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Large-Scale Compartment Fire Toxicity Study: Comparison With Small-Scale Toxicity Test Results

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National Bureau of Standards
National Engineering Laboratory
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U.S. DEPARTMENT OF COMMERCE, C. William Verity, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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LARGE-SCALE COMPARTMENT FIRE TOXICITY STUDY: COMPARISON WITH SMALL-SCALE TOXICITY TEST RESULTS

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Abstract

Ten large-scale single compartment fire tests were performed using two polyurethane foams and a cotton upholstery fabric. Animals were exposed to the products of decomposition of cushion assemblies burned under three different combustion modes: 1) smoldering combustion initiated by a cigarette; 2) flaming combustion initiated by a small natural gas diffusion burner; 3) smoldering-to-flaming transition combustion initiated by a cigarette and forced into flaming combustion after a prolonged period of smoldering by a small natural gas diffusion burner. Comparison of gas yields (CO, CO_2, and HCN) between these tests and prior large- and small-scale tests showed that the CO and CO_2 yields agreed within a factor of 3, while the NBS Toxicity Protocol produced 10 times more HCN in the flaming mode than the large-scale tests. Qualitatively, animal deaths were limited to within-exposure plus 24 hrs for the large-scale animal exposures, while small-scale animal deaths occurred primarily post-exposure. Within the errors of the NBS Toxicity Protocol (± 5-10 mg/ℓ), LC_{50} determinations in the large-scale tests were comparable to the small-scale tests, except for the small-scale ramped two phase heating and large-scale smoldering-to-flaming tests. The N-gas model for 30 minute exposures was expanded to include 4 gases, CO, CO_2, HCN and reduced O_2. Model calculations showed that within-exposure plus 24 hours animal deaths in small- and large-scale tests correlated with model values greater than 0.7. Burn room animal deaths could not be explained in terms of the four gases used in the N-gas model.

Keywords: Cotton; fire tests; large scale fire tests; polyurethane; small scale fire tests; toxicity; upholstery.

1.0 INTRODUCTION

Few large-scale fire evaluations in which animals have been exposed to the products of combustion have been reported in the literature. Even fewer studies have directly compared toxicity data from small- and large-scale tests. The work to date has previously been reviewed [1]. While the major effort of these researchers has been based on correlating material loading concentrations, little attention has been focused on quantifying and correlating gas yields and the nature of animal deaths between test regimes or developing other alternative correlation models.

The current experiments were intended to futher investigate the relationship between the small-scale results of the NBS Toxicity Protocol [2] and large-scale results. While the initial experiments involved a complex three compartment configuration with a simulated chair assembly, the present tests used a simplified single closed compartment and single cushion assembly. The basis for comparison between the large- and small-scale tests, however, remains the same. Comparisons are based on:

- The yields of CO, CO_2, and HCN and their relative contributions to lethality;
- The nature of those deaths, whether within- or post-exposure;

- The similarity of LC_{50} values;

  and

- The predictability of test animal deaths using the N-gas model.

Comparison will be made between the current test series, referred to as single compartment test, the prior large-scale tests, referred to as multi-compartment tests, and the results from the NBS Toxicity Protocol.

A single closed compartment configuration was selected to reduce the volume of the test space, as contrasted to previous tests [1], and, thereby, increase the concentrations of the various products of combustion. Use of a single closed room also made it possible to express directly the combustion product concentration in units of mg/ℓ and allowed for a simple comparison to be made to the bench-scale data. By contrast, the earlier investigation involved a complex flow path and required significant approximations to be made in order to deduce effective smoke concentrations. The previous effort employed a simulated chair assembly. While this added a touch of realism to the tests, it increased the tendency of the assembly to ignite spontaneously. To reduce the likelihood of this occurrence, single cushions were used in the current study.

In the large-scale tests, rats were exposed for 30 minutes in a manner similar to that used in the NBS Toxicity Protocol to the decomposition products from:

- smoldering combustion initiated by a burning cigarette;
- flaming combustion initiated by a small diffusion burner; and
- flaming combustion begun with a cigarette and, after a long

smoldering period, forced into flaming combustion with a small diffusion burner.

During experiments having a smoldering combustion phase (i.e., smoldering only and smoldering-to-flaming), test animals were also exposed directly in the burn room to the products of smoldering combustion. Because of the long term exposure (greater than 2 hr.), the results of these animal exposures could not be directly compared to 30 minute animal exposures used in the NBS Toxicity Protocol. These animal exposures, however, provided an opportunity to evaluate the effects of transporting decomposition products into the animal exposure chambers in assessing toxic potency.

Since the test materials used in these experiments had already been characterized in the small-scale tests in the preceding study, no additional small-scale tests were run. However, previously unpublished data on the polyurethane foam materials are presented showing the toxicity of the combustion products following a two phase decomposition in the NBS Toxicity Protocol apparatus (i.e., low temperature (300°C) to high temperature (800°C) pyrolysis). These results were compared to comparable large-scale tests (i.e., smoldering-to-flaming transition tests).

2.0 MATERIALS

The materials used in these experiments were the same as used in the previous study and are described in that report [1]. These materials were two flexible polyurethane foams and a cotton upholstery fabric. In order to simplify the experimental design and ensure that the test samples would not undergo spontaneous transition from smoldering to flaming combustion, cushion assemblies were made by placing two blocks of foam together and completely covering them with the cotton upholstery fabric. This resulted in a single square cushion 203 mm thick and 610 mm on a side. Approximately 60-70 % of the total mass of the cushion assembly was foam.

The two foams used in this study were based on similar formulations. One, however, contained a chlorinated phosphate fire retardant that allowed it to meet the State of California's requirements [3] for cigarette ignition resistance and also for flame resistance of resilient cellular material used in upholstered furniture. Both the treated (designated FR foam) and the non-treated (designated NFR foam) foam had a density of 22.3 kg/m^3. In the previous report [1], these foams were labeled foam 32X, for the FR foam, and foam 32, for the NFR foam.

The upholstery fabric was a Haitian cotton weighing 0.7 kg/m^2. It was selected to ensure that the entire assembly would smolder when exposed to a burning cigarette.

For smoldering experiments, the cushion assemblies were ignited by using standard cigarettes prescribed by the State of California [3] and the Upholstered Furniture Action Council [4]. They were 85 mm long and had a circumference of 25 mm. The cigarettes were made without filters from natural tobacco with a density of 0.27 ± 0.02 g/cm^3 and a total weight of 1.1 ± 0.1 g. Flaming experiments used a small diffusion burner described later in this report.

3.0 EXPERIMENTAL DESIGN

A total of ten experiments was conducted to evaluate the toxic potency of the atmosphere in the test compartment during various phases of fire development. Upholstered cushions, with an initial mass of approximately 2.5 kg, were placed on a load platform in a burn room and ignited with a cigarette or a small burner. In each test, rats, exposed to the decomposition products, were located either in the burn room or in the animal exposure chambers attached to the burn room. Analytical data on gas temperatures, smoke obscuration, mass loss, and concentrations of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen cyanide (HCN) were recorded. These measurements permitted calculations to be made of the decomposition rate and material mass loading in the burn room atmosphere based on mass consumed and an estimate of the gas yields. Material mass loading defines the toxic insult applied to exposed animals, while gas yields provide an indication of combustion conditions.

Three types of combustion conditions were investigated in this study; smoldering combustion, flaming combustion, and smoldering-to-flaming combustion. To initiate smoldering combustion, a smoldering cigarette (as described in section 2.0) was centered on the top surface of the test cushion. Flaming combustion was initiated by a small natural gas diffusion burner equipped with a remotely actuated ignitor producing approximately a 120 mm long flame from a gas flow of 1.7 ℓ/min (1 kW). The flame was directed at the upper portion of one side of the test cushion. Smoldering-to-flaming tests employed a cigarette to initiate smoldering as in the smoldering-only tests. At a predetermined time after the start of smoldering, the burner was ignited and used to force the transition to flaming combustion.

3.1 Test Plan

Table 1 summarizes the test plan for these experiments showing the number and placement of animals as well as the decomposition conditions. There were four smoldering experiments, two for each foam. These experiments represent replicate tests differing only in the number and placement of animals in the burn room and animal exposure chambers. In the second of each replicate, animals were exposed in both the burn room and the animal exposure chambers.

Two flaming experiments were conducted, one for each foam. No animals were placed in the burn room for the flaming experiments because of the anticipated high temperatures. Animal exposures during these tests were limited to three animal exposure chambers.

Two replicate tests, under conditions of smoldering-to-flaming combustion, were also performed for each foam. Animals placed in the burn room were exposed to the smoldering phase of combustion, while, during flaming combustion, animals were exposed to the decomposition products in the animal exposure chambers. During each experiment, the data that were collected continuously on the burn room environment included temperature, smoke, mass loss, O_2, CO, and CO_2. Each animal chamber was also continously monitored for temperature, O_2, CO, and CO_2. In both the burn room and animal exposure chambers, evacuated bulbs were used to obtain atmospheric "grab" samples for analysis of HCN.

3.2 Room Configuration

The experimental arrangement is shown in figure 1 and consisted of a single compartment measuring 2.44 m wide by 2.44 m high by 4.57 m long and lined with non-combustible materials. A doorway measuring 1.02 m wide by 2.03 m high provided access to the compartment. The compartment was constructed using the materials listed in table 2 (thermal property data can be found in [1]).

The doorway was closed for all of the tests. For the smoldering-only tests, the doorway was closed with a sheet of 3.2 mm thick polycarbonate with a 10 mm undercut. For all other tests, the doorway opening was closed with a sheet of calcium silicate covering the upper two-thirds of the doorway (i.e., the top 1.35 m of the door opening). The remainder of the door opening was covered with an aluminum foil covered lightweight wood frame. The aluminum foil covering provided for pressure relief in the event of a sudden increase in compartment pressure due to explosive combustion conditions. No such event ever occurred.

3.3 Instrumentation

Table 3 lists all the instrumentation used in these experiments and the location of the sampling points. Figure 2 shows the location of the instruments within the test compartment. Vertical lines of ten thermocouples each were located in the center of the compartment and in opposite corners. These were used to determine the upper compartment temperature and the location of the hot upper layer interface during flaming combustion. One vertical and six horizontal smoke meters were used to determine smoke particulate stratification within the compartment. Gas probes in the upper (centered, 0.3 m from the ceiling) and lower (room corner, 0.3 m from the floor, 0.6 m from each wall) portions of the compartment continuously monitored the CO, CO_2, and O_2 concentrations. HCN samples were periodically drawn from the burn room through the same sampling line that connected the burn room to the animal exposure chambers. In one test, toluene diisocyanate (TDI) measurements replaced the HCN samples and were taken from the same location. Since trace amounts of TDI had been detected in small-scale non-flaming tests, it was of some interest to see if similar concentrations were detected in the large-scale tests during smoldering combustion, that is, when HCN generation was very low. Cushion assemblies were placed on a load cell located near the center and 0.3 m above the burn room floor. The load cell continuously monitored mass loss.

For those animals located in the burn room, additional thermocouples were used to determine the thermal stress placed on the animals. These thermocouples were located either within the animal holding tubes (i.e., in contact with the animals) to monitor an approximation of the animals' body temperature or above the animals' heads to monitor air temperatures in front of the animals. HCN samples of the animal exposure chamber atmospheres were only taken while animals were actually being exposed.

3.4 Animal Exposures

Two exposure protocols were used in this series of experiments. In each case, Fischer 344 male rats weighing 200 to 300 g were exposed in the head-only mode. One involved a duplication of the exposure conditions previously employed [1], while the other involved direct animal exposure to burn room conditions. Because of differences in exposure times, direct quantitative comparisons could not be made between the two exposure protocols. However, direct animal exposures were considered important, since qualitative physiological comparisons were expected to reveal if any significant line losses of species not monitored occurred during the transfer of combustion products to the animal exposure chambers. Such an occurrence might account for the lack of agreement between previous large-scale tests and the NBS Toxicity Protocol with respect to post-exposure deaths of the animals. All surviving animals were kept and weighed daily for at least 14 days.

3.4.1 Exposure Chamber Animals

Three NBS toxicity protocol animal exposure chambers (200 ℓ each) were connected to the burn room via a 2.1 m long, 55 mm diameter Pyrex sampling line located directly above the cushion assembly and 0.3 m from the ceiling. Each exposure chamber could be isolated from the burn room by its own intake and exhaust shut-off ports. Throughout an experiment, even when animal exposure chambers were not being filled, flow of the burn room gases was maintained in a by-pass line, thus providing a means for sampling of the combustion gases for HCN or TDI analysis. An exhaust manifold allowed flow through the chambers and the by-pass line to be controlled by one blower motor. The exhaust gases were returned to the inside surface of the south wall of the burn room at 0.3 m from the ceiling.

For smoldering tests, the animal exposure chambers were opened and connected to the burn room. Room atmosphere was continuously drawn from the burn room and passed through each exposure chamber. At predetermined concentrations of CO, individual chambers were closed and six animals inserted for 30 minutes. This procedure was followed until all three animal exposure chambers were closed and animals inserted. In this way, three different smoke concentrations could be presented to the animals.

During those tests that involved flaming combustion (i.e., flaming and smoldering-to-flaming), animals were only exposed to the decomposition products from the flaming mode. During these experiments, the animal exposure chambers were initially disconnected from the burn room, while flow was maintained in the by-pass line. During active flaming, the animal exposure chambers were opened to the burn room and allowed to fill for predetermined amounts of time. This resulted in different material loadings each of the three exposure chambers for use in determining concentration-lethality relationships for the large-scale flaming tests. Six animals were inserted into each exposure chamber for 30 minutes.

3.4.2 Burn Room Animals

Smoldering tests afforded the opportunity of inserting animals in the burn room during the non-flaming thermal decomposition of the cushion assembly without undue thermal stress. (It was anticipated that upper compartment temperatures would not, on the average, exceed 40°C.) Two or six animals were inserted in animal holding tubes mounted on the north wall of the burn room within 0.3 m of the ceiling. The animal tubes extended 0.3 m into the burn room (figure 1). Animals were first placed in closed restraining tubes (figure 3), and connected to a respiration monitor via flexible tubing. The restraining tubes were placed into the animal holding tubes so that the animals were exposed in a head-only mode. This is similar to the exposure mode used in the NBS Toxicity Protocol. Because only two transducers were available for the monitoring of respiration, animals were monitored in groups of two. For those experiments involving only two animals, continuous monitoring was possible. When six animals were used, animals were monitored in groups of two for approximately three minutes per group. For those smoldering experiments that were forced into flaming combustion, all animals were removed from the burn room animal holding tubes and the tube ends sealed before initiation of flaming combustion.

4.0 RESULTS

4.1 Material Fire Characteristics

4.1.1 Smoldering Combustion Tests

Cushion assemblies were permitted to smolder in the closed burn room with a relatively quiescent atmosphere. Figures 4 and 5 show the mass loss data for two replicate tests of the non-fire retarded (NFR) and fire retarded (FR) polyurethane foam cushion assemblies, respectively, when exposed to a smoldering cigarette ignition source. The data show that the repeatability of the FR foam assemblies was better than the NFR foam assemblies. While initial average mass loss rates were the same for repeated tests of similar assemblies, the average maximum mass loss rates of repeated tests differed for the NFR assemblies (table 4). Initial average mass loss rates of 29 mg/s and 36 mg/s were observed for the FR assemblies. This was almost half of the initial average mass loss rates of the NFR assemblies, 56 mg/s and 53 mg/s. The average maximum mass loss rate for the second smoldering test (Test 3) of the NFR assembly was twice as high, 570 mg/s, than a similar assembly tested in Test 1, 320 mg/s. This difference was probably due to small differences in the construction of the cushions (i.e., fabric tension, presence of creases, size of seams, irregularities in the foam, etc.). The FR assemblies had similar average maximum smoldering rates of 120 mg/s and 130 mg/s, also less than half of that of the NFR assemblies.

Figures 6 and 7 show the CO and CO_2 gas concentrations in the burn room as a function of time for the four smoldering only tests. As expected from the mass consumption data, test 3, a NFR cushion assembly, generated higher concentrations of CO and CO_2 and earlier than the other tests. Table 5 summarizes the maximum CO and CO_2 and the minimum O_2 concentrations at the time of maximum CO concentration for each of the smoldering tests. The oxygen concentration never went below 19%.

The maximum concentration of HCN was determined to be approximately 25 ppm for Test 3 (NFR foam assembly) based on measurements made in one of the animal exposure chambers and 6 ppm for Test 4 (FR foam) also based on measurements made in one animal exposure chamber. The remaining tests showed less than 2 ppm of HCN in the burn room. During Test 3, burn room analysis for HCN was replaced by TDI measurements. Approximately 0.1 ppm of TDI was detected in the burn room. Since this represented measurements made near the lower detection limits of the analysis technique and because of the lower anticipated smoldering rates of the FR assemblies, this analysis was not repeated for the FR material nor any other large-scale tests.

Figure 8 shows typical smoke filling data for two foam cushion assemblies undergoing smoldering decomposition (Tests 2 and 3). Consistent with the mass loss data, the NFR foam assembly began filling the burn room with detectable smoke sooner than the FR foam assembly. In tests 2 and 4, FR foam assemblies, filled the burn room with smoke to the level of the load platform in approximately 3900 and 3600 seconds, respectively. In the NFR assembly, test 3, the smoke layer reached the level of the load platform in approximately 2500 seconds. Because of a failure in the smoke obscuration meters, comparable data were not available for test 1.

During these smoldering tests, the average upper compartment temperature never exceeded 43°C. The maximum recorded temperature was 53°C during the end of test 3.

4.1.2 Flaming Combustion Tests

Figure 9 shows the mass loss data for these two tests (Tests 5 and 6). Both tests exhibited a pre-heat period where the mass loss rate was relatively low, 270 mg/s for the NFR foam assembly and 80 mg/s for the FR foam assembly. Once active burning was established on the cushion assemblies, the average maximum mass loss rate was approximately 1900 mg/s for both foam cushion assemblies. Based on initial and final masses, approximately 90% of the NFR foam assembly was consumed during the flaming tests, while approximately 60% of the FR foam assembly was consumed. During the peak burning period, the upper layer gas temperature was approximately 120°C for both tests.

