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Aviation Research Division
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New Jersey 08405

Flammability of Materials in a Low-Concentration Hydrogen Environment

September 2017

Final Report

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16. Abstract

A series of tests was conducted to determine the effect that concentrations of hydrogen below its lower flammability limit can have on the burning of other materials. The vertical Bunsen burner test cabinet was set up to run tests with hydrogen concentrations varying between 0% and 4% by volume. Three different materials were tested: a 1/16″ thick woven carbon fiber, a fabric aircraft seat cover, and an 8-ply unidirectional carbon fiber. All three materials showed significantly increased after-flame times and burn lengths as the concentration of hydrogen increased. The burn rate of both carbon-fiber materials also significantly increased with increased hydrogen concentrations, whereas the burn rate of the seat-cover fabric remained relatively constant for all concentrations.

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LFL	Lower flammability limit
H_2	Hydrogen

EXECUTIVE SUMMARY

Industry is currently researching the use of hydrogen fuel cells for electrical power onboard aircraft. It is known that hydrogen is very explosive in concentrations above its lower flammability limit (LFL) (approximately 4.7% by volume in air), but what has not been researched is whether concentrations below this limit can increase the burning rate of aircraft materials. In order to determine this, testing was conducted using the FAA vertical Bunsen burner test method with the test cabinet filled with varying concentrations of hydrogen below its LFL.

The vertical Bunsen burner test cabinet was set up in the Components Fire Test Lab at the FAA William J. Hughes Technical Center, and operated remotely for safety reasons. The hydrogen concentration inside the test cabinet varied from 0% to 4% by volume in increments of 1%, while conducting the standard 12-second vertical Bunsen burner test.

Three different materials were tested: a 1/16-inch thick woven carbon fiber, an aircraft fabric seat-cover material, and an 8-ply unidirectional carbon fiber. For all three materials, the after-flame time and burn length significantly increased as the hydrogen concentration increased. Even concentrations as low as 1% hydrogen had a large effect on the test results. The burn rate was also calculated from the burn length divided by the after-flame time plus the 12-second Bunsen burner time. The burn rate significantly increased with increased hydrogen concentrations for both types of carbon fiber and stayed relatively constant for the fabric seat cover.

1. INTRODUCTION

1.1 BACKGROUND

Industry is currently researching the use of hydrogen fuel cells for electrical power onboard aircraft. The FAA has formed an Aviation Rulemaking Advisory Committee (ARAC) to identify potential hazards, mitigation means, and regulatory gaps with the use of hydrogen onboard aircraft. One item identified by this committee was the potential impact on material flammability in the event a small hydrogen leak occurs that results in a low-concentration hydrogen environment. Hydrogen leaks can occur due to holes, breaks, or defects in material surfaces, but can also occur through diffusion or permeation, through the surface of the confinement vessel [1]. A previous FAA study showed the lower flammability limit (LFL) of hydrogen in air to be 4.7% by volume [2]. Similar studies by other organizations produced similar results. However, very little is known about the effect hydrogen can have on burning materials when its concentration is below the LFL.

1.2 OBJECTIVE

The goal of this experiment was to determine the effect low concentrations of hydrogen in air can have on the burning of aircraft materials.

2. EXPERIMENTAL SETUP

2.1 TEST METHOD

All of the testing in this experiment was based on the Vertical Bunsen Burner test for Cabin and Cargo Compartment Materials detailed in the FAA Aircraft Materials Fire Test Handbook [3]. The exact test procedure was followed while varying the amount of hydrogen in the test cabinet from 0% to 4%. All testing was completed in the Components Fire Test Laboratory located at the FAA William J. Hughes Technical Center.

The handbook states that a Bunsen burner with a 3/8-inch inside diameter barrel with methane at 2.5 psig should be used as the fuel source, and there should be no premixing of the fuel with air. This produces a pure diffusion flame. The only adjustment that can be made to the burner is the flow rate of the methane gas with a needle valve. The flow rate of the fuel needs to be adjusted so the height of the flame is 1.5 inches. The flame height was set with no hydrogen in the surrounding air, and the methane fuel flow rate to the burner was kept constant for all tests. The burner flame appeared to be slightly taller (¼ inch or less) when the chamber contained hydrogen, so any increased intensity of the flame during the 12-second ignition period can be directly attributed to the presence of hydrogen in the surrounding air.

For the 12-second vertical Bunsen burner test, the burner is lit prior to testing and then moved into position ¾ of an inch below the material sample for 12 seconds before being removed. The data that are to be collected from this test are the flame time, drip flame time, and burn length. The flame time is the amount of time the test sample continues to burn after the burner is removed from beneath the specimen. The drip flame time is the time that any flaming material continues to burn after falling from the specimen to the floor of the chamber. The burn length is the distance from the original edge of the sample to the furthest point of flame damage on the specimen. The material sample to be tested must be at least 3- by 12-inches.

Three samples of each material must be tested. The test is considered a failure if the average flame time for all the specimens exceeds 15 seconds, the average drip flame time exceeds 5 seconds, or the average burn length exceeds 8inches.

For this experiment, the Bunsen burner cabinet was operated remotely from a control room as a safety precaution against a possible hydrogen explosion. The cabinet is 25 ft^3 in volume and was equipped with two pressure-relief blow-out panels that would relieve pressure in the event the hydrogen in the chamber was ignited above its LFL (figure 1). Figure 1 also shows the electric actuator, which moves the burner in and out of position under the test sample, and the hydrogen analyzer, which reads the hydrogen concentration inside the test cabinet.

