Relative toxicity of materials in fire situations

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A continuing need of those concerned with selection, design, and development of materials is the availability of up-to-date information on performance characteristics relevant to a particular application. For all applications involving people, fire safety is an important consideration, and toxicity of gases from accidental or intentional pyrolysis or combustion is a subject of concern.

An earlier compilation of relative toxicity data on materials under pyrolysis conditions listed test results on 162 materials, using a specific set of test conditions (1)[1]. Subsequent work has increased the number of materials evaluated to almost 300. Compilation and analysis of the data permit comparison of materials by generic type and chemical composition. Additional data on fabrics of mixed-fiber composition have provided the opportunity to explore synergistic effects.

The screening test method used at the University of San Francisco for evaluating the relative toxicity of pyrolysis gases involves the exposure of four free-moving Swiss albino male mice in a 4.2-liter hemispherical chamber to the pyrolysis gases generated by pyrolyzing a 1-g. sample under a specific set of test conditions. Procedure B, which has been used to evaluate the largest number of materials, employs a rising temperature program at 40° C./min. from 200 to 800° C., without forced-air flow. Earlier publications (1-5) contain the details of the apparatus used and the procedure.

Materials that were tested in the experiments are compared on the basis of the time to observation of various animal responses. Time to death is defined as the time to the observed cessation of movement and respiration in all four test animals. Time to first sign of incapacitation is defined as the elapsed time to the first observation of loss of equilibrium (staggering), prostration, collapse, or convulsions in any of the test animals; it is more subjective and more conservative, but this methodology has been found to correlate fairly well with more-sophisticated measures of laboratory animal incapacitation, such as shock-avoidance behavior (6).

Toxicity data

Relative toxicity data on polymers by generic type are presented in Table I, and they include findings for a total of 27 different materials, polymeric and otherwise. Data on wood and cellulosic board are included in the data compilation for comparison purposes. The values given are mean ± standard deviation between samples; with individual values in these tables being based on as many as 81 tests and 324 animals, any other standard deviation becomes difficult to manage. The data are arranged in order of increasing time to death, or decreasing toxicity under the specific test conditions. It should be noted here that the authors consider time to death to be a more precise measurement, because it is less dependent on individual alertness and subjective judgement, and is based on all four animals in a test rather than on the first animal in a test to exhibit signs of incapacitation.

Relative toxicity data on fibers and fabrics by generic type are presented in Table II. Testing was done on a total of more than 150 samples of materials, including natural, manmade, and varying blends of each. The data are arranged in order of increasing time to death, as groups of fabric blends in order of progressive composition changes. Although some generic materials may as a result appear more than once in this table, this grouping permits observation of any synergistic effects between two materials. Materials that are known to contain fire retardant are not included in these averages, with the sole exception being the important one of fire-retardant-treated 100% cotton fibers and fabrics.

The tables presented are listings rather than rankings, because the standard deviation that is assignable to each value requires the observed difference between any two values to be a certain magnitude before that difference can be considered to be statistically significant. Test results on individual samples of materials are contained in a separate earlier publication (7).

The wide range of performance that has been observed with different samples of some generic materials emphasizes the inadvisability of considering specific levels of performance as being typical or representative of those generic materials. The variation can be particularly pronounced in the case of generic materials that provide considerable flexibility in formulation or that may contain varying levels of fire retardants in order to meet the requirements of different markets; this is particularly true for polyurethane flexible and rigid foams and ABS. Comparisons between generic groups with the purposes of identifying differences due to chemical composition should therefore be made with the often-considerable overlap between generic groups in mind.

Comparison of materials

Among the synthetic polymers that were the subjects of experimentation, the sulfur-containing materials seemed to exhibit the shortest times to death of laboratory animals. Among the findings of interest are the following observations: Some chlorine-containing polymers tended to exhibit the longest times to death. Some halogen-containing polymers gave the shortest times to incapacitation. Polystyrene and polyisocyanurate rigid foam, on the other hand, appeared to exhibit the longest times to observed incapacitation of all materials tested.

When the synthetic polymers are compared with wood on a generic basis, only certain sulfur-containing polymers would appear to be more toxic than wood on the basis of time to death, and only certain halogen-containing polymers would appear to be more toxic than wood on

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1: Numbers in parentheses designate references at end of article.

the basis of time to incapacitation.

Among the fibers and fabrics, wool, silk, and polyester exhibited the shortest times to incapacitation and times to death. Polypropylene and nylon exhibited the longest times to death, and nylon and aromatic polyamide exhibited the longest times to incapacitation. Fire-retardant treatments seemed to render 100% cotton fabrics significantly less toxic on the average.