Figure 10 shows the comparison of CO, CO_2, O_2, and HCN development in the burn room during these flaming tests. Consistent with the mass loss data, the gas data show that the NFR foam assembly generated higher concentrations of CO and CO_2 than the FR foam assembly. HCN measurements during these tests showed that the maximum measured HCN concentration in the burn room was higher for the FR assembly, approximately 170 ppm, than for the NFR assembly, approximately 100 ppm. Also, based on the fact that nearly 1/3 more NFR assembly was consumed than FR assembly, it was not surprising to find that the oxygen concentration was lower for the NFR assembly than the FR assembly. These results are summarized in Table 6. Differences in the time to peak CO and CO_2 are indicative of non-flaming decomposition occurring in the cushion residue during the post-flaming period. Differences in peak times between CO_2 and HCN can be attributed to the HCN sampling interval and not necessarily to differences in HCN generation rates.

The development of the smoke layer in tests 5 and 6 can be seen in figure 11. The time for the development of a smoke layer to 2.0 m, 0.3 m and floor level are tabulated below. These times reflect differences in both ignition delay, as represented by the time to 2.0 m, and in rate of fire growth, as seen in the time from 2.0 m to 0.3 m and from 0.3 m to the floor.

Time for the Smoke Layer to Reach Various Levels

		Time (s)		
Material	Test #	2.0 m	0.3 m	Floor
NFR	5	240	600	1020
FR	6	300	1020	1320

4.1.3 Smoldering-to-Flaming Combustion Tests

The mass burning rate curves for both the NFR and FR foam cushion assemblies appear to exhibit three distinct burning phases (figure 12). The mass burning rate for each phase is summarized in table 7. The first two phases correspond to smoldering decomposition. As noted previously, the initial mass burning rate may be predominantly controlled by the decomposition of the cover fabric, while the second and larger mass burning rate can be attributed to in-depth smoldering of the foam cushion. While the former is a surface expansion of the smoldering front, the later is a volumetric (three-dimensional) expansion of the smoldering front. These values are comparable to those from the smoldering-only tests (section 4.1.1). Also, during flaming combustion, the mass burning rate for these tests was comparable to the flaming-only decomposition data (section 4.1.2) for the NFR foam cushion assembly, but about 70% to 90% greater than the previous FR foam cushion assembly tests. At the time of the transition to flaming combustion approximately 51% and 35% of the NFR and 17% and 23% of the FR cushion assemblies were consumed.

Figure 13 shows the comparison of CO, CO_2, HCN, and O_2 between replicate tests of the NFR cushion assembly. The same data are presented in figure 14 for replicate tests of the FR cushion assembly. The gas generation data were consistent with the mass loss data. Ignoring the time delay to initiate flaming combustion, which was controlled by the death and removal of the burn room animals, the NFR cushion assemblies appear to have more reproducible maximum CO, CO_2 and HCN and minimum O_2 concentrations than the FR cushion assemblies. The decrease in the concentration of gases beyond the time of the maximum values was due to the leakage of outside air into the burn room caused by the cooling of the burn room atmosphere.

Maximum CO, CO_2, HCN, and Minimum O_2 Concentrations

	NFR		FR	
	Test 7	Test 9	Test 8	Test 10
CO,ppm	9800	10500	9500	5900
CO_2,%	5.2	4.9	7.3	5.4
HCN,ppm	140	90	450	370
O_2,%	13.6	13.9	11.2	13.6

However, the FR cushion assemblies differed in initial weight by 0.22 kg (2.62 kg and 2.40 kg), while the NFR cushion assemblies differed by only 0.12 kg (2.62 kg and 2.50 kg). At the conclusion of the tests, nearly 100% of the NFR cushion assemblies and 75% of the FR cushion assemblies were consumed.

Figure 15 shows a comparison of the development of the smoke layer during these four tests. Because of the higher mass loss rates during smoldering combustion of the NFR cushion assemblies, the smoke layer reached the floor of the burn room sooner than for the FR cushion assemblies. Both cushion assembly types filled the burn room with smoke before the initiation of flaming combustion.

Time for the Smoke Layer to Reach Various Levels

		Time (s)		
Material	Test #	2.0 m	0.3 m	Floor
NFR	7	200	2920	3270
NFR	9	500	2900	4365
FR	8	800	4000	5700
FR	10	1100	3900	6600

Gas yields for all ten tests were calculated for CO, CO_2, and HCN. A tabulation of these results, table 8, show that CO and CO_2 yields were generally constant for a given decomposition mode. During smoldering combustion, the average CO yields were 0.09 kg/kg for NFR foam assemblies and 0.11 kg/kg for FR foam assemblies. At the same time, CO_2 yields were 0.4

kg/kg and 0.6 kg/kg for the NFR and FR foam assemblies, respectively. During smoldering combustion, HCN was not detected or detected only at very low concentrations. Therefore, no determination was made of HCN yields. For flaming combustion, the CO yields, 0.11 kg/kg for NFR and 0.12 kg/kg for FR foam assemblies, were comparable to the smoldering combustion data, while the CO_2 yields, 2.2 kg/kg for NFR and 1.9 kg/kg for FR foam assemblies, were 3 to 5 times greater than during smoldering combustion. While significant amounts of HCN were produced during direct flaming combustion, 2×10^{-3} kg/kg for NFR foam and 4×10^{-3} kg/kg for FR foam, 1½ times as much HCN was produced by smoldering NFR foam prior to flaming combustion, 3×10^{-3} kg/kg and 3×10^{-3} kg/kg, and 2½ times more for FR foam, 1×10^{-2} kg/kg and 1×10^{-2} kg/kg.

4.2 Animal Exposures During Smoldering Combustion

During the smoldering combustion phase of eight tests, long term animal exposures to the decomposition products in the burn room were conducted. In addition, 30 minute animal exposures were performed during two of the smoldering-only tests using three animal exposure chambers connected to the burn room. The purpose of the long term within-room exposures was to determine the extent to which transporting decomposition products to the animal exposure chambers would affect observed lethalities and the time of occurrence of death. The exposure chamber animal response data were used to make comparisons with small-scale test results.

4.2.1 Burn Room Animals

Since burn room animal exposures represented a new protocol, there was some concern that restraining the animals in closed holders and inserting them into extended exposure tubes would place undue stress on them, resulting in the restraining system itself causing injury or death. In order to determine the impact of the restraining system on animal survivability, a control test was conducted. Two animals were selected for long term exposure to test conditions without the presence of combustion products. The animals were placed in animal holders and inserted into the animal exposure tubes in a head-only mode. The animals were connected to the respiration monitor, and the temperatures within the restrainers as well as the atmospheric temperature at their noses was recorded for three hours. After this control run, the animals were returned to holding cages and observed for 14 days.

The ambient temperature to which the animals were exposed was 24°C. The temperature inside the animal holding tubes reached an average of 35°C with a maximum of 37°C. Figure 16 shows the growth data for the two control test animals and the average for a set of six control animals who were just kept in their cages. Prior to the exposure all of the animals exhibited approximately the same weight gain. Immediately after the exposure (i.e., within 24 hrs), the two test animals showed slight drops in weight, 7 g and 12 g, compared to the non-exposed control animals. However, normal growth rates were re-established within 48 hrs after the termination of the blank exposure. This has been shown [5] to be the normal animal response to the tubing or restraining process.

Table 9 summarizes the results of burn room animal exposures for the NFR foam cushion assemblies. Tests 1 and 9 involved the use of 6 animals per test; however, for test 1, individual animals were progressively removed from the burn room at increasing test times, for test 9, all animals were removed from the burn room at the same time. The removal times for test 1 were based on the CO concentration, while, for test 9, the removal time was based on the initial detection of arrested respiration (this would be indicative of death) of any of the animals. Tests 3 and 7 used only two animals per test. The exposures were allowed to progress to the death of both animals. While the time integrated average values for material loading based on mass consumed, CO, and CO_2 were low, the exposure time was long. The shortest exposure time was 4380 s and the longest was 8200 s. During the early development of smoldering in the cushion assembly, the concentrations of the lethal gases were near ambient conditions. With two exceptions, the onset of death based on the integrated CO value varied from 52,000 ppm-min to 83,000 ppm-min. One animal died after only a 23,000 ppm-min integrated CO exposure and one died after 109,000 ppm-min. Endpoint (death or removal of animals) concentrations of CO, CO_2 and O_2, appear not to be lethal at exposures up to one hour [6].

Since the burn room animals were exposed to a changing combustion atmosphere, an average material loading was computed. This was estimated by averaging the time dependent material loading from the start of the test until the termination of the exposure. The material loading at a specific time, t_i, was determined by computing the ratio of the cushion assembly mass loss until t_i, as measured by the load cell, and the upper layer volume at t_i, as measured by the smoke meters. The material loading calculations did not take into account any losses of smoke from the burn room or entrainment of air into the burn room. However, the horizontal smoke meters were used to correct for combustion product stratification in the burn room. Therefore, the average material loading was an estimate of the concentration of material consumed at the level of the burn room animals. The average material loading was found to vary from 3 mg/ℓ to 15 mg/ℓ.

Table 10 presents analogous results for the FR foam cushion assembly. With two exceptions, the onset of death based on the integrated CO concentration occurred between 67,000 ppm-min and 99,000 ppm-min. One animal died at an integrated CO concentration of 17,000 ppm-min. At the highest value of 143,000 ppm-min, 3 out of 6 animals survived the 14 day post-exposure observation period. Average material loading varied from 1 mg/ℓ to 6 mg/ℓ. Endpoint concentrations for CO, CO_2, and O_2 were low (i.e., when animals were removed from the burn room) and the cause of death does not appear to be caused by the presence of these gases alone.

4.2.2 Exposure Chamber Animals

Two tests involved the exposure of animals in the animal exposure chambers to steady-state concentrations of decomposition products from the smoldering phase of burning (Tests 3 and 4). Following a previously established protocol [1], three groups of six animals were exposed to increasing concentrations of decomposition products transported from the burn room to three animal exposure chambers. The animal exposure chambers were filled for varying times to allow for a variation in gas concentrations between each chamber. After the chambers were sealed from the burn room, animals were inserted into the chambers for 30 minute exposures. The calculated material loading and the average CO, CO_2, O_2, and HCN concentrations in each exposure chamber are listed in table 11 along with the animal response data. For the NFR foam cushion assembly, animal deaths were observed at exposure chamber material concentrations of 30 mg/ℓ and 32 mg/ℓ, based on mass consumed. The single animal death at 30 mg/ℓ was found during the second 24 hr period after the termination of the exposure. No post-exposure deaths were observed beyond this time in any other tests. At 32 mg/ℓ, one animal died during the exposure and one died within 24 hrs of the exposure. The maximum loading for the FR foam cushion assembly was 24 mg/ℓ. No animal deaths were recorded within- or post-exposure from the FR assemblies. However, the concentrations of gases were much lower than for the NFR assemblies.

4.3 Animal Exposures During Flaming Combustion

Six tests were conducted in which the animals were exposed to the products from the flaming phase of combustion. Two tests (5 and 6), one FR and one NFR, were initiated by a small diffusion burner causing the cushion assemblies to ignite into flaming combustion. The remaining four tests, two FR (7 and 9) and two NFR (8 and 10), were initiated by a smoldering cigarette and later forced into flaming combustion by a small diffusion burner. Only animals in the animal exposure chambers were exposed to the products of flaming decomposition.

Table 12 summarizes the results of the animal exposures during these tests. During the flaming initiated tests, tests 5 and 6, the lowest material loadings, at which deaths were observed to occur, were 25 mg/ℓ and 33 mg/ℓ for the FR and NFR foam cushion assemblies, respectively. All but one animal death occurred during the exposure period. With the exception of test 7 at 44 mg/ℓ loading in which one animal died within 24 hours of the test, all of the animals exposed to the decomposition products from the smoldering-to-flaming transition experiments died during the exposure. The data show that it was difficult to obtain conditions that resulted in partial deaths among the eighteen animals exposed in the animal exposure chambers per test. With the majority of the data showing 0 out of 6 deaths or 6 out of 6 deaths, the concentration-response curve for these materials must be very steep. The effects of gases, individually and in combination will be discussed in section 5.4.

5.0 DISCUSSION

5.1 Gas Yields

Since gas yields are determined by two measured variables, each with an independent measurement error, the yield calculations have a combined error approximating the sum of the individual instrument errors. The primary cause of uncertainty in the yield calculations during smoldering combustion is the small sample weight loss. For flaming combustion, the greatest uncertainty is in the determination of the smoke volume. Differences in yields of less than a factor of 3 and in yield ratios of less than a factor of 10 may not be meaningful. A comparison of the yield ratios for CO_2/CO and HCN/CO are listed in table 13 for the three testing environments. With the exception of the CO_2/CO and HCN/CO ratio for NFR foam and the HCN/CO for FR both during flaming combustion, the yield ratios differ by less than a factor of 3. The CO_2/CO yield ratio varied from 15 to 40 for FR foam and 20 to 80 for NFR foam assemblies during flaming combustion and 5 to 8 for non-flaming or smoldering combustion. During flaming combustion, the HCN/CO yield ratio varied from 0.01 to 0.11 for both foam assemblies. While little or no HCN was detected in the current single compartment experiments during smoldering combustion and, therefore, no determination was made of HCN yield, previous experiments [1] showed that the HCN/CO was very small for smoldering combustion, less than 0.001 to approximately 0.01. For flaming combustion, the NBS Toxicity Protocol had the highest HCN/CO ratio.

While gas yield ratios minimize random errors from sample weight or smoke volume measurements, systematic errors in gas yield measurements from either the small- or large-scale tests could result in comparable gas yield ratios. Thus it is also necessary to examine the yield values themselves. Analysis of the actual yield data, table 14, shows that the production of HCN, on a unit mass basis, exhibited a similar trend between the three testing environments. While very little HCN (less than 0.1×10^{-3} kg/kg for NFR assemblies, and only 0.4×10^{-3} kg/kg for FR assemblies) was produced in any of the smoldering tests for both materials or non-flaming decomposition tests in the NBS Toxicity

Protocol, flaming combustion in each test environment produced comparable large increases in HCN yields. For each material, the greatest HCN concentration occurred during the smoldering-to-flaming tests. For the NFR foam, the smoldering-to-flaming tests produced 2 to 18 times more HCN than the flaming-only tests. Three to 9 times more HCN was produced for FR foam during smoldering-to-flaming transition experiments than during flaming-only tests. It should also be noted that, since the HCN concentrations were not continuously determined, the values presented may not represent peak concentrations.

In general, the decomposition environments developed in the three test conditions for the three combustion regimes were performed under comparable ventilation conditions as defined by the CO_2/CO ratio. In those cases where HCN was measured at both scales, the NBS Toxicity Protocol results were similar for HCN production to the large-scale single room tests in 3 out of 4 cases (table 14). The HCN yields from the multi-room tests were consistently an order of magnitude lower than from the single room tests. No simple explanation is available for this difference in HCN behavior between single and multi-room geometries. HCN production was greatest for smoldering-to-flaming combustion and lowest for smoldering or non-flaming combustion. Flaming combustion produced an intermediate amount of HCN.

5.2 Time of Mortality

The NBS Toxicity Protocol data and large-scale multi-compartment data[1] taken from the previous study are, for convenience, shown on tables 15 and 16 along with the data from the present study. The results of the NBS Toxicity Protocol show that for FR and NFR foams in the non-flaming exposures caused almost exclusively post-exposure deaths. Deaths, for the non-fire retardant foam, occurred as late as 28 days post-exposure and, for the fire retardant foam, as late as 10 days post-exposure. The cotton fabric produced deaths 4 days post-exposure.

During the multi-compartment large-scale smoldering exposures, no deaths were observed for FR and NFR foam cushion assemblies within- or post-exposure in the animal exposure chambers. During the current series of experiments, tests were designed to increase the likelihood of animal deaths by increasing gas concentrations in the animal exposure chambers. In this way, a better determination might be made of the differences in within- and post-exposure deaths between large- and small-scale tests.

In the smoldering mode, for the NFR foam cushion assembly, two within-exposure deaths were observed (table 15). In one case, there was a post-exposure death within 24 hours of the termination of the exposure. Fifteen animals survived the initial exposure plus 24 hours. No additional deaths resulted during the post-exposure observation period. The CO concentrations for single compartment tests were comparable to or greater than those reported for the small-scale tests and the CO_2 and O_2 concentrations were very similar. For the FR foam cushion assembly (table 16) decomposed in the smoldering mode, no deaths were observed at CO concentrations two times greater than the small-scale FR foam tests and comparable to the small-scale cotton fabric tests.

In 1982, Birky [7] reported on preliminary results of comparisons between the smoldering combustion of flexible polyurethane foam slabs in large-scale single closed compartment tests and in the NBS Toxicity Protocol. He similiarly observed that, while post-exposure animal deaths were common for flexible polyurethane foam under non-flaming conditions in the NBS Toxicity Protocol, no post-exposure animal deaths occurred following a comparable 30 minute exposure to the decomposition products from smoldering the same foam in a large-scale compartment.

Flaming-only animal exposure tests were not performed during the multi-compartment large-scale tests. However, single compartment flaming tests data are available for comparison to small-scale flaming tests. Small-scale flaming tests produced some within-exposure deaths, but also showed a large fraction of post-exposure deaths for the FR foam. Under flaming conditions no deaths were observed for the NFR foam or cotton fabric in the small-scale tests at the highest material concentration. The NFR foam cushion assembly under direct flaming conditions produced 11 out of 18 animal deaths in the single compartment test. The FR foam cushion assembly had 9 out of 18 animal deaths. All of these deaths occurred within the 30 minute exposure period. The FR foam tested in the small-scale test had both within- and post-exposure deaths.

