79-4025

Laboratory Fire Testing of Cabin Materials Used in Commercial Aircraft

C.P. Sarkos,* J.C. Spurgeon,† and E.B. Nicholas‡
FAA National Aviation Facilities Experimental Center, Atlantic City, N.J.

The purpose of this paper is to familiarize individuals with the kinds of materials currently used in the cabin interior of a commercial airliner, to describe some of the more important fire tests used to evaluate these materials, and to summarize the behavior of these cabin materials when subjected to each of the fire test methods. Specifically, a detailed description is presented of the following respective test methods for flammability, smoke, and toxic gas emissions: vertical Bunsen burner test, National Bureau of Standards (NBS) smoke chamber, and a combustion tube furnance test. Fire test data on 75 cabin materials are summarized for burn length, flame-out time, specific optical density (D_s) of smoke, and yields of hydrogen cyanide (HCN) and carbon monoxide (CO).

Background

THE interior of a commercial aircraft cabin is lined and furnished with a large quantity and great variety of synthetic and natural polymeric materials. Under fire exposure conditions of sufficient intensity, any of these materials can ignite, burn, and emit heat, smoke, and toxic fumes. In order to minimize the danger associated with the involvement of interior materials in a cabin fire, the Federal Aviation Administration (FAA) has sought to promulgate standards to limit the selection of materials to those meeting certain fire safety levels. Initially, emphasis was placed on the problem of in-flight cabin fire. Flammability regulations were first adopted in 1947 with a requirement that cabin materials burn no greater than 4 in./min in a horizontal orientation when subjected at one end to a Bunsen burner flame. Control of the flame spread rate was intended to provide sufficient time for the extinguishment of an incipient fire. These regulations remained in effect during a period when the major concern in aircraft fire safety was directed toward engine and fuel spillage fires rather than the ignition of the interior materials themselves. With the availability of new and better fire-resistant materials, the FAA was able to upgrade the materials flammability regulations in 1967, and again in 1972. Presently, under Federal Aviation Regulation (FAR) 25.853, except for an insignificant quantity of small parts, all interior materials must be "self-extinguishing" in a vertical orientation when subjected to a Bunsen burner flame along the bottom edge.[1]

The crash of a Boeing 727 at Salt Lake City in 1965 is considered by many people to have kindled the concern and controversy which persists over the potential fire hazard in a habitable enclosure constructed of synthetic materials.[2] A fire originating at a ruptured fuel line underneath the cabin floor instantly spread at first impact into the cabin, which remained intact during the entire crash deceleration. The hazard created by the rapid fire involvement of the cabin materials was believed to have contributed to the heavy loss in life. One important aspect stressed by the survivors was the very heavy smoke that obscured vision and seriously impaired the ability of passengers to evacuate the cabin. The concern with smoke emissions fostered the development in the late 1960's by government and industry of a number of laboratory-type smoke measuring devices.[3] Of those available test methods, the NBS smoke chamber was considered by the FAA to be the most promising for characterizing the smoke emission characteristics of aircraft cabin materials. In 1975, the FAA issued a proposed regulatory notice to govern the selection of cabin materials based on the NBS smoke chamber test.[4] This notice, in conjunction with an earlier advanced notice, was most effective in encouraging industry to develop and market new low-smoke materials.

The Salt Lake City crash in 1965 also provided the first indication in an actual accident of the potential dangers associated with the toxic combustion products emitted by burning cabin materials. As part of an extensive crashworthiness program by industry and government arising out of this accident, the FAA contracted with the Bureau of Standards to measure the smoke and toxic gas emissions of a large number of aircraft interior materials.[5] These early efforts resulted in the expansive growth of FAA in-house facilities capable of combustion gas analysis and toxicity evaluations. Laboratories and resources were further improved following the successive accidents in Chicago in December of 1972, which received wide publicity over passenger fatalities attributed to cyanide poisoning. In December 1974, the FAA issued an advanced regulatory notice soliciting responses from the public on a series of questions related to the combustion toxicity of cabin materials.[6] Although many respondents shared the FAA's concern with this problem area, caution was also expressed about taking precipitous action until suitable test methods could be developed.

Since the early 1970's, considerable research in combustion toxicity has been undertaken in the United States, with perhaps the most comprehensive programs at the University of Utah.[7] The FAA has concentrated on the development of a materials toxicity test method using either gas analysis methods and/or animal exposure systems. A cooperative program between the FAA's National Aviation Facilities Experimental Center (NAFEC) and Civil Aeromedical Institute (CAMI) utilizing this approach was completed based on the analysis of 75 in-service materials.[8,9]

Description of Typical Cabin Materials

In order to systematically describe and study the interior materials used in a wide-body cabin, it was found useful to consider the materials by usage categories. Table 1 contains descriptive information on typical materials found in each of

Received Feb. 14, 1978; revision received Aug. 3, 1978.

Index categories: Cabin Environment, Crew Training, and Life Support; Safety.

*Supervisory Aerospace Engineer, Fire Safety Branch.
†Supervisory Research Chemist, Fire Safety Branch.
‡Aerospace Engineering Technician, Fire Safety Branch.

the ten categories. The panels are the cabin lining materials which constitute the sidewall, stowage bin, ceiling, and partition surfaces. From a fire safety consideration, panels are clearly the most important category because of their 1) large surface area and 2) upper cabin location where peak fire temperatures are expected. Panel construction is somewhat similar in the three wide-body jets, consisting essentially of a decorative laminate bonded to a fiberglass sheet facing which is bonded to a Nomex® honeycomb core. However, the decorative laminates are notably different, depending on the end use and type of aircraft. They can consist of Tedlar® films ranging in thickness from 2-10 mil, or 12-15 mil Tedlar®/polyvinyl chloride (PVC) laminates. Evaluation of the decorative laminates can be considered an important process since they can be readily pyrolyzed and burned during a cabin fire. The National Aeronautics and Space Administration (NASA) and the airframe manufacturers have undertaken a major program to develop and fabricate sandwich panels exhibiting improvements in flammability, smoke, and toxic gas emission characteristics.[10] Sandwich panels are relatively lightweight, ranging from about 2.5-6 lb/yd^2. The older narrow-body jets are lined with vinyl/aluminum sidewalls and vinyl/fiberglass hatracks, headliners, and ceilings, although many are now being retrofitted with wide-body kits consisting of sandwich panel construction.

Passenger seats constitute three usage categories—foams, fabrics, and coated fabrics. Seat cushions are made of fire-retardant (FR) urethane foam. In order to provide optimum comfort and wear, the cushion is actually comprised of bonded sections of urethane foam having different densities (1.4-5.0 lb/ft^3). Although urethane foam is quite flammable by itself, the seat upholstery fabric and ticking do add a degree of ignition protection. Presently, the most popular seat upholstery fabric found in commercial aviation is the wool/nylon blend at a 90/10 ratio. These have replaced the Nomex® upholstery fabrics which were prevalent when the wide-body jets were first introduced into service. The coated fabrics are used primarily for seat armrests and seat bottom diaphragms, and thus are used in far smaller quantities than either the seat upholstery or cushions.

Wool carpets are used extensively as floor covering material in today's jet airliners. Although the floor does constitute a relatively large surface area within the cabin, floor coverings are not expected to become highly involved in a cabin fire beyond the immediate vicinity of the fire origin.