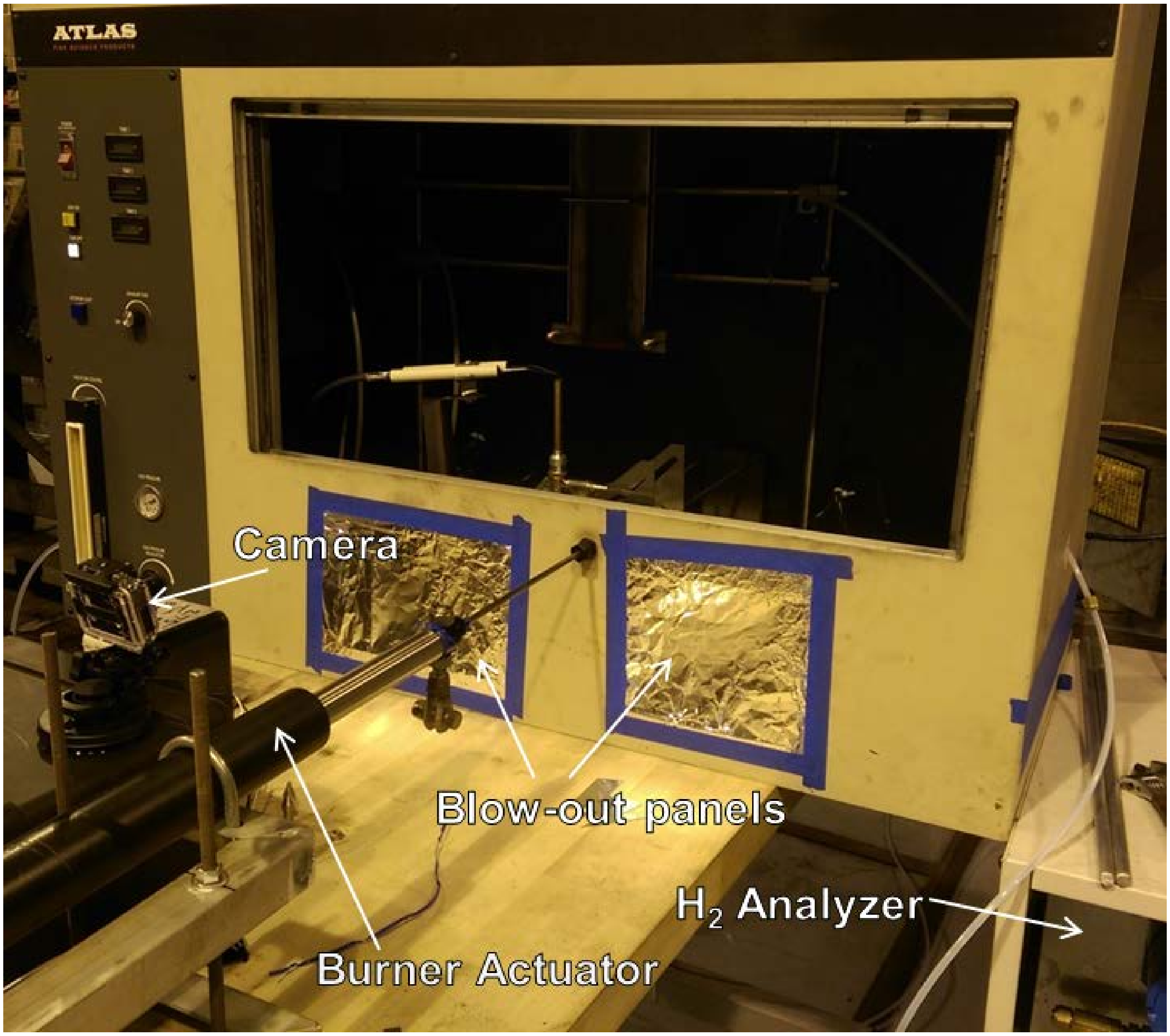

Figure 1. Automated vertical Bunsen burner cabinet that can be filled with varying amounts of hydrogen

The inside of the chamber was equipped with the moveable Bunsen burner, the electric spark igniters, the test sample and holder, two 30 ft^3/min (CFM) mixing fans to keep the hydrogen mixture homogeneous throughout the chamber, and intake and exhaust lines for the hydrogen analyzer (figure 2). The hydrogen analyzer used in the testing was model H2Scan HY-Optima 2799, with an accuracy of ±0.15% absolute for hydrogen concentrations of 0.1% to 10%. The hydrogen added into the chamber and the methane fuel for the burner were each controlled by an electronic solenoid valve.

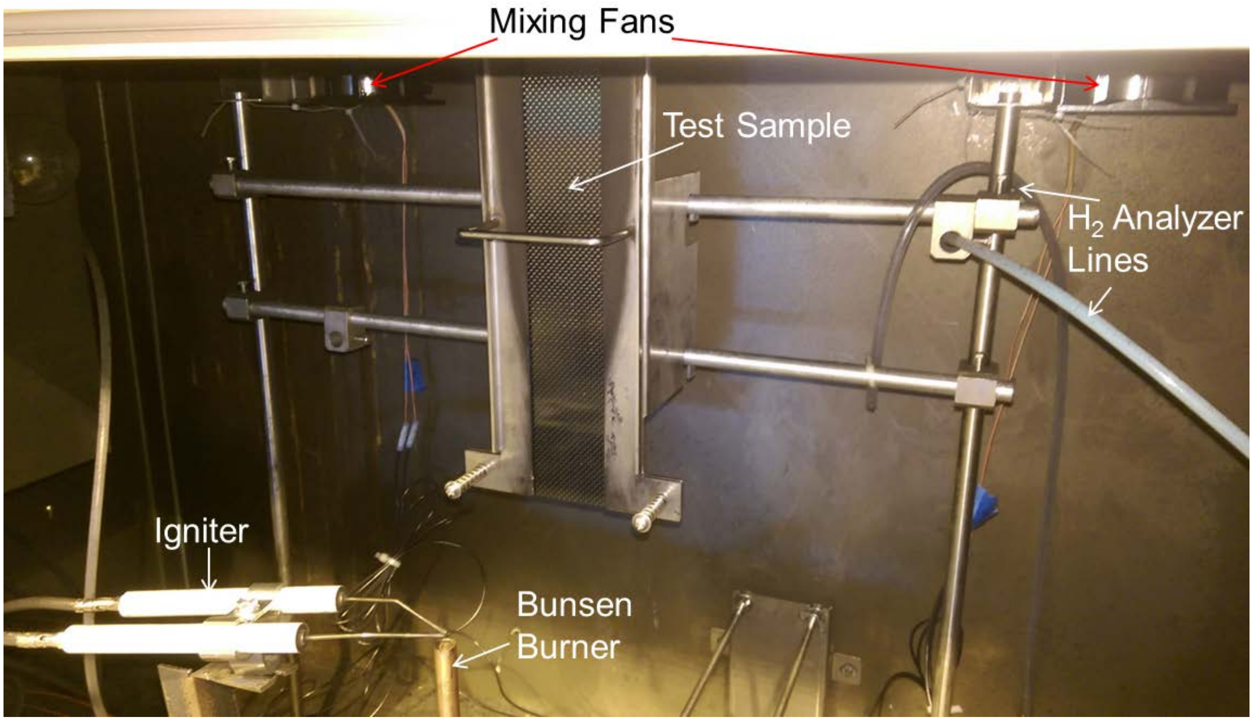

Figure 2. Bunsen burner test cabinet interior showing most of the added parts to conduct this experiment remotely

2.2 TEST PROCEDURE

For this experiment, tests were conducted on three different materials: a 1/16-inch thick woven carbon fiber, a fabric aircraft seat-cover material, and an 8-ply unidirectional carbon fiber. The hydrogen concentration in the chamber was varied from 0% to 4% in increments of 1%. Three samples of the woven carbon fiber and seat cover material were tested at each concentration, yielding 15 tests each. There was less of the unidirectional carbon-fiber material available, so only two were tested at 0% and 4% and one at every other concentration.