Smoldering-to-flaming transition tests were carried out to assess the increase in toxicity of pre-smoldering the foam cushion assemblies. Small-scale toxicity assessment of this combustion condition was recently conducted [8] for the NFR foam. In these small-scale tests, out of eighteen animals tested, 9 died within the 30 minute exposure and 5 died post-exposure. The last death was 14 days from the termination of the exposure. The multi-compartment tests showed that, at high concentrations, the resulting decomposition products were lethal within exposure for both the NFR and FR foam cushion assemblies, generally, killing all of the test animals. However, one post-exposure death was observed in the multi-compartment chair assembly tests as well as one post-exposure death during single compartment cushion assembly tests. Both post-exposure deaths were observed for the NFR foam assembly (i.e., within the first 24 hrs). While the single compartment tests were conducted at lower material concentrations than the multi-compartment tests, the results were not substantially different. In general, animal deaths occurred within exposure and, as just noted, no surviving animals died after the first 24 hrs post-exposure.

While every testing regime can develop combustion product concentrations resulting in the death of exposed animals, qualitative differences exist in the time of death between the large- and small-scale tests. Post-exposure (beyond 24 hrs) animal deaths are more likely in the NBS Toxicity Protocol than in the large-scale tests.

5.3 Mortality

The lack of post-exposure animal deaths in the earlier multi-compartment experiments prompted the decision to place animals into the burn room in a head-only exposure during smoldering combustion. The exposure times were greater than the 30 minutes used in the NBS Toxicity Protocol. Direct comparisons between animal responses in the large-scale tests and the NBS Toxicity Protocol could therefore not be made. Levin et al [9] have used rats similiar to those used in this investigation to study the relationship between exposure time and gas concentration for three simple gas mixtures - CO alone, CO with 5% CO_2, and CO plus 1/2 the LC_{50} concentration of HCN. Their study involved exposure times extending from 360 seconds to 3600 seconds. Their data can be summarized for each gas mixture by computing the time integrated CO concentration, CT, over the entire test period such that

$$CT = \sum_{i=1}^{n} [CO]\cdot(t_i - t_{i-1}) \ , \qquad (1)$$

where

$[CO]$ = CO concentration (ppm) at time t_i and

t_i = the i^{th} time interval (minutes).

Linear regression fits of their data are shown in figure 17. For illustrative purposes only, their data have been extrapolated to 9000 seconds - dotted lines in figure 17.

Equation (1) was applied to the burn room CO data for those tests involving smoldering combustion and burn room animal exposures. The CT values for CO at the time of burn room animal removal or death were computed. Burn room animal deaths occurred between 4290 seconds and 9000 seconds. These values are shown in figure 17 as individual data points for both NFR and FR assemblies.

If CO intoxication was the primary cause of death, the computed burn room CT values at death would be expected to be close to the CO line shown in figure 17. It can be seen that the large-scale CT data lie well below the extrapolated pure gas data. This indicates that other atmospheric agents were present during these tests to increase the toxic potency of the decomposition products beyond that accounted for by CO and CO in combination with CO_2. As previously noted, since little HCN is produced during smoldering combustion, attempts were made to detect the presence of TDI, with negative results.

Three possibilities exist to account for this level of toxicity: the existence of other direct toxicants; the existence of indirectly acting toxicants (i.e., a decomposition component that the body can metabolize to form a toxic product); or the effects of smoke particulates on the respiratory system. A more detailed analysis of the possible decomposition products may reveal other possible agents, directly or indirectly acting. However, additional thought must be directed to the effect of small- and large-scale tests on soot particulates which could affect the inhalation toxicity of the decomposition products.

5.4 LC_{50}

The LC_{50} values in the NBS Toxicity Protocol, based on mass consumed, for the two foams and cotton fabric were previously found to be:

Combustion Mode	Material	LC_{50} (30 min + 14 days) (mg/ℓ)
Non-Flaming	NFR	33
	FR	23
	Cotton	25
Flaming	NFR	>40
	FR	26
	Cotton	>50
Ramped	NFR	22

During the multi-compartment tests, no LC_{50} value could be determined for either NFR or FR chair assemblies undergoing smoldering combustion. While no LC_{50} could be determined for the smoldering-to-flaming tests of the FR chair assembly, the LC_{50} value for this test was less than 64 mg/ℓ. For the NFR chair assembly smoldering-to-flaming tests the LC_{50} was estimated to be between 44 mg/ℓ and 55 mg/ℓ.

For the single compartment large-scale tests, estimated LC_{50} values were:

Combustion Mode	Material	LC_{50} (30 min + 14 days) (mg/ℓ)
Smoldering	NFR-cushion	34
	FR-cushion	>24
Flaming	NFR-cushion	32
	FR-cushion	20-28
Smoldering-Flaming	NFR-cushion	46
	FR-cushion	26

An uncertainty of 15-40% has generally been associated with the NBS Toxicity Protocol determination of LC_{50}. This represents a 5 to 10 mg/ℓ variation about the reported LC_{50} value. These include the variabilities in the measurement process and animal responses. The large-scale tests can not be expected to have an error range better than the NBS Toxicity Protocol. Therefore, differences of less than about 40% are unimportant. Applying the lower error range to the results of both tests shows that for smoldering/non-flaming and flaming conditions the LC_{50} of the foam cushion assembly has an equivalent toxicity to the polyurethane foams in the NBS Toxicity Protocol. The smoldering-to-flaming large-scale experiments had an LC_{50} for NFR of 46 mg/ℓ and for FR of 26 mg/ℓ. Ramped two phase heating tests of the FR foam were not performed in the NBS Toxicity Protocol. The ramped two phase heating of NFR foam had an LC_{50} of 22 mg/ℓ. While these results differ by more than the upper error bound, it should be noted that the ramped two phase heating tests in the NBS Toxicity Protocol do not represent flaming combustion of the substrate residue and are, therefore, not comparable to the smoldering-to-flaming large-scale tests.

5.5 The N-Gas Model

Recently, the National Bureau of Standards has developed the N-Gas Model [9,10] which approximates the toxicity of combustion atmospheres based on the primary toxic gases generated during the flaming and thermal decomposition of materials. During the earlier multi-compartment experiments, the model used was based on the interaction of 3 gases, CO, CO_2, and HCN. It was empirically determined that combining 30 minute within-exposure deaths with 24 hour post-exposure deaths resulted in a model that related the three gas interaction by:

$$\frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}(HCN)} \geq 1, \qquad (2)$$

where m and b were the slope and y-intercept of the no death line of CO in the presence of CO_2 and [CO], [CO_2], and [HCN] are average atmospheric exposure concentrations during a 30 minute exposure period. Values for m and b have been recomputed to represent the LC_{50} line of CO in the presence of CO_2 and were found to be -18 and 121788, respectively. The LC_{50}(HCN) is 160 ppm, the lethal concentration of HCN that will kill 50% of the exposed animals in 30 minutes. Values below 1 indicate that no animals are expected to die, while a value of 1 or more indicates that animals would be expected to die from the exposure. Equation (1) has now been expanded to include the effects of reduced oxygen [8] by an additional term:

$$\frac{m[CO]}{[CO_2]-b} + \frac{[HCN]}{LC_{50}(HCN)} + \frac{21-[O_2]}{21-LC_{50}(O_2)} \geq 1, \qquad (3)$$

where $LC_{50}(O_2)$, the lethal concentration that will kill 50% of the animals, is 5.4%.

Tables 15 and 16 apply equation (3), the 4-gas model, to the data from the current set of experiments as well as to the multi-compartment experiments of foam cotton assemblies and to the NBS Toxicity Protocol tests on the individual components. The data are organized according to increasing N-gas model predictions within a test series. As was noted in the previous work [1], the

N-gas model, with N=3, did correctly predict animal survivability. In the current experiments, the N-gas model, with N=4, shows that for the single compartment tests there was sufficient CO, CO_2, HCN, and reduced O_2 to account for the observed deaths for both the FR and NFR foam cushion assemblies under all modes of decomposition. With the exception of one NFR exposure chamber containing combustion products resulting from smoldering-to-flaming combustion (i.e., 1.26), the largest 4-gas value associated with no animal deaths was 0.75. The FR foam cushion assembly tests exhibited a similar exception (i.e, 1.01), and the largest 4-gas value associated with no animal deaths was 0.95. Applying the 4-gas model to the NBS Toxicity Protocol results showed that the model correctly predicted no within- plus 24 hour post-exposure animal deaths, but underestimated the observed toxicity for the non-flaming and flaming tests by not including post-exposure deaths. For the ramped two phase non-flaming experiments, the N-gas model produced values between 0.95 and 1.58. This correctly predicts the within-exposure animal deaths. Again, post-exposure animal deaths were observed and not predicted by the model.

The 4-gas model correctly predicts within- plus 24 hour post-exposure animal deaths for model calculations resulting in values of 0.8 and greater for NFR foam and of 0.7 and greater for FR foam in the large-scale tests and in the NBS Toxicity Protocol.

6.0 SUMMARY

The large-scale experiments performed in this report represent a simplified geometric configuration extending the techniques of previous experiments conducted with the same materials. Using the same criteria developed for comparison of large-scale multi-compartment tests and the NBS Toxicity Protocol, the data from these experiments were compared to the previous results. The basis for a detailed comparison was determined by:

- The nature (yield) of the decomposition products and their contribution to the relative toxicity of the combustion atmospheres;
- The occurrence of death, whether within- or post-exposure;
- The similarity of LC_{50} values;

  and
- The predictability of the N-gas model with N=4 (CO_2, CO, HCN and O_2).

In addition, long term (1 to 2½ hr from the start of the experiment) burn room exposures were conducted to determine the possible impact of line losses on the observed toxicity of exposure chamber animals. The basis for evaluation was a comparison of animal responses during long term (up to 1 hr) pure gas (CO, CO_2 and HCN) exposures.

A comparison of gaseous yields between the large- and small-scale tests showed that, for both the FR and the NFR foams, the CO and CO_2 yields did not vary by more than a factor of 3, except for the NFR flaming CO yield following prolonged smoldering combustion, which showed a factor of 4 difference between the two large-scale tests. These differences, however, may not be significant because of multiple measurement errors.

Under flaming-only combustion conditions, the HCN yields for both FR and NFR were about the same for the small-scale and single compartment large-scale tests. The multi-compartment large-scale tests were an order of magnitude lower. During the flaming phase of the smoldering-to-flaming experiments, the HCN yield was greatest for the NBS Toxicity Protocol followed by the single compartment tests and the multi-compartment tests. Differences between the three tests varied by an order of magnitude for the NFR foam. For the FR foam, the NBS Toxicity Protocol and the single compartment tests were comparable, while the multi-compartment tests differed by less than a factor of three.

Comparing the yield ratios of CO_2/CO and HCN/CO for all three test conditions showed that good agreement was obtained for the FR foam with the exception of HCN/CO yield ratio during flaming combustion in the NBS Toxicity Protocol. Good agreement was also observed for 5 of the 8 groups of measurements for the NFR foam. The exceptions were flaming combustion CO_2/CO yield ratios for the multi-compartment and NBS Toxicity Protocol and for the HCN/CO yield ratio for the NBS Toxicity Protocol.

As observed in the previous large-scale multi-compartment tests, no post-exposure animal deaths were observed beyond the first 24 hours in the large-scale single compartment tests. This is in sharp contrast to the large number of post-exposure deaths beyond the first 24 hours observed in the NBS Toxicity Protocol. The N-gas model did not predict these deaths, since it was developed to predict within-exposure plus 24 hour deaths. A qualitative difference (the time at which animal deaths are observed) remains unexplained between large-scale tests and the NBS Toxicity Protocol.

Under those conditions where an LC_{50} value could be computed, the single compartment results were in reasonable agreement with the NBS Toxicity Protocol, assuming that the large-scale single compartment tests had a range of uncertainty comparable to the NBS Toxicity Protocol.

With several exceptions, the N-gas model (with N=4) provided a reasonable assessment of within-exposure deaths of all three test conditions. Only twice out of 24 exposures during the single compartment experiments did the N-gas model predict within-exposure animals deaths and none were observed.

Long term burn room animal exposures during smoldering decomposition showed that toxic atmospheres could be developed. Although lethal concentrations of CO and CO_2 were insufficient to account for the observed within-exposure deaths (which is consistent with the NBS Toxicity Protocol results), no post-exposure deaths beyond the first 24 hours were recorded. No animal deaths were observed during smoldering decomposition of FR foam assembly. This was due to the apparent extinguishment of the assembly and not to the inherent reduced toxicity of its decomposition products.

7.0 CONCLUSIONS

Ten large-scale single compartment fire tests were performed using two polyurethane foams and a cotton upholstery fabric. The toxicological and combustion results of these tests were compared to previous small- and large-scale tests on the same materials. It was found that:

- Within an order-of-magnitude both the large-scale tests and the NBS Toxicity Protocol yield similar LC_{50} results. However, the qualitative differences in time of animal deaths between small- and large-scale tests indicate that significant differences exist.
- Based on HCN production, the decomposition mechanisms in the large- and small-scale tests are not the same.
- The N-gas model for 4 gases, CO, CO_2, HCN and reduced O_2, was able to account for animal deaths within-exposure plus 24 hours during the large-scale tests and the lack of within-exposure plus 24 hours animal deaths during the small-scale tests.
- Burn room animal deaths, associated with smoldering fires, could not be accounted for by the concentrations of the four gases used in the N-gas model.

8.0 RECOMMENDATIONS

While the N-gas model has proven to be a useful predictive tool for within-exposure plus 24 hour deaths in both large- and small-scale tests, the current lack of correlation with regard to post-exposure deaths beyond 24 hours suggests further avenues of research. These are:

1. Because of the varying relative importance of HCN and the currently unknown toxicants, true smoldering combustion should be studied in the NBS Toxicity Protocol. This can be accomplished with the cotton fabric and foam assemblies studied in this report.

2. The search for the unknown toxicant(s) produced during smoldering and non-flaming combustion of flexible polyurethane foam should continue and be expanded to include a study of the effects of particulates on the observed toxicity of smoke from polyurethane foam and cotton fabric. Particulate characterization for smoldering and non-flaming modes of decomposition should be conducted and correlated to the observed animal responses.

3. While a relationship has been developed between the large-scale tests and the NBS Toxicity Protocol, this has been limited to a detailed study of polyurethane foam and cotton fabric combustion. More materials need to be investigated in large- and small-scale studies to determine the universality of the existing work.

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Table 1

Test Plan for Single Compartment Experiments

			Within Room		External Chamber	
Test #	Sample	Combustion Mode	Number of Animals	Exposure Condition	Number of Animals	Exposure Condition
1	NFR[a]	Smoldering	6	Sm[d]	0	--
2	FR[b]	Smoldering	6	Sm	0	--
3	NFR	Smoldering	2	Sm	18	Sm
4	FR	Smoldering	2	Sm	18	Sm
5	NFR	Flaming	0	--	18	Fl[e]
6	FR	Flaming	0	--	18	Fl
7	NFR	Smolder/Flame[c]	2	Sm	18	Fl
8	FR	Smolder/Flame	2	Sm	18	Fl
9	NFR	Smolder/Flame	6	Sm	18	Fl
10	FR	Smolder/Flame	6	Sm	18	Fl

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a) NFR: Non-Fire Retardant
b) FR: Fire Retardant
c) Smolder/Flame: Smoldering-to-Flaming Transition Tests
d) Sm: Animals Exposed to Products of Smoldering Decomposition
e) Fl: Animals Exposed to Products of Flaming Decomposition

Table 2

Construction Materials of Large-Scale Single Compartment Tests

Location	Material	Thickness (mm)	Density (kg/m^3)
Ceiling and Wall substrate	Gypsum Board	12.7	930
Ceiling and Wall interior finish	Calcium Silicate	12.7	720
Floor substrate	Concrete	102	2280
Floor interior finish	Gypsum Board	12.7	930

Table 3

Location of Instrumentation

Burn Room

Load Cell

load platform 06.m by 0.6 m, 0.3 m from floor (1.23 m from north wall and 2.16 m from east wall).

Thermocouple Trees

Tree 1 - Southeast corner (0.6 m from the south and east walls)
10 thermocouples; 0.15, 0.66, 0.97, 1.12, 1.27, 1.42, 1.57, 1.88, 2.03, and 2.15 m from the floor.

Tree 2 - Center of room (1.23 m from the north wall and 1.85 m from the east wall)
10 thermocouples; 0.15, 0.66, 0.97, 1.12, 1.27, 1.42, 1.57, 1.88, 2.03, and 2.15 m from the floor.

Tree 3 - Northwest corner (0.6 m from the north and west walls)
10 thermocouples; 0.15, 0.66, 0.97, 1.12, 1.27, 1.42, 1.57, 1.88, 2.03, and 2.15 m from the floor.

Thermocouple

North Wall - 4 thermocouples end of animal holding tubes (0.3 m from north wall and 0.3 m from ceiling).

2 thermocouples in burn room animal restrainers.

Animal Exposure Chambers - 3 thermocouples, one for each exposure chamber.

Smoke Meters

Vertical - 1 smoke meter (1.23 m from north wall and 1.39 m from east wall).

Horizontal - 6 smoke meters (1.39 m from east wall)
0.61, 0.91, 1.22, 1.52, 1.83, and 2.29 m from floor.

Gas Probes

Burn Room - CO, CO_2, O_2
Ceiling - 0.3 m from the ceiling (1.23 m from the north wall and 2.15 m from the east wall).

Floor - 0.3 m from the floor (0.6 m from the south wall and 0.6 m from the west wall).

HCN
taken from animal exposure chamber sampling line.

Animal Exposure Chambers - CO, CO_2, and O_2, port for HCN.