Polycarbonate is used exclusively in wide-body jets for the construction of passenger service units and modules. It has replaced the far-smokier acrylonitrile-butadiene-styrene (ABS) found in the older narrow-body aircraft, and can be processed to pass the proposed FAA smoke rule. In some of the earlier B-747's, the window reveals were also formed from polycarbonate although a changeover was made in the later models to the sandwich panel construction.

The remaining four categories in Table 1 consisting of cargo liners, transparencies, insulation, and elastomers are not considered as important as the previously discussed categories from a postcrash fire safety viewpoint. In this fire situation, cargo liners are not expected to contribute significantly to the hazard existing in the cabin compared to materials contained in the cabin itself. Transparencies and elastomers are similarly of less importance because of their relatively small abundance. Finally, although thermal and acoustical insulation can constitute almost 25% of the weight of cabin nonmetallic materials, it is not expected to pose a major fire threat because of its low resin content and isolation between the fuselage skin and interior sandwich panel.

Of the many factors which must be taken under consideration during the selection of cabin interior materials, perhaps the greatest attention, after fire safety, is given to weight and cost. The approximate weight of nonmetallic materials, excluding seats, in the passenger cabin of a typical B-727 (narrow-body) or B-747 (wide-body) aircraft is approximately 3500 and 9400 lb, respectively. Respective costs of these materials in the B-727 and B-747 are approximately \$350,000 and \$1,250,000. Incorporation of improved fire-safe materials into a typical wide-body cabin is an expensive proposition. In a report funded by the FAA, the recurring cost of improved materials in a "hypothetical" wide-body cabin was estimated at about \$300,000.[11] Recurring costs do not include, for example, the expense of developing a new production design or purchasing additional manufacturing equipment, nor operating costs which estimated over a 20-year period would practically equal the recurring cost.

Seventy-five interior materials used in wide-body transport aircraft were fire tested for the purpose of determining the toxic gas emission levels[8] and other properties. The samples

Table 1 Categorization of wide-body cabin materials

Category	Usage	Description (typical)	Weight, oz/yd^2	Thickness, in.
Panel	Sidewall, ceiling, stowage bin, partition, etc.	Finish: Tedlar® film Facings: epoxy-fiberglass Core: Nomex® honeycomb	39.6-93.0	0.276-0.958
Foam	Seat cushion	FR urethane	11.3-38.8	0.5[a]
Fabric	Upholstery	FR wool (90%)/nylon (10%)	11.3	0.037
Coated fabric	Seat armrest	PVC/cotton	26.9	0.058
Flooring	Carpet	Pile: wool Backing: polyester Pad: urethane	51.3	0.345
Thermoplastic	Passenger service units	FR polycarbonate	47.4	0.054
Cargo liner	Cargo liner	Epoxy-fiberglass	35.1	0.039
Transparency	Window cover	FR polycarbonate	46.2	0.052
Insulation	Thermal and acoustical insulation	Melamine-fiberglass	2.28	0.5[a]
Elastomer	Seal	Silicone	86.3	0.094

[a] Maximum thickness, flammability (FAR 25.853), and smoke (NPRM 75-3) tests.

Table 2 Description of materials

No.	Chemical composition[a]	Thickness, in.	Unit weight, oz/yd^2	Designation	Cabin use
1	PVF/epoxy-fiberglass/Aramid honeycomb/epoxy-fiberglass	0.388	48.5	Panel	Ceiling panel
2	Epoxy-fiberglass/Aramid honeycomb/epoxy-fiberglass (No. 1 without PVF finish)	0.376	39.6	Panel	Ceiling panel
6	PVF/Aramid fiber-phenolic	0.048	56.4	Panel component	Face for sidewall or window reveal (upper surface)
6a	PVF/Aramid fiber-phenolic	0.050	58.4	Panel component	Face for sidewall or window reveal (lower surface)
9	Aluminum/Aramid honeycomb/aluminum	0.371	86.3	Flooring	Floor
10	Fiberglass-polyester	0.039	35.1	Cargo liner	Side cargo liner
12	PVF/polyester-chopped glass/Aramid honeycomb/polyester-chopped glass	0.525	90.4	Panel	Overhead stowage door assembly
14	PVF/Nomex®-epoxy/Aramid honeycomb/epoxy fiberglass	0.532	49.7	Panel	Acoustic wall panel
15	PVF/Aramid-epoxy (acoustic skin for No. 14)	0.015	9.75	Panel component	Face of acoustic wall panel
18	PVF (clear film)	0.001	1.11	Panel component	Panel finish
20	PVF/epoxy-fiberglass/Aramid honeycomb/epoxy-fiberglass/PVF	0.958	82.8	Panel	Partition
24	Epoxy-fiberglass/PVC/epoxy-fiberglass	0.410	117	Flooring	Floor
25	PVF/fiberglass-epoxy/PVF	0.051	76.7	Cargo liner	Cargo liner
26	Fiberglass-epoxy	0.013	16.3	Cargo liner	Cargo liner
27	Melamine-fiberglass	1.19	5.43	Insulation	Fuselage insulation
28	Aluminized PVF/nylon scrim	0.007	1.33	Insulation	Cover for insulation batt
32	Polycarbonate	0.054	47.4	Thermoplastic	Molded part
33	Wool pile/polyester backing/latex coating	0.265	51.8	Flooring	Carpet
34	Wool pile/polyester backing/latex coating/urethane pad	0.345	51.3	Flooring	Carpet
37	PVF/phenolic-fiberglass screen/Aramid honeycomb filled with phenolic-fiberglass batt/phenolic-fiberglass	0.517	77.2	Panel	Center ceiling panel
38	Epoxy-coated phenolic-fiberglass (backing for No. 37)	0.017	18.4	Panel component	Backface of ceiling panel
39	Epoxy-coated phenolic-fiberglass (adhesive used in No. 37)	0.018	17.6	Panel component	Adhesive used in ceiling panel
40	Aramid honeycomb filled with phenolic-fiberglass batt (core for No. 37)	0.451	10.8	Panel component	Ceiling panel core
41	Epoxy-coated phenolic fiberglass (screen used in No. 37)	0.038	15.3	Panel component	Screen used in ceiling panel
42	PVF (acoustic skin for No. 37)	0.015	12.7	Panel component	Ceiling panel finish

[a] ABS: acrylonitrile/butadiene/styrene; FR: flame-retardant treated; PVC: polyvinyl chloride; PVF: polyvinyl fluoride.