Strict comparisons between test results that have been observed in generic types of materials should be made with particular caution in the case of fabrics, because it must be kept in mind that the presence of backcoatings may be a confounding factor. It can be argued that if a particular material requires backcoating to render it commercially acceptable, that backcoating becomes an inherent part of the commercial material.

Evaluation of the performance of blends of two generic types of fabrics showed that such performance did not differ significantly from that which might have been expected from simple linear interpolation between the individual generic types based on weight fraction of each component. There is, therefore, no evidence of synergism under these test conditions.

The apparent tendency of fire-retardant additives to reduce the relative toxicity of 100% cotton fabrics is similar to the significant reduction in relative toxicity that can be observed when fire retardants were incorporated in polyurethane flexible foams in order to meet the requirements of the State of California and the Federal Aviation Administration (8). The use of fire retardants, therefore, seems to have a beneficial effect, if any effect can be considered significant, under these particular test conditions. The unusual toxic effects that have been publicized appear to be encountered only under very specific test conditions (9), and this raises a degree of doubt as to whether such unusual toxic effects would be encountered in many, or *any*, fire situations.

Most of the comparisons that have been made between the various tested materials under these specific test conditions (Procedure B) are expected to remain unchanged despite changes that may occur in test conditions, although the response times may change in some degree. Some reversals may be observed, but in general the most-toxic materials and the least-toxic materials tend to be highly consistent (4,5,10).

If the natural cellulosic materials (wood and cotton) are considered acceptable in a residential environment, there appear to be relatively few materials that could be considered significantly more toxic than these baseline materials. Wool and silk seem to be the most toxic of all tested materials under these test conditions; restricting their use may be impractical, and restricting the use of other, less-toxic materials would therefore be similarly impractical. These toxicity studies may have defined the toxicity problem as nonexistent because the general public, by its acceptance of certain materials, therefore also accepts the existing levels of hazard (a risk/benefit evaluation) and is not likely to change.

While the preceding observations may be valid for residential environments, more stringent levels of acceptance may be appropriate for limited-egress situations (such as aircraft and surface transportation vehicles), limited-mo-

Table I. Relative toxicity of polymers by generic type[a]

Polymer	No. of samples	Time, min, To death	Time, min, To incapacitation	No. of tests
Polyether sulfone	3	12.30 ± 2.08	11.25 ± 1.93	7
Polyphenylene sulfide	4	13.21 ± 3.80	11.53 ± 2.68	9
Polyaryl sulfone	2	13.48 ± 3.17	10.31 ± 0.42	5
Wood	12	14.03 ± 1.48	9.92 ± 1.09	33
Polyurethane flexible foam	29	14.15 ± 2.84	10.45 ± 1.36	81
Polyamide (nylon)	3	14.36 ± 1.71	12.35 ± 1.44	7
Polyphenyl sulfone	1	15.46	13.32	2
Polyurethane rigid foam	7	15.49 ± 4.06	11.77 ± 2.95	17
Polymethyl methacrylate (PMMA)	1	15.58	12.61	2
Polyvinylidene fluoride	1	15.86	6.50	2
Cellulosic board	8	16.57 ± 3.54	10.10 ± 1.35	28
Polyvinyl chloride (PVC)	2	16.60 ± 0.33	9.32 ± 4.77	4
Acrylonitrile/butadiene/styrene (ABS)	3	17.13 ± 2.45	11.82 ± 1.52	9
Polyethylene, including foam	5	17.31 ± 3.73	10.67 ± 3.65	11
Acrylonitrile rubber (NBR)	3	19.13 ± 2.89	12.46 ± 2.56	9
Polyphenylene oxide, modified	1	19.96	8.65	2
Bisphenol A polycarbonate	3	20.40 ± 3.77	14.71 ± 1.68	24
Polyvinyl fluoride	1	20.50	16.94	2
Ethylene/propylene/diene (EPDM)	2	20.69 ± 0.04	12.97 ± 3.04	5
Chlorosulfonated polyethylene	2	20.88 ± 2.07	12.64 ± 6.25	7
Polyisocyanurate rigid foam	2	21.68 ± 1.38	18.90 ± 1.55	4
Polyisoprene (natural rubber)	1	22.13	15.35	3
Chlorinated polyvinyl chloride	2	22.25 ± 0.69	7.64 ± 1.92	4
Polychloroprene, including foam	6	22.33 ± 3.80	13.61 ± 1.69	21
Polystyrene	2	23.10 ± 4.33	17.11 ± 2.73	4
Styrene-butadiene rubber (SBR)	1	24.11	15.73	3
Chlorinated polyethylene	2	26.08 ± 1.80	9.31 ± 2.55	4

a: USF test method, procedure B. Values given are mean ± standard deviation between samples.

bility situations (such as hospitals and nursing homes), and environments where wood and cotton are not acceptable. The baseline materials for aircraft interiors, for example, may very well be bisphenol-A polycarbonate and polyvinyl fluoride.