Table 4

Average Initial and Maximum Mass Loss Rates for FR and NFR Polyurethane Foam and Cotton Fabric Cushion Assemblies Exposed to a Smoldering Cigarette

Material	Test #	Average Mass Loss Rate (mg/s) Initial	Average Mass Loss Rate (mg/s) Maximum	Material[c] Consumed (%)
NFR[a]	1	56	320	35
	3	53	570	56
FR[b]	2	29	120	26
	4	36	130	33

---

a) Non-Fire Retarded Foam
b) Fire Retarded Foam
c) mass consumed/initial mass

Table 5

Extreme Gas Concentrations of CO, CO_2, and O_2 Near the Burn Room Ceiling During Smoldering Combustion

Material	Test Number	Time[a] (s)	Maximum CO (ppm)	Maximum CO_2 (%)	Minimum O_2 (%)
NFR[b]	1	7000	2300	0.6	19.8
	3	6119	4800	0.9	19.1
FR[c]	2	7950	2100	0.6	20.1
	4	9391	2900	0.8	19.9

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a) Time of maximum CO concentration
b) Non-Fire Retarded Foam
c) Fire Retarded Foam

Table 6

Extreme Gas Concentrations of CO, CO_2, HCN, and O_2 Near the Burn Room Ceiling During Flaming Combustion of Cushion Assemblies

		Maximum Gas Concentration and Time						Minimum	
Material	Test #	CO (ppm)	Time[a] (s)	CO_2 (%)	Time[b] (s)	HCN (ppm)	Time[c] (s)	O_2 (%)	Time[d] (s)
NFR[e]	5	5900	1800	7.1	1440	104	1440	11.4	1440
FR[f]	6	4600	2460	4.3	2160	168	1920	14.7	2160

Time to:
- a) Maximum CO
- b) Maximum CO_2
- c) Maximum HCN
- d) Minimum O_2

e) Non-Fire Retarded Foam

f) Fire Retarded Foam

Table 7

Average Mass Burning Rate for FR and NFR Cushion Assemblies During Smoldering and Flaming Decomposition

		Mass Loss Rate (mg/s)		
		Smoldering		Flaming
Material	Test #	Initial	Maximum	Maximum
NFR[a]	7	56	290	1820
	9	48	220	2120
FR[b]	8	31	130	3400
	10	32	120	2830

---

a) Non-Fire Retarded Foam
b) Fire Retarded Foam

Table 8
Comparison of the CO, CO_2, and HCN Gas Yields for the Large-Scale Fire Tests

Material	Test #	CO (kg/kg)		CO_2 (kg/kg)		HCN (kg/kg)
		Smolder	Flame	Smolder	Flame	Flame
NFR[a]	1	0.08	---	0.4	---	---
	3	0.11	---	0.3	---	---
	5	---	0.09	---	1.9	2×10^{-3}
	7	0.08	0.11	0.4	2.6	3×10^{-3}
	9	0.07	0.12	0.4	2.2	3×10^{-3}
FR[b]	2	0.11	---	0.5	---	---
	4	0.08	---	0.5	---	---
	6	---	0.10	---	1.3	4×10^{-3}
	8	0.14	0.15	0.7	2.2	1×10^{-2}
	10	0.11	0.11	0.6	2.1	1×10^{-2}

---

a) Non-Fire Retarded Foam

b) Fire Retarded Foam

Table 9

Summary of Results for Burn Room Animal Exposures During the Smoldering Combustion Phase of NFR Foam Cushion Assemblies

				Average[a]						At Time of Animal Removal				
Test #	Animal #	Removal Time (s)	Animal Condition	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	Temp[c] °C	Sum of CO[b] (ppm-m)	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	Temp[c] °C
1	1	6270	Alive	10	500	0.22	20.5	31	50,000	27	1800	0.50	20.0	37
	6	6870	Alive	12	600	0.25	20.5	32	71,000	35	2300	0.60	19.8	36
	5	7100	Died	13	650	0.26	20.5	32	80,000	37	2200	0.63	19.8	35
	3	7170	Died	13	675	0.26	20.5	32	82,000	37	2200	0.63	19.8	35
	4	7200	Died	13	700	0.26	20.5	33	83,000	37	2400	0.65	19.8	33
	2	7930	Died	15	825	0.30	20.4	32	109,000	39	2100	0.63	19.9	30
3	2	5520	Died	5	570	0.12	20.7	32	52,000	27	2700	0.44	19.9	42
	1	5655	Died	7	640	0.13	20.7	32	60,000	31	3400	0.60	19.6	45
7	1	4380	Died	3	315	0.10	20.7	30	23,000	15	1300	0.47	20.3	35
	2	5370	Died	7	660	0.21	20.6	33	59,000	38	3200	1.04	19.3	36
9	1-6[d]	8200	Died[e]	7	560	0.19	20.2	35	77,000	29	2600	0.86	19.5	40

---

a) Average over entire exposure time
b) Summed (integrated) CO data, i.e., ΣCt
c) Nose Temperature
d) All animals removed at the same time
e) 3 animals died within exposure
3 animals died within 24 hrs of exposure

Table 10

Summary of Results for Burn Room Animal Exposures During the Smoldering Combustion Phase of FR Foam Cushion Assemblies

				Average[a]					Sum of	At Time of Animal Removal				
Test #	Animal #	Removal Time (s)	Animal Condition	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	Temp[c] °C	CO[b] (ppm-m)	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	Temp[c] °C
2	1	4830	Alive	2	230	0.03	20.8	26	19,000	4	800	0.12	20.6	30
	6	6540	Alive	3	450	0.09	20.6	27	49,000	12	1400	0.38	20.4	32
	5	7225	Alive[d]	4	550	0.12	20.6	28	67,000	14	1500	0.47	20.2	32
	2	7815	Alive	5	650	0.15	20.5	28	85,000	16	1800	0.51	20.1	32
	3	8295	Died	6	720	0.17	20.4	28	99,000	19	1900	0.52	20.1	32
	4	8295	Died	6	720	0.17	20.4	28	99,000	19	1900	0.52	20.1	32
4	2	4290	Died	1	240	0.07	20.8	28	17,000	3	700	0.16	20.7	31
	1	6960	Died	3	600	0.15	20.6	29	69,000	13	1900	0.44	20.3	33
8	1	7035	Died	4	700	0.17	20.6	29	82,000	15	2100	0.57	20.2	34
	2	7200	Died	4	740	0.18	20.6	29	89,000	16	2500	0.64	20.1	35
10	1-6[e]	9000	Died[f]	5	950	0.22	20.5	28	143,000	18	2500	0.64	20.1	30

---

a) Average over entire exposure time
b) Summed (integrated) CO data, i.e. ΣCT
c) Nose Temperature
d) Died within 24 hrs
e) All animals removed at the same time
f) 1 animal died within exposure
   2 animals died within 24 hrs of exposure
   3 Survived the exposure

Table 11

Conditions in Animal Exposure Chambers and Animal Responses During FR and NFR Smoldering Combustion Exposures

		Mass Cons.	Average Gas Concentrations				No.Died/No.Tested	
Test #	Material	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	HCN (ppm)	Within Exp.	Post-Exp.
3	NFR[a]	15	1300	0.8	19.6	3	0/6	0/6
		30	3300	1.4	18.5	20	1/6	0/6
		32	3800	1.1	19.1	15	2/6	0/6
4	FR[b]	13	1300	0.3	19.8	4	0/6	0/6
		20	2000	0.5	19.6	6	0/6	0/6
		24	2200	0.6	19.9	5	0/6	0/6

---

a) Non-Fire Retardant
b) Fire Retardant

Table 12

Conditions in Animal Exposure Chambers and Animal Responses During FR and NFR Flaming Combustion Exposures

			Mass Cons.	Average Gas Concentrations				No.Died/No.Tested	
Material	Test #	Mode of Decomp	Loading (mg/ℓ)	CO (ppm)	CO_2 (%)	O_2 (%)	HCN (ppm)	Within Exp.	Post-Exp.
NFR[a]	5	Flaming	29	1400	3.8	16.5	25	0/6	0/6
			33	2100	5.2	13.7	62	5/6	0/6
			39[d]	4100	6.4	16.1	67	6/6	0/6
	7	Smold/Flam[c]	44	2800	3.0	17.2	40	1/6	1/6
			55	4200	4.7	15.2	71	6/6	0/6
			62[d]	6300	4.9	18.5	79	6/6	0/6
	9	Smold/Flam	19	1500	1.5	19.2	32	0/6	0/6
			40	3500	3.0	17.0	51	0/6	0/6
			71	6800	3.7	18.0	72	6/6	0/6
FR[b]	6	Flaming	19	1700	2.7	18.0	69	0/6	0/6
			25	1900	3.5	16.1	82	4/6	0/6
			33[d]	3000	4.3	18.0	73	5/6	0/6
	8	Smold/Flam	40	3700	3.5	16.5	170	6/6	0/6
			55	4200	---[e]	14.3	200	6/6	0/6
			58[d]	6400	5.7	18.2	200	6/6	0/6
	10	Smold/Flam	20	1700	1.3	19.6	102	0/6	0/6
			33	3000	3.1	17.0	219	6/6	0/6
			42	4100	3.7	17.1	169	6/6	0/6

---

a) Non-Fire Retardant
b) Fire Retardant
c) Smoldering-to-Flaming Experiments
d) Corrected for the addition of O_2
e) Instrument failure

Table 13

Comparison of CO_2/CO and HCN/CO Yield Ratios for Single Compartment, and Multi-Compartment Large-Scale Tests with the NBS Toxicity Protocol for Non-Fire Retardant (NFR) and Fire Retardant (FR) Foams

Combustion Mode	Test Environment	Cotton Cover	Material			
			NFR		FR	
			CO_2/CO	HCN/CO	CO_2/CO	HCN/CO
NF[a]	NBS Tox Pro[b]	-[h]	7	0.01	8	0.01
S[c]	Multi-Comp	+[i]	-[d]	-	-	-
S	Single Comp	+	5	ND[e]	6	ND
F[f]	NBS Tox Pro	-	80	0.10	30	0.12
F	Multi-Comp	+	70	0.01	40	0.01
F	Single Comp	+	20	0.02	15	0.03
S/F[g] NF	NBS Tox Pro	-	ND	ND	ND	ND
S	Multi-Comp	+	7	<0.01	5	<0.001
S	Single Comp	+	5	ND	5	ND
S/F R[j]	NBS Tox Pro	-	ND	ND	ND	ND
F	Multi-Comp	+	30	0.04	20	0.03
F	Single Comp	+	20	0.03	20	0.08

---

a) Non-Flaming (i.e., pyrolytic combustion)
b) NBS Toxicity Protocol
c) Smoldering Combustion
d) Test Not Performed
e) Not Determined
f) Flaming Combustion
g) Smoldering-to-Flaming Combustion results reported individually as smoldering phase and flaming phase
h) cotton cover fabric not present
i) cotton cover fabric present
j) Ramped heating from NF state

Table 14

Comparison of CO, CO_2, and HCN Average Yield Values for Single Compartment, and Multi-Compartment Large-Scale Tests with the NBS Toxicity Protocol for Non-Fire Retardant (NFR) and Fire Retardant (FR) Foams

Combustion Mode	Test Environment	Cotton Cover	Material					
			NFR			FR		
			CO (kg/kg)	CO_2 (kg/kg)	HCN[k] (kg/kg)	CO (kg/kg)	CO_2 (kg/kg)	HCN[k] (kg/kg)
NF[a]	NBS Tox Pro[b]	-[h]	0.03	0.2	4×10^{-4}	0.04	0.3	3×10^{-3}
S[c]	Multi-Comp	+[i]	-[d]	-	-	-	-	-
S	Single Comp	+	0.09	0.4	-	0.11	0.6	-
F[f]	NBS Tox Pro	-	0.02	1.6	2×10^{-3}	0.05	1.6	6×10^{-3}
F	Multi-Comp	+	0.04	2.9	2×10^{-4}	0.06	2.2	4×10^{-4}
F	Single Comp	+	0.11	2.2	2×10^{-3}	0.12	1.9	4×10^{-3}
S/F[g] NF	NBS Tox Pro	-	ND	ND	ND	ND	ND	ND
S	Multi-Comp	+	0.15	1.0	$<1 \times 10^{-4}$	0.17	0.7	$<1 \times 10^{-4}$
S	Single Comp	+	0.08	0.4	-	0.13	0.7	-
S/F R[j]	NBS Tox Pro	-	ND	ND	1×10^{-2}	ND	ND	1×10^{-2}
F	Multi-Comp	+	0.09	2.8	2×10^{-4}	0.12	2.7	4×10^{-3}
F	Single Comp	+	0.40	2.4	3×10^{-3}	0.13	2.2	1×10^{-2}

---

a) Non-Flaming (i.e., pyrolytic combustion)
b) NBS Toxicity Protocol
c) Smoldering Combustion
d) Test Not Performed
e) Not Determined
f) Flaming Combustion
g) Smoldering-to-Flaming Combustion results reported individually as smoldering phase and flaming phase
h) cotton cover fabric not present
i) cotton cover fabric present
j) Ramped heating from NF state
k) Values taken from previous report [1] have been rounded-off to more accurately reflect measurement accuracies.

Table 15

Comparison of N-Gas Model Calculations with Chemical and Toxicological Results in Animal Exposure Chambers for Single Compartment Tests and Selected Multi-Compartment and NBS Toxicity Protocol Tests for Non-Fire Retardant (NFR) Foam alone and in Combination with Haitian Cotton Cover Fabric

		Average Gas Concentration				No. Died/No. Tested			Prediction N-Gas Model
Mode of Decomposition	Source	CO (ppm)	CO_2 (%)	O_2 (%)	HCN (ppm)	Within Exp	Post Exp	Latest Day of Death	Within-Exp+24 hrs
Smoldering	Chair[a]	150	0.3	20.6	ND[f]	0/6	0/6	---	0.02
		700	0.5	20.3	2	0/6	0/6	---	0.11
		1050	0.8	20.2	ND	0/6	0/6	---	0.17
Smoldering	Cushion[b]	1300	0.8	19.6	3	0/6	0/6	---	0.31
		3800	1.1	19.1	20	0/6	1/6	1	0.83
		3300	1.4	18.5	15	2/6	0/6	---	0.84
Non-Flaming	Foam[c]	710	0.5	20.4	10	0/6	1/6	28	0.35
		1160	0.3	20.4	11	0/6	2/6	2	0.35
		1400	0.4	20.2	--	0/6	3/6	8	0.40
Non-Flaming	Cotton[c]	2050	1.1	20.1	--	0/6	4/6	3	0.48
		2570	1.2	19.7	--	0/6	5/6	1	0.61
		3200	1.5	19.6	--	0/6	4/6	2	0.77
Flaming	Chair[a,d]	----	---	----	--	---	---	---	----
Flaming	Cushion[b]	1400	3.8	16.5	25	0/6	0/6	---	0.75
		2100	5.2	13.7	62	5/6	0/6	---	1.40
		4100	6.4	16.1	67	6/6	0/6	---	2.01
Flaming	Foam[c]	320	2.3	18.4	--[g]	0/6	0/6	---	0.08
		420	2.7	17.7	--	0/6	0/6	---	0.11
		670	3.1	17.2	--	0/6	0/6	---	0.73
Flaming	Cotton[c]	900	---[e]	18.9	<1	0/6	0/6	---	
		1070	2.9	18.1	--	0/6	0/6	---	0.30
		1480	3.1	17.5	2	0/6	0/6	---	0.43
Smoldering/ Flaming	Chair[a]	2050	4.5	15.6	20	3/6	1/6	1	0.95
		1810	7.5	13.0	119	6/6	0/6	---	1.95
Smoldering/ Flaming	Cushion[b]	1500	1.5	19.2	32	0/6	0/6	---	0.56
		2800	3.0	17.2	40	1/6	1/6	1	1.04
		3500	3.0	17.0	51	0/6	0/6	---	1.26
		4200	4.7	15.2	71	6/6	0/6	---	1.83
		6800	3.7	18.0	72	6/6	0/6	---	2.09
		6300	4.9	18.5	72	6/6	0/6	---	2.21
Ramped-2 Phase Heating	Foam[c]	2160	0.4	20.2	91	3/6	3/6	4	0.95
		2140	0.5	20.0	90	0/6	2/6	14	0.96
		3380	0.6	19.8	156	6/6	0/6	0	1.58

---

a) Burn Room, Multi-Compartment Test
b) Burn Room, Single Compartment Test
c) NBS Toxicity Protocol
d) Not Tested with Animals
e) Instrument Failure
f) Not Detected
g) HCN not measured during animal tests, but analytical results showed HCN less than 44 ppm

Table 16

Comparison of N-Gas Model Calculations with Chemical and Toxicological Results in Animal Exposure Chambers for Single Compartment Tests and Selected Multi-Compartment and NBS Toxicity Protocol Tests for Fire Retardant (FR) Foam alone and in Combination with Haitian Cotton Cover Fabric