All the tests were operated remotely from a control room, even when no hydrogen was added. To begin a test, the burner was positioned underneath the spark igniter. For the tests with no hydrogen, the methane fuel solenoid was opened and the spark igniter was turned on simultaneously. When the flame was lit, the igniter was turned off and the actuator was used to move the burner into position underneath the sample. The burner was left under the sample for 12 seconds and the fuel was then shut off. A stopwatch was used to determine the after-flame time, and the exhaust fan was turned on to remove the smoke from the cabinet before the burn length was measured.

For tests with hydrogen, the mixing fans were turned on and the hydrogen solenoid valve was opened until the desired concentration was reached, as indicated by the hydrogen analyzer. The flow of hydrogen and the mixing fans were turned off before igniting the burner and moving it into position under the sample for a test. The hydrogen analyzer was running throughout the duration of the test. The test cabinet was not airtight, and some hydrogen was consumed by the flames from the burner and burning samples during testing, so the hydrogen concentration decreased from its initial setting as each individual test progressed.

3. TEST RESULTS

3.1 1/16 INCH WOVEN CARBON FIBER

The first material tested was the 1/16-inch -thick woven carbon fiber. When tested without hydrogen in the surrounding environment, three samples produced an average after-flame time of 40 seconds and an average burn length of 0.63 inches. This is considered a failure in the 12-second vertical Bunsen burner test, but the sample self-extinguished with a very short burn length so it could still provide a good basis for comparison.

Adding hydrogen to the surrounding environment increased the flame time and burn length dramatically. Even a low average hydrogen concentration of 1.08% for the next three samples tested increased the average flame time to 168 seconds and the average burn length to 5.87 inches. The flame times and burn lengths continued to increase as the hydrogen concentration increased until the entire length of the sample was burned at 3% hydrogen concentration. The flame time then decreased at 4% hydrogen concentration, while still burning the full length of the sample because the flame consumed the material faster. Figure 3 shows the flame time and burn length for each sample tested.

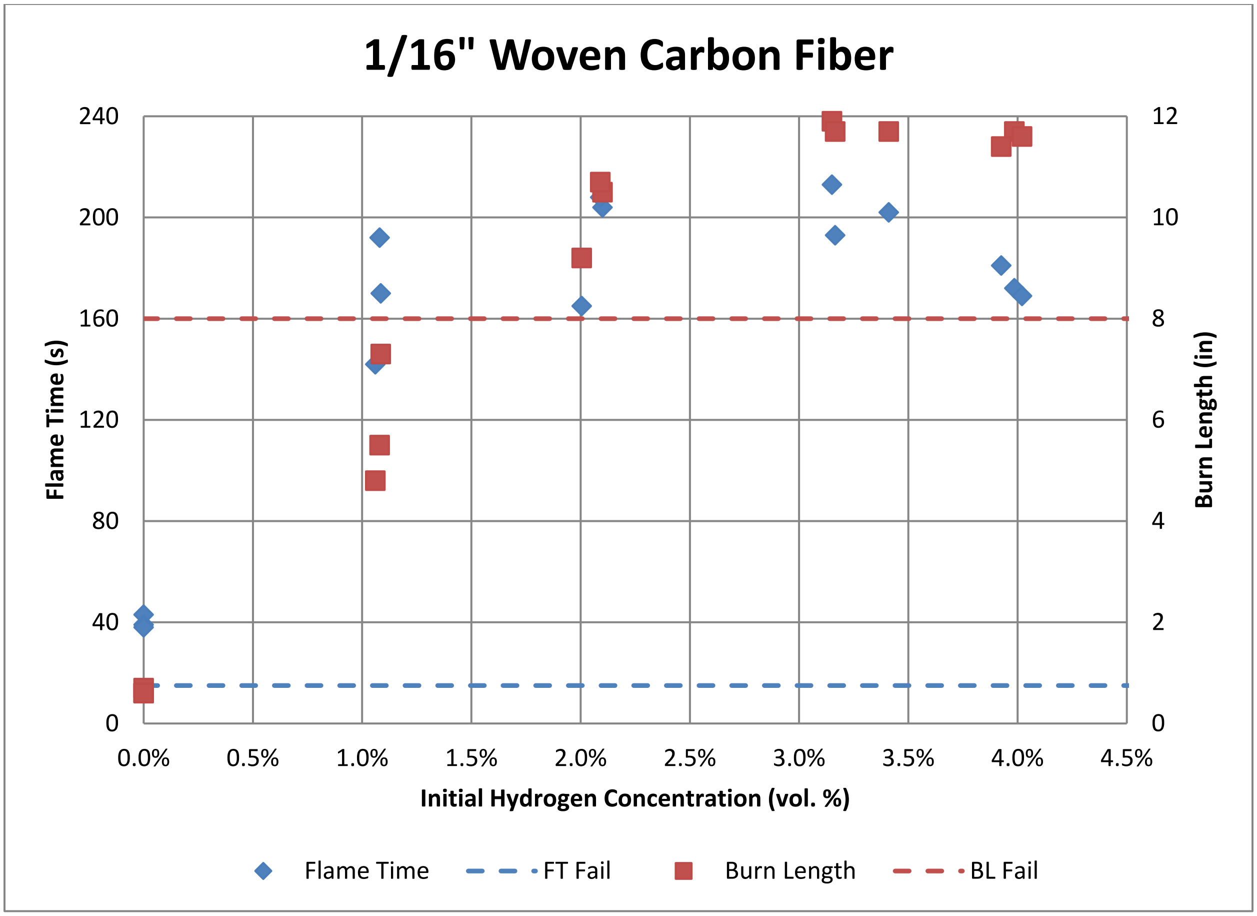

Figure 3. Flame time and burn length of each tested 1/16″ woven carbon-fiber sample

Three examples of the woven carbon-fiber, after being tested, are shown in figure 4. Moving from left to right, these samples were tested at hydrogen concentrations of 0%, 1%, and 4%. The 0% sample had a 0.6″ burn length; 1% had a 5.5″ burn length; and 4% had an 11.7″ burn length. The sample holder likely caused the flame to extinguish before reaching the full 12″ in the case of 4% hydrogen.

