TOXICITY OF SMOKE DURING CHAIR SMOLDERING TESTS AND SMALL SCALE TESTS USING THE SAME MATERIALS

by

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Toxicity of Smoke During Chair Smoldering Tests and Small Scale Tests Using the Same Materials

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ABSTRACT

Toxicity of Smoke During Chair Smoldering Tests and Small Scale Tests Using the Same Materials. Alarie, Y., Stock, M.F., Matijak-Schaper, M. and Birky, M.M. (1983). *Fundam. Appl. Toxicol.* 3:619-626. Toxicological evaluation of smoke produced during smoldering chair tests was undertaken by exposing mice to smoke emitted prior to, as well as following, flaming ignition of the chairs. By exposing several groups of mice, using undiluted smoke from the room containing the chairs, as well as various dilutions of the smoke, different levels of acute lethality were obtained. From these experiments, chairs constructed with polyurethane foam were found to create higher toxic atmospheres than chairs constructed with polyester or cotton fiber cushions. The same materials (polyurethane foam, polyester and cotton fibers) were also thermally decomposed in a small scale system and mice were exposed to the smoke to evaluate acute toxicity. Again polyurethane foam was found to produce smoke more toxic than smoke produced by polyester and cotton fibers. Sensory irritation monitored in mice during the smoldering tests indicated that an intense level of irritation was present long before large amounts of smoke were generated and long before flaming ignition occurred. The phenomenon of eye, nose and throat irritation would therefore be the first effect impeding escape attempts of individuals in a fire situation. Sensory irritation was followed by asphyxiation as evolution of carbon monoxide or hydrogen cyanide, or both, occurred. The same pattern of responses was observed with smoke generated with the small scale decomposition system.

INTRODUCTION

Toxicity of smoke in fire situations has become a major issue. Several small scale tests results have been reported, offering the possibility of comparing the toxicity of smoke from different materials (Alarie and Anderson, 1981, Lawrence *et al.*, 1978; Levin *et al.*, 1982). However, there is only one report on an attempt to correlate toxicity found in a small scale test with the results obtained in a medium scale test (Alarie *et al.*, 1981). In this instance, toxicity rankings for several materials were well correlated in the two test systems. However, this is insufficient evidence to conclude that a correlation will always exist between small scale and medium scale tests because the range of materials tested was too limited. In order to explore a wider variety of materials, we have undertaken this limited study on chairs ignited from a burning cigarette, as a common fire scenario. The results with the same small scale decomposition protocol previously used (Alarie and Anderson, 1979) are then compared with the results from the medium scale fire test.

MATERIALS AND METHODS

Medium scale fire: smoldering chairs

Fire scenaro

The details of this type of test have been presented (Braun *et al.*, 1982). Briefly, an upholstered chair was placed in a closed room with a burning cigarette placed on the cushion. The chairs were placed on a load cell to monitor weight loss during burning. Concentrations of CO_2, CO, HCN and total hydrocarbons were monitored as well as oxygen depletion in the room during the entire test (Braun *et al.*, 1982). The room was equipped to monitor obscuration created by the evolving smoke. The room dimensions were 3 × 3 × 2.4 m with walls and ceilings made of gypsum board. One port, 1.7 m above the floor, was used to draw air at a rate of 20 liters/minute from this room to the exposure chambers holding the animals for toxicological evaluation of the combustion products. This air was returned to the room after passing through the exposure chambers held outside of the room. A lighted non-filter cigarette was placed into the crevice formed by the seat cushion and right sidearm so that the non-burning end of the cigarette was about 75 mm from the corner formed by the side and the back. The cigarette was covered by a piece of cotton sheeting and left burning without further modification. All chairs were constructed with a wood frame and had cellulosic cover fabrics. Chairs 1 and 2 contained primarily polyurethane foam filling material while chairs 5 and 6 had cushions made out of polyester batting and cotton batting filling material respectively.

Animal exposures

The animal exposures were designed to evaluate the toxicity of the products of smoldering combustion as well as the products from subsequent flaming combustion. Consequently, one group of animals was exposed to the atmosphere from the room into which the chair was placed from the time at which the cigarette was placed on the chair. Other groups were exposed as soon as possible after flaming ignition.

System to expose animals

As shown in Figure 1, smoke from the test room was distributed to several exposure chambers. Chamber No. 1 was always connected from the time of placing the cigarette on the

