Ablative Insert Development for a Nitrous Oxide-Ethane Engine

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This paper presents the development plan of an ablative insert for a bipropellant engine, along with the current progress and results. The engine is an 800 lb thrust Nitrous Oxide-Ethane engine that uses blowdown pressurization with a chamber pressure of roughly 500 psi. Preliminary development focused on basic characterization of ablating fiber-resin composite materials, and how factors such as fiber material, epoxy resin mass fraction, and layer number impact the measured temperature on the backside of a flat aluminum specimen. A butane torch was used to simulate the combustion flame for qualitative comparison across samples. This preliminary data was used to inform acquisition of future test materials and higher fidelity test design. Future development topics include fiber materials, potential additives such as silica microspheres, manufacturing and integration into the engine, and application of experimental ablative regression into current engine model.

I. Introduction

THE design of a bipropellant rocket engine has innumerable areas for development, from injector, chamber, and nozzle geometries to propellant chemistry to performance factors to controls and valving. When designing the initial generation of an engine, it can be difficult to understand the implications of seemingly small design choices on a system level, unless thousands of trade studies and cases are evaluated within a simulation. Often, an initial set of characteristics are adopted with the expectation that many will have to be adjusted. Then, as certain aspects of the design become more concrete, some decisions must be altered or reversed. This is the case with the cooling method of NOE-1, a first generation nitrous oxide-ethane engine in development by the Space Hardware Club at the University of Alabama in Huntsville. Preliminary designs of the engine employed a boundary layer cooling, with the expectation that an unknown secondary cooling method would have to be employed. The sole mechanism of film cooling relies on increased fuel injection along the walls of the combustion chamber to decrease the oxidizer-fuel ratio and decrease combustion temperatures. However, due to the low heat capacity of ethane gas, a significant amount of volume would have to be added to the tanks to adequately cool the engine. In order to reduce weight and system volume without having to significantly redesign the engine and fluid systems, the team is researching and testing the feasibility of an aluminum engine cooled by a composite ablative insert. Secondary fuel injection near the throat was also considered for cooling, but has similar issues are film cooling due to the limitations of ethane. A heat sink engine with an external coating and increased external surface area was also considered, but it was determined that the engine may not reach steady state during burn, making this option less optimal. Regenerative and transpiration cooling were very quickly eliminated due to complexity. Therefore, ablative cooling shows the most promise as a low cost, easily integrated cooling mechanism.

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II. Background

Polymeric ablatives (PA's) are one of the largest classes of ablatives currently in use. A polymer ablative is a material placed in a hyperthermal environment in order to absorb energy in a chemical reaction and protect surfaces from heat. This ablative process is diagrammed in Figure 1 [1].

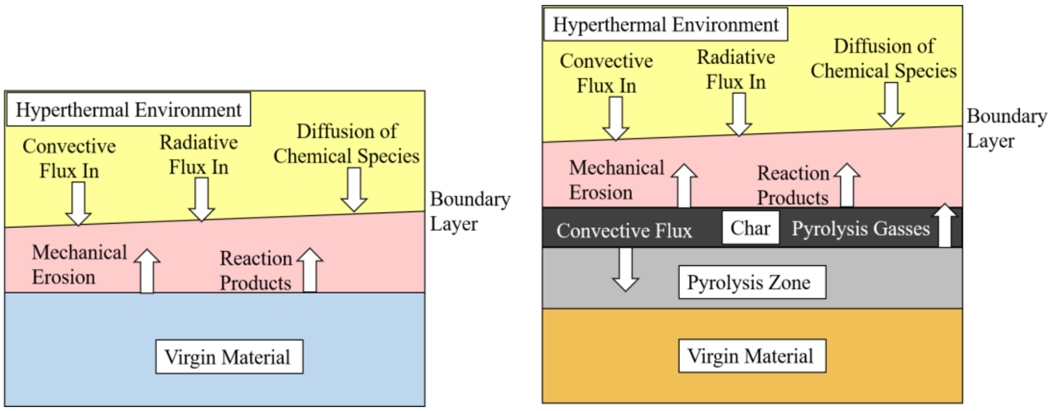

Figure 1. Diagram of Polymeric Ablative Process[1]

The char layer serves an important role in the protection of the pyrolysis zone. The pyrolysis zone is an area where the material has become heated enough to produce gases, which force the pyrolysis zone material to expand until the pressure is high enough to permeate through the char layer. Once the pyrolysis gases permeate the char layer, a boundary layer is is formed. This boundary layer helps insulate the engine walls from combustion by creating a barrier between the incoming stream and ablator wall, which protects the char layer thermally and chemically. The pyrolysis products escaping through the char layer cause more porosity in the char layer, until the products diffused at a rate higher than they are produced. At the point, the boundary layer is near non existent and the combustion begins heating virgin material. This virgin material become a new layer of char, and the process begins again[1]. A specific benefit of Fiber Reinforced Polymeric Ablatives (FRPA's) is the increased mechanical properties of the fibers, which help maintain each char layer for longer than if there were no fibers.