Table 2 Description of materials (continued)

No.	Chemical composition[a]	Thickness, in.	Unit weight, oz/yd^2	Designation	Cabin use
43	PVF/phenolic-fiberglass screen/ Aramid honeycomb/Aramid honeycomb filled with phenolic-fiberglass batt/phenolic-fiberglass	0.732	85.8	Panel	Drop ceiling panel
46	PVF/PVC/phenolic-fiberglass/ Aramid honeycomb/epoxy-fiberglass	0.500	79.2	Panel	Upper sidewall panel
50	Wool carpet/phenolic-fiberglass/ Aramid honeycomb/epoxy-fiberglass	0.445	95.0	Panel	Lower sidewall panel
52	Wool carpet/epoxy adhesive/aluminum/ balsa wood/epoxy adhesive/aluminum	0.690	198	Flooring	Floor panel
56	PVC/stainless steel/epoxy adhesive/ Aramid-phenolic honeycomb/epoxy adhesive/stainless steel	0.490	168	Flooring	Floor panel
60	Epoxy-fiberglass	0.018	22.9	Cargo liner	Cargo liner
61	PVF/PVC/phenolic-fiberglass epoxy adhesive/Aramid honeycomb/epoxy adhesive/phenolic-fiberglass	0.500	69.1	Panel	Overhead stowage panel
66	Silicone-treated phenolic-fiberglass	1.38	6.09	Insulation	Fuselage insulation
67	PVC/phenolic-fiberglass/Aramid honeycomb/epoxy-fiberglass	0.273	68.1	Panel	Door liner
69	PVF/PVC/phenolic-fiberglass/Aramid honeycomb/epoxy-fiberglass	0.531	93.0	Panel	Door assembly
70	FR wool (90%) /nylon (10%)	0.037	11.3	Fabric	Upholstery
73	FR urethane	0.500	17.4	Foam	Seat pad
74	FR urethane	0.500	12.4	Foam	Seat pad
78	Aramid	0.046	12.1	Fabric	Upholstery
79	FR polyether urethane	0.500	13.7	Foam	Seat cushion
80	FR urethane	0.500	11.3	Foam	Seat cushion
81	PVC (untreated)	0.096	25.3	Fabric	Upholstery
82	FR wool (76%) /PVC (24%)	0.039	12.6	Fabric	Upholstery
84	PVC/cotton (untreated)	0.058	26.9	Coated fabric	Arm rest cover
85	ABS-PVC (untreated)	0.060	56.4	Thermoplastic	Seat side panels and trays
86	PVC (untreated)	0.500	28.8	Foam	Flotation cushion and padding for seat back and arm rest
88	FR wool	0.055	17.2	Fabric	Upholstery
89	FR PVC/nylon	0.059	26.3	Coated fabric	Seat arm cap
92	Aramid	0.036	11.8	Fabric	Upholstery
93	FR cotton	0.012	3.06	Fabric	Upholstery
95	FR rayon	0.041	15.4	Fabric	Upholstery
96	Wool (49%) /PVC(51%)	0.044	13.8	Fabric	Upholstery
97	FR PVC-polyester	0.018	11.4	Coated fabric	Seat bottom diaphragm
99	FR PVC-polymethyl methacrylate	0.044	39.6	Thermoplastic	Seat shroud
100	FR PVC/ABS	0.092	86.9	Thermoplastic	Seat shroud

Table 2 Description of Materials (continued)

No.	Chemical composition[a]	Thickness, in.	Unit weight, oz/yd^2	Designation	Cabin use
102	FR polyethylene (rigid)	0.500	13.7	Foam	Flotation cushion
104	FR polyester urethane	0.500	40.1	Foam	Seat cushion
107	ABS-PVC	0.127	122	Thermoplastic	Molded part
108	FR polymethyl methacrylate	0.054	46.6	Transparency	Scratch shield
109	Polymethyl methacrylate	0.260	228	Transparency	Window pane
111	Polycarbonate	0.052	46.2	Transparency	Windscreen
112	Silicone	0.094	86.3	Elastomer	Door seals
113	PVF/polycarbonate/PVF	0.431	151	Thermoplastic	
115a	Phenolic-fiberglass	1.09	6.40	Insulation	Fuselage insulation
116	Polycarbonate	0.043	36.8	Thermoplastic	Passenger service units and luminaries
117	Polyphenylene oxide	0.041	31.4	Thermoplastic	Flight station and lavatory parts
118a	Fiberglass-epoxy/asbestos	0.020	28.9	Cargo liner	Cargo liner
123	Silicone	0.124	116	Elastomer	Door seals
127	Modacrylic	0.032	8.63	Fabric	Drapery
130	Cotton/rayon	0.040	15.0	Fabric	Upholstery
136	PVC/cotton	0.057	28.3	Coated fabric	Upholstery
142	FR wool (90%) /Nylon (10%)	0.035	10.3	Fabric	Upholstery
143a	FR polyether urethane	0.500	13.9	Foam	Seat cushion
143c	FR polyester urethane	0.500	38.8	Foam	Seat cushion
144	PVF/epoxy-fiberglass/Aramid honeycomb/epoxy-fiberglass	0.276	43.3	Panel	Wall panel

were obtained with the cooperation of major transport and seat manufacturers. They were first screened to verify compliance with the FAA flammability requirements (FAR 25.853) and tested in the NBS smoke chamber[12] for comparison of smoke densities with those limits proposed for rule-making.[4] The flammability, smoke, and toxic gas emission characteristics of the 75 materials as measured are discussed below. Table 2 contains a description of the materials, including chemical composition, thickness, unit weight, designation (category), and cabin use. Descriptive information on makeup and chemical composition was provided by the manufacturers.

Flammability

The flammability test apparatus prescribed by the FAA in FAR 25.853 for testing interior materials is based on Federal Test Method Standard No. 191, Method 5903.2.[13] The essential parts of the apparatus consist of a Bunsen burner ignition source, a synthetic gas mixture of specified composition, a ventilated metal cabinet to provide a draft-free environment, a rigid specimen holder to assure rigid specimen support, a stopwatch, and a graduated scale. The Bunsen burner flame height is adjusted to 1½ in. in order to produce a flame temperature of 1600°F minimum. The distance between the lower edge of the test specimen and the top of the burner is ¾ in.

The test specimen is a rectangle 2¾ in. by 12 in. with the long dimension in the vertical position. Specimens are conditioned to 70°F and 50% relative humidity for a minimum of 24 h (also applicable to smoke and toxicity test specimens). Specimens are tested in the thickness used in the aircraft, except that the seat cushions are tested in ½-in. thickness. Seat fabrics that have a warp and fill direction must be tested in both directions to determine the critical flammability condition.

The simple test procedure consists of exposing the specimen to the Bunsen burner flame for a prescribed period of time. The time interval after removal of the burner to the cessation of specimen flaming is defined as flame time. Burn length is the distance from the original edge to the farthest evidence of damage to the specimen due to flame impingement, including areas of partial consumption, charring, or embrittlement, but not including areas sooted, stained, warped, or discolored. FAR 25.853 specifies a 60-s burner exposure time for panels, and a 12-s exposure for the remaining material categories listed in Table 1. The allowable burn lengths are 6 and 8 in., respectively. Flaming time cannot exceed 15 s for all material categories. The major assets of the vertical test are ease of operation, rapid testing, low operating and equipment costs, and dual application for quality control.