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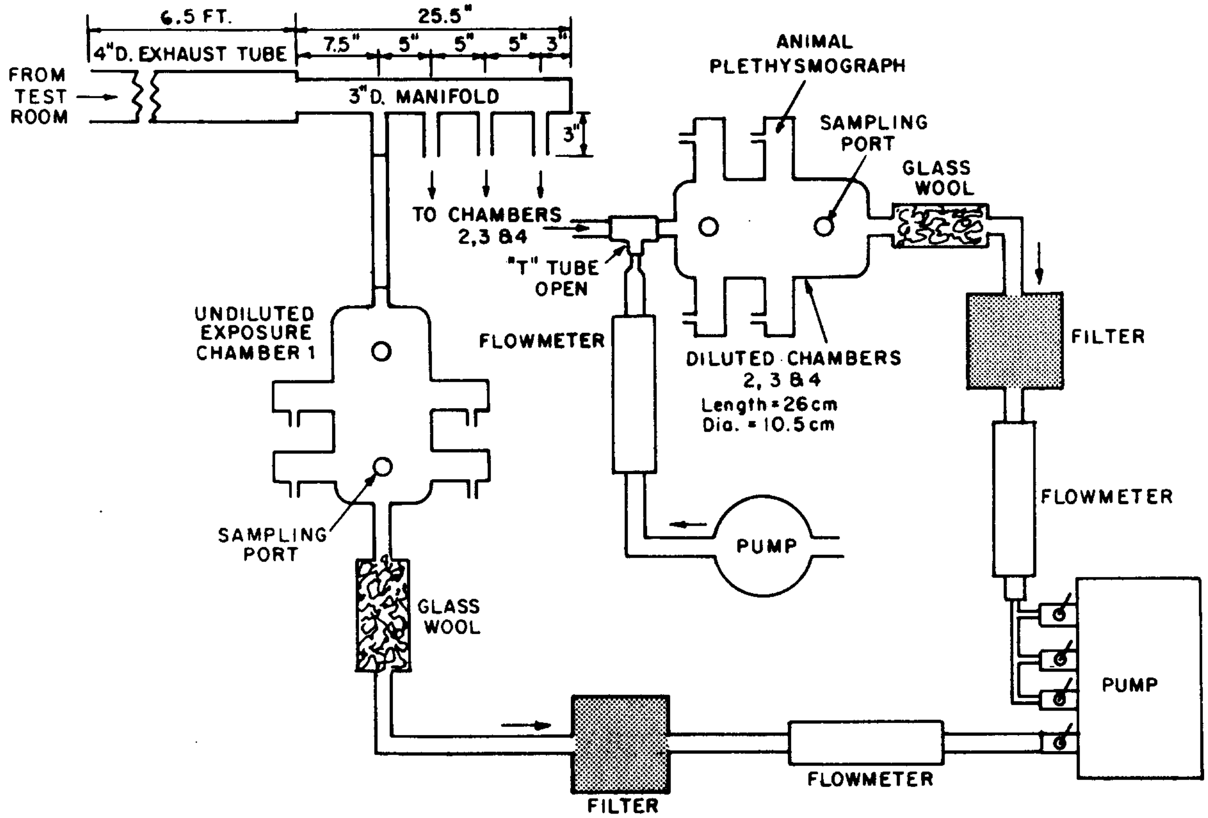

FIG. 1. Diagram of exposure system used to expose simultaneously four groups of mice to different smoke concentrations from the test room. Smoke was drawn from the test room at the rate of 20 liters/minute and undiluted in chamber 1. The exhaust tube from inside the test room to the manifold was 6.5 feet long. For chambers 2, 3, and 4, the same flow rate is maintained in each exposure chamber but fresh air is pumped at the entrance of each chamber to reduce the volume drawn from the test room. Mice are held in the body plethysmograph with only the head of each animal protruding into the exposure chamber. A pressure transducer attached to each body plethysmograph permits continuous monitoring of respiratory rate and pattern to evaluate sensory irritation, asphyxiation and respiratory paralysis (Alarie and Anderson, 1979).

chair and received undiluted smoke from the test room. The other chambers received smoke from the test room once flaming ignition occurred with one chamber receiving undiluted smoke while the smoke was diluted with various amounts of fresh air for the other chambers. In the case of chair 5, flaming ignition did not occur but these exposure chambers were also used at various times during smoldering as indicated below. For each exposure, four male Swiss-Webster mice weighing between 22 and 30 grams were used. Animals were placed in body plethysmographs and only the head of the animals protruded into the exposure chamber. For the first group of animals exposed to undiluted smoke from the start of each experiment pressure transducers were attached to each body plethysmograph to obtain tidal volume and respiratory rate. The average respiratory rate of the four animals was displayed continuously on an oscillograph as previously described (Alarie and Anderson, 1979). Once flaming ignition occurred, the transducers were attached to the other exposed groups. The temperature in the animal exposure chamber did not increase by more than 5 °C above room temperature during these tests.

Small scale fire test

The filling materials used for the cushions of chairs 1 and 2, commercial polyurethane foam, and for chairs 5 and 6 polyester batting and cotton batting fibers, respectively, were tested by the method previously described (Alarie and Anderson, 1979). Briefly, the samples were decomposed by placing them in a furnace at room temperature and heating them by increasing the temperature at 20 °C/minute until decomposition was complete. Airflow through the furnace was maintained at 11 liters/minute and the smoke was diluted by 9 liters/minute of air prior to entering the exposure chamber. The exposure chamber was the same as described in Figure 1. Respiratory rate and tidal volume were monitored as described for the smoldering chair test. Exposure of the animals was started when 0.2% weight loss was recorded from the weight sensor attached to the platform inside the furnace on which the samples were placed. Exposure continued for 30 minutes unless all animals died within this period. By changing the sample size loaded in the furnace a series of experiments was conducted to yield between 0 and 100% lethality within the 30 minutes of exposure and a 10-minute recovery period following exposure. Thus the LC_{50}, the sample size necessary to produce sufficient smoke to kill 50% of the animals, was calculated by the method of Thompson and Weil (1952). Also the time for 50% lethality (LT_{50}) at the LC_{50} sample size was obtained. Monitoring of respiratory pattern and respiratory rate also permitted recognition of sensory irritating and asphyxiating effects of the smoke as previously described (Alarie and Anderson, 1979).

RESULTS

Medium scale tests

Chairs 1 and 2

Both chairs were of the same construction and gave similar results as shown in Figures 2 and 3. Flaming ignition occurred at 69 minutes for chair 1 and at 59 minutes for chair 2. Unfortunately the monitors for carbon monoxide, oxygen and carbon dioxide failed immediately following flaming ignition for chair 1. However, the peak HCN concentration was similar for both, reaching 95 ppm for chair 1 and 100 ppm for chair 2. The amount of material burned was slightly less for chair 1 than for chair 2 as indicated by the weight loss records presented in Figures 1 and 2. This amount was fairly low, representing about 10% of the total weight of each chair. This weight loss occurred with flaming ignition which lasted only a few minutes after which no appreciable weight loss was detected. For chair 1, exposure of group 1, up to 40 minutes during the smoldering phase of the test, resulted in gradual depression of respiratory rate as shown in Figure 2 with a pattern characteristic of sensory irritation (Alarie and Anderson, 1979). This occurred even prior to any change in optical density as shown in Figure 1. Exposure of group 2 was initiated at minute 45 and terminated at minute 55 during which time optical density increased from 0 to 2. At minute 55 the average respiratory rate for this group was 25% of the preexposure rate, again with a characteristic pattern of sensory irritation. Group 3, exposed from minute 60 to minute 69 showed the same response as

