and criteria setting are described and an illustrative example aircraft wire and cable is briefly discussed. (Most criteria involve more than one fire/smoke property, so that considerable flexibility in meeting the criteria is allowed.)

**I. Introduction**

Hazard assessment is the process of quantifying the life safety threats, or hazards, of a fire and relating them to the fire and smoke properties of the materials product burning.

This field of endeavor has come about because:

1. While laboratory flammability tests are generally made under a fixed set of exposure conditions, the tested product may encounter a variety of different potential fire exposure conditions in actual use, conditions under which its performance may be radically different that it displayed in tested in the laboratory.
2. The effects of a fire are influenced as much by the location, geometry and people at risk as they are by how the fuel is burning.
3. It is now easier to accomplish. Advances in fire science and computational capabilities make hazard assessment an engineering tool instead of a research curiosity.

Nevertheless it is this third aspect which needs additional attention. Although mathematical models characterizing fire performance can often be customized for individual applications, they require both validation and acceptance before they have much practical utility.

The thesis of this presentation is that the modeling aspects of many hazard assessments can be simplified to a set of closed-form equations without compromising the overall precision. This is an advantage because, in order to be of practical regulatory use, the results of hazard assessment must be simply expressed and relatable to material product properties which can be measured by test methods.

Hazard assessment is distinguished from more traditional approaches to fire safety in two

ways. First it allows one to trace the contribution of a given product fire property to the hazard of the fire, so that the effects of changes in the product design or materials of construction can be quantified. Second, the resulting requirements are often more flexible and tend to avoid lists of fixed criteria.

## **II. Steps in the Process**

There are four steps in the hazard assessment process: 1.) analyzing fire scenarios to identify the most important aspects of hazard and leverage points for controlling them; 2.) formulating safety objectives by setting limits on the allowable contribution of material products to the overall hazard; 3.) identifying the fire and smoke properties to be controlled and the test methods needed; 4.) setting criteria and establishing the order of the requirements:

### **Step 1 - Scenario Analysis**

Fire incidents can be classified by scenario: the combination of physical circumstances surrounding the incident. Common elements included in the scenario are fire location, ignition source, item ignited and severity. In general, a different analytical procedure is required for each scenario for which a hazard assessment is desired. For this reason, there is usually a great premium placed on identifying a few scenarios which represent reasonable limiting situations of various kinds.

Aircraft fire scenarios may be classified both by the source of a fire exposure and the type of product affected. A simplified matrix showing seven (and potentially nine) different types of scenario is presented in Table I. Three potential sources of fire exposure are listed: fires originating in the aircraft cabin itself; fires originating in the "operating" portions of the aircraft, e.g. such as electronic and luggage bays, e.g., electrical short-circuits; and those originating outside the cabin, as in an engine fire or a post-crash fire. Three classes of potentially ignitable products can be identified: cabin furnishings, such as seats and wall linings; wire and cable used for power and communications; and concealed combustibles, such as nonmetallic structural components, carry-on baggage and stowed luggage. A hazard analysis would be required for each scenario deemed plausible. In this case, the ignition of wiring and concealed combustibles by an exterior fire may not be realistic or have manageable consequences, so they are of questionable plausibility.

As an illustrative example of the approach, this paper will concentrate on potential hazard occasioned by the ignition of wiring in an operating space and the exposure of passengers to the resulting heat and smoke.

### **Step 2 - Formulating Safety Objectives**

Although it is desirable to detect and extinguish all fires while they are confined to the item of origin, this cannot always be accomplished so a hazard assessment usually proceeds from somewhat more broadly-framed objectives, such as:

"Wire and cable shall be resistant to ignition from a small source. If exposed to a larger source, the cable shall contribute no more hazard than that produced by the exposure fire itself."

Of course, this objective cannot be met until one defines exactly what one means by a large source. This task in practice may require a survey of fire experience and a good deal

**TABLE 1**  
**Ignition Scenarios for Various Fuel Types and Locations**

<u>Source of Exposure Fire</u>	<u>Cabin Furnishings</u>	<u>Wire/Cable</u>	<u>Concealed Combustibles</u>
passenger cabin	direct or radiant ignition	spread or burn through from interior required	spread or burn through from cabin interior required
operating spaces	spread or burn through to cabin interior required	direct or radiant ignition	direct or radiant ignition
exterior (post crash)	direct radiant exposure through windows or openings in fuselage	?	?

of analysis. For purposes of illustrating the technique, an exposure fire of 250 kW will be used. A fire of this size can be sustained by a ventilation through an opening about two feet (.6m) on a side and would typically involve burning of a fire bed of 5 to 10 square feet (.5 to 1 sq. m). As such, it is of a size to be reasonably expected, for example, from a burning item or luggage of burning waste container.

In addition, since wiring is continuous and not a discrete fuel package, like a seat, it is necessary to define a "basis amount" of cable for which requirements will be set. This is also a matter of choice, and will depend on the function of the cable/wiring but, for purposes of this example, a basis amount of 50 one-meter lengths is used.

### **Step 3 - Formulating Protection Strategies and Safety Expectations**

Strategies will be product-specific. For cable systems it is suggested that a high level of radiant energy be required to ignite the cable. In such cases, the cable will usually burn only when it is exposed to a fire of considerable size and, if the exposure fire is removed, the burning cables will generally go out. Thus, it is possible to set requirements on smoke production which are related to the exposure fire - as in "a fixed number of unit length cables will provide no more than 'x' percent of the hazard of the exposure fire".

### **Step 4 - Test Method Selection**

Six fire/smoke properties are important:

- The critical radiant flux for ignition;
- The ignition time at some elevated radiant flux, e.g., 40 kW/m<sup>2</sup>;
- The heat release rate per unit area at the elevated flux;
- The mass loss rate per unit area at the elevated flux;
- The specific extinction area of the smoke (i.e. the optical density of a given mass concentration of smoke);
- The toxic potency of the smoke, measured under the same radiant flux conditions as the other properties.

At the present, the most widely used method for obtaining everything but the toxic potency is the cone calorimeter, ASTM E13254 (1). An alternative is the Factory Mutual Flammability Apparatus (2). Smoke toxic potency can be measured directly using any of several animal exposure protocols (3,4,5) or indirectly using chemical analysis of the smoke in combination with an 'n-gas' computational scheme (6).

### **Step 5 - Setting Criteria**

The objective defined above dictates the quantitative requirements. In this case, there are four of them:

- A close packed horizontal array of cable shall not ignite at a radiant flux of 25 kW/m<sup>2</sup> or less.

- The heat release rate of burning of cable shall be such that a burning 1 meter run of 50 cables shall be no more than that of the exposure fire.
- Smoke production of cable shall be such that a burning 1 meter run of 50 cables will diminish escape time in a compartment no more than the exposure fire alone.
- Smoke from a burning 1 meter run of 50 cables shall have an incapacitating effect no greater than that of the exposure fire.

The four criteria can be written as mathematical expressions involving one or more of the seven measurable cable properties - six fire and smoke parameters plus the cable diameter. This means that more than one set of cable properties can meet the requirements. This will continue to be true in principle so long as the number of different cable properties measured is at least one more than the number of requirements.

The formulation of the requirements into a test scheme is presented in Figure 1. The derivation of each requirement is given in the Appendix.

### III. Discussion

#### A. Applicability

The practice is based upon the formalism of setting a limit on the allowable contribution of a given amount of the product to the total heat and smoke produced, assuming that the total fire is the sum of the exposure fire and the product fire. It depends upon requiring that the product be relatively resistant to ignition and anticipates that, under conditions where only the exposure fire and product are burning, if the exposure fire were removed or extinguished, the product itself would burn at a very low rate or be extinguished. It also assumes that the tests (e.g. toxic potency) employed really do predict product performance under actual combustion and exposure conditions.

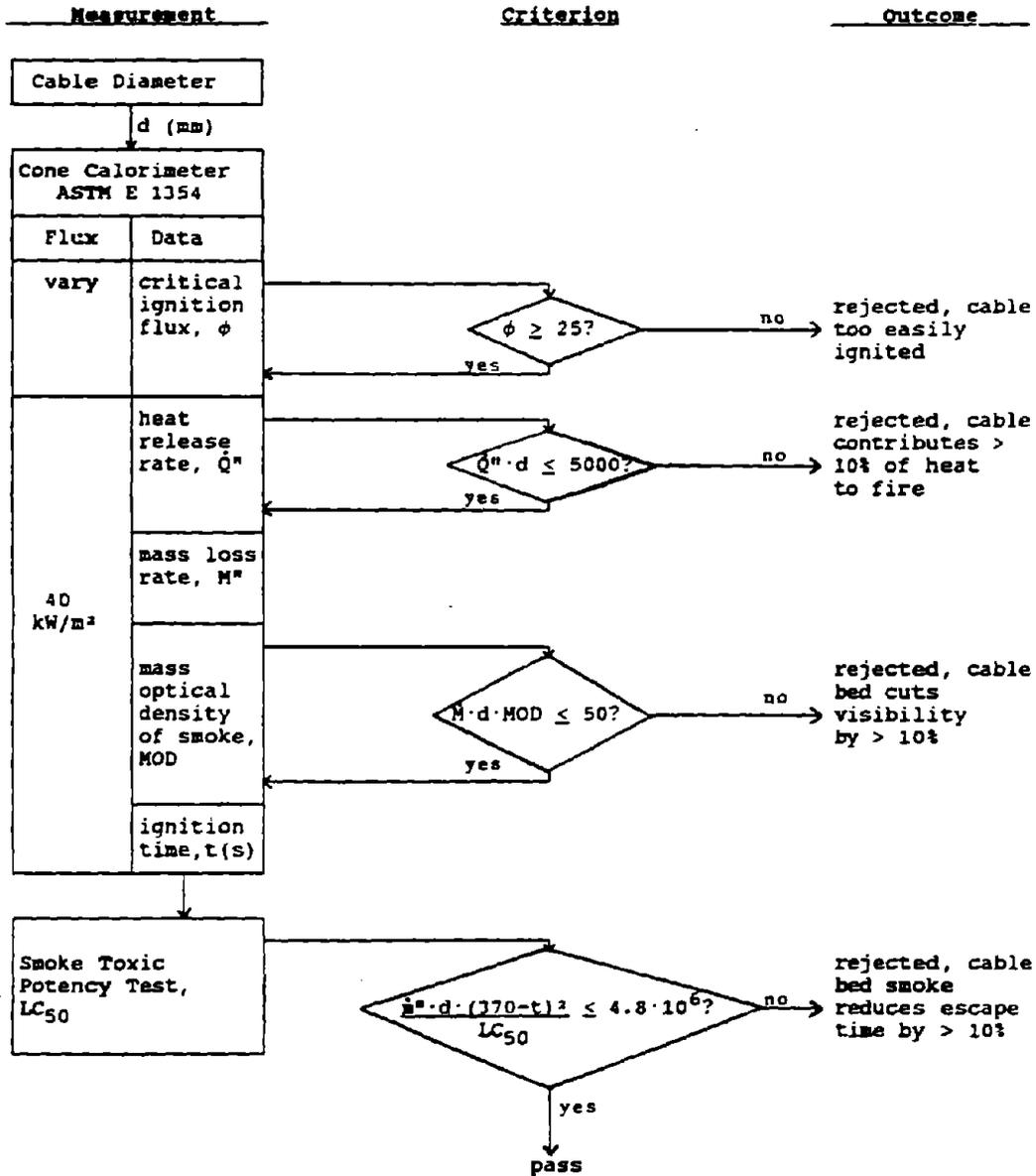
In effect, the size of the exposure fire which is selected is a measure of the stringency of the performance criteria for the product. The smaller the fire selected, the smaller will be the allowable amount of heat, smoke, etc. produced by the product. Whether to use the maximum possible fire size, the most probable fire size, or some other value, which corresponds to the smallest *serious* fire likely to occur is the choice of the analyst.

This analysis is based on pre-flashover conditions. When the fire reaches flashover the approximations and assumptions which underlie the analysis no longer hold. Nevertheless, the pre-flashover situation is by far the more appropriate for treatment of in-flight fire safety, because physical escape is not immediately possible. In this respect, it is useful to note that the buildup of smoke, as controlled by the criteria, may have more useful alternative formulations depending on the overall philosophy of fire control.

#### B. Flexibility

For example, it may be desired to limit the incapacitation time of the smoke from the exposure fire and the cable to a level closer to that of the exposure fire alone. Table 2 shows the burning behavior and toxic potency of the smoke required for the incapacitation time to more closely approach its value when only the exposure fire is burning. Moving  $r$  from 0.5,

**FIGURE 1**  
**Practical Hazard Assessment:**  
**Sample Test/Criteria Scheme for Cable**



**TABLE 2**

**Dependence of Incapacitation Time of Burn  
and Toxicity Properties of Cable**

<u>Fraction (r) of Incapacitation Time from Exposure Fire Alone (t<sub>0</sub>)</u>	<u>Criterion: <math>\dot{m} (r t_0 - t_i)^2 / LC_{50}</math></u>
.5	$\leq 2$
.8	$\leq .4$
.9	$\leq .2$
.95	$\leq .07$

- $\dot{m}$  = mass loss rate of basis cable amount at 50 kW/m<sup>2</sup>
- t<sub>i</sub> = ignition time of cables at 50 kW/m<sup>2</sup>, s
- LC<sub>50</sub> = toxic potency of combustible cable sheating g/m<sup>3</sup>

50% of the incapacitation time of the exposure fire, to 0.9, 90% of the original incapacitation time (i.e., confining the cable contribution to 10% of the total toxic hazard), requires about a 30-fold improvement in the aggregate cable properties as expressed by the term on the right that involves mass loss rate, ignition time and toxic potency.

In general, other objectives and assumptions can be employed, so long as they can be approximated by closed-form expressions or some mechanism of keeping apparent the relationship between fire properties and expected hazard. Practical hazard assessment, because of its relatively simple formulation, permits the regulator or designer to see readily the engineering consequences of a given fire safety objective and, conversely, allows one to estimate fairly quickly the expected benefits of alternative choices in products and materials.

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**APPENDIX**  
**Derivation of Performance Requirements**

**I. DEFINITIONS**

Toxic Potency

- LC<sub>50</sub> (g/m<sup>3</sup>) - smoke concentration which kills half (50%) of the exposed animals in an exposure period of 30 minutes.
- LC(Ct)<sub>50</sub> (g-min/m<sup>3</sup>) - lethal smoke dose, the product of smoke concentration and exposure time necessary to kill half of the exposed animals.  
(Note that L(Ct)<sub>50</sub> = LC<sub>50</sub> × 30 min)
- TI (no units) - toxicity index, alternative formulation to LC<sub>50</sub>. TI = 100 g/m<sup>3</sup>/LC<sub>50</sub>.

Fire Properties

- $\dot{Q}$  (kW) - heat release rate of a burning material
- $\dot{m}$  (g/s) - mass loss rate of a burning material
- $\dot{Q}''$ ,  $\dot{m}''$  (kW/m<sup>2</sup>) - heat release and mass loss rate per unit area of burning sample
- H (kJ/g) - heat of combustion
- $\phi$  (kW/m<sup>2</sup>) - heat flux, radiant energy imposed per unit area of sample

Other Parameters

- $\sigma$  (m<sup>2</sup>/g) - specific extinction area [i.e., the extinction coefficient] of the smoke, also called the mass optical density, or MOD
- t (s) - time
- V (m<sup>3</sup>) - volume
- d (mm) - cable diameter

Subscripts: "c" refers to cable; "f" refers to exposure fire

## II. Assumptions

- The dose of smoke necessary for incapacitation is one quarter of the lethal dose.
- Aircraft cabin volume,  $V = 350 \text{ cu.m}^3$
- Fuel for exposure fire:
  - $\dot{m}_f$  = mass loss rate = 10 g/s
  - $H_f$  = heat of combustion = 25 kJ/g
  - $\sigma_f$  = specific smoke extinction area = .25m<sup>2</sup>/g
  - $L(Ct_{50})_f$  = toxic potency dose of fuel smoke = 600 g-min/m<sup>3</sup> (LC<sub>50</sub> = 20 g/m<sup>3</sup> TI = 5)

## III. Computations

### Heat Release Requirement

Heat release rate of 1 meter run of 50 cables shall be no more than 250 kW (equal to exposure fire)

Heat Release Rate of Exposure Fire = 250 kW = Heat Release Rate of Cable

Heat Release Rate of Cable =  $\dot{Q}''$  x Surface Area of Cable Run

Surface area  $\cong 50 \times d \times 1\text{m} = (.05d) \text{ m}^2$ , since  $d$  is in mm

$$\dot{Q}'' \times (.05d) \leq 250 \text{ kW}$$

$$\dot{q}'' \leq \frac{5000 \text{ kW/m}^2}{d}$$

### Smoke Production Requirement

Smoke density in compartment

$$OD = \frac{t}{V} (\dot{m}_f \sigma_f + \dot{m}_c \sigma_c)$$

The limiting smoke density for sight-directed escape is commonly taken as  $0.25 \text{ m}^{-1}$ . When only the exposure fire is burning ( $\dot{m}_c = 0$ ), the time,  $t_0$ , to reach this level of smoke density is

$$t_0 = \frac{0.25 V}{\dot{m}_f \sigma_f}$$

If the cable is allowed to contribute as much smoke as the exposure fire when the requirement is that, when the time elapsed is 50% of  $t_0$ , the smoke density not exceed the level needed for escape

$$0.25 \geq \frac{0.5 t_0}{V} (\dot{m}_f \sigma_f + \dot{m}_c \sigma_c)$$

Substituting for  $t_0$ , one obtains

$$\frac{\dot{m}_c \sigma_c}{\dot{m}_f \sigma_f} \leq 1$$

$$\text{or } \dot{m}_c \sigma_c \leq 2.5 \text{ m}^2/\text{s}$$

$$\text{as above, } \dot{m} = \dot{m}'' \times (.05d)$$

#### Escape Time Requirement

The smoke dose takes on over time  $t$ , during which a material is burning, is the integral of the smoke concentration for that period:

$$D = \int_{t_1}^{t_2} c dt = \frac{1}{V} \int_{t_1}^{t_2} \dot{m} dt$$

The incapacitating and lethal effects of smoke from different sources are thought to be additive, so the smoke dose from a fire in which cable is exposed can be written:

$$\frac{D_c}{L_c} + \frac{D_f}{L_f} = \text{total fraction of lethal dose}$$

The limit to escape time is reached when the smoke dose taken on by those exposed reaches an incapacitating level, here taken to be one quarter of the lethal dose, i.e..

$$\frac{D_c}{L_c} + \frac{D_f}{L_f} = \frac{1}{4}$$

When only the exposure fire is burning, i.e., there is no cable present, the escape time limit,  $t_o$ , is given by

$$\frac{1}{4} = \frac{D_f}{L_f} = \frac{1}{L_f V} \int_0^{t_o} \int_0^{t_o} \dot{m}_f dt^2 = \frac{\dot{m}_f t_o^2}{2 L_f V}$$

$$\text{and } t_o^2 = \frac{L_f V}{2 \dot{m}_f} ; t_o = 740s$$

When the cable is burning as well, we require that the incapacitating dose not be exceeded when the time,  $t$ , is 50% of  $t_o$ , or 370s.

$$\frac{1}{4} \geq \frac{D_f}{L_f} + \frac{D_c}{L_c} = \frac{\dot{m}_f t^2}{2 L_f V} + \frac{\dot{m}_c (370 - t_{ig})^2}{2 L_c V}$$

(The cable does not burn for the entire time interval  $t$ , but only after it ignites at  $t_{ig}$ )

Noting that  $t^2 = .25 t_o^2$ , and substituting for  $t_o$ ,

$$\frac{\dot{m}_c (370 - t_{ig})^2}{V L_c} \leq .375, \text{ or:}$$

$$\frac{\dot{m}_c (370 - t_{ig})^2}{L C_{50}} \leq 2.4 \times 10^5 \text{ sm}^3, \text{ where, again } \dot{m} = \dot{m}'' (.05d)$$

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FIRE RESISTANCE AND MECHANICAL PROPERTIES FOR PHENOLIC PREPREGS

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ABSTRACT

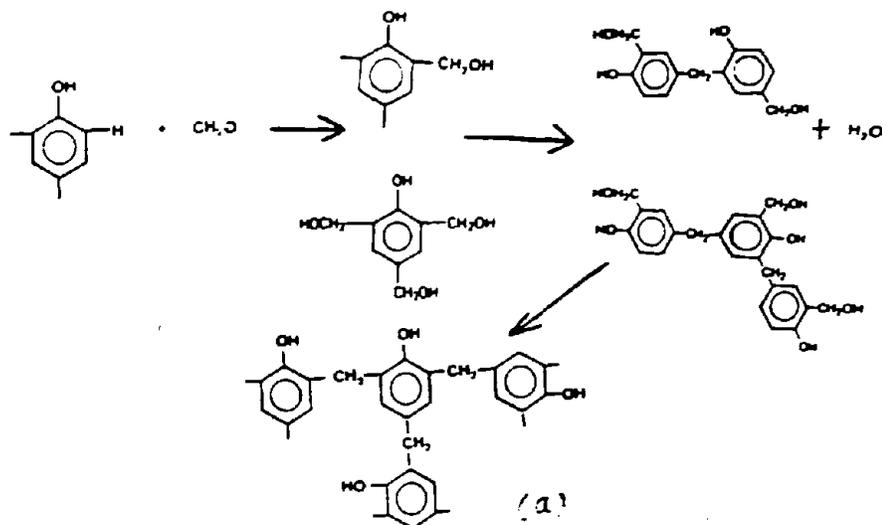
This paper discusses fire resistance performance, thermal analysis and mechanical properties of glass fiber laminates prepared with four thermal cure phenol/formaldehyde resins. Prepregs for the laminates were produced by conventional solution process. This study was performed to optimize FR, and thermal and mechanical properties by changing formaldehyde/phenol (F/P) mole ratio.

An optimum F/P ratio was identified for maximum fire resistance and thermal properties without any sacrifice in mechanical properties. The resins evaluated in this study easily met Federal Aviation Administration (FAA) requirements for OSU heat release and NBS smoke tests. Also, all laminates exceeded the mechanical limits of MIL-R-9299C specifications. The resins are suitable for prepregs and honeycomb for aircraft interior applications.

INTRODUCTION

Today phenol-formaldehyde (PF) resins are used in the aircraft interiors primarily due to their excellent fire resistance performance. PF resins are inherently fire resistant, they offer good chemical resistance and elevated temperature properties at a relatively low cost<sup>(1-3)</sup>. Recent articles by Sorathia et. al.<sup>(4-5)</sup> have shown superior fire resistance characteristics of PF laminates compared to several thermoplastics and thermosets products. Zaks et. al.<sup>(6)</sup> studied effects of substituted phenol and formaldehyde monomers on flammability and char yield. All the available data have discussed phenolics in general without disclosing phenol to formaldehyde mole ratio.

This study was performed with four PF resole resins with different F/P ratios to determine their fire resistance performance, thermal analysis and mechanical properties. The purpose was to establish a baseline information to optimize properties. A product with an optimized F/P ratio and maximum fire resistance performance is more desirable for further modifications to meet end users toughness and processing requirements. The chemistry of resole resins as shown below involves addition and condensation reactions which lead to crosslinked resins.



The structure (a) is expected to vary with F/P ratio and should give maximum number of crosslinks after cure with stoichiometric amounts of phenol and formaldehyde. F/P of 1.5 was considered for stoichiometric amounts. In this investigation, F/P ratios were below (excess phenol) and above (excess formaldehyde) the stoichiometric values. The ratios are not disclosed due to the company proprietary policy.

#### EXPERIMENTAL DETAILS

Some information on resin properties and prepregs is summarized in Table 1. Prepregs were produced using 19" wide 7781 glass fabric with A-1100 soft finish by conventional solution impregnation process. Fourteen-ply (18" x 36") and ten-ply laminates were produced for mechanical and FR evaluations, respectively. All laminates were cured at 325°F for ten minutes under 250 psi.

Phenolic System	F/P Ratio	Resin		Prepreg	
		Solids (%)	Free Formaldehyde (%)	Resin Content (%)	Flow (%)
A	Low	66.5	0.4	33.9	8.0
B	↓	63.2	0.6	33.8	6.0
C	↓	63.0	0.6	34.0	6.5
D	High	62.7	0.8	35.5	6.5

Flow: 4" x 4" -- 5 minutes @ 340°F under 500 psi

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Flexural, tensile and compression tests were performed as per ASTM test procedures:

Flexural - ASTM D-790-90  
Tensile - ASTM D-638-89 Type 1  
Compression - ASTM D-695-89 Type 1

OSU heat release test (ASTM E-906) was conducted by Dr. Ed Smith of Ohio State University on 6" x 6" specimens. NBS smoke optical density (ASTM F-814) for 3" x 3" plaques and Flame Spread Index (FSI) ASTM E-162 were performed by HPMA Laboratory (Reston, VA). FSI was determined on 6" x 18" specimens, the standard test method for surface flammability of materials using a radiant heat energy source, provides a quantitative measure of surface flammability.

Limiting Oxygen Index (LOI) was determined on 0.5" x 5" specimens by VTEC Laboratories (Bronx, NY) using ASTM D-2863 procedure. LOI reveals flammability behavior; high values correspond to fire resistance. For char yield, Thermogravimetric Analysis (TGA) were run on neat cured resins. The scan was run on 10-15 mg sample from ambient to 900°C at 10°C/minute under nitrogen. The percent weight retention at 900°C was reported as percent char yield. Tg's on six-ply laminates were measured by DuPont DMA-982 at a heating rate of 10°C/minute.

## RESULTS AND DISCUSSION

All prepregs had low tack and good drape. Tack/drape and flow remained unchanged after two months at room temperature. During prepregging, the resin advancement was noted higher for high F/P ratio compositions. Therefore, low F/P compositions provided wider B-staging windows (less sensitive to processing conditions) than the high F/P formulations.

Results on fire resistance performance determined by OSU heat release, NBS optical smoke density, Limiting Oxygen Index, and Flame Spread Index are summarized in Tables 2 through 4. Data for flex, tensile and compression are presented in Tables 5 through 7.

Thermal analysis results measured by Dynamic Mechanical Analysis and Thermogravimetric Analysis are presented in Tables 8 and 9, respectively. In Tables 10 and 11, effects of several solvents on retention of mechanical properties at room temperature and 500°F are shown only for Laminate C. Specific details for all results are discussed below:

### Fire Resistance

The heat release data on all laminates were significantly below the FAA 65/65 requirement. A close comparison showed lowest values for Laminate C. This appears to be in agreement with the char yield (below) results on Laminate C. Table 2 also showed the effect of thickness for Laminates A and C on the OSU response. No difference was found (within experimental variation).

In Table 3, the specific optical density ( $D_s$  @ 4 min.) and maximum specific optical density ( $D_m$ ) are shown for all laminates in flaming mode only. Interestingly,

the Laminate C smoke emissions were the lowest, in particular the maximum specific optical density. FSI and LOI results are presented in Table 4, F/P had no effect on these tests. FSI's were comparable to the published results for phenolic laminates. LOI of 100% are higher than those reported in the literature (60-85%). LOI results on these laminates were generated at 25°C. The results are temperature dependent (higher temperatures correspond to lower values).

Table 2			
OSU HEAT RELEASE RESULTS			
Phenolic System	Resin Content	F/P	2 Min. Heat Release/Max. Heat Release Rate (KW min. <sup>-2</sup> /KW m. <sup>-2</sup> )
A	32.0 <sup>a</sup> 32.0 <sup>b</sup>	Low	13/28 18/28
B	28.4 <sup>a</sup>	↓	15/30
C	29.0 <sup>a</sup> 34.0 <sup>b</sup>	↓	3/25 3/16
D	31.9 <sup>b</sup>	High	7/40
<sup>a</sup> 10 Plies <sup>b</sup> 6 Plies			

Table 3		
NBS Smoke Results		
Phenolic System	Ds @ 4 minutes	Gm @ Minutes
A	5	16 @ 12.5
B	1	10 @ 12
C	0	3 @ 16.5
D	4	9 @ 11.4
10-Ply Laminates		

Table 4		
FLAME SPREAD INDEX (FSI) AND LIMITING OXYGEN INDEX (LOI)		
Phenolic System	FSI	Limiting Oxygen Index (%)
A	1	100 <sup>a</sup>
B	1	100 <sup>a</sup>
C	1	100 <sup>a</sup>
D	1	100 <sup>a</sup>
10 Ply a = Extinguished Immediately		

#### Mechanical Properties

Flexural and tensile properties are summarized in Tables 5 and 6. They were close for all laminates. No significant change was noted with an increase in F/P ratio. For comparison, MIL-R-9299C mechanical requirements (criteria for Boeing Nomex Core Specification B-124-N) are included. All laminates were above the MIL 9299 Grade A and Grade B requirements. Results were comparable to polyester and epoxy laminates<sup>(7)</sup>.

Compressive strengths shown in Table 7 were above the MIL specifications. Laminate A with the lowest F/P had the highest compressive strength. This is associated to the higher resin modulus due to excess phenol. In a separate experiment, neat resin modulus was measured. It was highest for System A. Low CV's by these tests demonstrated controlled test conditions, good consolidation and homogeneous curing.

Table 5					
ROOM TEMPERATURE FLEXURAL PROPERTIES (ASTM D-790)					
Phenolic Resin	Resin Content (%)	Flexural Strength (psi)	CV (%)	Flexural Modulus (psi x 10 <sup>6</sup> )	CV (%)
A	31.6	96,390	3.3	4.36	1.4
B	28.4	87,620	2.3	4.22	2.4
C	31.5	96,540	1.2	4.08	2.4
D	34.1	102,220	2.0	3.70	1.1
MIL-R-9299C Requirement	----	50,000 <sup>c</sup> 73,000 <sup>d</sup>	----	3.0 <sup>c</sup> 3.5 <sup>d</sup>	

Table 6						
ROOM TEMPERATURE TENSILE PROPERTIES (ASTM D-638, TYPE I)						
Phenolic Resin	Resin Content (%)	Tensile Strength (psi)	CV (%)	Tensile Elongation (%)	Tensile Modulus (psi x 10 <sup>6</sup> )	CV (%)
A	31.6	68,390	2.7	2.2	4.43	3.4
B	28.4	53,780	1.0	1.8	4.19	1.4
C	31.5	70,950	1.6	2.2	4.49	2.2
D	34.1	65,840	1.1	2.4	4.00	1.3
MIL-R-9299C Requirement	----	40,000 <sup>c</sup> 46,000 <sup>d</sup>	----	----	----	--

Table 7					
ROOM TEMPERATURE COMPRESSIVE PROPERTIES (ASTM D-695)					
Phenolic Resin	Resin Content (%)	Compressive Strength (psi)	CV (%)	Compressive Modulus (psi x 10 <sup>6</sup> )	CV (%)
A	31.6	94,950	2.6	4.22	0.7
B	28.4	70,180	3.8	4.08	1.7
C	31.5	84,680	3.1	4.30	1.4
D	34.1	73,300	2.7	4.01	2.0
MIL-R-9299C Requirement	----	35,000 <sup>c</sup> 58,000 <sup>d</sup>	----	----	--
<sup>c</sup> Grade A Requirement <sup>d</sup> Grade B Requirement					

#### Tg and Char Yield Evaluations

Table 8 shows Tg results for as-made and post-cured specimens. Tg's were taken as loss modulus maximum peaks. Laminate C showed the highest Tg for both as made and post cured samples. This is attributed to maximum crosslinks for this composition. TGA results on neat resins are given in Table 9. The highest weight retention was obtained for System C. TGA and Tg results for Laminate C were consistent with the OSU and maximum smoke density values.

Table 8			
T <sub>g</sub> BY DMA FOR AS-MADE AND POST CURED LAMINATES			
Phenolic Laminate	F/P	T <sub>g</sub> (°F) - Loss Modulus Max.	
		As-Made	Post Cured
A	Low	350	450
B	↓	406	560
C	↓	415	600
D	High	392	540

As-Made: 325°F cure for 11 minutes.

Post-Cured: 2 hours @ 350°F followed by 2 hours @ 450°F for DMA specimens (0.12" x 0.4" x 3.0")

Table 9		
TGA CHAR YIELD VS F/P RATIO		
Resin	F/P	% Wt. Retention @ 900°C
A	Low	55.2
B	↓	60.6
C	↓	65.0
D	High	61.0

Test: 10°C/minute to 900°C under N<sub>2</sub>, 10-15 Mg cured resin sample.

All laminates were soaked in 10% sodium hydroxide solution. Laminate C showed best resistance in 10% sodium hydroxide solution. This plaque, after a two-month soak in the caustic solution, did not disintegrate and was dimensionally stable. Laminate D swelled but did not disintegrate; Laminates A and B completely disintegrated.

#### Solvent Resistance and Elevated Temperature Performance

Due to optimum FR and thermal properties, Laminate C was further evaluated for solvent resistance and elevated temperature properties. Results are summarized in Tables 10 and 11. High retention of flexural strength after a three-month soak demonstrated excellent solvent resistance for Laminate C. The 500°F flex strength data have easily met the MIL 9299 criteria.

Table 10 FLEX STRENGTH RETENTION AFTER 3-MONTH SOAK FOR LAMINATE C	
Solvent	% Flex Strength Retention @ RT Compared to Control
H <sub>2</sub> O	100
10% NaCl Solution	100
5% NaOCl Solution	95
10% NH <sub>4</sub> OH	100
Control: Laminate C, Kept @ RT - No Soak	

Table 11 EFFECT OF POST CURING ON PROPERTIES FLEXURAL PROPERTIES AT 500°F FOR LAMINATE C			
Postcure	Test Temp. °F	% Strength Retention Compared to Room Temperature	% Modulus Retention Compared to Room Temperature
100 hours @ 500°F	500	89	75
200 hours @ 500°F	500	65	75
500 hours @ 500°F	500	37	54

#### SUMMARY

A systematic study for F/P ratio versus performance has identified one composition "C" with excellent fire resistance, high char yield, and high retention of properties after soaking in different solvents at room temperature. This composite also demonstrated excellent flexural properties at 500°F. System C is more suitable than A, B and D for further modifications to meet the end users toughness and processing needs. Resin System C has been commercialized as GP-5236 for solvent-based prepreg and honeycomb applications.

#### ACKNOWLEDGEMENTS

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## BIOGRAPHY

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

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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/m<sup>2</sup> and total heat release of 65 kW min/m<sup>2</sup>.

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

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. Therefore, 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 (Mittler, 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 Mittler 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.

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FLAMMABILITY PARAMETERS OF MATERIALS:  
Ignition, Combustion, and Flame Spread

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ABSTRACT

In this paper, flammability parameters associated with the ignition, combustion, and flame spread processes and their usefulness for the advanced fire resistant aircraft interior materials are discussed. The flammability parameters discussed are: a) *critical heat flux (CHF)* and *thermal response parameter (TRP)*, associated with ignition, b) *heat release parameter (HRP)* and *fire propagation index (FPI)*, associated with combustion and flame spread.