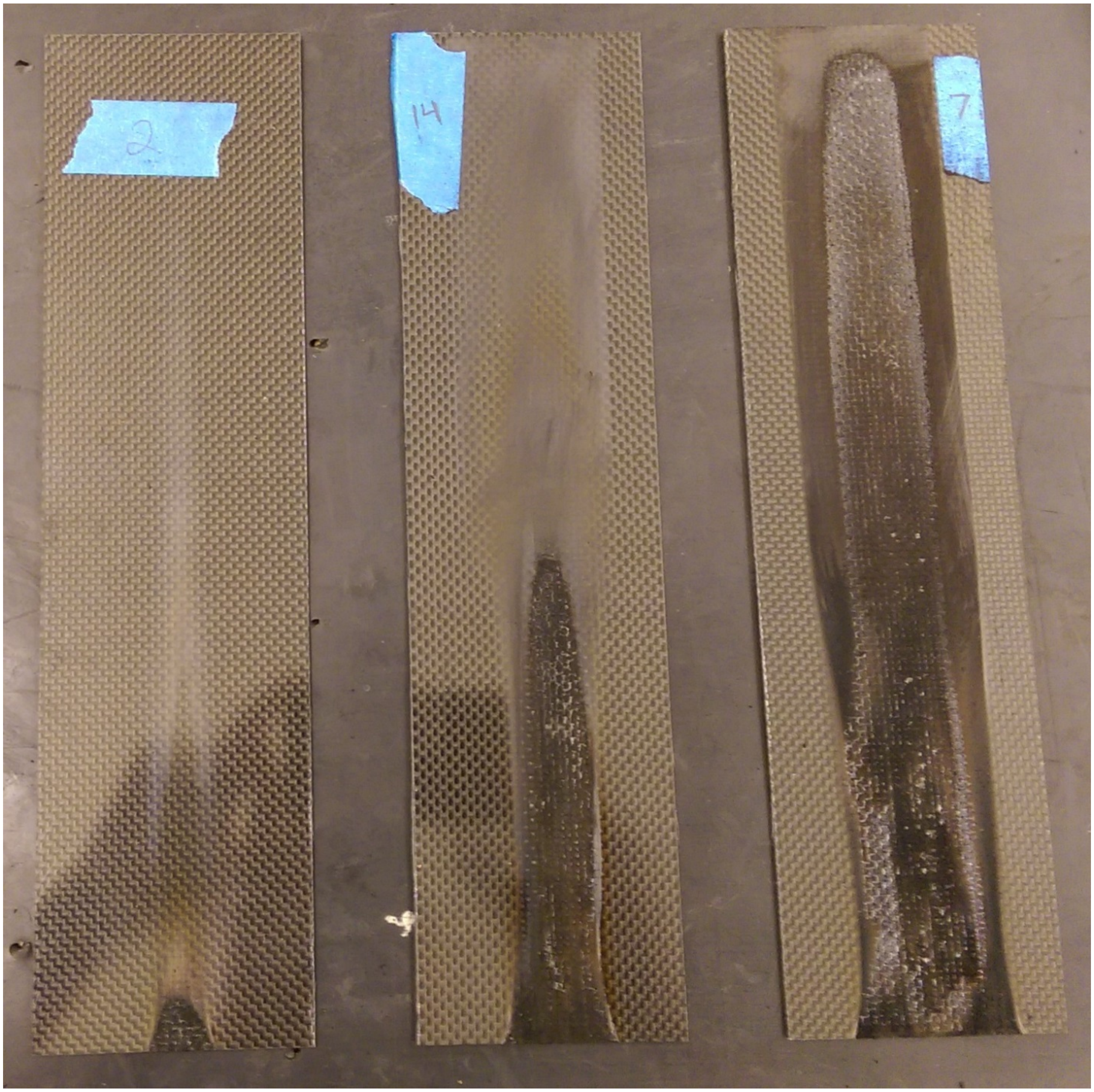

Figure 4. Post-test woven carbon fiber from left to right: 0% H_2, 1% H_2, and 4% H_2

The rate at which each sample burned is not a normal calculation that is done in the vertical Bunsen burner test, but it proved to be useful in this experiment. It was calculated by dividing the burn length by the 12-second time the burner was under the sample, plus the after-flame time. The burn rate of each sample is shown in figure 5. As the hydrogen concentration increased, the rate at which the flame consumed the sample also increased.

