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Research on Lightning Strike of Composite Structures

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Final report

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NOTICE

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16. Abstract

As aircraft industry moves from traditional metal construction to advanced composite materials, there is a concern that current techniques used to detect lightning-caused sparks within fuel tanks may ignite fuel vapor due to the difference in physics involved. Existing standard SAE Aerospace Recommended Practice (ARP) 5416A defines two test methods for detection of voltage sparks in metallic structures. The first is ignition of a standard hydrogen/oxygen/argon gaseous mixture and the second is detection of light, which is a simpler and less hazardous approach. Both techniques require a 200 microjoule (μJ) minimum fuel ignition threshold induced by discharge of a standard voltage spark source. The standard defines the pass criterion either by demonstrating the absence of a minimum light detected by camera or by no ignition of the flammable gas mixture. These 200 μJ voltage sparks are generated based on sparking occurring between metallic components. However, when carbon fiber composite materials are involved, other sources of sparking appear, which have not yet been properly characterized in regard to ignition of aircraft fuel. The light emission and sparking sources include a voltage phenomenon called edge glow, incandescent particles, and hot gases ejected from fastener joints. The existing photographic test method outlined in the SAE ARP 5416A is not closely linked to the heat energy of these ignition sources, resulting in a large number of false failures, or cases in which light is detected, but ignition of the flammable mixture will not occur. This project investigates feasibility of utilizing time-integrated digital photography imaging (photographic method) for predicting the ignition conditions of the standardized flammable gas mixture imposed by an incandescent heat source. The study showed that the ignition could be predicted by analyzing the hue histogram of the detected light emission source. Thus, based on the research findings to date, appearance of the yellow hue alongside the defined incandescent heat signature has been observed to be coincident with ignition of standardized gas mixture for several investigated materials. A round robin test was conducted during year three of this research with the purpose of validating the work done in the first two years of the program. As an outcome, development of a new or augmented test method suitable for characterization of composites and metal ignition sources simultaneously will be developed with the purpose of supplementing or superseding the existing standard. The project development is carried out under the continuous monitoring by the Federal Aviation Administration (FAA) and in a close partnership with the SAE AE-2 and EUROCAE WG-31 Lightning Committees.

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Acronyms

Acronym	Definition
μJ	Microjoule
ARP	Aerospace Recommended Practice
CFRP	Carbon Fiber Reinforced Plastic
CMOS	Complementary metal–oxide–semiconductor
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
HSB	Hue, Saturation, Brightness color model
kA	Kiloampere
MIE	Minimum Ignition Energy
PMC	Polymer-Matrix Composites
RGB	Red, Green, Blue color model

Executive summary

The SAE International Aerospace Recommended Practice (ARP) 5416A Lightning Test Methods standard section 7.7 Methods for Detection of Ignition Sources defines existing photographic and ignitable mixture detection methods in application to fuel ignition caused by lightning in composite fuel tanks (Society of Automotive Engineers (SAE) International, Revised 2013). The standard defines the pass criterion either by demonstrating the absence of light detected by camera or by no ignition of the flammable gas mixture. The ignitable mixture method and the photographic method are considered equivalent. Testing in the ignitable mixture is effective for both carbon fiber and metal, but this method is undesirable due associated time and cost penalties. Because the existing photographic test method defines a minimum light emitted during the test as an ignition source, a high percentage of false failures occur during the testing of carbon fiber reinforced polymer (CFRP). When subjected to lightning strikes, CFRP is known to produce edge glow, or light emission by a partial ionization of the gas medium surrounding the tips of exposed carbon fibers due to voltage induced glow. Edge glow alone has been shown to be incapable igniting the flammable gas mixture. For ignition to occur during testing of CFRP, a thermal ignition source must be present.

The National Institute for Aviation Research (NIAR) at Wichita State University (WSU) NIAR was funded through the Federal Aviation Administration (FAA) Center of Excellence for Advanced Materials program to reassess these existing photographic and ignitable mixture detection methods. The initial approach of the research investigation was to develop a test methodology for composite structures utilizing a standard incandescent source in place of the 200 microjoule (μJ) voltage spark source currently used for metallic structure for both the photographic and ignitable mixture tests. When it became evident that development of a standard incandescent ignition source was unfeasible due to issues with repeatability and complexity, the research shifted focus toward a different means of “detection” by characterizing the color signature of light emitted by incandescent ignition sources. The result of this research is a new proposed detection methodology, utilizing existing photographic test equipment used for metallic structure testing, with an additional step in which the color signature of the potential ignition source is analyzed. Various materials heated to incandescence were tested with the flammable gas and photographic methods simultaneously to allow comparison of color signature from the digital test images with ability to ignite gas. Through analysis of the test images in cases when ignition occurred, and when it did not, a characteristic hue signature was discovered, indicating ignition conditions. This characteristic hue signature is defined as the “incandescent signature,” a presence of a continuous range of red-orange hues, as well as the occurrence of the critical yellow hue, indicating the temperature required for ignition has been reached. The hue data is obtained when the test image is converted from RGB (red, green, blue) format to HSB

(hue, saturation, brightness) format. The histogram of the hue channel of the image is then analyzed to determine whether the incandescent signature is present. This image analysis technique is referred to as “digital color emission spectrometry”, which is proposed to augment the existing photographic test method for composite structure testing.

This report provides a description of the research findings obtained over the course of the four-year program, the outcome of which resulted in a proposed new methodology entitled “digital color emission spectrometry.”

1. Introduction

As aircraft industry moves from traditional metal construction to advanced composite materials, there is a concern in the ability to accurately detect lightning-caused sparks within fuel tanks that may ignite fuel vapor due to the difference in physics involved, and also, due to the current requirements in regard to the pass/fail criterion of the existing test method itself. Aircraft certification requirements presently demand that “no ignition source may be present at any point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors” (14 CFR 25.981 – Fuel Tank Ignition Prevention.). Therefore, prevention of all potential ignition sources in fuel tanks due to lightning is an ideal requirement and the goal of all lightning protection designs.

It is presently theorized that at least two distinct modes of sparking exist in composites: high voltage sparking and thermal arcing. Lightning strike to composites can result in effects like hot ejected particles, edge glow, edge incandescence, electrical breakdown between plies, and electrical breakdown between metal fasteners and other metallic components. Heat from the lightning strike can result in effects such as “delamination of the structural plies, microscopic cracks in the composite, and the formation of small pyrolized or mass-depleted regions” (U.S. Patent No. 7,515,263 B2., 2009). The nature of sparking generated in metal versus composite materials differs greatly due to inherent physical dissimilarities of these two types of materials. This includes microstructural heterogeneity and macro-structural anisotropy, physical properties such as mechanical strength and electrical/thermal conductivities, mechanism and kinetics of materials degradation under fast Joule heating, as well as influence of materials aging (oxidation, water absorption, thermal resistance, and corrosion). If these differences are not properly accounted for in design and testing, lightning strike could put composite aircraft at higher risk than their metallic counterparts could.

Understanding the physical mechanism of lightning strike on composite structure is key to mitigating the risk. Current test methods for detecting ignition sources due to lightning may be more conservative for composite structure than for metallic structure, due to physical differences between composites and metals (conductivity, type of spark created). Improved test methods will lead to better designs and certification procedures. Industry supports research in this area, based on a need to better understand the performance of composite structures subjected to lightning. Improved testing methods for composite structure will reduce both the cost of testing and of manufacturing by allowing testing to be less conservative, while continuing to detect all potential ignition sources.

The existing industry standard outlined in the SAE International Aerospace Recommended Practice (ARP) 5416A *Lightning Test Methods* standard section 7.7 *Methods for Detection of Ignition Sources* utilizes a 200-μJ voltage spark as an ignition source for detection of fuel ignition caused by lightning within fuel tanks (Society of Automotive Engineers (SAE) International, Revised 2013). This voltage spark is not closely linked to the heat energy evidenced produced by composite materials including incandescent ejections, hot spots, and edge glow in the environment of hot outgassing. Therefore, the primary goal of this research program was to develop an approach for characterizing heat signatures of incandescent ignition sources (incandescent particles, hot gases, and edge glow discharge) and associated flammable gas mixture ignition thresholds produced by carbon fiber reinforced plastic (CFRP) fastener-composite joint assemblies. The secondary goal was to assess adequacy of the existing 200-μJ fuel ignition-based standard, encompassing the photographic and ignitable mixture methods, in application to fuel ignition induced by an incandescent ignition source. As an outcome, a new detection method suitable for characterization of composite sources simultaneously has been developed with the purpose of supplementing or superseding the existing standard. The project development was carried out under the continuous monitoring by FAA and in a close partnership with the SAE AE-2 and EUROCAE WG-31 Lightning Committees.

Methods for preventing ignition sources due to lightning strikes for metallic aircraft are mature and are based on years of research into natural lightning characteristics and effects upon airplane structures and systems. Existing standard SAE ARP 5416A (Society of Automotive Engineers (SAE) International, Revised 2013) *defines two test methods for detection of voltage sparks in metallic structures*: ignition of a standard ignitable gas mixture or detection of light, which is a simpler and less hazardous approach. Both techniques requiring to be related to a 200-μJ minimum fuel ignition threshold induced by discharge of a standard voltage spark source. The test standard defines the pass criterion either by demonstrating the absence of light detected by camera or by no ignition of the flammable gas mixture. These 200-μJ voltage sparks are considered generated because of sparking occurring between metallic components.

The standard currently relates the two test methods to be equivalent, and typically only one test type is used at a time, gas or photographic. While the gas test generally guarantees a lower percent of false failures due to higher reliability, it involves associated time and cost penalties. This method is generally assumed equally effective in metal, composite or hybrid test articles. However, when carbon fiber composite materials are involved, incandescent particles, hot gases, and edge glow appear from fastener joints to present another source of sparking, which has not yet been properly characterized concerning ignition of aircraft fuel. Ejections may be produced but will not ignite the gas during testing and, thus, remain undetected, which is potentially hazardous as a result of impossible to control situations when hot particles propagating at fast velocities and various trajectories coming into the contact with fuel tank walls. This highlights the necessity for all ejections to be detected.

The 200 μJ voltage sparks are high-voltage, low current discharges occurring in small gaps to permit breakdown of a non-conducting gas at the applied voltage. However, a high-current pulse applied to carbon fiber polymer-matrix composites (PMC) results in production of localized incandescent areas, material evaporation forming hot gaseous species, and possibly, hot particles ejected from fastener joints. Thus, as a result of discussions that took place during the EUROCAE WG-31 ED105/ARP5416 meeting in October 2016 at Cobham Technical Services (Abington, United Kingdom), hot particle ejections were eliminated from any further evaluations and considered as part of this study as a guaranteed failure arising from the already initiated materials deterioration. This is considered a conservative approach, but it is necessary due to inability to measure true energy content of the ejected particle.

Initially, the focus of the research was to develop a standardized incandescent ignition source, with the intent that it would replace the 200-μJ spark source for CFRP lightning testing while tests for metallic components would retain the 200-μJ spark source. The standard incandescent source would be incorporated into a set of tests identical in procedure to the existing flammable gas method and photographic method currently used for metallic structures. Composite structure testing would utilize the standard incandescent source for verification of the ignitability of the flammable gas mixture, as well as for a camera verification procedure to establish the brightness threshold required to ignite the flammable mixture. The general nature and variety of incandescent materials presented difficulty with development of a standard incandescent source test apparatus for use in place of the 200-μJ spark source. It must be capable of reaching temperatures high enough to ignite the flammable gas mixture, heating at a rate comparable to lightning tests, and be highly consistent and repeatable. In order to achieve the fast heating rate and high temperature, the size of the source must be sufficiently small, such as a thin wire or filament. Materials must have very high melting temperatures and low rates of oxidation. Any material oxidation or degradation over time and after multiple uses is not be acceptable for a standard incandescent ignition source.

Development of a viable standard incandescent source using commonly available materials was determined to be unfeasible, resulting in the evolution of a new approach to characterize the ignition threat of edge glow and incandescence. Through experimentation on numerous materials during the attempt to develop the incandescent source, it was discovered that each time ignition occurred a similar appearance of light was produced, leading to the approach of ignition source characterization based on the color of light emitted.

With the purpose of augmenting the existing SAE ARP 5416A *Aircraft Lightning Test Methods* standard section 7.7 *Methods for Detection of Ignition Sources*, this project investigates feasibility of utilizing time-integrated digital photography imaging (photographic method) for predicting the ignition conditions of the standardized flammable gas mixture imposed by an incandescent heat source. The study shows that ignition can be predicted by analyzing the hue histogram of the detected light emission source. Thus, based on the research findings to date, appearance of the yellow hue alongside the incandescent heat signature has been observed to be coincident with ignition of standardized gas mixture for several investigated materials. The incandescent signature is defined as a continuity of colors in the red-orange-yellow range, corresponding to a minimum specified range falling in the 0-42 hue value span (bins) based on the 0-255 total bins for an 8-bit image in the HSB color space. Digital color emission spectrometry is the image analysis technique developed because of this research.

The most advantageous aspect of the digital color emission-spectrometry method is that its implementation can be completed at little or no cost. The method requires no additional equipment, utilizing existing digital cameras and test chambers already in place in test labs for the ARP 5416A photographic method. Use of the digital photographic sensor is low cost, easily available for purchase, and simple to implement. Additionally, the recommended software for analysis, ImageJ, is open-source image processing software, making it widely available and obtainable at no cost. Multiple alternative image-analysis software options exist, allowing flexibility for the user. The digital color emission-spectrometry method aims to reduce the number of false failures for composite structure tests due to edge glow that occur with the overly conservative existing photographic method. Edge glow presents no threat of ignition to the flammable gas mixture on its own; therefore, the light emitted by edge glow during the test should not be considered an ignition source. Characterization of the hue signature of incandescent ignition sources allows for straightforward determination of whether light emitted was due to edge glow, or due to incandescence. Only when the incandescent hue signature is present should the test be considered a failure when using the dominant color emission-spectrometry method.

These findings were received and acknowledged by the industry and FAA representatives at the SAE AE-2 (Oklahoma City, Oklahoma, September 2017) and EUROCAE WG-31 (Germany, October 2017) lightning committee meetings. Therefore, a launch of a round robin investigation testing has been authorized with the purpose of validating this approach and augmenting the existing photographic method. The validity of the proposed approach is to be endorsed by several laboratories including but not limited to, NIAR/WSU, Boeing, DNB Engineering Inc., National Technical System (NTS) Lightning Technologies Inc. in the United States, Element, Laboratorio Central Oficial de Electrotecnia (LCOE) and Direction Générale de L'armement (DGA) laboratories in Europe, and Subaru in Japan.

This report provides a description of the research findings obtained over the course of the three-year program, including the development of a new test methodology entitled "digital color emission spectrometry." Finalization of a test procedure for the round robin investigation composed in accordance with the SAE ARP 5416A style, and the implementation of the round robin testing were done in year three. The round robin test is intended to validate the findings of the first two years of research.

2. Phase 1: Preliminary studies - Experimentation

2.1 Digital color emission spectrometry

The digital color emission-spectrometry method was developed because of this research. The detector utilized for the method is a digital camera that has been validated according to the SAE AE-2 Lightning Committee whitepaper (SAE AE-2 Lightning Committee White Paper, Rev. NEW. January 2018). The digital camera detects light via a complementary metal–oxide–semiconductor (CMOS) sensor overlaid with a red, green, and blue color-filter array, as seen in Figure 1. Each color filter allows red, green, or blue wavelengths of light to pass through to the sensor, generating color data at that pixel for only one of the RGB colors. The resulting image

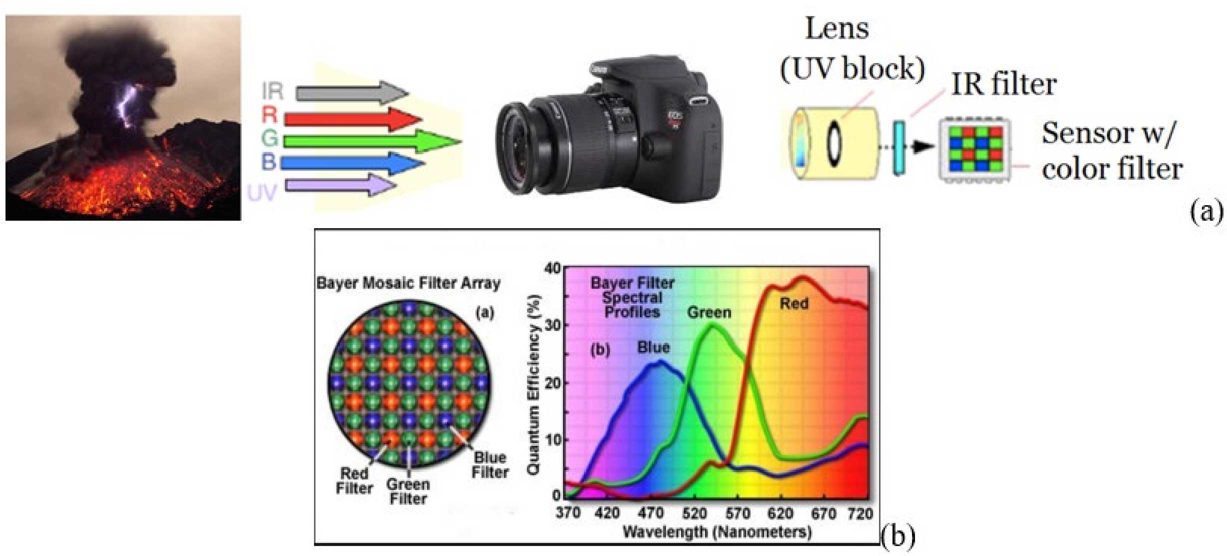


Figure 1. Digital camera RGB sensor (a) and color filter array spectral response (b).

produced is a grid pattern matrix of RGB values. The color data in the image is then "demosaiced," an internal process performed within the camera, in which the RGB values are interpolated to display the full range of perceived visible colors. Image analysis is performed on the resulting RGB color image, the standard output image of the digital camera.

All image analysis utilized ImageJ, an open source image processing software (Schindelin, 2012). The test photo is converted from the standard camera output format, the RGB color space/model, to the HSB (hue, saturation, and brightness) color model, as depicted in Figure 2.

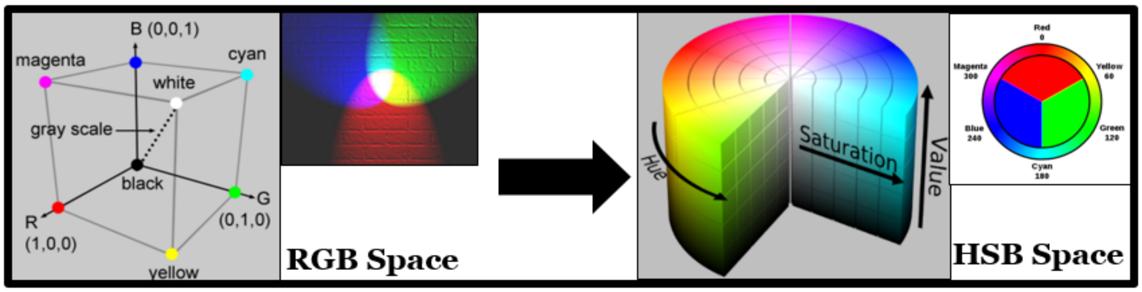


Figure 2. RGB to HSB conversion.

The hue channel is the focus of image analysis for determining ignition conditions. Hue represents the component of color, which would be described as "pure color," not taking into account how bright or dark the color is, or how much gray it contains. Hue refers to the dominant wavelength of emitted light, and corresponds to how humans typically describe different colors. For example: red, blue, and yellow are all different hues, whereas light blue, medium blue, and dark blue all share the same hue value but differ from each other in brightness. A histogram of the hue channel, displaying the number of pixels in the image occurring at each hue value (ranging from 0-255 for an 8-bit image), is generated in ImageJ. The region of the image selected for inclusion in hue histogram analysis includes the incandescent source, while excluding the low intensity hue noise (light leaks or reflection of light on surfaces in the test chamber, hot pixels on the camera sensor, etc.) from the background area that is not representative of an ignition source.

Analysis of hue histograms is conducted to determine whether the incandescent signature is present. If the incandescent signature occurs in the test image, the light source should be considered capable of igniting fuel. The incandescent signature is defined as the presence of a minimum continuity of hue values in the red-orange range, corresponding to the 0-41 hue value range based on the 0-255 total bins for an 8-bit image in the HSB color space. The number of consecutive bins that make up the continuous spectrum can affect the sensitivity of the method. To be certain that all ignition cases are detected, this part of the incandescent signature requires further investigation, which is encompassed in the round robin test. The round robin test during year 3 of the project intends to define this range more strictly to ensure an adequately conservative test. The critical yellow ignition hue value is 42.

The continuity of consecutive hue values between 0 and 41, accompanied by the critical yellow hue indicates that ignition will occur. Figure 2 shows an example of a typical incandescent signature with ignition conditions. The incandescent signature is the continuous spectrum **and** peak at critical yellow hue 42.

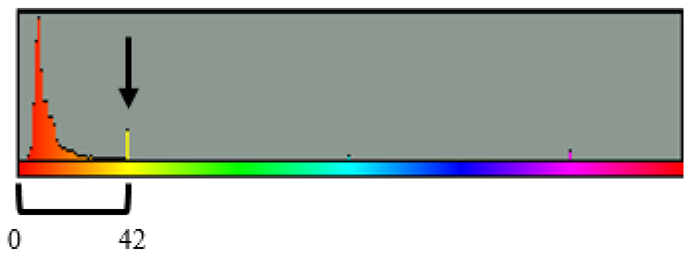


Figure 3. Histogram displaying ignition conditions.

It is important to note that both components of the incandescent signature must be present to indicate ignition. The presence of the critical yellow hue 42 alone does not signify ignition conditions. The critical yellow hue must be accompanied by the continuity of a minimum number of hue values between 0-41 in order to be considered an incandescent ignition source capable of causing ignition.

The continuity of red-orange values falling within the hue range 0 to 41 can be assumed to represent the temperature gradient that naturally occurs in incandescently heated sources, which are not a uniform temperature throughout, but typically have one region of peak temperature, while the surrounding material temperature decreases as distance increases. Presence of yellow hue value 42 indicates that the peak temperature of the incandescent source has reached the temperature required to ignite the flammable gas. The yellow hue can primarily be attributed to the surface temperature of the material due to resistive heating. The wire temperature can be approximated by treating it as a black body/gray body, as seen in Figure 4. The yellow hue can also be attributed in part to surface reactions of the material, such as high temperature oxidation and burning.

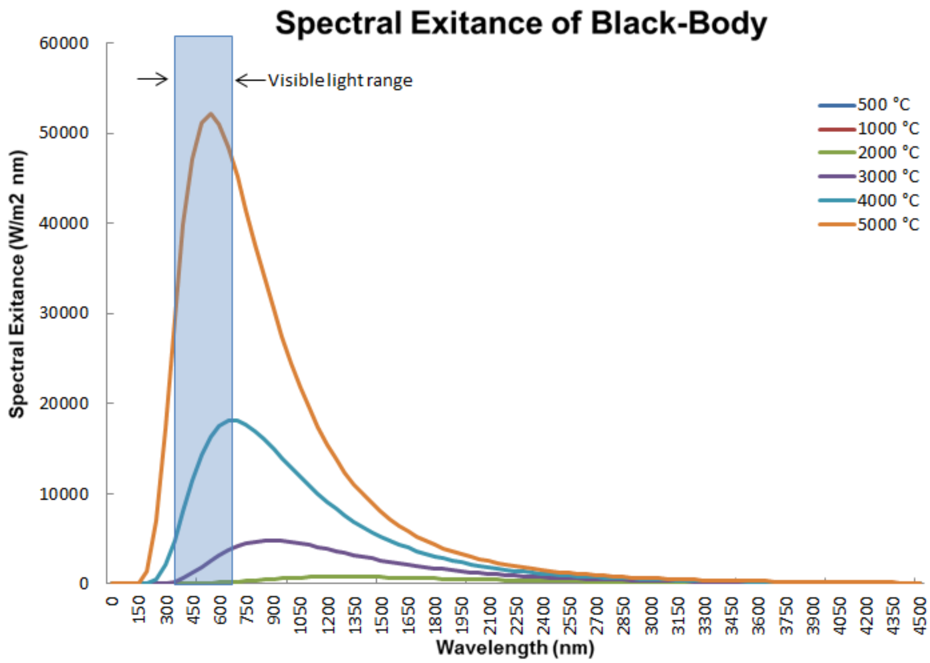


Figure 4. Planck's curve spectral exitance of black-body radiators, dislaying visible light range emitted by incandescent sources from 700 to 400 nm, as well as infrared (thermal) emissions at wavelengths greater than 700 nm.

The digital color emission spectrometry method is intended to be used only for evaluating light emitted from carbon fiber composite components, which represents the most common source of “false failures” when testing composite structures. The purpose of the method is to distinguish the presence of edge-glow light sources that are not capable of igniting the flammable mixture, from ignition-causing incandescent sources produced in composite structure. The digital color emission spectrometry method currently does not currently apply to metal components, which will continue to be tested under the traditional photographic method in ARP 5416A (Society of Automotive Engineers (SAE) International, Revised 2013). Likewise, the method is not currently applicable to voltage sparks, corona discharge, or any other light emitting source besides light emission from carbon fiber composite components. It is possible that the method could be expanded in the future.

2.2 Experimental details

The following describes the details of experimentation for the investigation of the influence of hot spot temperatures imitated by thin filaments and composite edge glow on ability to ignite the flammable gas mixture. The objective was to establish a characteristic light signature for various materials over a range of energy levels to distinguish between cases in which ignition of the flammable gas mixture occurred and cases when no ignition occurred.

Experiments were carried out in the light and airtight photo chamber in the atmosphere of six percent hydrogen in dry, filtered shop air utilizing the scaled-down lightning generator in Figure 5. Canon Rebel t5 digital cameras were utilized as the photographic sensor, and the digital images were collected by leaving the camera shutter open for the duration of the experiments. The test setup remained unchanged for each test material, with the only change being sealing with putty and electrical tape to prevent contact sparking for certain test materials. Testing was repeated in both the ignitable gas mixture and in air to ensure that the critical yellow hue as not an artifact of gas ignition and combustion by demonstrating that it would occur in the absence of the ignitable gas mixture. The critical yellow hue occurred at the same test levels in air as it did in the ignitable gas mixture. Additionally, the combustion of hydrogen in oxygen produces an invisible flame, which will not affect the color of light emitted during testing (Vollmer M and Möllmann K-P, 2013). For all investigated wires, the maximum applied peak current was chosen

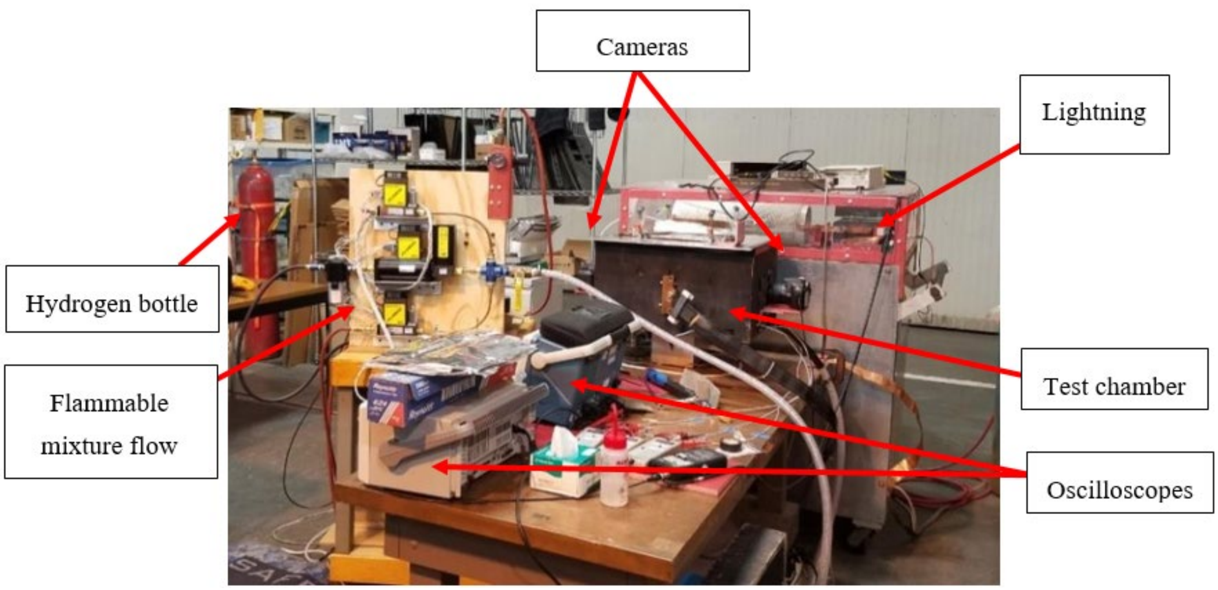


Figure 5. Test setup including lightning generator, light-tight photo chamber, and gas setup.

to incandescently heat the wires to the pre-explosive state while avoiding their explosion. The incandescent materials investigated were tinned copper wire, nitinol wire, steel wire, thin aluminum foil strips, and carbon fiber bundles subjected to various rates of Joule heating because of applied current Component A, as listed in Table 1.