A bar graph of the burn lengths and flame times measured for the 75 materials is shown in Fig. 1. The data have been grouped into usage categories to facilitate analysis, with each category arranged either by increasing weight (e.g., panels, foams) or into subgroups with similar chemical compositions (e.g., fabrics, thermoplastics). The data are for one test only,

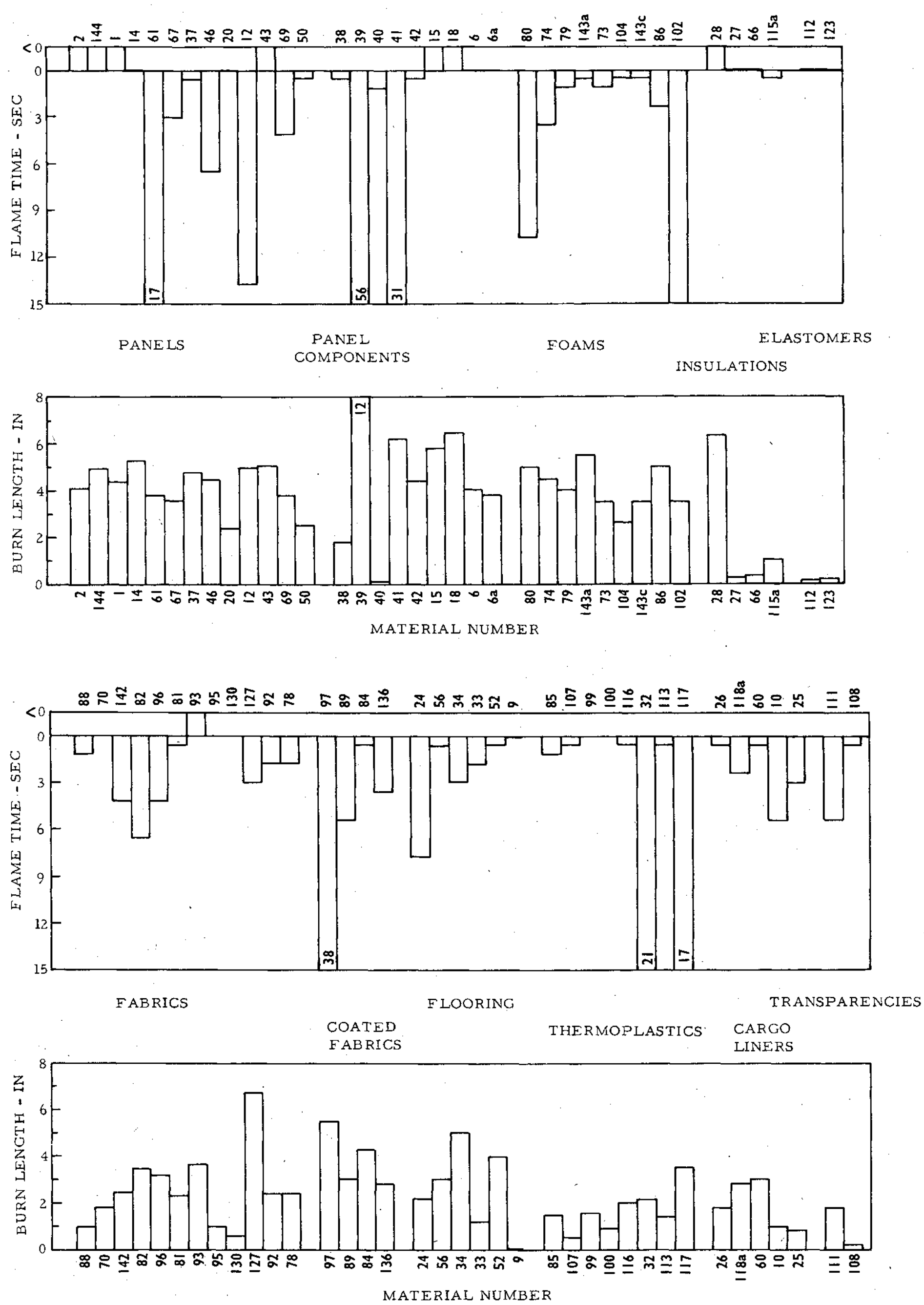

Fig. 1 Flammability characteristics of 75 cabin materials.

although a minimum of three specimens must be tested per FAR 25.853. Since a small, immobile flame that can vary in duration from one test to another is observed on some materials after removal of the burner flame, flame time generally is less reproducible than burn length. This probably accounts for the random distribution of flame times, compared to burn lengths, in some usage categories.

When the panel specimens were subjected to the burner flame, the decorative laminate rapidly burned and withdrew from the ignition source. For a number of panels, material flaming ceased before the burner was removed. In Fig. 1, panel burn length varies from 2 to 5 in. and is a measure of the burn length along the decorate laminate. Very little damage was experienced by the Nomex® honeycomb core, which was directly exposed along the bottom edge of the specimen to the burner flame. The honeycomb core appears to offer excellent resistance to flame penetration, as verified by the test results for bare honeycomb material (panel component No. 40). This finding has also been observed in larger scale flame penetration studies using a burner simulating the heat output of large fuel fire.[14] Another interesting observation is that panel components are more flammable when tested individually than as an assembled sandwich. Most notable in this respect is the epoxy-coated bonding laminate (panel component No. 39).

Urethane seat cushions used in air transport cabins are flame-retardant treated to produce a "self-extinguishing" characteristic. The first seven materials in the "Foams" category in Fig. 1 are urethanes arranged sequentially with increasing density. Flame times appear to decrease as a function of urethane density; however, burn lengths appear to be somewhat invariant. Examination of the test samples reveals that the latter is a misleading parameter since it is observed that the *consumption* by flame of material clearly diminishes with increasing density. The long flame time for material No. 102, which was a rigid polyethylene flotation cushion, is the result of a small, wick-like flame.

Very little burning was experienced by the three fiberglass insulations (Nos. 27, 66 and 115a), each containing a different resin binder, and the two elastomers. A burn length of 6.3 in.

was measured for material No. 28, which was an insulation batting cover composed of aluminized Tedlar® interwoven with a nylon tear stopper.

The test results for the fabrics exhibited several interesting trends. These fabrics included wool, wool/nylon blends, wool/PVC blends, cotton, rayon, cotton/rayon, modacrylic, and Nomex®. A lightweight FR cotton ticking (No. 93) experienced the fastest flame spread rate, an average velocity of about 0.7 in./s and the longest burn length was recorded by a modacrylic drapery (No. 127). The most fire-resistant fabrics were the rayon (No. 95) and cotton/rayon blend (No. 130). Both burned 1 in. or less and flaming ceased immediately after burner removal. Materials Nos. 82, 96, and 81 are wool/PVC fabrics displayed in the order of increasing PVC content. Burn length and flame time both decrease with increasing PVC content, demonstrating the benefit in flame retardancy that may be achieved by PVC blending. One of the PVC-coated fabrics (No. 97) produced an unusually long flaming time. Compared to the other coated fabrics which had cotton or nylon backings, No. 97 was less than half the weight and was constructed of a polyester backing.

Flooring materials were some of the heaviest materials tested, and thus had a natural tendency to resist ignition. An important observation that must be made when conducting the vertical test is the flame spread across the backside surface of the specimen, which is observable by the use of a mirror. Material No. 34 is a wool pile carpet with a urethane form padding. The burn length was significantly longer for this material than a similar wool pile carpet without padding (No. 33).

The thermoplastic materials, consisting of various blends or laminates of PVC, ABS or acrylic, and polycarbonate and polyphenylene oxide sheets, generally exhibited shorter burn lengths than other major usage categories. The unusually long flame times were for a polycarbonate injection molded material (No. 32) and a polyphenylene oxide thermoformed material (No. 117).

Cargo liners and transparencies, which are considered lesser usage categories, both exhibited relatively good resistance to small flame ignition.