		Average Gas Concentration				No. Died/No. Tested			
Mode of Decomposition	Source	CO (ppm)	CO_2 (%)	O_2 (%)	HCN (ppm)	Within Exp	Post Exp	Latest Day of Death	Prediction N-Gas Model Within-Exp+24 hrs
Smoldering	Chair[a]	420	0.3	20.6	<1	0/6	0/6	---	0.06
		700	0.4	20.3	2	0/6	0/6	---	0.11
		1100	0.7	20.4	ND	0/6	0/6	---	0.17
Smoldering	Cushion[b]	1300	0.3	19.8	4	0/6	0/6	---	0.27
		2000	0.5	19.6	6	0/6	0/6	---	0.40
		2200	0.6	19.9	5	0/6	0/6	---	0.41
Non-Flaming	Foam[c]	700	0.3	20.5	1	0/6	2/6	2	0.15
		860	0.4	20.4	5	1/6	5/6	10	0.19
		880	0.3	20.4	2	0/6	4/6	5	0.19
Non-Flaming	Cotton[c]	2050	1.1	20.1	--	0/6	4/6	3	0.48
		2570	1.2	19.7	--	0/6	5/6	1	0.61
		3200	1.5	19.6	--	0/6	4/6	2	0.77
Flaming	Chair[a,d]	----	---	----	--	---	---	---	----
Flaming	Cushion[b]	1700	2.7	18.0	69	0/6	0/6	---	0.95
		1900	3.5	16.1	82	4/6	4/6	---	1.22
		3000	4.3	18.0	73	5/6	5/6	---	1.33
Flaming	Foam[c]	1000	2.0	18.5	80	1/6	1/6	13	0.76
		1090	2.1	18.2	70	1/6	3/6	11	0.72
		1280	2.8	17.6	140	2/6	3/6	1	1.23
Flaming	Cotton[c]	900	---[e]	18.9	<1	0/6	0/6	---	
		1070	2.9	18.1	--	0/6	0/6	---	0.30
		1480	3.1	17.5	2	0/6	0/6	---	0.43
Smoldering/ Flaming	Chair[a]	2900	1.0	16.0	145	6/6	0/6	---	1.70
		2600	4.7	15.2	123	6/6	0/6	---	1.77
Smoldering/ Flaming	Cushion[b]	1700	1.3	19.6	102	0/6	0/6	---	1.01
		3700	3.5	16.5	170	6/6	0/6	---	2.12
		4100	3.7	17.1	169	6/6	0/6	---	2.14
		3000	3.1	17.0	219	6/6	0/6	---	2.22
		4200	---[e]	14.3	200	6/6	0/6	---	
		6400	5.7	18.2	200	6/6	0/6	---	3.21

---

a) Burn Room, Multi-Compartment Test
b) Burn Room, Single Compartment Test
c) NBS Toxicity Protocol
d) Not Tested with Animals
e) Instrument Failure
f) Not Detected

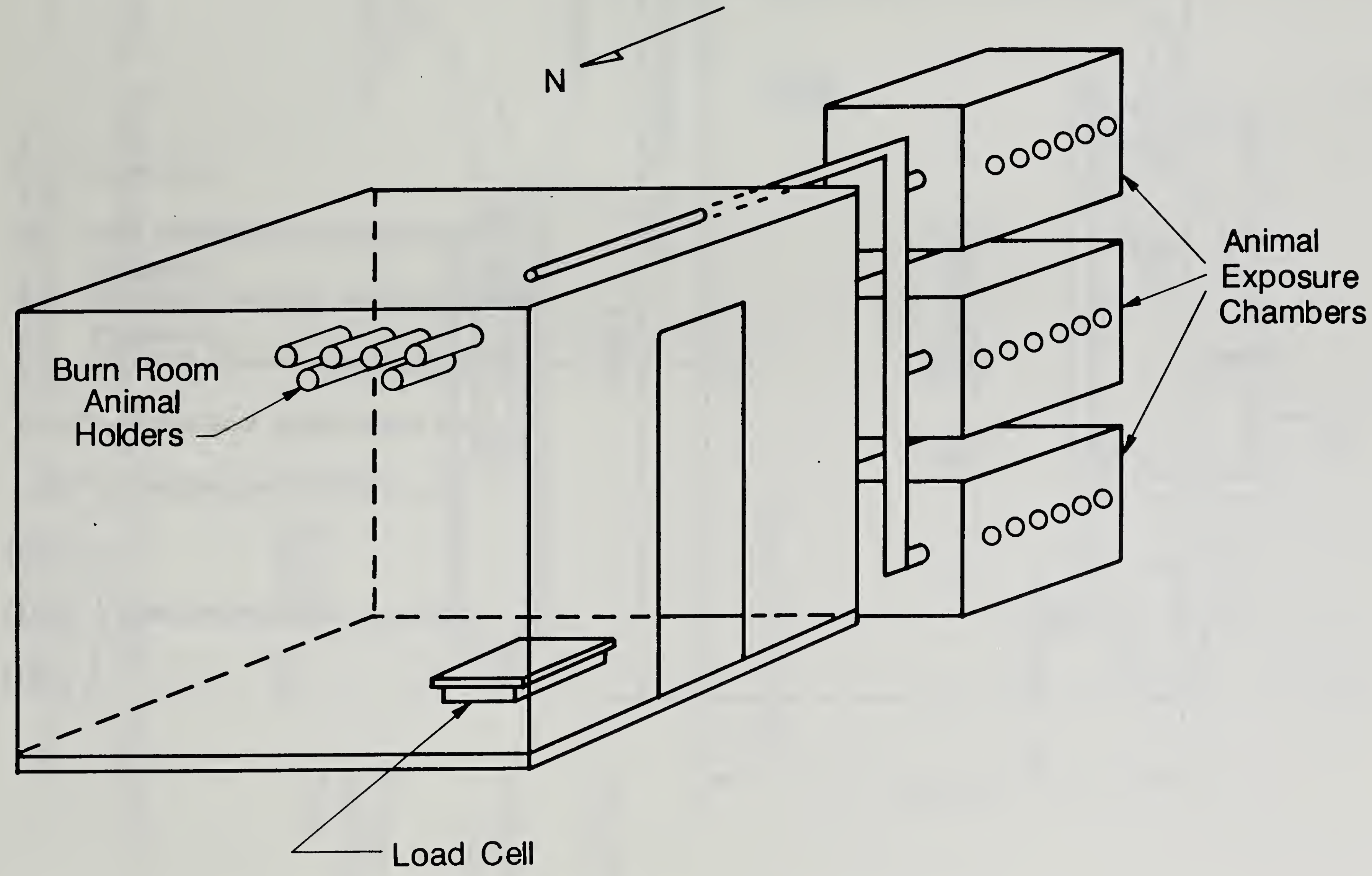


Figure 1. Configuration of Test Room Showing the Sampling Locations for Burn Room Animal Exposures and Exposure Chamber Animal Exposures.

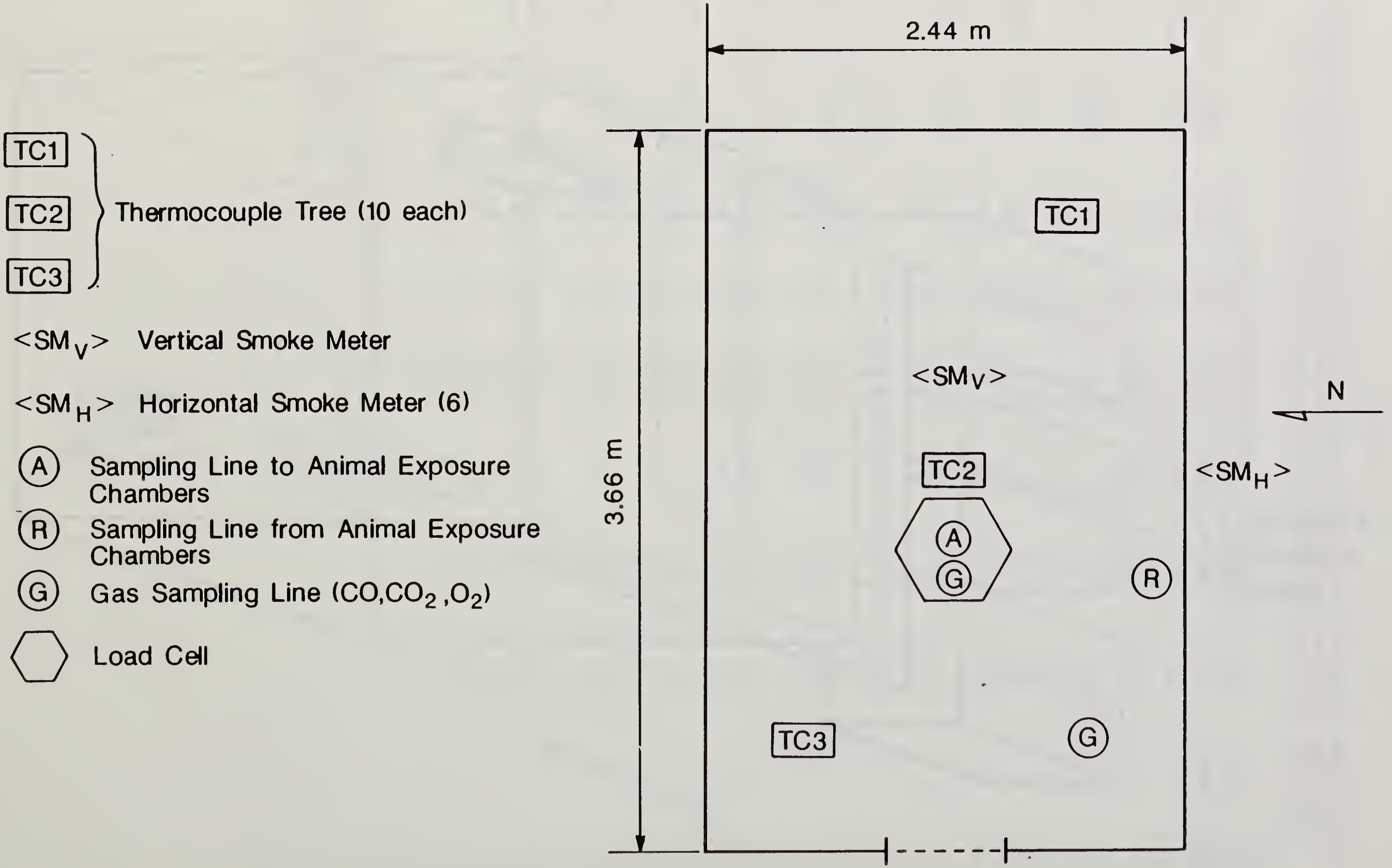
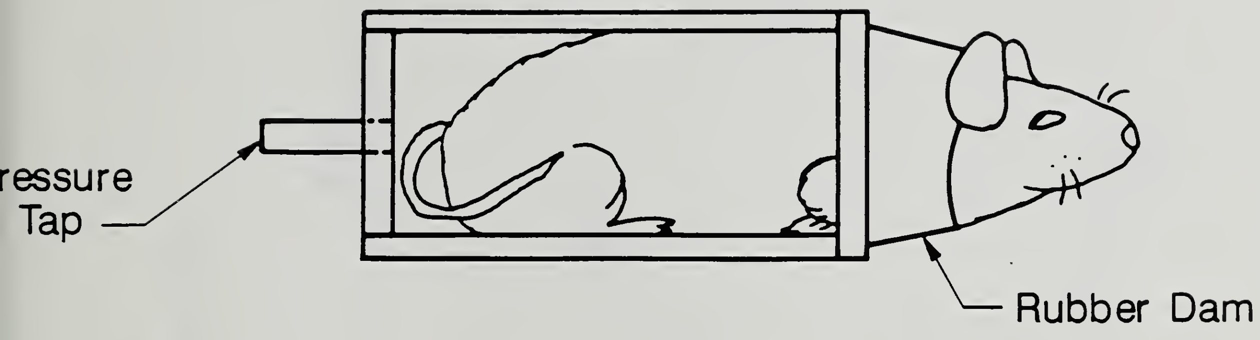
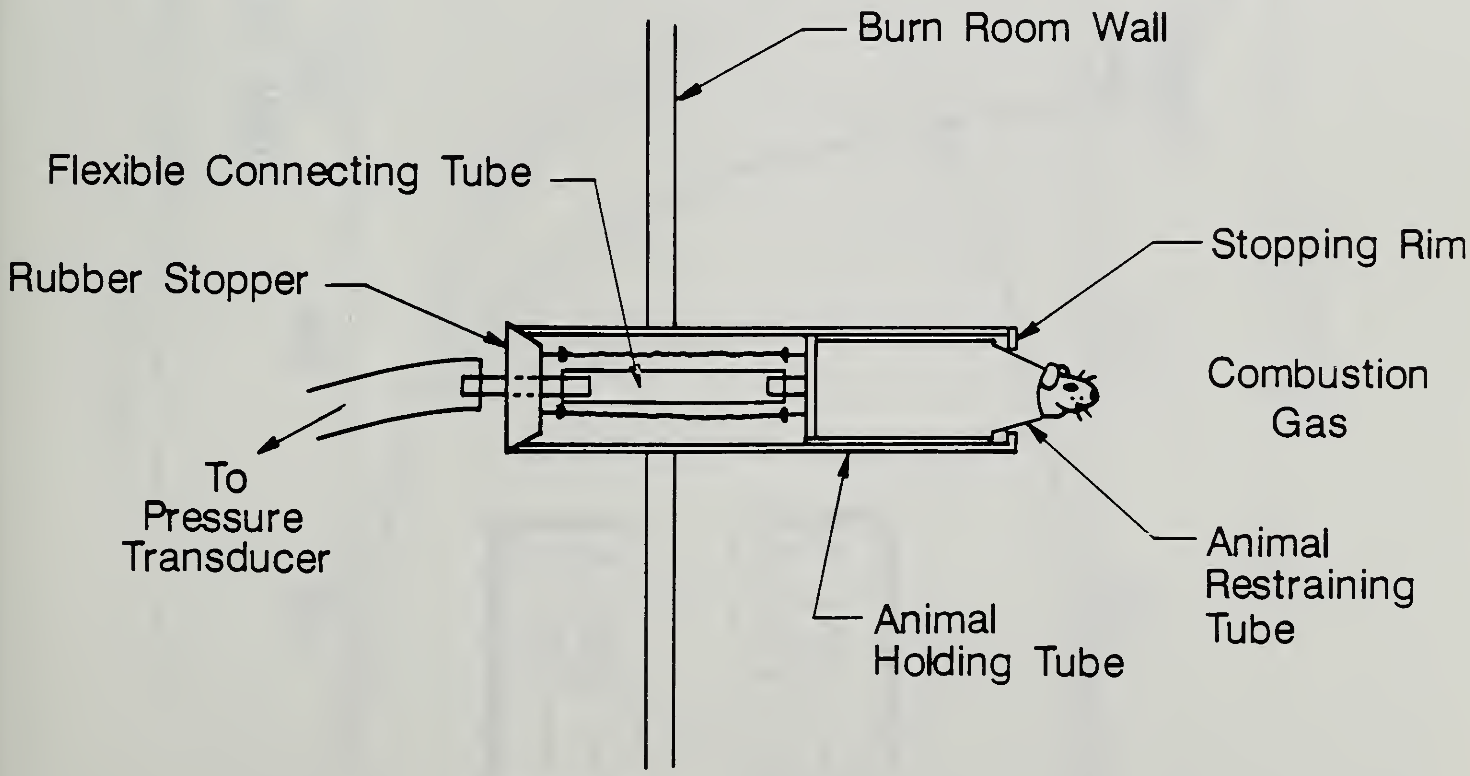


Figure 2. Schematic Floor Plan of Large-Scale Single Room Compartment Test Facility Showing Instrument Locations.



(a) ANIMAL RESTRAINING TUBE



(b) ANIMAL RESTRAINING TUBE PLACED IN ANIMAL HOLDING TUBE

Figure 3. Schematic Representation of Burn Room Animal Restrainers Mounted in Burn Room Wall.

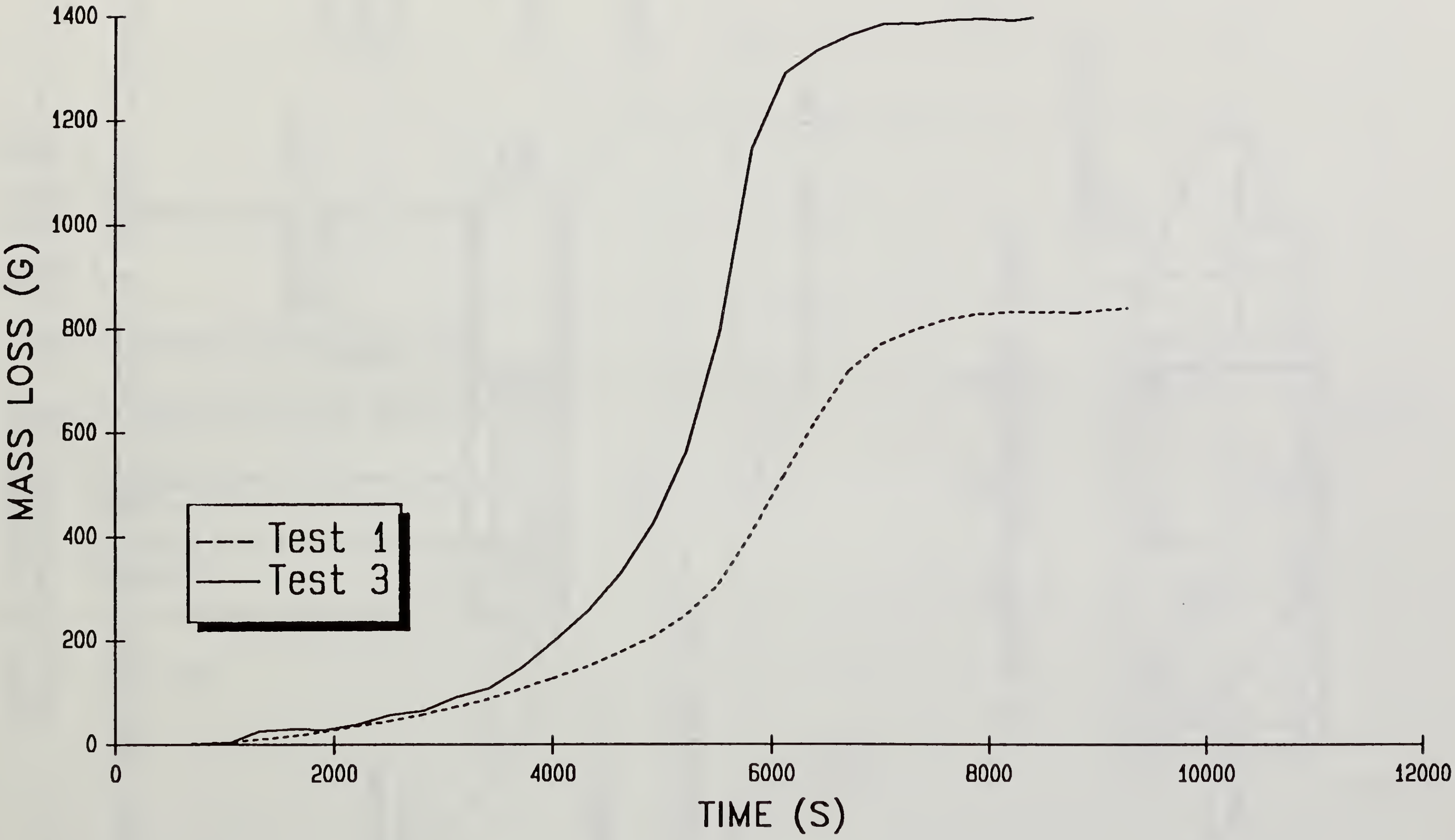


Figure 4. Mass Loss of NFR Cushion Assemblies During Smoldering Decomposition.