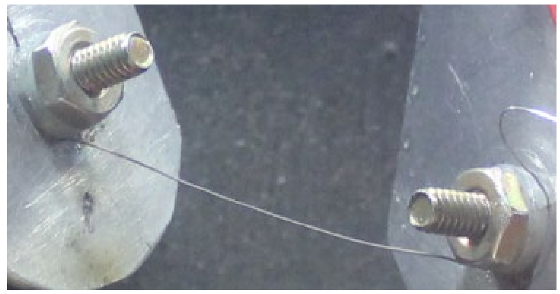
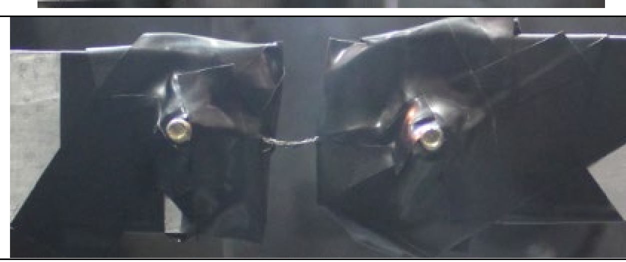
Testing began at the minimum current level required to cause visible glowing of the wire. The current level was gradually increased in subsequent test shots to determine the minimum peak current amplitude (scaled down Component A) required to cause light emission. Testing was conducted in air before it was conducted in gas to determine required input energy and to evaluate if there would be sparking at the contacts which must be isolated from the flammable gas. Once testing in air was complete, testing in gas was performed to determine the input energy into the test material required to cause ignition of the gas.

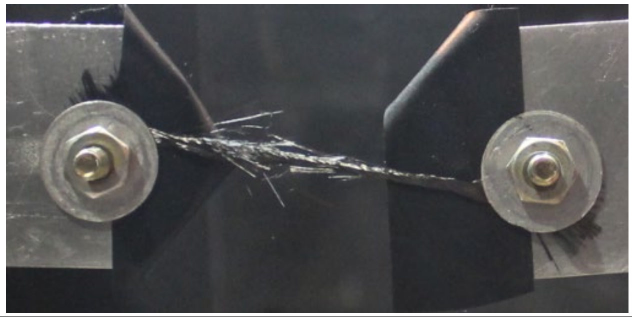
Table 1: Experimental Matrix

Materials	**Current Component A Level, kA**	**Materials Specifications**
1. Cu-Sn wire	2.11, 2.17, 2.20, 2.25	30 gauge tinned copper, approximately 1.5″ in length, with additional wire wrapped around the connections at each end.
2. Ni-Ti wire	Start at 1 kA, increasing in increments of 50 A.	30 gauge Nitinol (Ni-Ti) wire, approximately 1″ in length, with additional wire wrapped around the 2 bolts
3. Al foil strip	In air: Start at 2 kA, increasing in increments of 250 A.	0.001″ Aluminum foil, approximately 3/16″ wide and 1.5″ in length
4. Carbon fibers	Start at 150 A, increasing in increments of approximately 15 A.	Twisted bundle of multiple fibers, 0.01″ (0.27 mm) in diameter
5. Carbon fibers (pre-cut)	Start at 150 A, increasing in increments of approximately 15 A.	Twisted bundle of multiple fibers, frayed, 0.01″ (0.27 mm) in diameter before fraying. If supplied by NIAR, how to standardize
6. CFRP strip	Start at about 3 kA, increasing in increments of 500 A.	Approximately 2″ wide, spanning the length of the box. to encourage glow, one edge has rough exposed fibers due to cutting

The experimental setup for the installation of each of the materials listed in Table 1 is depicted in Table 2. All of the wires were clamped against the electrodes by tightening down a nut and washer. For materials that were prone to sparking at the contacts, the electrode connection bolts were sealed with putty and electrical tape. The CFRP strip was connected to the lightning generator by clamping between copper bars outside the test chamber.

Table 2. Experimental setup for test materials.

Material	Photo
Tinned Copper Wire	
Nitinol Wire	
Aluminum Foil Strip	
Steel Wire	
Carbon Fibers	

Material	Photo
Pre-cut Carbon Fibers	
CFRP Strip	

3. Phase 1: Preliminary studies - Results and discussion

The goal of this experimentation was to establish a threshold of ignition of the gas mixture for edge glow and various incandescently heated materials, while relating it with the hue signature of the light emitted by the material. Tests were repeated both in gas and in air to ensure that the critical yellow hue along with the incandescent signature was not an effect of gas ignition and combustion.

All investigated materials were subjected to conducted current-resistive heating with the purpose of producing edge glow or incandescent heat-light emission sources. The following summarizes the observed effects of the investigated materials in ability to ignite the flammable gas mixture:

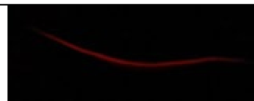
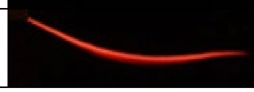
1. Particle ejections ignite gas,
2. Edge glow without incandescent signature observable in CFRP and carbon fibers does not ignite gas,
3. Metal wires and carbon fiber with incandescent signature but <u>without</u> yellow hue do not ignite gas,
4. Metal wires and carbon fibers with incandescent signature <u>and</u> yellow hue ignite gas.

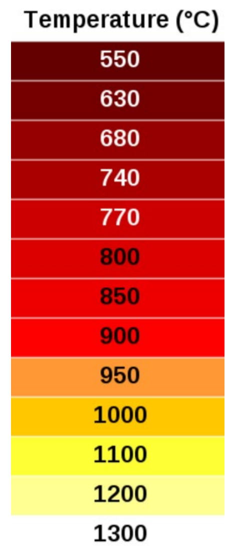
3.1 Light emissions by incandescent glowing wires

Any increase in energy into the wire is accompanied by an increase in brightness of the light emitted by the glowing wire, as well as a gradual shift in hue from a dim red glow to a slightly brighter orange glow, eventually toward a bright yellow, and finally a white glow. It was discovered that regardless of the incandescent material, the gas ignites only when the incandescent source reaches the critical yellow hue, and the yellow hue is only present during ignition conditions. Even when the wire is heated significantly higher than the minimum temperature required to cause ignition, possibly glowing bright white, the yellow hue is still present in the temperature gradient near the cooler edges of the wire, and will still be detected by the digital color emission-spectrometry method.

Table 3 presents sequences of color evolution as a function of increased current amplitude for scaled down current components A, B/C*, and C. Figure 6 plots this data to reveal the influence of rate of temperature change on gas mixture ignition for each current component. Temperature of heated material can be estimated using color (Chapman, W. A. J., 1972). Findings indicate that regardless of the dI/dt or dT/dt, which vary widely among three investigated current components, ignition occurs when the incandescent temperature of the wire surface exceeds approximately 1000 ºC.

Table 3. Temperature evolution and ignition thresholds as function of heating rate, dI/dt, and current level.

Current	Digital Image	Temperature, ºC
Component A (duration 0.5 ms)		
<2.01 kA	No Glow	
2.11 kA		~580
2.16 kA		~745
2.23 kA		Ignition >1000
2.25 kA		Ignition >1200
Component B/C (duration 12 ms)*		
274 A		~790
285 A		~940
290 A		Ignition >1000
292 A		Ignition >1200
Component C (duration >2500 ms)*		
9.00 A	No Glow	
10.6 A		~580
11.2 A		~940
11.9 A		Ignition >1200



Incandescent temperature color chart from reference.

Note: Temperatures were estimated with the standard incandescent color chart. Temperature estimates are utilized as a relative comparison between tests.

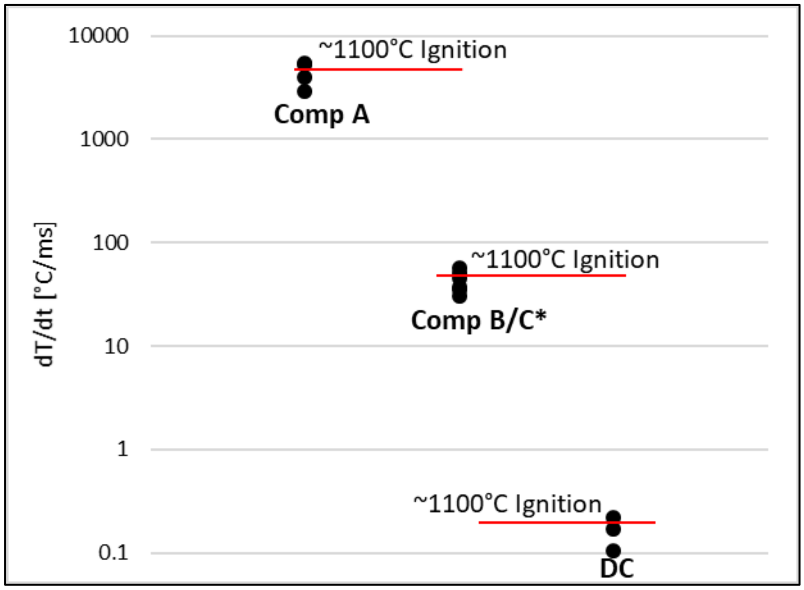


Figure 6. Influence of temperature rate on ignition of flammable mixture.

Each data point in Figure 6 represents the peak temperature divided by duration of applied current waveform for a single test shot for incandescently heated copper wire. Peak temperature was estimated by comparison of test photos to the incandescent color chart from Table 3.

3.1.1 Interpreting histogram data

Histograms display the number of pixels on the Y-axis, and the hue value on the X-axis ranging from 0 to 255. Figure 7 gives a visualization of the color corresponding to each hue value.

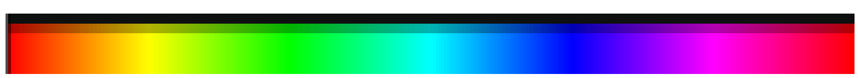


Figure 7. Hue range scale for 8-bit image.

It is important to note that the Y-axes of the hue histograms are based on the total number of pixels present in the analysis area of the image. Since the size of the area of image analysis was not necessarily consistent between the different materials investigated and displayed below, comparison between their histograms can only be made on a relative basis. The hue histograms within one figure, for example Table 4 below contains two images along with two histograms, can be compared directly with one another because the analysis area of the images was the same. Image analysis area was selected to include the entire incandescent source while excluding as much of the background area as possible.

In future work, it is desired to update the procedure for image analysis to eliminate the need for a selection area. This will allow for comparison between histograms of incandescent sources of different geometries and orientations relative to the camera. Brightness thresholding is one method that could replace selection areas, in which the entire image is analyzed, but the pixels not relevant to the incandescent source (black background area) are excluded from analysis. The most effective method for removing excess background area will be determined in the round robin test during year three of this project.

The histograms shown in tables 4, 5, 6-11, 13, 14, and Figures 22, 25, and 26 use a bracket for ease of visualization of the continuous spectrum hue range 0-41, along with an arrow pointing to the critical yellow hue, value 42, in cases where ignition occurs or is expected to occur. No arrow is added to mark the yellow hue for cases in which the yellow hue appears without the corresponding presence of the continuous spectrum, since ignition will not be expected to occur.

3.1.2 Tinned copper (Cu-Sn) wire

Tinned copper wires were tested both in air and in the flammable mixture (Table 4 and Table 5). Testing was done with current component A as with all test materials, but component B/C* and DC current were also investigated. Table 6 shows some results of tinned copper wires tested in flammable mixture with component B/C* and C*. The change in hue because of increase in current is depicted in Figure 8. HSB Color Model Cylindrical Display of Cu-Sn Wire: Gas, Current Component A., in HSB cylindrical format. Hue is represented by location around the outer circumference of the cylinder, saturation represented by distance along radius, and brightness by height, white being located at the top and black at the bottom of the cylinder.

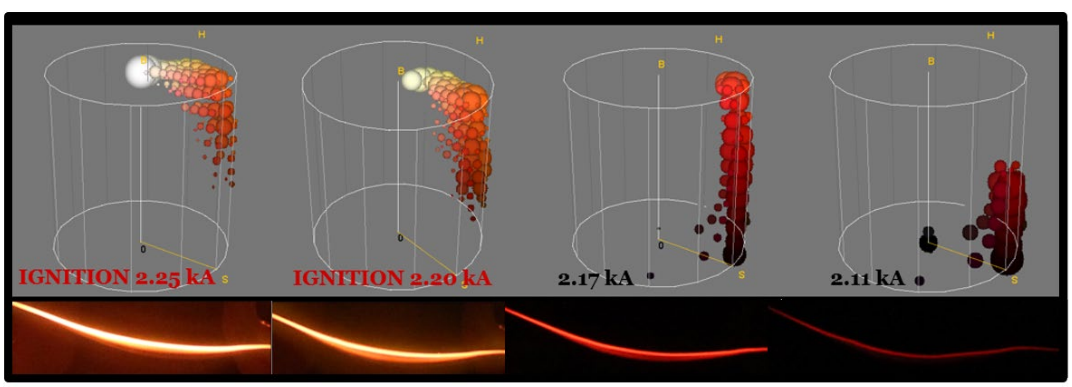


Figure 8. HSB Color Model Cylindrical Display of Cu-Sn Wire: Gas, Current Component A.

Table 4. Cu-Sn Wire: Air, Current Component A.

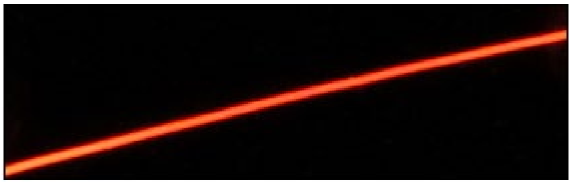
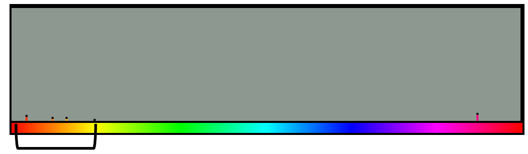
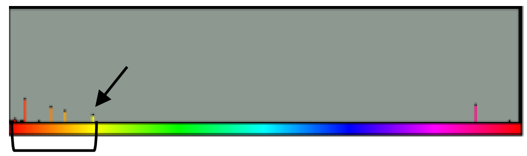
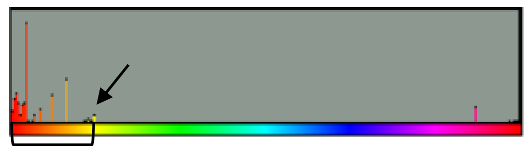
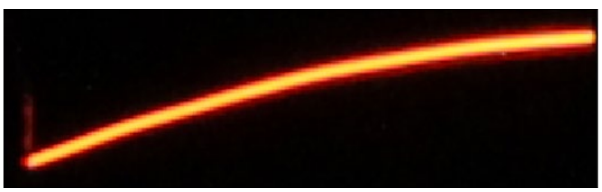
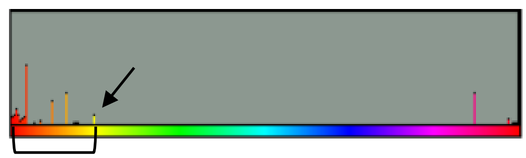
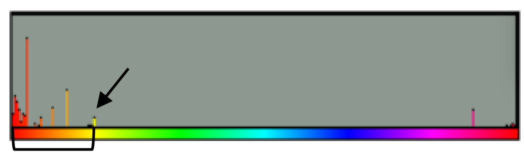
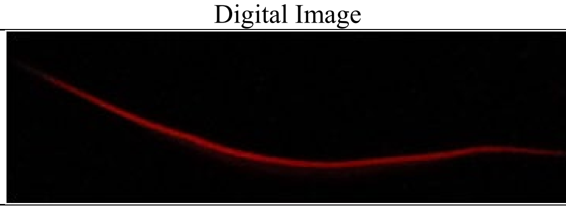
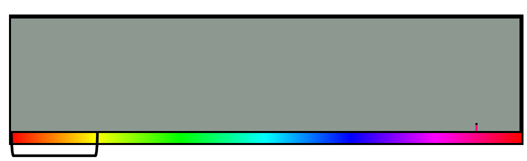
Tinned Copper Wire in Air, Current Component A		
Current	Digital Image	Hue Histogram
2.19 kA		
2.22 kA		
2.226 kA		
2.23 kA		
2.27 kA		

Table 5. Cu-Sn Wire: Gas, Current Component A.

Tinned Copper Wire in Gas, Current Component A		
Current	Digital Image	Hue Histogram
2.11 kA		

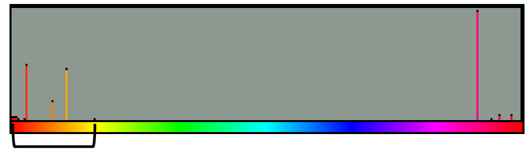
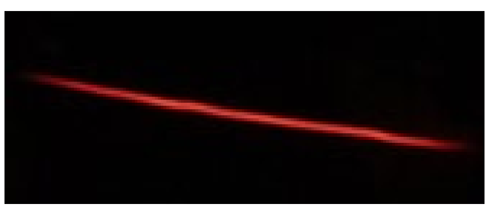
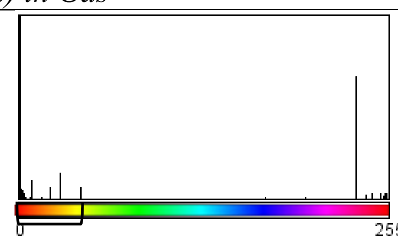
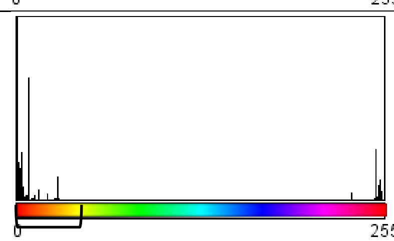
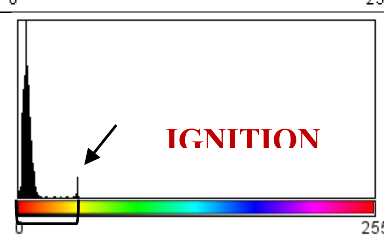
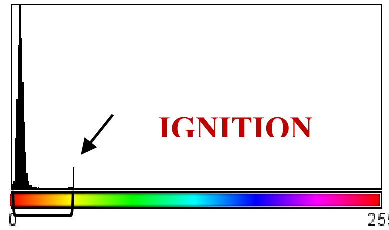
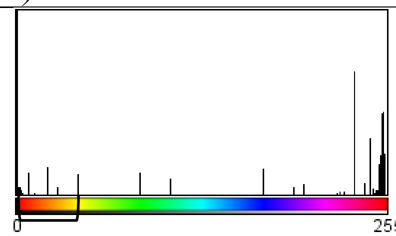
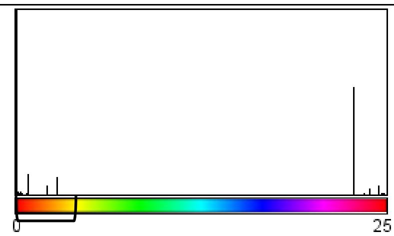
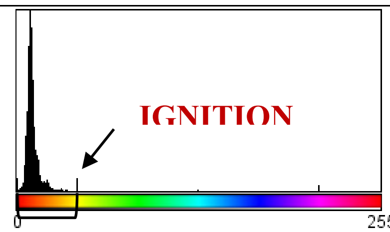
Tinned Copper Wire in Gas, Current Component A		
Current	Digital Image	Hue Histogram
2.16 kA		
2.23 kA		
2.25 kA		

Table 6. Cu-Sn Wire: Gas, Current Component B/C* and C*.

Current	Digital Image	Hue Histogram
Component B/C (duration 12 ms) in Gas		
274 A		
285 A		
290 A		

Current	Digital Image	Hue Histogram
292 A		
Component C (duration >2500 ms) in Gas*		
10.6 A		
11.2 A		
11.9 A		

3.1.3 Nitinol (Ni-Ti) wire, current component A

Nitinol wire was tested in both air and in the flammable mixture as shown in Table 7 and Table 8. Contact sparking was very difficult to eliminate, and required extensive sealing material (putty and electrical tape) to isolate the sparking from the flammable mixture. Due to the high resistance of the wire, a very low-test level was required to create incandescence. Three wires were twisted together to decrease the current density in the wire and allow higher test levels within the lightning generators range of capability during all testing of nitinol. Shorter lengths of nitinol wire were used to minimize the change in wire geometry that occurred during heating, which had a negative effect on test photos.

Table 7. Nitinol Wire: Air, Current Component A.

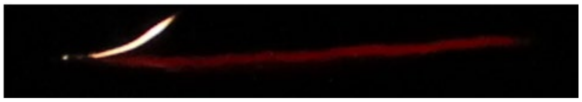
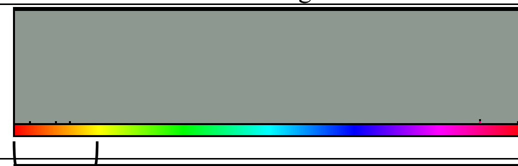
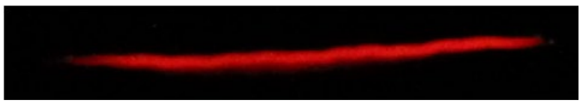
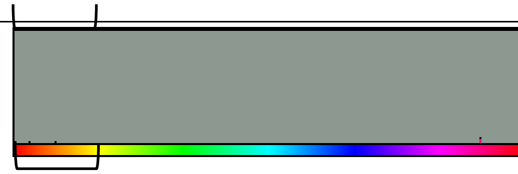
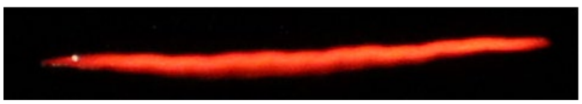
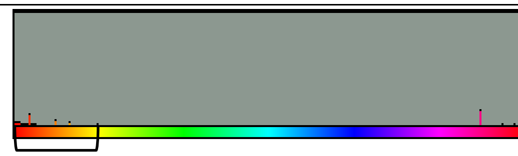
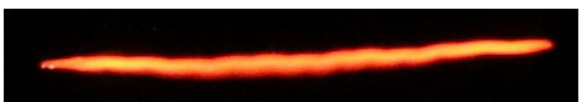
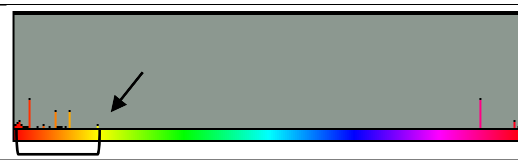
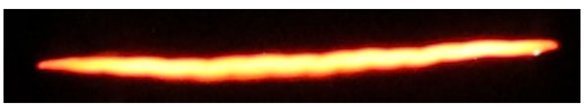
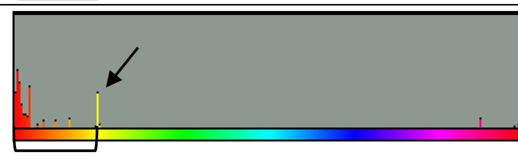
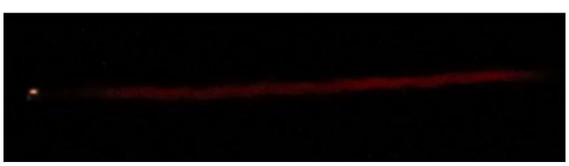
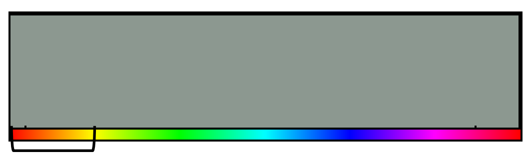
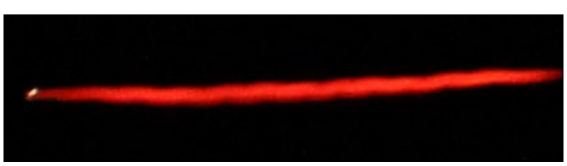
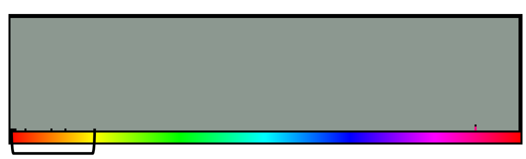
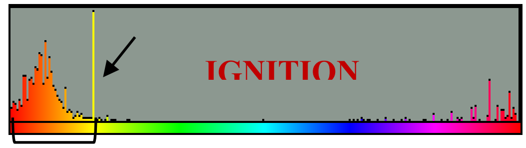
Nitinol Wire in Air, Current Component A		
Current	Digital Image	Hue Histogram
1.08 kA		
1.12 kA		
1.17 kA		
1.23 kA		
1.29 kA		

Table 8. Nitinol Wire, Gas, Current Component A.

Nitinol Wire in Gas, Current Component A		
Current	Digital Image	Hue Histogram
1.12 kA		
1.19 kA		

Nitinol Wire in Gas, Current Component A		
Current	Digital Image	Hue Histogram
1.27 kA		

3.1.4 Twisted carbon fibers: current component A

Twisted bundles of carbon fiber in air were utilized instead of a single fiber due to the extremely low energy required to heat a single fiber without damaging it. A tightly twisted bundle of intact fibers was tested first to demonstrate incandescence, as seen in Table 9 and Table 10. A second bundle of carbon fibers was then tested that was twisted more loosely, with cut and frayed fibers pulled away from the bundle to demonstrate both incandescence and edge glow, as shown in Figure 9.

Table 9. Twisted Carbon Fibers: Air, Current Component A.

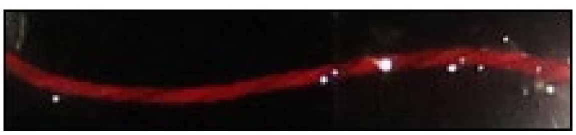
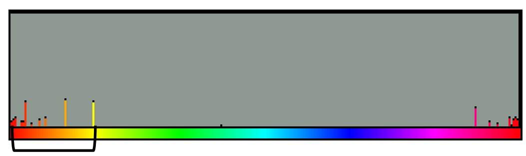
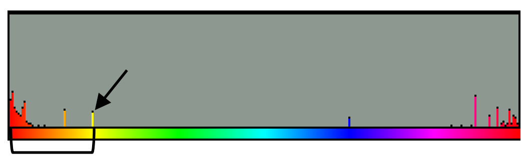
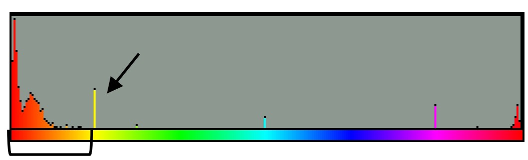
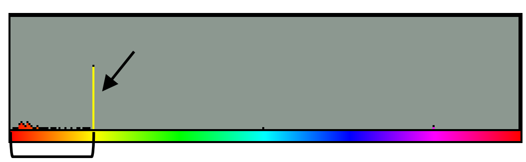
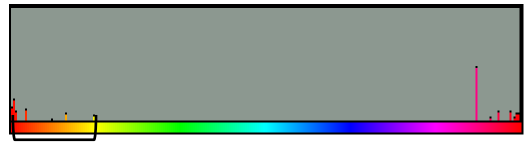
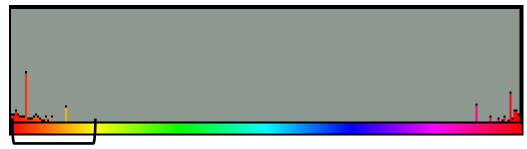
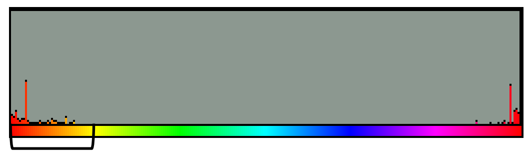
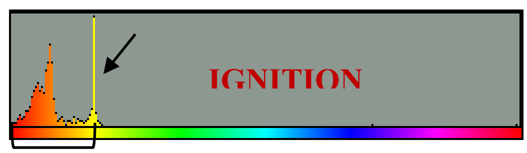
Twisted Carbon Fibers in Air, Current Component A, 0.22mm bundle diameter		
Current	Digital Image	Hue Histogram
173.3 A		
185.5 A		
209 A		
231.6 A		

Table 10. Twisted Carbon Fibers: Gas, Current Component A.