The FAA is presently studying the characteristics of four other flammability test procedures; i.e., Ohio State rate of heat release apparatus,[15] ASTM E-162 radiant panel for surface flammability,[16] ASTM D-2863 limiting oxygen index (LOI) method,[17] and thermogravimetric analyses. An advanced test method that describes the behavior of a material subjected to intense heat and flame simulating a large postcrash cabin fire might be advantageous as a supplement to the existing vertical Bunsen burner standard which generally addresses the ignition resistance of a material to a small flame, which is more analogous to an in-flight incident. Both the Ohio State and E-162 test methods expose relatively large specimens to intense radiant heat and flame. The E-162 method appears more suitable for the measurement of surface flame spread rate, while the Ohio State method was designed primarily for heat release rate determinations. The Ohio State method, which is a fairly new test still undergoing development, has several design and data output features that are relevant to describing actual fire conditions, viz., 1) capability of vertical and horizontal specimen orientation, 2) selection of incident heat flux level, 3) determination of release *rate* values, and 4) display of rate changes with time.

Test results from a typical decorative honeycomb ceiling panel tested in the Ohio State apparatus at two incident heat flux levels are shown in Fig. 2. The discrete peaks indicate the involvement of the decorative laminate and fiberglass facing /honeycomb core combination. The burning duration and total heat release from the decorative laminate is similar at both the high and low incident heat levels. However, at the high heat level the fiberglass facing/honeycomb core starts burning at about 30 s and releases significant quantities of heat. Conversely, at the low heat level a gradually increasing but fairly minimal involvement of the fiberglass facing/honeycomb core is evident.

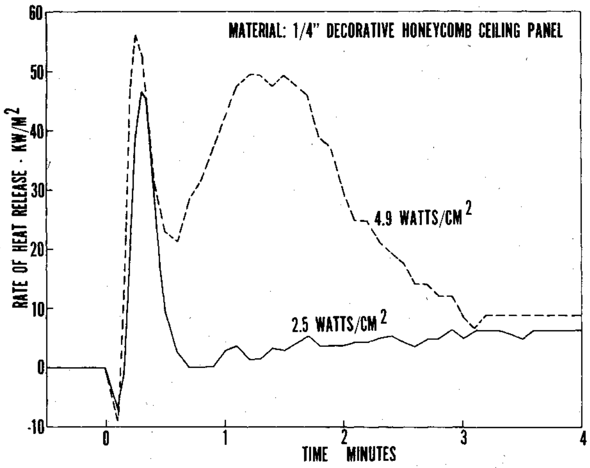

Fig. 2 Heat release rate history of ceiling panel at different heat exposure levels.

In the LOI test method, the minimum concentration of oxygen that will allow ignition of a small sample is determined. Compared to the vertical Bunsen burner test, the LOI offers better discrimination between advanced polymers under development for future cabin usage. Anaerobic char yield determined by thermogravimetric analysis has been proposed as a parameter for indicating the relative fire safety of polymers.[14] However, the utility of the previously discussed flammability tests will be judged in the end on the basis of comparisons made with future full-scale cabin fire tests.

Smoke

The NBS smoke chamber[18] was the test procedure considered most promising to control the smoke emission qualities of a cabin interior material.[4] The essential components of this test are an 18-ft^3 closed, chemically resistant enclosure; a radiant heater and propane/air burner for simulating flaming and nonflaming fire conditions; a vertical holder for mounting a 3-in^2 specimen; a 3-ft vertical photometric system for the continuous measurement of percentage light transmission through the generated smoke; and a millivolt recorder. The radiant heater is set at 2.5 W/cm^2 (2.2 Btu/ft^2-s). The final data format is usually a plot of specific optical density against time.

There are numerous features of the smoke chamber worth summarizing which attest to its wide popularity.

1) It can test materials in the thickness used in their application.

2) The use of two standard exposure conditions tends to differentiate between flaming and nonflaming (smoldering) smoke emissions.

3) The chamber is sealed; this is a favorable feature not found in other tests which allow undetermined amounts of smoke to escape.

4) A vertical photometric system averages out stratification effects.

5) The fraction of light transmission T is used to compute the optical density D which is defined as

$$D = \log(I/T)$$

Optical density is the single measurement most characteristic of the "concentration of smoke."

6) Test results are expressed in terms of specific optical density D_s, representing the optical density measured over unit path length L within a chamber of unit volume V produced by a burning material of unit surface area A. Thus,

$$D_s = D(V/AL)$$

and test results expressed as specific optical density may be related to: a) areas of materials which potentially could be involved in a fire; b) distances of light paths from observers to exitways; and c) the volume of enclosed space.

7) A continuous smoke concentration recording is more beneficial than the ultimate total weight of smoke obtained by filter deposition methods.

8) The smoke chamber has sufficient resolution to continuously measure the quantity of smoke released for most cabin materials. It is capable of recording optical densities up to 5.0, corresponding to light transmission values of 0.001%.

9) Only the front surface of the material or composite is exposed to ignition, thus representing a realistic cabin combustion condition.

The NBS smoke chamber is commercially available from the American Instrument Company. Since its commercial introduction in the early 1970's, over 220 smoke chambers have been purchased, including many by countries outside the United States. The NBS smoke chamber is by far the most widely used test method for the measurement of smoke emission characteristics of solid materials.

The aforementioned notice of proposed rule-making on smoke included, for most material usage categories, specific optical density acceptablity limits of 100 and 200 at 90 s and 4 min, respectively.[4] Within 4 min, most cabin materials achieve peak accumulated smoke production, and 90 s is the FAA demonstration requirement for passenger emergency evacuation. A lower allowable specific optical density of 100 at 4 min was proposed for the inherently less smoky cabin materials such as fabrics and insulations. Limiting D_s values were essentially set at levels to eliminate the smokier materials from cabin usage.

A bar graph of the specific optical density value at 90 s and 4 min for the 75 materials is shown in Fig. 3. The materials have been grouped in the same manner as previously for flammability. These smoke data reflect one test at the flaming exposure condition and were measured coincident with the gathering of bag samples for gas analysis.[12] The relative smoke emission characteristics of typical in-service cabin materials, however, is displayed.