The CHF, TRP, and HRP values can be derived from the data measured in the most commonly used apparatuses: 1) the Ohio State University (OSU) Heat Release Apparatus, which is the Federal Aviation Administration's (FAA) standard apparatus, 2) the Factory Mutual Research Corporation (FMRC) Flammability Apparatus, and 3) the National Institute of Standards and Technology (NIST) Flame Spread Apparatus (LIFT) and the Cone Calorimeter. The OSU and FMRC Apparatuses and the Cone Calorimeter generate very similar data for ignition and heat release rate for small horizontal and vertical samples under ambient conditions. The NIST LIFT and the FMRC Apparatuses generate very similar data for lateral, upward and downward flame spread for slabs and cylinders under ambient conditions. The FMRC Apparatus is also used to perform Flame Radiation Scaling experiments to determine the range of flame radiative and convective flame heat fluxes transferred to the surface during combustion in small- to large-scale fires, pertinent to the aircraft interior material fire scenarios leading to flashover.

This paper describes the flammability parameters in terms of the fundamental scientific principles. Numerous examples of data are presented in tables and graphs.

INTRODUCTION

For the protection of life and property from fires, quantitative information is needed for fire initiation, heat release, flame spread, and generation of smoke, toxic, and corrosive products to assess fire hazard and ease of fire control and extinguishment. If heat is the major contributor to hazard, it is defined as thermal hazard (Tewarson 1992). If fire products (smoke, toxic, corrosive and odorous compounds) are the major contributors to hazard, it is defined as non-thermal hazard (Tewarson 1992). Fire extinguishing agents can also contribute towards non-thermal hazard (Tewarson 1992). For obtaining quantitative information, fundamental relationships have been developed and numerous apparatuses identified as heat release rate, flammability, and flame spread apparatuses calorimeters, etc. are now being used. The FAA has developed improved fires test standards based on some of these apparatuses to improve aircraft interior fire safety (Sarkos 1989).

Heat is generated as a result of the chemical reactions between: 1) pyrolyzing material vapors and oxygen in the gas phase, and 2) pyrolyzing material surface and oxygen in the solid phase. Heat generated in chemical reactions is defined as the chemical heat (Tewarson 1988). The rate of generation of chemical heat is defined as the chemical heat release rate. The chemical heat release rate distributes itself into a convective component, defined as the convective heat release rate, and into a radiative component, defined as the radiative heat release rate (Tewarson 1988). Convective heat release is associated with the flow of hot products-air mixture and radiative heat release is associated with the electromagnetic emission from the flame.

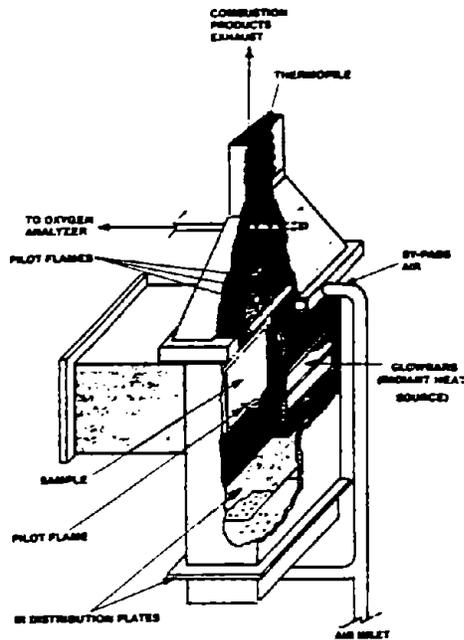
The release of heat in the gas phase is generally associated with two zones: 1) **Reduction Zone**: materials are pyrolyzed and generate pyrolysis products, for example materials with carbon and hydrogen atoms in their chemical structures, generate mostly soot, CO, hydrocarbons and other intermediate products. The amounts and nature of the pyrolysis products depend on the chemical structures of the materials, exposed surface area, and the imposed heat flux. No heat is released in this zone and 2) **Oxidation Zone**: the pyrolyzed products are oxidized, for example, soot, CO, hydrocarbons, and other intermediate products are oxidized to CO<sub>2</sub> and H<sub>2</sub>O with the consumption of O<sub>2</sub>, and chemical heat is released into a convective and a radiative component. If the materials are oxidized completely to CO<sub>2</sub> and H<sub>2</sub>O, the *generation efficiency* ( $\eta_j$ ), of CO<sub>2</sub> and H<sub>2</sub>O and the *chemical efficiency of combustion* ( $\chi_{chem}$ ) are all unity;  $\eta_j$  is defined as the ratio of the generation rate of a product to the maximum stoichiometric generation rate of the product;  $\chi_{chem}$  is defined as the ratio of the chemical heat of combustion ( $\Delta H_{chem}$ ) to the net heat of complete combustion ( $\Delta H_T$ ):

If the materials are not oxidized completely, the pyrolysis products for example, soot, CO, hydrocarbons, and other compounds are also released and  $\chi_{chem} < 1$  and  $\eta_j$  values for soot, CO, hydrocarbons, and other intermediate products become significant. The extent of oxidation and the amounts of chemical, convective, and radiative heats, soot, CO, hydrocarbons, and other intermediate products released depend on the flame temperature, amount of oxygen (ventilation), entrainment of air by the flame, and generation rates of the pyrolysis products. The  $\eta_j$  and  $\chi_{chem}$  values can be derived from the chemical heat release rates, generation rates of various products and mass combustion and pyrolysis rates measured in the Ohio State University (OSU) Heat Release Apparatus (Fig. 1A), the Factory Mutual Research Corporation (FMRC) Flammability Apparatus (Fig. 1B) and the Cone Calorimeter (Fig. 1C).

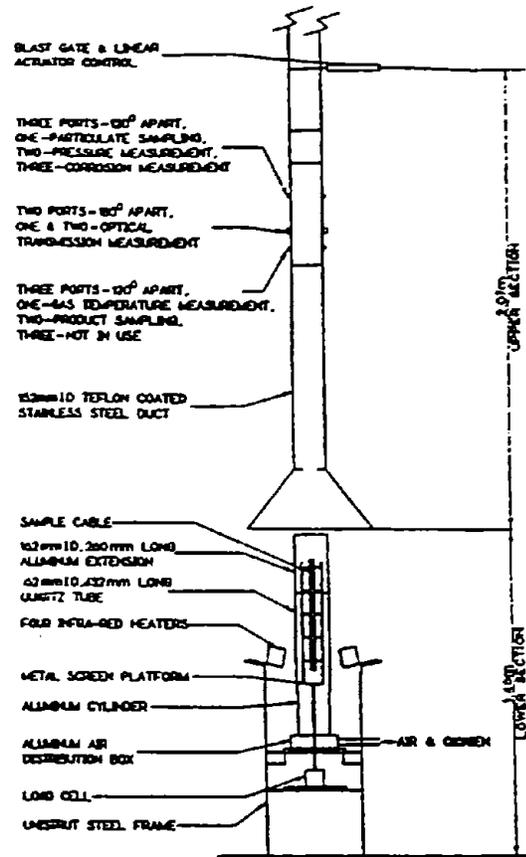
When the material surface is exposed to heat flux from its own flame and/or from external heat sources, vapors are generated due to *pyrolysis*. The vapors combine with air to form flammable vapor-air mixture. The mixture either auto-ignites or is ignited by heat sources that may be present, such as a pilot flame, spark, hot objects, and others. The process is defined as *ignition*. As a result of the heat flux exposure, the pyrolysis boundary or front is formed and moves across the surface of the material. *The movement of the pyrolysis front across the surface is defined as the flame spread and its rate as the flame spread rate* (Quintiere 1988, Tewarson and Khan 1988, Tewarson and Ogdén 1992). For self-sustained flame spread, convective and radiative heat release rates provide the necessary heat flux required for material pyrolysis (Quintiere 1988, Tewarson and Khan 1988, Tewarson and Ogdén 1992). Flame spread behavior of material is divided into three categories (Tewarson and Khan 1988, Tewarson and Ogdén 1992): 1) *decelerating or non-propagating*: flame spread rate decreases with time or flame spread is limited to ignition zone. Materials which show this type of flame spread behavior are classified as Group 1 materials. 2) *non-accelerating*: flame spread rate is independent of time. Materials which show this type of flame spread behavior are classified as Group 2 materials, and 3) *accelerating*: flame spread rate is a direct function of time. Materials which show this type of flame spread behavior are classified as Group 3 materials. The flame spread behavior of materials can be quantified in the NIST LIFT Apparatus (Fig. 1D) and the FMRC Apparatus (Fig. 1B).

In the ignition and flame spread processes, the pyrolysis products continue to combine with air and oxidize and generate heat and products. This process is defined as *combustion*.

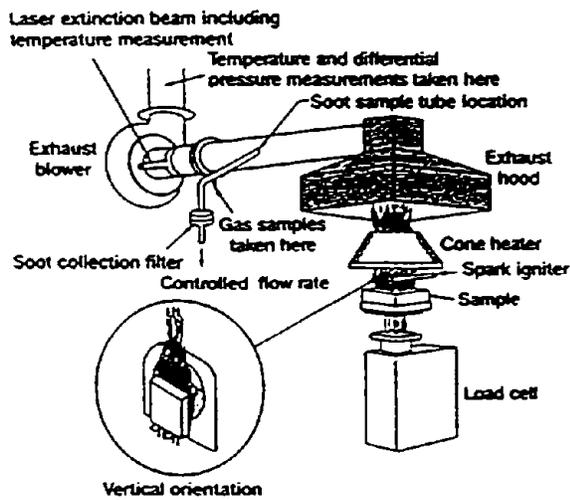
Heat, smoke, toxic, and corrosive products are generated in all the processes associated with ignition, pyrolysis, combustion and flame spread. *Flammability parameters* for ignition, pyrolysis, combustion and flame spread thus are important to assess thermal and nonthermal hazards in fires.



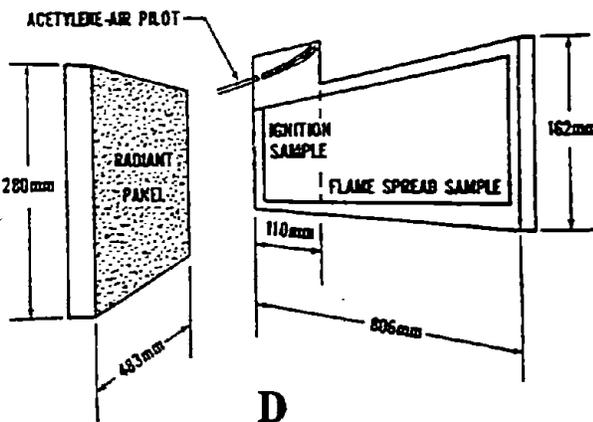
A



B



C



D

Figure 1. Heat Release and Flame Spread Apparatus. (A): The OSU Apparatus; (B): The FMRC Apparatus; (C): The Cone Calorimeter; (D): The LIFT Apparatus.

## FLAMMABILITY PARAMETERS AND EXPERIMENTAL MEASUREMENTS

### Critical Heat Flux (CHF) and Thermal Response Parameter (TRP) from Ignition Experiments

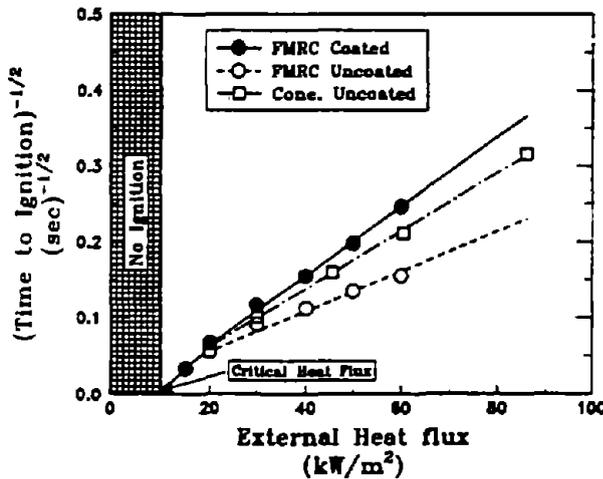
For fire initiation, a material has to be heated beyond its *critical heat flux (CHF) value*, defined as the minimum heat flux at or below which flammable vapor-air mixture is not generated and there is no sustained ignition (Tewarson and Khan 1988, Tewarson and Ogden 1992). As the surface is exposed to heat flux from the flame and/or external heat flux, initially most of it is transferred to the interior of the material. The rate with which heat is transferred, depends on the ignition temperature ( $T_{ig}$ ), ambient temperature ( $T_a$ ), material thermal conductivity ( $\kappa$ ), material specific heat ( $c_p$ ) and the material density ( $\rho$ ) (Quintiere 1988, Tewarson and Khan 1988, Delichatsios 1991, Tewarson and Ogden 1992). The combined effect of these parameters is expressed by the thermal response parameter (TRP) of the material (Tewarson and Khan 1988, Tewarson and Ogden 1992):

$$TRP = (\kappa \rho c_p)^{1/2} (T_{ig} - T_a) \quad (1)$$

where  $\kappa$  is in kW/m-K,  $\rho$  is in g/m<sup>3</sup>,  $c_p$  is in kJ/g-K, and TRP is in kW-s<sup>1/2</sup>/m<sup>2</sup>. Almost all the materials exposed to external heat in the OSU, the FMRC and the LIFT Apparatuses and the Cone Calorimeter behave as thermally thick materials, for which inverse of the square root of time to ignition is a linear function of external heat flux :

$$t_{ig}^{-1/2} = (4/\pi)^{1/2} \dot{q}_e'' / TRP \quad (2)$$

where  $t_{ig}$  is time to ignition (sec) and  $\dot{q}_e''$  is the external heat flux (kW/m<sup>2</sup>).



In the experiments,  $t_{ig}$  values are measured at various  $\dot{q}_e''$  values as shown in Fig. 2 for coated and uncoated polymethylmethacrylate (PMMA) sample. In the FMRC Apparatus, the sample surface is always coated with a very thin layer of black paint or fine graphite powder to avoid errors due to differences in the radiation absorption characteristics of the materials. In Fig. 2, the plot of  $t_{ig}^{-1/2}$  versus  $\dot{q}_e''$  is linear except close to the CHF value, as expected from Eq. (2). The TRP value is determined from the inverse of the slope of the linear portion of the curve, away from the CHF value (Tewarson and Khan 1988, Tewarson and Ogden 1992).

Figure 2. Ignition Data for Polymethylmethacrylate. The CHF value is determined from the

ignition experiments at several  $\dot{q}_e''$  values until a value is reached at or below which there is no sustained ignition for 15 minutes (Tewarson and Khan 1988, Tewarson and Ogden 1992). The Cone Calorimeter data in Fig. 2 are from Bahrauskas and Parker (1987). Sample surface is not coated in the Cone Calorimeter and in the OSU Apparatus. The time to ignition for same external heat flux values thus is longer and the calculated TRP value higher from the OSU Apparatus and the Cone Calorimeter than from the FMRC Apparatus. For example, for un-coated PMMA sample, the TRP

values from the FMRC Apparatus and the Cone Calorimeter are 434 and 382 kW-s<sup>1/2</sup>/m<sup>2</sup> respectively, compared to a value of 274 kW-s<sup>1/2</sup>/m<sup>2</sup> for the coated sample (Tewarson and Ogden 1992). The ignition data are also determined from the flame spread experiments in the NIST LIFT Apparatus (Fig. 1D) and are reported in term of  $\kappa\rho c_p$  and  $T_{ig}$  values. TRP values thus can also be obtained from the LIFT Apparatus.

The TRP values for selected materials derived from the ignition data for coated samples from the FMRC Apparatus and for un-coated samples from the Cone Calorimeter are listed in Table 1 as examples. As expected, for the common samples tested, the TRP values from the Cone Calorimeter are higher than they are from the FMRC Apparatus.

Higher CHF and TRP values suggest that materials are hard to ignite and have higher resistance to flame spread. In general, thermosets have higher TRP values than the thermoplastics. As expected, use of fire retardants and coatings increase the TRP values. As can be noted in Table 1, the ceramic and intumescent coatings increase the TRP values of vinyl ester-glass composite from 281 to 676 and 1471 kW-s<sup>1/2</sup>/m<sup>2</sup>, of epoxy-graphite composite from 481 to 2273 and 962 kW-s<sup>1/2</sup>/m<sup>2</sup>, and of phenolic-graphite composite from 400 to 807 and 1563 kW-s<sup>1/2</sup>/m<sup>2</sup> respectively. The glass fibers also increase the TRP values, for example for isophthalic polyester with 77 % glass from 296 to 426 kW-s<sup>1/2</sup>/m<sup>2</sup>, for polyvinyl ester with 69 % glass from 263 to 444 kW-s<sup>1/2</sup>/m<sup>2</sup> and for epoxy resin with 69 % glass from 457 to 688 kW-s<sup>1/2</sup>/m<sup>2</sup>.

**Table 1**  
**Thermal Response Parameter from the FMRC**  
**Flammability Apparatus<sup>a</sup> and the Cone Calorimeter<sup>b</sup>**

Materials <sup>c</sup>	TRP (kW-S <sup>1/2</sup> /m <sup>2</sup> )	
	FMRC	Cone
Flexible polyurethane foam	105	-
Polystyrene foam	125	168
Wood (red oak)	134	-
Wood (Douglas fir)	138	-
Polystyrene	162	-
Wood (hemlock)	-	175
Acrylic fiber 100%	-	180
Polypropylene	193	291
Styrene-butadiene	198	-
Wool 100 %	-	232
Crosslinked polyethylene	239	-
Polyester-30 % glass	-	256
Polyoxymethylene	269	-
Nylon	270	-
Polymethylmethacrylate	274	-
Polyether ether ketone-30 % glass	-	301
ABS	-	317
Polyethylene (high density)	-	364
Vinyl ester panel	440	-
<u>Halogenated Materials</u>		
Isoprene	174	-
Polyvinylchloride (PVC)	194	-
Plasticized PVC-3, LOI 0.20	-	285
Tefzel (ETFE)	356	-
Rigid PVC, LOI 0.50	-	388

(Table 1 continued on next page)

Table 1 (continued)

Materials	TRP ((kW-S <sup>1/2</sup> /m <sup>2</sup> ))	
	FMRC	Cone
Plasticized PVC-4, LOI 0.35	-	345
Plasticized PVC-3, LOI 0.30	-	397
Plasticized PVC-3, LOI 0.25	-	401
Teflon (FEP)	682	-
<i>Thermosets</i>		
Polyvinyl ester	-	263
Polyester <sup>a</sup> -glass composite	275	-
Vinyl ester-glass composite	281	-
Isophthalic polyester	-	296
Polyester <sup>b</sup> -glass composite	338	-
Polyester <sup>c</sup> -glass composite	382	-
Epoxy <sup>d</sup> -glass composite	388	-
Graphite composite	400	-
Phenolic-graphite composite	400	-
Kevlar-phenolic composite	403	-
Polyester <sup>e</sup> -glass composite	406	-
Epoxy <sup>f</sup> -glass composite	420	-
Isophthalic polyester -77 % glass	-	426
Polyester <sup>g</sup> -glass composite	430	-
Polyvinyl ester resin-69 % glass	-	444
Epoxy resin	-	457
Epoxy-graphite composite	481	-
Epoxy <sup>h</sup> -glass composite	500	-
Modified acrylic-FR	-	526
Epoxy <sup>i</sup> -glass composite	540	-
Phenolic composite	610	-
Vinyl ester-glass composite / cc	676	-
Phenolic laminate- 45 % glass	-	683
Epoxy resin-69 % glass	-	688
Phenolic-graphite composite / cc	807	-
Epoxy-graphite composite / ic	962	-
Vinyl ester-glass composite / ic	1471	-
Phenolic-graphite Composite /ic	1563	-
Epoxy-graphite composite / cc	2273	-
<i>Aircraft panel materials</i>		
Phenolic fiberglass	105	172
Epoxy kevlar	120	169
Epoxy fiberglass	156	198
Phenolic kevlar	185	258
Phenolic graphite	333	212

a: from Macaione and Tewarson 1990, Tewarson and Khan 1988, Tewarson and Ogden 1992; b: from Scudamore *et al* 1991; c: from Tewarson and Zalosh 1989. cc: ceramic coating; ic: intumescent coating

The above discussion suggests that the ignition technique can be used to determine the flammability parameters associated with ignition (CHF and TRP) for the advanced fire resistant aircraft interior materials to assess the reduction in fire hazard because of their use and passive fire protection provided by their fire resistant treatment.

## Flame Heat Flux from Combustion Experiments

Combustion is a process associated with the generation and oxidation of material vapors when the surface is exposed to heat flux primarily from its own flame and secondarily from external heat sources. Both thermal and nonthermal damages due to generation of smoke, toxic and corrosive products are important. The mass combustion rate is expressed as (Tewarson 1982, 1988, Tewarson and Ogden 1992):

$$\dot{m}'' = (\dot{q}''_e + \dot{q}''_{fr} + \dot{q}''_{fc} - \dot{q}''_{rr}) / \Delta H_g \quad (3)$$

where  $\dot{m}''$  is the mass combustion rate ( $\text{g}/\text{m}^2\text{-s}$ ),  $\dot{q}''_e$  is the external heat flux ( $\text{kW}/\text{m}^2$ ),  $\dot{q}''_{fr}$  is the flame radiative heat flux transferred to the material surface ( $\text{kW}/\text{m}^2$ ),  $\dot{q}''_{fc}$  is the flame convective heat flux transferred to the material surface ( $\text{kW}/\text{m}^2$ ), and  $\Delta H_g$  is the heat of gasification ( $\text{kJ}/\text{g}$ ).

The results of numerous small- and large-scale fire tests with pool-like geometry under ambient conditions, show that  $\dot{q}''_{fr}$  value increases and reaches an asymptotic limit, whereas  $\dot{q}''_{fc}$  value decreases and becomes much smaller than the  $\dot{q}''_{fr}$  value at the asymptotic limit in large-scale fires (Hottel 1959).

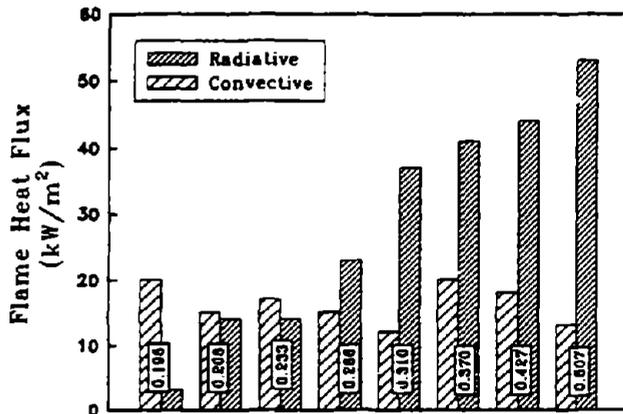


Figure 3. Flame Convective and Radiative Heat Flux to the Surface at Various Oxygen Mass Fractions for Polypropylene (Tewarson et al 1981)

It is also known that for a small-scale fire of fixed size, with buoyant turbulent diffusion flame, as the oxygen mass fraction,  $X_o$ , is increased,  $\dot{q}''_{fr}$  value increases and reaches an asymptotic limit, comparable to the limit in large-scale fires, whereas  $\dot{q}''_{fc}$  decreases and becomes much smaller than the  $\dot{q}''_{fr}$  value such as shown by the data in Fig. 3 for  $0.10 \times 0.10 \times 0.025$  m thick slab of polypropylene from the FMRC Apparatus (Tewarson et al 1981).

The increase in the  $\dot{q}''_{fr}$  value with  $X_o$  is due to the increase in the flame temperature and soot formation and decrease in the residence time in the flame (Tewarson et al 1981).

*Variation of  $X_o$  values in small-scale fires to simulate  $\dot{q}''_f$  values, expected in large-scale fires, is defined as the Flame Radiation Scaling Technique.*

The Flame Radiation Scaling Technique has been used to determine the range of  $\dot{q}''_{fr}$  and  $\dot{q}''_{fc}$  values for various materials in the FMRC Flammability Apparatus (Tewarson et al 1981, Tewarson 1988). The  $\dot{q}''_{fr}$  and  $\dot{q}''_{fc}$  values are obtained by measuring the  $\dot{m}''$  values at various  $X_o$  values, using heat and mass balances, Eq. (3) and the derived convective heat transfer coefficient for the FMRC Apparatus (Tewarson et al 1981). The lower and upper limits for the  $\dot{q}''_{fr}$  and  $\dot{q}''_{fc}$  values are established by performing experiments with  $X_o$  values close to flame extinction limit and  $X_o$  values  $\geq 0.30$  respectively (Tewarson et al 1981). For  $X_o \geq 0.30$  at the asymptotic limit, Eq. (3) is expressed as (Tewarson et al 1981):

$$\dot{m}''_{\text{ASYM}} = (\dot{q}''_{\text{FR,ASYM}} - \dot{q}''_{\text{RR}}) / \Delta H_g \quad (4)$$

where  $\dot{m}''_{\text{ASYM}}$  and  $\dot{q}''_{\text{FR,ASYM}}$  are the asymptotic limits for the  $\dot{m}''_c$  and  $\dot{q}''_f$  values in small-scale fires with  $X_o \geq 0.30$  and in large-scale fires in normal air with large surface areas. The  $\dot{m}''_{\text{ASYM}}$  and  $\dot{q}''_{\text{FR,ASYM}}$  values determined for the pool-like configuration are listed in Table 2.

The data in Table 2 show that the  $\dot{q}''_f$  values, determined in the FMRC Flammability Apparatus, using the Flame Radiation Scaling Technique, are in good agreement with the values measured in the large-scale fires. The  $\dot{q}''_f$  values vary from 22 to 77 kW/m<sup>2</sup>, being dependent primarily on the mode of decomposition and gasification rather than on the chemical structures of the materials. For examples, for all the liquids, which gasify primarily as monomers or as very low molecular weight oligomers, the  $\dot{q}''_f$  values are in the range of 22 to 44 kW/m<sup>2</sup>, irrespective of their chemical structures. For polymers, which gasify as high molecular weight oligomers, the  $\dot{q}''_f$  values increase substantially to the range of 49 to 71 kW/m<sup>2</sup>, irrespective of their chemical structures. The independence of the  $\dot{q}''_f$  values from the chemical structures of the materials is consistent with the understanding of the dependence of flame radiation on optical thickness, soot concentration and flame temperature in large-scale fires.

*The Flame Radiation Scaling Technique can be used to determine the flame heat flux expected in large-scale fires of advanced fire resistant aircraft interior materials to assess the reduction in fire hazard because of their use and passive fire protection provided by their fire resistant treatment.*

**Table 2**  
**Asymptotic Values of Mass Combustion Rate and Flame Heat Flux for Pool-Like Configuration<sup>a</sup>**

Material	$\dot{m}''$ (g/m <sup>2</sup> -s)		$\dot{q}''_f$ (kW/m <sup>2</sup> )	
	Sp	Lc	Sp	Lc
<u>Aliphatic Carbon-Hydrogen Atoms<sup>d</sup></u>				
Polyethylene	26	-	61	-
Polypropylene	24	-	67	-
Heavy fuel oil (2.6-23 m)	-	36	-	29
Kerosene (30-80 m)	-	65	-	29
Crude oil (6.5-31 m)	-	56	-	44
n-Dodecane (0.94 m)	-	36	-	30
Gasoline (1.5-223 m)	-	62	-	30
JP-4 (1.0-5.3 m)	-	67	-	40
JP-5 (0.60 - 17 m)	-	55	-	39
n-Heptane (1.2 - 10 m)	-66	75	32	37
n-Hexane (0.75 - 10 m)	-	77	-	37
Transformer fluids (2.37 m)	27-30	25-29	23-25	22-25
<u>Aromatic Carbon-Hydrogen Atoms<sup>d</sup></u>				
Polystyrene (0.93 m)	36	34	75	71
Xylene (1.22 m)	-	67	-	37
Benzene (0.75 - 6.0 m)	-	81	-	44
<u>Aliphatic Carbon-Hydrogen-Oxygen Atoms<sup>d</sup></u>				
Polyoxymethylene	16	-	50	-
Polymethylmethacrylate (2.37 m)	28	30	57	60
Methanol (1.2 - 2.4 m)	20	25	22	27
Acetone (1.52 m)	-	38	-	24

(Table 2 continued on next page)

**Table 2 (continued)**

Material	$\dot{m}''$ (g/m <sup>2</sup> -s)		$\dot{q}''_f$ (kW/m <sup>2</sup> )	
	S <sup>b</sup>	L <sup>c</sup>	S <sup>b</sup>	L <sup>c</sup>
<u>Aliphatic Carbon-Hydrogen-Oxygen-Nitrogen Atoms<sup>d</sup></u>				
Flexible polyurethane foams	21-27	-	64-76	-
Rigid polyurethane foams	22-25	-	49-53	-
<u>Aliphatic Carbon-Hydrogen-Halogen Atoms<sup>d</sup></u>				
Polyvinylchloride	16	-	50	-
Tefzel (ETFE)	14	-	50	-
Teflon (FEP)	2	-	52	-

<sup>a</sup>: Data taken from Tewarson, *Prog. Ener. Combust. Sci* (to be published); <sup>b</sup>: S: Small-scale fires, pool diameter fixed at 0.10 m, Flame Radiation Scaling Technique was used in the FMRC Flammability Apparatus,  $X_{i,1} \geq 0.30$ ; <sup>c</sup>: L: Large-scale fires in normal air; <sup>d</sup>: numbers in m in parentheses are the pool diameters used in large-scale fires.

**Heat Release Rate from Combustion Experiments**

Heat release rate ( $\dot{Q}''_i$ ) is defined as the product of mass combustion rate and the heat of combustion:

$$\dot{Q}''_i = \dot{m}'' \Delta H_i \quad (5)$$

where  $\dot{Q}''_i$  is in kW/m<sup>2</sup>,  $\dot{m}''$  is in g/m<sup>2</sup>-s and  $\Delta H_i$  is in kJ/g, subscript i represents chemical, convective and radiative. Chemical heat release rate,  $\dot{Q}''_{chem}$ , is determined from the generation rates of CO<sub>2</sub> corrected for the generation of CO (Tewarson 1982,1988) and O<sub>2</sub> consumption rate (Tewarson 1982,1988, ASTM E 1354-90). Convective heat release rate,  $\dot{Q}''_{con}$ , is determined from the mass flow rate of the fire products-air mixture, specific heat of the mixture (at the gas temperature), and gas temperature above ambient (ASTM E 906-83, Tewarson 1982,1988). Radiative heat release rate,  $\dot{Q}''_{rad}$ , is determined from the difference between  $\dot{Q}''_{chem}$  and  $\dot{Q}''_{con}$  values, as heat losses in the sampling duct of the FMRC Apparatus are negligibly small (Tewarson 1982,1988).

The  $\dot{Q}''_{chem}$  values are determined in the OSU and the FMRC Apparatuses and the Cone Calorimeter. The  $\dot{Q}''_{con}$  values are determined in the OSU and the FMRC Apparatuses and the  $\dot{Q}''_{rad}$  values are determined in the FMRC Apparatus.

**Heat of Combustion from Heat of Formation, Oxygen Bomb, and Combustion Experiments**

The energy associated with the cleavage of old chemical bonds and formation and rearrangement of the new chemical bonds is defined as the heat of combustion. In the following reactions,  $\Delta H_{chem}$  values are calculated from the standard heat of formation in kJ/mole:

PMMA (C<sub>5</sub>H<sub>8</sub>O<sub>2</sub>) (g) = -442.7; O<sub>2</sub> (g) = 0; CO<sub>2</sub> (g) = -393.5; H<sub>2</sub>O (g) = -241.8; CO (g) = -110.5; C (s) = 0; C<sub>2</sub>H<sub>4</sub> (g) = + 26.2.

	$\Delta H_{chem}$ (kJ/g)	$X_{chem}$
C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> (g) + 6.0 O <sub>2</sub> (g) = 5CO <sub>2</sub> (g) + 4H <sub>2</sub> O(g) ,	24.9	1.00
C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> (g) + 5.5 O <sub>2</sub> (g) = 4CO <sub>2</sub> (g) + 4H <sub>2</sub> O(g) + CO(g) ,	22.1	0.89
C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> (g) + 4.5 O <sub>2</sub> (g) = 3CO <sub>2</sub> (g) + 4H <sub>2</sub> O(g) + CO(g) + C(s)	18.2	0.73
C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> (g) + 3.0 O <sub>2</sub> (g) = 2CO <sub>2</sub> (g) + 3H <sub>2</sub> O(g) + CO(g) + C(s) + 0.50 C <sub>2</sub> H <sub>4</sub> (g)	11.5	0.46

The  $\Delta H_{chem}$  and  $\chi_{chem}$  values decrease as CO, carbon, and ethylene are formed at the expense of  $CO_2$  and  $H_2O$  and reduced  $O_2$  consumption, a typical condition found in under-ventilated fires (Tewarson 1988). The upper limit of  $\chi_{chem}$  is 1.0 and the lower limit is 0.46, corresponding to complete and unstable combustion respectively. For complete combustion,  $\Delta H_{chem} = 24.9$  kJ/g, which agrees very well with the net heat of complete combustion measured in the Oxygen Bomb Calorimeter. The lower limit of  $\chi_{chem}$  is very close to the flame extinction limit ( $\chi_{chem} \leq 0.40$ ) (Tewarson 1988). For various materials, the net heat of complete combustion values are either calculated from the heat of formation values or are measured in the Oxygen Bomb Calorimeter. The  $\Delta H_{chem}$  values on the other hand are determined from the ratio of the chemical heat release rate to mass combustion rate.

### Heat Release Parameter from Combustion Experiments

For well-ventilated fires, from Eqs. (3) and (5):

$$\dot{Q}_i = (\Delta H_i / \Delta H_g)(\dot{q}_e + \dot{q}_{fr} + \dot{q}_{fc} - \dot{q}_{rr}) \quad (6)$$

where  $\Delta H_i / \Delta H_g$  is defined as the Heat Release Parameter (HRP), and  $i$  is chemical, convective, and radiative. HRP is a characteristic material property and depends on its chemical structure and additives therein. From Eq. (6),  $\dot{Q}_i$  is expected to be a linear function of  $\dot{q}_e$ , and the slope equal to the HRP value, especially when  $\dot{q}_e \gg \dot{q}_{fr} + \dot{q}_{fc} - \dot{q}_{rr}$ . This is supported by the experimental data in Fig. 4 measured in the FMRC Apparatus.

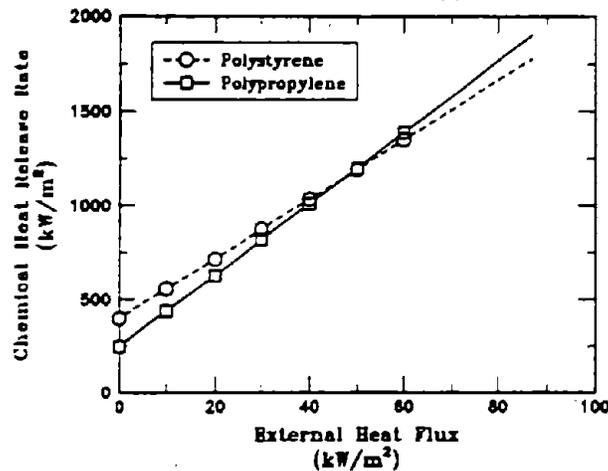


Figure 4. Chemical Heat Release Rate Versus External Heat Flux for Polyethylene and Polystyrene.

between the OSU and the FMRC Apparatuses and the Cone Calorimeter. The lower the HRP value, lower is the heat release rate for a defined fire size or heat flux. *In general, materials with chemical-HRP values of less than about 4 have difficulty in sustaining combustion and flame spread. Even in the presence of external heat sources, the fires of these materials are of low intensity.* This is consistent with the fire behavior of phenolic-fiberglass aircraft panel with the chemical-HRP value of 4. The phenolic fiberglass aircraft panel had very low intensity fires in full-scale testing and was selected as a benchmark for the selection of the performance criteria of aircraft panel materials by the FAA (Sarkos 1989). Several highly chlorinated materials, composites and aircraft panels satisfy this condition.