A. Amateur Resources for Ablative Development

Student rocket teams often find the work of amateur or hobbyist rocketeers relevant to their own projects for a variety of reasons. Most amateur sources do not dive as deeply into the theory of phenomena, have limited budgets and facilities, and produce applicable results to student level projects. This appeals to student design groups who are working on developing technologies in parallel to understanding the theories behind the technology, and allow students to see how theoretical concepts work with hardware. Richard Nakka is a retired engineer who is a proponent Amateur Experimental Rocketry, and has been running a website documenting his various projects and tests since 1997. This includes everything from recovery delay ejection devices to the correction of theoretical performance equations based on data collected from hobby rocket motors. In 2007, Richard Nakka performed experimentation with 8 commonly available ablative materials. These materials included epoxy, glass microspheres, Bondo, J-B Kwik Weld, and Hydrated Magnesium Sulfate. Richard Nakka's research into ablative materials was used as a starting point for the team's experimental procedure, which is detailed in Preliminary Testing and Results. Additionally, the usage of glass microspheres suspended in epoxy and commercial filler Bondo was noted by the team for future testing.

B. Institutional Sources

Polymeric Ablatives for Thermal Protection Systems is a comprehensive guide of ablative and nonablative Thermal Protection Systems, including review of non-polymeric materials. Reference 1 was written in the context of re-entry vehicles more so than engine ablatives, but provided a very useful overview of the research into various materials. Using this reference, the team was able to quickly eliminate ceramic and metal ablatives from the trade space due to manufacturing difficulties and cost. Carbon-carbon ablatives were also ruled out due the high temperatures (2500-2800 °C) required to create a low porosity insert.

The discussion of polymeric ablatives proved most useful to the team once other options were eliminated. A diagram of the types of polymeric ablatives is shown in Figure 2 [1].

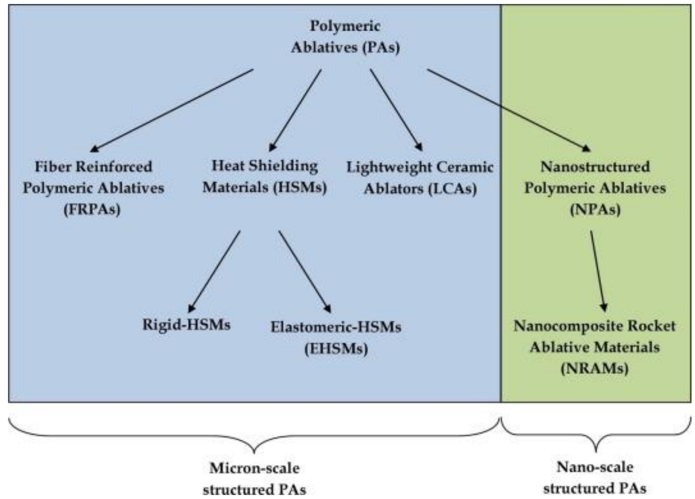

Figure 2. Organization of Polymeric Ablatives[1]

Fiber reinforced polymeric ablatives appealed to the team due to their previous experience working with fiber composites for vehicle airframe construction. Fiber reinforced polymeric ablatives (FRPA's) are also the most common ablative used in rocket engines, due to their good mechanical properties in the presence of high temperature gasses. In solid rocket motors, the throat ablation rate can be dramatically higher due to the condensation of solid alumina during combustion of common solid rocket propellants. However, this is not a concern for the team, as the products the Nitrous Oxide-Ethane combustion do not condense into solids. Due to the film cooling on the engine's walls, the ablative insert will be additionally protected from radiation. Reference 1 also established the expectation that fiberglass reinforced composite will ablate more than carbon fiber composite, as well as the necessity of testing multiple materials for our engine conditions, as "no single ablative can effectively work in a wide range of hyperthermal environments" .

In addition to material selection, Reference 1 also impacted the testing plan. Young engineers often overdesign or underdesign subsystem testing. Overdesign is driven by the desire to match test environments as closely to the flight environment as possible, which often results in low feasibility, high cost testing. When the obvious challenges of the initially thought out testing become more clear, the plan can often swing too far towards high feasibility and low cost, and become non-representative of the flight conditions. This gives false confidence in the testing results and can be dangerous when planning the test matrix for a full scale hot fire. This paper established the fundamental principle in ablative design that "...in practically all cases, some characteristics of the real environment are not well reproduced; thus, the data gathered in a full scale test instrumented with sensors are of extreme importance." [1] This allows the team to accept lower fidelity testing and enter hot fire with a more conservative hot fire test matrix.