Twisted Carbon Fibers in Gas, Current Component A, 0.27mm bundle diameter		
Current	Digital Image	Hue Histogram
~430 A		
440 A		
450 A		
470 A		

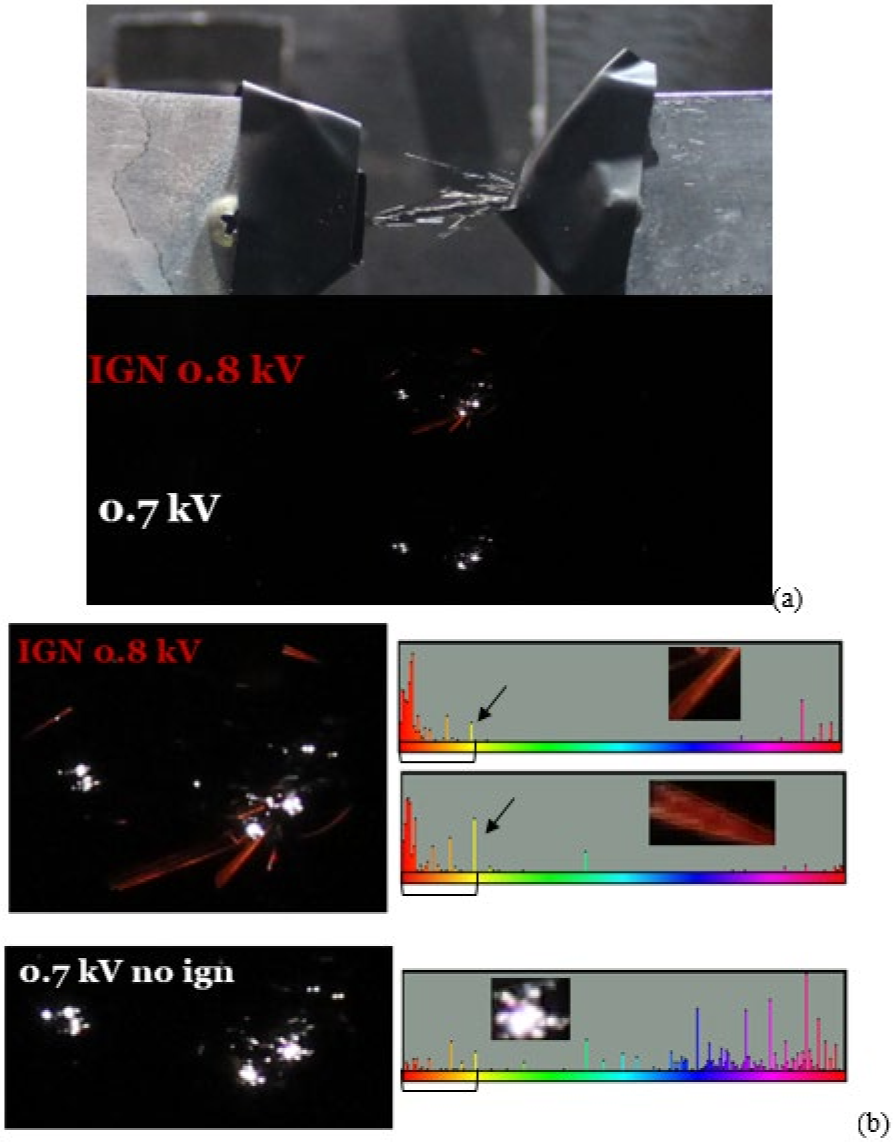
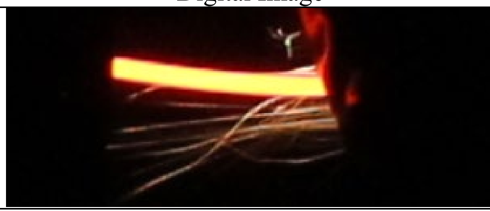
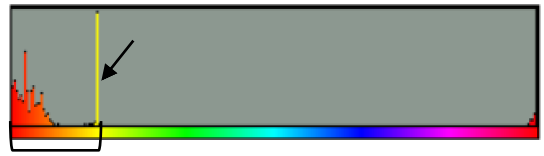


Figure 9. Pre-cut twisted carbon fibers: Gas, Current Component A (a), Hue Histograms of Ignition and No Ignition (b).

3.1.5 Steel (Fe-C) wire: Air, current component A

Steel wires were not tested in the flammable mixture due to the inability to eliminate sparking at the contacts. The hue histogram in air demonstrated the incandescent signature as seen in Table 11, so it is expected to cause ignition of the flammable mixture. The sparking at contacts and rapid rate of oxidation led to the discontinuation of steel from this study. Figure 10 shows an example of steel wire was oxidized due to heating.

Table 11. Steel Wire: Air, Current Component A and Hue Histogram

Steel Wire in Air, Current Component A		
Current	Digital Image	Hue Histogram
3.41 kA		

(

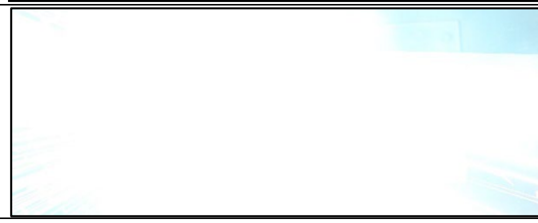
Figure 10. Comparison of new wire and wire that oxidized due to heating

3.1.6 Aluminum (Al) wire in air

Aluminum foil and aluminum wire were subjected to current component A, which resulted either in no detectable glow of the wire, or destruction/explosion of the wire, shown in Table 12. It was not successfully heated to produce incandescence. This was due primarily to the low melting temperature of aluminum, coupled with the deformities present in the soft, easily deformed aluminum wire and foil, creating areas of high current density and rapid heating, ultimately leading to material failure.

Table 12. Thin Aluminum Foil Strip: Air, Current Component A

Aluminum Foil Strip in Air, Current Component A		
Current	Description	Digital Image
N/A	Open box pre-test photo	

Aluminum Foil Strip in Air, Current Component A		
Current	Description	Digital Image
2.848 kA	No glow	
2.849 kA	Foil explosion (white out image)	

3.2 Light emissions by CFRP laminates

The objective of testing the CFRP laminate strip was identification of the ignition threshold of the ignitable gas mixture induced by the edge glow phenomenon because of applied current Component A, Figure 11. Testing of CFRP strips resulted in the discovery that edge glow alone will not cause ignition unless accompanied by the incandescent heat signature. Two quasi-isotropic eight-ply (~1 mm thick) composite strips, with one of the strips containing a plain weave surface ply, were subjected to various levels of peak current Component A to determine the threshold of transition from edge glow to the thermal arc regime. This threshold coincided with the threshold of ignition of the gas. Testing began at current amplitudes just high enough to initiate edge glow light emission. Current amplitude was gradually increased in subsequent test shots until thermal ignition sources were produced capable of igniting the flammable gas.

Appearance of edge glowing, which is a partial ionization of the surrounding gas medium, is marked by the 3.8 kA level with ensuing spot multiplication and merging at increased current amplitudes. At levels above 7.5 kA, appearance of ejections is evident, which is thought to give rise to gas mixture ignition. At this threshold, transition of the edge glow to a thermal arc regime is taking place in order to accommodate increased total current. This occurs through formation and multiplication of the mature cathode spots with characteristic surface temperatures exceeding approximately 1000 ºC as a result of thermionic emission sufficient to provide continuous supply of electrons to sustain the arc. ImageJ analysis and comparison of the edge glow areas and brightness between the two specimens, Figure 12, indicated that ignition depended on the surface roughness of the edge containing exposed fibers. Thus, the quasi-isotropic specimen characterized by a rougher surface edge, exhibited lower ignition threshold corresponding to 5.11 kA in contrast to the plain weave specimen, which ignited the gas at 7.54 kA. Furthermore, ignition occurred only in the presence of ejections at the edge glow areas exceeding 1 mm^2, and this area has also exceeded the area of the 200 µJ voltage spark. No evidence of the influence of maximum pixel brightness per edge glow spot on ignition was observed. Table 13 and Table 14 display histograms showing the development of incandescent hot spots because of an increase in energy into the composite strip in both air and flammable gas.

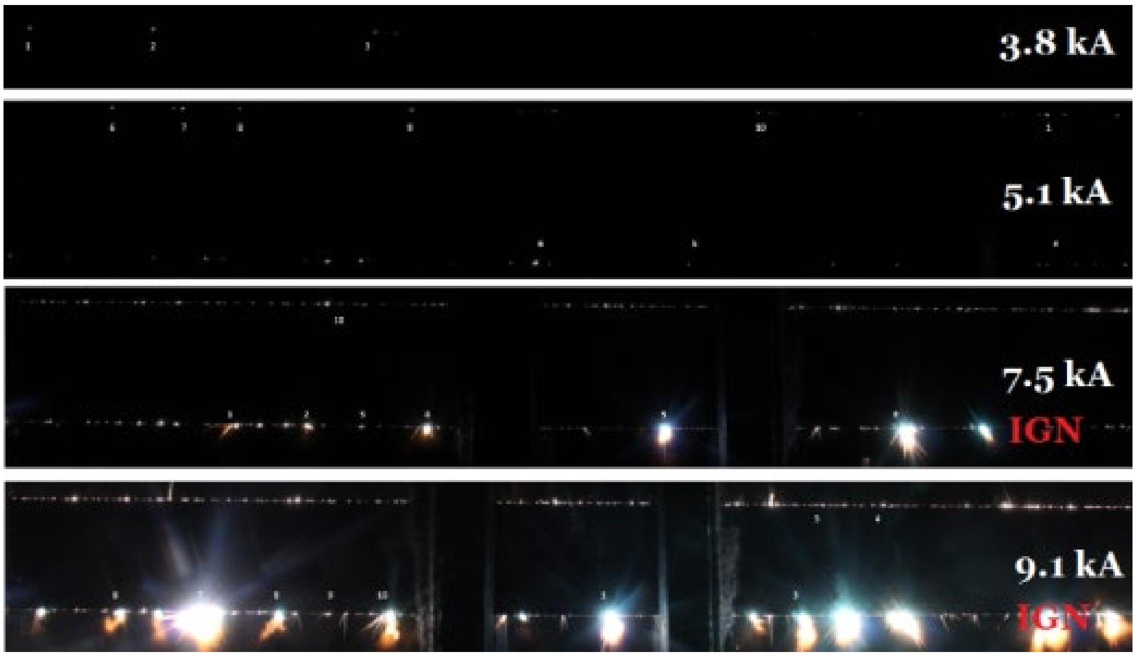


Figure 11. Digital photographs of the edge glow occurring in the plain weave specimen as a function of peak current.

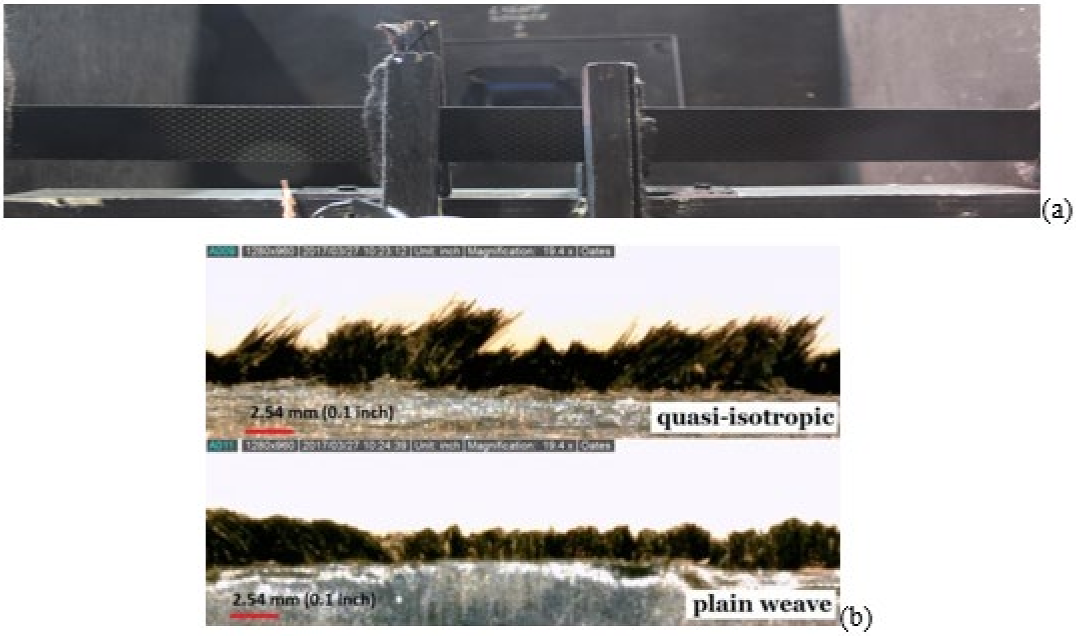
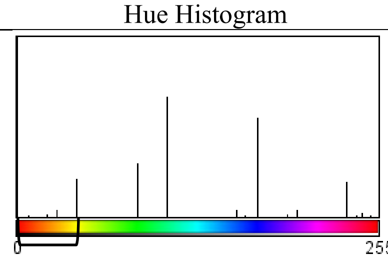
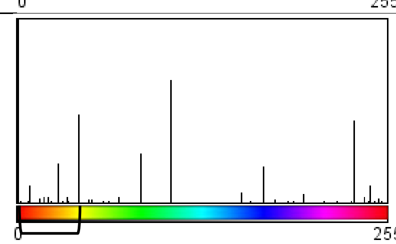
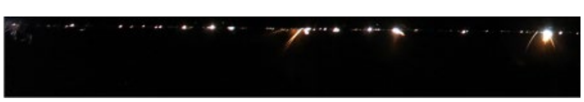
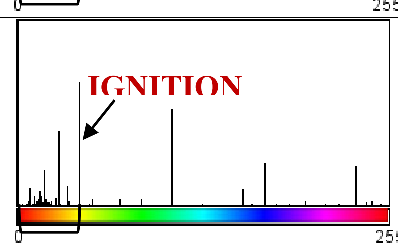


Figure 12. Experimental setup for a CFRP strip (a) and micrographs depicting surface roughness of the composite strips (b).

Table 13. CFRP Strip: Gas, Current Component A.

CFRP Strip in Gas, Current Component A		
Current	Digital Image	Hue Histogram
3.8 kA		
5.1 kA		
7.5 kA		

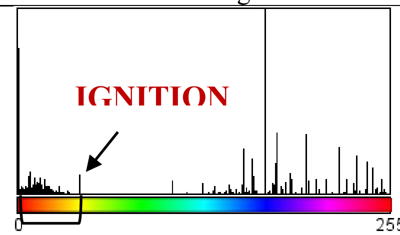
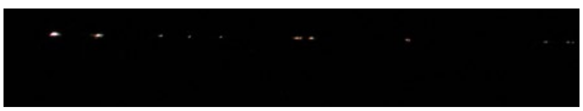
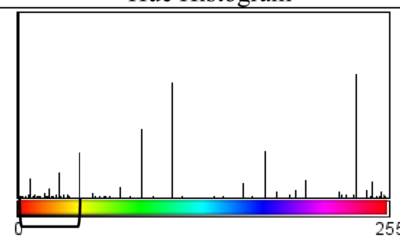
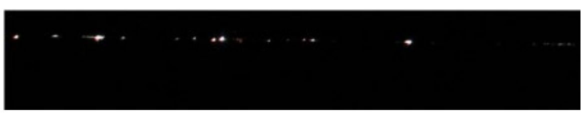
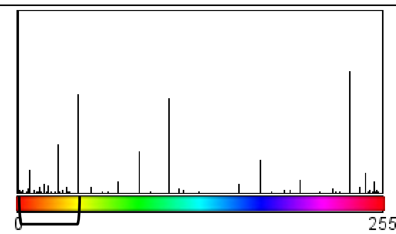
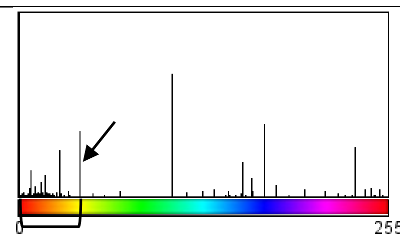
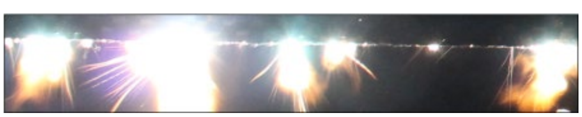
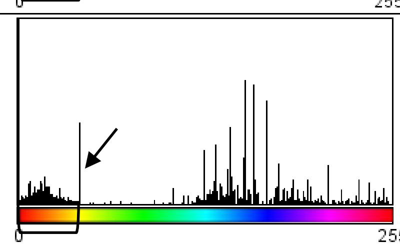
CFRP Strip in Gas, Current Component A		
Current	Digital Image	Hue Histogram
9.1 kA		

Table 14. CFRP Strip: Air, Current Component A.

CFRP Strip in Air, Current Component A		
Current	Digital Image	Hue Histogram
2.6 kA		
3.8 kA		
7.2 kA		
9.1 kA		

3.2.1 Comparison of edge glow brightness and 200-µJ spark brightness

Comparison of the peak brightness values of CFRP edge glow spots and standard 200 µJ voltage sparks was made to determine whether the ignition threshold of the flammable gas imposed by the edge glow coincided with the 200 µJ based brightness threshold. Peak brightness values of edge glow spots were plotted alongside the data from the 200-µJ spark calibration. Edge-glow brightness data from three test shots is plotted in Figure 13. Multiple brightness values are plotted for each test shot due to the appearance of many edge glow spots in each photo. Each data point represents the peak brightness value of an individual edge glow spot.

All images of edge glow spots contained brightness values that exceeded the 200 µJ based brightness threshold, resulting in false failures. Only one case was actually capable of igniting the flammable mixture, due to the presence of incandescent sources. This demonstrates that the use of the current photographic method is too conservative for use with edge glow. Brightness value of the light emitted by CFRP is not a good indicator whether ignition will occur.

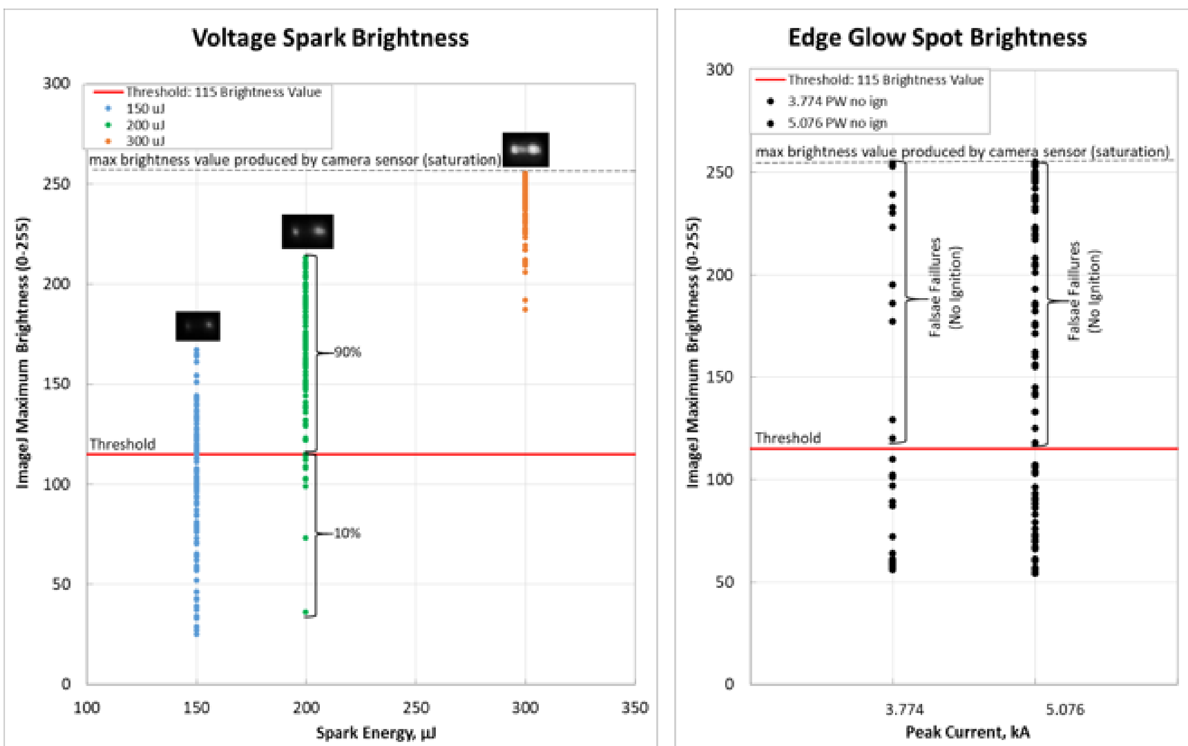


Figure 13. Comparison of maximum pixel brightness between voltage sparks and edge glow spots.

The images of the sparks were taken with the camera settings f/1.8, ISO-200, 5 second exposure time. The edge glow photos were taken with camera settings f/5.6, ISO-1600, 6 second exposure time. Though the individual settings were different, the combination of settings resulted in the same exposure value, or amount of light detected per unit area, allowing the brightness data from both data sets to be compared directly.

3.3 Light emissions by other sources

The following light sources were evaluated using image hue analysis techniques only for gaining more in-depth understanding of the camera sensor. Various techniques were explored to further understand and demonstrate the manner in which digital cameras detect light and reproduce color. To consider a variety of different emission spectra, light sources like butane and acetylene flames, tungsten filament bulbs, and LEDs were analyzed.

3.3.1 Voltage sparks

Voltage sparks of varying energy content were investigated using the digital color emission-spectrometry method, and their histograms are shown in Figure 14 and Figure 15. Sparks were created using a voltage spark generator with tungsten electrodes. An increase in spark energy level is evident due to the increase in spark brightness. The blue and violet hues, shown in the spark photo in Figure 16, indicate emissions due to electronic transitions during molecular dissociation, atomic/molecular excitations, and ionization of the air constituents. An increase in spark energy increases spark brightness (emission intensities) and area (size of spark). A corresponding increase of violet hue is due to higher-level transitions of oxygen and nitrogen. Additional voltage spark images were supplied by Airbus for comparison. Purple and pink hues are due to camera sensitivity to IR and UV.

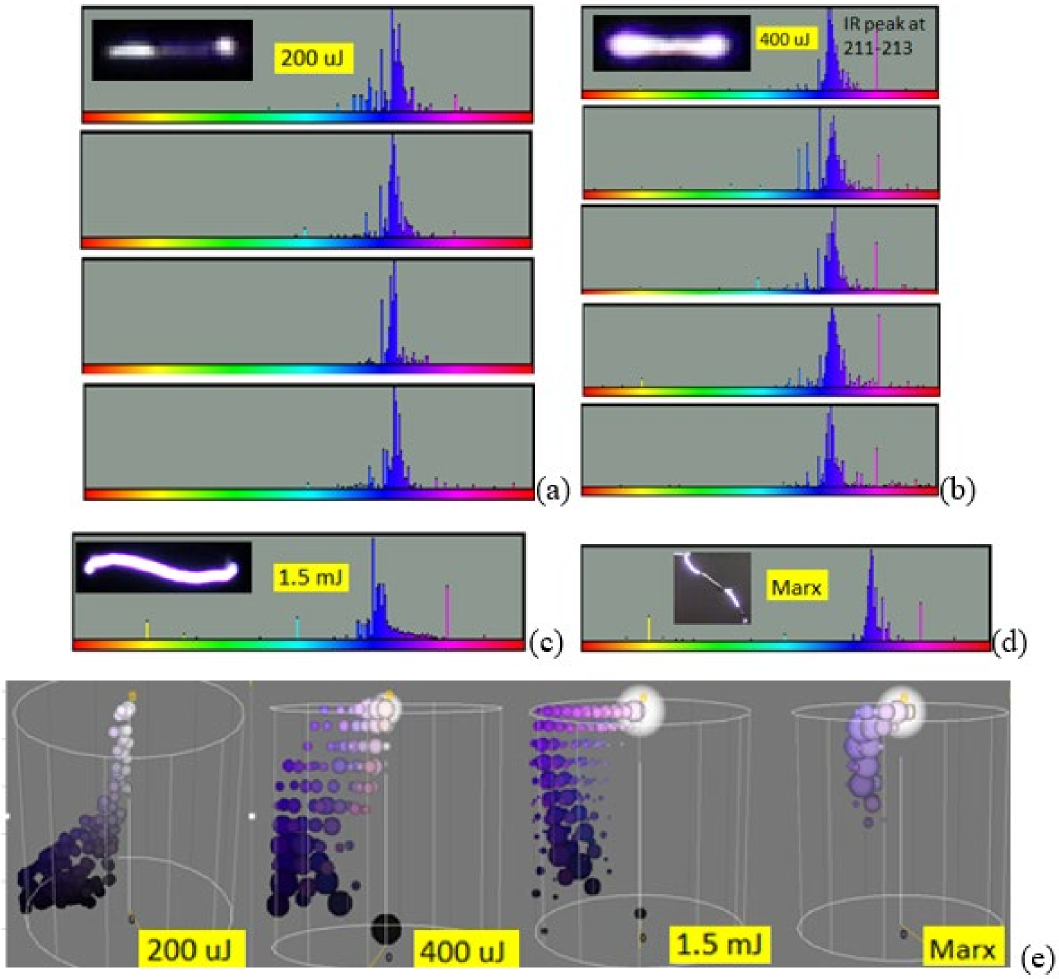


Figure 14. Comparison among the 200, 400 μJ, 1.5 mJ, and marx-generator voltage sparks in HSB hue histograms (a-d) and color space (e).

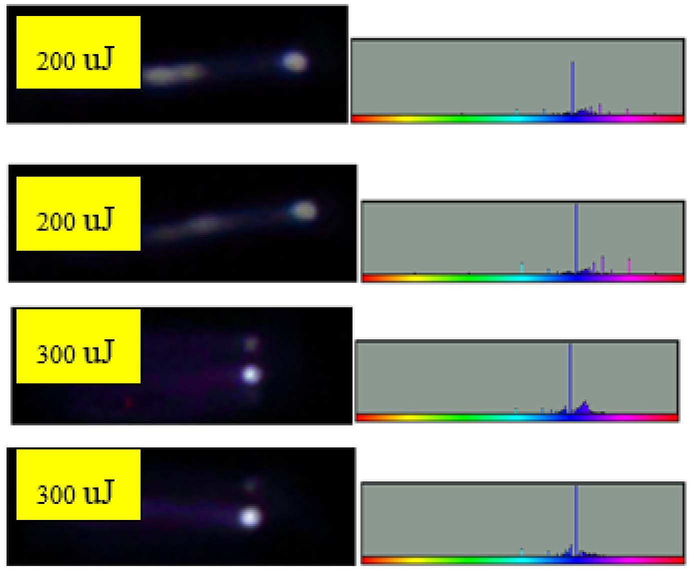


Figure 15. 200 µJ and 300 µJ voltage spark images supplied by airbus.

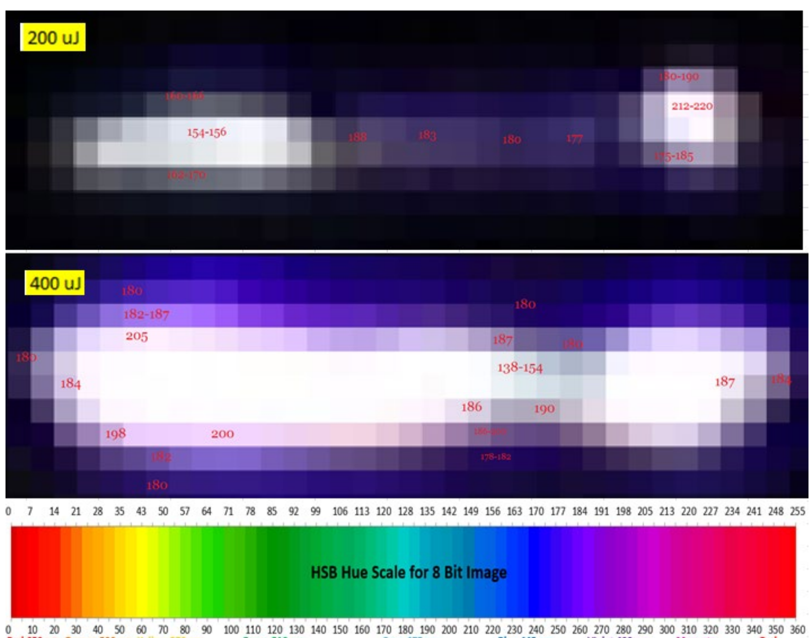


Figure 16. Comparison of 200 µJ and 400 µj voltage spark hue siganature with hue scale.

3.3.1.1 *Comparison of incandescent wire brightness and 200 μJ spark brightness*

Voltage sparks were investigated according to the procedure outlined in "SAE AE-2 Lightning Committee White Paper Recommended Camera Calibration and Image Evaluation Methods for Detection of Ignition Sources" (SAE AE-2 Lightning Committee White Paper, Rev. NEW. January 2018). A voltage spark generator with tungsten electrodes, Figure 17, was utilized in a light-tight photo chamber to produce 150 μJ, 200 μJ, and 300 μJ voltage sparks. Digital cameras were used to capture 100 spark events at each energy level. Camera settings were selected so that the sparks did not saturate the sensor, while also allowing a long enough exposure to capture the entire spark event. The photos were analyzed to determine the maximum pixel brightness of the spark in each image.

Figure 17. Voltage spark source used for White Paper calibration testing.

In Figure 18, peak brightness values were plotted and a threshold was determined based on the set of 100 images of 200 μJ sparks, such that 10% of the peak brightness measurements fall below and the remaining 90% above the threshold. The 300 μJ sparks were compared to the threshold to ensure that they all fell above the specified threshold.