In the OSU and the FMRC Apparatuses and the Cone Calorimeter,  $\dot{Q}_{chem}$  values are routinely measured at various  $\dot{q}_e$  values.  $\dot{Q}_{con}$  values are also measured routinely at various  $\dot{q}_e$  values in the OSU and the FMRC Apparatuses. Thus chemical and convective HRP values can be obtained from the heat release rate data from these Apparatuses. The chemical- and convective-HRP values for the well-ventilated fires, derived from the slopes of  $\dot{Q}_{chem}$  and  $\dot{Q}_{con}$  versus  $\dot{q}_e$  plots, constructed from the data measured in the OSU and the FMRC Apparatuses and the Cone Calorimeter are listed in Table 3.

The HRP values in Table 3 show that there is a reasonable equivalency

The HRP values can be quantified for the advanced fire resistant aircraft interior materials to assess the reduction in fire hazard because of their use and passive fire protection provided by their fire resistant treatment.

**Table 3**  
**Chemical and Convective Heat Release Parameters**

Materials	$\Delta H_{chem}/\Delta H_g$		$\Delta H_{con} / \Delta H_g$	
	FMRC <sup>a</sup>	Cone <sup>b</sup>	FMRC <sup>a</sup>	OSU <sup>c</sup>
ABS	-	22	-	-
Polyamide	21	-	-	-
Polypropylene	19	32?	11	-
Polyethylene	17	21	12	-
Polystyrene	16	19	6	-
Polymethylmethacrylate	15	14	10	-
Nylon	12	-	7	-
Polycarbonate	9	-	-	-
Douglas fir	7	-	5	-
Polyoxymethylene	6	-	5	-
<u>Chlorinated PE and Polyvinylchloride (PVC)</u>				
Polyethylene /25 % Cl	11	-	5	-
Plasticized-PVC-3, LOI 0.25	-	5	-	-
Plasticized-PVC-4, LOI 0.30	-	5	-	-
Plasticized-PVC-5, LOI 0.35	-	5	-	-
Polyethylene/36 % Cl	4	-	2	-
Rigid PVC-1 , LOI 0.50	-	3	-	-
Rigid PVC-2	2	3	1	-
Polyethylene/48 % Cl	2	-	-	-
<u>Polystyrene foams</u>				
GM53	20	-	6	-
GM49	19	-	8	-
GM51	18	-	7	-
GM47	13	1?	9	-
<u>Flexible polyurethane foams</u>				
GM-21	7	-	3	3
GM-23	9	-	5	6
GM-25	14	-	6	4
GM-27	9	-	4	2
<u>Thermosets</u>				
Polyvinyl ester -69 % glass	-	13	-	-
Epoxy resin	-	11	-	-
Polyester3-glass composite	10	-	-	-
Polyester2-glass composite	8	-	-	-
Vinylester1-glass composite	7	-	-	-
Polyester-30 % glass	-	6	-	-
Isophthalic polyester	-	6	-	-
Polyester1-glass composite	3	-	-	-
Polyester6-glass composite	3	-	-	-
Polyester5-glass composite	3	-	-	-
Polyester4-glass composite	3	-	-	-
Polyether ether ketone -30% glass	-	3	-	-
Vinylester2-glass composite	2	-	-	-
Kevlar-phenolic composite	2	-	-	-

(Table 3 continued on next page)

**Table 3 (continued)**

Materials	$\Delta H_{chem}/\Delta H_g$		$\Delta H_{com}/\Delta H_g$	
	FMRC	Cone	FMRC	OSU
Graphite-Epoxy composite	2	-	-	-
Phenolic-glass composite	2	-	-	-
Phenolic foam-glass faced	-	2	-	-
Epoxy resin-69 % glass	-	2	-	-
Polyvinyl ester resin-69 % glass	-	2	-	-
Modified acrylic -FR-glass	-	1	-	-
Phenolic laminate-45 % glass	-	1	-	-
Filled phenolic foam-50 % inert	-	1	-	-
Isophthalic polyester -77 % glass	-	1	-	-
<i>Aircraft panel materials</i>				
Epoxy Fiberglass	4	5	2	1
Epoxy kevlar	4	4	2	2
Phenolic kevlar	5	4	2	-
Phenolic graphite	4	3	1	-
Phenolic fiberglass	4	3	2	1

a: taken from Tewarson 1988; Macaione and Tewarson, 1990;  
 b: taken from Hirschler 1987, Scudamore *et al* 1991. c: taken from  
 Tewarson and Zalosh 1989; ?: uncertain values.

**Flame Spread from Combustion and Flame Propagation Experiments**

Surface flame spread is a process where the pyrolysis front, feeding the flame, moves across the surface (Quintiere 1988, Tewarson and Khan 1988, Tewarson and Ogdien 1992). The rate of movement of the pyrolysis front on the surface is defined as the flame spread rate (S):

$$S = dL_p/dt \tag{7}$$

where S is in mm/s and  $L_p$  is the pyrolysis front in mm.

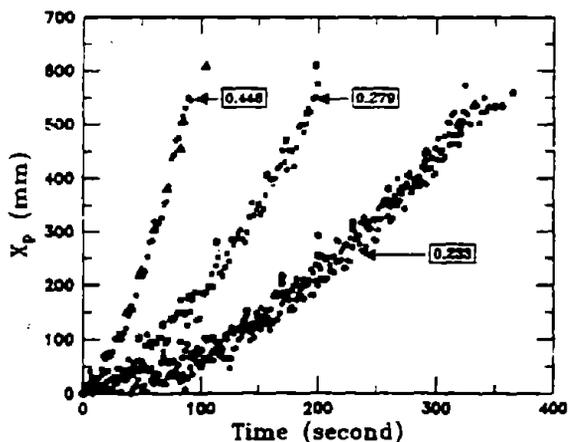


Figure 5. Pyrolysis Front Location Versus Time for the Upward Flame Spread for PMMA at Various Oxygen Mass Fractions (Tewarson and Ogdien 1992).

Figure 5 shows  $L_p$  as a function of time for upward flame spread on a vertical 0.60 m long and 0.025 m diameter PMMA cylinder. Experiments were performed in the FMRC Apparatus. The  $X_o$  values are indicated inside the frames. The  $L_p$  values increase rapidly with  $X_o$  or  $\dot{q}_f$  values as expected.

The upward flame spread rate for a thermally thick material with concurrent flow is expressed as the ratio of the flame heat flux transferred to the surface to the TRP value of the material. The flame heat flux transferred to the surface is assumed to be  $(X_{rad} \dot{Q}_{chem})^{1/3}$  (Tewarson and Khan 1988):

$$S^{1/2} = (\chi_{rad} \dot{Q}'_{chem})^{1/3} / TRP \quad (8)$$

where  $\chi_{rad}$  is the radiative efficiency of combustion efficiency.

The right hand side of Eq. (8) multiplied by 1000 with  $\chi_{rad} = 0.40$ ,  $\dot{Q}'_{chem}$  in kW/m, and TRP in kW-s<sup>1/2</sup>/m<sup>2</sup> is defined as the Fire Propagation Index (FPI) (Tewarson and Khan 1988):

$$(FPI)_{fmrc} = 1000 (0.40 \dot{Q}'_{chem})^{1/3} / TRP \quad (9)$$

The  $(FPI)_{fmrc}$  values for the upward flame spread, at the upper limit of the  $\dot{q}''_f$  value ( $\chi_o = 0.40$ ), is determined in the FMRC Apparatus (Tewarson and Khan 1988, Tewarson and Ogden 1992). Materials are classified into three groups (Tewarson and Khan 1988): 1) materials with  $(FPI)_{fmrc} < 10$  belong to Group 1. For these materials, flame spread is decelerating or there is no flame spread beyond the ignition zone, 2) materials with  $10 \geq (FPI)_{fmrc} < 20$  materials belong to Group 2. For these materials, flame spread is non-accelerating, and 3) materials with  $(FPI)_{fmrc} \geq 20$  belong to Group 3. For these materials, flame spread is accelerating.

The  $(FPI)_{fmrc}$  values for some selected materials as electrical cables, conveyor belts, and composites, determined in the FMRC Apparatus, are listed in Table 4. The variations in the  $(FPI)_{fmrc}$  values for materials as electrical cables and conveyor belts, within similar group of materials, are due to the presence of different additives, fire retardants, and differences in thicknesses or diameters. Decelerating flame spread, no flame spread and self-sustained flame spread beyond the ignition zone for Groups 1, 2, and 3 materials have been validated in large-scale fires for materials as electrical cables (Tewarson and Khan 1988,1989) and as conveyor belts (Khan 1991). The data in Table 4 show that the  $(FPI)_{fmrc}$  values are less than 10 for several materials as electrical cables, conveyor belts, and composite materials and thus these materials are Group 1 materials.

Relationship for lateral flame spread has also been developed, where flame spread rate is expressed as the ratio of the flame heat flux to the surface to the TRP value of the material (Quintiere 1988):

$$S = \Phi / (TRP)^2 \quad (10)$$

where  $\Phi$  is the flame spread factor (kW<sup>2</sup>/m<sup>3</sup>), a characteristic property of the material but depends on the gas velocity and  $\chi_o$  value. The  $\Phi$ ,  $\kappa\rho c_p$  and  $T_{ig}$  values are obtained from the lateral flame spread experiments in the LIFT Apparatus (Quintiere 1988). The TRP values can be determined from the  $\kappa\rho c_p$  and  $T_{ig}$  values and assuming  $T_s = 293$  K. Eq. (10) is of similar form as Eq. (9), if expressed as:

$$(FPI)_{lift} = 1000 \Phi^{1/2} / TRP \quad (11)$$

assuming  $\Phi^{1/2} = (0.40 \dot{Q}'_{chem})^{1/3}$ . We have used Eq. (11) to calculate the  $(FPI)_{lift}$  values from the data obtained in the LIFT Apparatus (Quintiere 1988, Quintiere *et al* 1985). The values are for the lateral flame spread in normal air for surface heated by external heat flux, less than the critical heat flux. The  $(FPI)_{lift}$  values calculated in this fashion are listed in Table 4 for ordinary combustibles, common plastics, carpets, and aircraft panel materials. As discussed previously, for the phenolic fiberglass aircraft panel material, the chemical HRP value of 4 (Table 3) suggests that the material is expected to have difficulty in sustaining combustion and flame spread and that it is a Group 1 material as indicated by the FPI value of 3 for phenolic fiberglass composite. This behavior is supported by the full-scale fire tests performed by the FAA (Sarkos 1989) but not by the  $(FPI)_{lift}$  value for the phenolic fiberglass aircraft panel.

**Table 4**  
**Fire Propagation Index (FPI) Derived from the Data**  
**Measured in the FMRC and the LIFT Apparatuses**

<b>Materials</b>	<b>Thickness or Diameter (mm)</b>	<b>(FPI)<sub>FMRC</sub><sup>a</sup></b>	<b>(FPI)<sub>LIFT</sub><sup>b</sup></b>
<i>Ordinary Combustibles</i>			
Hardboard	3.2	-	10
Hardboard (gloss paint)	3.4	-	5
Hardboard	6.4	-	6
Plywood plain	6.4	-	11
Plywood plain	12.7	-	13
Particle board	12.7	-	5
Douglas fir particle board	12.7	-	10
Fiber insulation board	-	-	7
Gypsum board, wallpaper	-	-	3
Gypsum board	12.7	-	10
Asphalt shingle	-	-	9
Fiberglass shingle	-	-	10
<i>Common plastics</i>			
Polyisocyanurate foam	50.8	-	37
Rigid polyurethane foam	25.4	-	28
Flexible polyurethane foam	25.4	-	16
Polymethylmethacrylate	1.6	-	11
Polymethylmethacrylate	12.7	-	11
Polycarbonate	1.5	-	7
<i>Carpets</i>			
Acrylic	-	-	17
Nylon/wool blend	-	-	15
Wool, untreated	-	-	13
Wool, treated	-	-	4
<i>Electrical Cables<sup>d</sup></i>			
PVC/PVC	3.6-13	36-11	-
PE/PVC	3.7-11	28-23	-
PVC/PE	34	13	-
Silicone/PVC	16	17	-
Silicone/XLPO	28	8	-
Silicone/XLPO	55	8	-
Silicone/XLPO/metal armor	55	6	-
EP/EP	10-25	8-6	-
XLPE/XLPE	9.5-12	17-9	-
XLPE/EVA	12-22	8-9	-
XLPE/neoprene	15	9	-
XLPO/XLPO	16-25	9-8	-
XLPO,PVF/XLPO	14-17	8-6	-
EP/PE-Cl-S	4.3-19	13-8	-
EP-FR/none	3.5-28	9	-
PE-Cl/none	15	18	-

(Table 4 continued on next page)

Table 4 (continued)

Materials	Thickness or Diameter (mm)	(FPT) <sub>max</sub> <sup>a</sup>	(FPT) <sub>lin</sub> <sup>b</sup>
PVC/PVF	5.0	7	-
FEP/FEP	9.7	5	-
<u>Conveyor belts<sup>c</sup></u>			
Neoprene	9	4	-
PVC	9-13	10-4	-
SBR	9-20	11-8	-
<u>Fiber Reinforced Composite Materials<sup>d</sup></u>			
Polyester-1	4.8	13	-
Epoxy-1	4.8	11	-
Epoxy-2	4.4	10	-
Polyester-2	4.8	10	-
	19	8	-
	45	7	-
Epoxy-3	4.4	9	-
Kevlar/phenolic	4.8	8	-
Phenolic	3.2	3	-
<u>Aircraft panel materials<sup>e</sup></u>			
Phenolic fiberglass	-	-	14
Phenolic kevlar	-	-	13
Epoxy kevlar	-	-	11
Phenolic graphite	-	-	9
Epoxy fiberglass	-	-	6

<sup>a</sup>:  $(FPT)_{max} = 1000 (0.40Q'_{max})^{1/2} / TRP$ ; peak values; Tewarson and Khan (1988). Values are for the upward flame spread at the upper limit of  $q''_f$  ( $X_s = 0.40$ ). Values would be lower at the lower limit of  $q''_f$  and in normal air.

<sup>b</sup>:  $(FPT)_{lin} = 1000 \times \Phi^{1/2} / TRP$ . Values are for the lateral flame spread, in ambient air with surface heated by external heat flux, less than the critical heat flux for ignition. Results are similar for downward flame spread and for axisymmetric flame spread from a small (pool) fire on a horizontal surface.

<sup>c</sup>: Quimiere (1988); <sup>d</sup>: Tewarson and Khan (1988,1989); <sup>e</sup>: Khan (1991); <sup>f</sup>: Tewarson and Macaione (1992); <sup>g</sup>: Quintiere *et al* (1985). With Nomex honeycomb and one surface covered with 2 mil white Tedlar.

Electrical cables, insulation/jacket: PVC: polyvinylchloride; PE: polyethylene; EP: ethylene-propylene; XLPE: cross-linked polyethylene; XLPO: cross-linked polyolefin; EVA: ethylvinyl acetate; PE-CI-S: chlorosulfonated polyethylene (hypalon); PVF: polyvinylidene fluoride; FEP: tetrafluoroethylene and ethylene copolymer with hexafluoropropylene.

## IMPROVED FIRES SAFETY STANDARDS FOR AIRCRAFT INTERIOR MATERIALS

The Federal Aviation Administration (FAA) has undertaken an unprecedented series of regulatory actions for the purpose of improving transport aircraft interior fire safety (Sarkos 1989). The FAA has developed improved fires test standards for seat cushions fire blocking layers, low heat/smoke release interior panels, burn-through resistant cargo liners, and radiant heat resistant evacuation slides and new requirements for in-flight detectors and extinguisher (Sarkos 1989).

The seat cushion blocking layer test methodology, developed by FAA, subjects seat back and seat bottom cushion specimens (upholstery cover, fire blocking layer, and foam cushion) to a two gallon/hour burner flame with temperature and heat flux typical of a cabin fire (minimum of 1850 °F for a distance of not less than 7 inches and at 4 inches from the end of the burner cone). The acceptance criterion consists of 10 % weight loss and a burn length of 17 inches- performance essentially matching that attained by the Vonar™ and Norfab™ blocking layer materials, proven effective in full-scale tests (Sarkos 1989). Majority of seats manufactured in the United States are constructed of either polybenzimidazole (PBI) felts or aramid fire resistant quilts, weighing 6 to 10 ounces per square yard (Sarkos 1989). The entire United States airline fleet, consisting of approximately 650,000 seats, is protected with seat cushion fire blocking layers (Sarkos 1989). An example of the combustion behavior of PBI is shown in Fig.5.

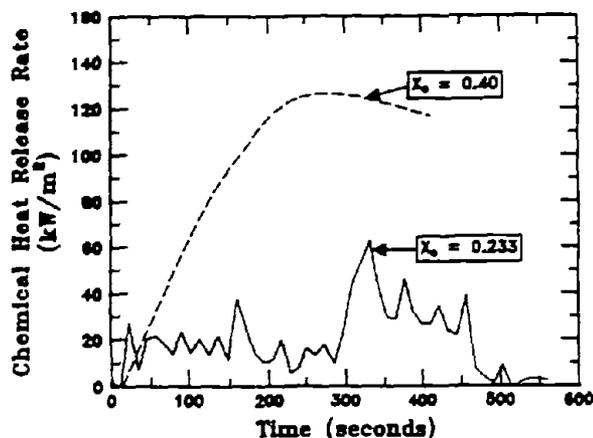


Figure 5. Chemical Heat Release Rate Versus Time for Polybenzimidazole Measured in the FMRC Apparatus at 60 kW/m<sup>2</sup> of External Heat Flux in Normal Air and at 0.40 Oxygen Mass Fraction.

In the experiments, 64 mm diameter and 3 mm thick PBI discs were exposed to 60 kW/m<sup>2</sup> of external heat flux in the FMRC Apparatus in normal air ( $X_{o_2} = 0.233$ ) and in an environment with  $X_{o_2} = 0.40$ , to simulate large-scale flame radiation conditions. In the experiments with normal air, there were no visible flames. In the experiments with  $X_{o_2} = 0.40$ , flames were very small, about 50 mm in height. There was no soot formation. A peak chemical heat release rate of 130 kW/m<sup>2</sup> for PBI at 60 kW/m<sup>2</sup> of external heat flux and  $X_{o_2} = 0.40$ , is significantly below the peak value for Group 1 materials and thus the results support the FAA finding for the seat blocking characteristic of PBI.

The low heat release interior panel testing technology was developed by FAA by performing full-scale tests in the C-133 wide body airplane fitted with interior panels such as sidewalls, ceiling, stowage bins, and partitions, fire blocked seats, and carpets (Sarkos 1989). Use of advanced composite materials prevented flashover when the fire was adjacent to a door opening or when an in-flight fire was started from a gasoline drenched seat (Sarkos 1989). In the more severe ruptured fuselage scenario, where seats are more directly exposed to the external fire, use of advanced panels resulted in a 2-minute delay to the onset of flashover (Sarkos 1989). In the tests with fire adjacent to an open door, phenolic kevlar and epoxy fiberglass aircraft panels displayed the earliest flashover, whereas the phenolic fiberglass panel delayed flashover by about 3 minutes (Sarkos 1989). The  $(FPT)_{min}$  values relate to the scenarios used by FAA in the full-scale tests, which is supported by the data in Table 4. The  $(FPT)_{min}$  values for epoxy fiberglass composites vary from 9 to 13, it is 8 for kevlar phenolic and 3 for phenolic fiberglass.

For testing of aircraft interior panels, FAA has selected the OSU Apparatus (Sarkos 1989) and phenolic fiberglass panel as a bench mark for the selection of the performance criteria for other panels. The pass/fail criteria consist of two limits for panel samples exposed to 50 kW/m<sup>2</sup> of external heat flux in the OSU Apparatus (Sarkos 1989): 1) a 65 kW-min/m<sup>2</sup> limit for the energy release in 2-minutes, and 2) a 65 kW/m<sup>2</sup> of peak heat release rate. A new requirement for smoke emission would be included in the final rule (Sarkos 1989).

The cargo liner burn-through resistance testing technology was developed with the features of severe liner exposure of maximum temperature and heat flux in full scale fire tests and realistic ceiling and sidewall liner orientation (Sarkos 1989). Criteria for acceptance are that there must be no flame penetration of ceiling and sidewall specimens and that the temperature measured above the ceiling specimen must not exceed 400 °F (Sarkos 1989).

The radiant heat resistance evacuation slide testing technology uses a laboratory test apparatus, where a slide fabric sample is mounted, pressurized, and exposed to external heat flux. The requirement for radiant resistance is the retention of pressure for 90 seconds for an external heat flux exposure of 1.5 Btu/ft<sup>2</sup>-sec (17 kW/m<sup>2</sup>) (Sarkos 1989)

## SUMMARY

1) Fundamental relationships have been used to develop flammability parameters associated with the ignition, combustion, and flame spread processes. The parameters are: *critical heat flux (CHF)*, *thermal response parameter (TRP)*, *heat release parameter (HRP)*, and *the fire propagation index (FPI)*. The parameters are useful to assess the reduction in fire hazard because of the use of advanced fire resistant aircraft interior materials and passive fire protection provided by their fire resistant treatment.;

2) The flammability parameters associated with ignition and combustion can be quantified in the OSU and the FMRC Apparatuses and the Cone Calorimeter. The flammability parameter associated with flame spread can be quantified in the FMRC and the LIFT Apparatuses, and in the OSU Apparatus (with a slight modification);

3) The Flame Radiation Sealing Technique developed for the FMRC Apparatus and applicable to the OSU Apparatus also, appears to be useful to simulate the scenarios expected in the aircraft interior panel material fires. The FPI value for the phenolic fiberglass composite material is 3, which is the lowest value amongst all the materials tested in the FMRC Apparatus. This material is found to be the best aircraft interior panel material in the full-scale tests by FAA and was selected as a benchmark for setting the selection criteria.

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FACTORS THAT AFFECT OSU THERMAL PERFORMANCE  
OF AIRCRAFT INTERIOR MATERIALS

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ABSTRACT

Decorative tapestries for interior vertical surfaces of aircraft are a complex system of materials of varying levels of flammability. This system can include face fiber, dyes and adjuvants, lubricants, backing, latex, adhesive, and rigid core materials, each of which can affect thermal performance. A new easily dyeable fiber, NOMEX\* THERMACOLOR™ aramid fiber, has recently been developed that exceeds FAA OSU thermal performance requirements and provides additional styling capability and reduced cycle time over producer colored NOMEX CGF®. This paper describes the systematic study of the carpet variables of pile height and weight, backing type, and latex type and weight on OSU thermal performance of cut pile tapestry carpets containing yarns of NOMEX THERMACOLOR™ fibers.

INTRODUCTION

The FAA 65/65 OSU regulation of 1988 [FAR 25.853 (a-1) through Amendment 25-66] required dramatic changes in the textile materials used in wall coverings on aircraft. NOMEX CGF® fiber was introduced to respond to this need in 1989.

This product is based on the same meta-aramid polymer used for more than 20 years in thermally protective apparel for military, fire service, and industrial applications with two key modifications to meet customer needs.

NOMEX CGF® is higher dpf, 7 vs. 1.5 dpf, and producer colored via a proprietary coloration process. This latter feature, while technically sophisticated to meet the demanding color fastness and shade matching requirements of customers, is not practical for the small lots of yarn needed to meet the styling creativity of tapestry designers. For example, the NOMEX CGF® color palette has grown from eight colors in 1989 to over 65 colors today.

Because of increasing demand for color variety, we have developed a new easily dyeable product based on this same meta-aramid polymer, called NOMEX THERMACOLOR™. This product can be readily dyed at atmospheric pressure without carrier and in equipment currently used for wool and nylon fibers.

Carpet yarn of NOMEX THERMACOLOR™ can be inventoried in undyed form and dyed to virtually any color or quantity as needed, significantly reducing cycle time and manufacturing costs. Moreover, this technology is readily adaptable to other deniers suitable for woven backings, floor coverings, and upholstery fabrics.

Prior to introduction of NOMEX THERMACOLOR™, we decided to develop an extensive OSU database to provide customer guidance on carpet construction and backing and latex selection. This paper summarizes the results of these studies.

\* Du Pont Registered Trade Mark

## OSU CALORIMETRY

The OSU calorimeter, which has been extensively studied and described (Hill, 1993), measures thermal performance of the entire wall covering system, not individual components.

High equipment variability and relatively poor agreement in round robin tests (Curry, 1990) leaves one with the general impression that developing a meaningful OSU database could be a major undertaking.

We believe that this study will show that with careful control of variables and a systematic approach to changing of variables, a clear picture emerges that validates the soundness of the OSU test. Key to this conclusion is control of OSU system variability, which includes the calibration of equipment, mounting of samples, application of adhesive, and selection and reproducibility of core material.

All OSU testing described in this work was performed by Schneller, Inc. at their FAA approved test facility in Kent, Ohio.

### Test Protocol

After equipment calibration, triplicate samples of 1/8" Schneller Standard Core Panel were run to verify an OSU Total Heat Release of  $30 \pm 5$  KW-min/m<sup>2</sup> and a Peak Heat Release of  $49 \pm 6$  KW/m<sup>2</sup> before test samples were run. All carpet samples were mounted to 1/8" Schneller Standard Core Panel with  $3.8 \pm 0.1$  oz/yd<sup>2</sup> PARABOND\* M-277 contact adhesive.

Figure 1 illustrates a typical OSU curve on the 1/8" Schneller Standard Core Panel alone, and shows the thermal degradation of the phenolic resin used to bind the face layers of fiberglass to a NOMEX honeycomb core.

The addition of 3.8 oz/yd<sup>2</sup> PARABOND M-277 contact adhesive to this core is also illustrated in Figure 1, which shows the thermal instability of PARABOND M-277 adhesive with a peak of over 100 KW/m<sup>2</sup> in only 17 seconds.

Despite its flammability, PARABOND M-277 is preferred because it allows rapid installation of wall coverings vs. less flammable adhesives. Fortunately, its high thermal instability can be significantly reduced by the addition of carpeting of NOMEX THERMACOLOR™, as illustrated in Figure 2.

As we shall see later, depending on pile weight and density and FR latex weight, the onset of degradation of PARABOND M-277 adhesive can be delayed as much as five minutes, which is beyond the scope of OSU testing. Likewise, low pile weight carpets used in woven loop pile Grospoint and Replin wall coverings can be expected to be very sensitive to PARABOND M-277 adhesive.

\*Para-Chem Southern registered trademark

### Carpet Construction Effects

In a carpet system where all the components have the same level of flammability, carpet construction would be expected to have relatively little effect on OSU results. However, a tapestry system is made up of several components with widely different flammabilities and accessibilities (Table 1), so construction can be important.

TABLE 1  
ANATOMY OF A TAPESTRY SYSTEM

	<u>Component</u>	<u>Typical Weight Range, oz/sq. yd</u>	<u>Relative Flammability</u>
	Face		
	Pile Fiber (NOMEX THERMACOLOR™)	20-70	Low
	Dyes, Additives, Lubricants	2-12	High
	Backing	4-15	High
	Latex	10-30	Low
	Adhesive	3 - 6	High
Back	NOMEX Honeycomb Panel	1/8-1" thick	Low

In this study a sample of 4" cut length NOMEX THERMACOLOR™ was commercially spun into 2.25/2 cc yarn on a woolen system, and commercially skein dyed to a Dog Red shade. Carpet was machine tufted (5/32" ga, 2 ends/needle) into 4 oz/yd<sup>2</sup> woven polypropylene backing (Patchogue Plymouth Style 2218) at nominal 3/8, 1/2 and 5/8" pile heights and nominal pile weights of 40, 50, and 60 oz/yd<sup>2</sup>. Actual pile heights, stitches/inch, and pile weights were measured on each sample.

Carpets were hand latexed with approximately  $26 \pm 4$  oz/yd<sup>2</sup> of General Latex FR Latex (2B-3194-FR), and 6" x 6" samples were mounted to 1/8" Schneller Standard Core Panel with 3.8 oz/yd<sup>2</sup> PARABOND M-277 adhesive.

### Total Heat

OSU data, summarized in Figure 3, show that there is a strong correlation between total heat and pile weight. In other words, total heat (integrated over the first two minutes exposure) is highly dependent on the mass of pile material exposed to the heat source.

In addition, the data show that at a constant pile weight, total heat increases as pile height increases. This is due to the decrease in pile density and increase in surface area of face fiber exposed to the heat source (accessibility).

An interesting correlation is found by multiplying the pile weight by the pile height, which is illustrated in Figure 4. Total heat is linearly dependent on this pile accessibility factor.

For all the pile weight and pile height variables tested, total heat averages 44.7 Kw-min/m<sup>2</sup> with a range of 35.2-51.1 Kw-min/m<sup>2</sup>, which is well below the FAA maximum of 65 Kw-min/m<sup>2</sup>. This shows that there are relatively few flammable volatiles on carpets of dyed NOMEX THERMACOLOR™.

#### Peak Heat

Peak heat results are also summarized in Figure 3, which show relatively little variation over the range of constructions tested. For example, average peak heat for all samples is 38.1 Kw/m<sup>2</sup>, with a range of 32.9 - 45.2 Kw/m<sup>2</sup>, well below the FAA maximum of 65 Kw/m<sup>2</sup>.

Even with a relatively flammable backing of polypropylene and flammable adhesive of PARABOND M-277, the combination of NOMEX THERMACOLOR™ and flame retardant latex provide sufficient thermal insulation to moderate the degradation of backing components and keep peak heat down.

Analysis shows that the time to peak is typically less than two minutes for this system, and this explains the overall correlation between the total and peak heat.

Figure 2 shows a typical OSU calorimetry curve for a representative tapestry construction of NOMEX THERMACOLOR™ in this data set.

#### Spun Yarn Variables

A new production lot of 6" cut length NOMEX THERMACOLOR™ was commercially spun on a semiworsted system to a 2.25/2 cc yarn, and was commercially skein dyed Charcoal Green. Yarns were tufted on a 5/32" gauge pass machine with 2 ends/needle into 3.3 oz/yd<sup>2</sup> woven polypropylene backing (Patchogue Plymouth Style 2234) at 1/2" pile height and at 40, 50, and 60 oz/yd<sup>2</sup> pile weight. Carpets were latexed with 36 ± 3 oz/yd<sup>2</sup> General FR Latex and mounted to 1/8" Schneller Standard Core Panel with 3.8 oz/yd<sup>2</sup> PARABOND M-277 adhesive. Six replicates of each construction were tested.

Total and peak heat data are summarized in Figure 5. Results are comparable to those for the Dog Red NOMEX THERMACOLOR™ spun on the woolen system (Figure 3). The OSU averages and ranges for the two production lots of NOMEX THERMACOLOR™ are compared in Table 2, which shows that variables such as yarn spinning system (4" woolen vs. 6" semiworsted), production lot, and color do not significantly impact OSU thermal performance. This gives the designer high flexibility.

**TABLE 2**  
**OSU RESULTS FOR WOOLEN AND SEMIWORSTED SPUN NOMEX THERMACOLOR™**

Spinning System	Cut Length, In	Color	Samples	Total (KW-min/m <sup>2</sup> )		Peak (KW/m <sup>2</sup> )	
				Ave.	Range	Ave.	Range
Woolen	4	Dog Red	24	44.7	35.2-51.1	38.1	32.9-45.2
Semi-worsted	6	Charcoal Green	18	42.8	37.3-49.0	37.6	35.3-40.9

### Carpet Backing Effects

In this experiment, a single lot of 2.25/2 cc Dog Red NOMEX THERMACOLOR™ was machine tufted at equivalent constructions, 3/8" pile height, 46-47 oz/yd<sup>2</sup> pile weight, into 4 oz/yd<sup>2</sup> woven polypropylene backing (Patchogue Plymouth Style 2218) and 9.5 oz/yd<sup>2</sup> cotton monk's cloth, commonly used for hand tufted tapestries. Each carpet was hand latexed with 24 ± 4 oz/yd<sup>2</sup> General Latex (2B-3194-FR) and mounted to 1/8" Schneller Standard Core Panel with 3.8 oz/yd<sup>2</sup> PARABOND M-277 contact adhesive.

OSU results, summarized in Table 3, show equivalent total heat, but significantly higher peak heat for the carpet with the 9.5 oz/yd<sup>2</sup> cotton backing compared with the lighter weight 4 oz/yd<sup>2</sup> polypropylene backing. Even with the higher peak heat, tapestries of NOMEX THERMACOLOR™ tufted into 9.5 oz cotton backing meet the FAA 65/65 requirements with a wide safety margin.

TABLE 3  
OSU THERMAL PERFORMANCE FOR DOG RED NOMEX THERMACOLOR™  
ON WOVEN POLYPROPYLENE AND COTTON BACKINGS

<u>BACKING</u>	<u>Weight</u> <u>oz/yd<sup>2</sup></u>	<u>Total Heat</u> <u>KW-min/m<sup>2</sup></u>	<u>Peak Heat</u> <u>KW/m<sup>2</sup></u>
Polypropylene	4.0	42.4	37.2
Cotton	9.5	40.8	51.1

The marked effect of backing on OSU peak thermal performance is illustrated by the OSU curves in Figure 6, which show identical responses in the first two minutes (total) and a new peak at 3.75 minutes for the item with the heavier weight cotton backing. Thus, OSU curves can provide valuable information about decomposition of individual components in a system.

### Effect of Latex on OSU Thermal Performance

Carpet latex provides tuft bind and thermal protection for flammable backings used in tapestries. Because tapestries are hand latexed, considerable variability in coating weights is observed, and it is important to understand the impact of latex type and weight on OSU thermal performance of carpets of NOMEX THERMACOLOR™.

Yarns of 2.25/2 cc Dog Red NOMEX THERMACOLOR™ were machine tufted into 4.0 oz/yd<sup>2</sup> woven polypropylene backing (Patchogue Plymouth Style 2218) at 1/2" pile height, 34 oz/yd<sup>2</sup> and 5/8" ph, 48 oz/yd<sup>2</sup>. Three commercial latexes, Table 4, were carefully applied by hand at weights from 10 oz/yd<sup>2</sup> to 45 oz/yd<sup>2</sup>. Latexed carpets were mounted to a 1/8" Schneller Standard Core Panel with 3.8 oz/yd<sup>2</sup> PARABOND M-277 contact adhesive.