These toxicity data were obtained using 1 g. of material for each test, therefore direct comparisons between materials are valid only when equal weights of the materials being compared are exposed in a particular application. The data are most useful when applied on an equal-weight substitution basis, and relative weights should be considered if materials are present in different amounts.

As noted at the outset of this article, an earlier work (1) presented toxicity data under pyrolysis conditions for 162 materials. These varied widely in structure and composition, including a selection of natural woods, leather, wool, cotton, and sisal—in addition to foamed and non-foamed plastics materials.

It was pointed out in that work that the extent to which gases other than carbon monoxide increase the toxic hazard in fires depends on the chemical composition of the material and on the many variables in an actual fire. Since no two fires are exactly alike, and the so-called "typical" fire may never be defined to the satisfaction of a majority of those concerned, there is an established and continuing need for apparatus and methods of procedure to provide reliable measures of the relative toxicity of materials under other-than-full-scale fire situations. The need exists for many reasons, not least of them that full-scale testing of each material simply is not economically feasible. It is our hope that the test data presented in that earlier work, and in the discussion on these pages, has advanced the available amount of information applicable to the understanding, and control, of fire toxicity.

The present work was performed at the Fire Safety Center of the University of San Francisco with the support of the National Aeronautics and Space Administration under NASA Grant NSG-2039, D.A. Kourtides, technical monitor. The authors also are indebted to Dr. Arthur Furst, Dr. Henry A. Leon, and Dr. John A. Parker for their assistance and support.

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Table II. Relative toxicity of fibers and fabrics by generic type[a]

Fiber/fabric	No. of samples	Time, min. To death	Time, min. To incapacitation	No. of tests
Wool, 100%	4	7.65 ± 1.29	5.31 ± 0.48	10
Wool, 85-90%/nylon	4	8.87 ± 1.01	5.68 ± 1.06	10
Nylon, 100%	9	16.78 ± 3.49	12.01 ± 1.74	18
Silk, 100%	2	9.18 ± 0.35	6.70 ± 1.22	4
Silk, 70%/rayon 30%	2	12.33 ± 0.58	8.94 ± 0.01	4
Rayon, 100%	10	15.40 ± 2.41	9.22 ± 0.85	20
Polyester, 100%	3	10.70 ± 2.25	8.15 ± 0.74	6
Polyester, 65-87%/cotton	3	10.45 ± 0.28	8.28 ± 0.78	7
Cotton, 59-70%/polyester	2	15.66 ± 1.17	9.14 ± 0.13	4
Cotton, 100%	10	13.08 ± 2.14	8.39 ± 1.40	37
Cotton, 100%	10	13.08 ± 2.14	8.39 ± 1.40	37
Cotton, 100% FR	6	14.19 ± 3.64	8.85 ± 0.65	13
Cotton, 100%	10	13.08 ± 2.14	8.39 ± 1.40	37
Cotton, 82-86%/rayon	2	12.00 ± 0.16	9.04 ± 0.81	4
Cotton, 52-75%/rayon	8	14.53 ± 2.06	9.14 ± 1.30	16
Rayon, 54-75%/cotton	18	12.70 ± 2.49	8.55 ± 1.56	37
Rayon, 100%	10	15.40 ± 2.41	9.22 ± 0.85	20
Rayon, 100%	10	15.40 ± 2.41	9.22 ± 0.85	20
Rayon, 56-73%/polypropylene	2	14.08 ± 2.16	10.68 ± 1.66	4
Polypropylene, 100%	4	16.64 ± 2.76	9.31 ± 1.55	8
Rayon, 100%	10	15.40 ± 2.41	9.22 ± 0.85	20
Rayon, 52-72%/nylon	3	15.60 ± 3.86	10.99 ± 3.07	6
Nylon, 57-62%/rayon	2	15.62 ± 0.15	12.18 ± 0.26	4
Nylon, 100%	9	16.78 ± 3.49	12.01 ± 1.74	18
Aromatic polyamide, 100%	3	14.71 ± 1.13	12.58 ± 1.12	7

a: USF test method, procedure B. Values given are mean ± standard deviation between samples.