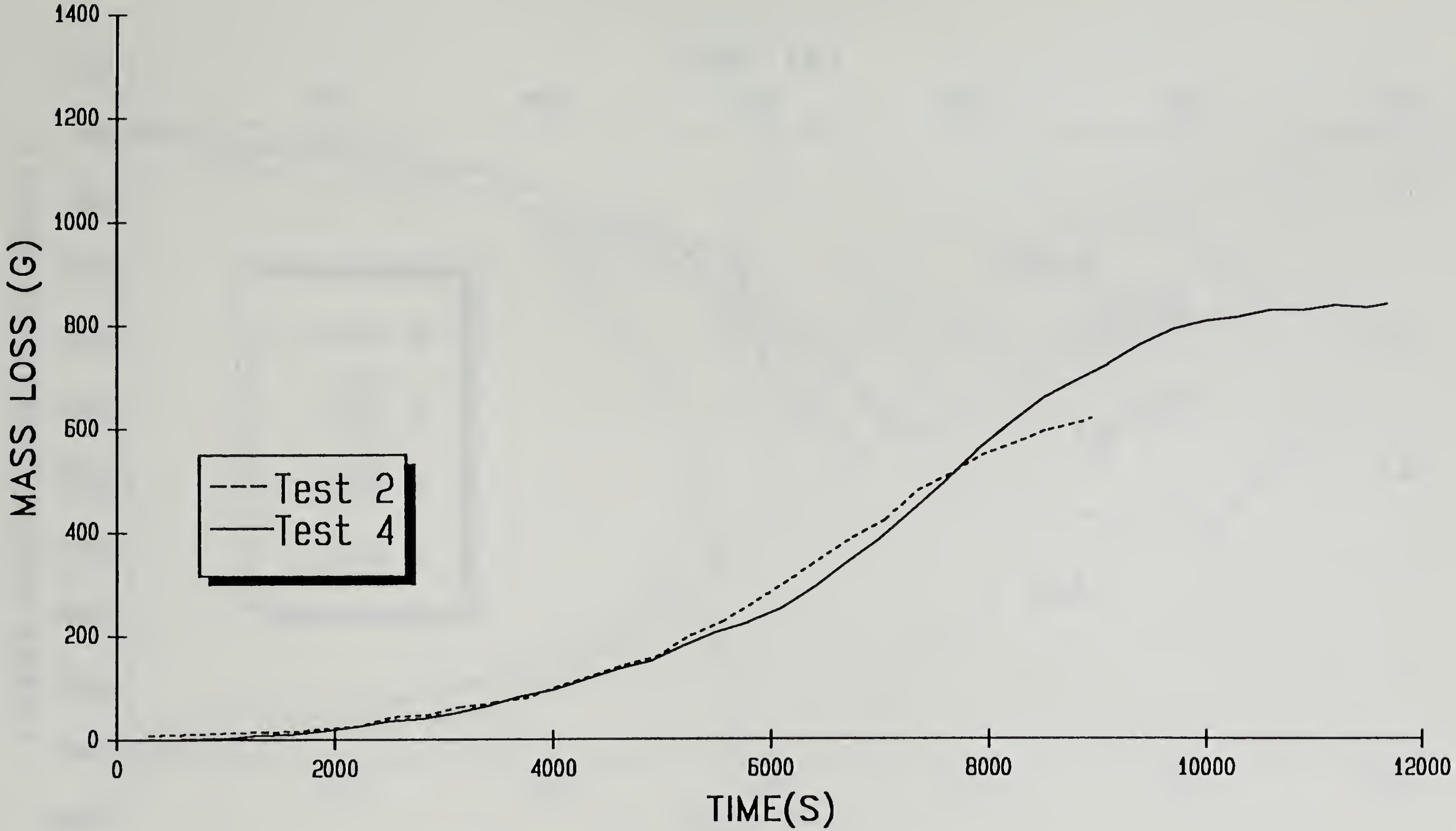


Figure 5. Mass Loss of FR Cushion Assemblies During Smoldering Decomposition.

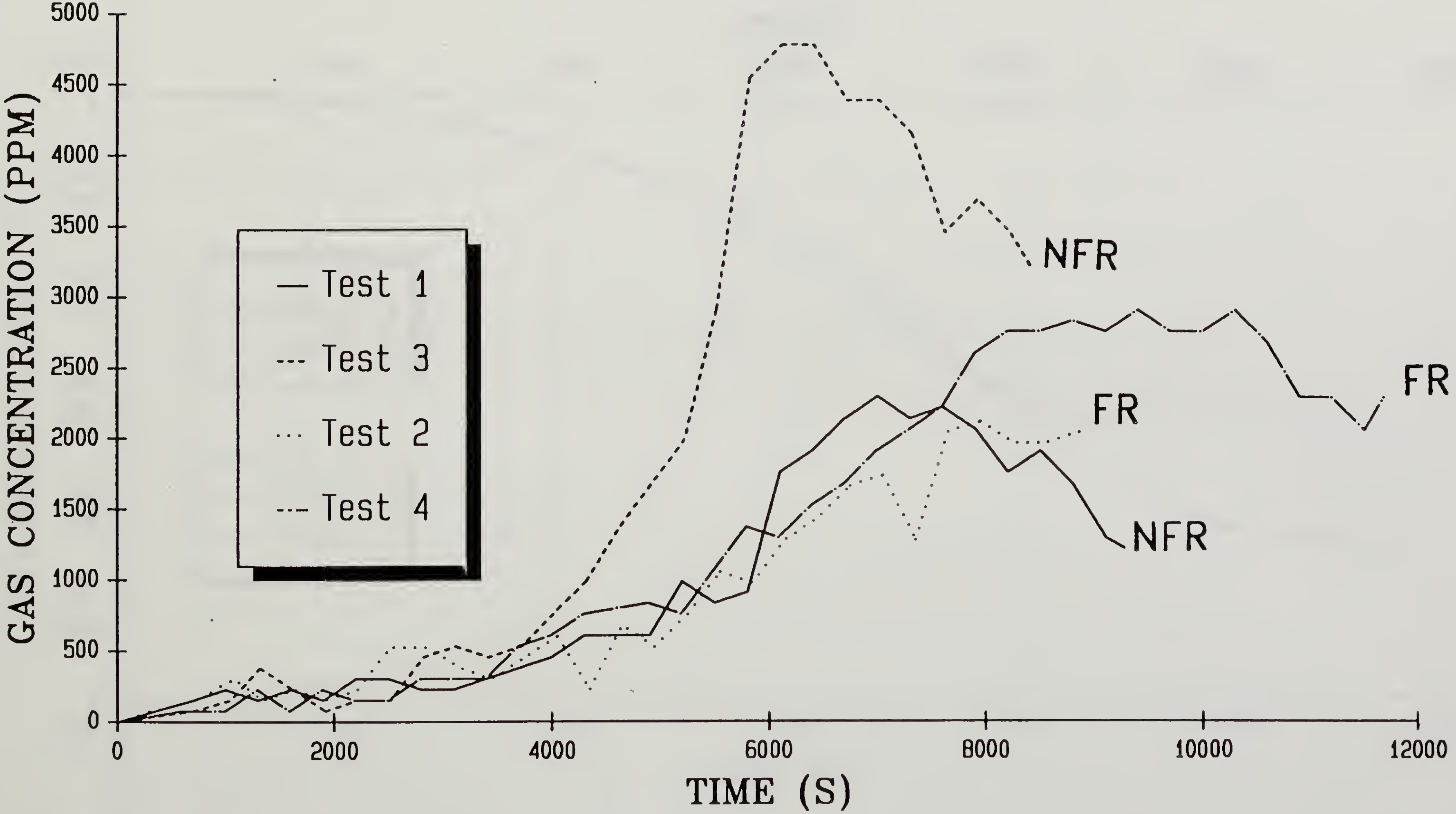


Figure 6. Comparison of CO Generation During Smoldering Combustion of FR and NFR Cushion Assemblies.

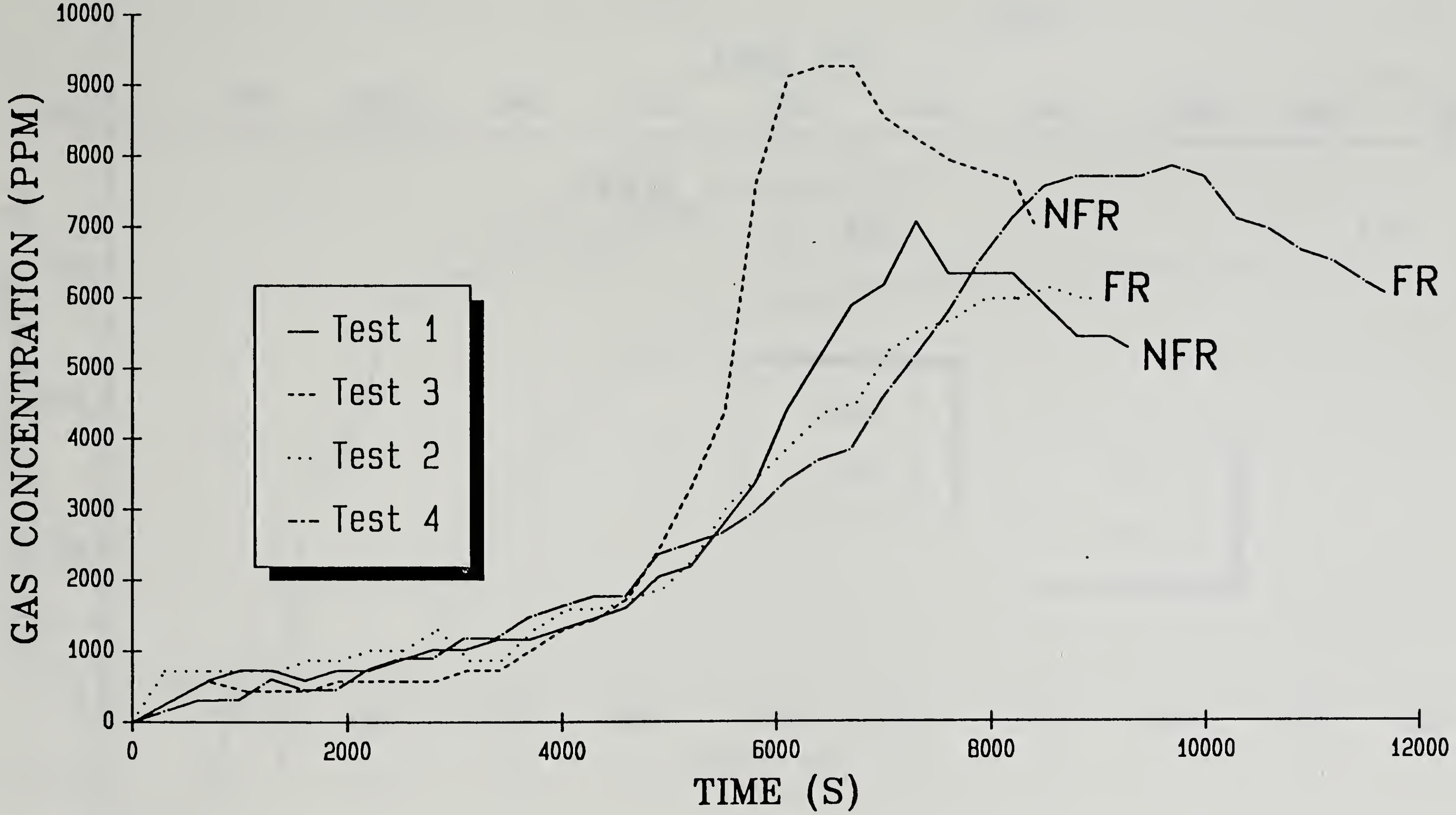


Figure 7. Comparison of CO_2 Generation During Smoldering Combustion of FR and NFR Cushion Assemblies.

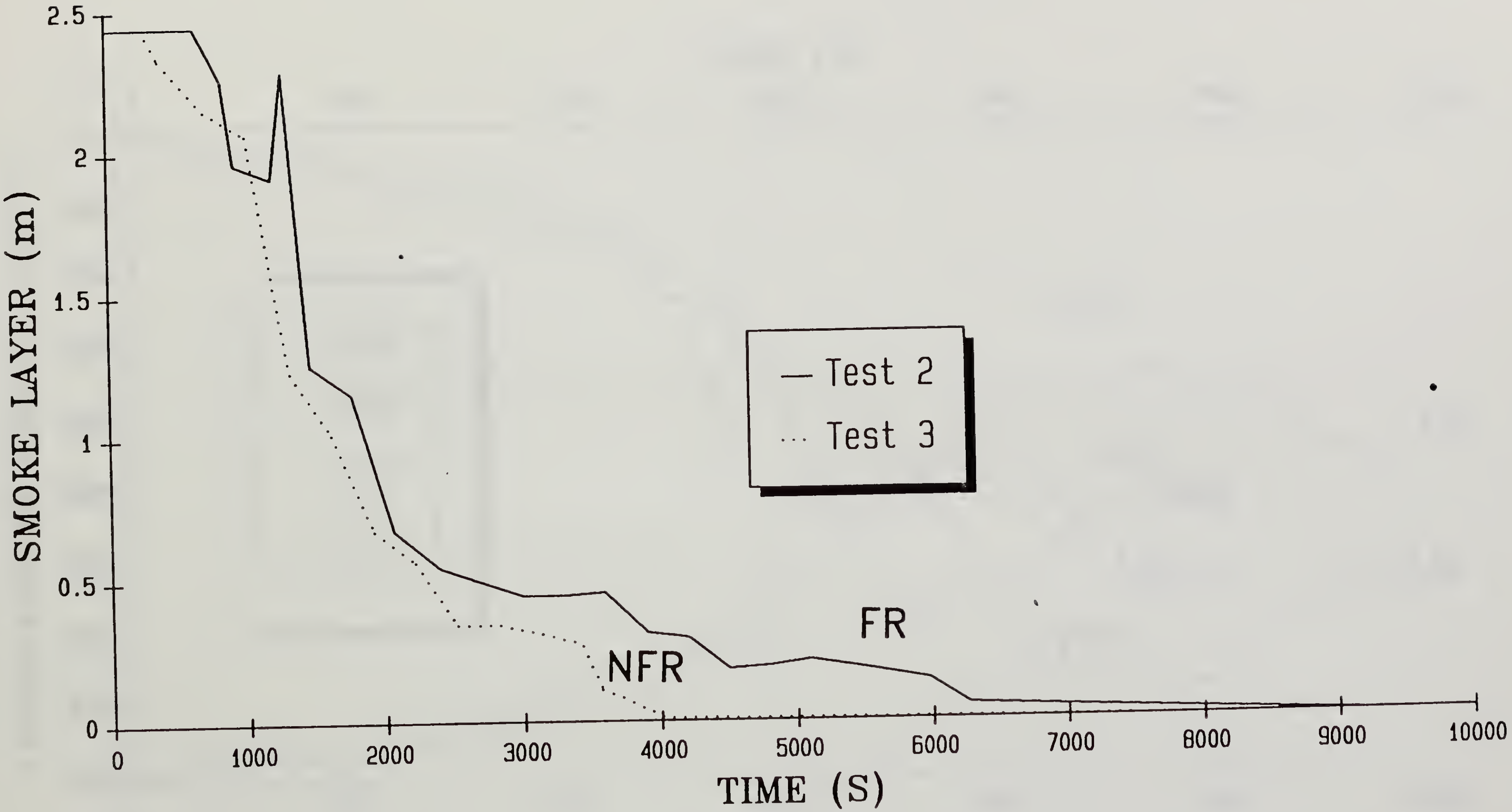


Figure 8. Typical Smoke Layer Development for FR and NFR Cushion Assemblies Undergoing Smoldering Decomposition.