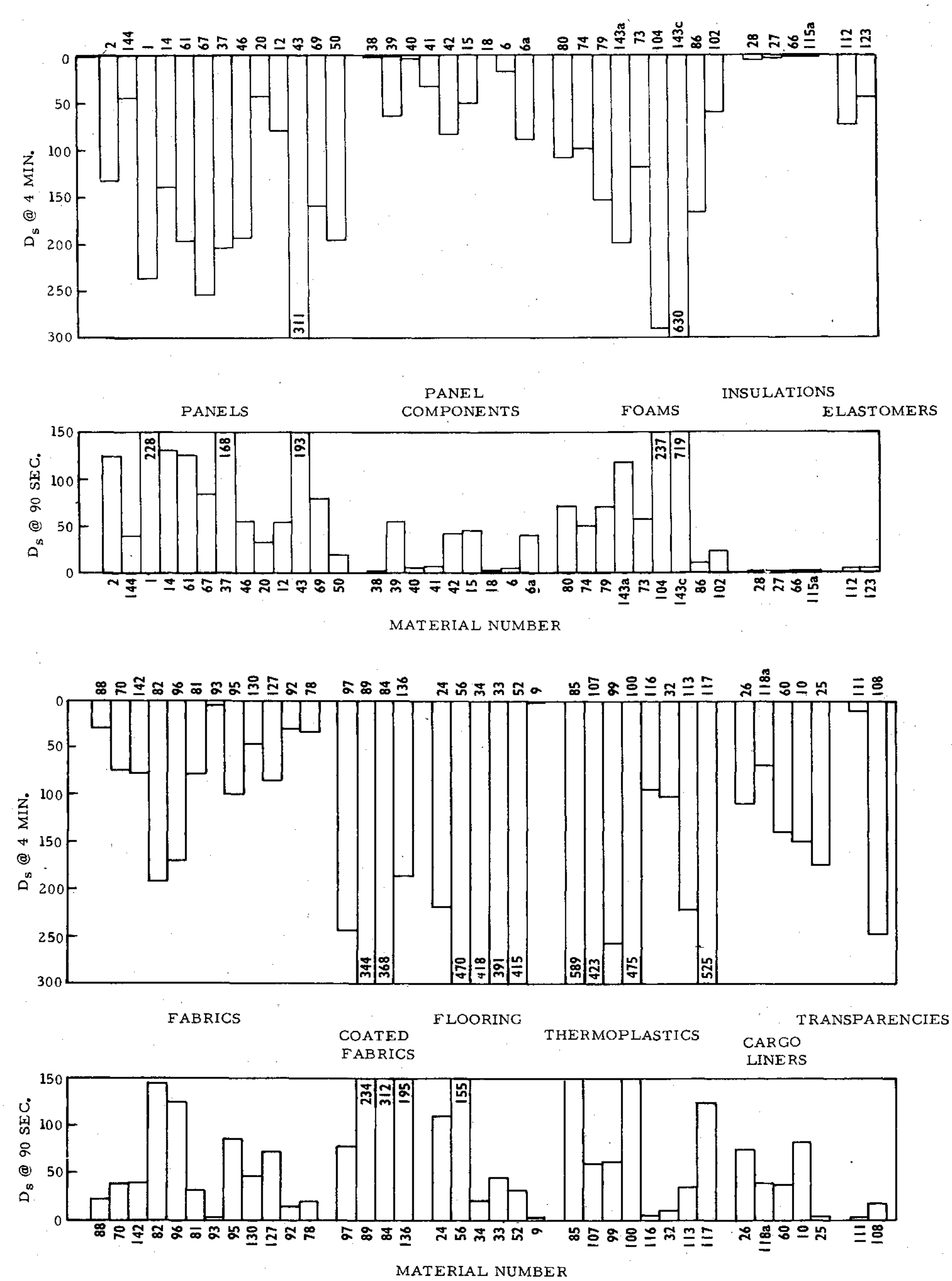

Fig. 3 Smoke emission characteristics of 75 cabin materials.

Because of their composite construction, panels have a tendency to produce higher smoke levels within the first 90 s of the test than most of the remaining usage categories. Six of the 13 panels exceeded a D_s value of 100 at 90 s. The major smoker in the panel construction is the epoxy resin used in the fiberglass facings and as an adhesive. Since the decorative laminate is rapidly eliminated upon heat and flame exposure, the epoxy sublayers are subsequently exposed early in the test. Early smoke generation is predominant in the perforated acoustic panels (e.g., material Nos. 37 and 43), where apparently the exposure of the epoxy and scrim materials is even faster. Epoxies were selected amongst other considerations because of their excellent peel strength, long shelf life, and relatively low cost. NASA and the airframe manufacturers are presently evaluating improved resin systems, such as modified epoxies and phenolics, bismaleimides, and polyimides.[10]

Under the thermal exposure conditions used in the smoke chamber, urethane foams are consumed quite rapidly. After about 1 min, the bulk of the specimen is eliminated from the vertical holder, and material combustion is limited to melted drippings collected in the sample trough. As shown in Fig. 3, except for material No. 73, the rate of smoke emission increased with foam density. Compared to the polyether types, the polyester urethanes (material Nos. 143a, 104, and 143c) produced higher smoke emission levels. In fact, material No. 143c produced a higher smoke emission rate and maximum specific optical density than any of the 75 materials.

Smoke from the fiberglass insulations was barely detectable and from the silicone elastomers was relatively low.

The seat upholstery fabrics used in air transport cabins are generally low smokers. Only the two wool/PVC blends exceeded a D_s value of 100 at 4 min. Material Nos. 82 and 96 are wool/PVC blends and No. 81 is a PVC fabric which was previously shown to exhibit improved flammability ratings with increasing PVC content. Interestingly, a reduction in smoke emissions was also found with increasing PVC content, demonstrating that improvements in flammability are not always achieved at the expense of greater smoke emissions.

PVC-coated fabrics are inherently smoky materials. Although used abundantly in the older narrow-body aircraft, they are significantly less used in wide bodies except for seat parts.

Except for an aluminum-faced structural flooring panel (material No. 9), smoke levels were generally high for flooring materials. The popular wool carpets (material Nos. 33, 34, and 52) which take a finite time to heat up and burn, exhibit low smoke levels at 90 s but D_s values are near or above 400 after 4 min.

A wide range of smoke emission values were found for the thermoplastic materials, probably more so than any other usage category. The PVC plastics blended or laminated with ABS or acyrlic, and the polyphenylene oxide produced copious amounts of smoke compared to the polycarbonates. The smokier thermoplastics are found in small quantities in the passenger cabin primarily as complex door parts and seat tray and surround panels. Large surface area thermoformed items such as passenger service assemblies and light defectors are constructed of the less smoky polycarbonates. NASA and the airframe manufacturers are evaluating advanced low-smoke thermoplastics, including polyethersulfone, polyphenylene sulfide, polysulfone, chlorinated PVC, modified polycarbonate, etc.[10]

The smoke emission characteristics of the cargo liners can be altered, for example, by adding asbestos (material No. 118a) to reduce the overall levels, or by coating with Tedlar® (material No. 25) to delay smoke evolution. Of the two transparencies tested, the acrylic was by far smokier than the polycarbonate.

A number of plastic manufacturing companies are developing and evaluating improved materials with potential application in aircraft cabin interiors. Table 3 contains flammability and smoke data on some of the newer materials

Table 3 Flammability and smoke characteristics of improved materials

Description	Thickness, in.	FAR 25.853 Burn length, in.	FAR 25.853 Flame time, s	Smoke (NPRM 75-3) D_s, 90 s	Smoke (NPRM 75-3) D_s, 4 min	ASTM E-162 flame spread index (Is)	ASTM D-2863 limiting O_2, %
Modified nylon	0.035	2.5	0	9.9	23	...	...
Nylon fabric/neoprene foam	0.080/0.130	12	330	49	117	193	...
	0.040/0.150	10	121	31	102	163	...
Wool/nylon							
95/5	0.035	2.5	3	75	163	...	...
85/15	0.035	2.5	6	48	96	...	...
Neoprene							
Company A	0.5	...	...	52	147	...	...
Company B	0.5	...	...	65	144	...	...
Polycarbonate							
Company C	0.065	3.3	2	4.2	58	23	...
Company D	0.090	...	...	4.4	78	88	32
Polysulfone							
Company E	0.060	...	...	0	7	19	32
Company C	0.070	...	...	3.7	13	25	...
Polyethersulfone							
Company F	0.137	1.5	0	0	4.4	...	...
Company E	0.125	4.3	0	0	1.5	...	...
Chlorinated PVC	0.065	2.5	0	13	89	3.4	...
Polyvinylidene fluoride							
laminate	0.004	2	0	12	13	...	48
film	0.004	5.6	0	...	...	...	28

which have been tested by NAFEC. An untreated nylon fabric backed with neoprene foam is flammable by conventional standards, although publicized large-scale seat tests demonstrate significant protection provided by the backing material. Smoke emissions from wool/nylon blends can be altered considerably by changing the relative quantities of the constituent fibers. Neoprene foams are now available with smoke emission levels significantly lower than were attainable several years ago. New thermoplastics such as polycarbonate, polysulfone, polyethersulfone, and chlorinated PVC produce relatively low smoke levels, especially the sulfonated materials. Polyvinylidene fluoride is a candidate replacement for the decorative laminated finishes presently used in panel construction.