TABLE 4  
OSU LATEX EVALUATION - IDENTIFICATION

<u>Latex Supplier</u>	<u>Identification</u>	<u>FR</u>
Rhone-Poulenc	Compound 9370	No
General Latex	2B-3194-FR	Yes
Mydrin	CB-12	Yes

OSU thermal performance results, summarized in Figure 7, show that there is only a slight effect of latex type and weight on the total heat of the two carpet constructions evaluated. This agrees with the hypothesis that total heat depends mainly on pile fiber thermal performance.

In contrast, peak heat release rate depends strongly on both type and amount of latex, as well as carpet construction. For example, for the lighter weight, lower pile height carpet tested, peak heat increases linearly with the amount of non-FR latex. As pile weight and height increase, more thermal insulation is provided, so there is less degradation of the non-FR latex. Both FR latexes tested are essentially equivalent in protecting the flammable polypropylene backing and PARABOND M-277 adhesive, and higher FR latex weights give better protection, particularly at lower pile weight/pile height.

#### SUMMARY

Systematic analysis of variables affecting OSU thermal performance of cut pile tapestries of NOMEX THERMACOLOR™ shows that both Total and Peak Heat Release measurements are predictable based on a systems approach.

Two-minute Total Heat Release depends strongly on pile system thermal performance and five-minute Peak Heat Release depends strongly on backing system thermal performance.

Increased pile weight and height give increased Total Heat due to greater mass and accessibility but have little affect on Peak Heat.

Total Heat is independent of carpet backing, while Peak Heat is sensitive to relative flammability and mass of backing.

If FR latex is used, Total Heat is independent of amount of latex over the normal application range, while Peak Heat that arises from a flammable backing system is reduced with additional FR latex.

Systems with NOMEX THERMACOLOR™ have been reproducibly demonstrated that exceed FAA 65/65 requirements, and give customers considerable flexibility for choices in styling and backing selection.

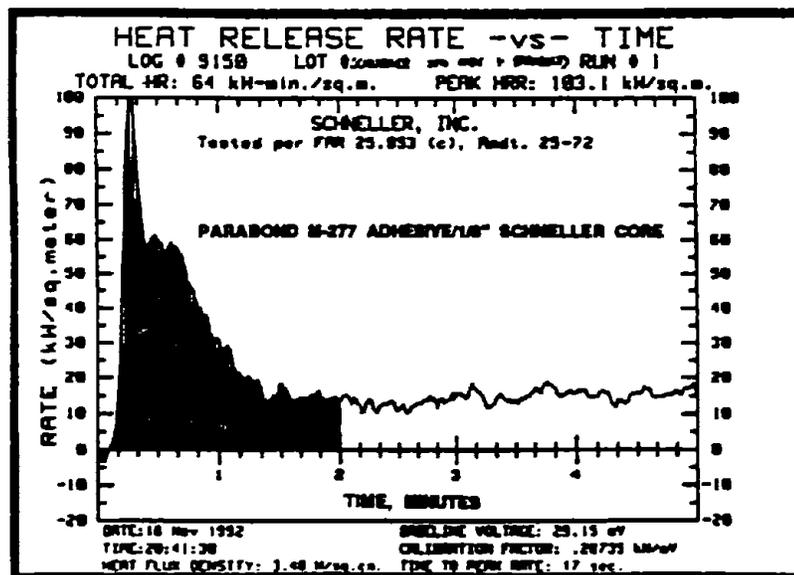
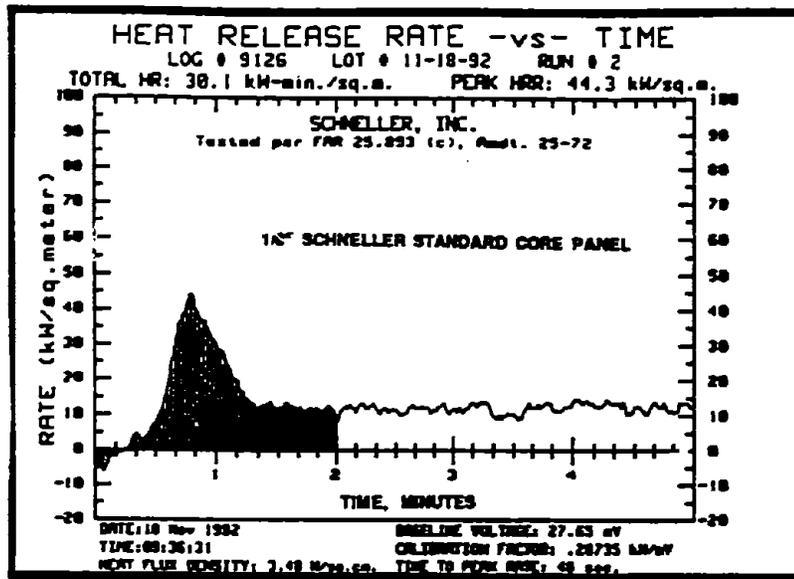
#### ACKNOWLEDGMENTS

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**FIGURE 1**  
**OSU COMPARISON OF**  
**1/8" SCHNELLER CORE/PARABOND ADHESIVE**



**FIGURE 2**  
**OSU HEAT RELEASE**  
**OF NOMEX THERMACOLOR™**

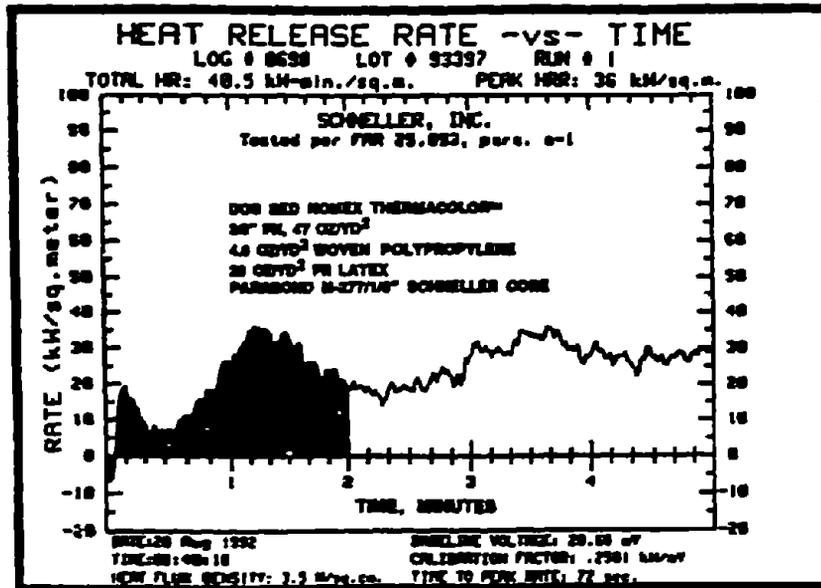


FIGURE 3

OSU HEAT RELEASE VS. PILE WEIGHT/HEIGHT  
FOR DOG RED NOMEX THERMACOLOR™

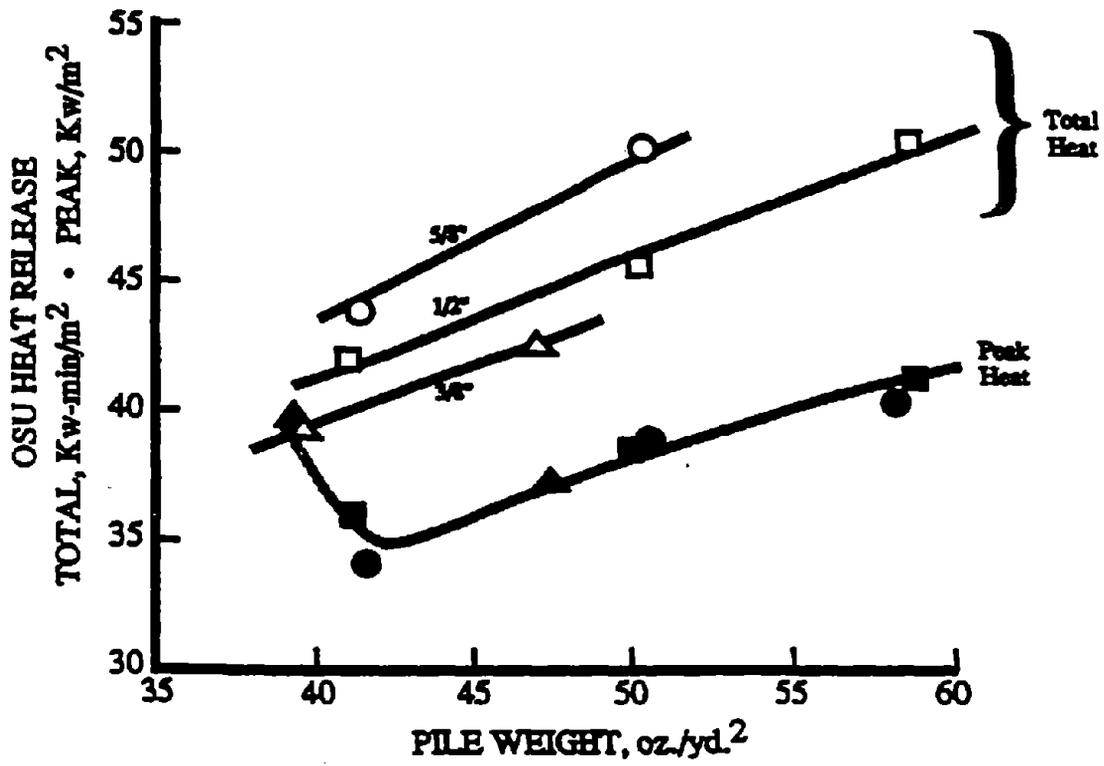


FIGURE 4

OSU TOTAL HEAT RELEASE VS. PILE ACCESSIBILITY FACTOR FOR DOG RED NOMEX THERMACOLOR™

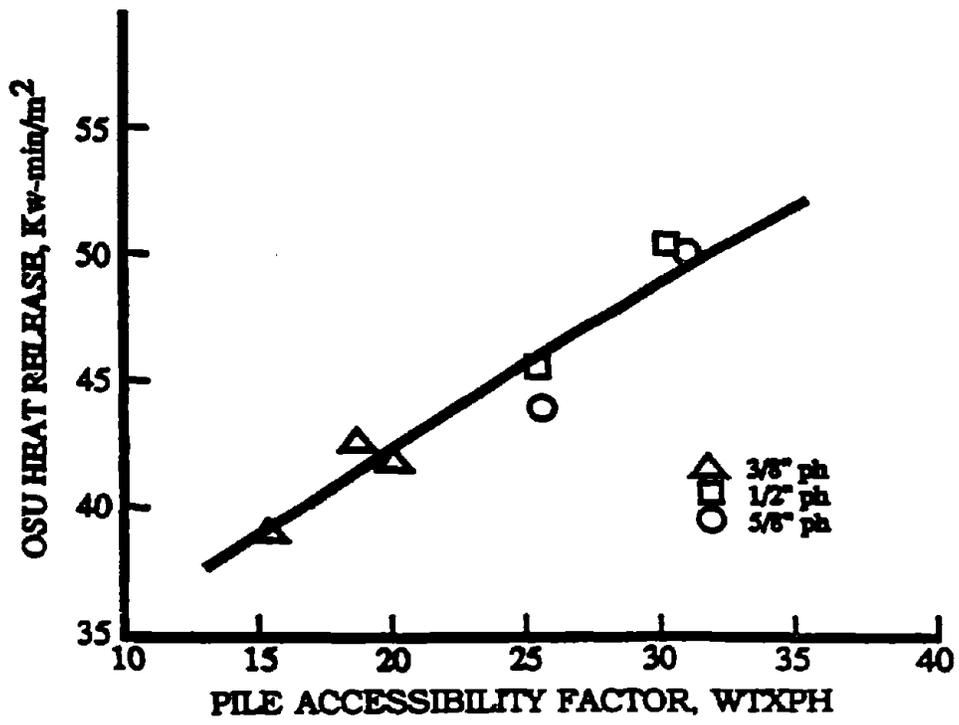


FIGURE 5

OSU HEAT RELEASE VS. PILE WEIGHT AT 1/2" PH  
FOR CHARCOAL GREEN NOMEX THERMACOLOR™

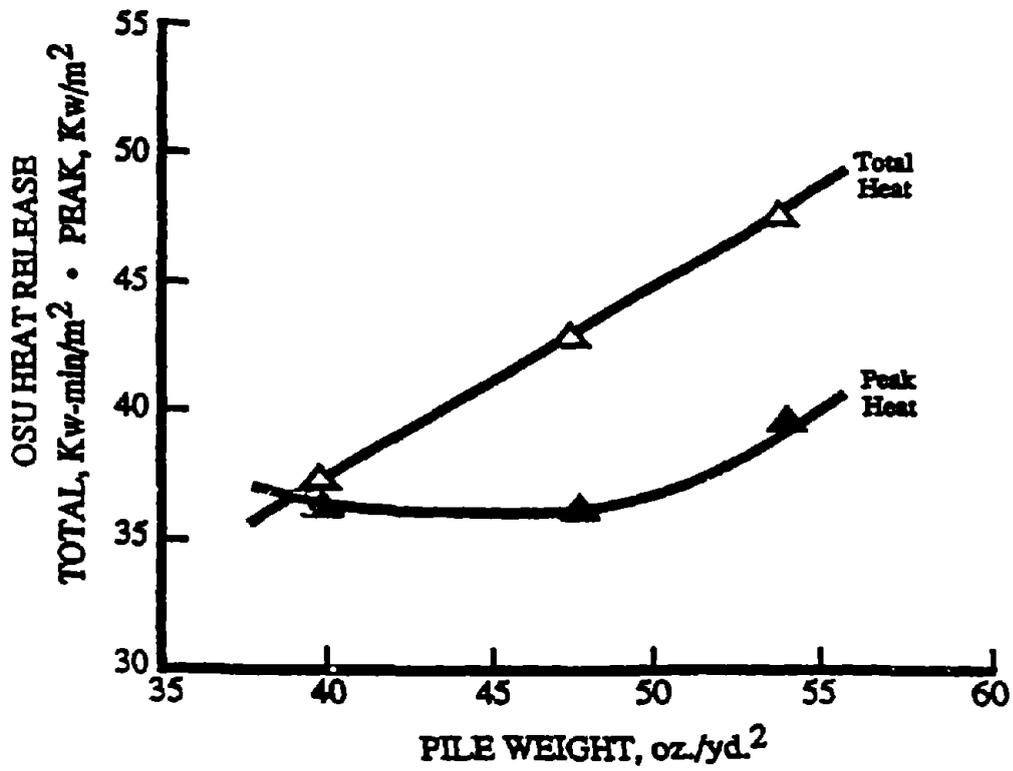


FIGURE 6

OSU HEAT RELEASE OF POLYPROPYLENE AND COTTON BACKINGS ON NOMEX THERMACOLOR™

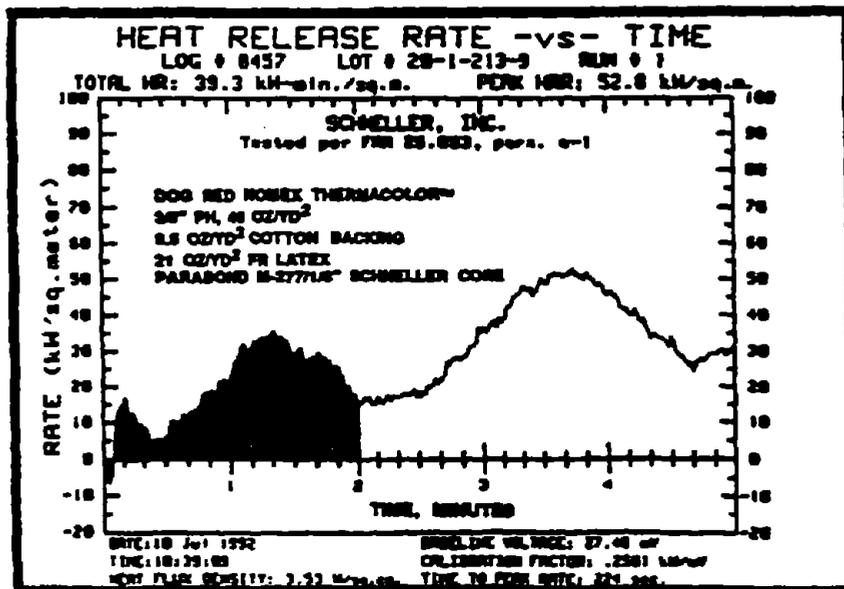
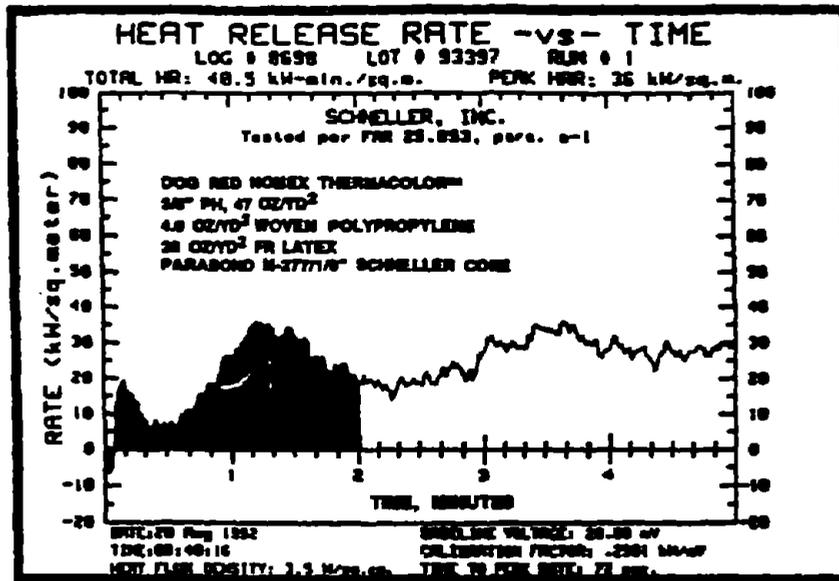
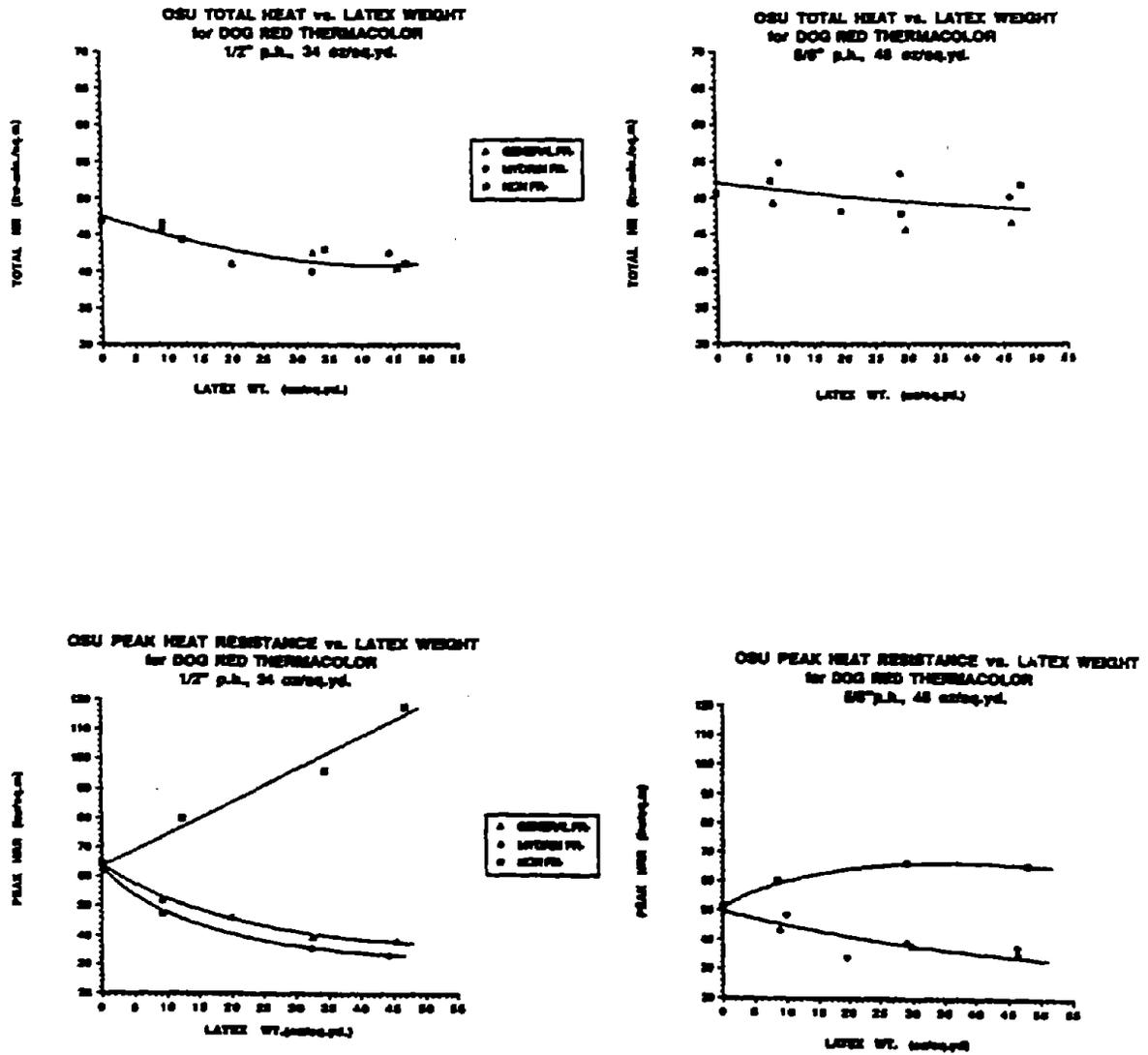


FIGURE 7

OSU HEAT RELEASE VS. LATEX WEIGHT/TYPE ON NOMEX THERMACOLOR™



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**AIRCRAFT MATERIAL FIRE TESTING AND THE CREATION OF AN  
INTERNATIONAL WORKING GROUP**

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**INTRODUCTION**

The Fire Safety Branch at the Technical Center in Atlantic City, New Jersey is The Federal Aviation Administration's (FAA) Research and Development (R&D) organization responsible for providing data to the regulatory organizations within the FAA for their use in developing, modifying and/or interpreting rules and regulations pertaining to aircraft fire safety. In carrying out that responsibility, the Fire Safety Branch has developed a number of new or modified fire test methods for aircraft interior materials that have been adopted as requirements by not only the FAA, but also the Joint Airworthiness Authority (JAA) and other regulatory airworthiness authorities around the world. As a result, the Fire Safety Branch has a responsibility to the world aviation community when questions or problems arise pertaining to those test methods. The Fire Safety Branch is a leader in aircraft fire safety R&D and is committed to improving aviation safety worldwide through international cooperation.

**BACKGROUND**

During the development of the FAA heat release test requirement, which specifies the Ohio State University (OSU) heat release method, it was determined that comparative (Round Robin) testing among laboratories was necessary to establish the repeatability and reproducibility of the test apparatus and procedures. The initial round robin tests with the OSU heat release method were conducted within the United States by four laboratories. The average relative standard deviation for the 2 minute total heat release was 25.2%. Because of this relatively high variability, various modifications to the equipment and procedures were made. Following the modifications, a second round robin was conducted and the average relative standard deviation was lowered to 14.1%. Again, additional modifications were made. A third and final round robin showed a further lowering of the average standard deviation to 7.7%, which is excellent considering the inherent variability in burning processes and test specimen composition.

During the conduct of the heat release round robin, other laboratories within and outside the United States expressed interest in the test program. At its completion, a revised test method was developed and adopted as the required test method. Because of the widespread interest, the Fire Safety Branch tried to accommodate the laboratories not involved in the round robin by conducting numerous workshops in the U.S., Europe and Japan in order to standardize the heat release testing of aircraft panels.

Since the implementation of the heat release requirements, the Fire Safety Branch has served as a technical advisor to the FAA regulatory offices on problems that have developed or arisen with the test method. Typical questions included how to test unusual materials, and how to retain pilot flaming when testing materials that offgas large quantities of fire retardant additives. Many of the problems are not normally encountered or even duplicated by a research laboratory (lab) as compared to a testing facility. The Fire Safety Branch, as a research lab, has limited access to a large variety of materials and conducts a limited number of tests by highly

trained personnel. Conversely, a testing facility conducts a large number of tests on a wide variety of materials, at times on more than one shift, with a cross section of personnel (some with limited training). It became apparent that comparative laboratory testing (round robin) was the best approach to develop solutions to these problems. Because of the success of the heat release round robin and initial smoke chamber test variability among member labs, the Aerospace Industries Association (AIA) requested that the FAA conduct another round robin using the NBS chamber to examine its reproducibility between labs. Because of the large number of laboratories interested in conducting heat release and smoke tests on aircraft materials, it was decided that more than the four labs that participated in the heat release tests would be included. Participation was opened to any laboratory that could operate or have access to an NBS smoke chamber capable of being run in accordance with ASTM F814-83 "Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials for Aerospace Applications", as specified in the rule (FAR Amendment 25-66). Eighteen laboratories from around the world volunteered to participate in the testing.

In order to coordinate such a large round robin, a meeting was held at the FAA Technical Center with all participating laboratories. Ground rules for the round robin were discussed as well as a schedule and the reporting of data. At that time, industry expressed interest in this type of process for dealing with problems in other required or even proposed fire/smoke test methods. Since this approach worked well in providing useful and needed data to the FAA, in particular to the Fire Safety Branch, the activities of the group were expanded to include any fire test method utilized in aviation. Thus, the International Aircraft Materials Fire Test Working Group was born.

## INTERNATIONAL AIRCRAFT MATERIALS FIRE TEST WORKING GROUP

### OBJECTIVE

The main objective of the group is to provide a broad base of technical data to the Fire Safety Branch for use in formulating technical advice to regulatory authorities pertaining to aircraft flammability and smoke test methods. Other objectives are to bring together laboratories from around the world to discuss problems encountered and possible solutions; to keep all testing labs current in terms of proper testing procedures, and, to allow an interface between authorities and industry.

### ORGANIZATION

The group is organized and chaired by the Fire Safety Branch. The group is open to any laboratory that conducts aircraft flammability or smoke tests worldwide. At present, there are three scheduled meetings a year. One is held at the FAA Technical Center in Atlantic City, New Jersey; another hosted by a member lab in North America; and, a third hosted by a member lab outside of North America (Europe, Asia). The Fire Safety Branch prepares the agenda (with the assistance of the host lab) and chairs all meetings.

A lab does not have to attend all, or any, of the meetings in order to participate. Information pertaining to the technical activities discussed at each meeting is mailed to each member. Involvement in any of the round robin test programs is voluntary. All information obtained by the group is shared by the group. All information and documents generated by the group are open for member comments. All information and/or data generated is not regulatory; that is, no regulatory decisions can be made by the group. However, the information and/or data is made available to regulatory authorities.

## EXAMPLE OF GROUP ACTIVITIES

The round robin on the NBS smoke chamber is a good example of the workings of the group. Eighteen labs participated in the testing. The first phase of testing used only two materials. One was an aircraft epoxy fiberglass panel and the other was a paper material supplied by the National Institute of Standards and Technology (NIST) [formerly National Bureau of Standards-(NBS)] as a standard reference material for the NBS chamber.

The data showed a wide range of variation with the average relative standard deviation for the NBS standard material a high 60.8%. The epoxy fiberglass was better, but still very high at 32.1%. The epoxy fiberglass panel was also tested by (sixteen labs) using the OSU heat release test. The two minute heat release average relative standard deviation was 11.0%, and for the peak heat release rate, the value was 13.9%. It was decided that before proceeding with any more smoke testing, the calibration of each unit should be checked. Each lab had their transducer compared to the transducer at the Technical Center. The full round robin was conducted evaluating thirteen aircraft materials (with heater calibration traced to the Technical Center) and a disappointing 31.6% average relative standard deviation was obtained.

Analysis of the data showed a problem with the pilot flames remaining lit. Changes were made in the pilot gas flow rate and size of the pilot flames. A one inch pressure relief line was also required to eliminate high pressure buildup that reduces the pilot flame length or extinguishes the pilot flame. Other minor modifications were made to the test method before another full round robin, testing four materials, was conducted. The average relative standard deviation improved significantly to a very respectable 13.3%.

Two mini round robins were conducted at the same time as the second full round robin to study the effects of vertical sample retention wires and the extinguishment of the 45 degree pilots on test results. The results were as follows:

The use of 2 vertical wires lowered the specific optical density ( $D_g$ ) on some samples. It was agreed by the labs conducting those tests that the reason for the lower numbers was that, in the affected materials, the wires held the samples in place better, which did not allow the materials to swell up and to get closer to the furnace (that is, to be exposed to a heat flux higher than the required  $2.5 \text{ W/cm}^2$ ). Testing showed no difference on the burning pattern of the sample because of the wires. Wire sizes from .0015 of an inch to .0025 of an inch performed the same.

It was noted by some labs that the 45 degree pilots did extinguish during some tests. Data presented showed much lower results with the 45 degree pilots out.

A modified test method which incorporated the various changes was developed. The test method was then reviewed by all group members. Comments were discussed by the group and resolved. The test method was then submitted to the regulatory authorities. On December 14, 1990, the FAA Aircraft Certification Service, ANM-100, issued a policy letter stating "round robin testing is now essentially complete and the Technical Center has developed a smoke test specification which incorporates the findings of the round robin and constitutes an equivalent, and in fact, the preferred, method of conducting the test."

## OTHER ACCOMPLISHMENTS

Although the main focus of the group at that point had been the NBS smoke test method, the group has addressed other problems. Work by the group on the OSU heat release test method has led to modifications of the equipment and procedures. The group has reviewed and commented on the FAA's Fire Test Handbook, leading to changes in that document. The group has also become a platform for international information exchange on aircraft fire test methods. For example, when a number of European labs complained that they were not aware that the FAA had videos on a number of the fire test methods, BASF volunteered to make copies (in European format) for anyone sending them a blank tape. Problem Solved!

## PRESENT TASKS

Tasks presently underway by the group are as follows:

### 1. NBS Smoke Test Method.

A project by NIST to develop an easier method for calibrating the chamber has been completed. The project developed a new heating element that should allow easier chamber calibration. Additional round robin testing is underway to verify the equivalency of the new heating element.

### 2. Electrical Wire Testing

Round robins are now underway aimed at developing proposed test methods in the areas of arc tracking and smoke production of aircraft electrical wiring.

### 3. Fire Test Handbook.

The Fire Safety Branch has committed to updating all the test methods in the Fire Test Handbook. The updating will include modifications to the equipment and/or procedures to improve repeatability, reproducibility, or reliability. Changes will also be made to simplify and/or minimize testing. For all proposed changes, data is being generated that shows that the present level of safety will be maintained or raised.

The target date for the completion of the handbook modification and other recommendations on requirements is March of 1993. The modifications, data and recommendations produced by the group will be transmitted to the regulatory authorities for their use. This work may or may not be used in whole or in part as the basis of future regulatory action.

## GROUP FUTURE

The group is expected to continue its work on present round robin testing. New test methods, such as those for electrical wiring will be documented using the same format employed in the handbook. Problems with any present test method will be addressed and worked on as needed.

## CONCLUSION

The International Aircraft Materials Fire Test Working Group has become and will continue to be an important part of aircraft fire test method development and modification.

*omit*

**SESSION IV**  
**FUTURE NEEDS AND REQUIREMENTS**

Thursday, February 11, 1993

Session Chairman  
**Mr. Dennis Warren**  
Civil Aviation Authority (United Kingdom)  
Safety Regulations Group



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**DEVELOPMENT AND ANALYSIS OF INSULATION CONSTRUCTIONS  
FOR AEROSPACE WIRING APPLICATIONS**

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**ABSTRACT**

The Wright Laboratory Materials Directorate at WPAFB, Ohio recently completed a research and development program under contract F33615-89-C-5605 with the McDonnell Douglas Aerospace Company, St Louis, Missouri. Program objectives were to develop wire insulation performance requirements, evaluate candidate insulations, and prepare preliminary specification sheets on the most promising candidates. Aircraft wiring continues to be a high maintenance item and a major contributor to electrically-related aircraft mishaps. Mishap data on aircraft show that chafing of insulation is the most common mode of wire failure. Improved wiring constructions are expected to increase aircraft performance and decrease costs by reducing maintenance actions. In the laboratory program, new insulation constructions were identified that had overall improved performance in evaluation tests when compared to currently available MIL-W-81381 and MIL-W-22759 wiring. These insulations are principally aromatic polyimide and cross-linked ethylene tetrafluoroethylene (ETFE), respectively. Candidate insulations identified in preliminary specification sheets were principally fluoropolymers with a polyimide inner layer. Examples of insulation properties evaluated included flammability, high temperature mechanical and electrical performance, fluid immersion, and susceptibility to arc propagation under applied power chafing conditions. Potential next generation wire insulation materials will also be reviewed.

**INTRODUCTION**

The increased emphasis and reliance on electronic systems for modern aircraft has resulted in wiring becoming a critical safety of flight system. Aircraft now routinely use fly-by-wire systems with minimal or no mechanical backup systems. McDonnell Douglas Aerospace Company has a very active program in developing new insulation and connection systems and providing technical support to aerospace systems under development and in production. A recent study initiated by the Materials Directorate reported 34% of all electrically-related aircraft mishaps were related to interconnection failures involving wiring and connectors (Galler and Slenski, 1991). The Materials Directorate System Support Division conducts failure analysis investigations in support of Air Force accident boards, aircraft program offices, and depot operations. In this capacity wiring failures have been found to initiate hydraulic and fuel fires via electrical arcing or cause malfunctions in flight control systems and in other critical areas. At high operating temperatures some insulations can soften and are susceptible to chafing damage that

normally would not occur at room temperatures. Examples where wire chafing led to arcing, a fire, and an aircraft mishap are shown in Figures 1 and 2. In both cases, the insulations were pure fluoropolymer constructions and had chafed against a metallic structure. Loss of electrical connections can also lead to severe degradation of aircraft performance. An example of this failure mode is shown in Figures 3 and 4. This is an example of an arc propagation failure in a primarily polyimide wire or MIL-W-81381 construction. In this case, polyimide was carbonized by high temperatures of an electrical arc produced by a metallic structure intimately contacting an exposed conductor carrying electrical power. Polyimide does not melt, but degrades into carbon at temperatures in excess of 650°C, which is much lower than the temperature of an electrical arc. In Figure 4, wiring adjacent to the initial chafe site was degraded by the high arc temperatures. The damaged insulation sustained additional arcing which led to over 30% of the wiring being severed. The arc propagation event can take place before the thermal circuit breakers interrupt current flow. This scenario requires several independent conditions which include an exposed conductor, sufficient current and voltage, and intimate contact between a conductor and metallic structure. Fortunately, this is one reason why arc propagation events are rare. The damage, however, can be severe enough that even a rare failure should be a concern in new and existing aircraft designs. Reported instances of arc propagation and maintenance difficulties with currently available wiring led the Materials Directorate to initiate an in-house program and then a contractual effort to develop new wire insulation constructions. Program goals were to have similar weight, volume and mechanical properties to MIL-W-81381 construction, have increased flexibility, yet not be susceptible to arc propagation failures. The new insulation constructions would also need to be manufacturable by more than one source and be available at a cost comparable to insulations currently used on aircraft.