An additional piece of literature that was reviewed was *Thermal Conductivity of Composite Materials Made From Plain Weaves and 3-D Composite Weaves*. Reference 3 was used a resource for both material choices as well as testing methodology, as well as a general primer on the thermal behavior of composites. Reference 3 studied the effect that composite matrix material and epoxy volume fraction had on the steady state thermal conductivity. While not wholly applicable to this application, useful data can still be found. The importance of the epoxy volume fraction can be clearly seen in the results, with an increase in epoxy volume fraction leading to a decrease in thermal conductivity. The materials chosen for testing in this paper also informed our material choices. While 3D composites are beyond the scope of SHC's fabrication capabilities, all three simple composites were chosen as part of the testing matrix. This paper also highlighted the low thermal conductivity of Kevlar composites, leading to it being added as a material of interest for the team's ablative insert.

III. Preliminary Testing and Results

After reviewing literature and determining the most promising materials for testing, the team began the acquisition process. Many fiber materials were ordered in small quantities to reduce cost and limit excess unused material after the final trade selections were made. These limited materials included kevlar, kevlar-carbon fiber cross weave, and specialty thickness fiberglass. Many of the sources detailing ablative development of FRPAs did not specify the exact layer thickness or mass fraction. The team determined that it would be beneficial to determine the effects of those parameters on the insulating properties of the FRPA in order to optimize and control them during later testing with less available materials. For this preliminary testing, on-hand carbon fiber and fiberglass were laid up in various configurations and tested using a propane torch and basic ablative specimen setup. The ablative test articles were flat plates. There are drawbacks to the use of flat plates. This test setup does not accurately model the internal combustion pressures, which will affect the diffusion of the boundary layer through the char layer in an actual engine and cause faster ablation rates than in unpressurized testing. Additionally, the combustion is not well accounted for, as a torch firing at a 3 inch distance is much less destructive than active combustion in a chamber. However, the goal of this testing is to compare the performances of each ablative, not derive any engine models of ablation rates. For that reason, the testing is adequate as a low fidelity preliminary examination of the material properties in relation to one another.

C. Test Day 1

1. *Procedure*

The primary purpose of the first day of testing was to establish and verify that the test day procedures were valid. The test procedure consisted of three primary operators, along with several secondary operators. The first operator was in charge of conducting the test by starting and stopping the propane torch, as well as recording the elapsed burn time. The second operator was in charge of recording the backside temperature of the aluminum plate with the digital infrared thermometer. The third primary operator was the camera operator, who recorded the thermometer readings with a video camera to allow for data analysis at a later time. The secondary operators all had additional video cameras, and were in charge of recording the ablative itself from various angles during the burn. The initial burn time decided for this experiment was twenty seconds, as that is the simulated burn time of NOE-1. All participants in the ablative testing, regardless of role, were required to wear safety glasses at all times. All roles are labeled and outlined in red in Figure 3.