Toxic Gas Analysis

A cooperative program at NAFEC and CAMI on combustion toxicity of cabin materials has resulted in the development of an animal response test apparatus than can be used in conjunction with gas analysis methods. Development of the former has been described previously.[19] The latter was developed at NAFEC for generating toxic combustion products for subsequent chemical analysis and is shown in Fig. 4. The basic components of this flow-through system consist of an annular furnace and temperature control module, a quartz combustion tube for accomodating the sample, a vacuum pump for drawing air through the system, a manifold for dividing and passing the combustion tube effluent into four fritted bubblers containing appropriate collection liquids, and a series of downstream rotameters and a single upstream rotameter for controlling air and effluent flow rates, respectively.

The test procedure consists of first establishing the desired total airflow rate and dividing this into equal components through each bubbler. At the beginning of the test, the sample is manually injected into the isothermal zone of the combustion tube which, in turn, is properly positioned in the preset, hot furnace. Over the test duration the bubbler rotameters, which are fitted with a needle valve, are continuously monitored and adjusted to maintain equal flow rates. The test is run for a period of 5 min. After the test, the bubbler contents are analyzed for hydrogen cyanide (HCN), hydrogen sulfide (H_2S), hydrogen chloride (HCl), hydrogen bromide (HBr), formaldehyde (HCHO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and hydrogen fluoride (HF). Differential pulse polarography is used for the analysis of HCN, H_2S, HCl, HBr, and HCHO, UV/VIS spectrophotometry for NO_2 and SO_2, and ion-selective electrodes for HF. Compared to combustion gas analysis methods used in the past, polarographic techniques have the advantage of simultaneously measuring multiple species and detecting the presence of interfering species. A detailed discussion of the analytical procedures is contained in Ref. 8. Carbon monoxide (CO) was measured by replacing the bubblers with a plastic bag for collecting the combustion products and analyzing the contents with a nondispersive infrared analyzer.

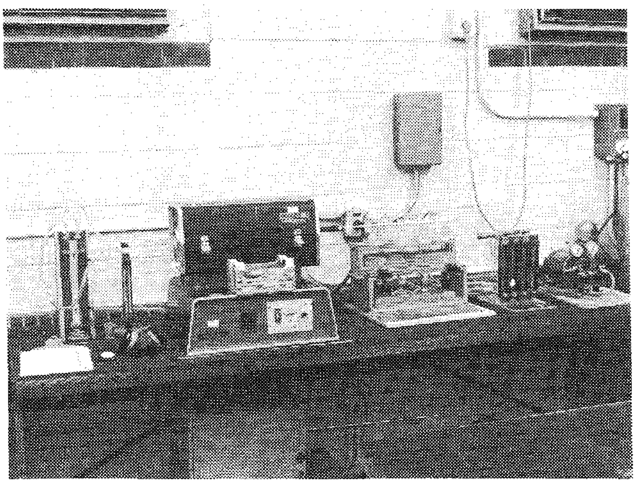

Fig. 4 Tube furnance system for generating toxic combustion gases.

A 250-mg sample is exposed to a temperature of 600°C for 5 min while maintaining an airflow rate of 2 liters/min. through the combustion tube. Compared to 400 and 800°C, a combustion temperature of 600°C is more discriminatory in terms of combustion toxicity. In addition, at 800°C many materials have been found to decompose with similar, explosive velocity, and it is difficult to protect the exposed animals from thermal stress and anaerobic conditions.[19] The combination 250-mg sample weight and 2-liter/min. airflow rate provide oxidative conditions in the combustion zone and prevent overflow and saturation of the gas-collecting bubbler contents.[8]

The FAA's combustion tube flow-through system was selected after a study comparing it with the static approach represented by the NBS smoke chamber.[20] Tests on identical cabin materials revealed better reproducibility and higher acid gas yields with the combustion tube system. The collection of the total combustion mixture in the combustion tube system vs discrete sampling and uncertain wall losses in the smoke chamber are major differences between the two approaches. A preliminary study using an improvised combustion tube system indicated for a small number of nitrogen-containing cabin materials a correlation between animal toxicity measured at CAMI and HCN yields measured at NAFEC.[20] In contrast, a recent study concluded that the smoke chamber and standard operation procedure was not suitable for toxicity screening tests using laboratory animals, primarily because of the difficulty in evoking a behavioral response under standard test conditions.[21]

A detailed description of the analysis of the 75 cabin materials for the nine toxic gases is contained in Ref. 8. A bar graph of the yields in milligrams per gram of CO and HCN is shown in Fig. 5. These gases were selected because they appear to be the major toxicants of the nine gases selected. The gas yields for each material are the average of three tests. Repeatability, as indicated by the average relative standard deviation for the 75 materials, was 9 and 23% for CO and HCN, respectively. Oxidized species such as NO_2, SO_2, and HCHO were less repeatable, apparently because they are influenced to a greater degree by random variations in the combustion process. The materials are arranged within each usage category in Fig. 5 in the order of decreasing toxicity.[9]

Because of their layered structure, panels are difficult to compare using the combustion tube approach. In an actual cabin fire, only the front face of the panel will probably be initially exposed to thermal stress, while in the combustion tube the total sample is immersed in radiant heat, including the core and backface materials. Involvement of the latter panel components is probably not representative of what would occur in an actual fire. However, a reliable more realistic test is not yet available.

All the panels produced CO, HCN, NO_2, and the majority released HCl, HBr, and HF, with the latter produced by the decorative laminate. As was the case for most materials tested in the combustion tube, the yield of NO_2 was more than an order of magnitude less than the yield of HCN. Conversely, for the panels the yield of CO was about 10-40 times the yield of HCN, and this ratio was usually greater than 20. Panel component No. 40, which is a Nomex® honeycomb core for panel No. 37, produced more than five times the yield of HCN than any of the other panel components.