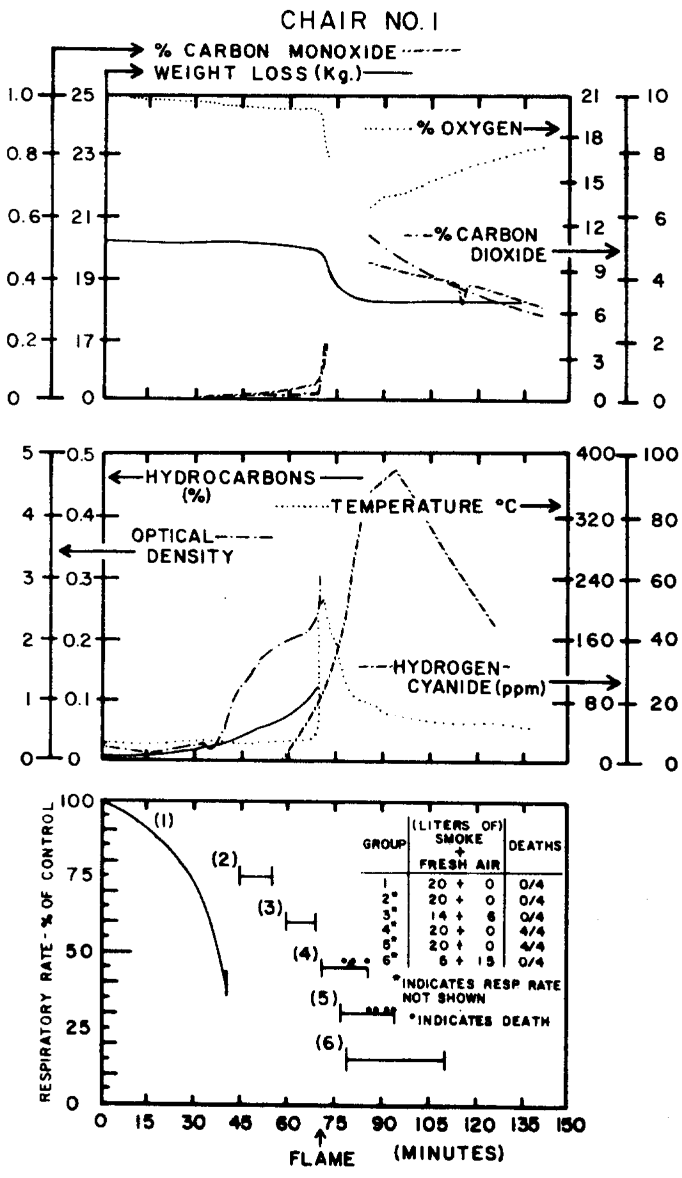

FIG. 2. Measurements were made with chair 1, polyurethane cushions, in the test room. A burning cigarette was placed on the cushion at time zero. Continuous monitoring of respiratory rate results is shown only for group 1 with the results for the other groups given in the text. Time of exposure for groups 2 to 6 is given by the horizontal bars next to each group number. The arrow indicates when flaming ignition occurred. Results for concentrations of oxygen, carbon dioxide and carbon monoxdide are not given for a period of time because of failure of these instruments when flaming ignition occurred.

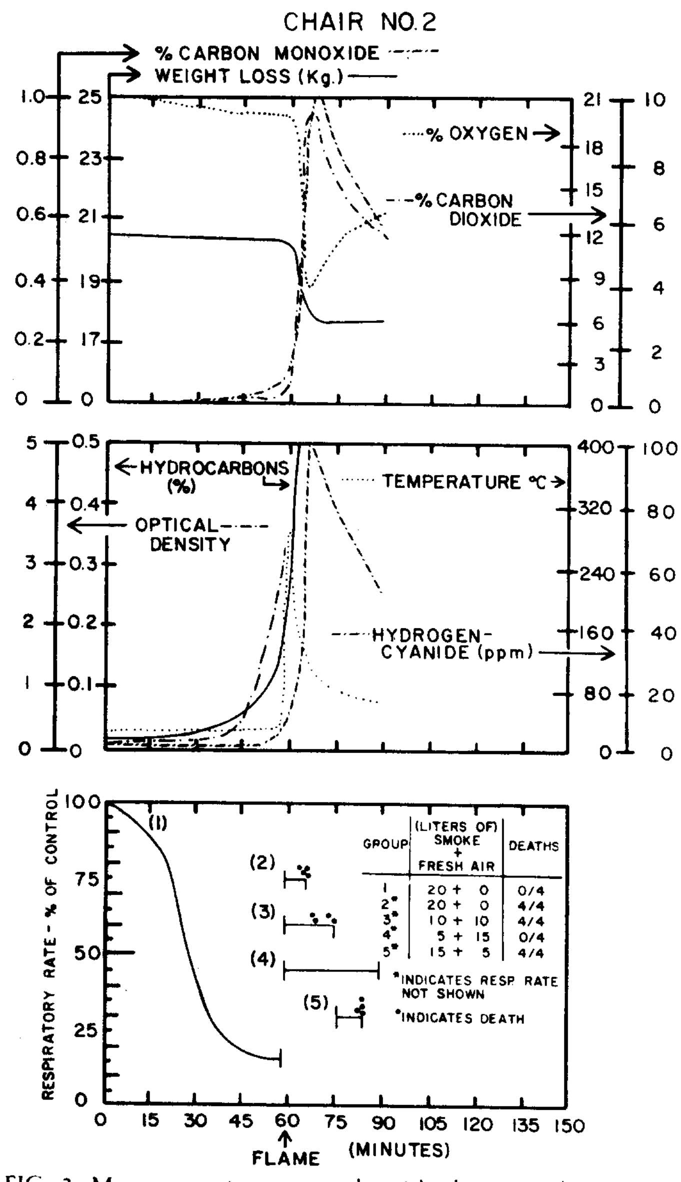

FIG. 3. Measurements were made with chair 2, polyurethane cushions, in the test room. A burning cigarette was placed on the cushion at time zero. Continuous monitoring of respiratory rate results is shown only for group 1 with the results for the other groups given in the text. Time of exposure for groups 2 to 5 is given by the horizontal bars next to each group number. The arrow indicates when flaming ignition occurred.