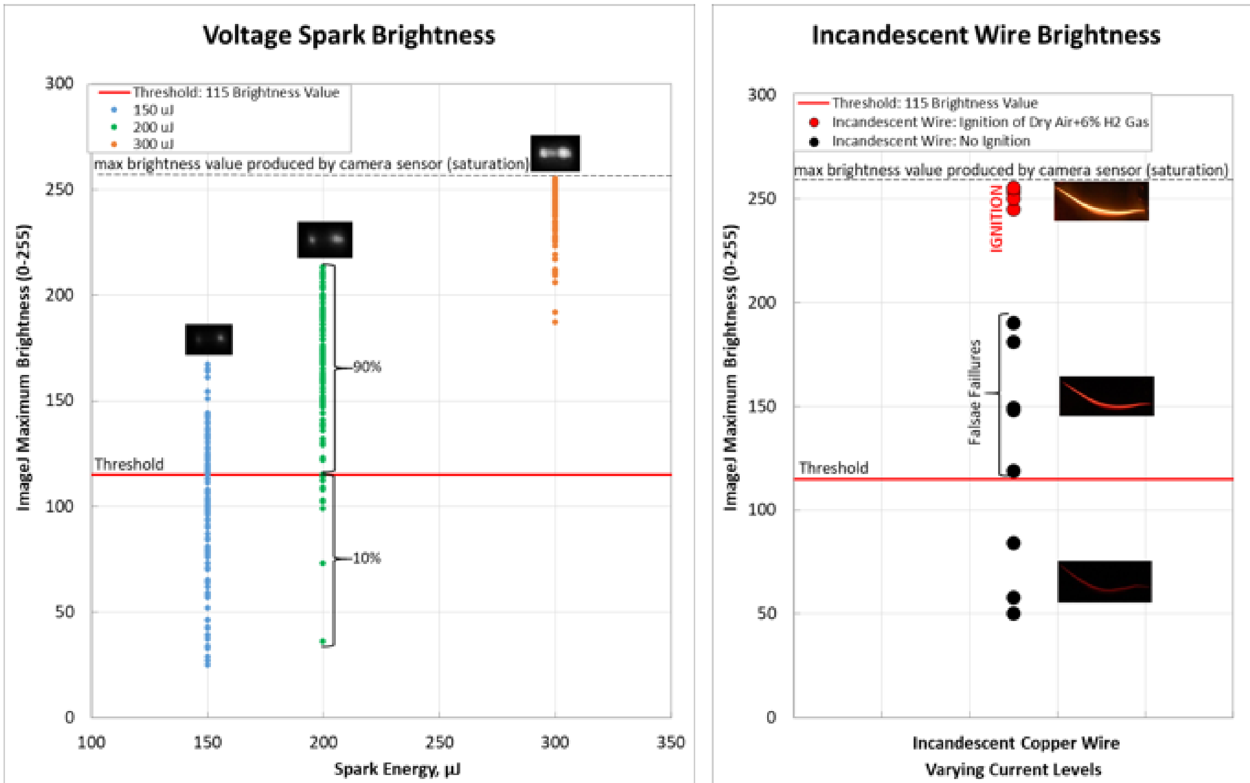


Figure 18. Comparison of maximum pixel brightness between voltage sparks and incandescent Cu-Sn wire.

Comparison of the peak brightness values of incandescent glowing wires and standard 200 µJ voltage sparks was made to determine whether the ignition threshold of the flammable gas imposed by the incandescent source coincided with the 200 µJ based brightness threshold. Peak brightness values of incandescent tinned-copper wire were plotted alongside the data from the 200-µJ spark calibration data.

All wires that caused ignition of the flammable gas were brighter than the threshold of ignition for voltage sparks, resulting in a number of false failures for the incandescent source. This demonstrates that use of the current photographic method is too conservative for use with incandescent ignition sources.

The images of the sparks were taken with the camera settings f/1.8, ISO-200, 5 second exposure time. The wire photos were taken with camera settings f/5.6, ISO-1600, 6 second exposure time. Though the individual settings were different, the combination of settings resulted in the same exposure value, or amount of light detected per unit area, allowing the brightness data from both data sets to be compared directly.

3.3.2 Gas ignition imaging with TELOPS FAST M3k high speed infrared camera

For better understanding of the ignition mechanism of the ignitable gas mixture, as well as the heating behavior of composite strips being subjected conducted current, the TELOPS FAST M3k high-speed infrared camera was utilized during a portion of testing. Figure 19 shows the ignition kernel in the flammable gas mixture propagating outward from the incandescent hot spot at the edge of the carbon fiber strip. It also shows the increase in temperature of the fibers running the length of the CFRP strip due to resistive heating.

Figure 19. Plain weave CFRP strip ignition sequence in gas mixture.

Figure 20 shows the thermal signature produced by the 200-μJ voltage spark source, and Figure 21 details the early stages of gas ignition because of the 200-μJ spark.

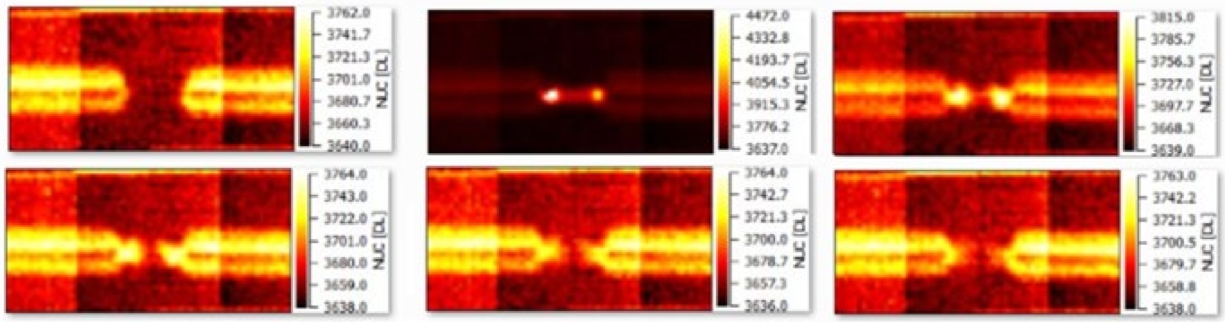


Figure 20. Spark formation in air (no ignition of gas).

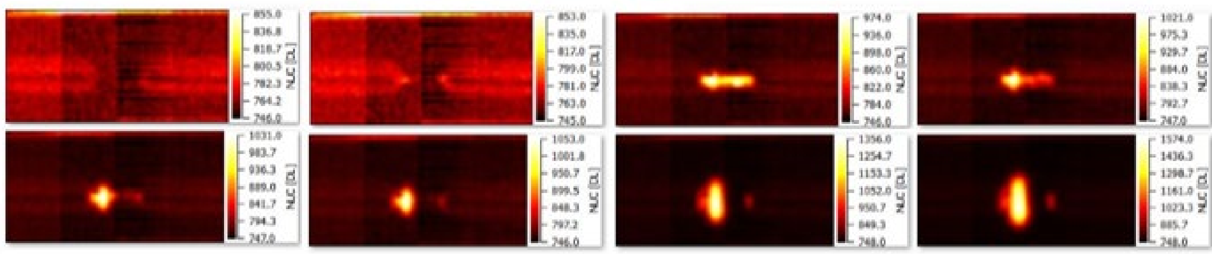


Figure 21. Voltage spark ignition sequence of gas mixture (kernel formation).

3.3.3 Light emission by wire electrical explosion

During the initial experimentation on incandescent tinned-copper wires, some of the wires were subjected to higher current densities than could be tolerated. The resulting wire explosion emitted green light, due to the ionization/excitation of copper.

Two open-shutter digital images captured the entire event of the wire exploding in air, obtaining an image of the dominant wavelength (color) of light produced by the wire explosion from both the front and the back, Figure 22. Three distinct light emitting sources can be identified: incandescence of the heated wire radiating in the yellow down to red range, high-intensity explosive white glow, and a green-blue colored radiating emission characteristic of the thermally excited copper in air. The histograms are heavily influenced by the green-blue hue emitted during wire explosion. The Y-axis scale of the histogram is skewed to represent the overwhelming presence of green pixels, making the incandescent signature of the heated wire difficult to locate visually. An alternate histogram with more appropriate Y-axis scaling confirms the presence of the incandescent signature. Presentation of data in this report is limited to visual analysis of histograms, but typical analysis does not rely solely on visual histograms. The incandescent signature will not be overlooked under typical analysis of histogram data, which utilizes the numerical histogram data produced by ImageJ.

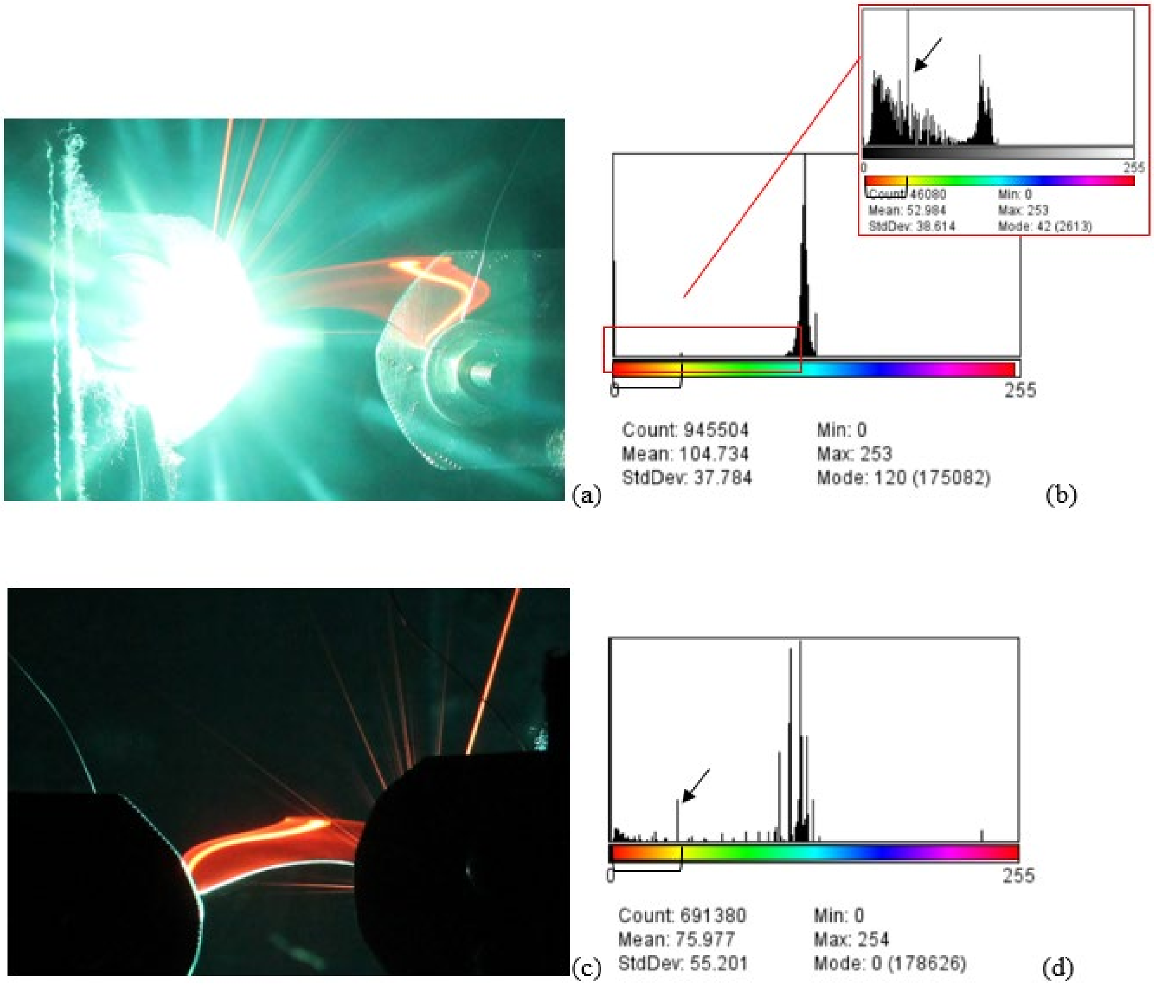


Figure 22. Cu-Sn wire explosion: Air, Current Component A, 2.3 kA. Front view photo (a), front view histograms (b), rear view photo (c), rear view histogram (d).

3.3.4 Optical diffracted light signatures of diffusion flame, LED and fluorescence sources

Digital cameras "split" light by filtering it through RGB filters. To compare how closely RGB filtering of light compares with splitting light through a prism or diffraction grating, photos of various light sources were taken directly and through a spectroscope. Histograms of the direct light signature and the split light are shown in Figure 23 and Figure 24. The spectroscope passes light through a diffraction grating and splits it into individual wavelength bands. The hue histograms of the typical images and the split light images were compared with each other, and with published emission spectra for each source. The light sources used with the spectroscope included diffusion flames, a "white" LED source, and fluorescent bulbs.

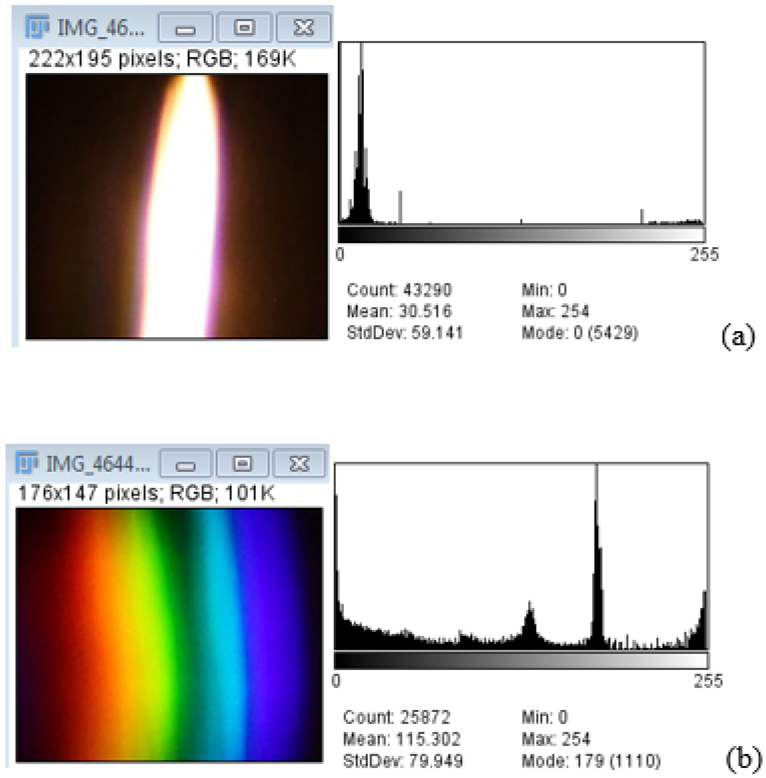


Figure 23. Diffusion butane flame typical image and histogram (a), and spectroscope image and histogram(b).

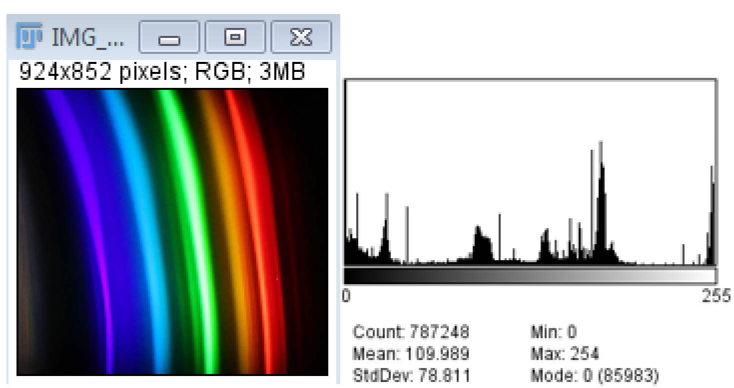


Figure 24. Fluorescent light spectroscope image and histogram.

3.3.5 Light signature of incandescent tungsten filament

A repeatable standard incandescent source was desired for comparison to the experimental incandescent sources. A tungsten filament incandescent bulb was coupled with a rheostat to allow the temperature and brightness of the filament to be controlled. The hue histogram, Figure 25 and Figure 26, was analyzed and compared to the hue histograms of experimental incandescent sources that caused ignition of the flammable gas.

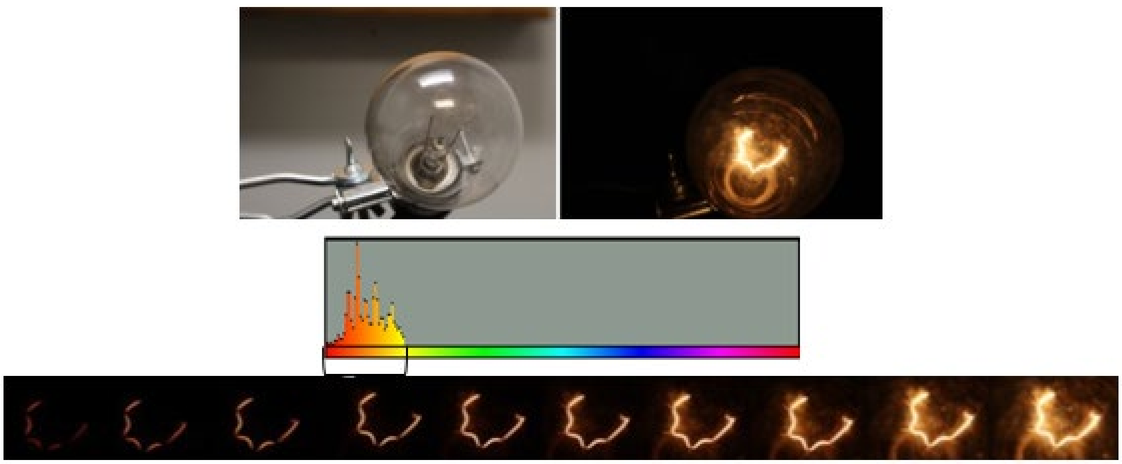


Figure 25. Incandescent bulb and hue histogram.

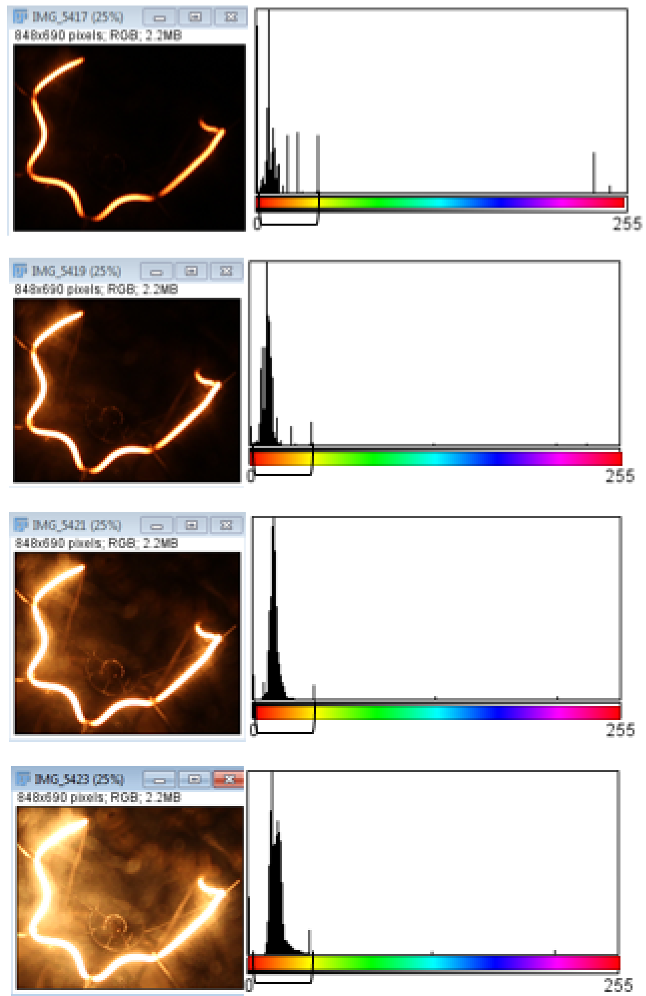


Figure 26. Tungsten filament incandescent bulb at increasing current levels, and corresponding hue histograms.

4. Phase 2: Round robin investigation

A round robin test was organized with input from committee members from the SAE AE-2 Lightning Committee as well as the EUROCAE WG-31 Lightning Committee with the intention of validating the performance and repeatability of the incandescent ignition source-detection method. The procedure was revised with input from both the AE-2 and WG-31 lightning committees at multiple committee meetings as well as discussions with the participating labs. Testing was carried out by multiple participating laboratories worldwide, including NIAR/WSU, Boeing, DNB, in the United States, Element, and LCOE laboratories in Europe, and Subaru in

Japan. NIAR/WSU organized, monitored, and coordinated all testing. The test procedure is defined in the written test procedure developed by NIAR, available in Appendix A: Round Robin Test Procedure. Validation of the incandescent detection method is necessary to prove that the incandescent signature consistently detects ignition conditions across all laboratories, cameras, and test setups.

4.1 Development of round robin test procedure

The test procedure is divided into three main sections: incandescent signature verification, material sample testing, and image analysis. The first two activities are summarized in sections 4.1.1 and 4.1.2 . The image analysis requires more detail. It is covered in section 4.2.

4.1.1 Incandescent signature verification

The first portion of the test is the "incandescent signature verification procedure," which intends to verify the ability of the camera to detect and reproduce a distinct incandescent hue signature corresponding with ignition. The incandescent signature verification process analyzes test photos of copper wires heated to incandescence, which are obtained during flammable gas testing. The wires and other test materials are tested using conducted Waveform 5A to ensure waveform consistency between all participating labs. This test is repeated multiple times, producing a set of test photos of incandescent wires near the ignition threshold of the flammable gas. Comparison between ignition data and non-ignition data in the test photos is made to determine the camera-specific incandescent signature of ignition, defined by the continuous hue value range and the value of the yellow hue of ignition. This camera-specific incandescent signature is used as the pass/fail criteria for future testing with that particular camera. The camera-specific incandescent signature must be determined for each test camera prior to use for testing.

4.1.2 Material sample testing

Once the incandescent signature is obtained, the material sample testing begins. Round robin test materials include loose carbon fibers and carbon fiber composite coupons to both produce incandescence and edge glow. Hue histograms of test images are compared with the defined camera-specific incandescent signature to determine whether an incandescent ignition source is present.

NIAR provided the test articles for each of the round robin participants, including copper wire (Arcor Electronics 30 AWG, 2″ length), carbon fibers (A&P Technology Fibers removed from BIMAX-H-48 fabric), and carbon fiber composite coupons (Cycom 5320-1

[(0/90/0/90/90/0/90)$_T$/(0$_{pw}$)$_T$]). The composite materials were supplied by the NIAR composites lab. Five to ten test samples of each material were provided to each participating lab.

NIAR performed preliminary testing of the materials to determine recommended test levels for the round robin test. Verification was required to show that the composite coupon would produce edge glow when subjected to conducted current. This testing was completed after the test materials were manufactured and immediately prior to the release of the final version of the round robin procedure document to the participating labs. Current waveform 5A was conducted through each material to generate incandescence and/or edge glow. The suggested minimum test levels are at the lower threshold of light emission.

4.2 Data returned and method of analysis

Selecting the appropriate method of hue histogram analysis for an image is essential to determine the success of the incandescent detection method. The desired outcome is a clear distinction in the histogram signatures between ignition and non-ignition cases across all materials. This distinction will have some amount of error, because there may be overlap between some of the ignition and non-ignition cases occurring right near the ignition threshold. This overlap must be identified as ignition to ensure conservative results of the incandescent detection method. The analysis method must perform consistently across all variables (material, test setup, camera, brightness of object, etc.). It must be determined to evaluate the hue data without manipulating the data or results. Multiple analysis techniques were investigated to determine the best technique for identifying ignition conditions in test photos. These techniques are detailed in Sections 4.2.2 through 4.2.7 .

4.2.1 Differences from preliminary studies

For the preliminary study tests in Section 3, a reduced amplitude current Component A was utilized for the round robin test to generate incandescence from each test material. Waveform 5A was selected over a reduced current Component A for this round robin test to allow the labs participating in the round robin to reproduce the required waveform more easily. Some of the participating labs indicated that they were unable to produce the reduced amplitude Component A waveform, but all participants had capability to produce Waveform 5A at the required amplitudes.

For the round robin data, the histogram data analysis was modified from what was used in the preliminary studies from Year 1 and 2. In the preliminary studies, the incandescent signature of ignition was defined as the presence of some continuous range of pixels falling in hue bins 1-41, accompanied by the presence of pixels in bin 42, critical yellow. Both the continuous range and critical yellow were used to determine ignition conditions during preliminary studies.

During initial analysis of the round robin data, it was discovered that many of the participating labs provided test photos of non-ignition cases in flammable gas, which contained a non-zero value of hue 42. A more reliable predictor of ignition was determined by more strictly defining the continuous range. This range was generally bounded by an overall range from hue 1 to hue 41, but was evaluated further for each data subset to define the narrowest continuous range that occurred for any given material during ignition.

This signature varied somewhat significantly from cameras, test materials, and test setups. The criteria for the definition of this signature was any continuous range of *consecutive* hue bins containing 10 or more pixels per bin. Examples of the defined ranges are in Section 4.4 . The continuous range defined for each dataset was the only criteria defining the incandescent signature for the round robin data analysis. The presence or absence of this incandescent signature determines whether the test image is classified as ignition or non-ignition.

4.2.2 Manual histogram comparison

The first method of analysis investigated was manual comparison in spreadsheets of hue histograms in the HSB color space. The histogram analysis was repeated for each of the various noise removal techniques listed in Sections 4.2.5.1 to 4.2.5.4 . The histogram analysis is repeated for each camera and test setup to determine the incandescent signature during the "incandescent verification procedure", and then again to determine the success of the incandescent signature when applied to test data.

Hue histograms consist of 256 bins, each bin representing a specific hue value, and each containing the total count of pixels in the image, which contain that specific hue value. Hue histogram analysis was used to determine ignition signature based on a range of consecutive bins where pixel count values are greater than or equal to ten. Ten was selected as the minimum significant pixel count per bin, since the very large number of pixels in the image combined with low-level noise results in most of the hue bins containing nonzero pixel counts.

All of the histogram plots in Section 4.4 were generated using this method.

4.2.3 Train/test data sets

The second method of analysis employed was a train/test split of the data. This method was applied to the hue histograms. The purpose of the train/test data split is to allow the data to be both *trained*, or have the ignition signature to be determined; as well as *tested* or have the data validated based off of the signature determined in the train phase.

This data split was initially intended to occur by separating the round robin into an "incandescent verification procedure" and the data from the test articles. However, because the signatures could not be applied across multiple materials, this was not possible, resulting in the need to further divide the test data for each material into two distinct test/train groups. This resulted in multiple very small datasets. For these datasets, 80% of the test photos in each set were designated as train photos, and the remaining 20% of the test photos were the test photos. The photos were assigned to test or train at random.

Determining the success of the test photos required establishing the terms: true fail, false fail, true pass, false pass. True results indicate that ignitions or non-ignitions were identified successfully. False results indicate that ignitions or non-ignitions were misidentified.

- A false fail indicates that the photo fails the incandescent method and is identified as an ignition, but **did not** have sufficient energy to ignite gas.
- A false pass indicates that a photo passed the incandescent method and is identified as a non-ignition, but **did** have sufficient energy to ignite gas. A false pass is considered unacceptable unless it is statistically insignificant/a statistical outlier.

All of the true and false failure and pass rates listed in Section 4.4 for the incandescent method were defined using the definitions in Table 15.

Table 15: True and false failure and pass definition for incandescent method

Ignition Hue Spectrum	**Gas ignited**	**Gas did not ignite**
Ignition hue spectrum present	True fail	False fail
Ignition hue spectrum is not present	False pass	True pass

4.2.4 Dataset size and image histogram normalization

The hue data obtained through this test is a result of various relative sensors (digital cameras) which can be assumed to reproduce hue data slightly differently. During the test-planning phase, it was assumed that the test photos of all materials could be analyzed in a single dataset, so the small number of each sample was not expected to be an issue. After testing and initial photo analysis, it was determined that photos for each material must be analyzed separately. The datasets were divided into smaller subsets by laboratory and by material. The small dataset sizes were a result of the number of test samples provided to each participating lab: 10 copper wires, 5 carbon fiber bundles, and 5 CFRP coupons.

One attempt was made to improve the results of machine learning applications by increasing histogram bin sizes to normalize the hue distributions. Hue bins were summed (groups of 2 and 4) to widen each bin size and reduce the total number of hue bins to create a smoother, less noisy histogram. The true fail, false fail, true pass, and false pass rates of these histograms showed that the normalized hue signatures were less distinct, thus this data was never used with the machine learning algorithms. This method of normalization was unsuccessful.

4.2.5 Noise removal techniques

Due to the nature of the camera sensor, low-level noise is present in many pixels in each image. Although the test photos are taken in a blackout chamber, some of the pixels in the image do not appear as true black due to the noise in the sensor. Black and grayscale pixels have a hue value of zero. Any pixel that is not 100% black (or 100% grayscale) contains a nonzero hue value. The nonzero hue data from these nearly black pixels is difficult to distinguish from the ignition source pixels in a hue histogram. Any pixel in the background of the image or in any region that is not illuminated by the ignition source is considered noise. A sample image demonstrating noise in the hue channel is shown in Figure 27.

To ensure the hue histograms only include data relevant to the ignition source, it is necessary to remove noise. Several methods to eliminate the noise pixels from analysis were explored, with emphasis on maintaining the quality of the data. These methods are detailed in Sections 4.2.5.1 to 4.2.5.4 .