## DEVELOPMENT OF A PROGRAM FOR NEW WIRE INSULATIONS

The AF Materials Directorate, McDonnell Douglas Aerospace Company and other aerospace organizations actively evaluated arc propagation and other characteristics of many insulation candidates as potential replacements for MIL-W-81381 during the mid 1980's. Testing revealed that an insulation construction consisting of various combinations of polyimide tape and polytetrafluoroethylene (PTFE) layers would significantly improve arc propagation resistance (Cahill, 1987). These hybrid constructions combine the desirable properties of polyimide and fluoropolymer materials. The introduction of a high temperature fluoropolymer interrupts the carbon path formed by thermally degraded polyimide during the arcing process. Arc propagation is just one of many wire characteristics that must be considered when selecting wiring for an aircraft. In 1988 a program was conceived by the Materials Directorate that would provide a comprehensive evaluation of selected new insulation constructions. The ground rules were to evaluate commercially available materials that could be available within two years as a wire insulation product from multiple sources. In addition, an industry-supported wire performance test method document being developed by the SAE AE-8D Wire and Cable Subcommittee, AS 4373, would also be used as a testing guideline. McDonnell Douglas was awarded the two year wire development contract, F33615-89-C-5605, in late 1988. Work began in early 1989, and a final report was published by the government in mid 1991. The program was organized by tasks which included the following: establishment of wire performance requirements, selection of ten insulation constructions for evaluation, a highly focused screening evaluation of the most critical wire insulation characteristics, additional

performance testing to provide comprehensive data on the top four insulations, an assembly and handling evaluation on selected insulations, and preliminary specification sheets on the most promising insulation candidates (Soloman, 1991). All testing included the two baseline aerospace wiring constructions MIL-W-81381/11,/7,/9 and MIL-W-22759/43,/44,/33.

## **WIRE PERFORMANCE REQUIREMENTS**

Initially, the test program identified minimum wire performance requirements in the areas of assembly and handling, combat damage, thermal analysis, electrical, environmental, mechanical, marking, and wire volume and weight. Forty-three tests were identified and ranked or weighted on a scale of one to five, with five being the most critical. Weighting was based on probability of a failure, field frequency of a failure, and seriousness of failure. The most critical tests were selected to initially screen insulation candidates. Overall ranking of insulation candidates included a weighting factor based on the identified performance requirements. Weighting factors were determined by a survey of three aerospace companies and several government organizations. In all cases minimum performance requirements had to be exceeded in order for a new insulation construction to remain in the evaluation.

## **INSULATION CONSTRUCTIONS SELECTED**

Insulation candidates were submitted by insulation manufacturers and material suppliers. Ten candidates were initially selected from a field of twenty-two proposed constructions. Nine of the ten candidates consisted of various polyimide tape and fluoropolymer layers as shown in Table 1 (Soloman, 1991). Test specimens consisted of 22 gauge and 26 gauge airframe and hook-up wiring.

## **SCREENING TESTING RESULTS**

Screening tests shown in Table 2 were selected from the most important or heavily weighted wiring characteristics identified in the wire performance requirements (Soloman, 1991). Testing was conducted on the ten insulation candidates and the two baseline constructions. The most important tests were part of the verification of properties evaluation. Wire specimens were aged for 1000 hours at 200°C and then subjected to the selected screening tests. Thermally aging the wire specimens provided an indication of long term wiring field performance, since a 10,000 hour design life at 200°C will ultimately be required of any new insulation. Statistical analysis was used to rank insulations in each test and give an overall ranking. The best performing insulation construction was given a score of 0.0. Scores for other insulation constructions were determined by dividing the numerical difference between the best performer and selected insulation by the unbiased standard deviation. A weighted factor determined in the performance requirements evaluation was multiplied by the candidates' calculated score. For the screening evaluation, weighting ranged from 3 to 5.5. Screening test ranking of the candidates is given in Table 3 (Soloman, 1991). The ranking includes all construction types evaluated.

Selection of the top four candidates for further testing was based on overall screening test ranking and availability of a second manufacturing source. Based on these criteria the candidates selected for additional evaluation testing were Filotex, Thermatics, NEMA #3, and Tensolite. The Gore candidate was not continued in the program due to its single source availability. MIL-W-81381 and MIL-W-22759 baseline constructions ranked fifth and tenth, respectively. MIL-W-81381 failed to meet minimum performance requirements in the dry arc propagation test.

## **FULL PERFORMANCE EVALUATION**

A total of twenty-eight tests were conducted on the insulation candidates selected from the screening evaluation. Performance tests and their weighting are given in Table 4. Combined screening and performance evaluation results are given in Table 5 (Soloman, 1991). Data in Table 5 differs slightly from the referenced technical report due to the fact that several minor errors in the statistical analysis have been corrected. Candidate ranking was not affected by the corrections. The statistical approach used in the screening evaluation was also employed in the performance evaluation. Top performers were the Filotex and Tensolite constructions. The Filotex construction tested in the performance evaluation employed a fluorinated ethylene propylene (FEP) top coat, as opposed to the original PTFE top coat. The two top performing candidates and MIL-W-22759 were subjected to assembly and handling tests. Bundles were constructed and installed in an aircraft. During this evaluation characteristics such as insulation stripping, wire potting, splicing, handling, layout, damage susceptibility, and reparability were assessed. Overall the Filotex construction was a slightly better performer compared to the Tensolite and MIL-W-22759 constructions.

## **DISCUSSION**

Hybrid wire constructions exhibited higher overall performance than the baseline constructions evaluated. Hybrids gave a more balanced range of insulation properties. As an example, wet arc tracking results for the top three candidates and baseline constructions are given in Figure 5 (Soloman, 1991). Hybrid candidates performed as well or better than MIL-W-22759, which is usually considered to be a non-arc tracking insulation. MIL-W-81381 readily arc tracks in this test. Abrasion test results, which give an indication of chafe susceptibility are given in Figure 6 (Soloman, 1991). Several hybrids performed at a level equal to or above MIL-W-81381. One of the most desirable characteristics of MIL-W-81381 type wiring is its ability to retain its excellent mechanical properties over a wide temperature range. As can be seen by the abrasion data pure fluoropolymer constructions rapidly lose their mechanical properties at high temperatures. A common complaint from maintenance personnel is the stiffness and springback of MIL-W-81381. Springback results for hybrids and baseline constructions are given in Figure 7 (Soloman, 1991). Hybrids fall between a very stiff insulation (MIL-W-81381) and a very flexible insulation (MIL-W-22759). While the appropriateness of a test method for smoke quantity determination can be debated, the results in Figure 8 at least show comparisons between insulation

constructions (Soloman, 1991). Hybrids are comparable to MIL-W-81381, an insulation highly desirable for manned areas due to minimal smoke generation when the material is thermally degraded.

## **CONCLUSIONS**

Since completing the insulation program in 1991, hybrid insulations have continued to gain popularity as an aerospace wiring. Major aircraft companies have selected constructions similar to the Tensolite and Filotex candidates. Several military programs are in the process of selecting hybrid constructions for aircraft use. Hybrid insulations are also being evaluated for space applications. Wire insulation processors continue to improve hybrid designs and have several products that are commercially available. Overall, hybrids can provide improved performance over currently available aerospace wire insulations. Hybrid insulations retain mechanical properties over a wide temperature range, are arc propagation resistant, provide reasonable flexibility for installation and maintenance, and can be manufactured at a cost comparable to existing aerospace wire insulations.

## **ACKNOWLEDGMENTS**

The authors would like to gratefully acknowledge the program management and technical support provided by Mr. Ron Soloman and the technical support of Mr. Steve Domalewski that made the overall new insulation evaluation program possible. We would also like to acknowledge the time and material provided by the many companies and agencies that participated in the new insulation development program. These organizations include Barcel Wire and Cable, Brand-Rex Cable Systems Division, Champlain Cable Corp., E.I. DuPont De Nemours and Company, Filotex, W.L. Gore and Associates, Independent Cable Inc., Tensolite Company, Teledyne-Thermatics, Hudson International Conductors, Spectrum Technologies, Federal Aviation Agency, the SAE, Lockheed Aeronautical Systems Company, Grumman Aerospace Corporation, Douglas Aircraft Company, and the National Electronic Manufacturer's Association.

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Figure 1. Arcing site that ignited fuel and totally destroyed an aircraft.



Figure 2. In-flight fire initiated by wiring arcing to a hydraulic line.



Figure 3. Example of a dry arc propagation failure in MIL-W-81381.



Figure 4. Close-up of Figure 3 showing carbonized insulation.

TABLE 1. SELECTED INSULATION CANDIDATES AND TWO BASELINE CONSTRUCTIONS.

CONSTRUCTION	DESCRIPTION
BARCEL #1	2919 polyimide(50%OL)/Unsiatered PTFE
BRAND REX #1	XL-ETFE(50%OL)/616 polyimide/XL-ETFE(50%OL)
CHAMPLAIN #1	2919 polyimide(50%OL)/Extruded XL-ETFE
DUPONT #1	2 layers new polyimide-fluoropolymer (50%OL)/Fluoropolymer
FILOTEX	PTFE extrusion/616 polyimide/PTFE dispersion
GORE #3	PTFE(50%OL)/HSCR PTFE(50%OL)
THERMATICS #3	Modified PTFE(50%OL)/PTFE/polyimide/PTFE Tape/Modified PTFE
TENSOLITE #3	919 polyimide(50%OL)/PTFE(50%OL)
NEMA #2	PTFE(50%OL)/616 polyimide/PTFE(50%OL)
NEMA #3	616 polyimide/Extruded XL-ETFE
MIL-W-81381/7	616 polyimide(50%OL)/616 polyimide/polyimide topcoat
MIL-W-22759/43	Deal extrusion of ETFE
NEMA= National Electronic Manufacturers Association, FEP (fluoroated ethylene propylene) 029= 2.0 mil polyimide,0.5 mil 2919= 0.5 mil PTFE,1 mil polyimide,0.5 mil polyimide,0.5 mil PTFE 616= 0.1 mil FEP,1 mil polyimide,0.1 mil FEP 919= 0.5 PTFE,1 mil polyimide,0.5 mil PTFE PTFE= Polytetrafluoroethylene, ETFE= Ethylene tetrafluoroethylene XL= Crosslinked, OL=Overlap, HSCR= High Strength Crush Resistant	

**TABLE 2. SCREENING TESTS AND WEIGHTING FACTORS.**

SAE AS 4373 METHOD	TEST	WEIGHT FACTOR	SAE AS 4373 METHOD	TEST	WEIGHT FACTOR
901	Finished Diameter	4.2	(3)	Verification of Retained properties	5.5
(1)	Workmanship	3.0	701	Abrasion	5.5
301	Dry Arc Resistance	5.5	703	Dynamic Cut Through	4.5
(2)	Toxicity	5.0	(4)	Flex Life	5.5
708	Stiffness and Springback	4.2	707	Notch Propagation	5.0
801	Flammability	4.3	510	Voltage Withstand	5.5
601	Fluid Immersion	4.5	504	Insulation resistance	4.5
902	Finished Diameter	4.2	(5)	Examine Product	3.0
(1)- AS 4372, SAE Para. 3.1.4 (2)- Naval Engineering Standard 713, Issue 2 (3)- Specimens were aged for 1000 hrs at 200°C (4)- MDC B0482 (5)- SAE AS 4372 Para. 3.1.4					

**TABLE 3. SCREENING TEST RESULTS**

RANKING	SCORE	INSULATION	RANKING	SCORE	INSULATION
1	6.52	FILOTEX	7	9.92	CHAMPLAIN #1
2	7.23	THERMATICS #3	8	9.94	BARCEL #1
3	8.59	NEMA #3	9	10.97	NEMA #2
4	9.05	GORE	10	11.18	M22759
5	9.22	M81381	11	13.96	BRAND REX #1
6	9.59	TENSOLITE #3	12	14.19	DUPONT #1

**TABLE 4. PERFORMANCE TESTS AND WEIGHTING FACTORS.**

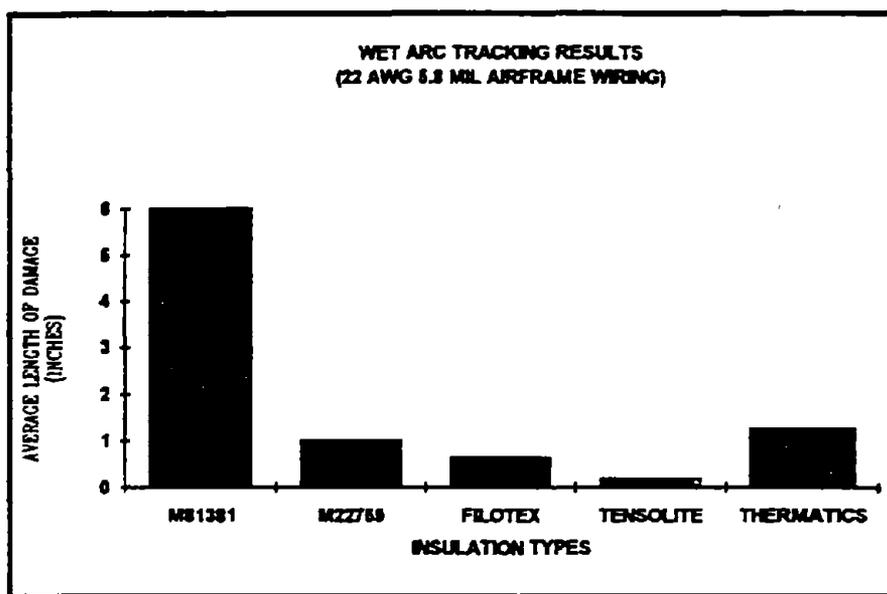
SAE AS 4373 Method	TEST	Weight Factor	SAE AS 4373 Method	TEST	Weight Factor
(1)	BSI Dry Arc Test	5.5	701	Abrasion	5.2
501	Dielectric Constant	2.0	702	Cold Bend	3.3
502	Corona Inception	3.3	703	Dynamic Cut Through	4.8
506	Surface Resistance	2.2	704	Flex Life	4.7
507	Time/Current to Smoke	3.3	705	Insulation Impact Resistance	3.1
509	Wet Arc Tracking	3.2	706	Insulation Tensile Strength	3.2
511	Wire Fusing Time	3.2	707	Notch Propagation	5.0
602	Forced Hydrolysis	3.5	803	Smoke Quantity	4.3
603	Humidity Resistance	2.2	804	Thermal Index	4.0
604	Weight Loss/Outgassing	2.2	805	Thermal Shock	4.0
606	Weathering Resistance	3.5	712	Wire Surface Marking	3.8
607	Wicking	3.5	(3)	Crush Resistance	3.0
(2)	Wire to wire Rub	5.2	807	Verification of Retained Properties	5.5

(1)- British Standard Institute 90/76828 and 90/80606  
 (2)- Douglas Aircraft Company Procedure (3)- ASTM D3032, Section 20

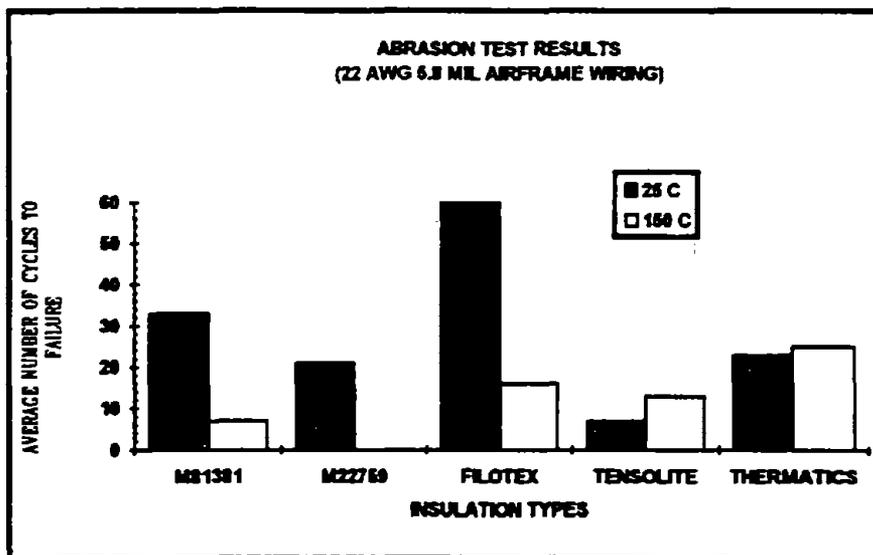
**TABLE 5. COMBINED SCREENING AND PERFORMANCE TEST RESULTS**

RANKING WEIGHTED	SCORE WEIGHTED	SCORE UNWEIGHTED	INSULATION
1	8.21	8.41	FILOTEX
2	8.22	7.79	TENSOLITE
3	9.20	9.10	M81381
4	9.38	9.88	THERMATICS
5	10.51	10.46	NEMA #3
6	11.36	11.23	M22759

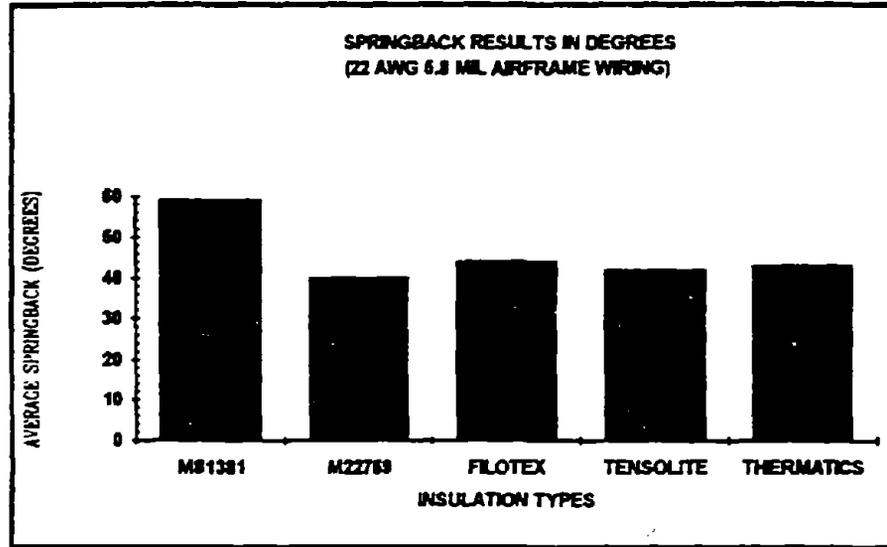
**FIGURE 5. WET ARC TRACKING RESULTS**



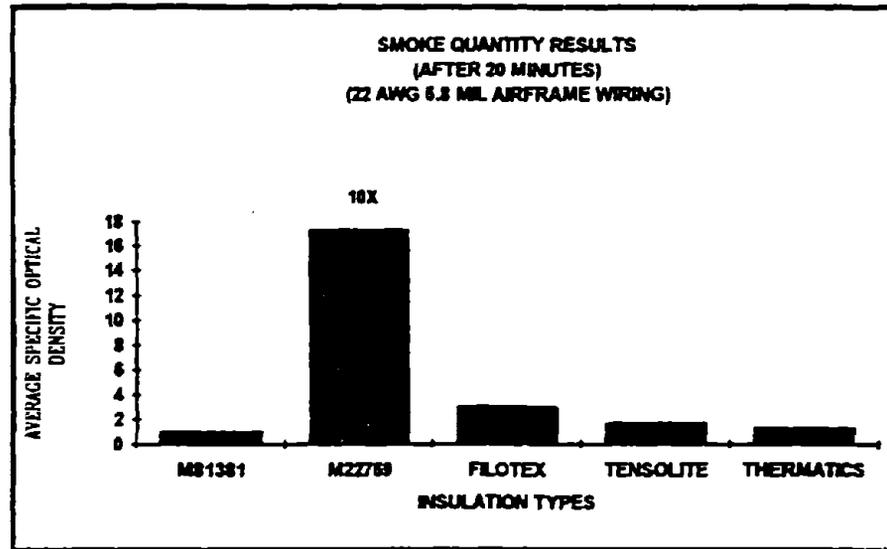
**FIGURE 6. ABRASION TEST RESULTS**



**FIGURE 7. SPRINGBACK TEST RESULTS.**



**FIGURE 8. SMOKE QUANTITY TEST RESULTS.**



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**Future Material Development Trends  
For Commercial Airplane Interiors**

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**ABSTRACT**

Advances in airplane interiors in the past have, for the most part, been made by airplane manufacturers primarily through initiatives to improve safety, but also to update appearance and functionality.

Recently, regulation has played a very large role in the design of airplane interiors. The Federal Aviation Administration (FAA) heat release rule was a major challenge to designers and materials suppliers, and required the development and incorporation of new materials on a very tight schedule. Industry was able to meet the rule, but the result was non-optimum solutions.

We suggest that all affected parties—regulatory and industry—work together in advance of regulation to continuously improve cabin furnishings. Strategic research and development programs involving all parties should be established, using an integrated material, design, and manufacturing philosophy. We have looked at how we can operate in a "continuous improvement mode", and will share with you how we are trying to incorporate this.

**INTRODUCTION**

Advances in airplane interiors in the past have, for the most part, been made by airplane manufacturers primarily through initiatives to improve safety, but also to update appearance and functionality. In new interior designs that incorporate materials and technologies with improved fire resistance, designers were also able to create more aesthetically pleasing interiors. In addition, new interiors have had to become more cost effective in design, manufacture and maintenance. The 747 interior, for example, was based and certified on upgraded fire safety criteria, and the design reflected a more attractive and comfortable ambience than its predecessors. Likewise, the DC-10, L-1011, A300, and 757 and 767 as well incorporated available new technologies in their passenger cabin interiors.

Recently, however, regulation has played a very large role in the design of airplane interiors. The heat and smoke release mandates from the FAA and other authorities was a major challenge to interior designers and materials suppliers, and necessitated the development and incorporation of new materials into future and existing designs on a very tight schedule. Material suppliers and airplane manufacturers worked together in an intense effort to meet the rules, but the result was reduced design flexibility.

Regarding the evolution of cabin interior designs, we suggest that all affected parties, regulatory and industry, work together in advance of regulation to pursue the continuous improvement of cabin furnishings. This approach would initiate strategic research and development programs involving regulatory agencies, material suppliers, airplane manufacturers and airlines. For this we need an integrated material, design, and manufacturing philosophy. We at Boeing have looked at how we might operate in a "continuous improvement mode", and will share with you now how we are trying to incorporate this.

## FACTORS INFLUENCING NEW MATERIAL DEVELOPMENT

Interior designs have come a long way from the days of wood framed seats and fabric liner panels. It is clear that interiors have been shaped not entirely by design but also by availability of requisite materials and manufacturing processes. This interdependence is a key recurring theme that is inextricably linked to the commercial success of material development efforts. Additional factors influence materials for future applications, and we can learn from the past to gain insight to change how we identify, validate, and incorporate new materials into new and existing airplanes.

Design technology evolves, as evidenced by the Boeing product line. Generally, major interior systems have trended toward simpler designs with higher levels of part integration, and increased influence of shape and architecture. This in turn has required changes in material and manufacturing technologies. For example, vinyl/aluminum material and its forming techniques was an established technology for 707/727/737 interiors. Part size and depth of draw were dictated by material limitations. Thermoset technology, while available at the time, was still in relative infancy with regard to manufacturing techniques which could compete cost effectively. The use of aluminum in the interior has dropped, while the use of thermosets and, ultimately, thermoplastic materials has grown because of their improved efficiencies of achieving design objectives and manufacturing goals. So sidewall panels, which in early interiors were vinyl/aluminum, have been replaced by thermoset epoxy/glass Nomex core sandwich panels. These in turn evolved into modern crushed core designs based on carbon/phenolic material systems. Today the 747-400 has these systems which offer superior strength to weight performance compared to glass fiber technology. The change from metal to thermoset composite was a breakthrough in design and manufacturing, which allowed more design freedom and improved manufacturing cycle times at lower overall cost. New materials need to deliver substantial benefits to the engineering and manufacturing communities.

However, one for one material substitutions do not offer the overall breakthrough improvements we feel are required. For instance, in order to achieve a desired stiffness of an interior panel, made of thermoset, we have two basic methods, with known trade-offs. We can use a lower modulus glass fiber composite which adds weight, or pay a higher raw material cost to work with carbon fiber. Either option addresses a very focused design issue, however, neither does anything to improve cycle time, prepreg kitting, material storage, tooling cost, or the amount of scrap material left behind. We believe that we are at the point of diminishing return for thermosets for interiors from a productivity perspective, and have established tough requirements for materials for the future.

A substantial productivity increase is needed to justify the implementation of new materials. The value of a new material is measured by its associated productivity increase. An example which illustrates the point is a comparison of two automobiles. The General Motors Lumina, which is a recent design, requires 32.2 hours to assemble while the Ford Taurus requires 17.8 hours. This equates roughly to a \$441 advantage for the Taurus (Reference 1). The assembly time differences reflect factory efficiencies, part count and design complexity, and are central to the future material and design programs. This integrated development approach has profound effects on the bottom line for any company. This example underscores the need to identify collective development objectives early in the design development process, to work as a collaborative team, and to challenge old design paradigms.

## OPPORTUNITIES FOR CHANGE

### New Airplane Programs

To be accepted for production commitment, new technology must be mature, e.g., minimum risk, when the program using it is begun. When a new airplane program is launched, technology including research, development, and innovation is typically placed on a schedule. On this schedule, production commitments are made at a firm, set time, and any new developments must be ready then or they will not be used since the economic exposure of potential failure is too great. The penetration of new technology on a new airplane is

thereby limited, especially if it requires a different manufacturing infrastructure. The cost of risk in carrying developmental programs past firm commitment dates has over the past several years become so great that new airplane programs can commit only proven technologies to production design schedules. We need to change the process of research and development in order to deliver breakthrough materials technology well in advance of program launch.

### Existing Airplane Programs

In the past, airplane manufacturers have introduced new interior technology when new airplane models were introduced. Changing the technology of existing models involves a very high cost due to the demands of configuration control. Also, high-cost factors such as reinvesting in tooling and capital equipment are important in decisions involving introducing new interiors to existing production models. To move into a continuous product improvement mode requires commitment to advance the product and a change in the current process of change itself to remove barriers which impede rapid technology transition.

### New Regulations

The effect of the heat and smoke release regulations in the eighties was to force the development and implementation of new technology into existing production programs. When the criteria and schedules were established, it was not known whether they could be met, or, if they could, what their impact on manufacturing would be.

We believe there is a need to set realistic performance requirements tempered by manufacturing realities. The new regulations did achieve the fire resistance criteria sought; however, the technology as measured by design or manufacturing criteria was essentially unchanged. Working together to dialogue with material suppliers and the manufacturing community, we should be working in advance of regulation to anticipate the impact of change and ensure that the value of new materials is captured.

### FUTURE INTERIOR MATERIAL AND DESIGN NEEDS

Our global vision of new materials and designs which need to be developed and proven are ones which will:

- Reduce the installed part cost by at least 50%;
- Reduce the development and production time by at least 50%;
- Reduce the cost and manufacturing impact of customer variations;
- Increase health and safety performance.

A key element for future development programs is to identify materials which increase the competitiveness of an interior. A summary of the material specific attributes of future materials and designs is listed in Table I.

**Table 1. Desired Material Attributes.**

Commonality	Design	Manufacturing
Design	Family of parts	Multi-process forming capability
Process	Multi-functional parts	Low capital investment (tooling, secondary operations)
Material	Installation-ready	Production line capability
	Tighter tolerance control	Simple tooling for change
	Z-Axis assembly	Minimized floor space requirements
	Minimized threaded fasteners	Minimized inventory
	Predictable future combinations	Reduced flow time
	Ease of repair (access)	Reduced touch labor
	Cost effective spares	R-robust processing
		Consolidated manufacturing processes
	Low impact on health/safety/ environmental issues	
	Recyclable	
	Ease of repair (access and reformability)	

Commonality of design, process, and material allows economies of scale to reduce the cost of installed parts. This basic fact, although easily recognized, has unfortunately not been adhered to uniformly in the past, so it is not uncommon therefore to see different constructions of similar interior parts that perform comparable functions. This adversely impacts fabrication and final assembly. In the future, we must do better.

Designs need to allow improved potential for part integration. Materials which, by their nature, allow higher degrees of integrated design thereby reduce touch labor content, and offer a significant competitive advantage. This includes designing the parts to reduce assembly and maintenance time, incorporating design features during the forming which can be easily trimmed off to create part families from common tooling, and selecting materials for designs that are readily repaired.

To minimize variety in the materials inventory, materials should be adaptable to a variety of forming processes. Materials which can be formed at lower temperatures and pressures offer substantial benefit in the form of lower cost tooling, smaller manufacturing cells, and faster cycle times. Materials that have an indefinite shelf life, and that are reprocessible and recyclable also serve to reduce manufacturing infrastructure by eliminating cold storage, as well as minimizing the environmental impact from scrapped parts. In summary, materials which offer the greatest latitude in design, part fabrication, installation, service, and ease of disposal will be the preferred materials of the future.

Another issue being addressed is the global applicability of technology development. Past programs have often involved point developments. In future, the global applicability needs to be emphasized, and we have taken steps to change how technology is identified.

An example of how this is being done is seen in a current, ongoing material development program to deliver a breakthrough material technology for interior panels. Supplier alignment was established to change the research and development process to deliver a material technology which is rapidly identified, validated in advance of new airplane program requirements, and able to transition easily across all airplane models with minimum impact.

The new program is aimed to develop an integrated material strategy to better address engineering, manufacturing, and customer concerns, and to support new technology development by using an efficient method for surveying the material industry and managing development programs. By this method we are able to reduce the valuable Boeing and supplier resources needed to develop and assess applications. By understanding past efforts we have the following process to guide and lead future development programs:

- Develop a cohesive material, design and manufacturing strategy;
- Focus development programs on high impact applications;
- Focus research resources across engineering and manufacturing to align development goals;
- Limit the number of suppliers participating based on established selection criteria and material strategy;
- Establish experienced R&D Design/Build Teams and suppliers with designated technical and business foci;
- Ensure timely communication of issues through regular technology reviews with suppliers;
- Begin internal marketing of program as soon as initial performance criteria are verified.

This process was initiated in 1991 and has major developments underway with six material suppliers. Selection of development areas was based on their expected impact on achieving the program goals. Three key development areas were targeted, based on their contribution to the interior cost. The three areas selected were contoured panels, flat panels, and insulation. The contoured panel program for sidewalls is highlighted to illustrate the key elements of future material development programs.

### BENCH MARKING

The best way to understand the problem is to look at the evolution of the interior sidewall panel. Through bench marking the requirements, several key criteria for material, design and manufacturing performance were identified. The program does not require that all three areas realize breakthroughs; however, there are minimum performance requirements associated with each area. There are trade-offs, as we illustrated earlier, which need to be made to assess the total value of a material. That value is based on the concept of system engineering which, as a method, develops a new design that optimizes part functionality. In the case of the sidewall, key material criteria includes in-service performance, fire resistance, mechanical properties (e.g., stiffness, strength, acoustic characteristics), and manufacturing properties such as cycle time, assembly time, ease of installation, and health/safety/environmental issues associated with its manufacturability.

### VALIDATION

The new sidewall material, based on thermoplastic technology, offers improved material performance in flammability, smoke and toxicity, the ability to integrate parts and assembly features, and faster shop cycle times with lower expense in tooling. The validation phase includes extensive material testing, prototype forming evaluations, scaled forming and in-service evaluations as well as documenting the cost impact based on the bench mark part.

## TRANSLATION

There are two distinct translation paths being followed to carry the material into production. The near term path is a direct one for one material substitution which involves small changes in the manufacturing process, yielding immediate results in reduced costs and improved sidewall panel performance. By implementing a one for one substitution, however, we compromise the benefits of the new material, but gain valuable in-service data which will in the long run facilitate implementation of an optimized design. In addition, the material supplier is able to establish initial business without waiting for a new airplane program.

The ultimate goal of the development program is to redesign a new sidewall to take advantage of the material's attributes. The redesign offers the potential to eliminate parts, secondary operations and streamline the assembly process through molded-in-assembly features. The greatest benefit of a new material system is achieved through design tailored to the material attributes. The product design has the greatest impact on manufactured cost and therefore should be an integral part of the material optimization process.

The development process applied to the sidewall program reinforces the need to:

- Establish clear goals to focus the development effort and help to establish a shared vision of success with the development partners;
- Balance business and technical issues by providing near term business opportunities via direct material substitutions while fulfilling the long term technical needs to optimize part design.

## CONCLUSION

In the future, new material development efforts should adopt a philosophy and implement a process of continuous improvement. This process will provide a method to systematically advance materials technology across all products while addressing design and manufacturing implications associated with new materials. The central objective in developing new materials is to deliver cost effective technology which adds value to the product manifested in improved fire safety, reduced installed part cost, and enhanced in-service performance. The speed of technology development can be facilitated by working in a collaborative environment with the industry and regulatory agencies. We believe that working in this new paradigm, the state of interior materials technology can be advanced to a new level of performance.