group 2. All animals in groups 1, 2 and 3 were observed for 14 days following exposure. All increased in body weight and no death occurred. Group 4 was exposed to undiluted smoke just after flaming ignition occurred. All animals died within 12 minutes. All showed a large decrease in respiratory rate with a characteristic pattern of sensory irritation initially which was rapidly followed by the characteristic pattern of asphyxiation, and followed by respiratory arrest. The same occurred for animals in group 5, exposed to undiluted smoke, exposed between 75 and 90 minutes. Only animals in group 6 survived exposure to smoke following flaming ignition. They were exposed almost simultaneously with group 5 but with a 1:3 dilution with fresh air.

The pattern of animal responses for chair 2 was similar to chair 1. Respiratory rate was monitored in group 1 until flaming ignition. As shown in Figure 3, there was a gradual depression in respiratory rate prior to an increase in optical density. The depression in respiratory rate occurred with a characteristic pattern due to sensory irritation and no sign of asphyxiation was observed in this group. These animals were observed for 14 days following exposure. All animals increased in body weight and no death occurred. Following flaming ignition of chair 2 three groups of animals were simultaneously exposed. Group 2 was exposed to undiluted smoke from the test room while group 3 was exposed to 10 liters of smoke from the test room diluted with 10 liters of fresh air. Group 4 was exposed to 5 liters of smoke from the test room diluted with 15 liters of fresh air. All animals in groups 2 and 3 died within 15 minutes, slightly more rapidly in group 2, with undiluted smoke from the test room, than for group 3, exposed to diluted smoke from the test room. Monitoring of respiratory rate in group 2 indicated severe respiratory depression due to sensory irritation immediately upon exposure. This pattern rapidly changed to an asphyxiation pattern followed by respiratory paralysis. All animals in group 4 (dilution 1:3) survived. These animals were observed for 14 days following exposure and no death occurred during this period. Exposure of group 5 to 15 liters of smoke from the test room diluted with 5 liters of fresh air was initiated 16 minutes after ignition. At this time, as shown in Figure 3, HCN and CO levels were decreasing while the oxygen level was increasing. However, all animals died and the respiratory pattern was similar to that observed in group 2.

Chair 5

This chair, covered with a heavy cotton fabric and filled entirely of polyester batting did not ignite. Figure 4 shows a gradual weight loss with smoldering at a fairly constant rate starting 20 minutes after initiating the test with the burning cigarette. Exposure of group 1 was continued until 70 minutes to undiluted smoke from the test room. Depression of respiratory rate occurred gradually with a pattern indicating sensory irritation and occurred before significant rise in optical density. Exposure of group 2 was initiated at minute 73 with dilution of smoke from the test room. The dilution was not high enough to prevent respiratory depression due to sensory irritation: the average respiratory rate for this group reached almost the same level of depression as in group 1. A third group was exposed, starting at 113 minutes, once total hydrocarbons and carbon dioxide had reached a plateau and a large amount of smoke had accumulated in the test room. Because of erratic performance with the carbon monoxide analyzer, these results were omitted from Figure 4 but the carbon monoxide concentration at that time was probably higther than 3000 ppm. One of the three exposed animals died while the other two recovered and appeared normal during the following 14-day post-exposure observation period.

Chair 6

For this chair, covered with the same cotton fabric as chair 5 but filled with cotton batting, flaming ignition occurred 23 minutes after initiation of the test as shown in Figure 5. Group 1 was exposed to smoke from the test room before, as well as after, flaming ignition. There was no depression in respiratory rate until 15 minutes into the test prior to flaming ignition. Respiratory depression, with the characteristic pattern of sensory irritation, was then observed and continued to be observed until the end of exposure. There was no sign of asphyxiation pattern and all animals survived and appeared normal during the following 14-day post-exposure observation period. Expo-