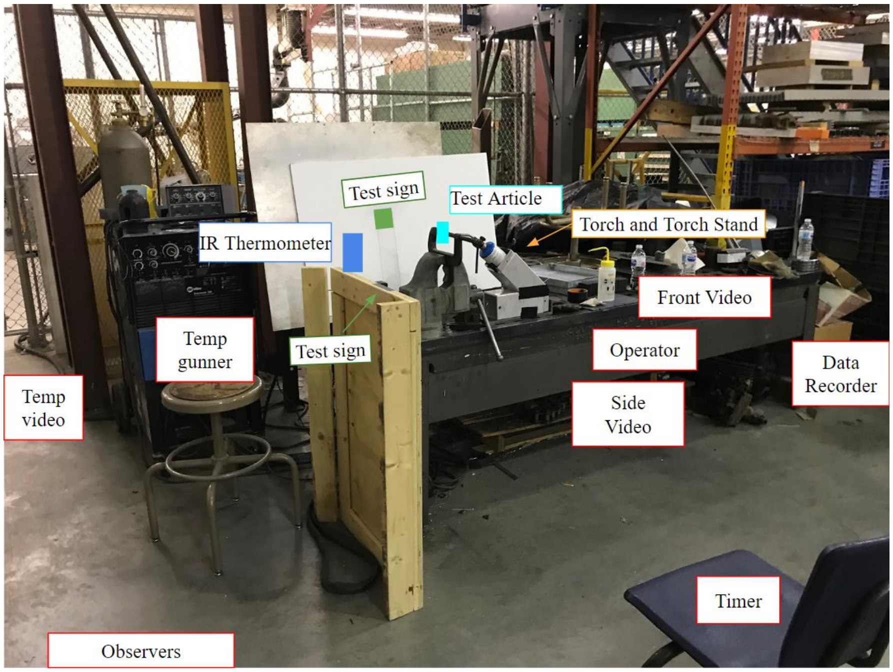

Figure 3. Labeled Image of Testing Setup

2. *Hardware Setup*

In order to test the effectiveness of our ablative materials, a simple, low cost testing setup was required to rapidly test samples. To accomplish this, the ablative sample was clamped into a vise, and a propane gas torch was secured approximately 3 inches from the surface of the ablative specimen. A propane torch was chosen for two primary reasons. Firstly, the combustion temperature of propane and oxygen (3600 °F) is very similar to the combustion temperature of ethane and nitrous (3200 °F) in NOE-1. Secondly, propane torches are both inexpensive and extremely common, allowing for easy purchase of testing equipment. In order to measure the temperature of the backside of the aluminum plate, an infrared thermometer was used. The screen of this infrared thermometer was recorded on video, then temperatures were recorded from the video in even time increments after the operator called “ignition”. A problem that was noted after the first trial was that the high emissivity of the aluminum's natural finish skewed the temperature readings from the infrared thermometer. To counteract this, the backside of the aluminum was spray painted matte black to provide a constant emissivity across test articles. This allowed for consistent temperature readings. Each test was videoed from multiple angles to examine the degradation of the material over time and the dissipation of the heat flux across the surface of the ablative due to the boundary layer.

After the first round of testing was completed, it was noted that fumes were not dissipating as fast as desired. To prevent the further buildup of fumes, the test setup was relocated to an area that had an extendable fume retractor for additional safety.

3. *Test Conditions*

In addition to its primary purpose as a dress rehearsal of the test day procedures and setup, two parameters of the samples were tested: the surface finish of the metal and the layers of material between the flame and the backing plate. All of the samples had an intended 1:1 mass fraction of fiber to matrix. They were each mounted on a 3” x 3” piece of ¼” aluminum plate, which had varying surface finishes from unfinished extrusion to die ground gouges in the material. These varying surface finishes are shown in Figure 4. The full test matrix for Day 1 can be seen in Table 1.

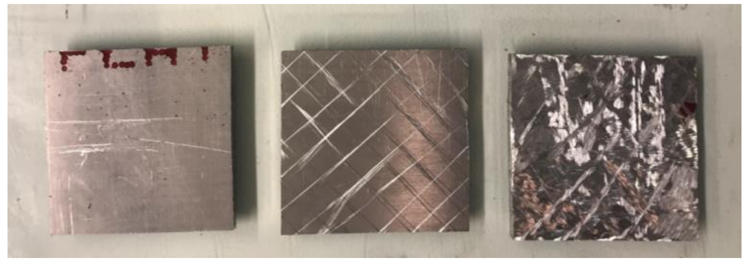

Figure 4. Unfinished, Diamond, and Rough Surface Finishes

Table 1. Test Specimen Matrix for Test Day 1

Specimen ID	Layers	Surface Finish	Notes
1F	2	Unfinished	Control
2F	2	Diamond	Diamond pattern scratched with file
3F	2	Rough	Texturized with die grinder
4F	1	Unfinished	-
5F	3	Unfinished	-
6F	2	Unfinished	Repeat of Control
1C	2	Unfinished	
2C	2	Diamond	
3C	2	Rough	
4C	1	Unfinished	
5C	3	Unfinished	

4. Data and Results

The results from Day 1 of testing was conclusive on the subject of layer count, and inconclusive on the subject of surface finish. As can be seen in Figure 6 and Figure 5, both fiberglass and carbon fiber perform as better ablatives when additional layers of material are added. This test also gave a preliminary indication that fiberglass was a better ablative than carbon fiber, with the single layer of fiberglass having similar performance to the two and three layer carbon fiber samples. Additionally, these tests served to validate the experimental configuration, showing that valid data could be produced and analyzed. The surface finish data was much more qualitative, with observations being made after each test was concluded. The team concluded that the surface finish has little effect on the adhesion of the ablative to the backing material in this configuration. This allowed the team to eliminate the surface finish of the backing plate from any further testing matrices in this testing configuration.