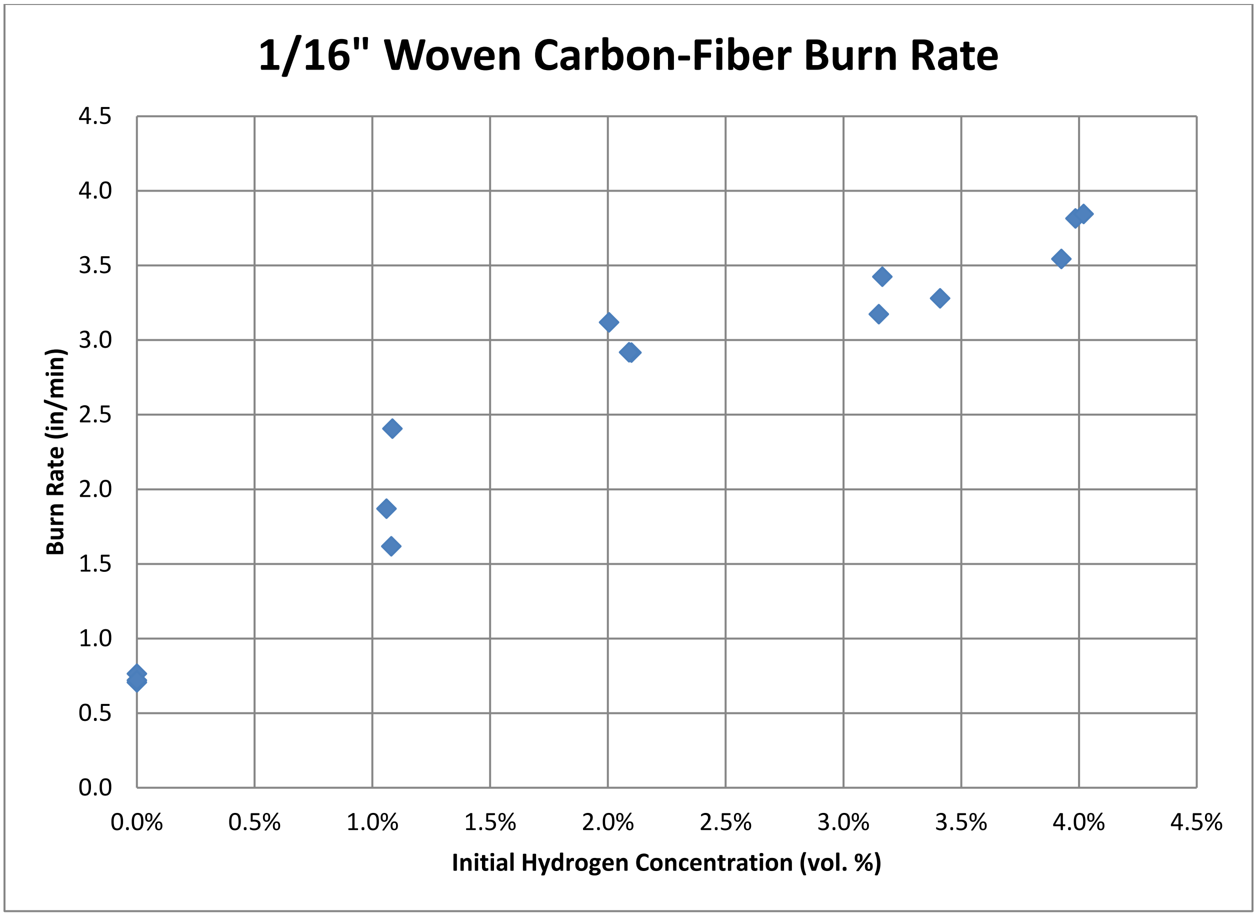

Figure 5. Burn rate of all 1/16″ woven carbon-fiber samples

All the data averaged for each hydrogen concentration are shown in table 1. Because the test chamber was not airtight, and some hydrogen was consumed by the flame during testing, the hydrogen concentration decreased as each test progressed. The initial hydrogen concentration is the concentration at the point the burner was placed under the sample, and the final hydrogen concentration occurred when the test sample self-extinguished. Also shown are the average flame time, burn length, and burn rate.

Table 1. Test data averaged for each hydrogen concentration for 1/16 inch woven carbon fiber

1/16 inch Woven Carbon-Fiber Average Data				
Initial H_2 %	Final H_2 %	Flame Time (s)	Burn Length (in)	Burn Rate (in/min)
0.00%	0.00%	40.00	0.63	0.73
1.08%	0.95%	168.00	5.87	1.96
2.07%	1.62%	192.33	10.13	2.98
3.24%	2.20%	202.67	11.77	3.29
3.98%	2.73%	174.00	11.57	3.73

3.2 FABRIC SEAT COVER

The next material tested was an aircraft fabric seat cover. This material was less consistent than the carbon fiber, but still showed the same basic trends of increasing flame time and burn length as the hydrogen concentration increased. Each sample was cut from the same piece of fabric, so it was unlikely that the inconsistency was caused by the material itself. It was most likely because it was difficult for the sample holder to hold each sample perfectly straight across the 2-inch opening. Any wrinkles or bends in the fabric could have affected the way the flame traveled up the sample.

All three of the samples tested without hydrogen had a short 0.5-second flame time and less than 3 inches of burn length. This was well under the criteria for a material to pass this test. When hydrogen was added, the flame times and burn lengths again increased dramatically. At 1% and 2% hydrogen concentrations, two of the three tested samples burned the full 12 inches in length. At3%, one of three burned the full length, and at 4%, all three samples burned the full length. Of the samples that did not get fully consumed, there was still an increase in the flame times and burn lengths as the hydrogen concentration increased. Figure 6 shows the results of all 15 tests.