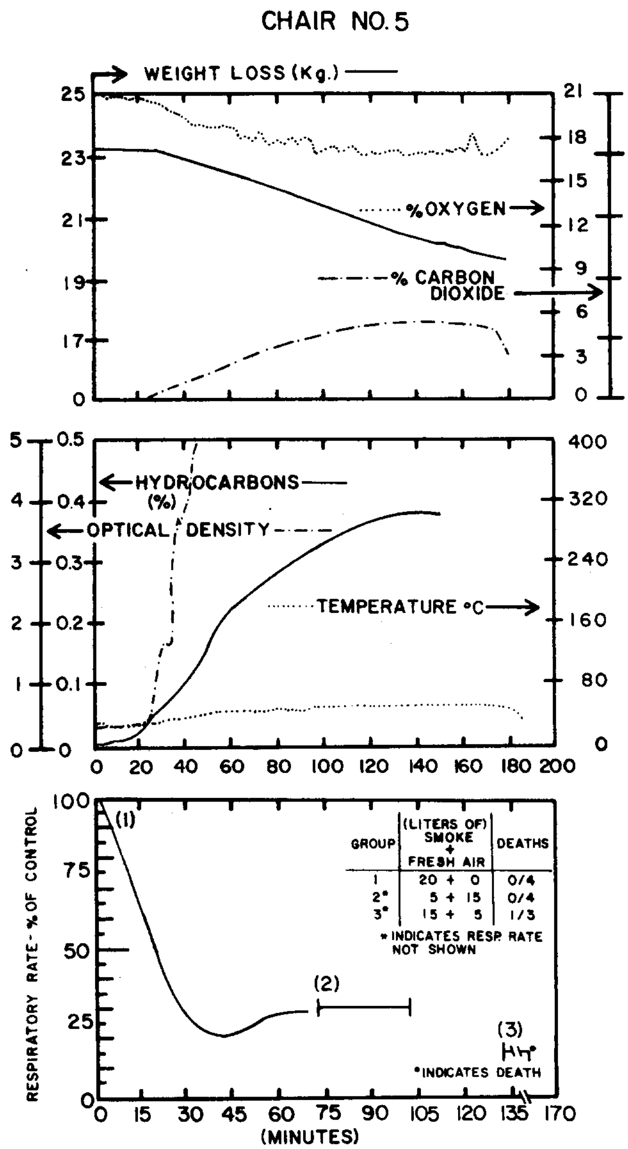

FIG. 4. Measurements were made with chair 5, polyester fiber cushions, in the test room. A burning cigarette was placed on the cushion at time zero. Continuous monitoring of respiratory rate results is shown only for group 1 with the results for the other groups given in the text. Time of exposure for groups 2 and 3 is given by the horizontal bars next to each group number. No flaming ignition occurred with this chair.

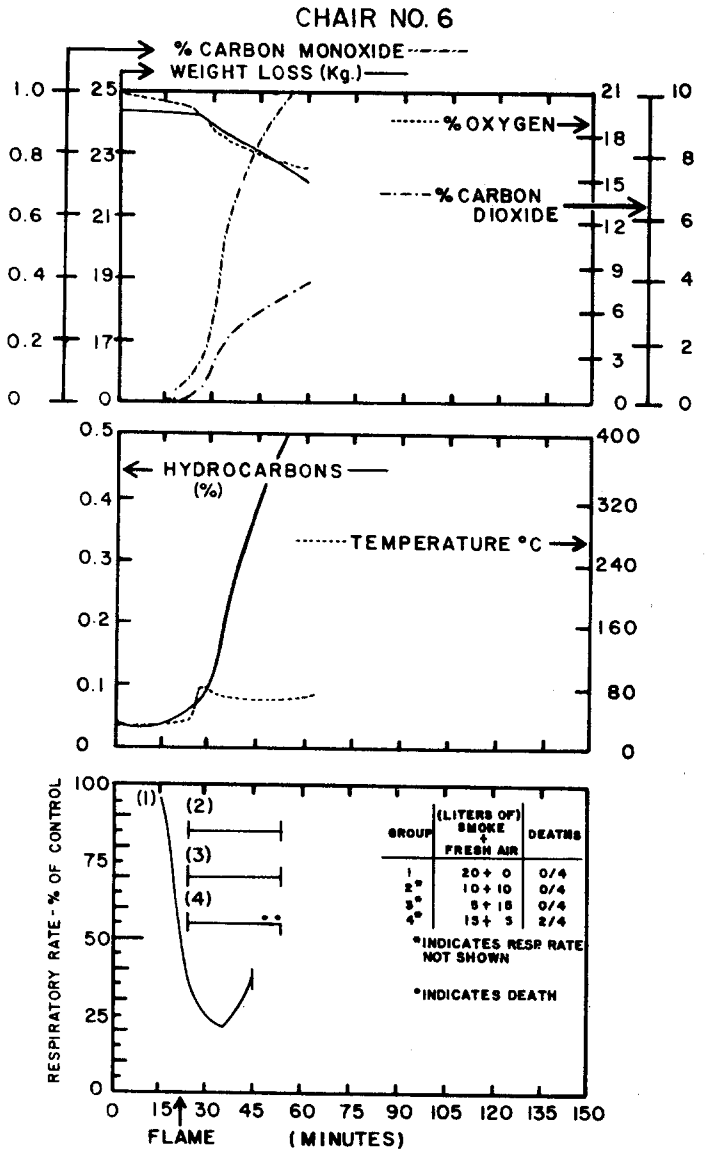

FIG. 5. Measurements were made with chair 6, cotton fibers cushions, in the test room. A burning cigarette was placed on the cushion at time zero. Continuous monitoring of respiratory rate results is shown only for group 1 with the results for groups 2, 3 and 4 given in the text. Time of exposure for groups 2, 3 and 4 is given by the horizontal bars next to each group number. The arrow indicates when flaming ignition occurred.

sure of this group was terminated 12 minutes after flaming ignition to allow comparison with the groups of mice exposed to undiluted smoke from chairs 1 and 2 which killed all the animals within 12 minutes. Groups 2, 3 and 4 were exposed to various levels of smoke from the test room by diluting with fresh air just after flaming ignition occurred. All groups showed respiratory depression due to sensory irritation but the characteristic pattern of asphyxiation followed by respiratory paralysis occurred in only two animals in group 4 toward the end of the 30 minutes of exposure. Except for these two animals, all others appeared normal during the following 14-day post-exposure observation period.

Small scale tests

Polyurethane

The results with the polyurethane foam used for the cushion of chair 2 are presented in Figure 6. From a series of experiments, the amount of this material loaded in the furnace to create sufficient smoke to kill 50% of the animals (LC_{50}) was found to be 13.1 grams with the 95% confidence interval being 11.9-14.3. The time required to kill 50% of the animals (LT_{50}) with this amount of material was found to be 18 minutes from the beginning of decomposition of this sample which occured at 195 °C and at which time the exposure was initiated. This is comparable to the results obtained previously with other polyurethane samples (Alarie and Anderson, 1979). As shown in Figure 6, flaming ignition occurred close to 500 °C and was preceded by the release of hydrogen cyanide and followed with the release of carbon monoxide and depletion of oxygen. Deaths occurred shortly after flaming ignition. Depression of respiratory rate due to sensory irritation started immediately with initiation of exposure. Only sensory irritation was observed until flaming ignition which was then followed by the characteristic pattern of asphyxiation, followed by respiratory paralysis at the concentrations just below, as well as above the LC_{50}.