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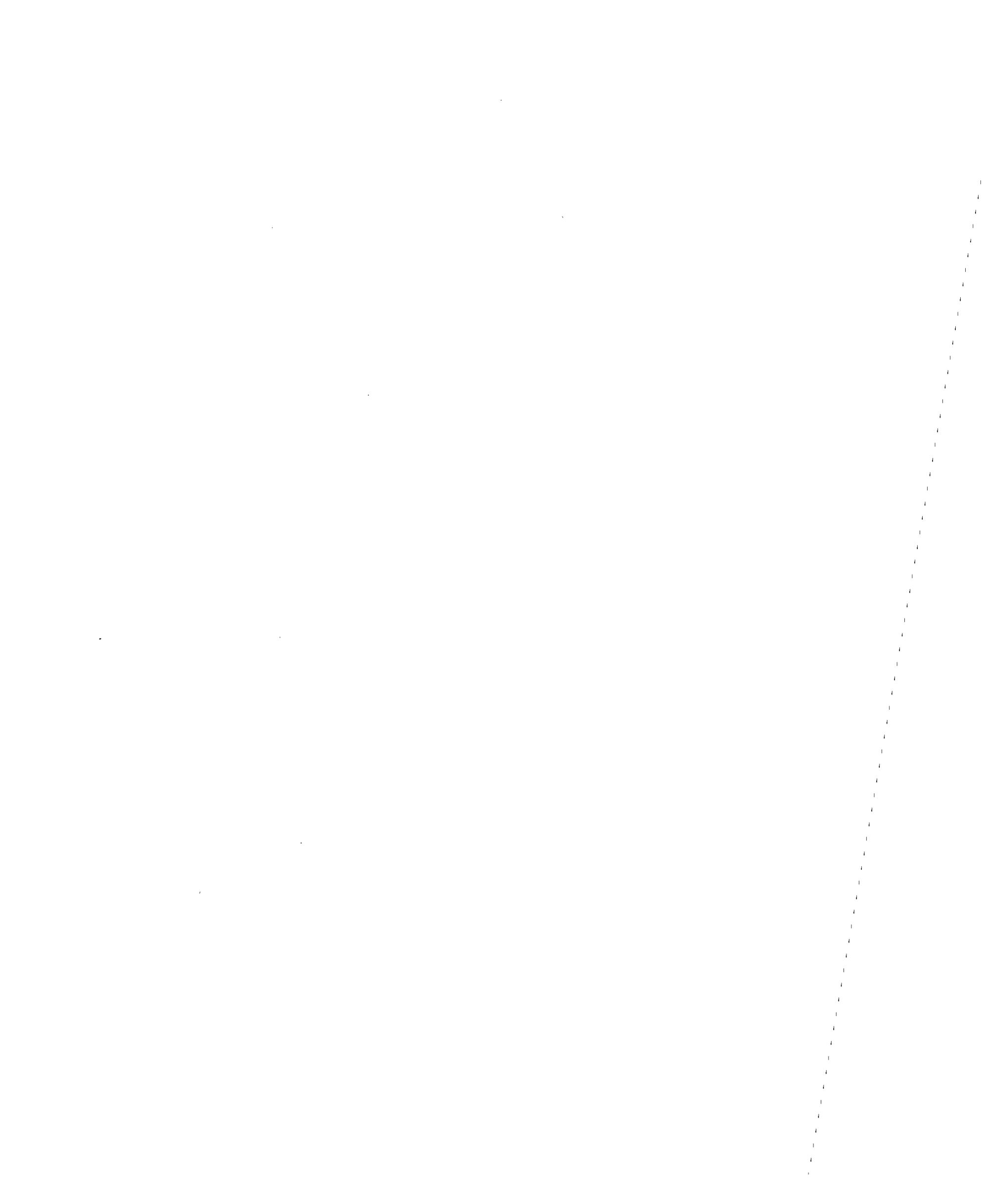
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**DEVELOPMENT OF A HYPERMEDIA KNOWLEDGE BASE  
OF AIRCRAFT FIRE SAFETY REGULATIONS**

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**ABSTRACT**

A knowledge base of aircraft fire safety regulations is being developed using Hyperties<sup>®1</sup>, a hypermedia engine based on an encyclopedia metaphor. This knowledge base attempts to consolidate in one place the current fire safety regulations related to commercial aircraft promulgated by the Federal Aviation Administration (FAA), along with background information on the bases for these regulations and on the fire test methods adopted by the regulations. The use of a hypermedia engine permits the unprecedented storage, linkage and retrieval of textual, graphic, audio and video information. Electronic links between related topics in a knowledge base permit the user to rapidly transfer between topics in order to follow a common thread among different topics.

Keywords: hypertext, hypermedia, aircraft, fire safety regulations

**INTRODUCTION**

Throughout the history of aviation, fire safety regulations have been developed and imposed largely in response to major disasters. Current fire safety regulations are the culmination of years of experience and research on aircraft fires and their consequences. These regulations are published by various regulatory bodies throughout the world, notably the Federal Aviation Administration (FAA) in the United States.

Generally, the bases for fire safety regulations are not made a part of the regulations. These bases are relegated to relative obscurity, either as part of the public record or in research reports. As a consequence, the user of the regulations may not understand or appreciate the bases or the purpose of the regulations.

Since regulations and standards are dynamic in nature and are located in disparate sources, a hypermedia knowledge base of aircraft fire safety regulations can serve as a useful tool for consolidating the regulations themselves, the historical background and failure experience leading to the regulations and the technical bases and test methods of the regulations. A hypermedia knowledge base offers the advantages that textual, graphical, audio and video information can be included together and information can be retrieved quickly through the use of electronic links to cross reference information

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<sup>1</sup>Hyperties is a registered trademark of Cognetics Corporation.

from various sources. Such a hypermedia knowledge base of aircraft fire safety regulations is being developed by the authors.

In this paper, some background information on hypermedia and hypertext systems is provided, followed by a discussion of the implementation, use and future enhancements of the hypermedia knowledge base of aircraft fire safety regulations being developed by the authors.

## BACKGROUND ON HYPERMEDIA

*Hypermedia* is a term used to describe the electronic collection and connection of textual, graphic, audio and video information in an organized manner to permit rapid traversal and retrieval of the information. The concept of *hypertext*, which is the electronic collection and connection of textual information only, can be traced to the 1940's. Vannavar Bush, the Science Advisor to President Franklin Roosevelt, recognized the impending information explosion after the end of World War II. In an article in the *Atlantic Monthly* (July 1945), Bush noted that "The summation of human experience is being expanded at a prodigious rate, and the means we use for threading through the consequent maze to the momentarily important item is the same as was used in the days of the square-rigged ships..."

Bush envisioned an imaginary machine he called a *memex*. A *memex* was a storage device in which thousands of pages of data could be stored and the items linked together, mirroring the associative way that humans think. "Wholly new forms of encyclopedias will appear, ready made with a mesh of associative trails running through them..."

The essential elements of hypertext and hypermedia systems are *nodes* and *links*. Nodes are the basic elements used to store information, while links are the electronic connections between nodes. In hypertext systems, nodes contain only textual information, while in hypermedia systems, nodes can contain textual, graphic, audio or video information.

Early hypertext systems were developed at various universities. Among the more notable projects were *Augment* at Stanford University, *Zog* at Carnegie-Mellon University, *Intermedia* at Brown University and *TIES* at the University of Maryland (Shneiderman and Kearsley, 1989). The widespread use of personal computers in the 1980's made hypertext and hypermedia a practical choice for the development of knowledge bases beyond the research labs of academia.

*TIES*, which is an acronym for The Interactive Encyclopedia System, was the original version of Hyperties. The TIES project was conducted under the leadership of Professor Ben Shneiderman, the Director of the Human/Computer Interface Laboratory at the University of Maryland. Some of the features of TIES that have been carried over into Hyperties include:

- The use of an encyclopedia metaphor, where the knowledge base consists of a number of articles cross-referenced with links established by the author. This contrasts with the metaphor of a stack of cards, as used in Apple's Hypercard for example, where each screenful of information represents a card. The encyclopedia metaphor permits each article to be longer than a single screen.

- The automatic creation of an index of all articles, which can be referenced by the reader.
- The inclusion of full text search and retrieval capability, so readers can locate information not accessible through hypertext links. Full text search can locate any word or phrase in a knowledge base.
- The inclusion of a history mechanism to permit the user to review his or her path through a knowledge base.

These are some of the reasons why Hyperties was selected for the implementation of the hypermedia knowledge base of aircraft fire safety regulations. The roots of Hyperties at the University of Maryland was also a factor in the selection, although not a predominant factor. By coincidence, the Airman's Information Manual published by the FAA has been published electronically using Hyperties, providing some added motivation for using Hyperties for this project.

## ELEMENTS OF HYPERTIES

Using Hyperties, knowledge bases are developed as "electronic encyclopedias." Information is stored in articles, which are the nodes used by Hyperties, and the articles are connected by electronic links established by the author of the knowledge base. These links provide the reader with a web of paths through the knowledge base and with cross references to related articles. One page of information is displayed at a time and each article can be many pages long. These concepts are illustrated in Figure 1 (Cognetics, 1992).

An article can consist of three parts:

- Content
- Short description
- Entry script

The content is the text, graphics or video which make up the main body of an article. As such, the content is usually the most important part of an article. The content text can contain links to other articles in the knowledge base. The content may be several screens long and can incorporate both textual and graphic information together.

Each article can have a short description. If an article consists only of a short description, it can be used to define terms or to display footnotes and other types of reference material. If an article also contains content, the short description can be used to introduce the content, so the reader can decide whether to read the entire article or to return to the current article.

An entry script is a series of instructions to the Hyperties program. Generally invisible to the reader, entry scripts are developed by the author of a knowledge base to perform a variety of operations, such as to begin playing a video segment.

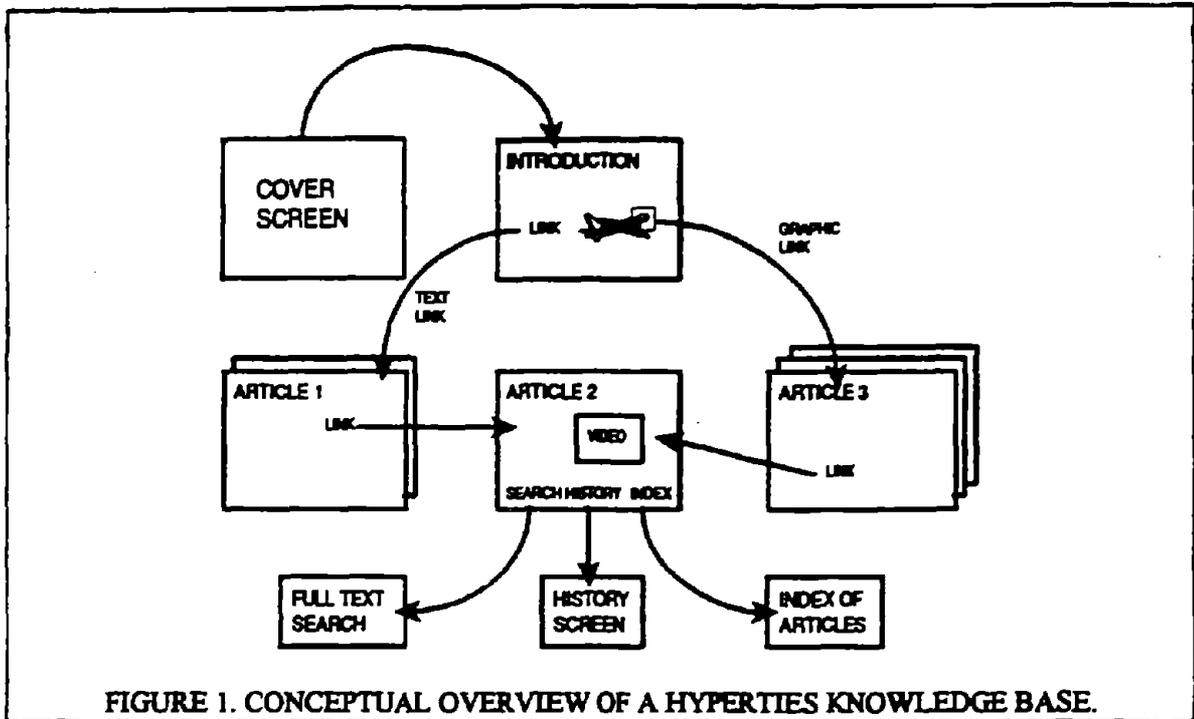


FIGURE 1. CONCEPTUAL OVERVIEW OF A HYPERTIES KNOWLEDGE BASE.

Links provide the connections between articles. There are three types of links in Hyperties:

- Text links
- Graphic links
- Buttons

Text links are words or phrases which link to another article or execute commands using the Hyperties scripting language. Hyperties automatically highlights links when an article is displayed. The reader can use the keyboard, a mouse or a touchscreen to select a link. When a link is selected, the target article for that link is displayed. A target article might contain information related to the topic of the current article, a glossary entry, a footnote, graphic information, or an audio-visual sequence. Alternatively, a link may contain a script to execute many possible actions, including the execution of an external program.

A graphic image may also contain links. These graphic links are sometimes called "hot spots" because they are selected by highlighting the spot on the graphic image containing the link. For example, an illustration of an aircraft may show the major systems of the aircraft, with each major system having a graphic link to an introductory article on that system.

A button is a special kind of link usually used to provide control functions. Some examples of control functions implemented with buttons include *search*, *back page*, *next page*, *history*, *index* and *return to previous article*.

## ORGANIZATION OF THE KNOWLEDGE BASE

At first, it might seem that the ability to establish electronic links among related topics would permit the knowledge base development process to advance in a piecemeal fashion. While this is true to some extent, careful planning of the organization and structure of a hypermedia knowledge base is important. Otherwise, the user, as well as the author, can become "lost in hyperspace" (Shneiderman and Kearsley, 1989). Since this is the first attempt by the authors to develop a hypermedia knowledge base, it is not yet clear whether the best approach was taken for this project. Only experience and feedback from users will establish this.

The knowledge base is organized in terms of major systems of commercial aircraft. The major systems used for this organization include:

- Passenger cabins
- Cockpit
- Cargo compartments
- Power plant
- Fuel system
- Miscellaneous systems

For each system, a short description is provided to permit the user to decide if he or she wants to continue along the selected path or return to the previous article. If the user decides to continue, an introductory article describes the fire safety issues and objectives of the system and provides a summary of related regulations. The introductory articles contain links to articles that summarize the regulations and to articles describing past fire experience leading to the regulations, to articles describing research related to the regulations and to articles describing related fire test methods and requirements. Links also exist between these various articles as appropriate.

This ability to link related topics in a web-like network rather than sequentially distinguishes hypermedia knowledge bases from printed books or manuals. While the same information can be recorded in both media, the connections between pieces of information in print must be made through a printed index or table of contents. In hypermedia, these connections can be made electronically, permitting the user to immediately move to a target article and back again.

## IMPLEMENTATION OF THE KNOWLEDGE BASE

The hypermedia knowledge base of aircraft fire safety regulations is being implemented in Hyperties. Hyperties offers a number of features to assist the author in the development of a knowledge base, including the construction of a cover, table of contents, index of articles, footnotes, running headers and introduction (Shneiderman, et al., 1992). The cover is shown automatically when the knowledge base is loaded for browsing. The cover is followed automatically by an introductory article.

The introductory article displays the graphic shown in Figure 2 and has some associated text telling the user to highlight the text box for the desired system. These text boxes serve as "hot spots." The selection of a hot spot causes the short description for the article associated with the selection to be displayed so the user can decide whether to proceed along that path.

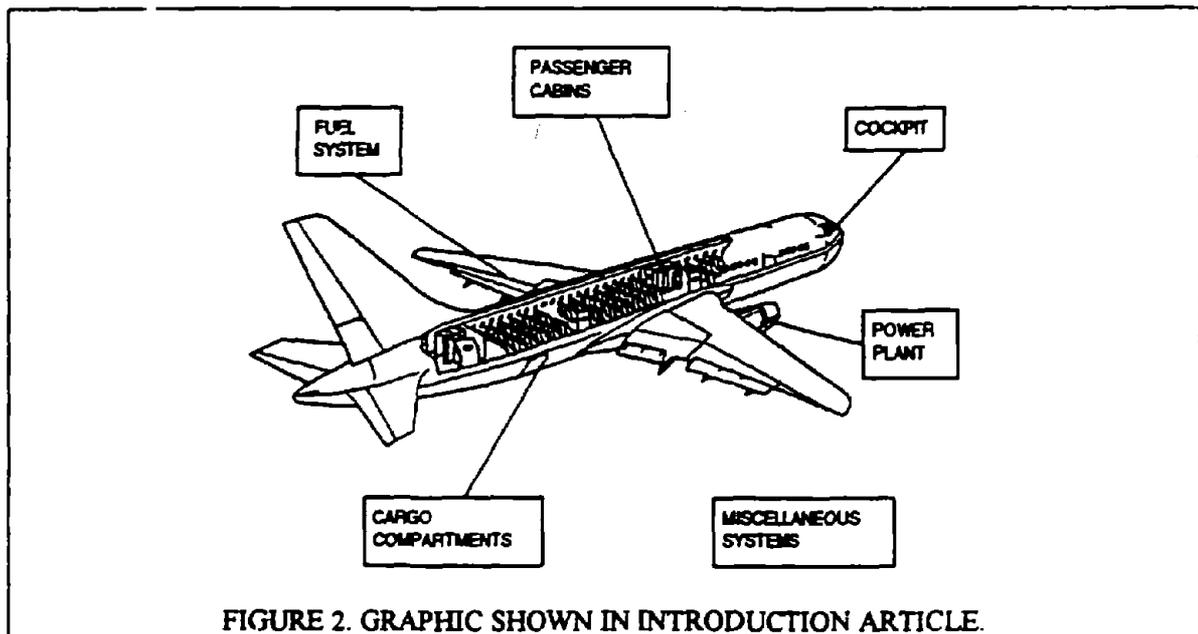


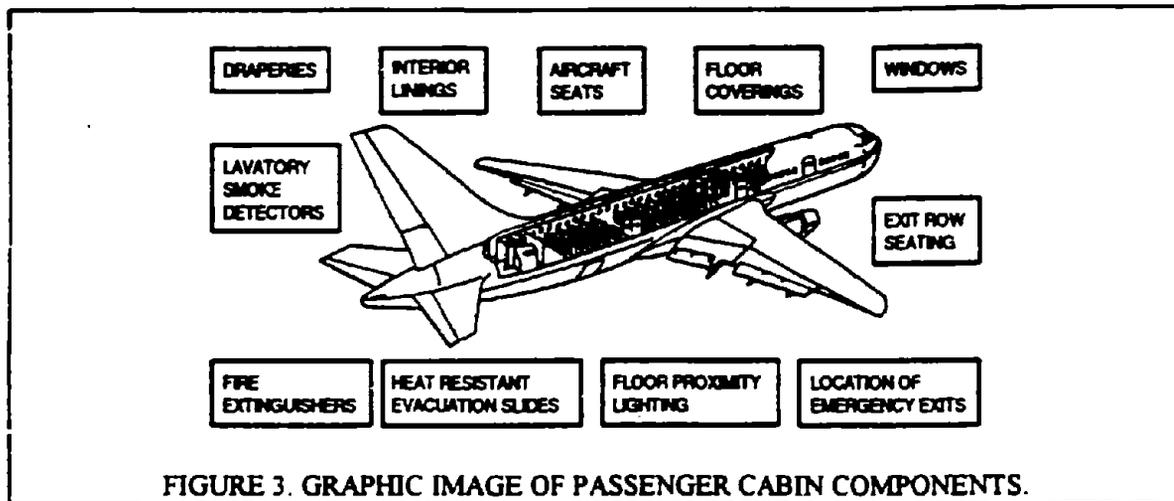
FIGURE 2. GRAPHIC SHOWN IN INTRODUCTION ARTICLE.

Many of the fire safety regulations for aircraft pertain to the passenger cabins because life safety of the passengers is of paramount concern. The remainder of this discussion with respect to the implementation of the knowledge base will focus on aspects of the passenger cabin systems. This will serve as an example of how the user might navigate through the knowledge base.

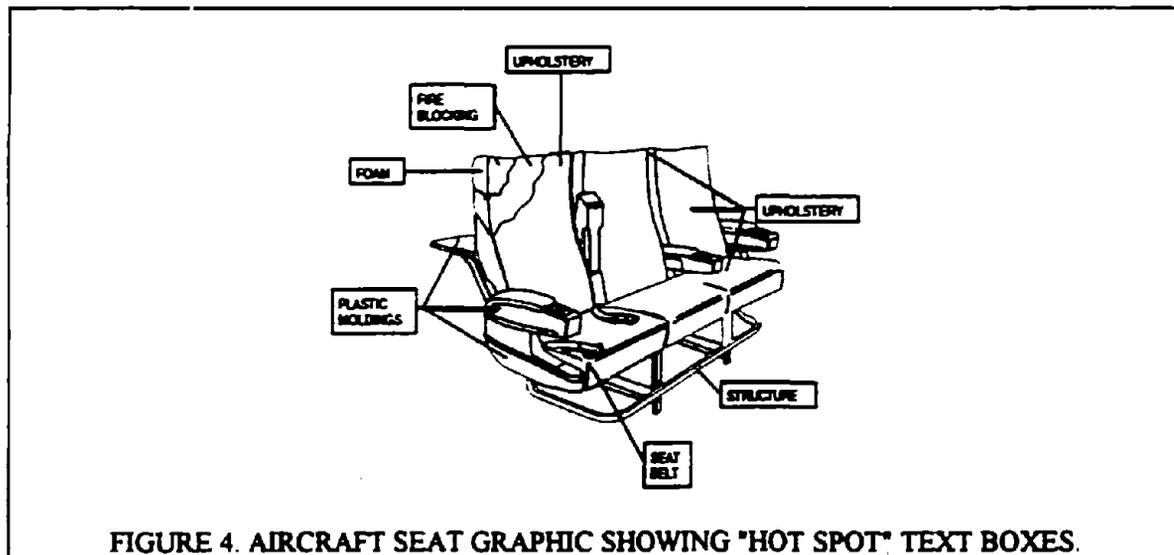
When the user selects the "Passenger Cabins" text box from the graphic in the Introduction article shown in Figure 2, the following short description pops up on the computer screen:

"You have chosen to review fire safety regulations related to passenger cabins. Regulations addressed in this article and in related articles include those related to the flammability of seats, interior linings, floor coverings, draperies and miscellaneous products, those related to egress requirements, and those related to fire extinguishers and lavatory smoke detectors."

The introductory article on passenger cabins contains a graphic image that contains a number of hot spots associated with the different components of the passenger cabins. This graphic image, which is similar to Figure 2 but with text boxes related to passenger cabins, is shown in Figure 3.



Selection of the "AIRCRAFT SEATS" text box in Figure 3 causes the user to transfer to an article on fire safety regulations related to the different components of aircraft seats. Another graphic image with text boxes is presented on the screen to permit the user to select among the different components. The aircraft seat graphic image is illustrated in Figure 4. Selection of any of the text boxes shown in Figure 4 transfers the user to an article on the fire safety regulations applicable to that component.



The other systems are treated similarly. Typically, graphic images are used to identify each system or component for which fire safety regulations exist. By selecting text box "hot spots" on these

graphic images, the user is transferred to an article discussing the fire safety regulations pertinent to the component. This article then leads to other articles on the history and fire experience related to the regulation and on the fire test methods adopted to enforce the regulations.

Much of the information stored in the knowledge base to date has been extracted from just a few sources, notably:

- Aircraft Material Fire Test Handbook (Boeing, 1990)
- Federal Aviation Regulations, Part 25
- Reports and papers prepared by personnel of the Fire Safety Branch of the FAA Technical Center

As the knowledge base is developed further, additional reference materials will be reviewed and incorporated.

## NAVIGATING THE KNOWLEDGE BASE

A number of methods exist for navigating the knowledge base. The user may enter the knowledge base as described above and simply browse through the system by selecting links to articles that seem of interest. This is the way the authors anticipate the system would normally be used. However, once users become familiar with the knowledge base, they may want to go directly to an article rather than follow the browsing routes described above. Two alternative methods to navigate a knowledge base also exist in Hyperties. These are:

- Index access
- Full text search and retrieval

These alternatives may be chosen by selection of the "Index" and "Search" buttons located at the bottom of all article screens, as illustrated in Figure 1.

As noted previously, Hyperties maintains an index of all articles in a knowledge base. This index lists articles alphabetically by article name. The user can scroll through the index and select the article of choice. The authors have attempted to give articles descriptive names, but in some cases the relationship between an article name and its content may not be intuitive.

The full text search and retrieval feature of Hyperties permits any word or expression, known as the search string, to be entered and all occurrences of the search string to be found automatically. This feature permits users to find their way through the knowledge base in ways not anticipated by the author and consequently not included in the design of the links. The Boolean operators AND and OR can be used in the search string to permit fairly complicated searches to be conducted.

All articles containing the search string are listed on a "search screen" in order of number of hits. These articles can be selected for reading just like any link. When an article is selected from the search screen, words in the search string are highlighted for easy reference.

## FUTURE ENHANCEMENTS

Graphical images with hot spots have been used extensively to aid the navigation process. This tends to make the navigation process more intuitive and certainly more interesting to use. This convenience and clarity come at a price, however. The old adage that a picture is worth a thousand words may be true from the standpoint of clarity, but not from the standpoint of data storage requirements. On a VGA screen, each line art graphic image is composed of up to 640 by 480 (307,200) pixels at 1 bit per pixel. At 8 bits per byte, each graphic of this size requires approximately 38,400 bytes of storage space. This is equivalent to approximately 38,400 text characters (1 byte per character), or about 6,400 words (assuming an average of 6 characters per word). For 16 color images (4 bits per pixel) and for 256 color images (8 bits per pixel), these storage requirements increase by factors of 4 and 8, respectively.

While the graphic images are somewhat smaller than the 640 by 480 pixels used by a full VGA screen, it is clear that the use of graphic images adds significantly to the size of a knowledge base. Nonetheless, such elements can be important components of hypermedia knowledge bases.

Video and audio clips impose even greater memory requirements than do still images. For example, video images are typically displayed at 30 frames per second to avoid a jittery appearance. If each frame is composed of a 160 by 120 by 256 color graphic image (19,200 bytes per frame), the memory requirements quickly become prohibitive even for short clips. For example, a 30 second clip at 30 frames per second for a 1/4 screen image at VGA resolution would require 17.3 megabytes of storage space. For this reason, the computer industry has been working on the development of data compression techniques for video. While there has been considerable progress on video compression techniques in recent years, commercial products (e.g., QuickTime<sup>2</sup> on the Macintosh<sup>®</sup> and Microsoft Video for Windows<sup>3</sup>) using these techniques have been released only recently and they still require considerable disk storage space. Hyperties does not yet link to any of these products.

In the meantime, laser discs offer one alternative for storing video clips, albeit a fairly expensive one. The professional version of Hyperties can be used to control certain types of laser disc players. This alternative would require the production of a master laser disc (or discs) with the desired video clips, followed by the production of an unknown number of laser discs for users, who would each need the correct type of laser disc player.

The use of audio and video clips offers attractive enhancements in terms of the power and utility of the knowledge base. For example, video clips of fire tests could be shown in the articles on the fire test methods to demonstrate the scope and procedures used by the fire test methods. For the current development of the knowledge base, however, the integration of video is too expensive. With additional resources and user interest, integration of audio and video clips will be a future enhancement to the knowledge base.

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<sup>2</sup>QuickTime and Macintosh are registered trademarks of Apple Computer, Inc.

<sup>3</sup>Windows and Video for Windows are registered trademarks of Microsoft Corporation.

A related enhancement that has not been integrated is the storage of fire test data for approved products and systems. For example, a listing of approved foams and fire blocking layers for aircraft seats could be maintained in the knowledge base. Eventually, video clips of the approval tests could also be integrated. The primary limitation on this expansion of the knowledge base would be the data storage requirements.

The knowledge base does not yet contain the full text of all pertinent CFR references. Rather, it simply provides appropriate references to many of these documents. If interested in reading the actual text of a CFR, the user would have to go to the printed CFR publication. With additional resources, the full text of the pertinent CFRs could be scanned, interpreted by optical character recognition software and integrated into the knowledge base. This would make the knowledge base more comprehensive.

Another feature that could be developed is the ability to shell to other programs. This would permit the user to run various models or other applications at appropriate times from within the knowledge base. For example, a user reviewing information on the flammability of cabin linings could switch to a model that predicts flame spread, then switch back to the knowledge base.

## SUMMARY AND CONCLUSIONS

A hypermedia knowledge base of aircraft fire safety regulations is being developed by the authors. The knowledge base is being developed using Hyperties, an IBM PC program that uses an encyclopedia metaphor for the hypermedia engine. Approximately 150 articles, combining textual and graphic information, have been integrated into the knowledge base to date. With future work and suggested enhancements, the number of articles in the knowledge base will grow. The incorporation of audio and particularly video clips is desirable, but has not been done yet due to cost limitations. Additional resources will be needed to incorporate video data.

The hypermedia implementation permits the user to rapidly traverse the knowledge base and to immediately follow common threads of information through the knowledge base. While the same information could be stored in print media, electronic links cannot be maintained in print. Consequently, printed documents can be considered as linear systems of information storage. One of the primary values of the electronic medium is the ability to link information from disparate sources in a cohesive system that permits nonlinear access and retrieval of data.

Based on the experiences of the authors to date, the storage of information related to aircraft fire safety regulations in a hypermedia knowledge base seems like a suitable and useful means of maintaining and retrieving this information. The authors encourage readers to obtain a copy of the knowledge base and to provide feedback on its potential utility. With additional resources, the authors look forward to continuing the development of this knowledge base to make it a truly comprehensive and useful reference source of information on aircraft fire safety.

## ACKNOWLEDGEMENTS

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**Future Needs in the Development of Materials for  
Aircraft Interiors and Equipment**

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## **INTRODUCTION**

The presentation will start with information on the state of the art of the materials for interior furnishings and equipment of the current Airbus Program.

The second part will deal with the intentions of Deutsche Aerospace Airbus with regard to further development of materials for interior furnishings and equipment.

A very important criterion for interior materials development is the improvement of fire safety.

In addition, aspects like human toxicity, environmental protection, repairability, costs and weight are important criteria for future new materials.

## **STATE OF THE ART OF MATERIALS OF AIRBUS AIRCRAFT**

Materials and components of the interior furnishings and equipment of Airbus aircraft comply with today's applicable fire protection regulations of JAA and FAA. The requirements of ATS 1000.001, Issue 5 of November 1989, are also met. This "in-house" regulation exceeds the requirements of JAA and FAA as far as requirements for materials with limited toxic smoke gas portions, but also reduced smoke gas emissions for major parts of the passenger cabin are concerned.

More than 80 % of the cabin interior furnishings and cargo compartment lining in Airbus aircraft consists of decorative sandwich panels with phenolic-resin glass-fabric top layers and Nomex honeycomb cores.

This sandwich construction can be manufactured very economically in the "one shot curing" process and today meets all FST (that is: Fire Smoke Toxicity) requirements in connection with decorative surfaces.

About 16 % of the cabin interior furnishings (such as passenger service units) consists of thermoplastics (for example PEI, PPSU, PC) which are manufactured by injection moulding. A considerable number of these parts is varnished to comply with design requirements.

Large areas of the Airbus interior (about 50 %), such as ceiling linings and stowage bin doors, are varnished. About 25 to 30 % of the interior furnishings is lined with decorative PVF foils. Only a small portion of less than 5 % is decorated with textile materials. This does not include carpeting. In the cargo compartment area, the sandwich liners are lined with simple white PVF foils.

Flat sandwich panels are manufactured largely automatically in the so-called "multi-tooling" system in platen presses. Panels measuring 2 x 3 m are manufactured with automatic introduction of core and edge fillers with several components of optimum combination; these are then used for producing the individual components by computer-controlled milling processes.

Curved components such as side walls and ceiling panels are increasingly manufactured in self-heating, multiple tools by press or "crushed core" technique. Today, fabric-reinforced thermoplastics are only seldom used in monolithic components.

#### FUTURE NEEDS IN THE DEVELOPMENT

Thinking today about the criteria and boundary conditions which must be applied in order to define the objectives for future developments with regard to materials and constructions for civil aircraft, the conflict of the following three-way relation must be accepted.



None of these three areas must be considered isolated in future developments. Well-balanced overall solutions will become more and more mandatory.

The introduction of new technologies without consideration of ecological effects will no longer be possible. In the same way, ecological aspects will have increasing economic effects.

Now, what does this mean for future developments in the field of materials for the interior and equipment? What demands must be made?

#### Technological Demands

One of the most important requirements for the interior will remain the improvement of the safety of passengers in the case of a fire. Here, in my opinion, improvements are mainly necessary in the field of the burn-through behaviour of fuselage structures in a "post crush fire" situation.

Further emphasis must be placed on the development of materials with further reduced smoke gas development. This must be a special aim for materials subject to heat release requirements. With the introduction of the Heat Release Rule, it became necessary to accept higher smoke gas development than the normal state of the art for various materials. This development must now be revoked.

Textiles used in the interior today are also not satisfying. It is still problematic to apply wall lining materials and simultaneously meet heat release requirements with the desired safety.

In addition to FST requirements, weight reductions are a definite objective. It is the opinion of the engineers at Deutsche Aerospace Airbus that it will be possible to reduce fuel consumption of aircraft by another 30 % within the next 10 years. Engine technology and aerodynamics will have to make essential contributions to this. Other contributions will have to come from a considerable weight reduction.

We assume that the structural weight of aircraft as compared to the technology established today will have to be 13 % lower. A necessary weight reduction by about 10 % was identified for components of the interior furnishings and equipment.

Particularly for large-area sandwich components this means that new lightweight fibre, matrix and core material systems will have to be introduced. There will have to be decorative systems which will weigh less and possibly be integrated. New production technologies permit a much better utilization of materials as well as the implementation of designs which allow the various requirements for the components to be met in a more intelligent manner at lower weight.

It will also be necessary to think over technical capabilities which are taken for granted today and which can possibly be abandoned in order to allow for the introduction of new technologies.

#### Ecological Demands

Today, strategic planning of the industry largely takes into consideration the understanding that economy and environmental protection do not preclude one another, but are complementary.

In future, preservation of the natural bases of human life and nature will have been established as a guiding principle for any actions. From this follows that pollution during manufacture, use and disposal of a product will have to be kept as low as possible.

It is also necessary to consider the entire life cycle of a product including the simplest possible disposal already during the development of new materials.

Two partial areas have to be distinguished during the manufacture and processing of materials. These are the optimization of the composition of the product with regard to its possible later recycling and disposal and with regard to occupational safety and health protection during processing.

Thus, Deutsche Aerospace Airbus has made every effort together with the suppliers to replace products containing CFC's and halogenated hydrocarbons and to eliminate flame-retardant products such as antimony trioxide and toxic bromine compounds.

As far as the use of phenolic formaldehyde resins is concerned, the state of the art is that free formaldehyde, phenol and solvents have been limited to well below legal requirements.

As far as recycling and disposal are concerned, we have started to discuss future solutions with the material manufacturers. For example, we have discussed a partial introduction of regranulated scrap components and waste in the manufacturing process of new parts with the manufacturers of thermoplastic injection-moulding materials. The addition of up to 20 % recyclate is possible at acceptable property changes. However, this procedure requires a quality-assured organization.

It is obvious that recycling will solve only part of the problems connected with disposal. In the end, large quantities of plastic parts will have to be disposed of. According to the present level of knowledge, the combustion of plastics at high temperatures ( $> 1000^{\circ}\text{C}$ ) in specially developed furnaces, for example with fluid-bed burning, will be of great significance.

In order to minimize pollution during this disposal process, a corresponding chemical formulation of the products is required. In this respect, the material manufacturers will have a greater responsibility in future. Only they will be capable of optimizing this cycle of production and disposal due to their accurate knowledge of the product. The aim must be that the material manufacturers take back their materials and products for recycling or disposal to a greater extent than is the case today.

#### Economic Demands

Economy, too, must have its well-balanced place in the above-mentioned three-way relation. Only economically successful companies are capable of contributing funds for research and development to improve the safety of the passengers or environmental protection. Therefore, their continuous effort is aimed at reducing manufacturing costs.

Considerable cost increases had to be accepted as a result of the introduction of the "Amdt-66 materials". Expenditures for processes as well as material prices increased. During the present consolidation phase, cost reduction programs are in progress in production. Talks with the material manufacturers focus on the introduction of a new generation of materials which can be procured at lower prices while all FST requirements are met and which help to reduce production costs.

Another important aspect in this connection is the supply of materials and processes for economic repair methods for components which are subject to stringent fire safety requirements. Normally, the high FST requirements are not met by conventional repair materials and repair processes.

#### CONCLUSION

The requirements necessary as a result of the safety of the passengers, the technological, ecological and economic demands are continuously increasing. The connections between boundary conditions and effects which are partly contradictory are becoming more complex instead of simpler.

Therefore it is necessary for all participants to closely cooperate in finding the best overall solutions.