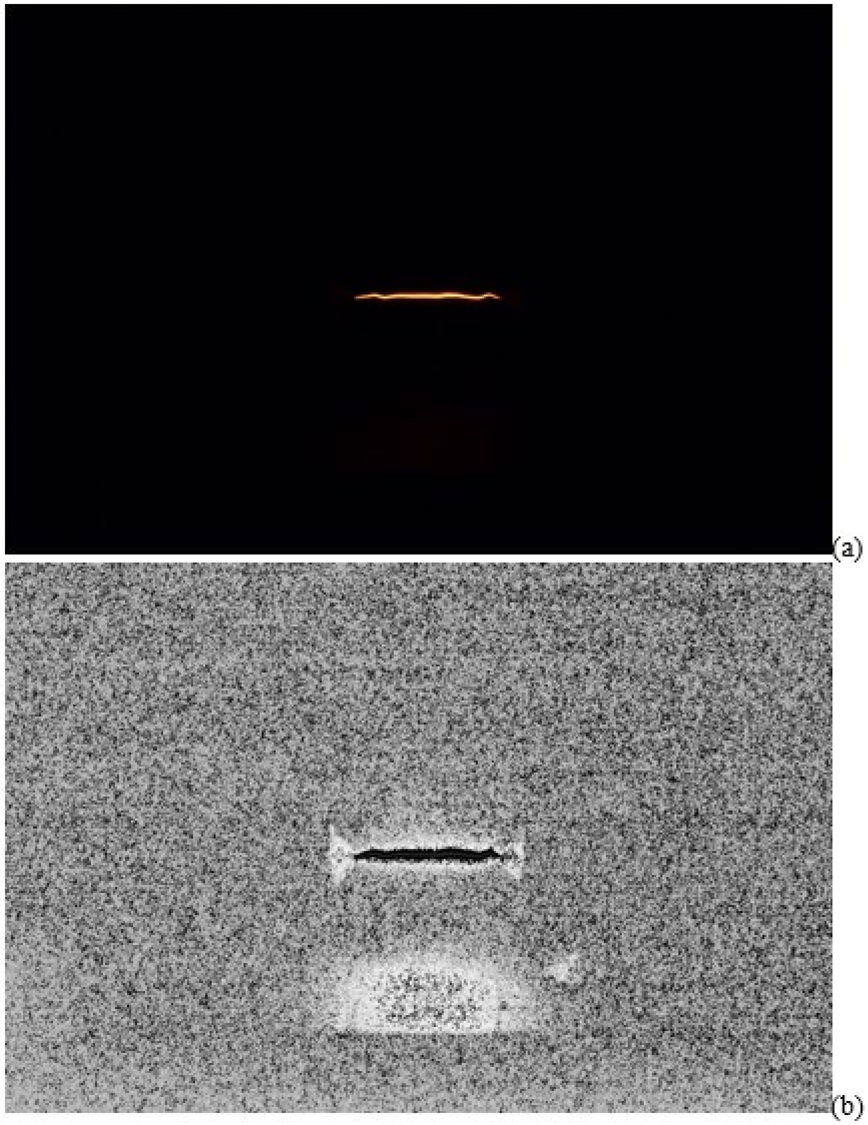


Figure 27. Sample photo of Cu Wire in Air in (a) RGB standard image format. (b) Photo converted to HSB space, showing noise (background noise manifests as brighter whites)

4.2.5.1 *Cropping*

The first method evaluated for noise pixel removal was cropping. The technique included manual selection of a window around the ignition source. After converting to HSB, the image is cropped such that the histogram is only of the area containing the test article and a small margin for ejected particles. This method successfully removed most of the noisy background area. It is not the recommended method because it relies on the user to define the selection area, which may be too large and leave in too much background noise, or too small which may exclude some of the ignition source from the analysis region, which is unacceptable/not allowable. Cropping also affects the dimensions of the region selected for image analysis, which makes comparison between images challenging. A sample image using the cropping method is shown in Figure 28. When the image is not cropped, the pixel dimensions are the same for all images from the same calibrated camera. Cropping was not used in any of the round robin data presented in this report.

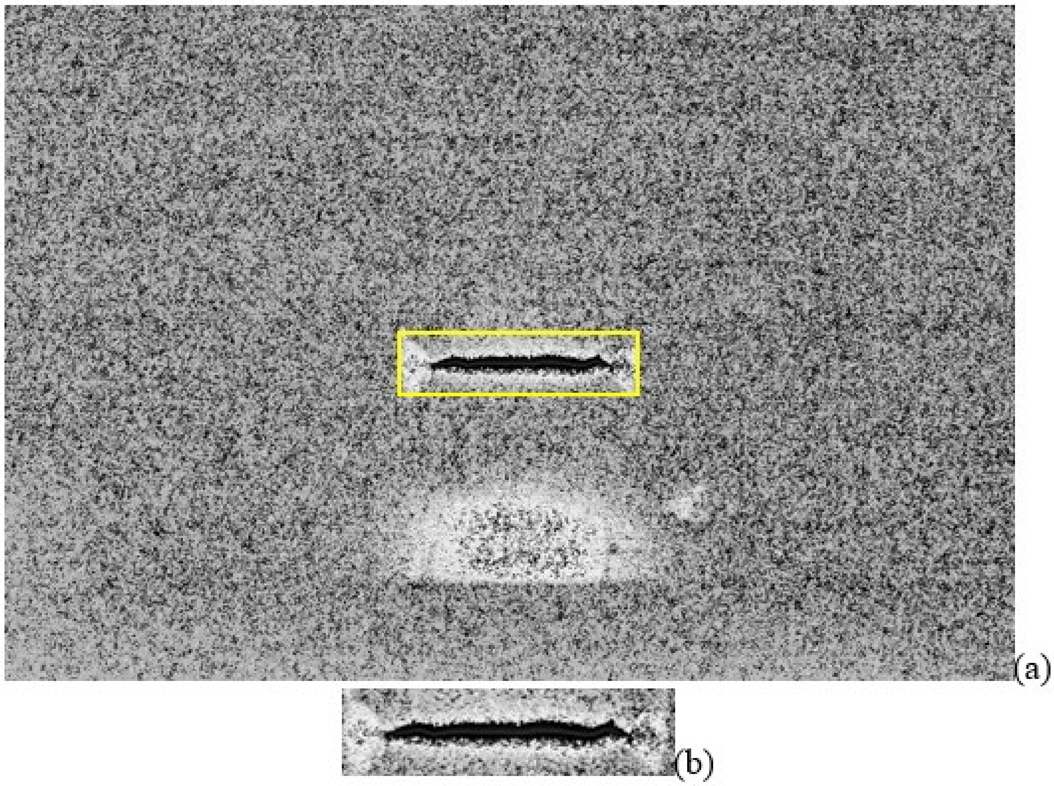
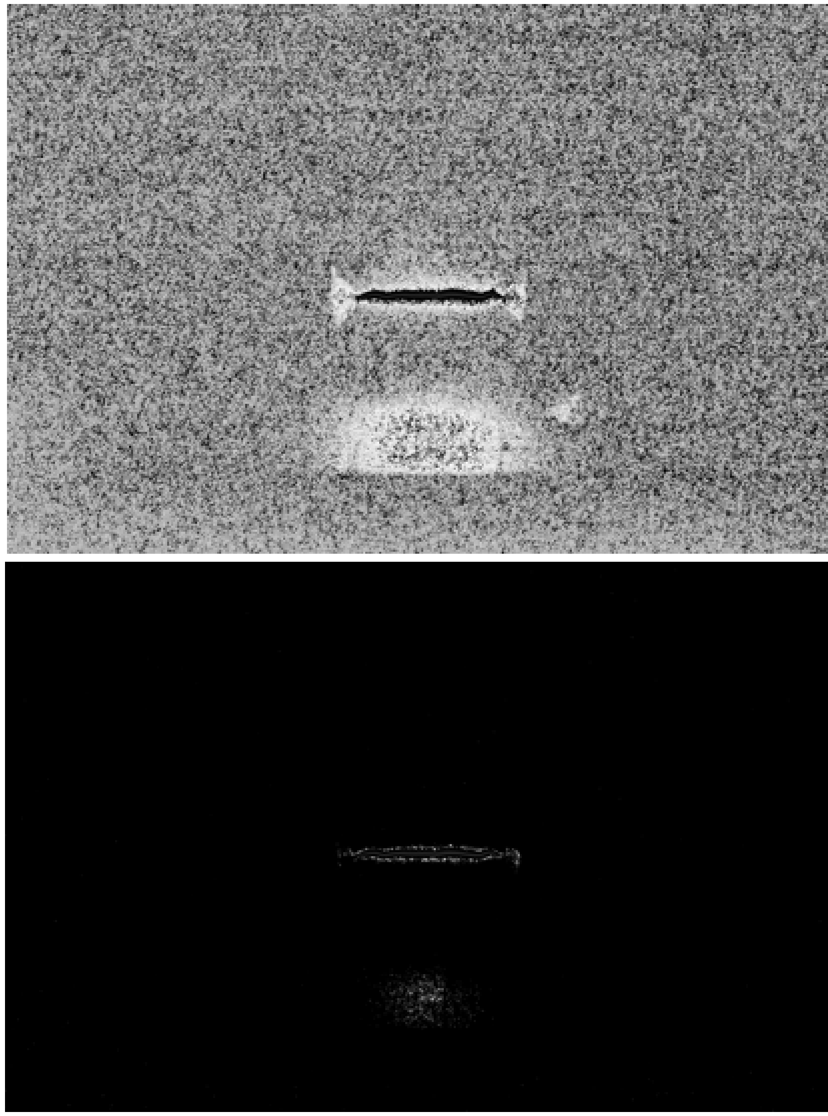


Figure 28. (a) Sample photo of Cu wire, hue channel, and (b) showing crop selection area

4.2.5.2 *Brightness threshold*

This technique involves filtering out pixels from the background area based on their brightness. Prior to converting to HSB, a brightness threshold is experimentally determined that is well below the brightness of the ignition source pixels and usually very close to zero (black). The identified pixels falling below this brightness are overwritten with black to remove the hue value noise at these locations. This threshold is selected to be as high as possible without removing any of the ignition pixels. A sample photo demonstrating the brightness threshold method is shown in Figure 29. This method was time consuming, slightly arbitrary, and not very successful in determining an ignition signature. This is done in ImageJ. This particular method of determining brightness threshold was not used in any of the round robin data presented in this report.



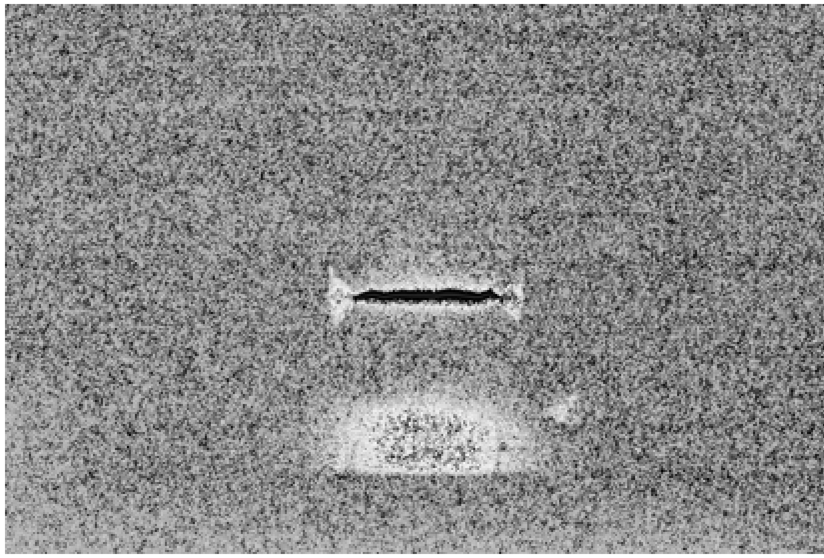
(a)

(b)

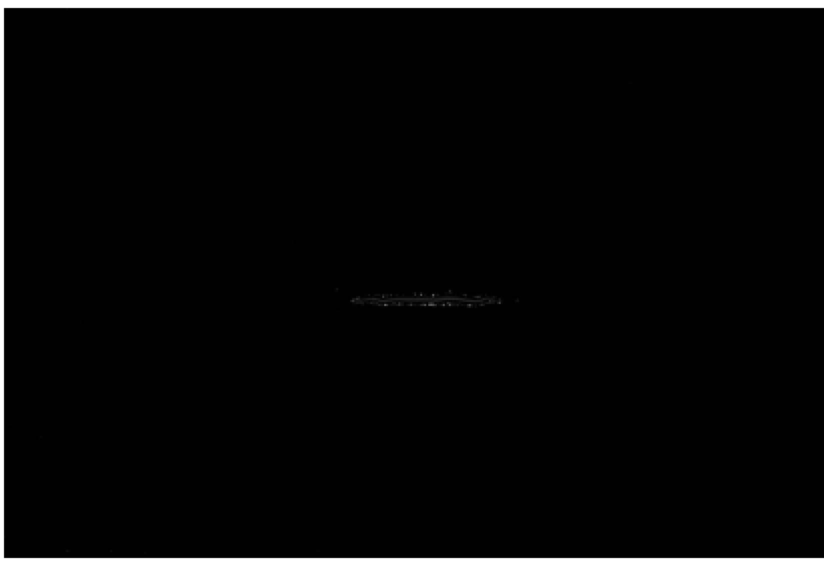
Figure 29. (a) Original sample photo of Cu wire, hue channel, and (b) that same photo that had background pixels removed based on a brightness threshold of 12 (selected subjectively to eliminate as much noise as possible)

4.2.5.3 *Photoshop overlay*

After importing the image into Photoshop, the background is painted over with black. This method is the most time consuming but also the most successful in thoroughly and accurately removing the background noise. This technique is not the best option for noise removal because it requires a second image processing software (Adobe Photoshop) in addition to ImageJ and the method in which the tools in Photoshop select the background area for removal. A sample photo demonstrating the Photoshop overlay technique is shown in Figure 30. It was not able to be determined if any data manipulation was occurring, so the method was eliminated. The Photoshop generated overlay was not used in any of the round robin data presented in this report.



(a)



(b)

Figure 30. (a) Original sample photo of Cu wire, hue channel, and (b) the same photo adjusted in Photoshop

4.2.5.4 *Ten percent calibrated brightness:*

This method is the same technique as the brightness threshold method, with a predefined threshold. This threshold was defined as a fraction of the calibrated brightness threshold determined during the brightness based camera calibration procedure, which is supposed to occur at approximately 50% of the dynamic range. The fraction was determined to be 10% of the camera's calibrated brightness threshold. This percentage was chosen because it is typically near the noise floor of the sensor, and well below the average brightness of the pixels at the location of the test article. While this does not remove all the noise, it does remove a majority of it. A sample image showing the 10% calibrated brightness threshold method is shown in Figure 31.

This is done in ImageJ. The 10% calibrated brightness threshold was utilized on all of the round robin data presented in Section 4.4 .

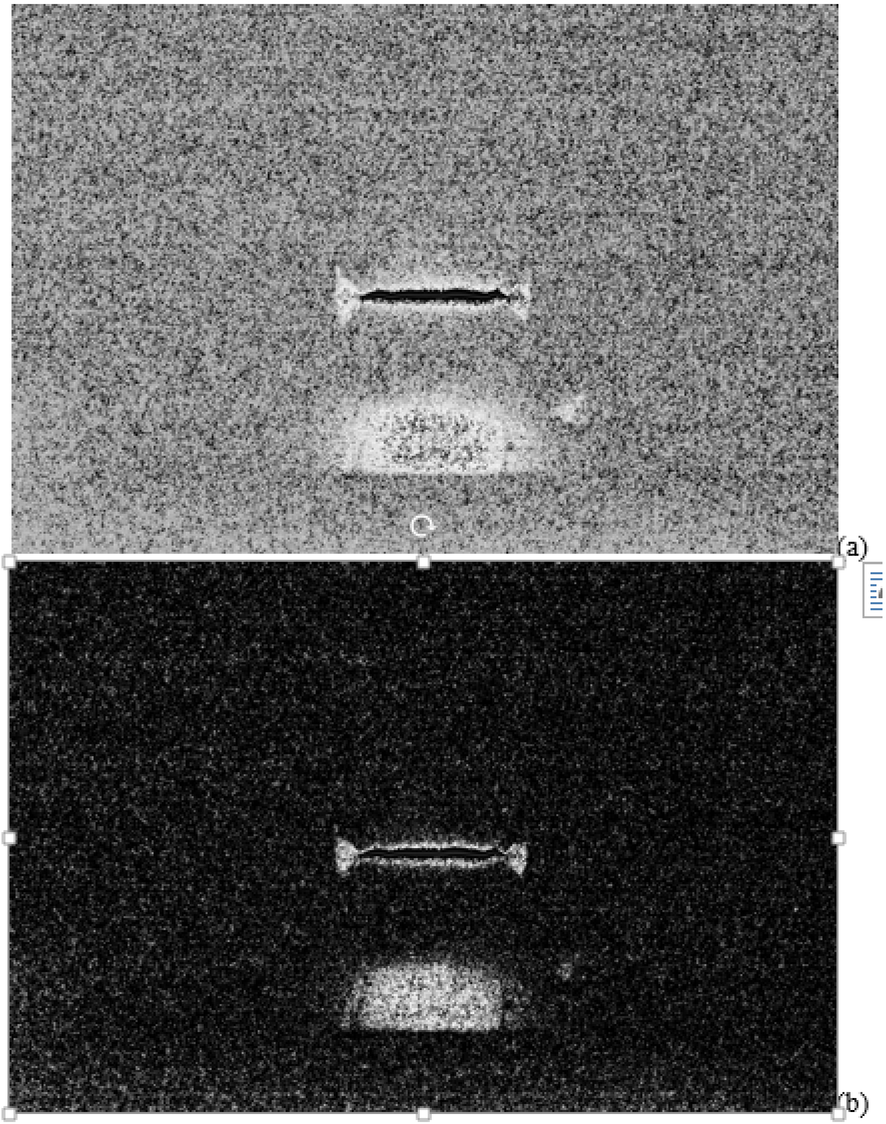


Figure 31. (a) Original sample photo of Cu wire, hue channel, and (b) the same photo that has had background pixels removed based on a brightness threshold of 5 (selected based on the calibrated camera)

4.2.6 K-means clustering

K-means clustering is an unsupervised machine-learning algorithm in which the user inputs a dataset, and specifies a number of clusters. The algorithm aims to cluster the data into subgroups with data points in each cluster being as close as possible in distance. A centroid for each cluster is defined, and a point falls in a particular cluster if it is closer to that cluster's centroid than to any other centroid.

The input data used by the K-means algorithm were hue values resulting from the 10% calibrated brightness-noise removal method histograms. Hue values from bins 1-42 (red, orange, and yellow) were included in the analysis since they represent the range of interest for the incandescent signature, while all other hue values were excluded. Best results (most distinct clustering) occurred with 15 clusters, though it was attempted using cluster values of 3-17. Resulting cluster centroids were plotted to determine whether a distinction between the ignition clusters and the non-ignition clusters exists.

An issue encountered with K-means demonstrated that the dataset size is insufficient. When the defined number of clusters is too large, the algorithm selected a random number for the x-axis value where there is insufficient data within the cluster. This resulted in misplaced centroids along the x-axis, because the algorithm iterated through the data for each cluster. When bins were plotted on the x-axis, no clusters beyond the hue value 42 should have occurred, but instances of clusters at 250 were observed.

In conclusion, there is insufficient ignition data for the K-means method to determine distinct signatures for ignition and non-ignition, given only five ignition photos per material per lab. K-means clustered data was not used in any of the round robin data presented in this report.

4.2.7 Support vector machine

The final method of analysis considered was the support-vector machine algorithm. The support-vector machine method uses a polynomial kernel function to raise the data to the third degree with a soft margin. The advantage of this method is that it can classify two distinct sets of data that overlap with each other. The algorithm iterates through the data to define a hyperplane in multidimensional space that efficiently separates the two data sets. Preliminary investigations using a support-vector machine algorithm showed that a third degree function would provide the most data separation while still allowing for a minor overlap. The minor overlap will help the algorithm to better classify photos falling in the gray area of the soft margin. An alternative option to the third degree function is a radial basis function kernel and a soft margin. The dataset was determined to be too small for this method to be worthwhile. It may become feasible after image normalization techniques are implemented.

Support vector machine data was not used in any of the round robin data presented in this report.

4.3 Issues with testing and data

Some of the test photographs received contained artifacts that affected the resulting hue histograms. These artifacts were caused by or included contact sparking, light leaks, reflections, and high amplitude ignitions with oversaturation. These effects are primarily due to issues with the test setup. Each of these artifacts will affect the hue histogram of the image by introducing illuminated pixels into the image, which are not directly related to the ignition source. Most cases of these artifacts were not included in the analysis because the issues were addressed and then the tests were repeated.

Contact sparking occurs at the area where the test article is attached to the generator. This sparking not only introduces light into the test chamber, but the spark also has potential to ignite the flammable mixture. Contact sparking must be eliminated to ensure that ignition is caused only by the incandescent source being investigated. An example is shown in Figure 32.

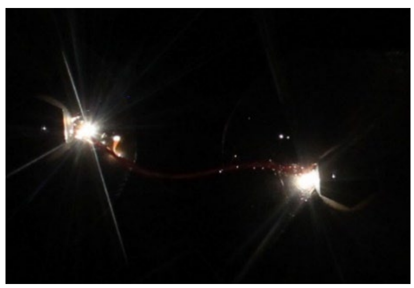


Figure 32. Sample image of carbon fiber bundle sparking at the contact area on both ends.

Light leaks occur when external light enters the test chamber and illuminates areas that are not related to the test article. The light leak displayed in Figure 33 occurred due to the pressure of ignition causing the top of the test chamber to move slightly, allowing external light to be visible to the camera.

Figure 33. Sample photo of external light leaking into the test chamber.

Reflections occur when the test article is positioned near a reflective surface. Reflections may appear with the same hue as the ignition source, and could affect the apparent ignition signature. The example in Figure 34 shows the test article illuminating multiple surfaces in the photo, which will affect the hue histogram of the overall image.

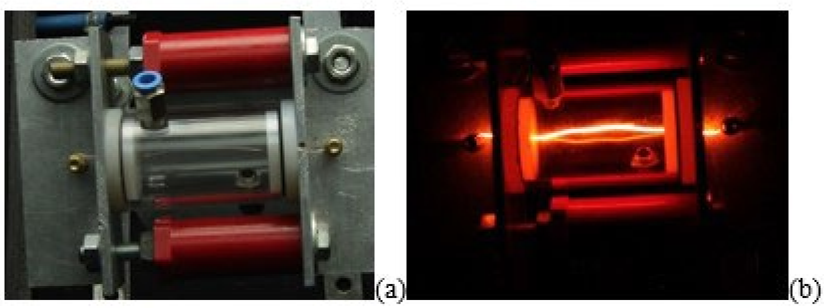


Figure 34. Sample photo of (a) illuminated test chamber containing a transparent cylinder (b) copper wire test, showing reflections interally on the cylinder surface, as well as surrouding surfaces.

High amplitude ignitions can cause oversaturation of the sensor. Any pixel that is exposed to light that exceeds the dynamic range will measure at a brightness of 255, or full brightness (white). No hue data exists in these oversaturated pixels. An example is shown in Figure 35.

Figure 35. Sample photo of oversaturated pixels on a copper wire.

4.4 Round robin results – individual laboratories

Round robin results for individual lab will be presented in the order of test parameters, train/test analysis results, brightness method results and sample test photos with corresponding hue histograms.

Test parameters for each lab are listed in Table 18, Table 26, Table 32, Table 38, Table 44, and Table 50. The parameters include camera type, sensor pixel dimensions, f-stop settings, ISO, shutter speed, focal length, white balance, brightness threshold, window material, and test gas mixture.

Train/test analysis results using the incandescent method for each lab are listed in Table 19, Table 20, Table 27, Table 33, and Table 39.

Brightness method results for comparison with the incandescent method results are listed in Table 21, Table 22, Table 28, Table 34, Table 40, and Table 46. The brightness-based photographic method from the AE-2 whitepaper was used on the same round robin data as the incandescent test/train results to allow direct comparison of the performance of the methods (SAE AE-2 Lightning Committee White Paper, Rev. NEW. January 2018). The calibrated brightness threshold for each camera was used as the pass/fail criteria to determine whether an image represented ignition or non-ignition conditions. The brightness analysis did not require the data to be divided into small datasets, because the brightness threshold applies to any material being tested with the same camera. The definition of true and false pass and fail for the brightness method is shown in Table 16.

Table 16: True and false failure and pass definition for brightness method

Peak Pixel Brightness	**Gas ignited**	**Gas did not ignite**
Peak pixel brightness greater than or equal to calibrated brightness threshold	True fail	False fail
Peak pixel brightness less than calibrated brightness threshold	False pass	True pass

The photos and histograms displayed throughout Section 4.4 show sample images from each dataset, and may not represent the dataset overall. The displayed photos have been cropped to preserve space and for ease of visualization. These photos were not cropped for analysis, and the histograms include the pixels from the entire uncropped photo.

The histograms were plotted using the hue data generated in ImageJ according to the procedure in Appendix A: Round Robin Test Procedure, and using the 10% brightness threshold noise-removal technique from Section 4.2.5.4 . The x-axis represents hue bins, usually displayed in a 0-42 (red to yellow) range, but the x-axis range is occasionally adjusted for histograms containing incandescent signatures past 42. The upper and lower bounds for the incandescent signature for each dataset are shown with vertical red lines. The y-axis represents the pixel count in each bin, and the axis scale has been adjusted based on the data for each histogram. There is a horizontal green line representing the 10-pixel minimum required for any bin to be considered part of the incandescent signature, as explained in Section 4.2.2 . For all ignition photos, all bins in the defined incandescent signature falls above this 10-pixel threshold. This threshold may be difficult to distinguish in cases where the y-axis is very large. For all non-ignition photos, at least one bin in the incandescent signature falls below this threshold, indicating that it does not meet ignition criteria, or it is identified as a false failure.

Table 17: Incandescent signature and brightness threshold for each lab and material

			Incandescent Signature		
Lab	Calibrated Brightness Threshold	10% Calibrated Brightness Threshold Value	Cu Wire	Carbon Fiber Bundles	CFRP Coupons
Lab 1 Cam 1	117	12	0-27	0-26	0-24
Lab 1 Cam 2	125	13	0-24	0-19	0-31
Lab 2	45	5	0-44	0-23	6-40
Lab 3	178	18	0-36	2-38	5-24
Lab 4	106	11	0-51	0-31	0-31
Lab 5	248	25	0-42	0-45	0-36
Lab 6	83	8	N/A	0-42	0-83

4.4.1 Lab 1 round robin data

Table 18: Test setup parameters, lab 1

Camera	Cam 1: Canon EOS Rebel T5		Cam 2: Canon EOS Rebel T5	
Pixel Dimensions	5184 X 3456	17.916 MP	5184 X 3456	17.916 MP
F-stop	5.6		5.6	
ISO	200		200	
Shutter Speed	3.2		3.2	
Focal Length	18mm		18mm	
White Balance	Manual		Manual	
Brightness Threshold	146 / **116.8**		156 / **124.8**	
Distance	11″		9″	
Test gas (by volume)	6% H2 and air		6% H2 and air	

Table 19: Train/test incandescent signature results, lab 1, camera 1

Ignition						Non-ignition	
Material	Training Set Photo Quantity	Signature	Testing Set Photo Quantity	True Fail	False Pass	False Fail	True Pass
Cu Wire	8	0-27	2	2/2	0/2	0/4	4/4
CF	4	0-26	1	1/1	0/1	1/9	8/9
CFRP	2	0-24	1	1/1	0/1	1/15	14/15

Table 20: Train/test incandescent signature results, lab 1, camera 2

Ignition						Non-ignition	
Material	Training Set Photo Quantity	Signature	Testing Set Photo Quantity	True Fail	False Pass	False Fail	True Pass
Cu Wire	8	0-24	2	2/2	0/2	0/4	4/4
CF	4	0-19	2	2/2	0/2	1/9	8/9

Ignition						Non-ignition	
CFRP	2	0-31	2	1/1	No data	1/14	13/14

Table 21: Brightness method applied to round robin photos results, lab 1, camera 1

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
117	Cu Wire	10	10/10	0/10	4	4/4	0/4
117	CF	5	5/5	0/5	9	9/9	0/9
117	CFRP	3	3/3	0/3	15	15/15	0/15

Table 22: Brightness method applied to round robin photos results, lab 1, camera 2

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
125	Cu Wire	10	10/10	0/10	4	3/4	1/4
125	CF	6	6/6	0/6	9	9/9	0/9
125	CFRP	4	4/4	0/4	14	14/14	0/14

Table 23 displays sample photos and hue histograms for the copper wires tested by Lab 1. No false failures were identified for this dataset.

Table 23. Sample photos of incandescently heated copper wire, Waveform 5A, lab 1.