Polyester

The results with polyester used for the cushions of chair 5 are presented in Figure 7. From a series of experiments the amount of this material loaded in the furnace to create sufficient smoke to kill 50% of the animals (LC_{50}) was found to be 28.0 grams with the 95% confidence interval being 27.5 -29.8. The time required to kill 50% of the animals (LT_{50}) with this amount of material was found to be 19.5 minutes from the beginning of decomposition of this sample which occurred at 400 °C and at which time the exposure was initiated. Flaming ignition of this sample occured around 475 °C and was accompanied with a large increase in carbon monoxide as well as oxygen depletion. A decrease in respiratory rate occurred immediately with initiation of exposure with the characteristic pattern of sensory irritation. This continued until ignition occurred and was followed by a pattern characteristic of asphyxiation, followed by respiratory paralysis at concentrations just bejow and above the LC_{50}.

Cotton

The results with the cotton fibers used for the cushions in chair 6 are presented in Figure 8. From a series of experiments, the amount of this material loaded in the furnace to create sufficient smoke to kill 50% of the animals (LC_{50}) was found to be 28.3 grams with the 95% confidence interval being 27.1 - 29.4. The time required to kill 50% of the animals (LT_{50}) with this amount of material was found to be 15.5 minutes from beginning of decomposition for this sample which occurred at 200 °C and at which time exposure of the animals was initiated. Ignition did not occur with this sample but major decomposition started around 300 °C with release of carbon monoxide and only a slight decrease in oxygen concentration. Decrease in respiratory rate occurred from the beginning of exposure due to sensory irritation. Following carbon monoxide release at the LC_{50} sample size and above, this pattern of sensory irritation changed to the characteristic pattern of asphyxiation and respiratory paralysis.

DISCUSSION

Comparing the situations created by placing a burning cigarette on chairs 1 and 2 vs. chairs 5 and 6, several differences were discernable. Chairs 1 and 2 yielded rapid release of toxicants upon flaming ignition, creating a lethal atmosphere. Both an increase in carbon monoxide and hydrogen cyanide

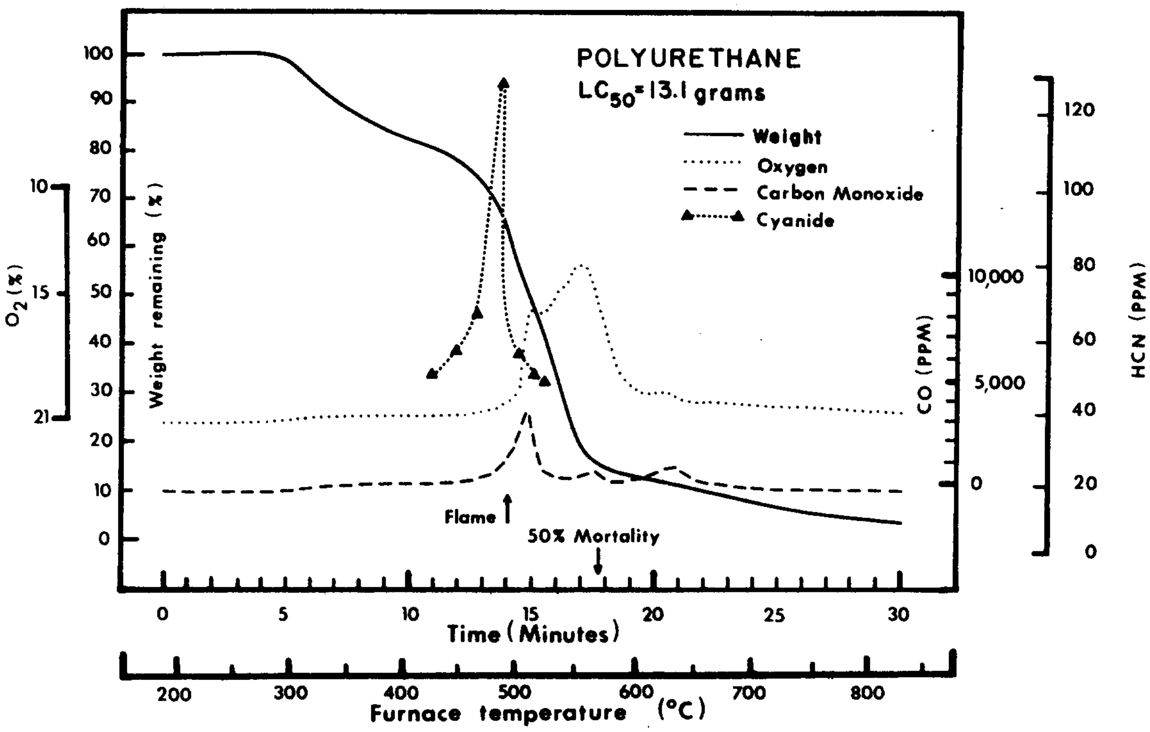

FIG. 6. Records of weight loss, CO and HCN release and oxygen depletion during increase in furnace temperature at 20 °C/minute with polyurethane foam from chair 2, at the sample size loaded in the furnace to produce sufficient smoke to kill 50% of the exposed animals. Exposure of the animals was initiated at 195 °C and an arrow indicates the time at which 50% mortality occurred. Flaming ignition is also indicated by an arrow at 495 °C.