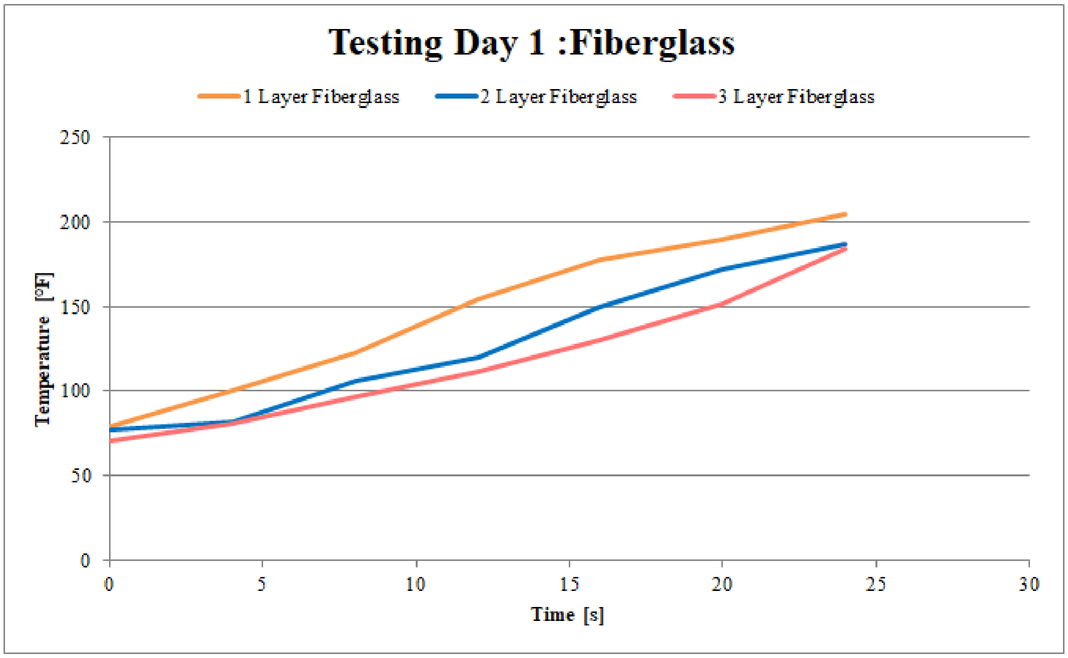

Figure 6. Results of Fiberglass Variable Layer Samples for Test Day 1

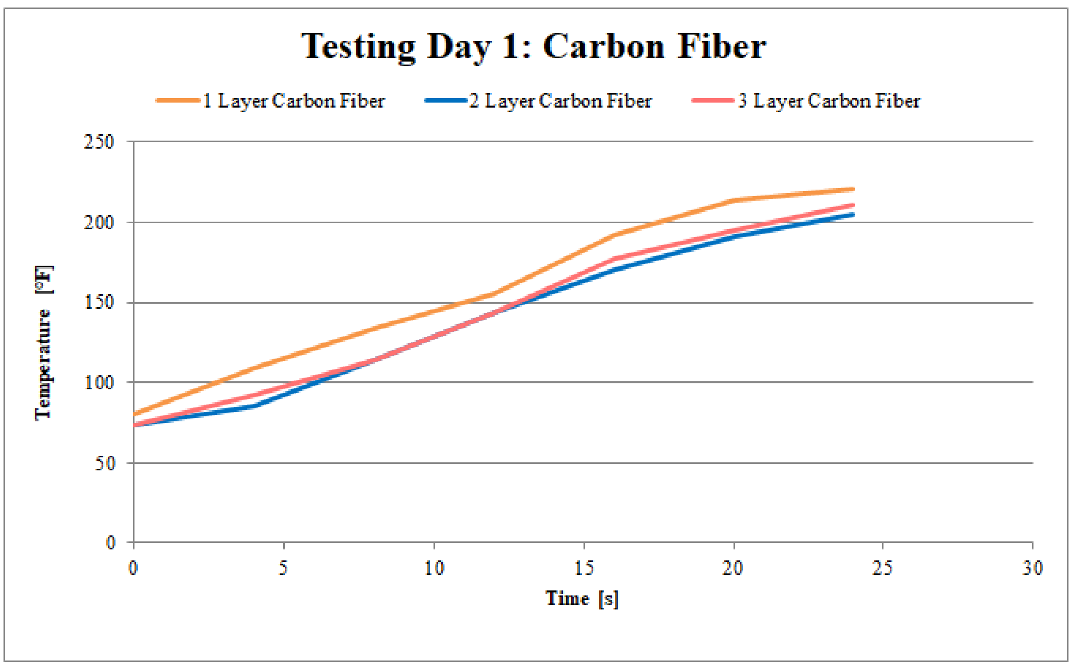

Figure 5. Results of Carbon Fiber Variable Layer Samples for Test Day 1

D. Test Day 2

1. Procedural Changes

For the second round of testing, several changes were made to the testing procedure. The most important was the addition of a second thermometer that was intended to measure the frontside temperature of the ablative. The intention of this frontside recording was to see if the order of the layers of composite had any discernible effect on the heat transfer through the ablative to the backing plate. However, this idea did not pan out as hoped. As the team was still in a pretesting phase intended to determine any errors in our testing procedure or setup, it was deemed unwise to purchase an expensive and fragile high temperature thermocouple. Instead, a second infrared thermometer was purchased. This thermometer was inadequate for two primary reasons. The first was the limited range of the thermometer, with a maximum temperature of 600 °F being inadequate to measure the 3,600 °F flame. Additionally, the combination of the shifting flame front across the face of the ablative combined with the gloss finish lead to inconsistent temperature measurements. While this frontside data will be useful in developing a full ablative model, it is not required for the preliminary section of materials to test. The backing material was also changed from ¼" aluminum to 16 GA steel. This switch was made for reasons of cost and manufacturability. The aluminum sheet stock needed to be cut to size using a bandsaw, leading to long manufacturing times and high costs to manufacture all the required backing plates for the Day 2 test matrix. The 16 GA sheet steel could be quickly and easily cut to size on a sheet metal shear. This sheet steel also already had a matte black painted face, removing the need to spray paint the backing plates, removing the painting and drying time from the fabrication process.