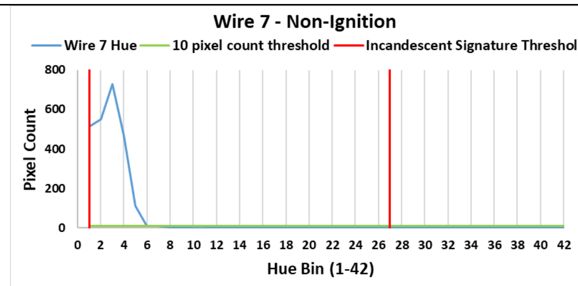
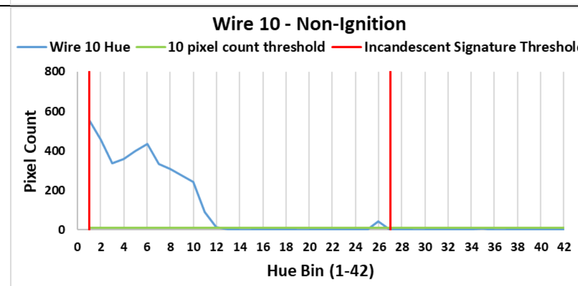
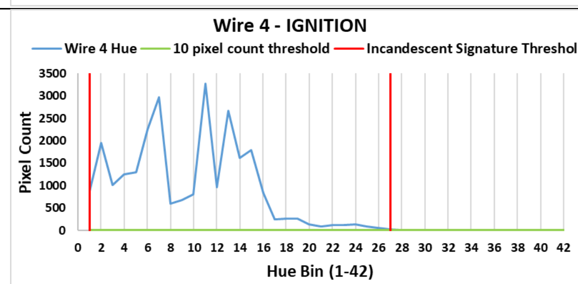
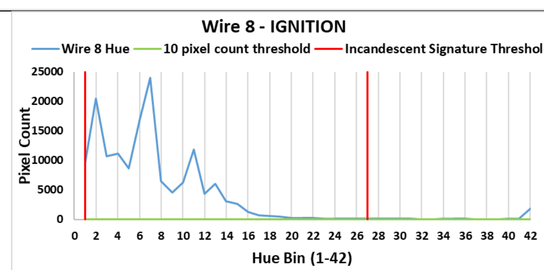
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-27, defined with train/test data)
Sample Wire Installation		N/A
Wire 7 Non-ignition		
Wire 10, Non-ignition		
Wire 4 IGNITION (lowest energy ignition,		
Wire 8 IGNITION (Highest energy ignition)		

Table 24 displays sample photos and hue histograms for the carbon fiber bundles tested by Lab 1. One false failure was identified for this dataset out of the nine non-ignition photos.

Table 24. Sample photos carbon fiber bundles, Waveform 5A, lab 1

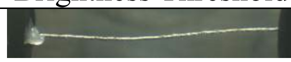
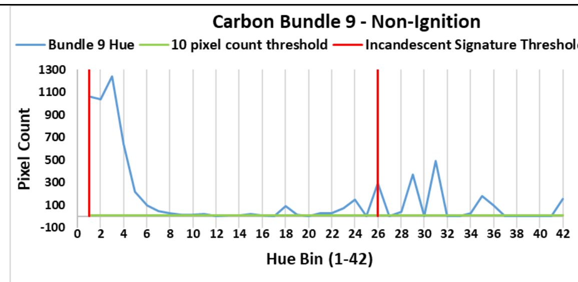
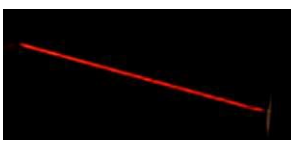
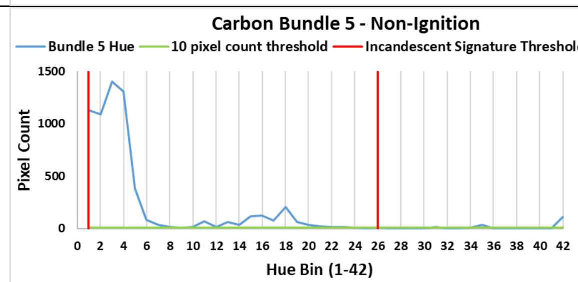
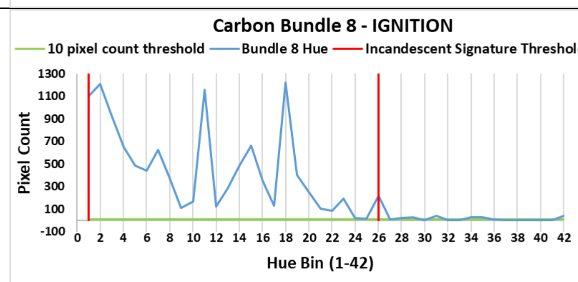
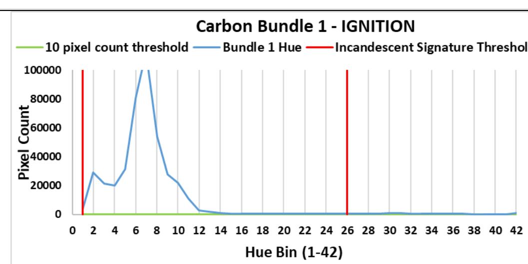
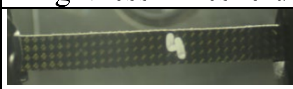
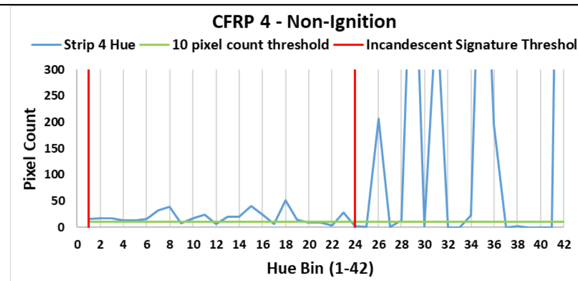
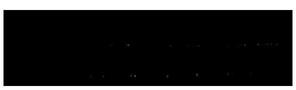
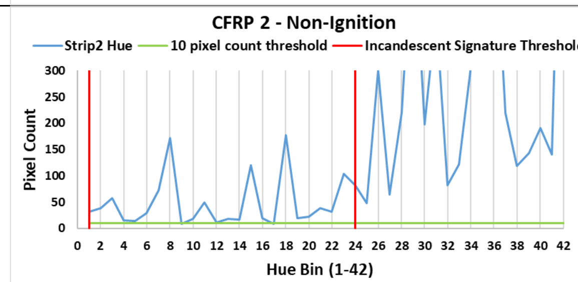
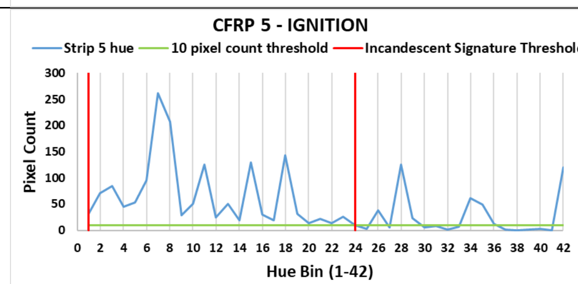
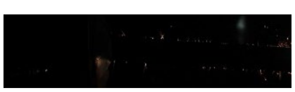
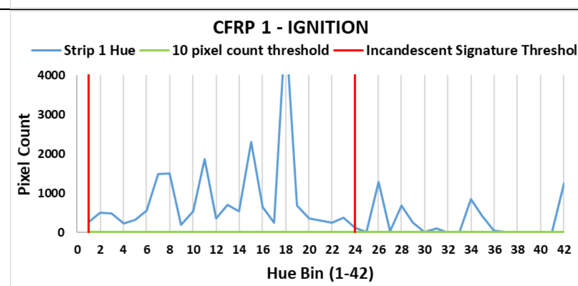
<table>
<tr><th>Test level
(Peak Current)</th><th>Test Photo, Front Camera, 10% Brightness Threshold</th><th>Hue Histogram
(Incandescent Signature 0-26, defined with train/test data)</th></tr>
<tr><td>Sample Carbon Bundle</td><td></td><td>N/A</td></tr>
<tr><td>Carbon Bundle 9 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Carbon Bundle 5, Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Bundle 8 IGNITION (lowest energy ignition,</td><td></td><td>
</td></tr>
<tr><td>Bundle 1 IGNITION (Highest energy ignition)</td><td></td><td>
</td></tr>
</table>

Table 25 displays sample photos and hue histograms for the CFRP coupons tested by Lab 1. One failure was identified for this dataset out of 14 non-ignition photos.

Table 25. Sample photos of CFRP strips, Waveform 5A, lab 1

Test Coupon	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-24, defined with train/test data)
Sample open box		N/A
CFRP 4 Non-Ignition		
CFRP 2 Non-Ignition		
CFRP 5 IGNITION		
CFRP 1 IGNITION		

4.4.2 Lab 2 round robin data

Table 26: Test setup parameters, lab 2

Camera	Nikon D610
Pixel Dimensions	6016 X 4016, total 24.160 MP
F-stop	16
ISO	3200
Shutter Speed	5s
Focal Length	50mm
White Balance	Manual, but “light source” is listed as tungsten in metadata
Brightness Threshold	57 = Tw / **45** = Tp/f
Window material	Lexan
Test Gas (by volume)	7.8% H2,

Table 27: Train/test incandescent signature results, lab 2

Ignition						Non-ignition	
Material	Training Set Photo Quantity	Signature	Testing Set Photo Quantity	True Fail	False Pass	False Fail	True Pass
Cu Wire	8	0-44	2	2/2	0/2	0/6	6/6
CF	8	0-23	2	2/2	0/2	0/17	17/17
CFRP	8	6-40	2	2/2	0/2	6/8	2/8

Table 28: Brightness method on round robin photos results, Lab 2

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
45	Cu Wire	10	10/10	0/10	6	5/6	1/6
45	CF	10	10/10	0/10	17	16/17	1/17
45	CFRP	10	10/10	0/10	8	8/8	0/8

Table 29. Sample photos of incandescently heated copper wire, Waveform 5A, lab 2 displays sample photos and hue histograms for the copper wires tested by Lab 2. No false failures were identified for this dataset.

Table 29. Sample photos of incandescently heated copper wire, Waveform 5A, lab 2

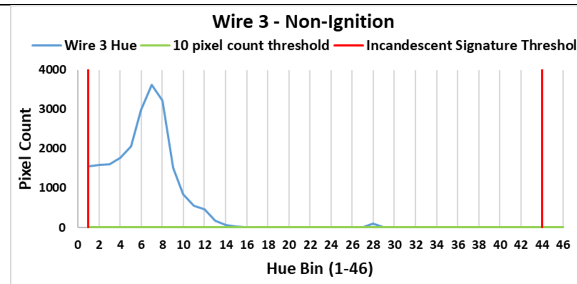
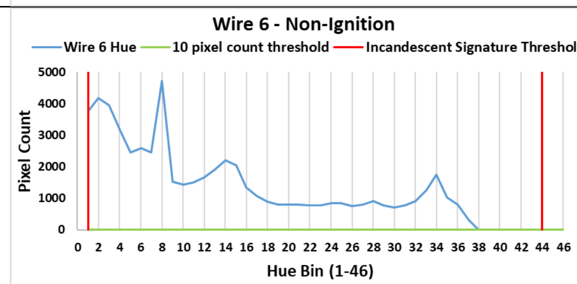
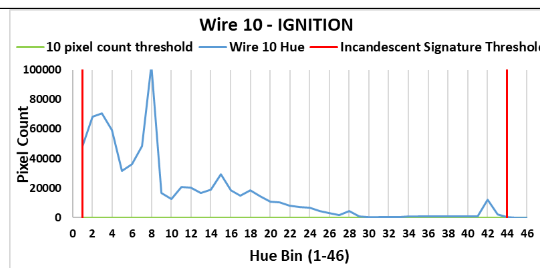
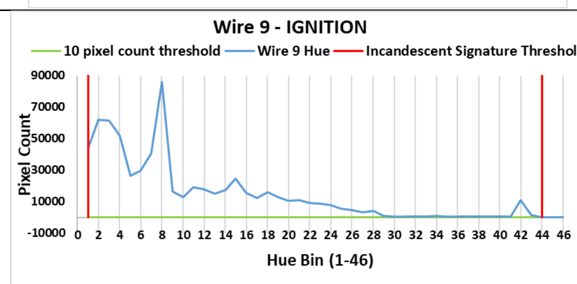
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-44, defined with train/test data)
Sample Wire Installation		N/A
Wire 3 Non-ignition		
Wire 6 Non-ignition		
Wire 10 IGNITION (lowest energy ignition,		
Wire 9 IGNITION (Highest energy ignition)		

Table 30 displays sample photos and hue histograms for the carbon fiber bundles tested by Lab 2. No false failures were identified for this dataset.

Table 30. Sample photos carbon fiber bundles, Waveform 5A, Lab 2

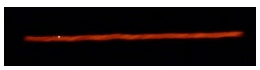
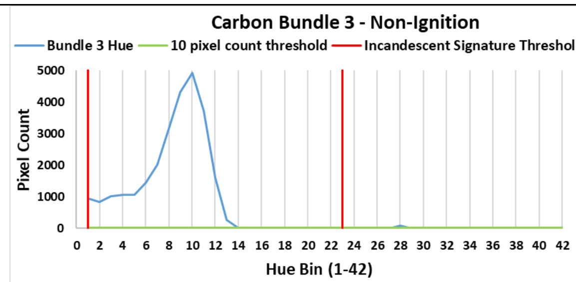
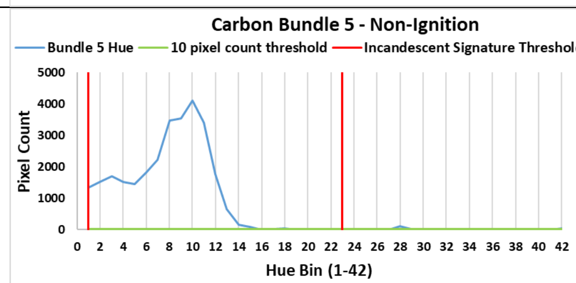
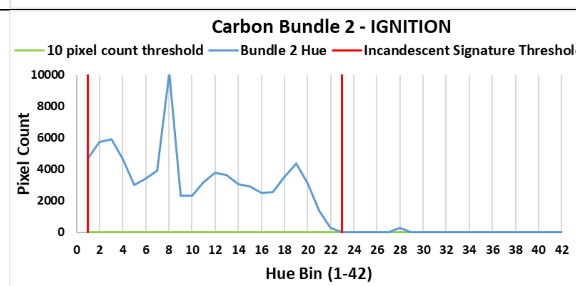
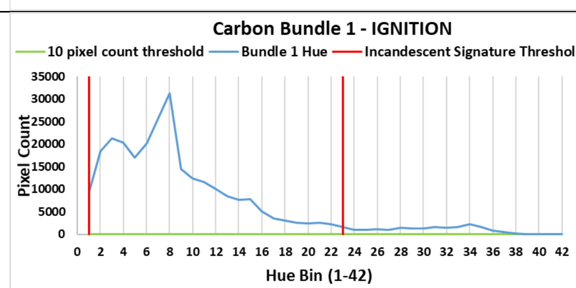
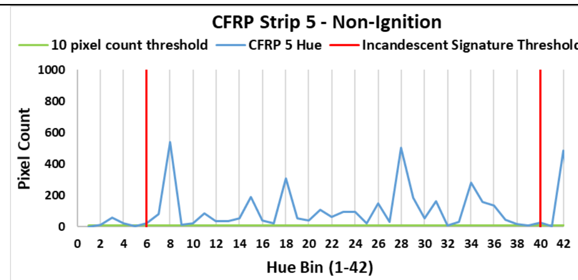
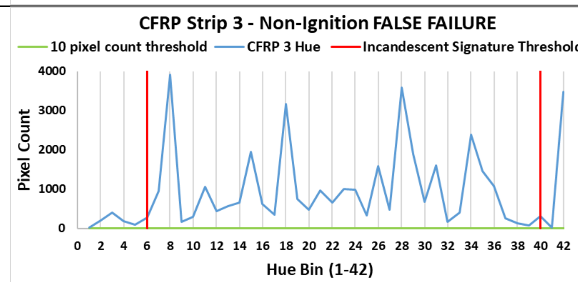
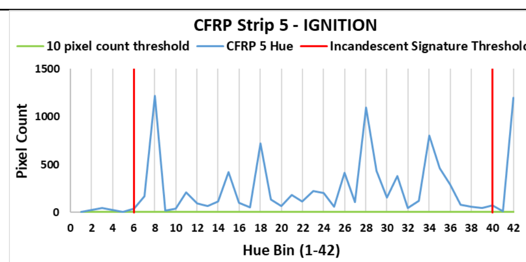
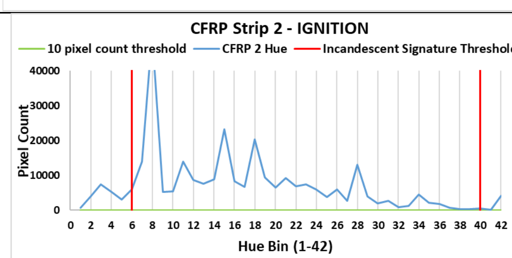
<table>
<tr><th>Test level (Peak Current)</th><th>Test Photo, Front Camera, 10% Brightness Threshold</th><th>Hue Histogram (Incandescent Signature 0-23, defined with train/test data)</th></tr>
<tr><td>Sample Carbon</td><td></td><td>N/A</td></tr>
<tr><td>Carbon Bundle 3 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Carbon Bundle 5 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Bundle 2 IGNITION (lowest energy ignition,</td><td></td><td>
</td></tr>
<tr><td>Bundle 1 IGNITION (Highest energy ignition)</td><td></td><td>
</td></tr>
</table>

Table 31 displays sample photos and hue histograms for the CFRP coupons tested by Lab 2. This data set had six out of eight non-ignitions misclassified as ignitions. In the sample photos in Table 31, it should be noted that CFRP 3 did not ignite the gas, but was identified as an ignition by the incandescent method, and is therefore considered a false failure. This particular image displays ejections, which by default should be classified as ignition.

Table 31. Sample photos of CFRP strips, Waveform 5A, lab 2

Test Coupon	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 6-40, defined with train/test data)
Samp le		N/A
CFRP 5 Non-Ignition		
CFRP 3 Non-Ignition FALSE FAIL		
CFRP 5 IGNITION		
CFRP 2 IGNITION		

4.4.3 Lab 3 round robin data

Table 32: Test setup parameters, lab 3

Camera	Canon EOS Digital Rebel XSi
Pixel Dimensions	4272 X 2848, total 12.167 MP
F-stop	16
ISO	1600
Shutter Speed	6 sec
Focal Length	50mm
White Balance	Auto
Brightness Threshold	**178**
Distance	13″
Gas Mix	7% H2 + air

Table 33: Train/test incandescent signature results, lab 3

Ignition						Non-ignition	
Material	Training Set Photo Quantity	Signature	Testing Set Photo Quantity	True Fail	False Pass	False Fail	True Pass
Cu Wire	8	0-36	2	2/2	0/2	0/2	2/2
CF	9	2-38	3	3/3	0/3	4/14	10/14
CFRP	11	5-24	3	2/3	1/3	11/16	5/16

Table 34: Brightness method on **r**ound **r**obin **p**hotos results, lab 3

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
178	Cu Wire	10	8/10	2/10	2	0/2	2/2
178	CF	12	12/12	0/12	14	14/14	0/14
178	CFRP	14	14/14	0/14	16	16/16	0/16

Table 35 displays sample photos and hue histograms for the copper wires tested by Lab 3. No false failures were identified for this dataset.

Table 35. Sample photos of incandescently heated copper wire, Waveform 5A, lab 3

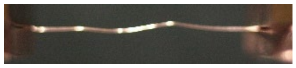
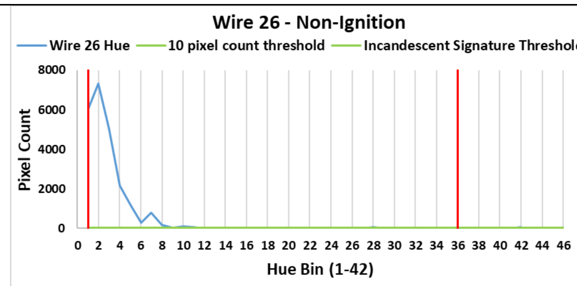
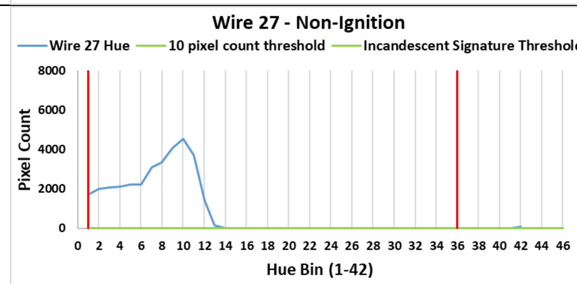
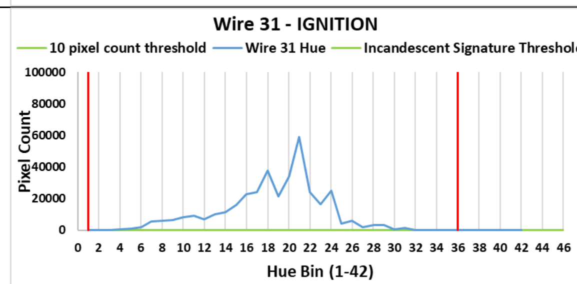
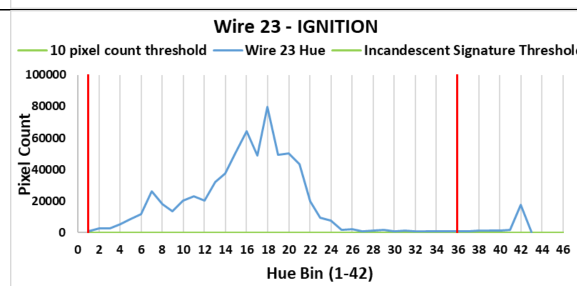
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-36, defined with train/test data)
Sample Wire		N/A
Wire 26 Non-ignition		
Wire 27 Non-ignition		
Wire 31 IGNITION		
Wire 23 IGNITION (Highest energy ignition)		

Table 36 displays sample photos and hue histograms for the carbon fiber bundles tested by Lab 3. Four false failures were identified for this dataset out of 14 non-ignition photos.

Table 36. Sample photos carbon fiber bundles, Waveform 5A, lab 3

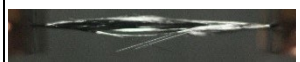
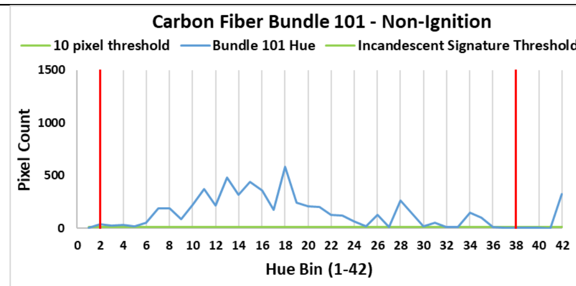
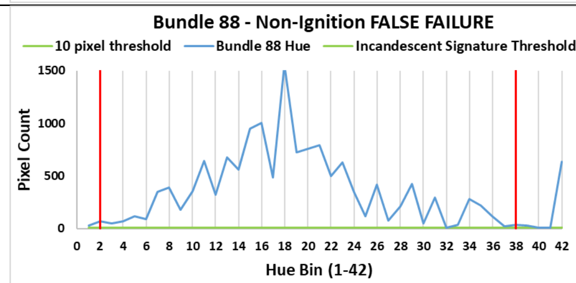
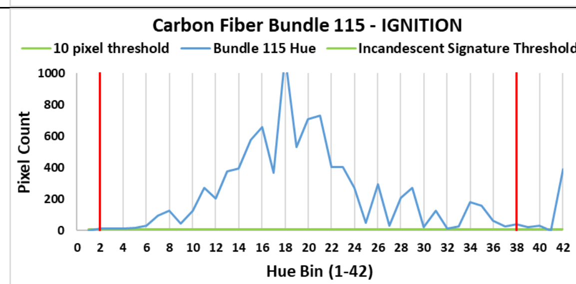
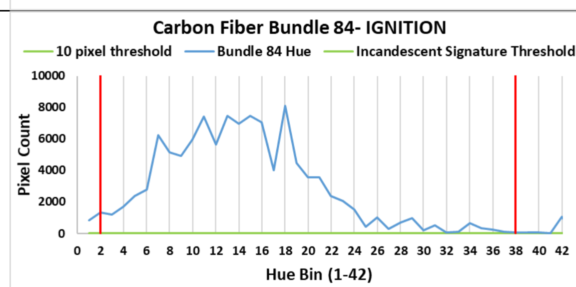
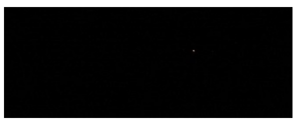
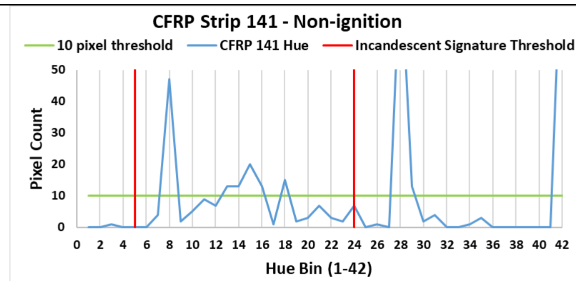
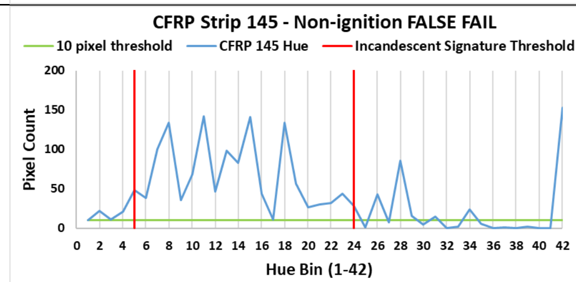
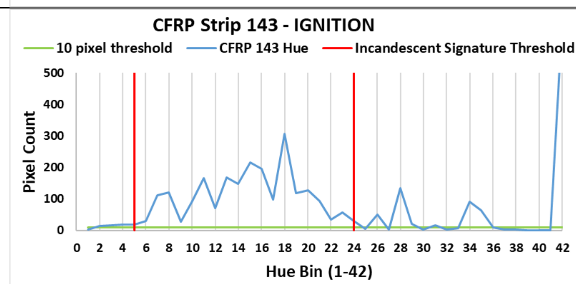
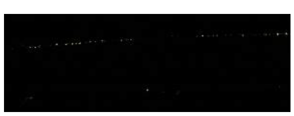
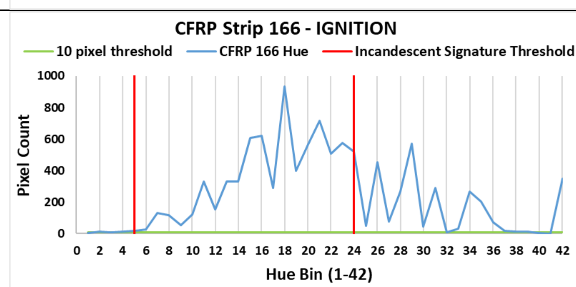
<table>
<tr><th>Test level (Peak Current)</th><th>Test Photo, Front Camera, 10% Brightness Threshold</th><th>Hue Histogram (Incandescent Signature 2-38, defined with train/test data)</th></tr>
<tr><td>Sample Carbon</td><td></td><td>N/A</td></tr>
<tr><td>Carbon Bundle 101 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Carbon Bundle 88 FASLE FAILURE Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Bundle 115 IGNITION</td><td></td><td>
</td></tr>
<tr><td>Bundle 84 IGNITION (Highest energy ignition)</td><td></td><td>
</td></tr>
</table>

Table 37 displays sample photos and hue histograms for the CFRP coupons tested by Lab 3. Eleven false failures were identified for this dataset, out of 16 non-ignition photos. One false pass (undetected ignition) occurred out of three ignition photos. This is the only instance of a false pass for any of the round robin data under the train/test analysis.

Table 37. Sample photos of CFRP coupons, Waveform 5A, lab 3

Test Coupon	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 5-24, defined with train/test data)
Sample open box		N/A
CFRP 141 Non-Ignition		
CFRP 145 Non-Ignition FALSE FAIL		
CFRP 143 IGNITION		
CFRP 166 IGNITION		

4.4.4 Lab 4 round robin data

Table 38: Test setup parameters, lab 4

Camera	Nikon D5300 with DX VR AF-P 18-55mm 1:3.5-5.6 G lens
Pixel Dimensions	6000 X 4000, total 24.00 MP
F-stop	6.3
ISO	1000
Shutter Speed	8s
Focal Length	24mm
White Balance	Auto
Brightness Threshold	**106.4**
Distance	300mm
Window material	Perspex 5mm
Test Gas (by Volume)	6% H2 in Air

Table 39: Train/test incandescent signature results, Lab 4

Ignition						Non-ignition	
Material	Training Set Photo Quantity	Signature	Testing Set Photo Quantity	True Fail	False Pass	False Fail	True Pass
Cu Wire	7	0-51	2	2/2	0/2	0/1	1/1
CF	20	0-31	5	5/5	0/5	2/22	20/22
CFRP	16	0-31	4	4/4	0/4	3/5	2/5

Table 40: Brightness method **a**pplied to **r**ound **r**obin **p**hotos results, lab 4

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
106	Cu Wire	9	9/9	0/9	1	1/1	0/1
106	CF	25	25/25	0/25	22	22/22	0/22
106	CFRP	20	20/20	0/20	5	5/5	0/5

As seen in Table 41, only one non-ignition photo provided by Lab 4 for the copper wires tested in the flammable mixture. No false failures were identified in this dataset.