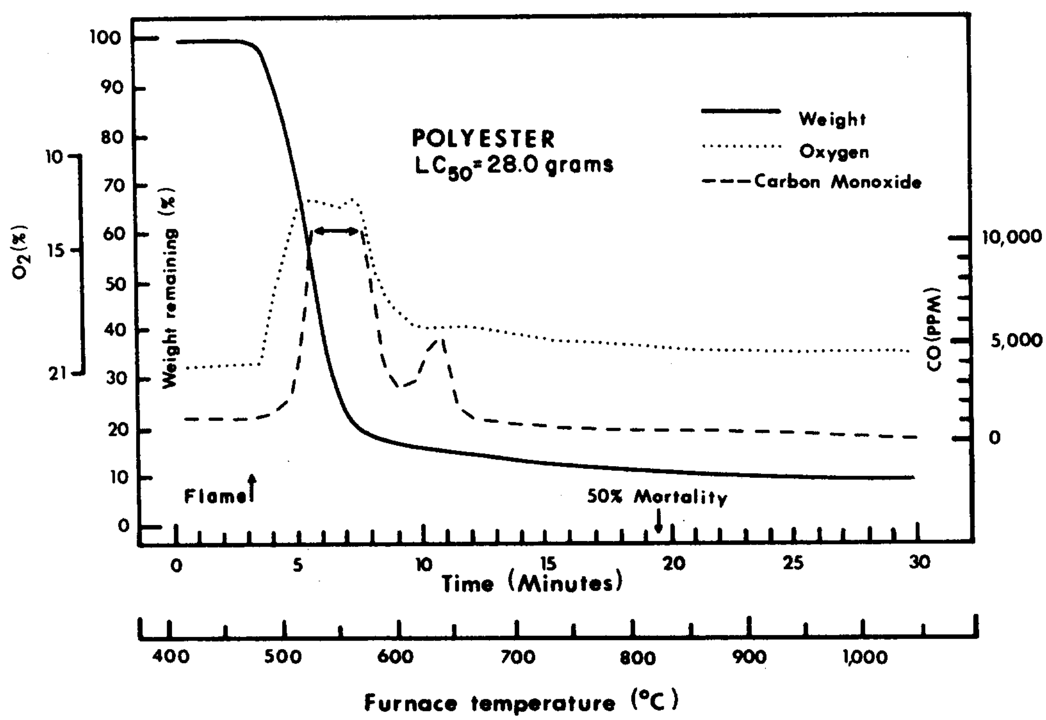

FIG. 7. Records of weight loss, CO release and oxygen depletion during increase in furnace temperature at 20 °C/minute with polyester fibers from chair 5, at the sample size loaded in the furnace to produce sufficient smoke to kill 50% of the exposed animals. Exposure of the animals was initiated at 400 °C and an arrow indicates the time at which 50% mortality occurred. Flaming ignition is also indicated by an arrow at 475 °C.

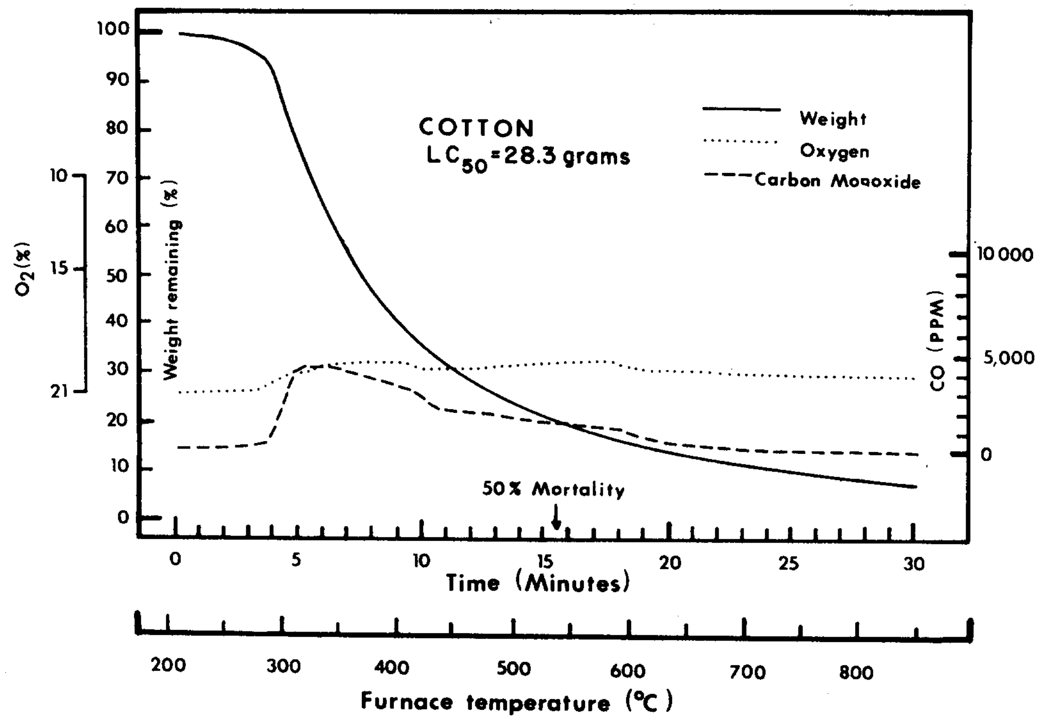

FIG. 8. Records of weight loss, CO release and oxygen depletion during increase in furnace temperature at 20 °C/minute with fibers from chair 6, at the sample size loaded in the furnace to produce sufficient smoke to kill 50% of the exposed animals. Exposure of the animals was initiated at 200 °C and an arrow indicates the time at which 50% mortality occurred. Flaming ignition did not occur.

and depletion of oxygen probably combined for the mortality observed in groups 4 and 5 for chair 1 and groups 2 and 3 for chair 2. Dilution of the smoke from the test room was necessary for the animals to survive (group 6, chair 1 and group 4, chair 2). Survival was possible with chair 6 for 25 minutes after ignition with group 1 which had also been exposed prior to ignition. Even for group 4, chair 6, where 50% mortality occurred, these deaths were noted 30 minutes after ignition. For chair 5, there was no ignition, only very slow decomposition due to smoldering; it was possible to induce death only after a long period of accumulation of thermal decomposition products. The major factor involved in creating lethal atmospheres with chairs 1 and 2 vs. chairs 5 and 6 was the very rapid release of toxicants with chairs 1 and 2. The difference in toxicity between chairs 5 and 6, although chair 6 ignited while chair 5 did not, is not large enough for a definite choice to be made between these two.