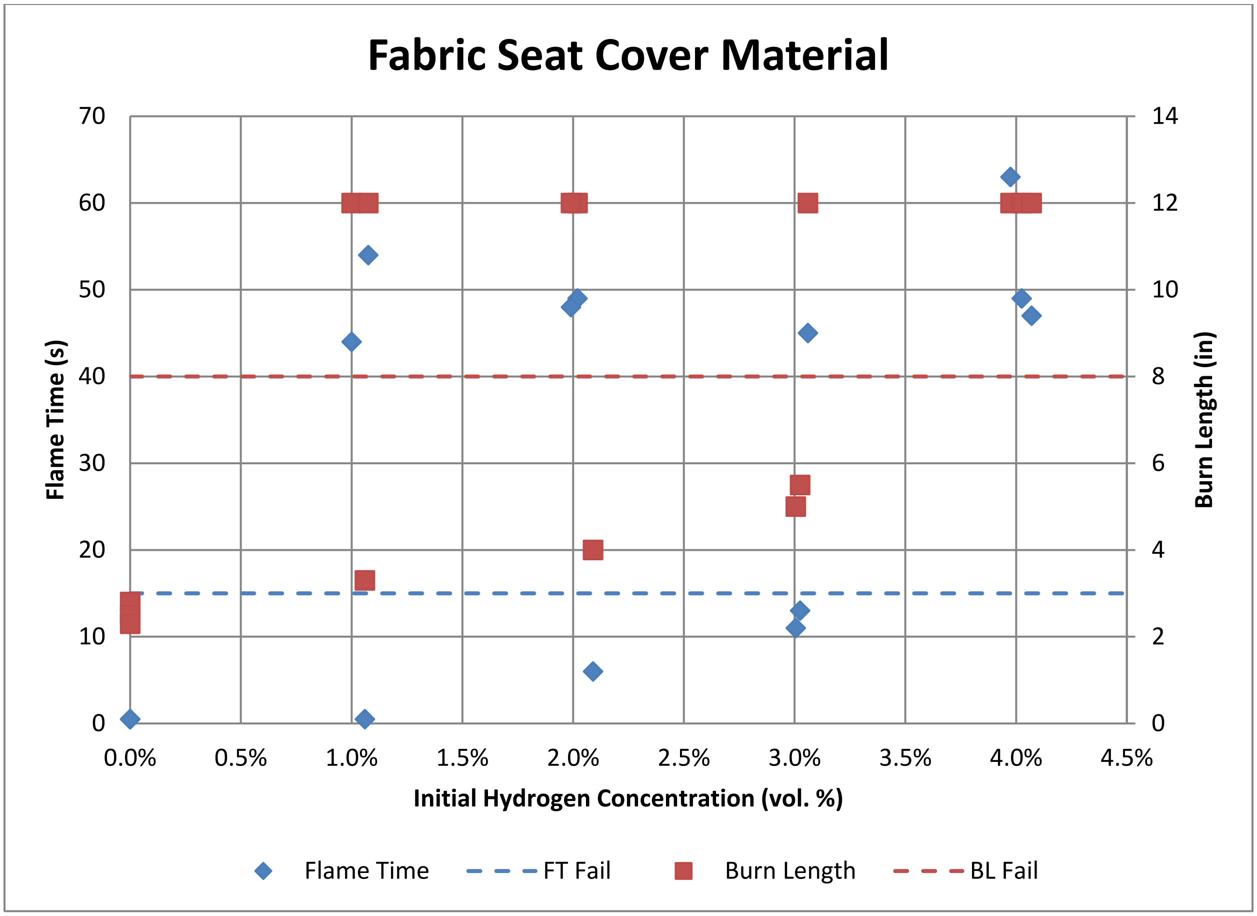

Figure 6. Flame time and burn length of each fabric seat cover sample tested

Three examples of the seat-cover fabric post-test are shown in figure 7. From left to right in the picture, they were tested at hydrogen concentrations of 0%, 2%, and 4%. Their burn lengths were 2.8″, 4.0″, and 12″, respectively.

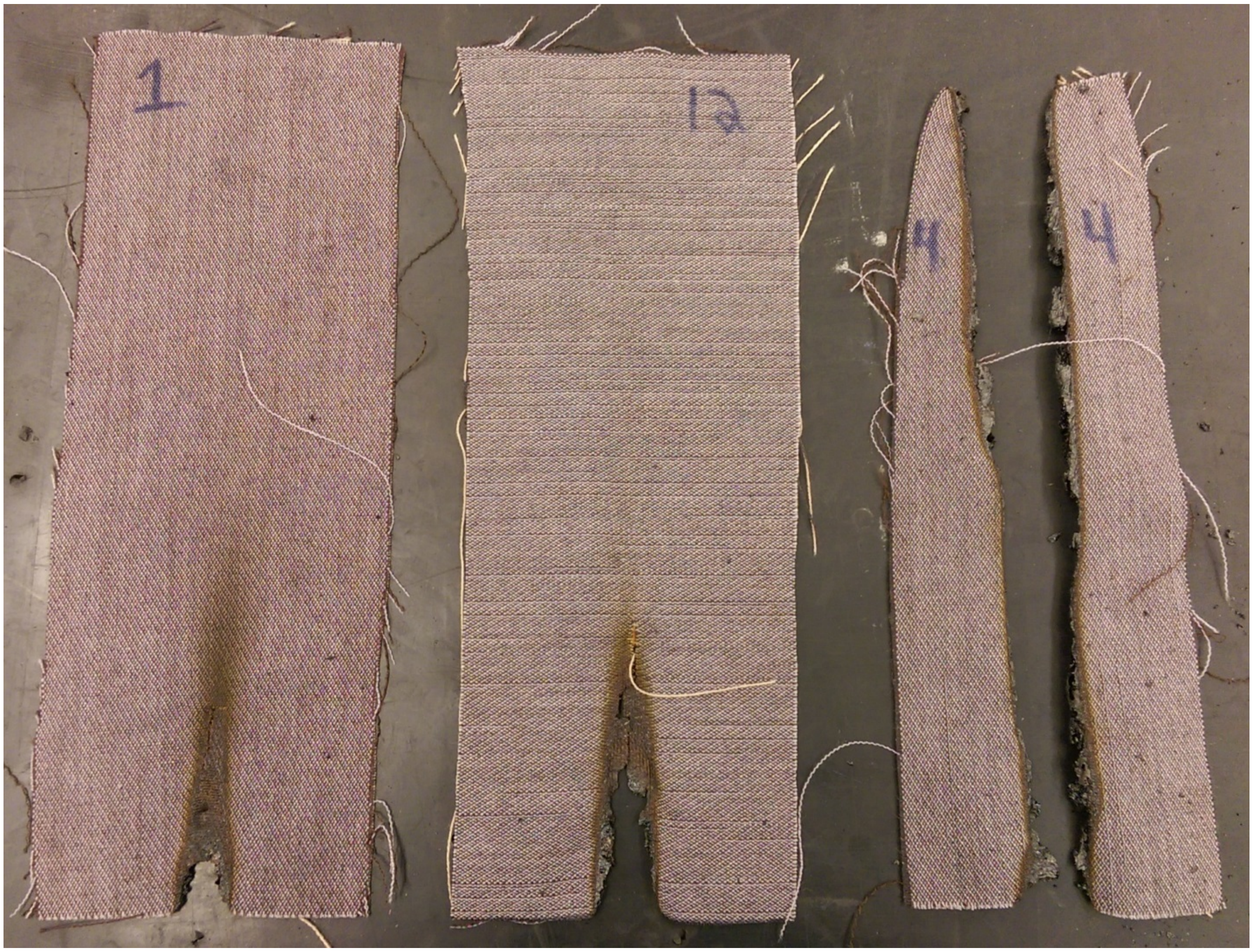

Figure 7. Post-test fabric seat cover from left to right: 0% H_2, 2% H_2, and 4% H_2

The burn rate of the seat-cover fabric stayed relatively constant as the hydrogen concentration increased, which was different than the carbon-fiber material tested. The hydrogen seemed to affect only the amount of material consumed in the fire, but not how fast it burned. The burn rates for all 15 samples are shown in figure 8. Table 2 shows the average hydrogen concentrations at the beginning and end of each test and the average test results.