Table 41. Sample photos of incandescently heated copper wire, Waveform 5A, Lab 4

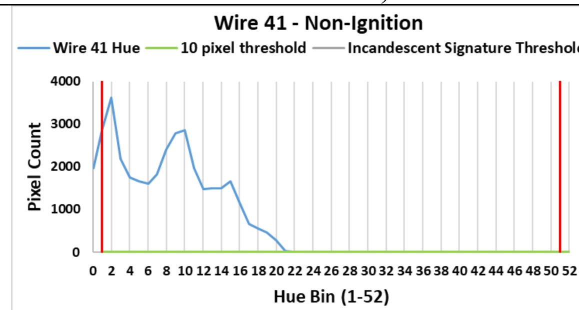
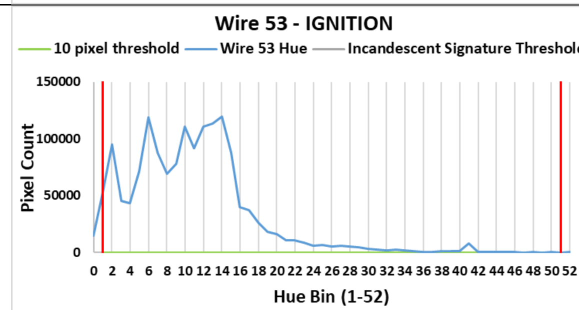
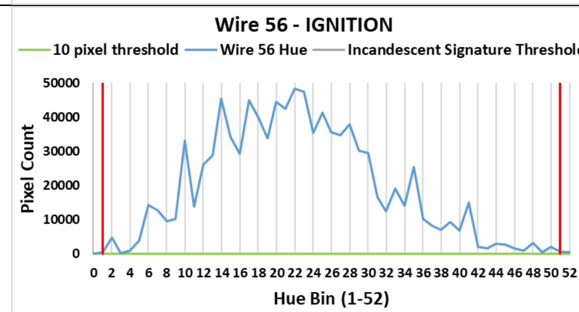
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-51, defined with train/test data)
Wire 41 Non-ignition		
Wire 53 IGNITION (lowest energy ignition,		
Wire 56 IGNITION (Highest energy ignition)		

Table 42 displays sample photos and hue histograms for the carbon fiber bundles tested by Lab 4. Three false failures were identified for this dataset out of five non-ignition photos.

Table 42. Sample photos carbon fiber bundles, Waveform 5A, lab 4

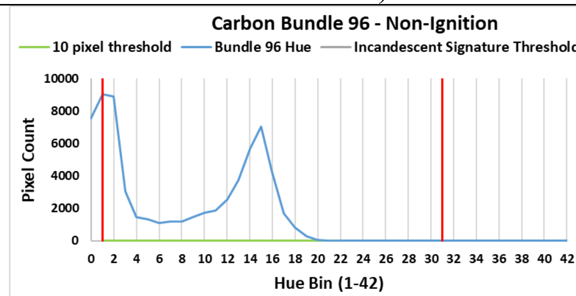
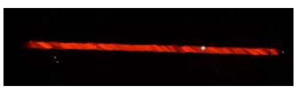
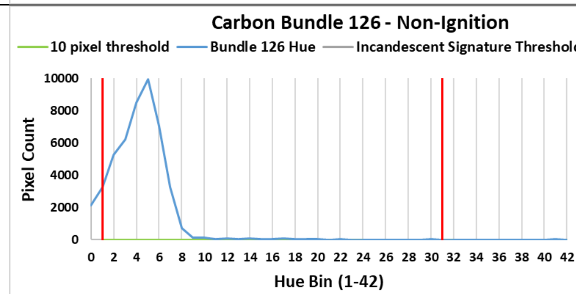
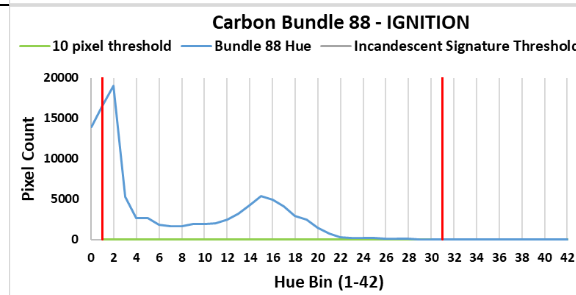
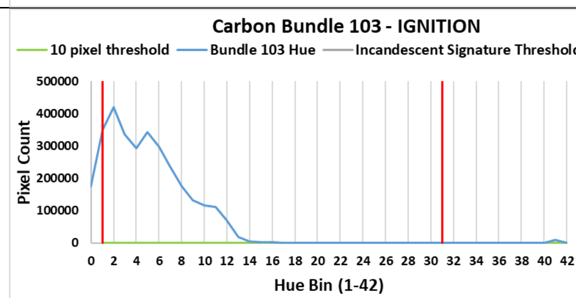
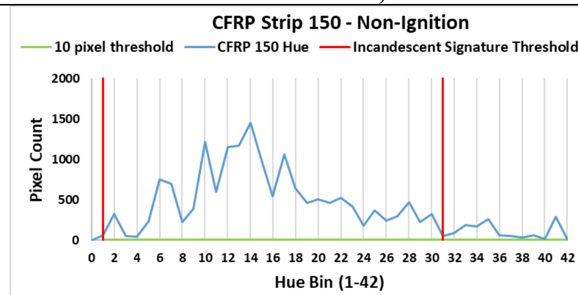
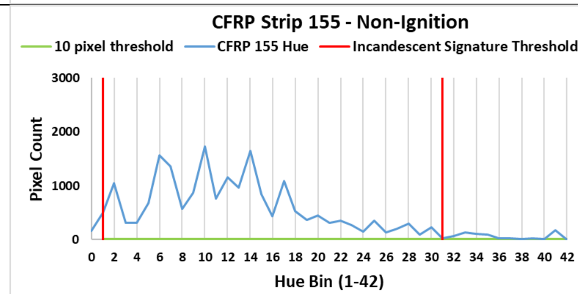
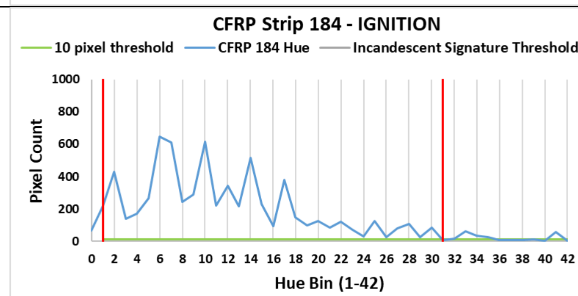
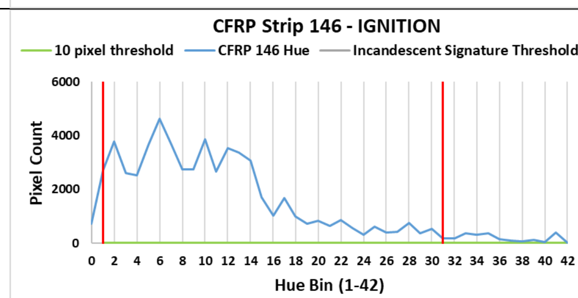
<table>
<tr><th>Test level (Peak Current)</th><th>Test Photo, Front Camera, 10% Brightness Threshold</th><th>Hue Histogram (Incandescent Signature 0-31, defined with train/test data)</th></tr>
<tr><td>Carbon Bundle 96 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Carbon Bundle 126 Non-ignition</td><td></td><td>
</td></tr>
<tr><td>Bundle 88 IGNITION (lowest energy ignition,</td><td></td><td>
</td></tr>
<tr><td>Bundle 103 IGNITION (Highest energy ignition)</td><td></td><td>
</td></tr>
</table>

Table 43 displays sample photos and hue histograms for the CFRP coupons tested by Lab 4. Two false failures were identified for this dataset out of 22 non-ignition photos.

Table 43. Sample photos of CFRP strips, Waveform 5A, lab 4

Test Coupon	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-31, defined with train/test data)
CFRP 150 Non-Ignition		
CFRP 155 Non-Ignition FALSE FAILURE		
CFRP 184 IGNITION		
CFRP 146 IGNITION		

4.4.5 Lab 5 round robin data

Table 44: Test setup parameters, lab 5

Camera	Canon 500D
Pixel Dimensions	3168 X 4752, total 15.054 MP
F-stop	2.8
ISO	1600
Shutter Speed	5s
Focal Length	17mm
White Balance	Manual
Brightness Threshold	248
Test Gas (by Volume)	6.67% H2

Table 45: Train/test **h**istogram **a**nalysis **r**esults – lab 5,

Ignition						Non-ignition	
Material	Training set (Photo #)	Signature	Testing set (Photo #)	True Fail	False Pass	False Fail	True Pass
Cu Wire	8	0-42	3	3/3	0/3	1/7	6/7
CF	3	0-45	1	1/1	0/1	0/9	9/9
CFRP	5	0-36	2	2/2	0/2	8/15	7/15

Table 46: Brightness method **a**pplied to **r**ound **r**obin **p**hotos results, lab 5

Ignition					Non-Ignition		
Calibrated Brightness Threshold	Material	# of Ignition Photos	True Fail	False Pass	# of Non-Ignition Photos	False Fail	True Pass
248	Cu Wire	11	10/11	1/11	7	1/7	6/7
248	CF	4	4/4	0/4	9	6/9	3/9
248	CFRP	7	7/7	0/7	15	12/15	14/15

Table 47 displays sample photos and hue histograms for the copper wires tested by Lab 5. One false failure was identified for this dataset out of seven non-ignition photos.

Table 47. Sample photos of incandescently heated copper wire, Waveform 5A, Lab 5

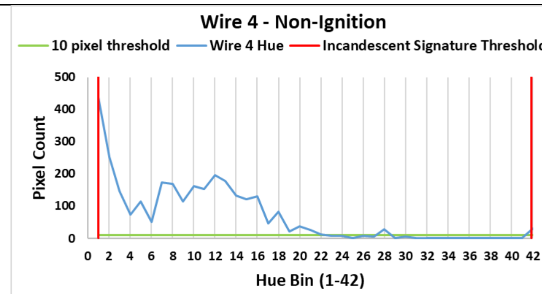
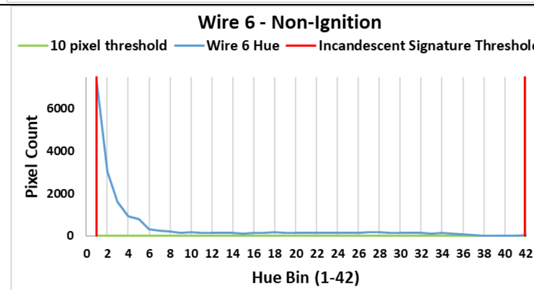
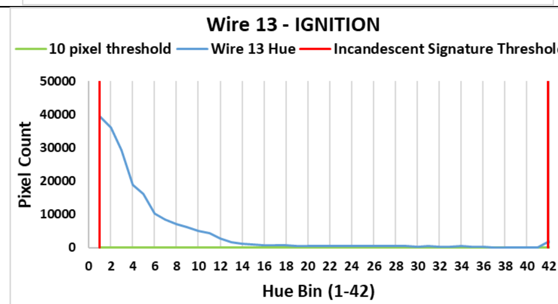
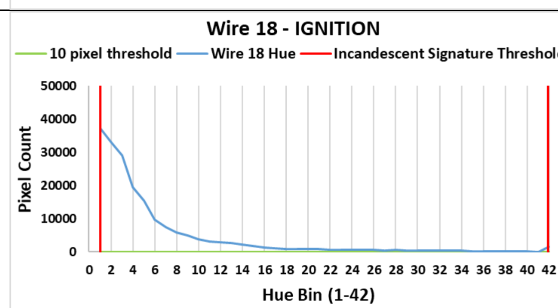
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-42, defined with train/test data)
Sample Wire Installation		N/A
Wire 4 Non-ignition		
Wire 6 Non-ignition		
Wire 13 IGNITION		
Wire 18 IGNITION		

Table 48 displays sample photos and hue histograms for the carbon fiber bundles tested by Lab 5. No false failures were identified for this dataset out of nine total non-ignition photos.

Table 48. Sample photos carbon fiber bundles, Waveform 5A, lab 5

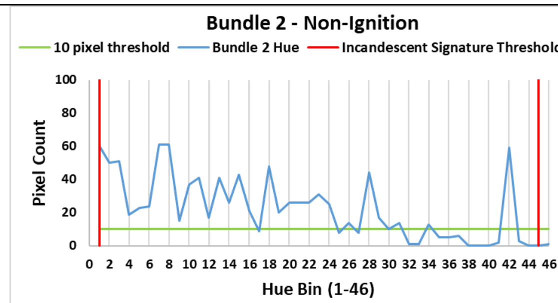
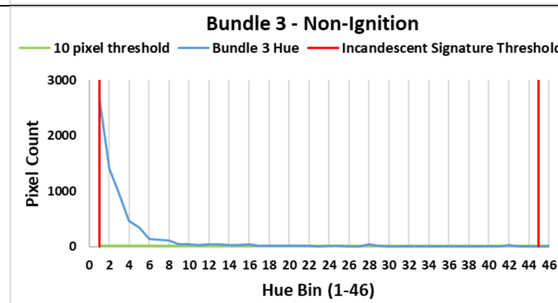
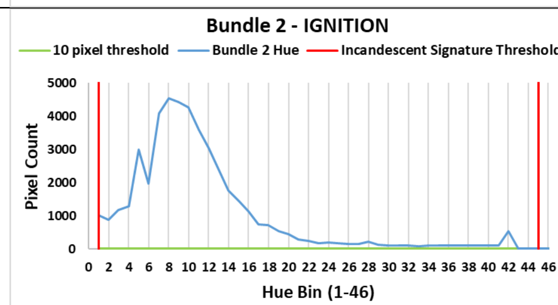
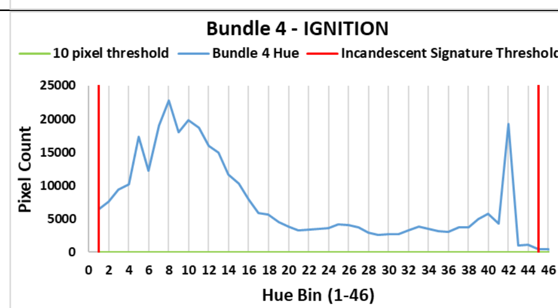
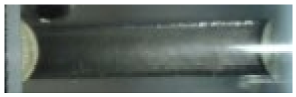
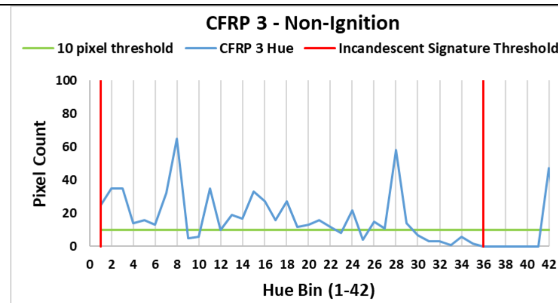
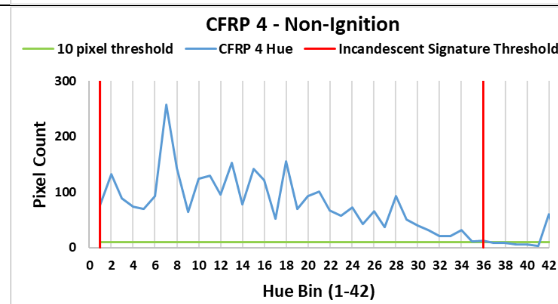
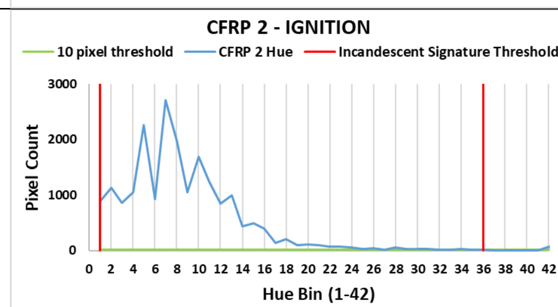
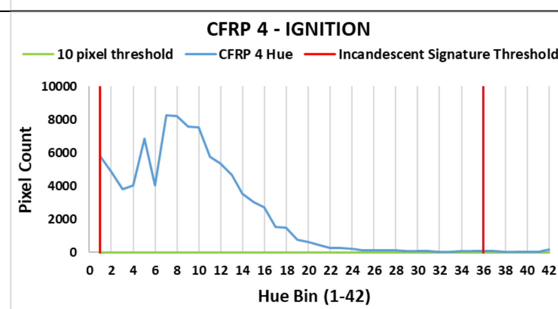
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-45, defined with train/test data)
Sample Carbon		N/A
Carbon Bundle 2 Non-ignition		
Carbon Bundle 3 Non-ignition		
Bundle 2 IGNITION (lowest energy ignition,		
Bundle 5 IGNITION (Higher energy ignition)		

Table 49 displays sample photos and hue histograms for the CFRP coupons tested by Lab 5. Eight false failures were identified for this dataset out of 15 non-ignition photos.

Table 49. Sample photos of CFRP strips, Waveform 5A, Lab 5

Test Coupon	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-36, defined with train/test data)
Sample open box		N/A
CFRP 3 Non-Ignition		
CFRP 4 Non-Ignition		
CFRP 2 IGNITION		
CFRP 4 IGNITION		

4.4.6 Lab 6 Round Robin Data

Table 50: Test setup parameters, lab 6

Camera	Nikon D5300 + Nikon Ai Nikkor 50mm f1.4 lens
Pixel Dimensions	6000 x 4000, total 24.0 MP
F-stop	F4.0
ISO	1600
Shutter Speed	10s (bulb was used for testing)
White Balance	Auto
Brightness Threshold	83
Distance	0.52 M
Test Gas (by Volume)	6.0% Hydrogen, 14.4% Oxygen, 79.6% Argon

Lab 6 provided very few ignition and non-ignition photos for each test material, making it difficult or impossible to divide the data into train/test datasets. Without a train or test set, there was no verification for the ignition photos against a hue signature, so true fail and false pass rates could not be determined. The false fail and true pass rates were determined using the hue signature defined by using all of the ignition photos, and are listed in Table 51. Data from Lab 6 was not included in the average train/test data results in Table 54.

Non-ignition photos were not provided. One test ignition photo for the copper wires was provided, so there was insufficient data to determine any incandescent signature for copper wires.

Table 51: Hue histogram analysis results – lab 6

				Ignition		Non-ignition	
Material	Total QTY of Ignition Photos Provided	Signature	Total QTY of Non-Ignition Photos Provided	True Fail	False Pass	False Fail	True Pass
Cu Wire	1	N/A	0	N/A	N/A	N/A	N/A
CF	6	0-42	6	N/A	N/A	5/6	1/6
CFRP	1	0-83	9	N/A	N/A	7/9	2/9

Table 52 displays a carbon fiber bundle non-ignition false failure photo and an ignition photo provided by Lab 6.

Table 52. Sample photos carbon fiber bundles, Waveform 5A, Lab 6

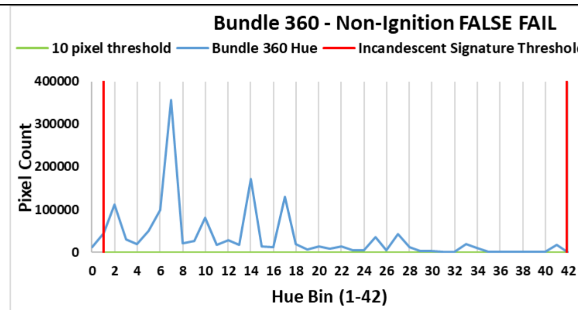
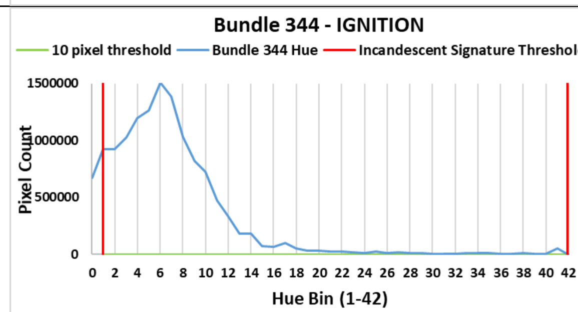
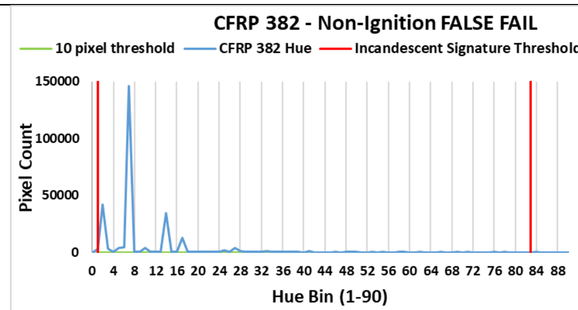
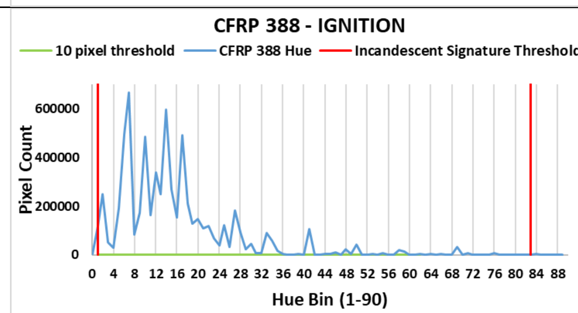
Test level (Peak Current)	Test Photo, Front Camera, 10% Brightness Threshold	Hue Histogram (Incandescent Signature 0-42, defined with all ignition photos)
Sample Carbon		N/A
Bundle 360 Non-ignition FALSE FAILURE		
Bundle 344 IGNITION		

Table 53 displays a CFRP coupon non-ignition false failure and an ignition photo provided by Lab 6.

Table 53. Sample photos of CFRP strips, Waveform 5A, lab 6

<table>
<tr><th>Test Coupon</th><th>Test Photo, Front Camera, 10% Brightness Threshold</th><th>Hue Histogram (Incandescent Signature 0-83, defined with one ignition photo)</th></tr>
<tr><td>Sample open box</td><td></td><td>N/A</td></tr>
<tr><td>Non-Ignition</td><td></td><td>
</td></tr>
<tr><td>IGNITION</td><td></td><td>
</td></tr>
</table>

4.5 Conclusions

For the round robin data analyzed with the incandescent method, the average false failure rate across all materials and labs is 19.2%, seen in Table 54. In comparison, the average false failure rate for the same data, analyzed with the existing brightness-based photographic detection method from ARP5416A, is 90.4%, seen in Table 55. The false failure rate specific to the CFRP coupons was reduced from 95.9% using the brightness method, to 45.1% using the incandescent method. CFRP materials are the most likely application for the incandescent method in practice, since CFRP is the source of edge glow.

These false failure rates indicate that the incandescent signature is more effective than the brightness method at classifying ignition and non-ignition conditions for this dataset of incandescent materials. Reducing the rate of false failures was the goal of this work and the reason the incandescent method was developed.

Table 54: Results of incandescent method train/test data averaged across all data

Overall average results of incandescent method applied to round robin photos							
Average results for all labs combined	Material	Ignition			Non-ignition		
		Average # of ignition photos per data set	True Fail	False Pass	Average # of non-ignition photos per data set	False Fail	True Pass
	Cu Wire	2.17	1/1 (100%)	0/1 (0%)	4.00	1/42 (2.4%)	41/42 (97.6%)
	CF	2.33	1/1 (100%)	0/1 (0%)	10.33	1/10 (10%)	9/10 (90%)
	CFRP	2.00	17/18 (94.4%)	1/18 (5.6%)	11.50	14/31 (45.1%)	17/31 (54.9%)
	All materials average	**2.17**	**53/54 (98.2%)**	**1/54 (1.8%)**	**8.61**	**14/73 (19.2%)**	**59/73 (80.8%)**

Table 55: Results of brightness photographic method averaged across all data

Overall average results of brightness photographic method applied to round robin photos							
Average results for all labs combined	Material	Ignition			Non-ignition		
		Total # of Ignition Photos	True Fail	False Pass	Total # of Non-Ignition Photos	False Fail	True Pass
	Cu Wire	60	19/20 (95%)	1/20 (5%)	24	7/12 (58.3%)	5/12 (41.7%)
	CF	62	1/1 (100%)	0/1 (0%)	80	19/20 (95%)	1/20 (5%)
	CFRP	58	1/1 (100%)	0/1 (0%)	73	70/73 (95.9%)	3/73 (4.1%)

	All materials	**180**	**59/60 (98.3%)**	**1/60 (1.7%)**	**177**	**160/177 (90.4%)**	**17/177 (9.6%)**

Based on the results of round robin test data analysis, ignition of the flammable gas mixture can be successfully classified the majority of the time when the incandescent detection method is used. The overall average true fail detection rate was 98.2% and an overall true pass rate was 80.8%. The rate of successful classification is lower for CFRP coupons, with an average true fail rate of 94.4%. This means that 5.6% of ignitions were *not* successfully identified. The true pass rate for CFRP coupons was only 54.9%. This means that of the CFRP non-ignitions, 45.1% were misclassified as ignitions, and are false failures. The train/test data incandescent signature results are in Table 54. Data from Labs 1-5 were included in this table, but Lab 6 was excluded due to insufficient data.

Due to the small dataset size, it cannot be determined if the digital color emission spectrometry method is sufficiently conservative. An average of 5.6% of CFRP ignitions were *not* detected by this method. The overall false pass rate is similar for both methods; with a 1.8% false pass rate for the incandescent method and a 1.7% false pass rate for the brightness-based method for all materials.

Additional testing of CFRP test articles, which are the main area of interest for edge glow and incandescence, should be completed. The best way to determine the conservatism of the method is to generate a large dataset with a sufficient number of ignition and non-ignition data points to determine whether the rate of false pass can be considered improbable. The testing should include carbon fiber composites containing various resins, fabric weaves, thicknesses, and other variables to help establish an overall general incandescent signature for carbon fiber composites. The testing that has been completed on CFRP during this research has been limited to one resin type and laminate thickness.

The successful participation of the round robin laboratories in this test shows that the incandescent method is feasible for implementation through use of existing test setups and test equipment, with limited time and expense required.

5. Phase 3: Further studies

5.1 Goal/plan of further studies

The further studies carried out in the final phase of this work were defined at the conclusion of the round robin investigation. The further studies tests intended to evaluate areas of uncertainty, which potentially affect the performance of the incandescent test method. The topics evaluated in this phase of work include camera resolution, camera lens type, distance from camera to test article, ignition source size, makeup of flammable gas mixture, automated image processing for classifying large datasets, and material selection for the "incandescent signature verification" procedure.

Based on the knowledge that larger hot objects require a lower temperature to cause ignition than smaller objects, a literature review of large and small thermal sources and their corresponding ignition temperatures was done to determine whether the temperatures seen with CFRP incandescence might vary enough to affect the incandescent signature.

While Phase 2 testing was underway, the SAE AE-2 committee ARP5416 task group began reviewing recommendations for flammable gas mixtures in ARP5416A. This led to discussion that in general, the existing recommended test gas mixture is very suitable for voltage-spark ignition sources, since test standards were originally based on voltage sparks. The task group recommended investigating alternative test gases, which may be more appropriate for potential thermal sources to include in ARP5416B. A literature review of this topic was completed to investigate whether hydrogen is an appropriate flammable gas mixture for use with CFRP edge glow and incandescent sources, as well as comparison with other test gas-mixture recommendations.

Camera sensor resolution was evaluated by testing to determine how it might affect the results or reliability of the method. This evaluation also aimed to determine the smallest incandescent hot spot that was detected during further studies testing. The minimum resolution of the camera must be sufficient to detect all incandescent ignition sources, for which the lower bound size is not currently defined in a standard detection test method. When more information is available regarding the minimum possible size of an incandescent ignition source, this will be added to the incandescent method test procedure as guidance for camera selection.

Camera lens type was evaluated to determine whether differences in image quality would result from use of a prime (fixed focal length) lens versus a similar variable zoom lens. This evaluation compared image sharpness primarily at the edges of the photos.

Camera distance from ignition source was evaluated to show its effect on resolution. Brightness and color were not evaluated in this camera distance study.

Material selection for incandescent signature calibration was investigated to determine whether a single incandescent signature could be determined for a camera using a generic CFRP test sample. Based on data from preliminary studies and round robin testing, the appearance of edge glow and incandescence can differ significantly from one CFRP coupon to the next, depending on materials, fabric type, and fiber orientation on the surface plies at the cut edge of coupons.

5.2 Literature review

Literature review was carried out for research topics for which full investigation exceeded the scope of this phase of work. Literature review topics include the makeup of flammable gas mixture, effect of test material size on incandescent method, and automated image classification methods to assist with image data processing.