Of interest is the fact that for all chairs intense sensory irritation was observed during smoldering prior to ignition. In each case, the level of sensory irritation observed as measured by depression of respiratory rate, would have been intolerable to humans (*i.e.* intense eye, nose and throat irritation with lacrimation, coughing, choking, suffocation) and would have impeded their escape (Alarie *et al.*, 1980). That intense sensory irritation with exposure to smoke occurs at very low concentration in humans and in mice has been reported before (Potts and Lederer, 1978, Alarie *et al.*, 1980). With Swiss-Webster mice a depression of respiratory rate by 50%, RD_{50}, has been shown to be a level of response inducing intolerable irritation in humans for known sensory irritants (Barrow *et al.*, 1978) while Potts and Lederer (1978) suggested that RD_{75}, obtained in Ha(ICR) mice, may correspond to incapacitation in humans exposed to smoke from red oak. This was observed before significant obscuration by the generated smoke and support the proposition previously made by Alarie and Anderson (1979) that sensory irritation will be the first important phenomenon as escape attempts are made. This is also supported by the findings of Jin (1974). Extensive studies by this Japanese investigator revealed that human subjects found it difficult to keep their eyes open and because of tears they had much greater difficulty in seeing exit signs while walking in a corridor filled with irritating smoke vs. non-irritating smoke. Walking speed in a corridor with low smoke density (extinction coefficients 0.3 - 0.45) was greatly reduced with irritating vs. non-irritating smoke as presented in Figure 9.

The small scale test revealed that polyurethane foam used for chair 2 released smoke twice more toxic than polyester or cotton used for chairs 5 and 6, respectively. These two latter samples having the same LC_{50}. Thus, the results of both situations, *i.e.* smoldering chairs and small scale furnace decomposition indicated that the polyurethane sample was the most toxic and that little difference was observed between polyester and cotton. These findings are similar to our previous observations, with very different materials and a very different fire scenario, where the toxicity observed in medium scale tests was similar to what was observed in the small scale test (Alarie *et al.*, 1981). Such results are encouraging but nevertheless are not a definitive indication that the small scale decomposition system will always predict medium scale results.

Since polyurethane ignited in both the medium scale as well as the small scale test with release of carbon monoxide and hydrogen cyanide and oxygen depletion in both situations, it is of interest to attempt to predict what should happen in a medium scale test from the results of the small scale test. This can be attempted as follows. In the small scale test, 13 grams of polyurethane foam were necessary to produce sufficient

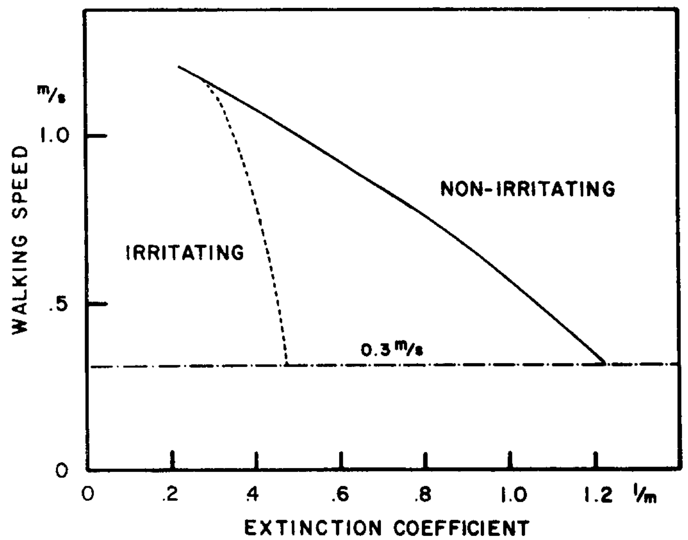

FIG. 9. Walking speed of human subjects in a corridor filled with irritating or non-irritating smoke of increasing opacity (measured by extinction coefficient). From the data presented by Jin (1974).

smoke, which when diluted with 200 liters of air (*i.e.* 20 liters/minute for 10 minutes during which major decomposition occurred, from Figure 6) resulted in 50% lethality. Since the smoldering chair test room dilution volume was 21 600 liters, it follows that 1.4 kilograms of polyurethane foam would be needed to produce the same effect if this dilution volume is used. The weight loss of chairs 1 and 2 (polyurethane cushions) was between 2 and 2.6 kilograms and in both instances all animals died when exposed to undiluted smoke from the test room, as would be predicted from the small scale test since according to the calculation given above 1.4 kg would result in 50% lethality. Also, animals exposed in the chair smoldering test to 5 liters of smoke from the room with 15 liters of fresh air dilution all survived. This dilution is the equivalent of reducing the weight loss to 0.7 - 0.9 kilogram and which, according to the results from the small scale test, is not sufficient to produce acute lethal effects. Thus a good prediction was achieved in translating toxicity from small scale to medium scale. Several other studies have been conducted on the toxicity of smoke from medium or large scale fire scenarios (Gaume, 1980; Nelson *et al.*, 1978; Potts *et al.*, 1978; Kuhn *et al.*, 1978; among others). However no attempt was made in those studies at quantitative comparisons or prediction of toxicity from small scale to medium scale. With the air dilution design used here and in our previous attempt (Alarie *et al.*, 1981) we were able to establish the range for lethality and survival.

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