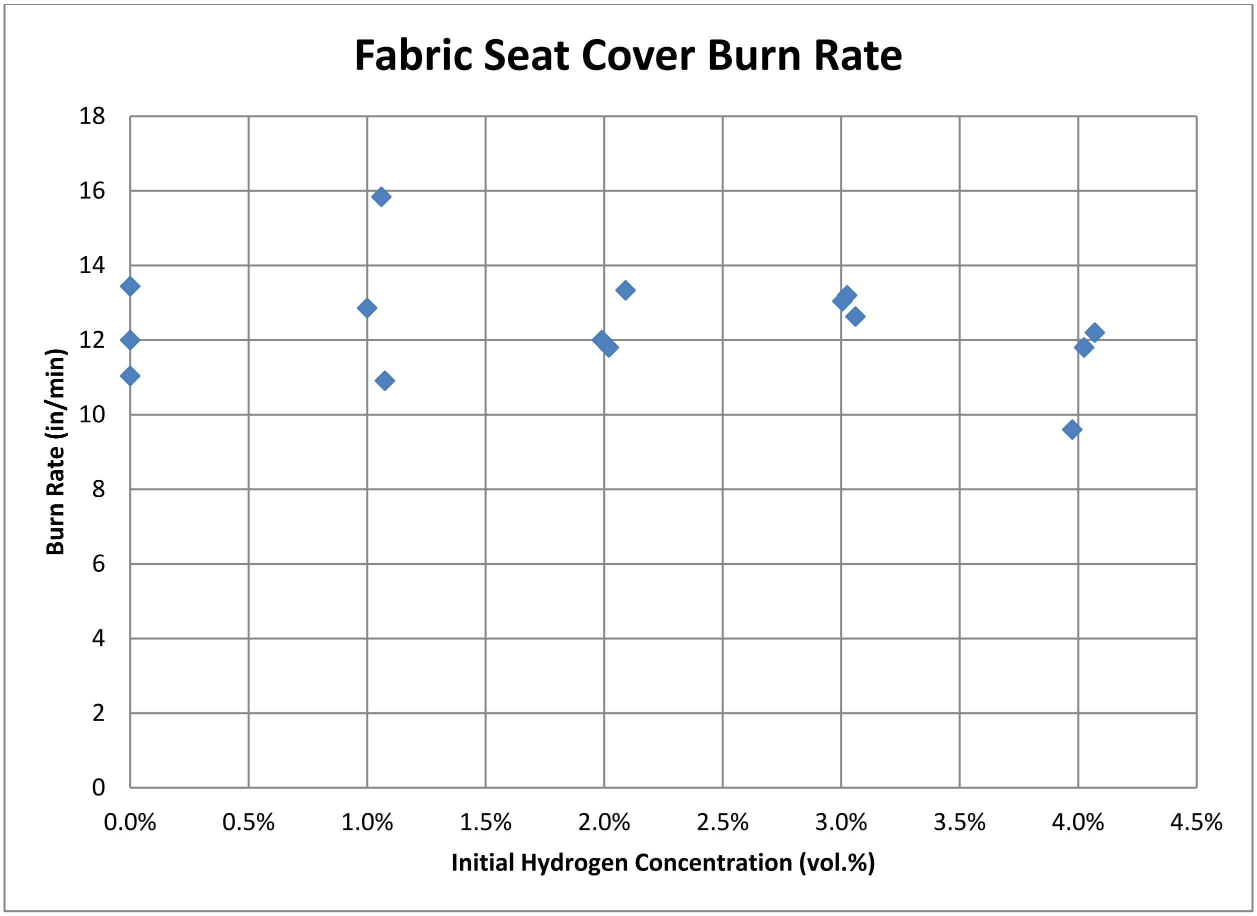

Figure 8. Burn rate of all fabric seat-cover samples

Table 2. Test data averaged for each hydrogen concentration for seat-cover fabric

Fabric Seat-Cover Average Data				
Initial H_2 %	Final H_2 %	Flame Time (s)	Burn Length (in)	Burn Rate (in/min)
0.00%	0.00%	0.50	2.53	12.16
1.05%	1.02%	32.83	9.10	13.20
2.03%	1.94%	34.33	9.33	12.38
3.03%	2.96%	23.00	7.50	12.96
4.02%	3.68%	53.00	12.00	11.20

3.3 8-PLY TC250 UNIDIRECTIONAL CARBON FIBER

The final material tested was an 8-ply TC250 unidirectional carbon fiber. There was little of this available, so only seven samples were tested. The test results still showed the same trend of increased flame times and burn lengths with increased hydrogen concentrations. There was a large increase from testing with no hydrogen compared to 1%, and then a smaller increase in burn lengths at higher concentrations. The results from each test are shown in figure 9.

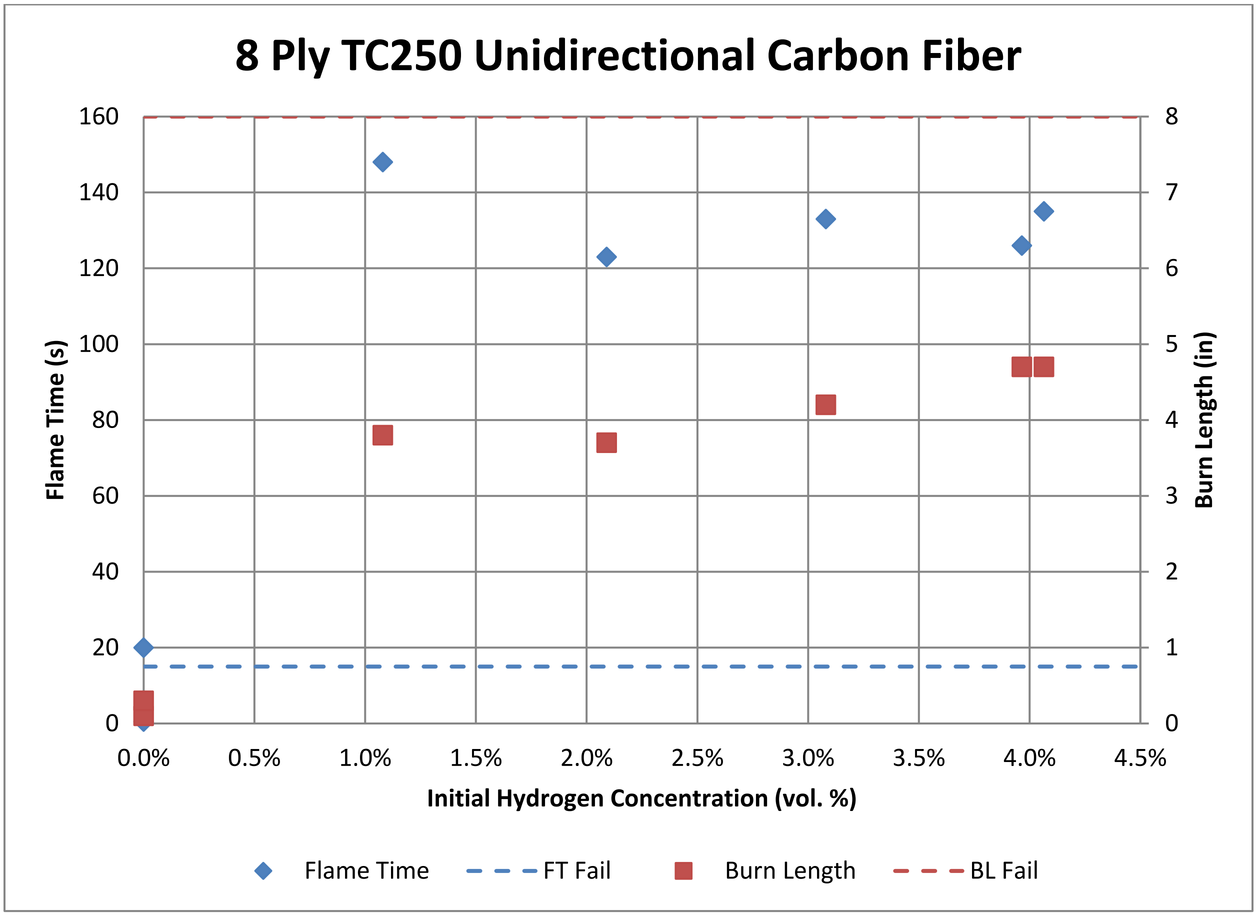

Figure 9. Flame time and burn length of each unidirectional carbon-fiber sample tested