All the urethane foams produced CO, HCN, and HCHO, but very little NO_2 or H_2S, and no HBr. Urethane foam No. 143c produced the highest apparent yield of SO_2 of any of the materials, and twice as much HCl as the PVC foam (No. 86). This particular urethane was also the smokiest material tested

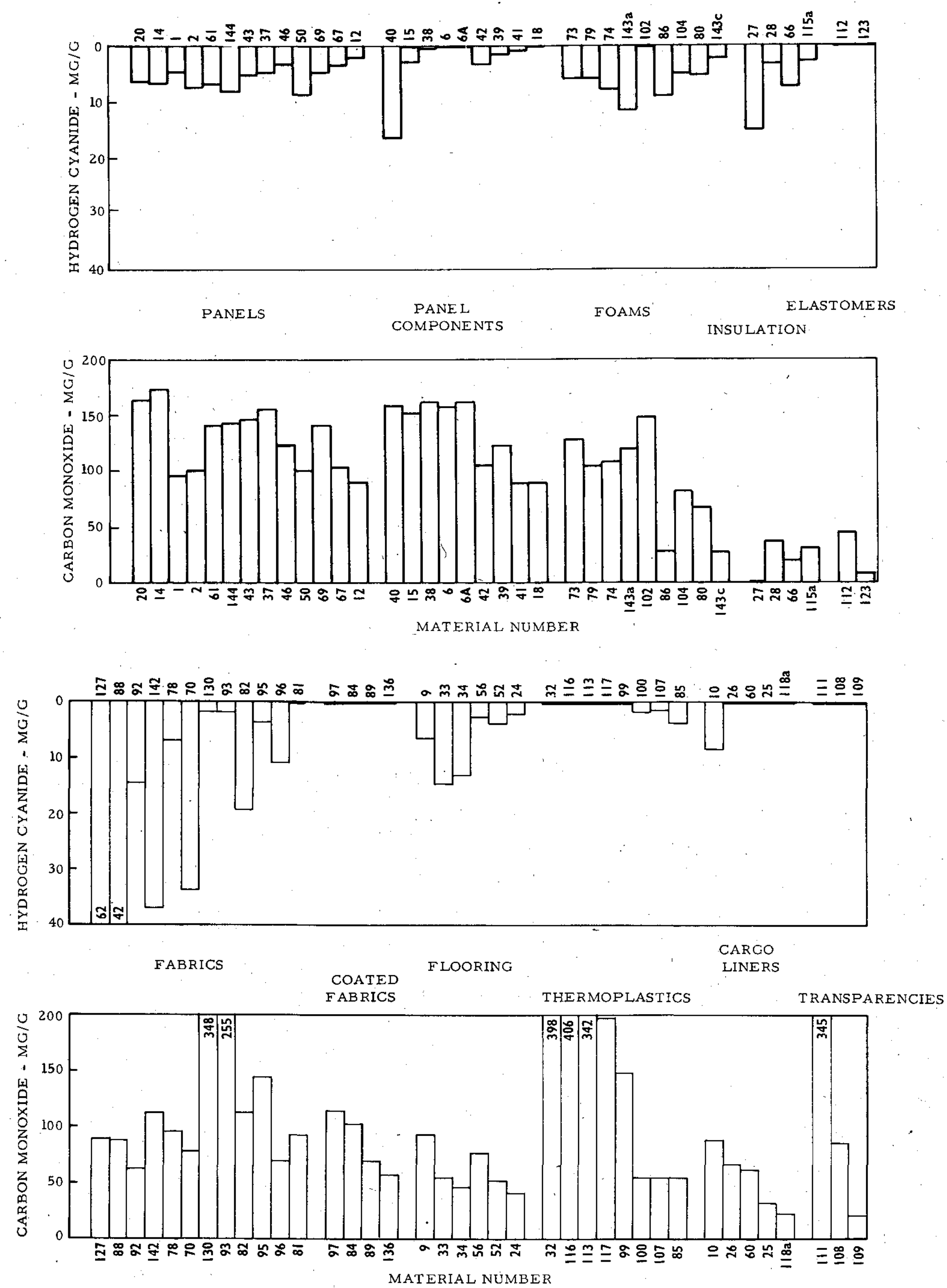

Fig. 5 Toxic gas emission characteristics of 75 cabin materials.

in the smoke chamber. Yet its yield of CO or of HCN was less than that produced by the other urethanes, which was apparently the reason for its relatively low toxicity. Although HCN was not detected from the rigid polyethylene flotation cushion (No. 102), this material produced a higher CO level than the remaining foams.

Fiberglass insulations and silicone elastomers produced low yields of CO compared to panels and most foams. The behavior of the melamine-fiberglass insulation (No. 27) was unique in that it was the only material which did not produce a detectable amount of CO. However, an HCN yield of 15 mg/g is considered to be relatively high, especially since the melamine binder constitutes only about 20% of the weight of insulation. Although HCN was not produced by the silicone elastomers, the aldehyde yields were exceptionally high compared to the materials in other usage categories.

For the fabrics, the highest CO yield was obtained from material No. 130, a cotton rayon blend, while the second and third highest CO yields were produced by cotton (No. 93) and rayon (No. 95), respectively. The modacrylic drape (No. 127) produced the highest yield of HCN of any of the materials tested. The wool (No. 88) and wool/nylon blends (Nos. 142, 70) also produced high yields of HCN, second to the modacrylic in overall ranking. The wools were the only materials that produced H_2S in significant amounts. A proportionality existed between the amount of wool in the wool (No. 88) and wool/PVC blended (Nos. 82, 96) materials and the yield of HCN, although this type of relationship did not exist for CO yields.

The coated fabrics produced only CO and HCl in significant quantities, and the yields of these gases were inversely related. A direct relationship was apparent between toxicity and yield of CO.

The flooring materials that produced the highest yields of CO were the structural floors constructed of Nomex® honeycomb cores. The yields of HCN were greatest for the wool carpets (Nos. 33, 34), although significantly lower than the wool upholstery fabrics.

The thermoplastics can be divided into two groups based on chemical composition, the polycarbonates and the ABS/PVC blends and laminates. Polyphenylene oxide (No. 117) and polymethyl methacrylate (No. 99) are approximately intermediate in behavior to the two groups. The polycarbonate materials (Nos. 32, 116 and 113) produced the highest yields of CO of any of the materials, significant yields of HBr but no HCN. The ABS/PVC materials (Nos. 100, 107, and 85) produced much lower CO yields, high HCl yields, and relatively low HCN yields.

The CO yields of the cargo liners varied from moderate to low, with only the polyester (No. 10) producing HCN. The toxicity was directly related to the yield of CO.

The only gases produced by the transparencies were CO, HBr, and HCHO. Polycarbonate (No. 111) again produced the highest CO yield. Although the polymethyl methacrylate produced much lower CO yields, the fire-retardant material (No. 108) produced more than four times as much CO as the untreated material (No. 109). However, the untreated material produced an exceptionally high yield of HCHO (63 mg/g).

Presently, an analysis of the CAMI toxicity data (animal incapacitation and death times) and the NAFEC gas analysis data for the same materials is in progress with the aim of correlating these data.

Full-Scale Tests

The preceding describes flammability, smoke, and toxic gas emissions measurements taken on a series of cabin materials with small-scale laboratory fire tests. However, the relationship between the laboratory fire test data, such as this, and the behavior of a material in a real fire is a controversial and provocative issue. Full-scale cabin fire tests to address this issue were recently initiated at NAFEC using a surplus C-133 aircraft modified into a wide-body configuration.[22] Initially, these extensive full-scale tests will provide valuable information on the characteristics of postcrash cabin fires and the role of burning interior materials in the overall hazard. As data becomes available pertaining to the behavior of materials in full-scale tests, attempts will be made to correlate these data with laboratory results. The ultimate objective is to develop a methodology for selecting cabin materials, based on laboratory tests, that has a proven relationship with the hazard created by a cabin fire.

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