2. Test Conditions

Table 2 shows the numerous specimens that were created for the Day Two testing. For each configuration, 3 specimens were created, to lessen the effect of fabrication defects and allow for the rejection of outlier data points. Configrations 1, 2, 5, and 6 were listed as control specimen. Each of these configurations were comprised of either three or four layers of the same ablative material. Configurations 3, 4, 7, 8, 9, and 10 however were combinations of both fiberglass and carbon fiber that were layered in differing orders. The layer order as shown is from base metal plate to surface as read from right to left (i.e. Configuration 7 with layer order FG/CF/FG/CF indicates that fiberglass was applied directly to the steel sheet followed by a layer of carbon fiber, then fiberglass, and then a final layer of carbon fiber which was exposed directly to the flame).

Table 2. Test Specimen Configuration Matrix for Test Day 2

Configuration ID	Layers	Material (s)	Layer Order
1	3	Fiberglass (FG)	-
2	3	UD Carbon Fiber (CF)	-
3	3	UD CF / FG	CF/FG/CF
4	3	UD CF / FG	FG/CF/FG
5	4	FG	-
6	4	UD CF	-
7	4	UD CF / FG	FG/CF/FG/CF
8	4	UD CF / FG	CF/FG/CF/FG
9	4	UD CF / FG	CF/CF/FG/FG
10	4	UD CF / FG	FG/FG /CF/CF
11	N/A	CF	Un-Woven Suspension

For the second round of testing, the team wanted to test how the properties of each ablative would combine with each other. Three and four layer ablatives were tested in various arrangements of carbon fiber and fiberglass, with the layer order listed from the backing plate to the flame front. Of particular note is Sample 11. This was created at the end of manufacturing the other specimens. While creating the carbon fiber layups, some of the fibers fell out of the weave and mixed into the extra epoxy left on the table. While cleaning, it was decided to create an extra sample using this carbon fiber suspension to see how the performance of an unwoven fiber compare to a woven fiber.

3. Data and Results

Figure 7 displays the temperature versus time readings that were recorded on the back side of the Day Two specimen throughout the duration of the tests. As evidenced from the figure, the four-layered specimen outperformed the three-layered specimen and were able to ablate more heat from the flame. This coincides with the findings from Day One. Additionally, Specimen 4 performed the best of all the three-layered specimen and Specimen 8 performed the best of all the four-layered specimen. This is significant because these two specimen were constructed by alternating material layers with a layer of fiberglass facing outward toward the flame. This suggests that alternating between the two materials proves to be more effective at dissipating the heat before it can reach the steel sheet. This also suggests that having a layer of fiberglass exposed to the flame is more effective at heat dissipation than having a layer of carbon fiber exposed directly to the flame.

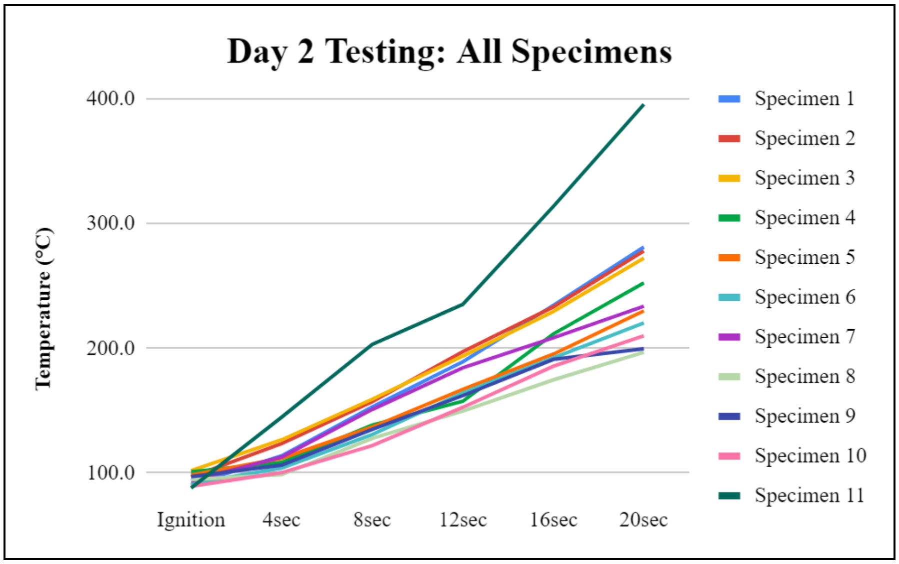

Figure 7. Plot of Average Temperature Curve for Each Configuration

Additionally, the poor performance of the unwoven suspension of carbon fiber (Specimen 11), shows the effect of how the woven fiber matrix better maintains the char layer, which results in better protection of the wall.