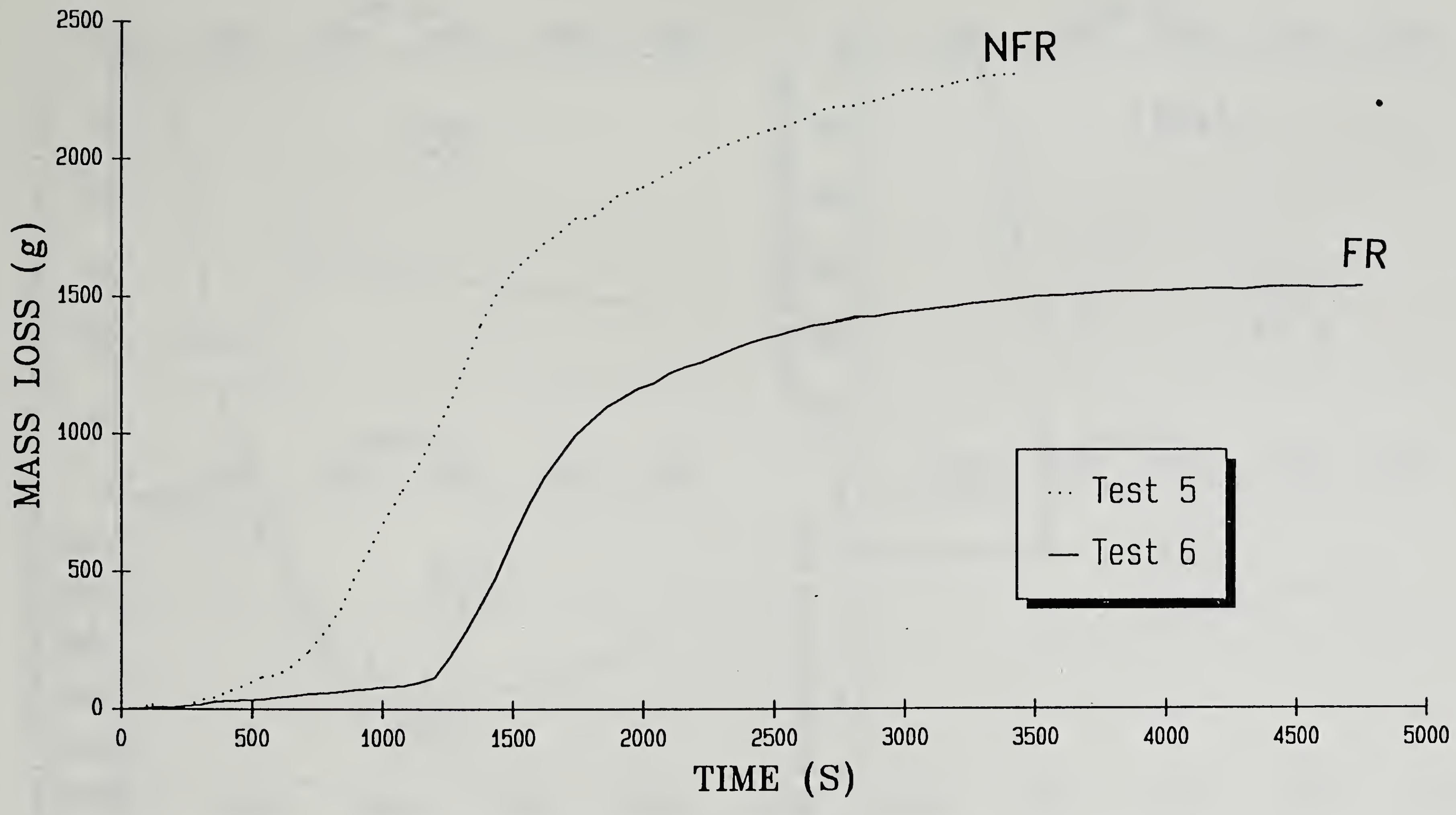


Figure 9. Comparison of Mass Loss of FR and NFR Cushion Assemblies During Flaming Combustion.

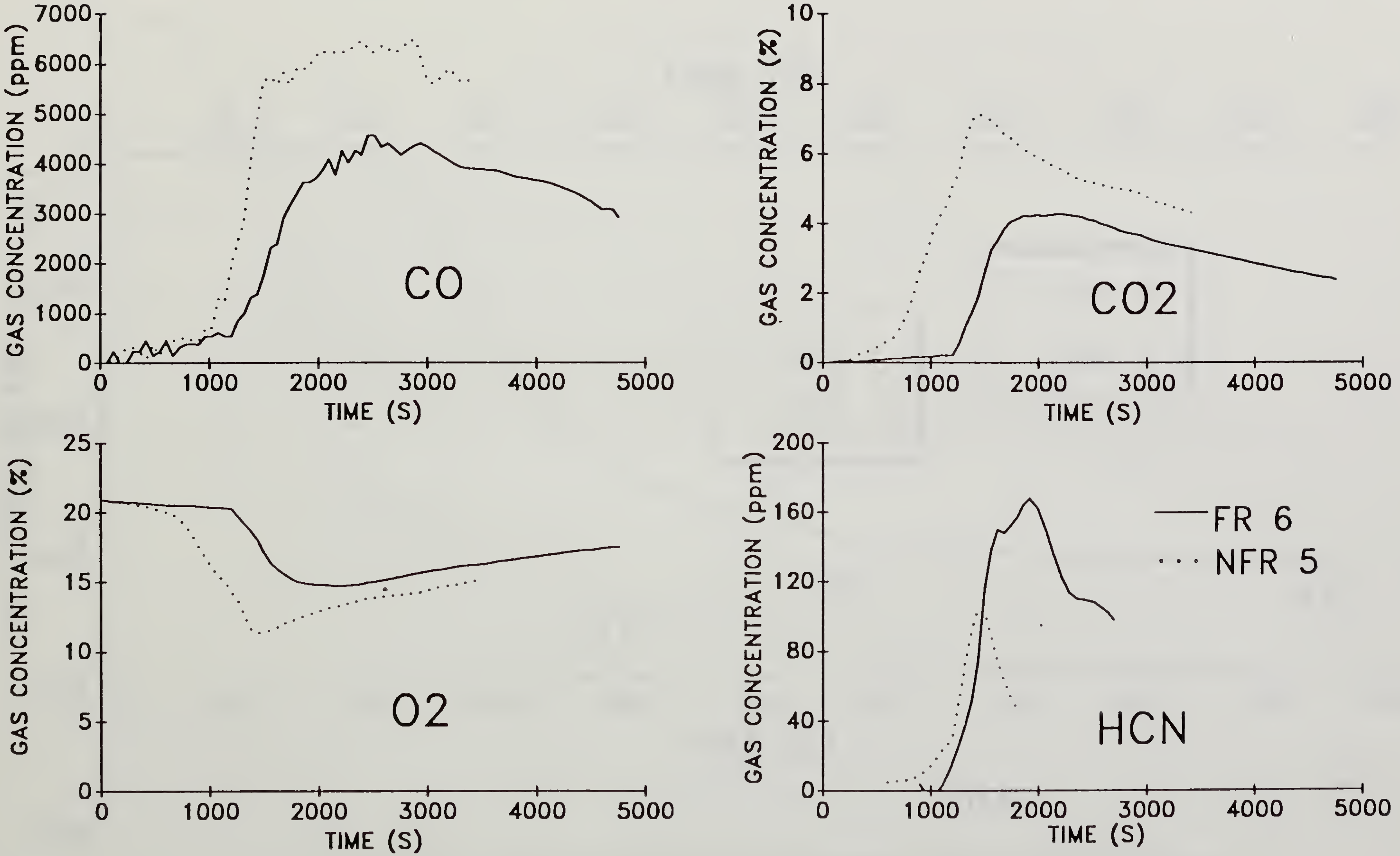


Figure 10. Comparison of CO, CO_2, O_2, and HCN Concentrations During Flaming Combustion of FR and NFR Cushion Assemblies.

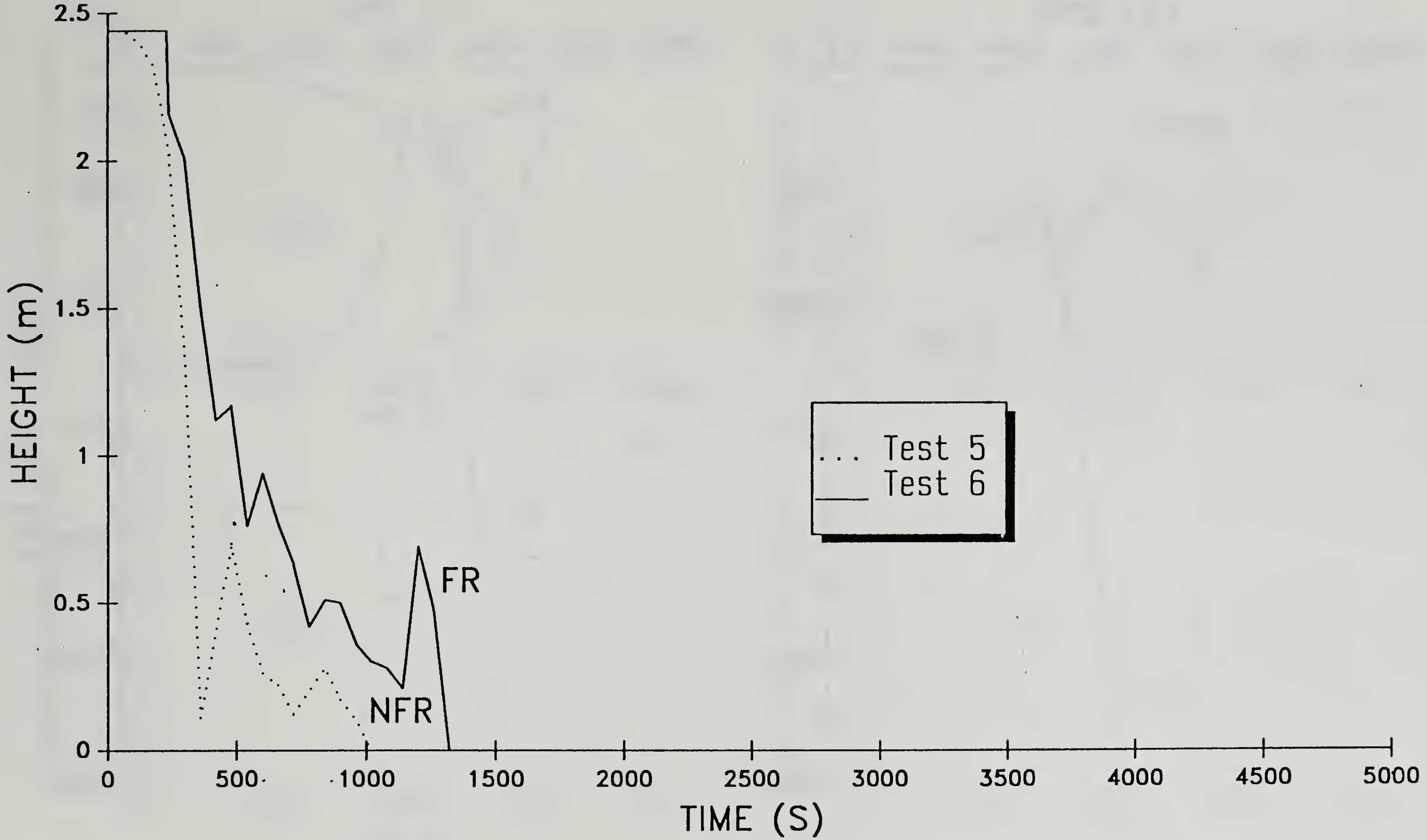


Figure 11. Comparison of Smoke Layer Development During Flaming Combustion of FR and NFR Cushion Assemblies.

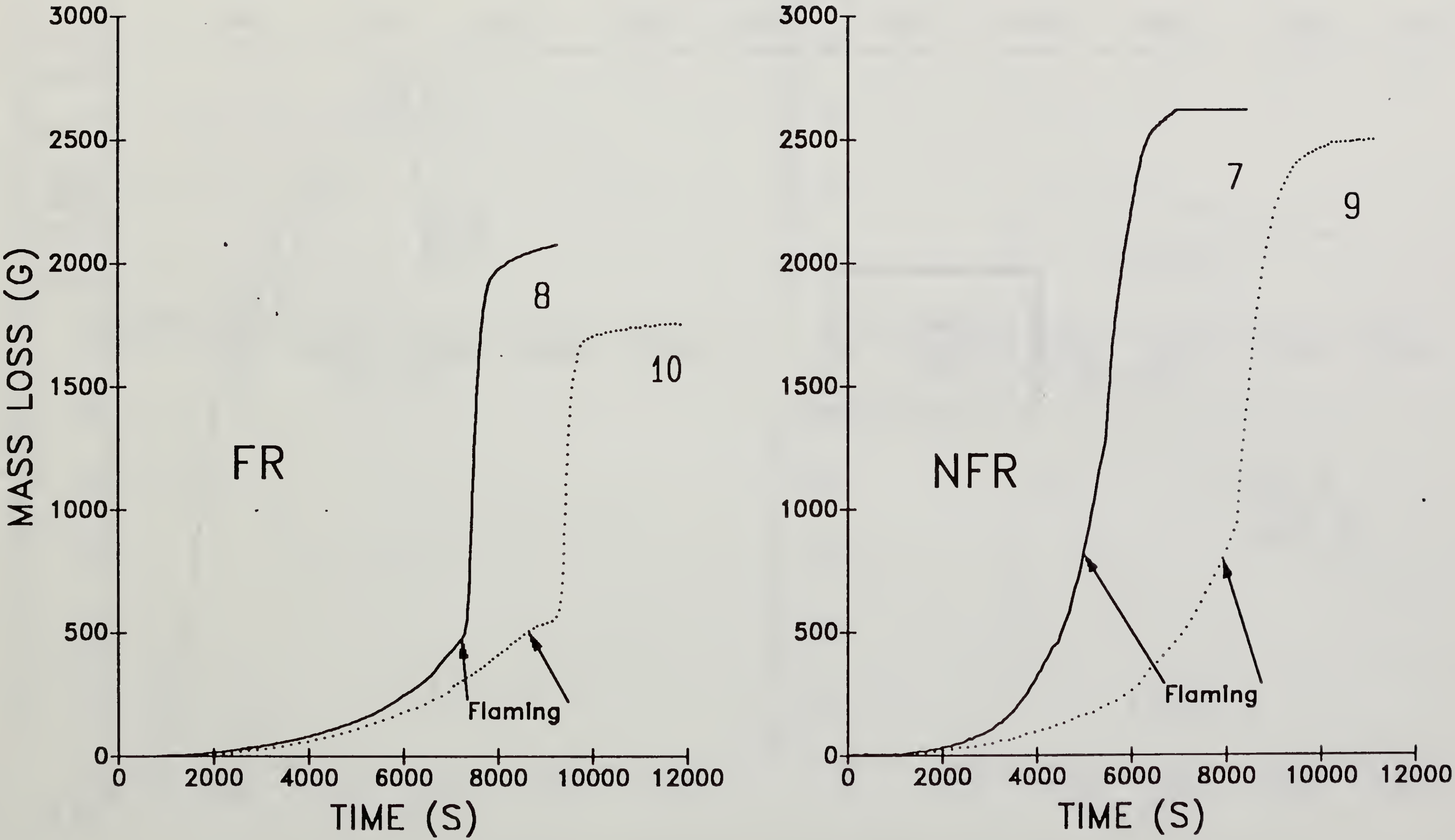


Figure 12. Comparison of Mass Loss for Replicate Tests of FR and NFR Cushion Assemblies During Smoldering-to-Flaming Transition Experiments.

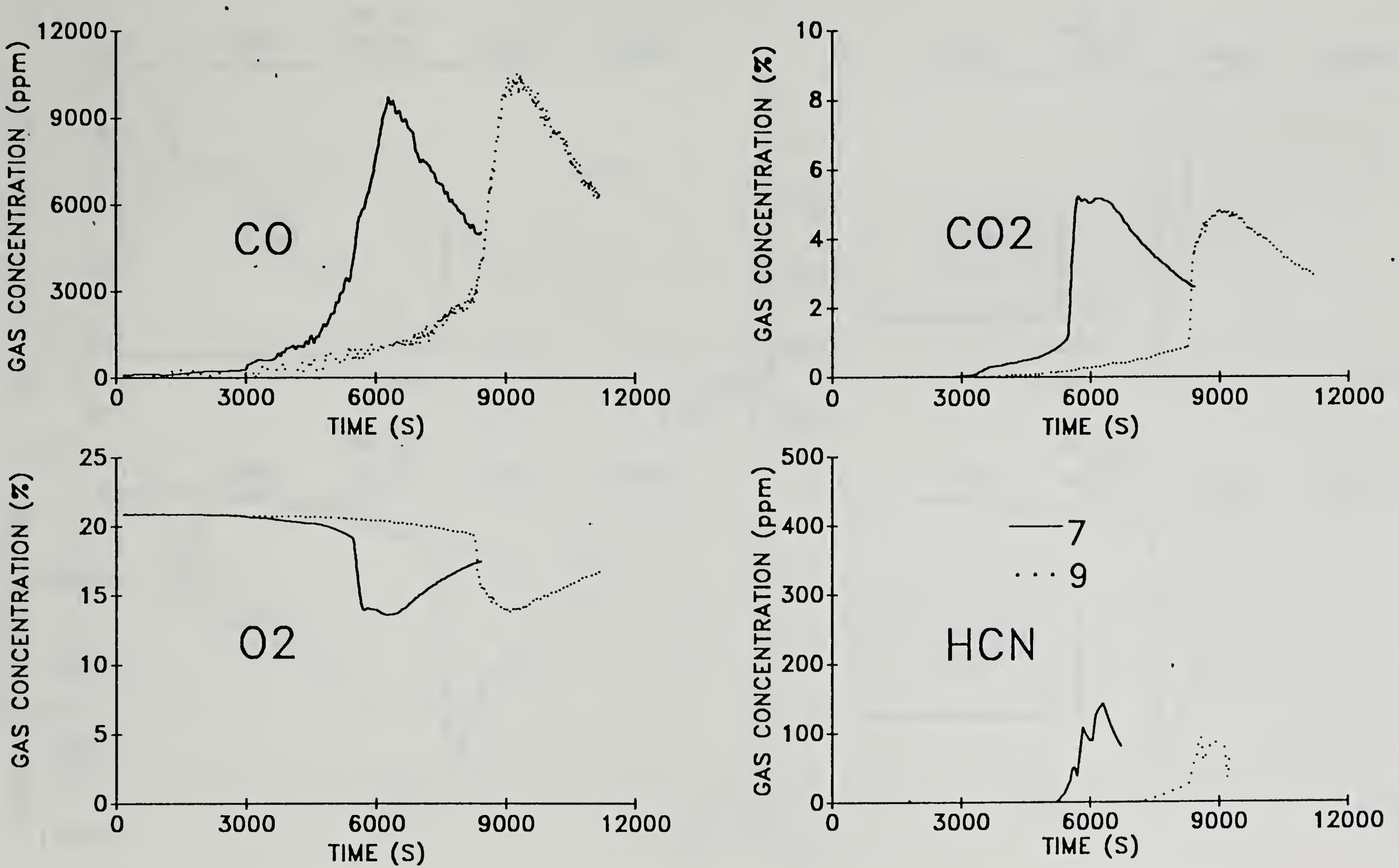


Figure 13. Comparison of CO, CO_2, O_2, and HCN Concentrations During Replicate Tests of NFR Cushion Assemblies.