Three of the samples tested are shown in figure 10. From left to right, the figure shows that they were tested at hydrogen concentrations of 0%, 2%, and 4%. Their burn lengths were 0.3″, 3.7″, and 4.7″, respectively. The flame damage on the upper sections of all three of these samples was from an unrelated test and had no effect on these test results.

Figure 10. Post-test unidirectional carbon fiber, from left to right: 0% H_2, 2% H_2, and 4% H_2

The burn rate of this material showed a very similar trend to the woven carbon fiber. The burn rate increased as the hydrogen concentration increased, with the biggest jump coming between 0% and 1% hydrogen. The results are shown in figure 11. The average initial and final hydrogen concentrations, along with the average test results, are shown in table 3.

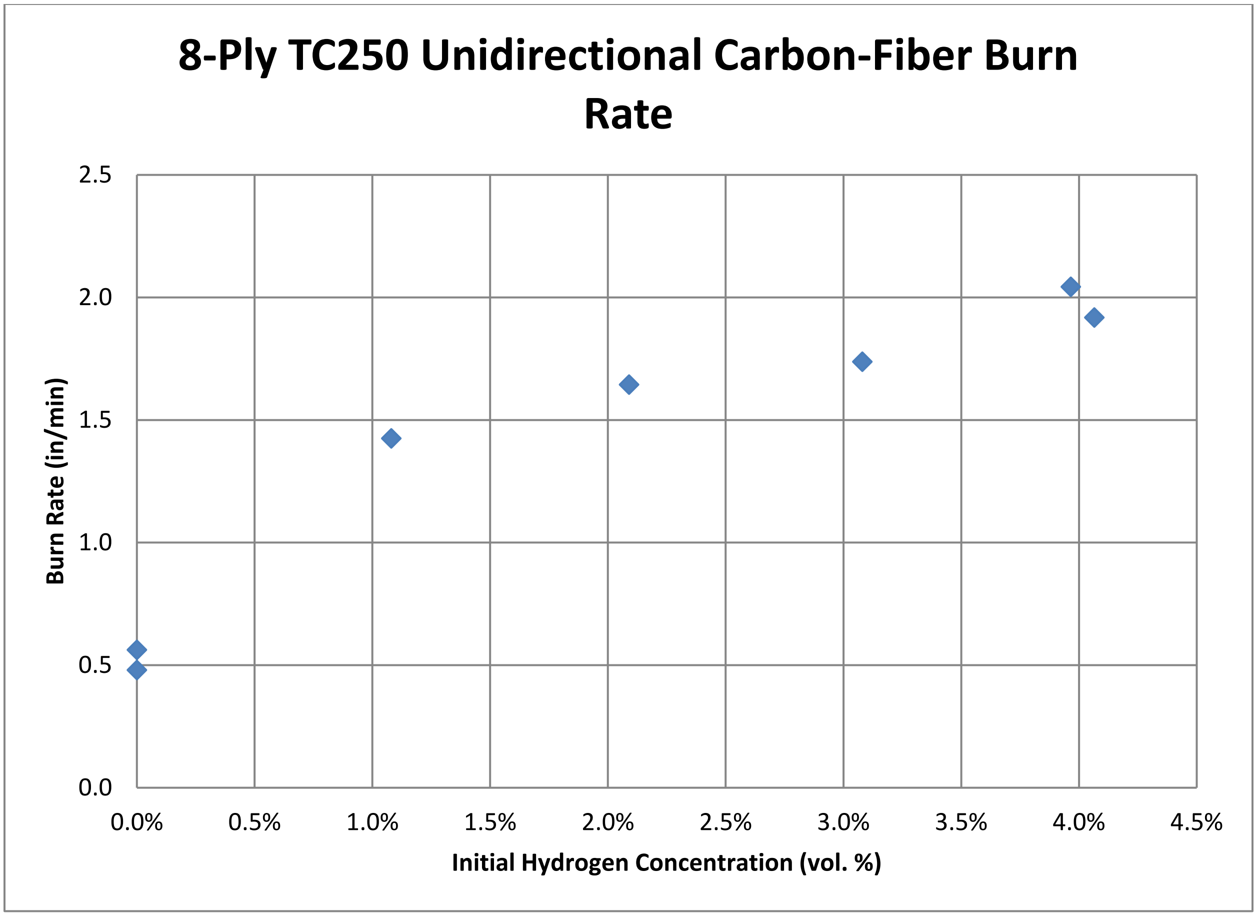

Figure 11. Burn rate of all unidirectional carbon-fiber samples

Table 3. Test data averaged for each hydrogen concentration for unidirectional carbon fiber

8-Ply TC250 Unidirectional Carbon-Fiber Average Data				
Initial H_2 %	Final H_2 %	Flame Time (s)	Burn Length (in)	Burn Rate (in/min)
0.00%	0.00%	10.25	0.20	0.52
1.08%	1.02%	148.00	3.80	1.43
2.09%	1.90%	123.00	3.70	1.64
3.08%	2.70%	133.00	4.20	1.74
4.02%	3.36%	130.50	4.70	1.98

4. CONCLUSION

Several tests were conducted to determine whether concentrations of hydrogen below the lower flammability limit could affect the burning of materials. The 12-second vertical Bunsen burner procedure was used with a hydrogen concentration in the test cabinet that varied between 0% and 4%. Three different materials were tested: a 1/16-inch-thick woven carbon fiber, an aircraft seat-cover fabric, and an 8-ply unidirectional carbon fiber. All of the test materials showed increased after-flame times and burn lengths with increased hydrogen concentrations. The burn rate for both carbon-fiber materials also increased as the hydrogen concentration increased. The burn rate for the seat-cover fabric stayed relatively constant.

5. REFERENCES

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