IV. Conclusion

Several meaningful conclusions can be drawn from the testing concluded. As discussed in the Day 2 testing results, Specimens 4 and 8 provided the best performance out of the three layer and four layer ablatives, respectively. As can be seen in Figure 8, Specimens 4 and 8 had nearly identical performances until approximately 12 seconds into the burn. At this point, it is theorized that the final layer of virgin material on Specimen 4 pyrolyzed. This lead to their being no insulation between the pyrolysis layer and the backing plate, causing the rate of temperature change to increase. The additional layer of carbon fiber on Specimen 8 ensured the backing plate remained insulated from the boundary layer, causing the rate of temperature increase to remain constant.

This effect can also be seen in Figure 9, where the three and four layer ablatives with outward facing carbon fiber have similar performances until approximately 12 seconds into the burn. At this point, the two curves diverge in a similar manner to Specimens 4 and 8. Additionally, it is apparent that outward facing fiberglass performs much better than outward facing carbon fiber. The carbon fiber the team

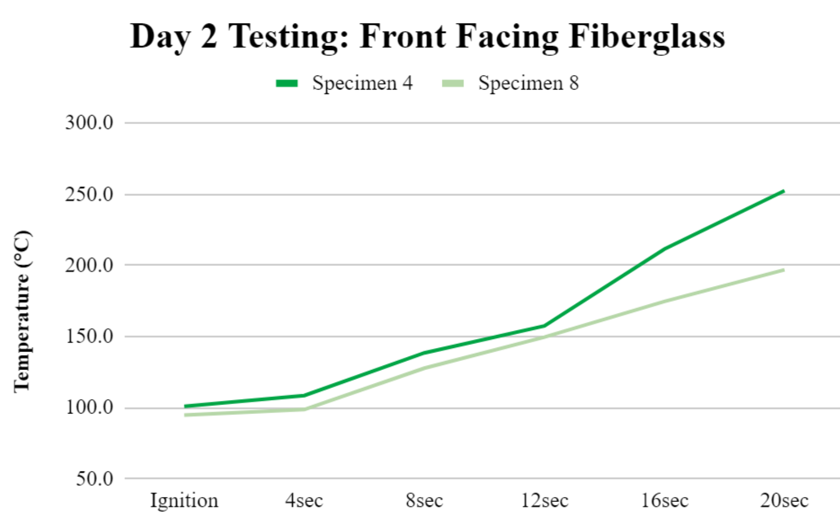

Figure 8: Comparison of 3 and 4 layer Front Facing Fiberglass Specimens.

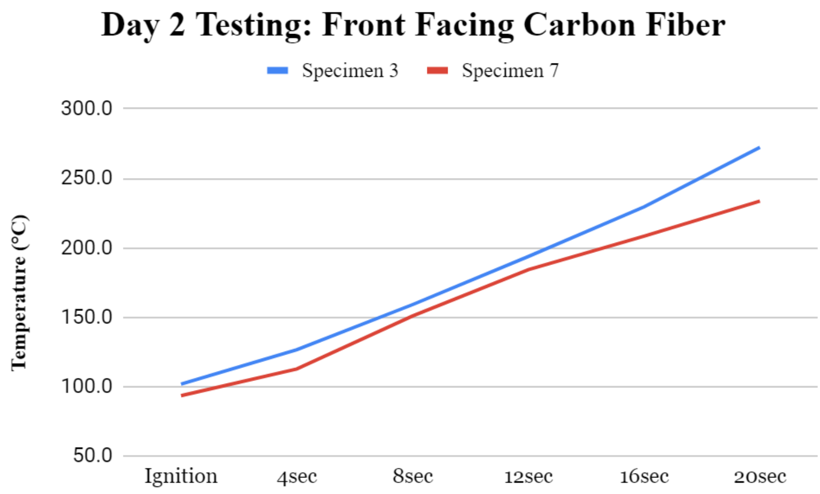

Figure 9. Comparison of 3 and 4 layer Front Facing Carbon Fiber Specimens

used during testing was unidirectional, meaning there was a lower fiber density when compared to fiberglass. In the context of the char layer, this would mean the char layer is both more porous and more susceptible to damage. A more porous char layer results in the pyrolysis gases leaking at lower pressures, which creates a less effective boundary layer. Therefore, the lower performance of the carbon fiber could potentially be due to the weave of the fiber more so than the fiber composition itself. However, it is worth noting that fiberglass is known to be a more effective ablative per Reference 1, showing there are multiple factors at play. In the future, unidirectional carbon fiber and fiberglass of similar fiber densities should be compared to reduce confounding variable and better compare the performance.