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**Health and Safety Issues for Aerospace Workers  
in the Use of Advanced Materials**

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**ABSTRACT**

The Boeing Company is committed to providing a safe and healthy working environment for its employees. Furthermore, the Company is committed to the well-being of communities in which the employees live and work. Wherever possible, hazardous materials and processes in the work place are being substituted with less hazardous materials and processes in the manufacture of aircraft. This change of substituting materials and processes must be achieved efficiently and cost effectively.

**INTRODUCTION**

The aerospace industry is rapidly adopting aggressive initiatives to safeguard its workers from injury and illness, and to prevent pollution of the environment. These initiatives are being accomplished where possible through substitution of less hazardous materials and processes, and through training and informational programs designed to increase worker awareness of existing hazards and precautions against them.

At the Boeing Company, workers' health and safety and the protection of the environment are integral parts of company business plans and operations. Safety, health and environment related initiatives underscore Boeing's commitment to the well-being of its employees and reflect the company's environmental responsibility to the communities in which employees live and work. Boeing also works closely with its suppliers to encourage the use of safe and environmentally sound manufacturing practices.

Recognizing the importance of managing change, the Boeing Company has entered a contractual commitment with the International Association of Machinists (IAM) to ensure that new materials and processes are evaluated for their health and

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safety impact prior to the implementation in the workplace. Furthermore, Boeing is committed to effectively communicate appropriate information to employees prior to introduction.

Over the past two years more than one hundred new materials or processes have been formally introduced. All substitution activity with regard to changes in materials and processes must be compatible with the performance requirements of the original product. Initiatives that potentially affect the safety, reliability or integrity of the aircraft must be pursued carefully, but even well-managed initiatives can become complex, time consuming, and costly. Changes must therefore be safe, cost-effective, and compatible with product performance requirements.

#### SAFETY

Safety is sometimes incorrectly defined as the absence of risk. That condition is seldom, if ever, met. A safe working environment can better be defined and characterized by three elements:

1. Identification of all hazardous properties of the material in question including the health hazards associated with its intended applications;
2. Communication of all hazardous properties to each customer/user, in a timely, completely and appropriate manner;
3. Control of those hazards through the use of personal protective equipment or facility modification.

The first two conditions can be met by the supplier through the effective use of a Material Safety Data Sheet (MSDS) or Material Bulletin. The using organization is then able to assess the working environment and manage the use of the material without undue hazards to the employees or to the environment. Only when information is appropriately disseminated are the health and safety risks in the working environment reduced.

Boeing encourages its employees identify and reduce hazards in the work place through aggressive training and informational programs. In some cases, cross-functional teams are formed by the employees themselves to implementing new and safe work practices, provide training to other employees when a new material is introduced into the work place and/or evaluate less hazardous alternatives.

## **COST EFFECTIVENESS**

Cost effectiveness can also be an easily misunderstood concept. Comparing products that meet production specifications based solely or primarily upon their purchase price may significantly distort their full cost. The full cost of a product is primarily determined by six factors:

1. Purchase price of the material;
2. Full impact of that material on production costs, e.g. labor, utilities, manufacturing flow time;
3. Associated costs of worker protection (or illness and injury);
4. Associated costs of air emission (and/or control equipment);
5. Cost of waste treatment and/or disposal;
6. The purchase cost of wasted/expired material.

When the non-purchase costs of a material are added to its purchase price, often significantly higher total costs result.

Non-purchase costs, particularly those related to environmental and worker health and safety, may be very difficult to estimate. These costs are added to the expenses of doing business and added on to the price of production, which affects Boeing's competitiveness in the global market.

It is crucial to recognize that change seldom stands alone. Any change affects the whole system and may trigger a series of processes modifications. Seemingly simple material or process changes can set off a ripple effect as they move through the production chain from raw materials to end use. Associated materials and processes must be re-evaluated and perhaps modified. For example, change or modification of a composite material might necessitate the introduction of new tooling, disposal and manufacturing procedures, and possibly facility modifications.

## **HAZARDOUS EVALUATION AND COMMUNICATION**

Each change must be evaluated for its impact on the environment and workplace health and safety, and appropriate controls devised and implemented. To respond to this demand for evaluation and control safety, health, and environmental affairs (SHEA) professionals need appropriate, accurate, and timely

information from suppliers. We can no longer accept that "no news is good news."

Hazard determination and communication is an iterative process involving each internal and external organization in the production/use chain. A resin manufacturer, for example, is in the best position to develop and disseminate basic toxicological information on its products. When the resin is used by a downstream prepreg manufacturer, its hazardous properties have been altered and the prepreg manufacturer must then provide the prepreg hazard information to its downstream customers. However, neither a resin manufacturer nor a prepreg formulator are expected to know all of the conditions under which a given prepreg may be worked during the forming of production components. That task of evaluation may either be left to the component manufacturer or cooperatively conducted.

For each organization in the chain to properly fulfill its requirement to inform their employees, customers, communities, and regulatory agencies, they must receive full, accurate, and timely disclosure from their suppliers. They must then carry out appropriate evaluation and communication at their level.

#### CASE EXAMPLES

##### Corrosion Inhibiting Compounds

Boeing and IAM have jointly exercised the introduction of many new materials in the past. One of the most extensive of these efforts was the introduction of a new corrosion inhibiting compound, impacting over twenty thousand employees. The history of that introduction illustrates the complexity of the communication process.

In 1988 Boeing initiated a change to improve the system used on aircraft structure for corrosion resistance. The old system contained solvents which evaporated and produced an undesirably high quantity of Volatile Organic Compounds (VOCs). Also the materials did not dry to hardness, and remained tacky.

Coordinating closely with suppliers and customer airlines, work was initiated to develop a low VOC, hard-drying persistent coating that would be equivalent in corrosion protection to the existing system. A suitable product was developed that provided equivalent corrosion protection to the old system, but the substitute produced an offensive odor.

Introduction of this material into production presented a potential health, safety, and employee relations problem. The odor of the formulation was the subject of numerous health

complaints. In response to this problem, the material was removed from the manufacturing processes.

A well-planned task force was then assembled, comprising members of the engineering, manufacturing, and health and safety organizations, to work with suppliers to reformulate the new material. The effort was successful, and the revised product was set for reintroduction.

A multi-stage implementation strategy was developed. First, the product was reformulated to reduce the offensive odor and to further reduce the vapor level of VOCs. Industrial hygiene personnel then conducted extensive monitoring both at Boeing and customer facilities to develop control methods. Spray locations and air handlers were modified to enhance ventilation efficiency. The product was successfully reintroduced to the production facilities after intensive Boeing/IAM coordination and employee training.

#### Boric Sulfuric Acid Anodize

Another example of Boeing's commitment to provide a safe and environmentally sound workplace is the introduction of Boric Sulfuric Acid Anodize (BSAA).

BSAA is a Boeing patented process that replaces chromic acid anodize (CAA) for surface treatment of aluminium alloys. Because CAA emits chrome vapor during processing which has been identified as a carcinogenic hazard, sophisticated control equipment has been installed by companies to minimize its health hazards. In addition, used CAA solution and its related rinse water must be free of chrome and heavy metals prior to disposal. For Boeing commercial airplanes, CAA is applied to over 70% of the aluminum substrate and is one of the most widely used surface treatments for aluminum alloys in the aerospace industry. Therefore, the operating and disposal expenses of CAA are major concerns to Boeing, in addition to its health and environmental hazards.

Both environmental and health/safety regulations have stringent requirements to minimize the chrome emission from CAA processing and waste disposal. Options to install costly control equipment, e.g. scrubbers, forced air fans around the processing tanks, and chemical additives have been adopted by various companies to reduce the chrome emissions for existing facilities where regulations apply. Alternative processing to replace CAA is being aggressively pursued.

However, because of its criticality to the safety and integrity of the airplane structure, even though BSAA is a less hazardous and environmentally preferred process, it was necessary to proceed with its implementation cautiously. After twelve years of intense research and development, BSAA was introduced to

production in 1991. BSAA is compatible to CAA's engineering requirements, emits no hazardous vapors to the workplace, and is less hazardous to the environment on disposal. The use of BSAA is a win-win situation for Boeing.

The successful implementation of BSAA exemplifies the Boeing Company's commitment to provide a safe and environmentally sound workplace and community.

#### SUMMARY

Safeguarding its employees and communities from injury and illness, and preventing pollution of the environment are primary goals to the Boeing Company. These initiatives are accomplished through substitution of less hazardous materials and processes in manufacturing, wherever possible. The costs to implement alternative materials and processes, including research and development, testing, training, implementation programs and many hidden associated costs, are increasing rapidly. Changes must be safe, cost-effective, and compatible with the required product performance. By working closely with its suppliers and informed workforce will ensure successful changes in a cost effective and safe manner.

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**ADVANCED AIRCRAFT MATERIALS RESEARCH AND DEVELOPMENT PLAN**

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**ABSTRACT**

In this paper we outline the DOT/FAA Long-Range Fire Safety Research Plan and discuss a preliminary strategy for developing advanced, fire-resistant, aircraft materials as an integral component of the program. Long-range research thrusts are also proposed in fire modeling, aircraft vulnerability analysis, improved systems, advanced suppression, and fuel safety. The research plan anticipates fire safety needs for next-generation aircraft and attempts to identify emerging materials and systems technologies where a focused, sustained research effort could lead to order-of-magnitude improvements in air transportation fire safety over the next two decades. The FAA's role in the proposed framework is to initiate and maintain a balanced program of basic university research, private-sector advanced development, and in-house applied research to facilitate technology insertion. The FAA Fire Safety Research Plan describes programmatic opportunities for the public from the increased research funding sought by the FAA for this activity. Leveraging of research dollars will be accomplished through collaboration and cost-sharing with government agencies having similar fire safety requirements. Technology transfer will occur through FAA-sponsored meetings, scientific publications, industrial liaisons, and student internships at the FAA Technical Center. It is expected that fire safety needs of the construction, manufacturing, and chemical process industries will provide opportunities for the utilization of advanced fire safety technology beyond commercial aviation.

**BACKGROUND**

Commercial air transportation has evolved into a fast, safe, and reliable way to travel over long distances. The high level of safety is achieved by minimizing the number of aircraft accidents that occur and by increasing crash survivability. Fire becomes the major threat to human life in impact-survivable airplane crashes because of the large quantities of aviation kerosene carried by passenger jets and the high heat-release of the kerosene when ignited. Burning fuel can melt the fuselage skin within a minute and subsequently ignite interior cabin materials—making post-crash fires severe and deadly. The incidence rate of post-crash fires can be lowered by fuel systems with fewer ignition sources, while passenger survivability times can be increased through the use of cabin materials meeting specific flammability test requirements. Although accident rates for commercial aircraft are low relative to other

forms of transportation, post-crash fire fatalities are possible whenever an accident involves fuel system failures.

Fatal inflight fires are highly unusual. However, the human life risk of such fires is associated with the substantial time required to descend from cruising altitudes and safely land the aircraft. Such times are typically 15 to 20 minutes in flights over the continental United States and can be hours on international flights. This provides an opportunity for small inaccessible fires from weak ignition sources to grow to a point where either the integrity of the aircraft or the lives of the passengers are imperilled. There are many design features and procedures in place to prevent or control inflight fires. These include flammability requirements for wire insulation, cargo compartment liner fire test requirements, fire extinguishing systems, and circuit breaker reset procedures.

The Fire Safety Branch at the Technical Center in Atlantic City, New Jersey is the Federal Aviation Administration (FAA) Research and Development branch responsible for providing data to the regulatory organizations within the FAA for their use in developing, modifying and/or interpreting rules and regulations pertaining to aircraft fire safety. Over the past several years the FAA has implemented numerous improvements in domestic and overseas aircraft fire safety- primarily by creating or modifying appropriate fire safety standards. Aircraft fire safety improvements recently mandated by the FAA include seat cushion fire-blocking, floor-level exit lighting, the adoption of a more stringent 65/65 peak/total heat release (OSU) requirement for flammability of interior panels, a requirement that transport aircraft carry at least two Halon 1211 fire extinguishers, a smoke detector and fire extinguisher in each lavatory, radiant-heat resistant evacuation slides to provide more time for escape in the event of a fuel fire, crewmember protective breathing equipment, and improved burnthrough resistance of cargo compartment liners.

Current engineering projects within the Fire Safety Branch include detection and mitigation of hidden fires, development of expert systems for aircraft command in emergency situations such as in-flight fires, fire-hardening of fuselage structures, measuring arc tracking/flammability/smoke-emission of aircraft wire insulation, in-flight smoke venting, compiling a handbook and training videos for fire testing of aircraft materials, evaluating cabin water-spray systems for fire suppression, fire testing of seat components, flammability assessment of Class B cargo compartments, auxiliary fuel tank protection, Halon replacement guidelines, oxygen systems safety, permeo-selective membrane separation of air streams into oxygen and nitrogen for emergency breathing and cargo bay blanketing, respectively, and investigating the flammability of materials at reduced pressure as a potential means of suppressing in-flight fires.

Engineering projects conducted at the FAA Technical Center are typically 3-5 years in duration and originate at the request of the FAA's regulatory agencies- usually in response to aircraft accidents involving loss of life. Recently however the FAA's fire safety research and development mission was expanded by the Aviation Safety Research Act of 1988 (Public Law 100-591) to include long-term projects "which [are] unlikely to result in a final rule making action within 5 years, or in initial installation of operational equipment within 10 years, after the date of the commencement of such project." Section 312 of the Federal Aviation Act is amended as following: "The Administrator shall undertake or supervise research to develop technologies and to conduct data analyses for predicting the effects of aircraft design,

maintenance, testing, wear and fatigue on the life of aircraft and on air safety, to develop methods of analyzing and improving aircraft maintenance technology and practices (including nondestructive evaluation of aircraft structures), to assess the fire and smoke resistance of aircraft materials, to develop improved fire and smoke resistant materials for aircraft interiors, to develop and improve fire and smoke containment systems for in-flight aircraft fires, and to develop advanced aircraft fuels with low flammability and technologies for containment of aircraft fuels for the purpose of minimizing post crash fire hazards." This Act freed the FAA to perform more comprehensive research in the identified areas and amended the FAA's existing appropriations authorization for RE&D to include a separate line-item for long-term research projects— i.e. proactive fire safety research was mandated by Congress.

## FIRE RESEARCH PLAN

The goal of FAA long-range fire research is the elimination of fire as a cause of fatalities in aircraft accidents. Major advances are needed to develop technologies for fire safety assessment, materials for a totally fire-resistant aircraft cabin, fire safe fuel systems, and for smart fire control and extinguishing systems. Long range fire research will focus on both current vintage aircraft and future designs. Current production aircraft models such as the Boeing 757 are sure to be in service for at least two more decades. All current production transport aircraft share major design commonalities from a fire safety research viewpoint. Most notable are aluminum hulls, kerosene fuel systems, turbofan engines, and interior materials meeting fire tests specified by regulation. Future commercial designs can be expected to differ significantly from current ones. A high speed civil transport may have either a titanium or composite hull. Current aluminum hulls melt when exposed to an external fuel fire providing a path for fire spread into the cabin. A titanium hull will not melt in a fuel fire because of its high melting temperature, but will heat interior materials to temperatures where spontaneous combustion occurs. A composite hull will burn, but at a rate which may be slow enough to provide the greatest protection of the three candidate hull materials. Higher fuselage skin temperatures associated with supersonic flight have the potential for generating additional in-flight fire hazards. Higher residual fuel temperatures during descent and landing can increase the post-crash fuel fire threat. Current fire safety design standards are based on over 30 years experience with the present aluminum hull fleet and may be inappropriate for future aircraft.

A plan for long-range Fire Safety Research has been developed by the FAA in conjunction with experts from government agencies, private industry, federally-funded research laboratories, and academia. The research plan anticipates fire safety needs for next-generation aircraft and attempts to identify emerging materials and systems technologies where a focused and sustained research effort could lead to order-of-magnitude improvements in air transportation fire safety over the next two decades. The FAA mission within the proposed framework is to initiate and maintain a balanced program of basic university research, private-sector advanced technology development, and in-house applied research to facilitate technology insertion. Leveraging of research dollars will be accomplished through collaboration and cost-sharing with government agencies having common research interests and through the transfer of advanced fire-safe technology to the construction, furnishings, and other transportation industries.

**Long-range research thrusts are proposed in the following six technology areas:**

- Fire Resistant Materials
- Fire Modeling
- Vulnerability Analysis
- Improved Systems
- Advanced Suppression
- Fuel Safety

Besides research thrusts in fire modeling and vulnerability analysis, long range aircraft fire research includes major thrusts in material research, fuel flammability, fire detection and suppression, aircraft cabin environment control, and integration of emerging technologies into airplane fire protection. While each of these major thrusts could be conducted independently, the production of a totally fire-safe passenger aircraft within the next two decades is most likely to occur through a concurrent engineering approach whereby basic researchers, materials scientists, and engineers, interact closely throughout the conception, design, and engineering development stages of program. A successful program will require creative, basic research with dedicated engineering support to achieve breakthrough fire-safety technology. Successfully integrating the long-, intermediate and short-term tasks will require timely exchange of information between participants and continuous reevaluation of program goals and objectives in light of new research and emerging technologies both inside and outside of the FAA program.

The primary challenge in managing a sustained technical effort, therefore, is maintaining focus and balance between short- and long-term program elements of various size and complexity. Figure 1 illustrates how the individual technical thrusts are expected to interrelate with regard to in-flight fires. New methodologies developed under the FAA Aircraft Catastrophic Failure Prevention Program will be used for evaluating the likelihood of system failure as a fire source. Fire Modeling will establish the susceptibility of various aircraft configurations to fire propagation and input these results to the Vulnerability Analyses which assigns probabilities to the risk associated with individual aircraft system and component failures. The reduced probability of risk associated with Improved Systems, Advanced Suppression, and new Fire Resistant Materials will be assessed in the Vulnerability Analyses. The thrust in Advanced Suppression is extremely important because reliable scientific data is lacking.

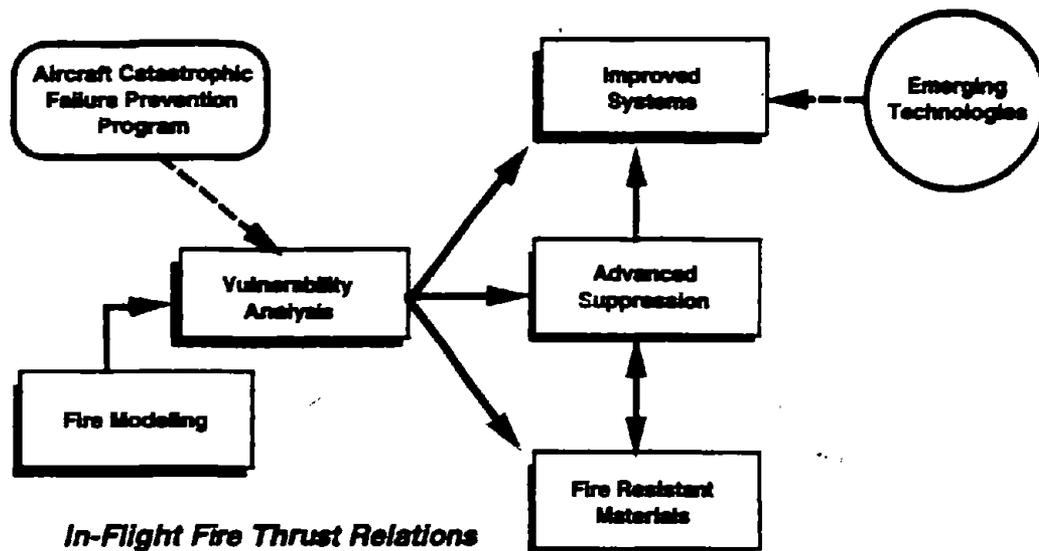


FIGURE 1. RELATIONSHIP BETWEEN FIRE SAFETY RESEARCH THRUSTS FOR IN-FLIGHT FIRES.

The thrust relationships for post-crash fire safety are shown in Figure 2. Ignition source probabilities for the Vulnerability Analyses will be obtained from the Crashworthiness Program in Aircraft Safety here at the FAA Technical Center. Fire Modeling will analyze fire propagation histories for a range of crash scenarios aircraft configurations and input the results to the Vulnerability Analyses. Fire modeling will also help evaluate the individual and cumulative effectiveness of Fire Resistant Materials, Advanced Suppression, and Fuels Safety in mitigating post-crash fires.

The goal of FAA Fire Safety Research is the preservation of human life. The scientific objectives in support of this goal are a fundamental understanding of materials flammability and fire physics as demonstrated in the creation of new fire-resistant materials and fuels. Technical objectives include significant advances in quantitative fire modeling, aircraft designs, fire-safety systems, and suppression technology.

These thrust areas will require multidisciplinary applied research in materials science, fire science, and engineering with basic supporting research in chemistry, physics, biology, and mathematics. Within the scope of FAA fire safety activities, Fire Safety Research will be structured as a distinct long-range effort which parallels engineering development and regulatory studies, as shown in Figure 3. Fire Safety Research will be conducted at the FAA Technical Center, which will also coordinate and integrate activities at universities, private research organizations, and outside government agencies. The FAA Technical Center will identify promising results from the research program and conduct supporting basic and applied research to transition newly developed technology to the private sector.

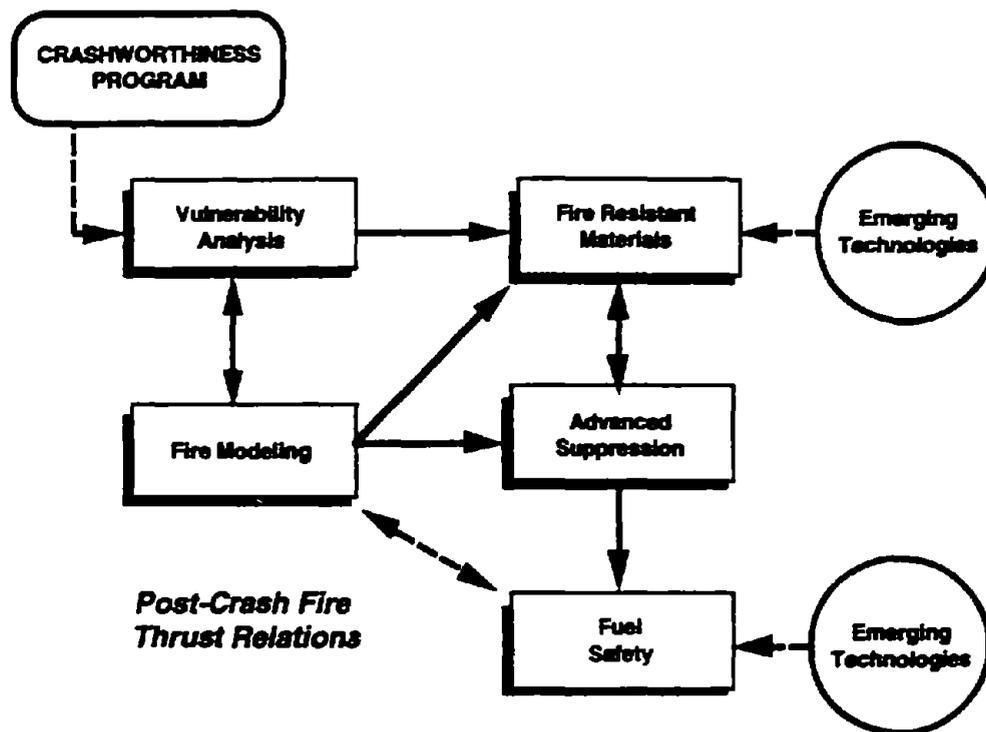


FIGURE 2. RELATIONSHIP BETWEEN FIRE SAFETY RESEARCH THRUSTS FOR POST-CRASH FIRES.

#### DESCRIPTION OF RESEARCH THRUSTS

The following sections provide a brief overview of the background, current status, FAA needs, and opportunities for research in each of the six technical thrust areas. We attempt to highlight some new scientific results and emerging technologies which are representative of work to be conducted in each thrust area, in an effort to stimulate feedback from the scientific and engineering communities rather than to serve as a comprehensive overview. Research in each of the thrusts should be consistent with FAA needs and programmatic objectives, although the particular approach will be determined to a large extent by the research interests of individual investigators.

#### FIRE RESISTANT MATERIALS

Flammability requirements for transport aircraft passenger cabins have become more stringent in recent years as a result of new regulations both on seat cushion flammability and on heat release rates allowable for cabin lining materials. Both regulations were based on full-scale fire tests that demonstrated that flashover in the cabin could be delayed if the heat contribution from burning interior materials was reduced. Research with a goal of a totally fire resistant cabin will involve development of new materials for seats and interior panels as well as consideration of the roles

played by many other interior materials not affected by the new regulations. The increasing use of fiber-reinforced polymer composites in commercial aircraft structural components requires that the flammability characteristics of these materials be determined and improved to mitigate fuel dispersal and fuselage burnthrough. Fire performance requirements for these advanced materials will come from fire research findings and vulnerability analyses. These requirements will translate into material specifications that would need to be met for a totally fire resistant cabin.

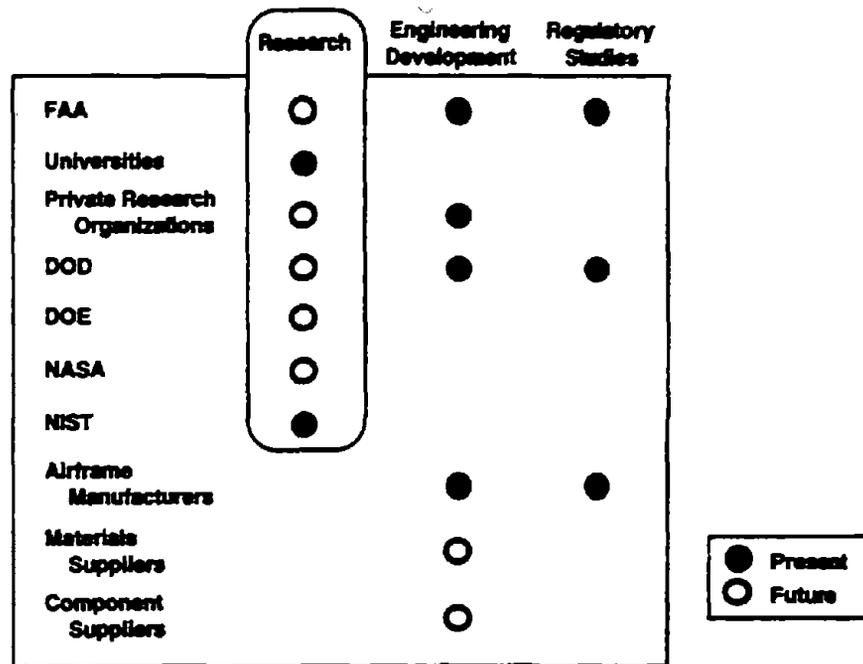


FIGURE 3. FAA FIRE SAFETY RESEARCH IMPLEMENTATION PLAN

We have listed in Table 1 several materials technology areas which have direct application to aircraft structures and interiors. Basic and applied supporting research in each of the technology areas is necessary to achieve order-of-magnitude improvements in overall aircraft fire safety within the next two decades. Fundamental studies are needed to answer questions about the underlying chemical and physical processes contributing to flammability and to help identify important material parameters for use in the fire modeling effort. Mechanistic studies of burning polymers and fiber composites will enable rational, molecular-design of non-flammable materials using novel synthetic routes and renewable or low-cost starting materials. Molecular dynamics simulations of the combustion process of polymers underway at NIST (reference 1) has great potential for relating polymer structure to material burning rate. Generally speaking, increasing the amount of crosslinking in a polymer enhances carbonaceous char formation and reduces the amount of volatile thermal decomposition products available for combustion. Char formation during fire exposure also acts to create an insulating layer on the polymer surface that prevents or delays fire involvement of underlying material. Developing the technology to relate

polymer composition and chemical composition to fire performance will provide a new capability to design fire safety into polymer systems.

The recent movement to ban halogenated flame-retardants in Europe because of toxic and corrosive combustion products emitted from these materials calls for additional emphasis on non-halogen approaches to flame-resistant materials. Inorganic polymers such as polyphosphazenes are inherently non-flammable but the hydrolytic stability of these materials must be improved (reference 2). A clear understanding of the polymerization reaction mechanisms for inorganic monomers must be developed before next-generation inorganic polymers with useful properties can be achieved. Polycarbosilanes and polysilazanes are non-flammable, semi-inorganic polymers shown in Figure 4, which thermally decompose to silicon nitride and silicon carbide, respectively, with char yields of ~60% (references 2,3).

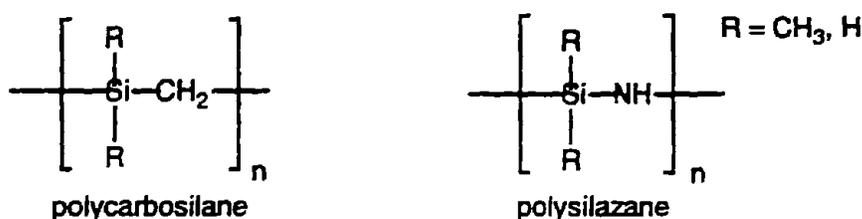


FIGURE 4. POLYMER PRECURSORS TO SILICON CARBIDE AND SILICON NITRIDE CERAMICS.

Organophosphorous chemistry is another viable route to polymeric materials with high char yield and inherent flame resistance. Figure 5 shows an example of a synthetic route to fire-resistant phosphorous-containing polymers using cardanol (a major component of cashew nut shell liquid)—a natural and renewable source of monomer (reference 4).

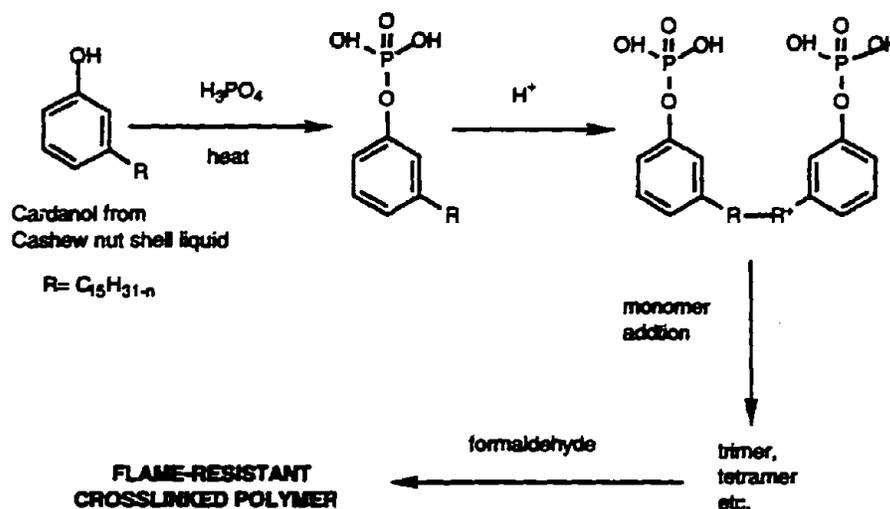


FIGURE 5. FIRE-RESISTANT THERMOSET POLYMER FROM NATURAL/RENEWABLE SOURCES AFTER REF. 4.

TABLE 1. SUPPORTING RESEARCH IN FIRE RESISTANT MATERIALS

AIRCRAFT APPLICATION	TECHNOLOGY AREA	SUPPORTING RESEARCH
Interior panels	Thermoset resins and Adhesives  Processing	<ul style="list-style-type: none"> <li>• Mechanistic studies of solid phase thermo-oxidative degradation and gas phase combustion in polymers</li> <li>• Chemistry of char formation</li> <li>• Chemistry of soot formation</li> <li>• Polymer-precursor ceramics</li> <li>• Inorganic polymers</li> <li>• Organophosphorous, organosilicon chemistry</li> <li>• Novel synthetic routes from commodity chemicals</li> <li>• Polymers from renewable sources</li> <li>• Toughening mechanisms</li> <li>• Surface chemistry</li>   <li>• Cure modeling</li> <li>• Chemorheology</li> <li>• Cure monitoring/sensors</li> <li>• Out-of-autoclave processing</li> <li>• Ionizing radiation cure</li> <li>• Smart processing/expert systems</li> </ul>
Thermoacoustic insulation	Low-density materials	<ul style="list-style-type: none"> <li>• Aerogel chemistry</li> <li>• Ultralow-density ceramics</li> </ul>
Seat cushions	Elastomers	<ul style="list-style-type: none"> <li>• Synthetic inorganic polymers</li> <li>• Thermoelasticity</li> </ul>
Textiles	Fibers	<ul style="list-style-type: none"> <li>• Liquid crystal materials</li> <li>• Synthetic routes</li> </ul>
	Composite preforms	<ul style="list-style-type: none"> <li>• Micro/macro mechanics of 3-D composite preforms</li> </ul>
Transparent glazing, molded seat components, wire jacketing, ...	Thermoplastic polymers	<ul style="list-style-type: none"> <li>• Nanophase composites</li> <li>• Thermodynamics of polymer blends</li> <li>• FR chemistry of polymer/additives</li> <li>• Novel synthetic routes</li> <li>• Viscoplastic models for impact, failure, fracture</li> </ul>
Fuselage fire-hardening	Intumescent coatings	<ul style="list-style-type: none"> <li>• Basic chemistry</li> <li>• Transparent processes in charring materials</li> </ul>
	High-temperature materials	<ul style="list-style-type: none"> <li>• Material behavior at high temps</li> </ul>
	Composite Materials	<ul style="list-style-type: none"> <li>• Mechanistic studies of burning</li> <li>• Fiber-matrix interface effects on combustion</li> <li>• Preform &amp; laminate micromechanics</li> <li>• Impact, failure, fracture</li> </ul>

Cyanate ester resin chemistry, which is known to provide exceptional thermal stability and high char yield in novolac-backbone thermoset polymers (reference 5), affords additional possibilities for utilizing natural and renewable products. Natural products such as cardanol in Figure 5 which contain hydroxyl (-OH) groups can be converted to cyanate ester thermoset resins. Pre-production quantities of cyanate ester resins are available for evaluation, and we have performed some preliminary work (reference 6) to determine the room-temperature rheological characteristics of a cyanate ester resin blend consisting of a high viscosity phenolic triazine resin (Primaset™ LMW, Allied-Signal) and a low-viscosity dicyanate monomer diluent (Arocy L-10, Ciba-Geigy) the chemical structures of which are shown in Figure 6.

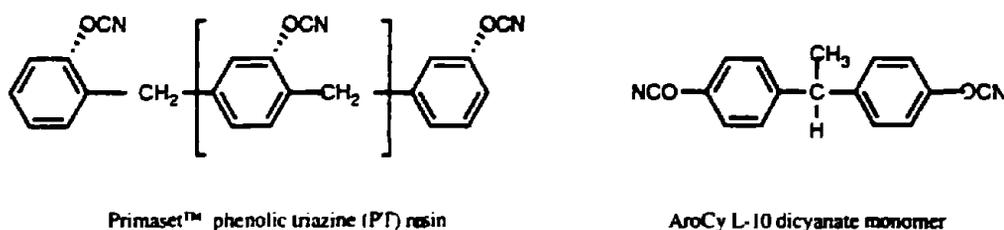


FIGURE 6. CHEMICAL STRUCTURES OF ALLIED-SIGNAL PHENOLIC TRIAZINE AND CIBA-GEIGY L-10 CYANATE ESTER MONOMERS.