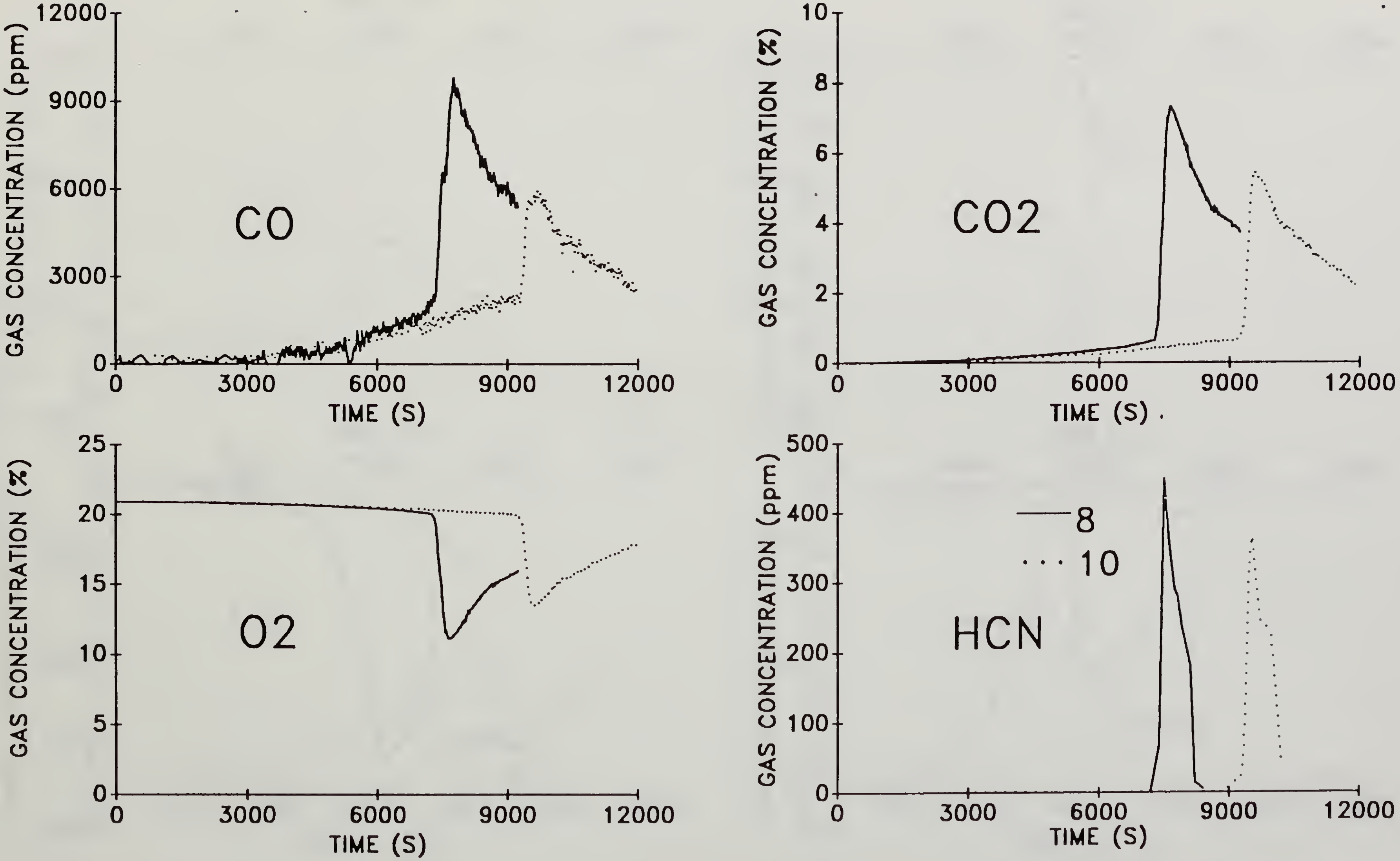


Figure 14. Comparison of CO, CO_2, O_2, and HCN Concentrations During Replicate Tests of FR Cushion Assemblies.

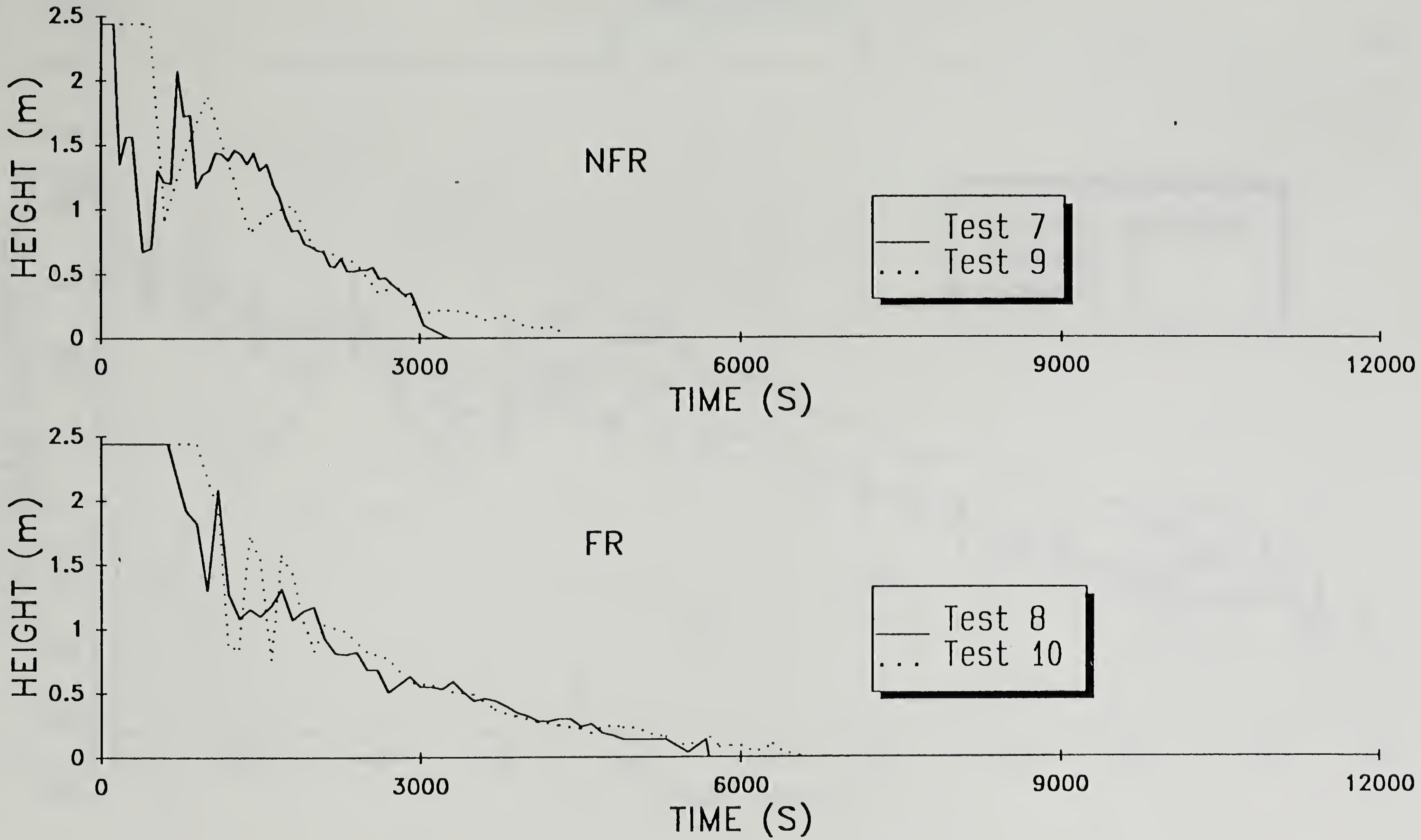


Figure 15. Comparison of Smoke Development During Replicate Tests of FR and NFR Cushion Assemblies.

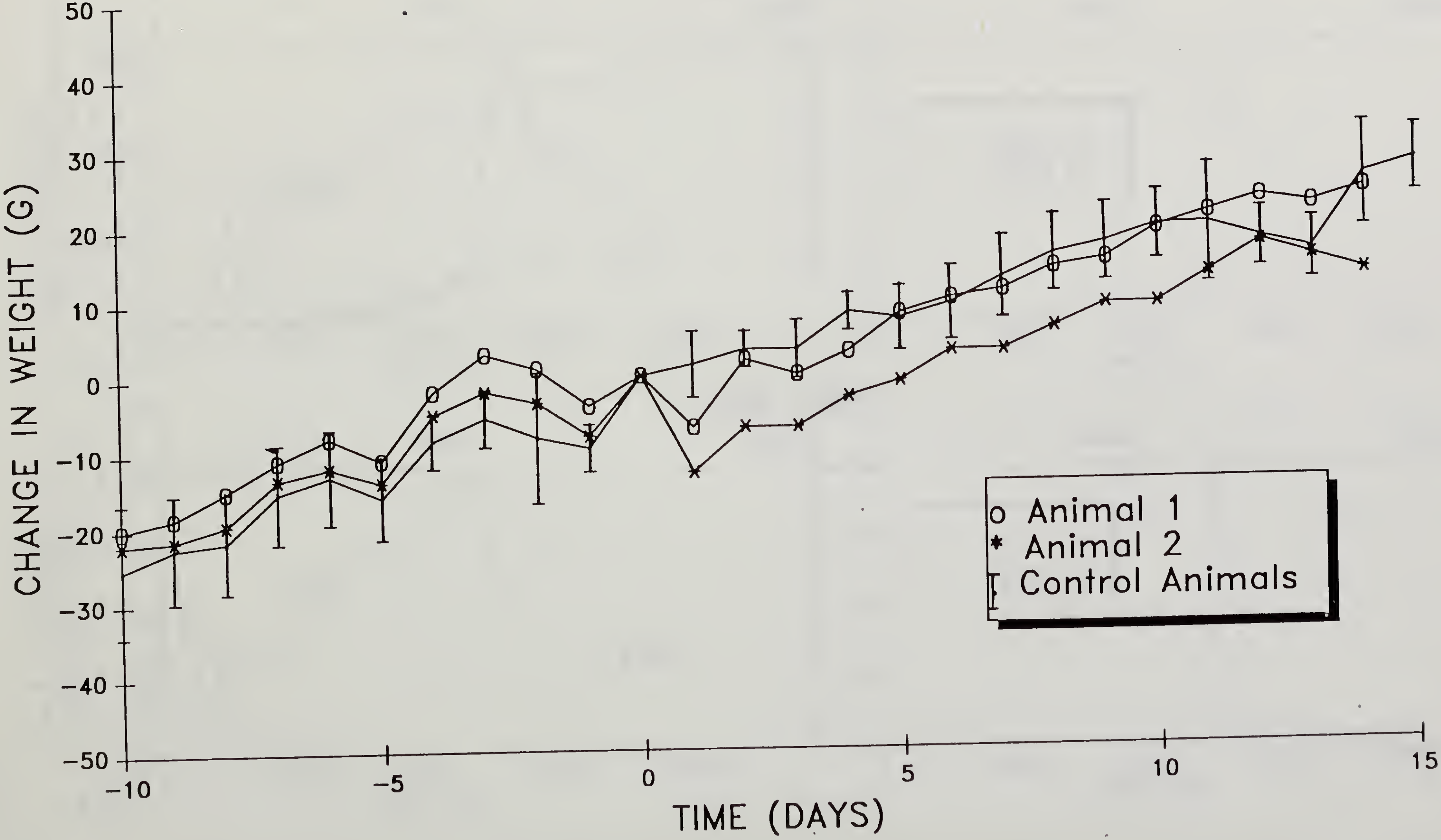


Figure 16. Comparison of the Average Weight Gain for Six Caged Animals and Two Burn Room Control Animals.

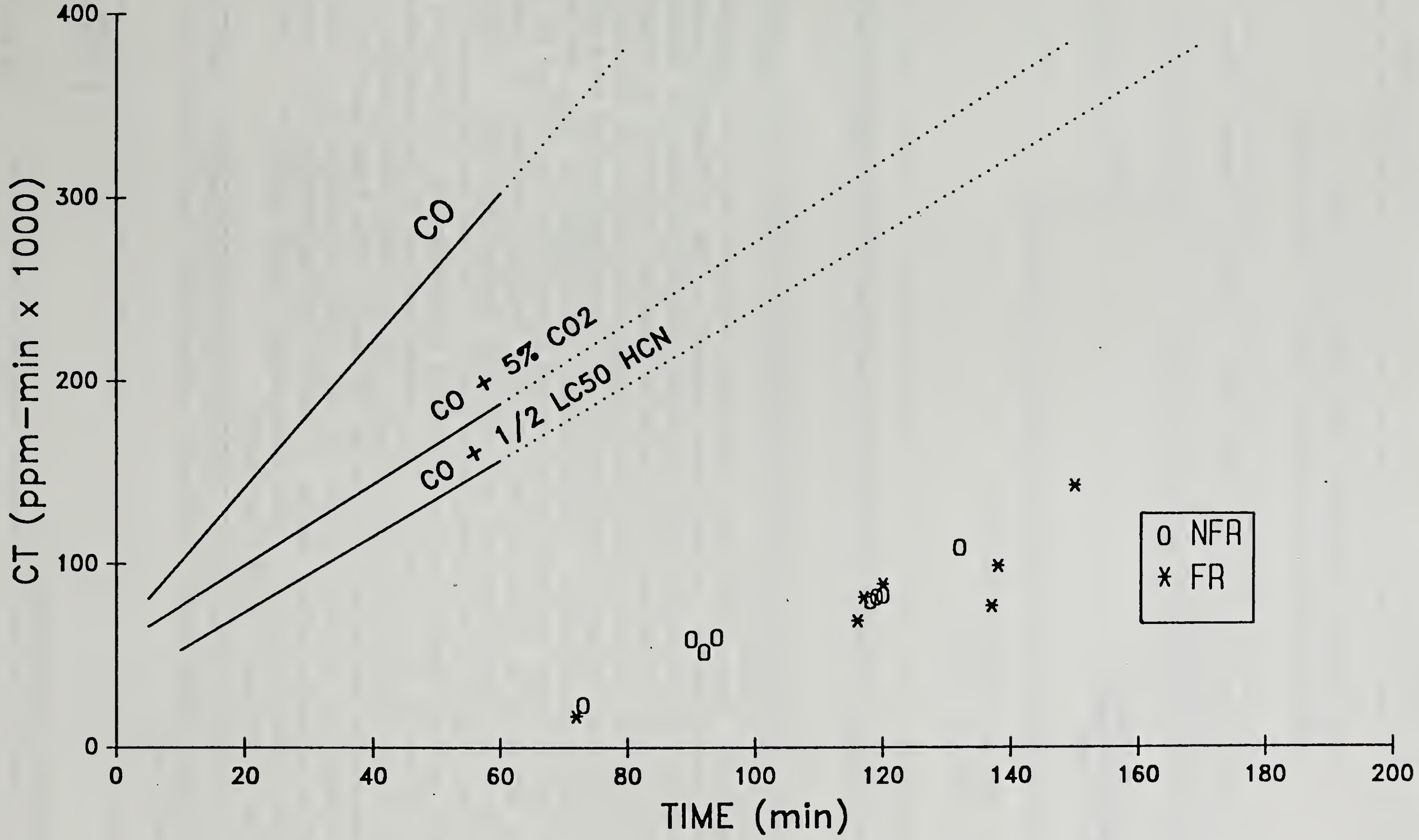


Figure 17. Comparison of the Integrated Pure CO and CO plus 5% CO_2 LC_{50} Values and the Burn Room Integrated CO at Death.

FORM **NBS-114A** (REV.11-84)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR-88/3764	2. Performing Organ. Report No.	3. Publication Date July 1988

4. TITLE AND SUBTITLE

LARGE-SCALE COMPARTMENT FIRE TOXICITY STUDY:
COMPARISON WITH SMALL-SCALE TOXICITY TEST RESULTS

5. AUTHOR(S) Emil Braun, Barbara C. Levin, Maya Paabo, Joshua L. Gurman, Helene M. Clark
Margaret F. Yoklavich

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10. SUPPLEMENTARY NOTES

~~[illegible]~~

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Ten large-scale single compartment fire tests were performed using two polyurethane foams and a cotton upholstery fabric. Animals were exposed to the products of decomposition of cushion assemblies burned under three different combustion modes: 1) smoldering combustion initiated by a cigarette; 2) flaming combustion initiated by a small natural gas diffusion burner; 3) smoldering-to-flaming transition combustion initiated by a cigarette and forced into flaming combustion after a prolonged period of smoldering by a small natural gas diffusion burner. Comparison of gas yields (CO, CO_2, and HCN) between these tests and prior large- and small-scale tests showed that the CO and CO_2 yields agreed within a factor of 3, while the NBS Toxicity Protocol produced 10 times more HCN in the flaming mode and ramped heating mode than the large-scale tests. Qualitatively, animal deaths were limited to within-exposure plus 24 hrs for the large-scale tests, while small-scale animal deaths occurred primarily post-exposure. Within the errors of the NBS Toxicity Protocol (± 5-10 mg/l), LC_{50} determinations in the large-scale tests were comparable to the small-scale tests, except for the small-scale ramped two phase heating and large-scale smoldering-to-flaming NFR tests. The N-gas model for 30 minutes exposures was expanded to include 4 gases, CO, CO_2, HCN and Reduced O_2. Model calculation showed that within-exposure animal deaths in small- and large-scale tests correlated with model values greater than 0.7. Burn room animal deaths could not be explained in terms of the four gases used in the N-gas model.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Cotton; fire tests; large scale fire tests; polyurethane; small scale fire tests; toxicity; upholstery.

13. AVAILABILITY

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