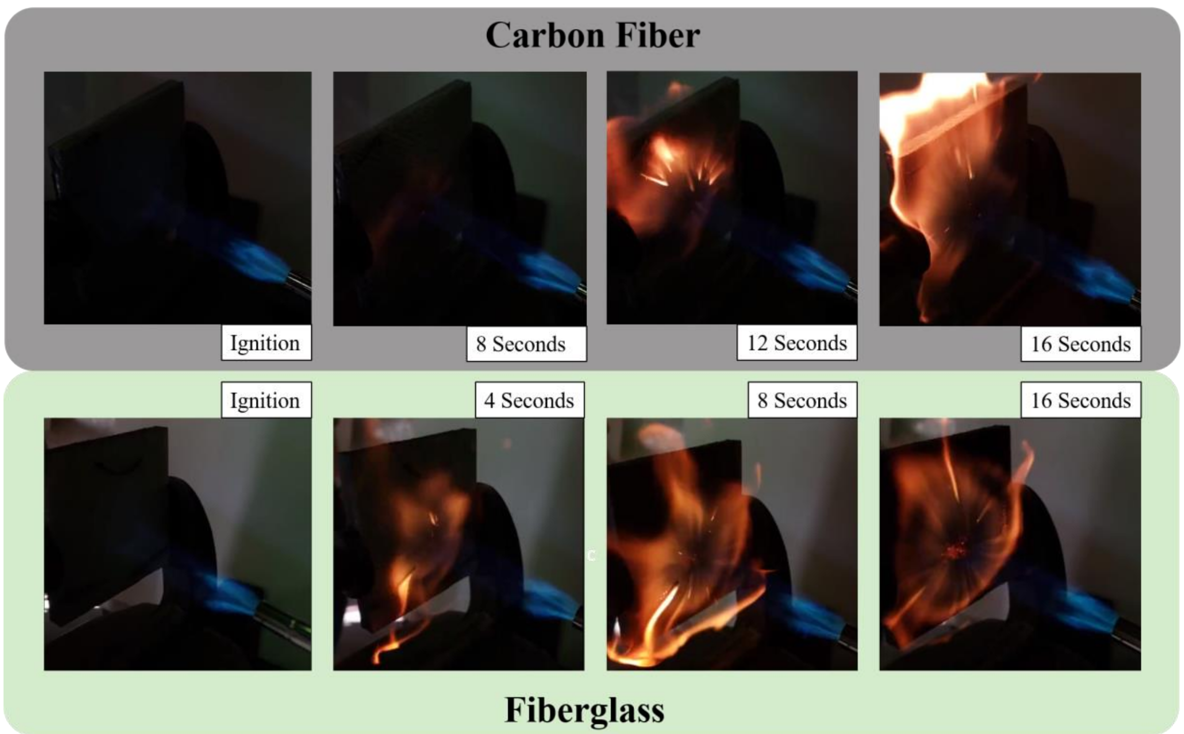

Figure 10. Comparison of Images During Carbon Fiber or Fiberglass Trials

Additionally, Day 1 testing video showed a fundamental difference in the behavior of carbon fiber and fiberglass. This difference is shown in Figure 10. Note that the time of each photo is different between the CF and FG trials. This is because the carbon fiber appears to be slower to pyrolize and create a boundary layer. The heat flux was not dislocated, and instead seemed to be absorbed by the CF. The boundary layer finally appears to be created at 12 seconds after ignition, meaning that the pyrolized gasses underneath the char layer finally reached a high enough pressure to permeate the char layer. This is in stark contrast to fiberglass, where the effects of the boundary layer are visible within 4 seconds of ignition. Additionally, by 16 seconds it seems that the heating of virgin material underneath the char and pyrolysis is visible, right in the center of the flame. These behaviors will be studied more in combination to better understand the mechanism and whether the delayed boundary layer CF can be used with the rapidly pyrolyzing FG to optimize insulating properties and longevity of the insert, especially in areas such as the throat.

V. Future Plans

With the test design and verification complete, work can begin on testing additional materials that aren't as readily available. Future plans include testing of silica microsphere suspensions, kevlar and kevlar-carbon fiber hybrid weaves, and varying thicknesses of fibers of all materials using this test procedure. Additionally, the instrumentation of the stand will be upgraded to use thermocouples linked to an Arduino DAQ which is currently in development. After this testing is complete, a final material choice will be made for the ablative insert of NOE-1. Once this choice is made, work will begin on designing and testing tooling to layup the ablative inserts into the aluminum engine. After this tooling is complete, subscale hotfire tests will be used to develop a model of the ablative. This model will be integrated into the full propulsion Simulink model that the team currently uses to predict engine performance, which is then used in a vehicle performance model. This model will allow for ablative characteristic changes to be iterated on rapidly without the need for testing each configuration, allowing the team to optimize the insert for maximum performance.

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