Figure 7 shows that PT / L-10 cyanate ester resin blends span almost four decades of viscosity at 24°C, making this combination of cyanate ester resins useful for a number of room-temperature processes such as wet-filament winding, prepregging, and resin transfer molding of fiber-reinforced composites, as well as formulation of adhesives.

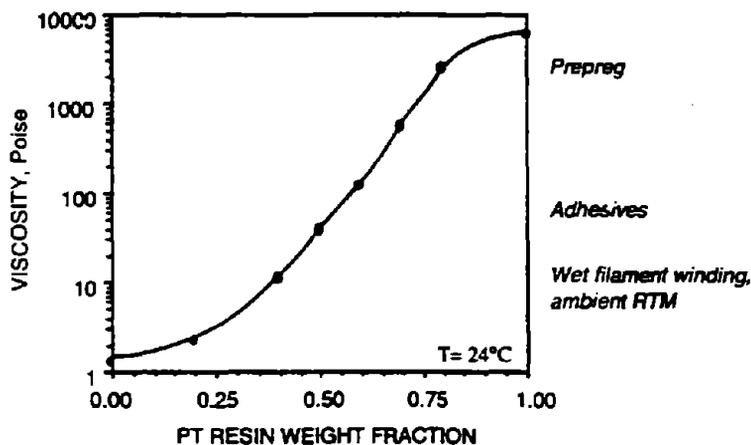


FIGURE 7. ROOM-TEMPERATURE VISCOSITY OF PRIMASET PT/ AROCY L-10 CYANATE ESTER LIQUID RESIN BLENDS.

The significance of the wide latitude in processability of cyanate esters is that consistently high char yields and low flammability is obtained for solid resin samples which had been cured at 250°C. Figure 8 shows the char yield at 1000°C in nitrogen for the PT/L-10 blends compared to the typical range for epoxies, phenolics, bismaleimides (BMI) and polyimides (PI) (reference 6).

Many small parts and accessories in the passenger cabin are presently fabricated from thermoplastics such as polycarbonate and PVC. They include such items as seatback trays, passenger service units, and window shades. These items are not covered by the regulation on heat release and smoke, and their contribution to aircraft fire severity is presently unknown. However, just as new developments in polymeric resin technologies offer opportunities for improved fire resistance, new products and new technologies in thermoplastics offer definite improvements in fire resistance of these accessory parts. Recent work (reference 7) has shown that even small amounts of polysiloxane added to thermoplastic polycarbonate reduces peak heat release by nearly 50% without adversely effecting other properties. Processing of high-temperature-capable thermoplastics has advanced to the point where these materials are being evaluated for the hull of supersonic passenger aircraft (reference 8).

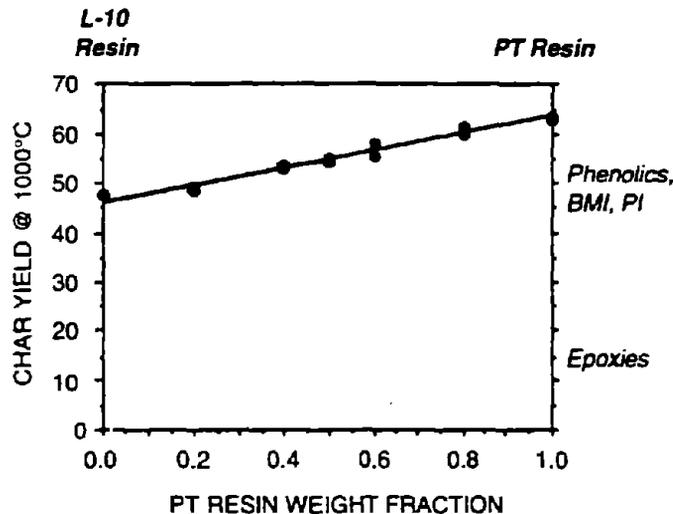


FIGURE 8. CHAR YIELD OF PRIMASET PT/ AROCY L-10 CYANATE ESTER RESIN BLENDS CURED 2H AT 250°C.

While composites and adhesives with low flammability are readily synthesized from thermally-stable polymers such as polyimides, bismaleimides, and cyanate esters, the poor fracture toughness of these unmodified, brittle resins translates into low peel strength and poor durability in composite structures and bonded joints. NASA Langley has a large program aimed at toughening polyimides such as PMR-15 using interpenetrating networks (IPN's) and thermoplastic modifiers for use in adhesives and fiber composites. This approach of heterogeneous (two-phase) toughening has promise for developing non-flammable polymers and adhesives having with high fracture energy by judicious selection of the second phase modifiers.

Potential heterogeneous mechanisms for reduced polymer flammability in transparent glazing materials extend to the emerging field of nanophase materials and composites where nanometer-sized particles which are too small to scatter visible light produce optically transparent plastics with dramatically improved thermal and oxidative stability when suspended in a polymer matrix (reference 9). Surface chemical modification of two-phase polymer blends, filled polymers, and fiber-reinforced composites could lead to dramatically reduced flammability through thermo-oxidative stabilization or enhanced char formation at interfaces.

Homogeneous or single-phase approaches to reduced polymer flammability function at the molecular level primarily through the incorporation of soluble additives and/or copolymerization with compatible monomers. Homogeneous modification is widely used when significant changes in mechanical properties are desired or can be tolerated. For example soluble flame-retardant plasticizers or co-monomers which lower the glass transition temperature of the base resin can broaden the relaxation spectrum to overlap the timescale of peeling and loading processes—thereby accessing energy dissipation mechanisms available to viscoelastic polymers to improve toughness and peel strength. Carboranes dissolved in phenolic resins at parts-per-million concentration catalyze the formation of crystalline graphite from glassy carbon to strengthen the char layer formed during polymer combustion (reference 10). Aerospace Corporation has extended this work to higher carborane concentrations and evaluated boric acid as an economical replacement. Unfortunately boric acid catalyzes the phenolic resin polymerization to an unacceptable level before significant gains in char formation can be achieved (reference 11).

Processing remains the largest single cost in the manufacturing cycle of thermoset polymer composites despite nearly three decades of polymer composite usage. Consequently we plan to conduct and support applied research in the area of composite processing with the goal of developing a sensor-based intelligent processing capability for advanced fire-resistant polymers and composites to offset potentially higher material costs. Process research activities will span a range of disciplines and focus on transitioning new materials from bench-scale to the manufacturing environment for the production of finished aircraft application. Mechanistic cure modeling of novel inorganic and semi-inorganic polymers will be conducted to elucidate reaction pathways and provide submodels for intelligent processing models.

We are presently collaborating with DOE/Lawrence Livermore National Laboratory and the University of South Carolina to develop fiber-optic Raman spectroscopy as a tool for polymer and composite cure and temperature monitoring (reference 12-14). Figure 9 shows the degree of cure versus time for an epoxy resin at room-temperature determined remotely and *in-situ* using Raman spectroscopy measured over 200-mm diameter quartz optical fibers with diode laser excitation (reference 14). The degree-of-cure calculated from the Raman peak ratios is seen to compare favorably to *ex-situ* near-infrared absorbance measurements conducted in a commercial FT-IR/NIR spectrophotometer. We have also made temperature measurements *in-situ* using fiber-optic Raman spectroscopy by measuring the Stokes and anti-Stokes scattering from the resin over the same optical fibers used to obtain the cure information (reference 13). Cure monitoring of bismaleimide resins using Raman spectroscopy is in progress and appears to be equally viable (reference 15).

Strongly coupled with the processing effort will be research into the nature of diffusion controlled reactions for the eventual creation of mechanistic chemorheology

submodels for intelligent process control. The viscosity of low molecular weight monomer increases by several orders of magnitude during the chemical reaction which produces high-molecular weight polymer, eventually shutting down the chemical reaction because of the low rate of monomer diffusion at high viscosity. The functionality of the monomer determines whether the resulting polymer will be a linear molecule such as thermoplastics (e.g. polycarbonate, acrylic, polyethylene), or a highly-crosslinked thermosetting network (e.g. epoxies, cyanate esters, bismaleimides, polyimides). Superimposed on the exponential viscosity increase with molecular weight during isothermal polymerization is the viscosity increase due to the changing glass transition temperature during the cure reaction. An example of the interrelationship between chemistry and rheology is shown in Figure 10 (reference 6), which plots viscosity versus the number average molecular weight,  $\bar{M}_n$ , for the epoxy resin determined from the data in Figure 9. This epoxy is a model compound of phenylglycidyl ether cured with n-aminoethylpiperazine having no possibility of crosslinking (i.e. a non-linear molecule) yet the room temperature viscosity increase with increasing molecular weight is 30,000 times greater than is typical of other linear polymers in the liquid state or in solution which exhibit a 3.4 power-law exponent. The reason for the anomaly is that this epoxy vitrified (turned solid and glassy) during the cure process although the chemical reaction went essentially to completion. Relationships like these must be understood at a mechanistic level and quantified mathematically to be able to control the cure chemistry of advanced fire-resistant materials as they emerge into the manufacturing arena.

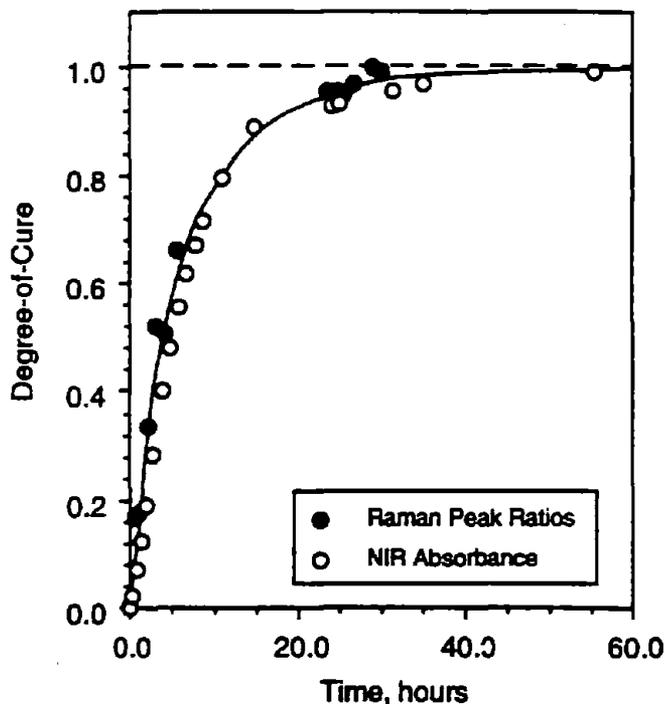


FIGURE 9. COMPARISON OF FIBER-OPTIC RAMAN AND NEAR-INFRARED ABSORBANCE METHODS OF MEASURING EPOXY RESIN CURE.

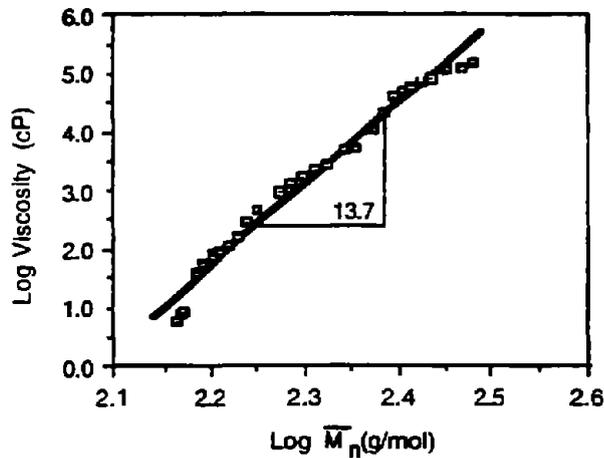


FIGURE 10. LOGARITHM OF VISCOSITY VERSUS LOGARITHM OF NUMBER-AVERAGE MOLECULAR WEIGHT FOR A MONOFUNCTIONAL EPOXY CURED WITH A TRIFUNCTIONAL AMINE.

In the area of fiber technology, thermally-stable liquid crystal polymer fibers are being developed which have the potential to replace Kevlar and Nomex aramid fibers in flame-resistant fabrics for cabin interiors. These fibers include poly(benzobisthiazole), PBT, which was developed by the Wright Patterson Air Force Base during the 1980's, poly(benzoxazole), PBO, currently being commercialized by Dow Chemical, and poly(benzimidazole), PBI, which owes much of its performance in simple flammability tests to 18% moisture content at equilibrium, and thermoplastic polyimide, TPI. Newer, more thermally stable polymers which are amenable to fiber spinning will undoubtedly be developed.

#### FIRE MODELING

Predictive computer fire modeling research for rooms, buildings, ships, and aircraft has been underway for more than twenty years. The earlier models were mostly of a type known as zone models which used a combination of simple fluid flow equations and empirical fire correlations. Solving these equations simultaneously as a function of time results in information on temperature growth and smoke movement. These zone models are very sensitive to the specific empirical equations employed. More recent zone models have found more widespread use in litigation and building hazard assessment.

In contrast are the so-called field models which involve solutions to complex fluid flow and energy transfer equations with detailed spatial resolution in an enclosure or in the open. These field models attempt to predict fire physics from as fundamental physical laws as are available. Limitations to progress in field modeling have been the result both of computer capability and gaps in understanding of fire behavior. However, over the last decade advances in computer speed and capacity and improved understanding of fire physics and chemistry have contributed to rapid

progress in field modeling to the extent that field models can be expected to become an accurate tool for aircraft fire prediction within ten to twenty years with continued funding support.

An example of the progress to date in field modeling is the prediction of downwind soot deposition from large fuel fires. The standard technique for predicting this involves use of an atmospheric zone model. The three zones are the fire plume which rises to a certain height, a horizontal plume traveling downwind at that height, and the rest of the atmosphere which is free of soot from the fire. The particulate distribution in the horizontally spreading plume is bell shaped around the center, and the diameter of this plume slowly increases as the distance from the fire increases. For a large fire, this model predicts that soot above the plume center would never reach the ground at all, and much of the rest would reach it very slowly. In contrast is a field model solution generated by Dr. Baum at NIST. This model shows the smoke plume detaching from the thermal plume with resultant earlier and much heavier particulate deposition on the ground. The model further shows how vortex motions caused by the plume result in a highly non-uniform deposition pattern on the ground.

The treatment of flow dynamics is presently the strongest aspect of field models. Attempts are underway to add realistic submodels for flame spread, material burning rate, and wall heat transfer. Unfortunately, most past research has involved burning of relatively simple materials which are not typical of aircraft construction materials. Also, most field models have dealt with enclosure fires with internal configurations and ventilation conditions vastly different from aircraft where post-crash cabin fire is usually initiated by a large external, wind-blown fuel fire. The physics of the fuel fire penetration into the fuselage have to be included in any useful aircraft fire field model. Although much of the required research can be patterned on methods used in building fire research over the last twenty years, aircraft fire phenomena are unique and will require novel approaches. Accurate predictive tools for aircraft fires are needed to establish effective countermeasures and design reconfigurations which can improve safety, and to help determine what materials properties must be optimized to make cabin interiors fire-proof.

#### VULNERABILITY ANALYSIS

Aircraft fire risk and vulnerability research is needed for both in-flight and post-crash fires. The considerations going into analysis are entirely different for these two type fires. In-flight fires can involve failed systems as ignition sources or systems failing as a result of fire exposure. A prime example is the Air Canada accident in 1983 where electrical load shedding and electrical failures resulted in the engine high pressure bleed valve failing closed. In the course of aircraft descent, this valve closure prevented the passenger cabin from receiving ventilation air. New methodologies developed under the FAA Aircraft Catastrophic Failure Prevention Program will be used for evaluating the likelihood of system failure as a fire source. Modeling techniques described in Chapter 4 will be used to predict fire growth and vulnerability of exposed systems and materials. Additionally, the fire involvement and energy contribution of potentially involved materials has to be determined. Recent risk analysis efforts in fire safety have attempted to determine a reasonable upper heat-release allowance for materials and assemblies involved in a realistic fire scenario. In-flight fire vulnerability research can show what systems are most likely to cause a fire, what systems are likely to fail in a fire, and what fire scenarios are most likely to have

catastrophic results. The sum of such probabilities provides a basis for estimating the fire safety of a given aircraft design. The relative magnitudes of the individual probabilities can be used to identify design features, systems, and materials where improvements will be most beneficial.

Whereas in-flight vulnerability analysis uses fire modeling as part of the overall hazard assessment, post-crash fire risk and vulnerability analyses are necessary inputs to the development of reliable and useful modeling techniques for post-crash fires. Because post-crash fire severity is strongly affected by wind direction, fuel spill amount and location, and fuselage structural damage, distributed probabilities have to be developed for a wide range of crash scenarios. Roughly half the fatal crash accidents involve some sort of fuselage separation into parts. This alone is probably the most challenging factor to be incorporated into post-crash fire models, and it is likely to strongly affect fire involvement of cabin interior materials. Inputs from the FAA Crashworthiness Research Program will be used to develop the range of fuselage structural failure modes that may precede post-crash fire growth. As the theoretical modeling capability develops to analyze these many scenarios and include the response of the aircraft structure to external and internal fire, major material and design vulnerability areas can be identified. Improvements can be hypothesized and analyzed through the modeling process for effectiveness.

#### IMPROVED SYSTEMS

Complementing the research on material systems that are more fire-resistant is a research thrust to improve aircraft electrical and mechanical systems to provide more fire safety. A prime example of this type potential improvement is in-flight smoke venting. Achieving the goal of a totally fire resistant cabin will drastically improve both post-crash and in-flight fire safety. However, flammability of luggage, freight, oxygen systems, and trash remain as significant potential sources for smoke and toxic gases. Assuring passenger safety requires improved means to keep the flight deck and passenger cabin free of noxious fumes.

In recent years the FAA has done considerable research to find improved ways of keeping the passenger cabin free of smoke. This included studies, analyses, flight tests of alternate emergency procedures, and flight testing of aircraft with modified systems. Control of smoke - particularly buoyant smoke - in an aircraft has proven to be singularly difficult. Unlike tall buildings, warehouses, and atriums, wherein the buoyant behavior can be used advantageously to eliminate the smoke, the slender diameter and horizontal orientation of a fuselage work against this type approach. However, analysis of the recent FAA research findings has uncovered the type and magnitude of aircraft cabin flows that are required to control smoke. The difficulty is developing a practical system that can meet these requirements.

Opportunities for fire safety improvements arising from computerization of aircraft systems continually emerge. A fairly primitive prototype known as ACES (Aircraft Command in Emergency Situations) has recently been completed by the FAA. This prototype involves installation of advanced fire sensors in inaccessible areas of aircraft and interfacing these sensors with flight deck computers and electronic checklists to guide the crew through appropriate emergency procedures. Future evolution of the ACES concept could incorporate artificial intelligence (AI) in the

decision making process as well as employing neural networks to enhance the specificity of fire detectors.

Permeo-selective polymer membrane technology has advanced to the point where it is used by the food industry to provide nitrogen-enriched atmospheres inside trucks for food preservation during shipment. Flowing air is supplied to these membrane devices and separated into two gas streams - nitrogen enriched and oxygen enriched. This membrane technology could be developed for aircraft use to supply nitrogen to the cargo compartment to reduce the likelihood of fire, and to provide oxygen for passenger emergency breathing. The latter will result in reduced fire hazards from oxygen storage systems.

Emerging technologies offer a multitude of opportunities for improved aircraft systems fire safety. Our approach will be to identify the weak system links from the vulnerability analyses, identify the appropriate advanced technology, and tailor that technology to eliminate the weak link. The vulnerability analyses can be used to quantify the safety cost to aviation of the particular weak link to determine whether improved technology cost effective.

#### ADVANCED SUPPRESSION

In many fire problems gas-phase reaction chemistry can be ignored due to the fact that these chemical reactions are extremely fast when compared to heat transfer, mixing, diffusion, and flow. These transport processes actually control fire ignition, fire growth and fire energy release. Fire suppression, on the other hand, involves the same transport phenomena plus gas phase chemical kinetic reactions. In addition, the act of suppressing a fire perturbs an already chaotic combustion environment.

Although some relatively simple suppression phenomena can be described theoretically, the vast array of aircraft fire suppression existing and potential applications are based on trial-and-error development and testing. The manner in which water puts out fire is a matter of speculation. Dry chemical powders are argued to extinguish fire by all types of competing and sometimes contradictory mechanisms. The behavior of chlorinated and fluorinated hydrocarbons, while easiest to understand, becomes problematic when real life installations are involved.

The fact that the science of fire suppression is so primitive does offer the possibility that tremendous technology improvements may be attained. The technology gaps to be closed, however, are extremely broad, and there are many viable approaches that can be pursued independently or in combination. The work on fire modeling and fuel safety can be used as a springboard from which to address the issues of reaction inhibition and process chaos. The work on fire resistant materials can be extended to look for synergies between aircraft materials and specialized suppressant agents. Emerging technologies associated with improved aircraft systems can be used to develop smart suppression systems that respond in ways appropriate for specific fires.

Developing a sound and useful science of fire suppression will undoubtedly require new discoveries and novel analytical techniques. While scaling laws and critical parameters have been found for the simplest reacting flows, the applicability of these laws or their derivatives to large and chaotic fire phenomena is unknown.

Developing an effective aircraft fire suppression system for the next century is clearly one of the most complex and challenging problems addressed by the thrust areas in the long-range fire research program.

## FUEL SAFETY

The major contributor to the post-crash fire human life hazard is the burning of spilled fuel. Compared to any aircraft polymeric materials, aviation kerosene is easily ignitable, has high heat release potential, and rapid fire spread characteristics. A large transport aircraft may be loaded with hundreds of thousands of pounds of jet fuel prior to take-off. A large burning spill can melt the aircraft skin within a minute. The actual passenger cabin survivability and escape times are strongly affected by fire location, fuselage door openings, and fuselage orientation in the wind. Further variables are fuselage separations and landing gear configuration. What makes a burning fuel spill particularly dangerous is the large production and projection of radiant heat. Materials that can resist ignition in a 100 percent of oxygen atmosphere may burn readily when exposed to the radiant heat of a large fuel fire. Reducing the fuel fire hazard is the most effective way to reduce aircraft fire fatalities, albeit the most difficult.

Over the past forty years, a multitude of test and evaluation efforts have been initiated in an attempt to reduce the incidence of post-crash fuel fires. Some have resulted in improved aircraft design considerations that attempt to minimize ignition sources for spilled fuel. Others have attempted to reduce fuel flammability through the use of additives. In the 1960's, these experimental additives were aimed at making the fuel in the wings take the form of gels or emulsions. In the 1970's the focus shifted to the use of high molecular weight polymers that would prevent spilling fuel from forming highly flammable fine sprays. In these additive evaluation efforts, small and intermediate scale tests usually demonstrated dramatic improvements in fuel flammability properties but full-scale airplane crash demonstrations resulted in dramatic failures in additive performance. Additionally, almost all additives investigated in the past have shown significant areas of incompatibility with aircraft fuel systems. These issues were serious enough that incorporation of any of these additives into the civil fleet might have resulted in a net increase in passenger fatalities due to increased accident rates.

The nature of the petroleum refining process precludes any drastic changes to overall chemical composition of aviation kerosene. Reducing fuel flammability requires the addition of one or several additives. Different families of additives can affect fuel flow behavior, fuel break-up characteristics, vaporization behavior, and fuel surface characteristics. Use of these additives can make fuel ignition less likely or reduce the fuel energy release rate when ignition does occur. Some additives have been reported that reduce soot formation of burning fuel. These additives could conceivably reduce the radiative energy output from burning fuel spills and thereby reduce their impact on fuselage structure.

Past major FAA efforts on safety fuels preceded the Aviation Safety Research Act of 1988 and consequently had the nature of test and evaluation programs centered around specific experimental additives offered up by the chemical industries. These programs had very little in the way of basic research. Consequently, in spite of the relatively large resources expended, the physics of post-crash fuel fire development is

poorly understood. Development of a correct technical framework is necessary to find the parts of the processes where intervention might be most effective. Spray combustion is one of the most complex and sophisticated subjects in engineering science. Theories and experiments generally deal with well-defined droplet distributions in fairly simple flow geometries. Modeling fuel release, break-up, and ignition while an aircraft is decelerating during a crash will be a major technical endeavor.

#### SUMMARY

The primary goal and benefit from long-range aircraft fire safety research is the elimination of fire as a cause of fatalities in aircraft accidents. Achieving this goal over the next two decades will result in additional benefits to society including a wealth of basic scientific information on why and how things burn, new materials, new processing technology, and the stimulation of natural product materials chemistry from renewable sources. Fundamental, science-based models and computer codes will be developed to predict complex, large-scale burning behavior of aircraft and other structures and coupled with new risk assessment methodologies to produce efficient, life-saving designs for human environments.

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THE FUTURE OF AIRCRAFT CABIN FIRE SAFETY

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INTRODUCTION

The Fire Safety Branch at the Technical Center in Atlantic City, New Jersey, is the Federal Aviation Administration's (FAA) Research and Development (R&D) organization responsible for providing data to the regulatory organizations within the FAA for their use in developing, modifying and/or interpreting rules and regulations pertaining to aircraft fire safety. The Fire Safety Branch has developed many of the fire safety standards adopted by civil aviation authorities throughout the world and is presently involved in R&D for future improvements.

The Safety Regulation Group of the United Kingdom Civil Aviation Authority (CAA) initiates and funds research which is conducted by agencies external to the Authority. The research is "Project Managed" by CAA staff working as a team involving technical experts, certification and regulatory specialists and a project manager. There are programs of work in which the CAA together with other Authorities jointly manage complementary studies, an example is the research into Cabin Water Spray Systems which has involved the CAA, FAA, Transport Canada, DGAC of France, and the European Commission. In the future, it is expected that CAA research activities will increasingly involve other European Joint Aviation Authorities (JAA) as partners and become integrated into a JAA-wide program of research

BACKGROUND

Over the past several years, Aviation Authorities worldwide have implemented numerous modifications to aircraft fire safety standards. Those modifications have vastly improved fire safety in transport aviation and include the following:

Seat Cushion "Fire Blocking" Rule. This rule requires that all cabin seat cushions in transport aircraft meet a large oil burner test. The result of this rule change was that most seat cushions were "fire blocked". The term fire blocking refers to encapsulating and protecting the relatively flammable urethane foam with a very fire resistant material. The fire blocker is usually a separate material, placed over the urethane foam and under the outer dress cover. The fire blocking materials presently available cannot be dyed, therefore, they are not used as outer covers. Until recently, urethane foam, (the only foam meeting airline operational requirements) could not be made fire resistant enough without a large, and unacceptable, increase in weight. The safety benefits of this rule have been documented in accident investigations. In one case, a Delta 727, in Dallas, Texas, on August 31, 1988, it was cited by investigators as having provided a longer evacuation time thus saving many lives.

Floor Level Lighting Rule. This is a requirement for emergency lighting near the floor in an aircraft. As a result, most airlines have installed floor track lighting (light strips on the floor).

Low Heat/Smoke Release Panel Rule. This is a requirement for large surface materials in an aircraft cabin (ceiling, sidewall, stowage bins, partitions, etc.), in newly manufactured or totally refurbished aircraft. It has also been referred to as the "OSU Rule" because of the test method required. This rule forced the airframe manufacturers to upgrade most of the materials used in aircraft interiors.

Cabin Fire Extinguishing Rule. A requirement of transport aircraft to carry at least two Halon 1211 extinguishers. The successful extinguishment of a hidden fire by crew members using Halon 1211 extinguishers may have prevented a catastrophic inflight fire in a Delta L1011 flying over the North Atlantic during March 1991.

Lavatory Smoke Detection Rule. This rule requires smoke detectors in all transport aircraft lavatories as well as a fixed extinguisher in U.S. aircraft (known as a potty bottle) in all lavatory trash receptacles. The main job of these systems is the protection against people smoking in the lavatory.

Radiant Heat Resistant Evacuation Slide Requirement. This was a change to the Technical Standard Order (TSO) that contains the requirements for emergency evacuation slides. The change incorporated a radiant heat test for slide material, designed to improve the ability of the slide to resist the heat from a large fuel fire nearby and remain inflated longer.

Cargo Compartment Rules. There have been three major rule changes affecting cargo compartments on transport category aircraft. The first was a change to newly certificated aircraft only. It reduced the allowable size of a class "D" compartment to 1000 cubic feet and imposed a new fire burnthrough resistance test method for cargo liners, seams, joints, and fastening systems. The second rule change was a retroactive rule requiring the modification of class "C" and "D" compartments. This rule has led to the removal of Kevlar and Nomex liners, the redesign of some fixtures and fastening systems, and new methods for patching damaged liners. The third rule change was an airworthiness directive (AD) changing the requirements for class "B" (Combi) cargo compartments.

It should be noted that the focus for improvements in fire safety has been in the area of materials flammability upgrading.

## EFFECTIVENESS

The frequency of accidents to jet aircraft involving fire has notably reduced since the accident at Manchester, United Kingdom, in 1985. There were 68 accidents in the 221 million hours flown before that time.

a rate of 3.1 per ten million hours, and 14 in the 88 million hours in the subsequent five years, a rate of 1.5 per ten million hours. The fatalities due to fire in these accidents also reduced from an average of 34, to 19 per accident. It is reasonable to assume that the fire protection measures introduced since 1985 have been a factor in this reduction.

## THE FUTURE OF AIRCRAFT FIRE SAFETY

### MATERIALS UPGRADE

Most of the material flammability upgrading to date has been aimed at the postcrash fire. New design standards are based on a fire entering the aircraft cabin from a large external fuel fire and spreading on the interior cabin materials. Although there are still some areas such as the seat compartments, curtains, and transparent fixtures that should be studied to determine if upgrading of standards would increase safety, initial full scale tests have indicated that incremental changes would lead to little improvement. Therefore, near term there seems to be limited safety improvement that can be expected from further cabin material flammability upgrades against the postcrash fire. Therefore, long range R&D will center on highly fire resistant (almost non-combustible) materials.

Although the materials in the cabin have been upgraded and fire safety greatly improved, little has been done to the materials that are the most likely to be involved in a serious inflight fire. Of concern are the hidden materials: materials behind the sidewall, over the ceiling, and below the floor. Full scale tests have shown that the presently used thermal acoustic insulation will not propagate a small fire. However, a small amount of contamination, such as oil, grease, lint, etc., causes the insulation blankets to become involved. That has been the case in actual inflight fire incidents.

Wire and cable has also been the source of a number of inflight smoke and fire problems. At present, the only test requirement is a Bunsen burner test for flammability. Work is presently underway to upgrade that requirement and to develop meaningful smoke and arc tracking test procedures.

### BURNTHROUGH REQUIREMENTS

In some accidents, for example, British Airtours 737, Manchester, United Kingdom, August 22, 1985, the external fire entered into the cabin by burning or melting through the fuselage. Full scale experiments have been conducted at the FAA Technical Center to determine the modes of hazard entry into an aircraft cabin from an external fuel fire. Work to date indicates that the most vulnerable area is the lower quadrant or areas with little or no thermal acoustic insulation. Hazard entry into the cabin is initially in the form of smoke followed by flames through the air return grill at the cabin floor level. A CAA program is now underway to develop a test facility to evaluate burnthrough improvements.

### SYSTEMS APPROACH

Since a giant step has been taken in upgrading material standards, and further improvements in that area will not solve the entire problem (cabin furnishings do not affect the smoke, heat, and flames entering the cabin from the external fuel fire), one must consider the other fuel sources on board, such as jet fuel, hydraulic fluid,

passenger carry-on materials and oxygen. What can be done to improve fire survivability? Have we gone far enough?

Examination of past accidents and full scale testing suggests that improvements to oxygen and hydraulic systems could improve both inflight and postcrash fire safety. Oxygen systems have been the cause of aircraft fires (ATA DC10 in Chicago, Illinois, August 1988, and Delta 727 in Salt Lake City, Utah, October 1988) and have contributed to the severity of postcrash fires (USAir 737 in Los Angeles, California, February 1991). Seven aircraft have been destroyed or severely damaged as a result of oxygen fires during servicing. For the near term, methods of containment (such as flow restrictors, fuses, or solid oxygen generation systems) should be explored. The final answer may be an oxygen nitrogen separation system. These systems (OBOGS-Onboard Oxygen Generating System) are presently available, however, with an extreme weight penalty. Long term R&D is needed to reduce the weight to output ratio.

Hydraulic fluid has also contributed to both postcrash (Korean Airlines 747, Seoul, South Korea, November 1980) and inflight (America West 737, Tucson, Arizona, January 1990) fire hazards. Work should be carried out to develop noncombustible fluids that meet the requirements of the transport airline industry.

#### AIRCRAFT HARDENING AGAINST EXPLOSIONS

This systems approach is of particular importance. One area that I would like to draw your attention is that of Aircraft Hardening Against Explosion. Major programs of research in this area have been initiated by the FAA and the CAA. Much effort is to be put into the design of structures and systems and into identifying materials able to mitigate the effects of explosions. However, candidate materials for explosion hardening, such as Kevlar, have already been found to be poor for fire containment purposes. The solutions to these explosion hardening problems must be worked together with fire safety. An explosion in baggage is very likely to start a major fire. It would be pointless to develop an aircraft, the structure and systems of which could withstand an explosion only to find that smoke and fumes caused it to crash.

#### CABIN WATER SPRAY SYSTEMS

Even with improvements to present systems, there is still the problem of the fuel fire. How can the hazards of the external fuel fire spreading into the passenger cabin be reduced? One method that is presently being studied and shows great promise is a cabin water spray system. The idea was popularized by a company called "SAVE" in the United Kingdom. The system would consist of a fixed quantity of water stored on board the aircraft that would be discharged from nozzles throughout the cabin in the event of a postcrash fire. Testing to date has shown the system to be extremely effective, reducing the hazards in a cabin and extending occupant survival time for most postcrash fire scenarios. The hazards associated with accidental discharge inflight have been studied by Airbus and Boeing. Current FAA work is on optimizing the system, or reducing the weight penalty. Based on recent optimization test results, a system for an aircraft the size of a 737 would require approximately 25 gallons of water to protect an airplane broken into three pieces. The next step is to develop design requirements and specifications.

#### ADDITIONAL PROBLEMS

With the banning of ozone depleting CFC's, the aviation industry faces additional problems. These problems are two fold. First, CFC's are no longer being used as propellants in aerosol cans. The replacement

propellants used are propane, which are highly flammable. This presents a major problem in cargo compartment fire protection. Solution options are to redesign some cargo compartments or redesign the aerosol cans. Second, the extinguishing agents used in transport aircraft are CFC's (actually halogenated hydrocarbons, or Halons). Production of all Halons will be banned from the end of 1993. There is a need to develop Halon recycling techniques, preserve existing stocks, and to develop new non-ozone depleting agents or alternate fire control systems. The Aviation Community has until recently shown little awareness of the need for action.

## CONCLUSION

There are still major improvements that can be made in aircraft fire safety, however, a systems approach is needed to identify and develop cost-effective solutions.



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