5.2.1 Flammable gas mixtures for detection of small thermal sources

Flammable gas mixtures were investigated on their appropriateness for detection of thermal sources such as hot surfaces and small hot particles associated with incandescent edge glow. The test gas mixture selected for flammable gas ignition source detection testing affects the sensitivity of the test. A lean (5-7%) hydrogen, oxygen, argon mixture is recommended as the flammable mixture in SAE ARP 5416A section 7.7.2.2 (Society of Automotive Engineers (SAE) International, Revised 2013).

This mixture recommendation originated after lean hydrogen mixtures were studied for probability of ignition and MIE with voltage spark ignition sources through testing and data extrapolation. However, the recommended mixture in ARP 5416A of 5% hydrogen is not ignitable with 90% probability at 200 µJ, and does not reach 90% probability of ignition until a spark energy over 1000 µJ is used. To improve the sensitivity of the hydrogen mixture, increasing the concentration to 7% to provide an ignition probability of at least 90% with a 200-µJ voltage spark (Bane, S. P. M., 2010).

Hydrogen-argon-oxygen mixtures exhibit different breakdown characteristics than are expected in the air environment in fuel tanks. For this reason, air, or nitrogen-oxygen are recommended over argon-oxygen for use with hydrogen. Nitrogen is a more appropriate diluent than argon as discharges in a nitrogen-oxygen environment consistent with air (Boettcher, P. and Kwon, E., 2019).

Lean hydrogen exhibits high variability in the MIE with minor changes the mixture ratio, particularly in the range of 4% and 10% hydrogen (Lewis, B, and G. von Elbe, 2012). This presents a problem since this range, particularly 7% hydrogen, is the most commonly used concentration for the test. This variability can affect the sensitivity of the detection method if there is error or uncertainty in mixing the test gas, which causes the mixture to fall outside of an acceptable 90% probability range.

Minor changes in hydrogen concentration also cause variability in flame propagation for lean hydrogen mixtures. Ignition cases with very weak flame propagation are difficult to detect with simple methods like physical displacement of the blowout panel due to pressure change from an ignition. Use of lean hydrogen mixtures near the lower flammability limit can "result in a flame with slow laminar flame speed and small expansion ration, which combined lead to slow flame front propagation, buoyant flames, and small pressure rises" (Boettcher, P. and Kwon, E., 2019). More sophisticated methods of ignition detected, such as thermocouples or pressure transducers to detect temperature or pressure rise in the test chamber may be required when lean hydrogen is used. Use of only simple visual detection methods for ignitions may run the risk of failing to detect an ignition.

Hydrogen as a test gas has been studied extensively in relation to the ignitability of jet fuel when using voltage spark ignition sources based on the 200- µJ test threshold defined for jet fuel, and has been found to be appropriate for detecting voltage spark ignition sources. Ignition criteria for thermal sources has not been studied as extensively as voltage spark sources for jet fuel. Lean hydrogen mixtures have not been equated to the behavior of jet fuel for these thermal sources, like hot spots, ejected particles, and thermal sparks (Crouch, K, 1994).

One recommended solution to the issues with the hydrogen mixture is use of ethylene-air mixtures. Ethylene-air mixtures do not exhibit problems with variability of the MIE with changes to mixture concentration in the way that hydrogen does. Additionally, the gas mixture concentration does not need to be as tightly controlled to maintain 90% probability of ignition at 200 µJ when ethylene-air is used, as compared the very specific concentrations required for hydrogen mixtures. Ethylene-air mixtures sensitive to a 200 µJ voltage arc "can be achieved both at lean and rich mixture ratios near stoichiometric where variability in the mixture has a much lower effect than near the flammability limits, as is the case with the hydrogen mixture" (Boettcher, P. and Kwon, E., 2019).

As a result of this investigation, the recommendations for test gas mixture for CFRP incandescent sources are use of either hydrogen-air or hydrogen-nitrogen-oxygen mixtures or an ethylene-air mixture, rather than the hydrogen-argon-oxygen mixture recommended by ARP 5416A.

5.2.2 Size of incandescent source relative to temperature of ignition

The ability of a heated object to cause ignition is typically dependent on size and temperature of the heated object. This topic is of interest due to concern that the appearance of heated incandescent ignition sources in test photos will differ depending on the geometry of the specific heated object. This is because "consistent with thermal ignition theory, the ignition temperatures increased with decreasing heat source dimensions", specifically measured in surface area of the heated objects (Kuchta, J. M., Bartkowiak, A., and Zabetakis, M. G., Vol. 10, No. 3, 1965).

Temperatures of ignition source surfaces increase with decreasing heat source dimensions. For very small heated sources, the rate of heating also affects the ignition. Experiments using hexane-air, a hydrocarbon test gas that has exhibited similar ignition characteristics to jet fuel. A linear relationship exists between increasing surface areas of heat sources and decreasing ignition temperatures for heated objects with surface area less than 40 cm^2 (Kuchta, J. M., Bartkowiak, A., and Zabetakis, M. G., Vol. 10, No. 3, 1965). Hexane-air also exhibits similar hot surface ignition temperatures hydrogen-air mixtures (Boeck, L. R., M. Meijers, A. Kink, R. Mével, and J. E. Shepherd, 2017).

The primary influence on the appearance of visual light (hue of a heated material) emitted by an incandescent source is the surface temperature of the heated object, based on the model of gray-body radiation (Izquierdo-Gil, M.A., Barragán, V.M. & Villaluenga J.P.G., 2021). The difference in surface area and surface temperature of individual incandescent edge glow spots would have to vary enough to exhibit a change in ignition temperature sufficient to affect the appearance of the incandescent signature. The size of edge glow spots evaluated in this testing fell within a range of only (.01″ to .12″, or 3 to 36 pixels) based on measured light area in the test images.

Additionally, larger incandescent edge glow spots typically are a result of a more intense (brighter) incandescent spot. These larger and more intense incandescent spots display more easily detectable incandescent hue signatures due to increased temperatures causing a larger continuous hue spectrum, and the physical size of the spot itself lends to higher pixel counts in the incandescent hue bin range (~0-42). Large incandescent spots also often eject particles, which is by default a failure of the test. The variation in size of incandescent edge glow spots has not been shown to reduce the appearance of the incandescent signature of ignition in a manner that would reduce the effectiveness of incandescent signature in detecting them as compared to smaller spots.

5.3 Test approach

Camera resolution was evaluated through comparison of similar cameras from the same manufacturer, one with smaller overall sensor dimensions, and one with a larger sensor. The specific cameras evaluated for comparison of camera resolution were the Canon Rebel T6i with a 24mm lens, and the Canon 6D with an equivalent focal length 40mm lens. The Rebel T6i has a smaller APS-C sensor (22.3mm x 14.9mm, 24.2 Megapixels) resulting in a 1.6 crop factor in relation to the larger 35mm full frame (36.8mm x 23.9mm, 26.6 Megapixels) sensor in the 6D. All camera settings were manually selected and were the same for both cameras.

Evaluations of camera lens types compared two identical cameras with different lenses, one variable zoom 18-55mm lens, and one 24mm prime lens, viewing the same ignition events to determine the relative sharpness of the resulting images. Sharpness is defined as “the amount of detail an imaging system can reproduce. It is defined by the boundaries between zones of different tones or colors” (Sharpness: What is it and How it is Measured, n.d.). All camera settings were manually selected and were the same for both cameras.

Camera distance was evaluated by photographing a target of known size at three distance increments. This was repeated with multiple cameras and lenses. The camera calibration recommends a distance from camera to test article be no greater than 1 meter. This may need to be re-evaluated during the “incandescent signature verification” phase of the test procedure to ensure that the edge glow spots are sufficiently resolved at the selected test distance. All camera settings were manually selected and were the same for all cameras.

Material selection recommendations for calibrating camera signature were made through comparison of test images from round robin testing and preliminary testing, as well as CFRP test coupon configurations tested for further studies. Comparisons took into account the quantity, size, hue, and brightness of edge glow spots both immediately below and above the ignition threshold level.

5.4 Test data

5.4.1 Camera resolution:

The overall pixel dimensions of test photos from the Canon T6i and Canon 6D are 6000 x 4000 pixels and 6240 x 4160 pixels respectively. Composite coupons used in this further studies testing were 5″ in length, clamped 0.5″ on each side. In photos from the Canon T6i with 24mm lens coupons were 1205 pixels (301 pixel/in), while the Canon 6D were 1220 pixels (305 pixel/in) long. The number of individual pixels is not significantly higher, though the overall sensor size of the Canon 6D is 1.6 larger than the Canon T6i. This means that the physical size of the individual pixels are larger, and may be more responsive to light as a result of that larger surface area collecting photons.

The example in Figure 36 shows a segment of the test article from the same ignition case, viewed by the Canon T6i and Canon 6D. Comparing resolution and pixel dimensions of edge glow spots from the same ignition case, the pixel measurements of the edge glow spots in the image range from 4 to 11 pixels for the Canon T6i, and 5 to 15 for the Canon 6D.

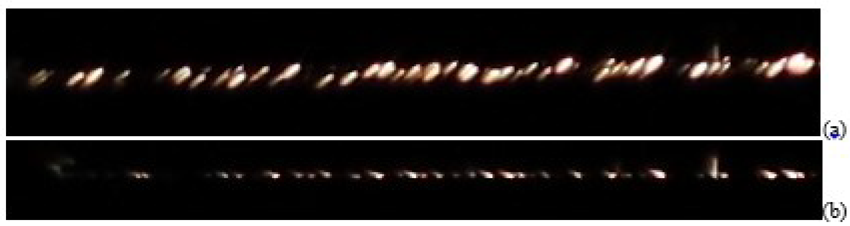


Figure 36. CFRP strip that ignited the flammable mixture with multiple edge incandescent glow spots viewed on cameras (a) Canon 6D and (b) Canon T6i

Since the pixels were larger in the Canon 6D and could have collected more light, the brightness was also measured for these edge glow spots. The brightness of individual spots ranged from 58 to 252 for the Canon T6i, and 112 to 254 for the Canon 6D. Though the visible appearance of shape of edge glow spots differs between the two cameras, the larger pixel size of the camera does not show an effect on ability to detect the spots based on pixel area or brightness.

5.4.2 Camera lens type

Figure 37 shows images of the same ignition event from two Canon T6i cameras, one with a 24 mm prime lens and one with an 18-55mm zoom lens. The definition of the individual edge glow spots is sharper on the photo with the 24mm prime lens, and the maximum brightness of the spots are 252 and 221 (out of a range of 255 max) for the 24 mm prime lens and 18-55mm zoom lens respectively.

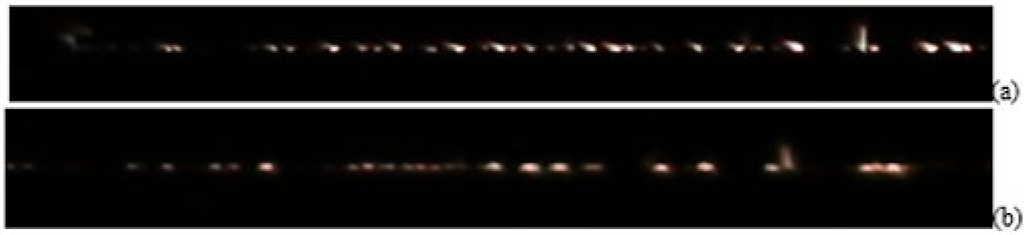
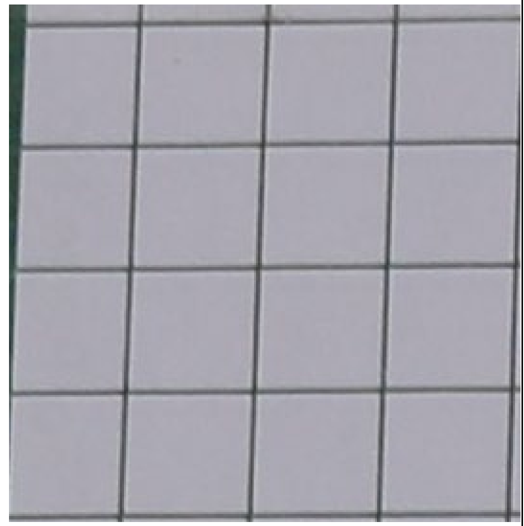
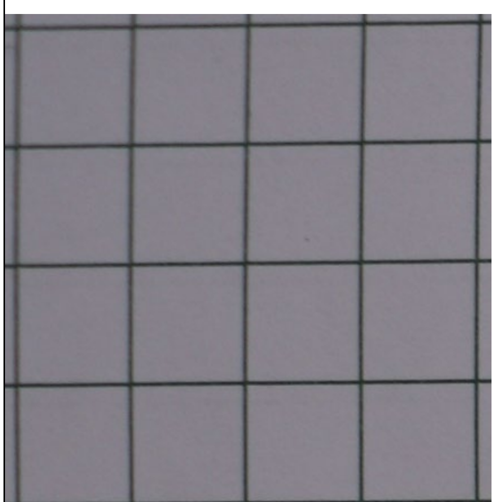
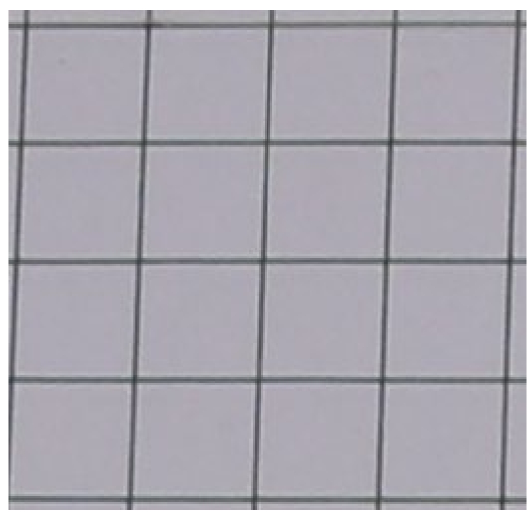


Figure 37. CFRP strip that ignited the flammable mixture with multiple edge incandescent glow spots viewed on Canon T6i cameras with (a) 24mm lens and (b) 18-55mm variable zoom lens

In photos taken of ¼″ grid paper with the two camera lenses at various distances from lens to test article, it was seen that sharpness is affected more by the combination of lens focal length and distance to test article than by the lens type itself. Sharpness is evaluated at high contrast edges within an image. Sharpness measurements of similar locations in each grid photo used the max and min grayscale values to determine the standard deviation from the mean. The images with lower standard deviation are less sharp, because they are displaying lower contrast and therefore higher amounts of blur at the edge. As seen in Table 56, grid paper images at 8″ show a sharper image on the zoom lens, but when the distance is increased to 24″ the prime lens is sharper. The measurements of standard deviation were obtained using the ImageJ grayscale histogram function for the same region of each image.

Table 56. Grid paper images from fixed lens and zoom lens cameras at increasing distance

Lens Type	Camera Distance = 8″	Camera Distance = 24″
24mm lens	 Std Dev: 18.12	 Std Dev: 22.68
18-55mm lens	 Std Dev: 24.24	 Std Dev: 22.93

5.4.3 Camera distance

To demonstrate the effect of camera distance on image resolution in pixels per length of test-article ignition source, photos of ¼″ grid paper were taken using three cameras with the same settings in manual mode. Cameras were positioned with the lenses at 8″, 16″, and 24″ from the paper. This study was not completed on an incandescent test article case, because it would have required multiple identical camera setups (camera model and lens the same for each) placed at incremental distance from the ignition source to simultaneously photograph the same ignition event to ensure comparability. This was not feasible due to the limited camera equipment available.

Distance from camera to target ties in heavily with how finely resolved the image of the target appears. Small incandescent sources appear smaller and seem to be distributed across fewer pixels with increasing distance. This is important to consider when choosing the size and geometry of the test article.

Table 57 shows that, based on the values for each camera, the resolution in pixels-per-inch scales linearly with distance from photographed object to camera. Minimizing the distance from the camera to the test article is recommended to maximize resolution of potential ignition sources. Based on this logic, the focal length of the lens should also be maximized to obtain the highest resolution of the test article, while ensuring that the entire test article remains within the frame.

Table 57: Pixel resolution of ¼″ photographed at incremental distances

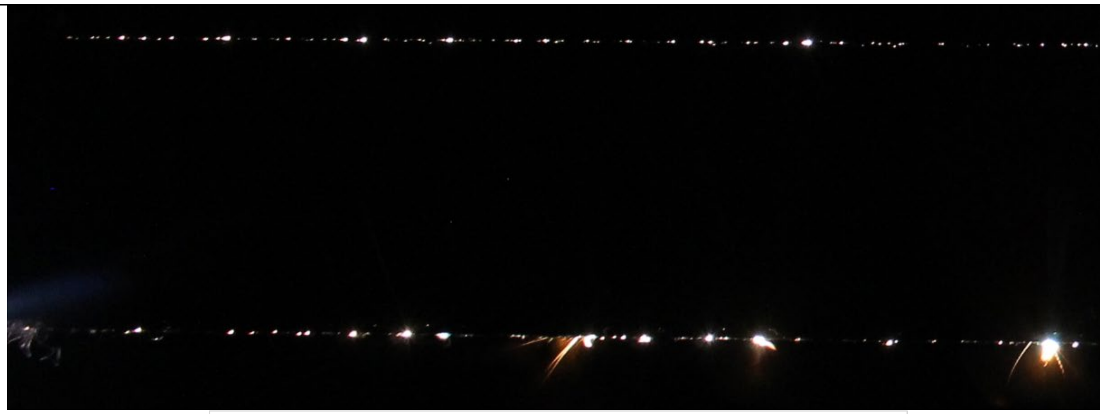
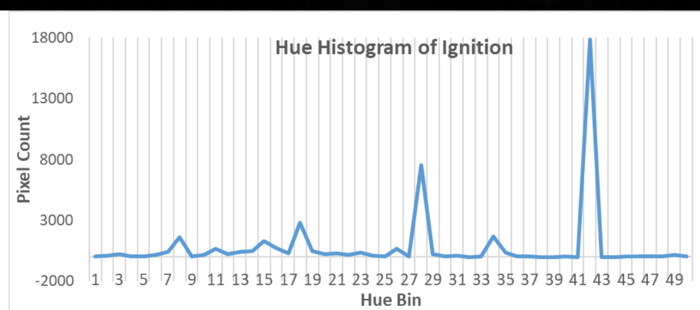
Pixels Per 1/4″ Grid Paper Unit			
Camera model, Distance from Camera to Target	8″	16″	24″
Canon T6i 24mm lens (6000x4000px)	70	102	208
Canon T6i 18-55mm lens at 24mm (6000x4000px)	63	92	176
Canon 6D with 40mm lens (6240x4160px)	72	110	225

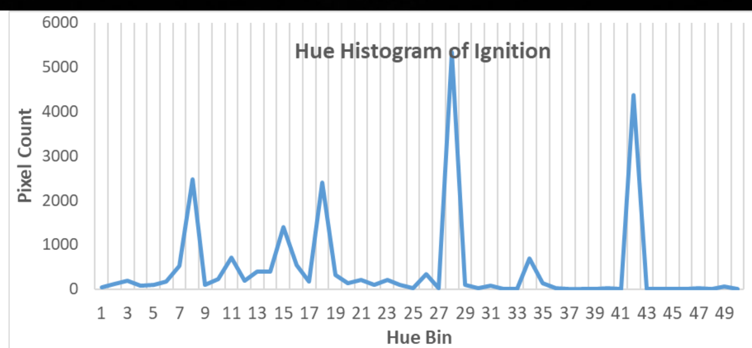
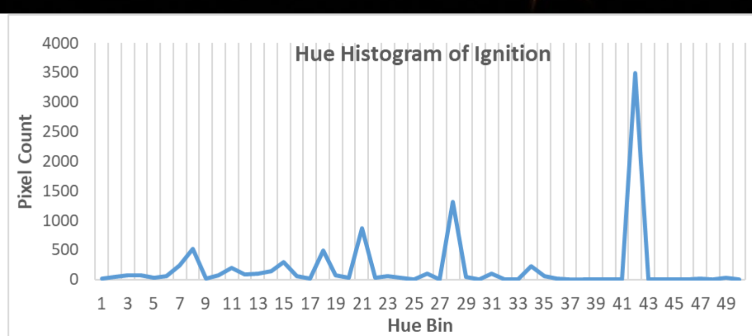
5.4.4 Material to use for incandescent signature verification procedure

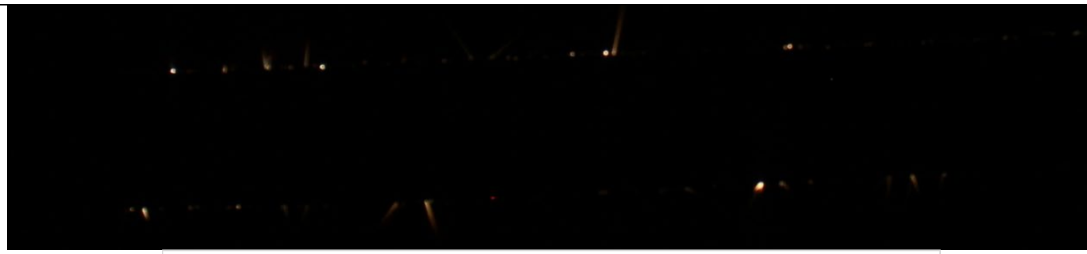
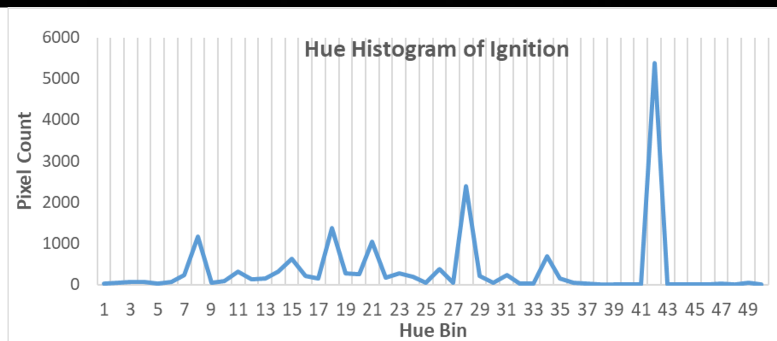
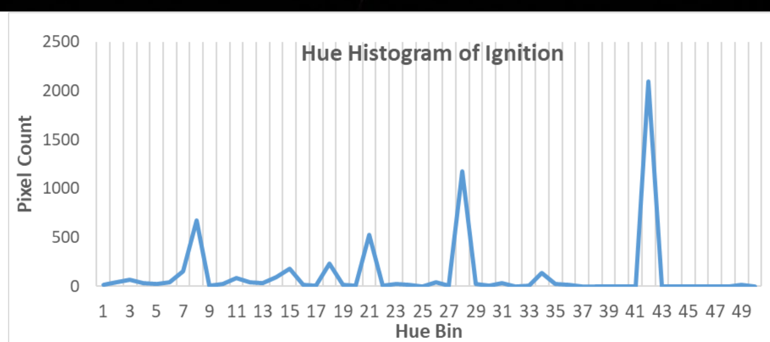
Comparisons of test images between multiple materials and coupon configurations showed that the factors affecting the appearance of edge glow (including quantity, size, hue, brightness of edge glow spots at ignition threshold) varied depending on the makeup of the CFRP material. Appearance of edge glow spots seems to be influenced by the angle that the top and bottom surface plies are oriented and cut at the edge, as well as the internal plies are oriented relative to the conducted current flow and their orientation at the cut edge of the coupon. The roughness of the edge finish of the surface at the cut fiber edge also has an effect.

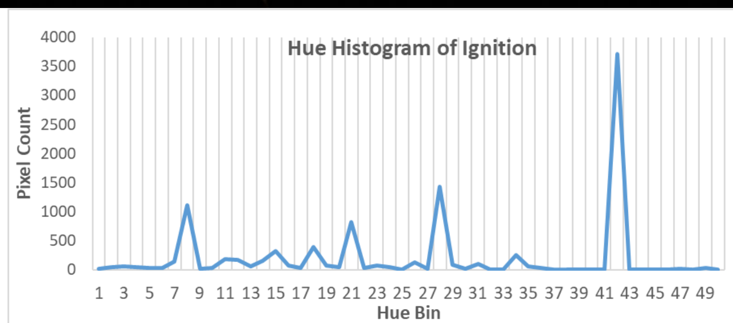
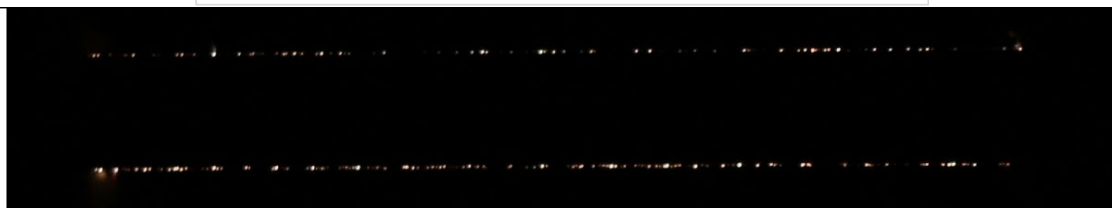
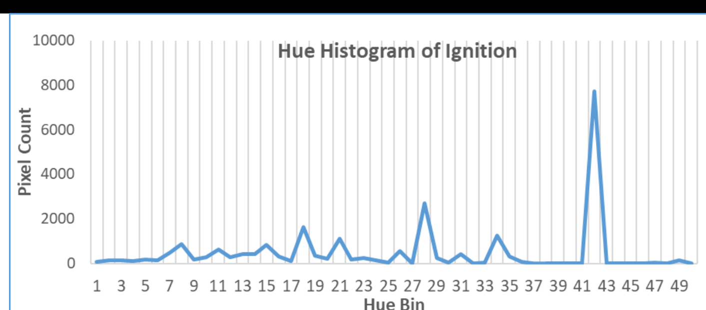
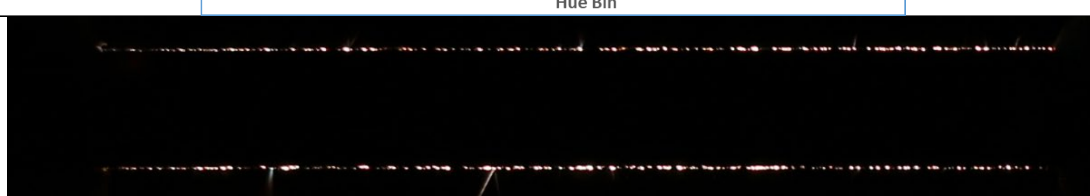
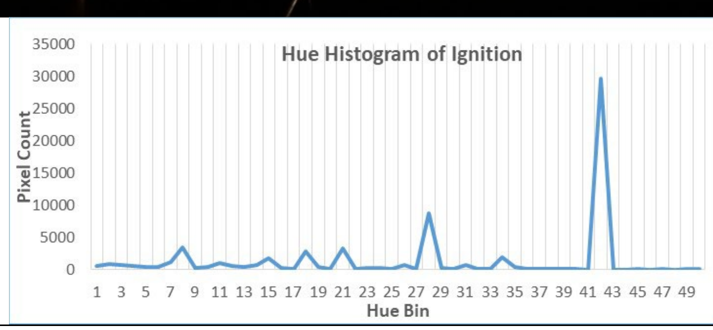
Examples of the differing appearance of edge glow on multiple test materials are displayed in Table 58. Overall, the incandescent signatures for all of the samples in below show a continuous spectrum in the 0-20 hue range, but overall pixel counts and appearance of the continuous spectrum in hue bins from 20-42 differ from sample to sample.

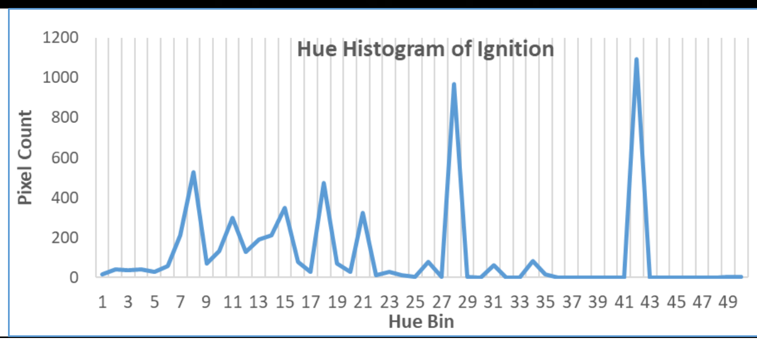
Table 58. Incandescent photo samples (all ignited the flammable mixture) demonstrating incandescent edge glow with differences in appearance.

Test Article Description	Test Photo and Hue Histogram
Preliminary Studies Front View CFRP Strip 1 (1 ply plain weave, 8 plies unitape)	 

Test Article Description	Test Photo and Hue Histogram
Preliminary Studies Back View CFRP Strip 1 (1 ply plain weave, 7 plies unitape)	 
Round Robin Front View Strip 4 (1 ply plain weave, 7 plies unitape)	 

Test Article Description	Test Photo and Hue Histogram
Round Robin Back View Strip 4 (1 ply plain weave, 7 plies unitape)	 
Round Robin Front View Strip 5 (1 ply plain weave, 7 plies unitape)	 

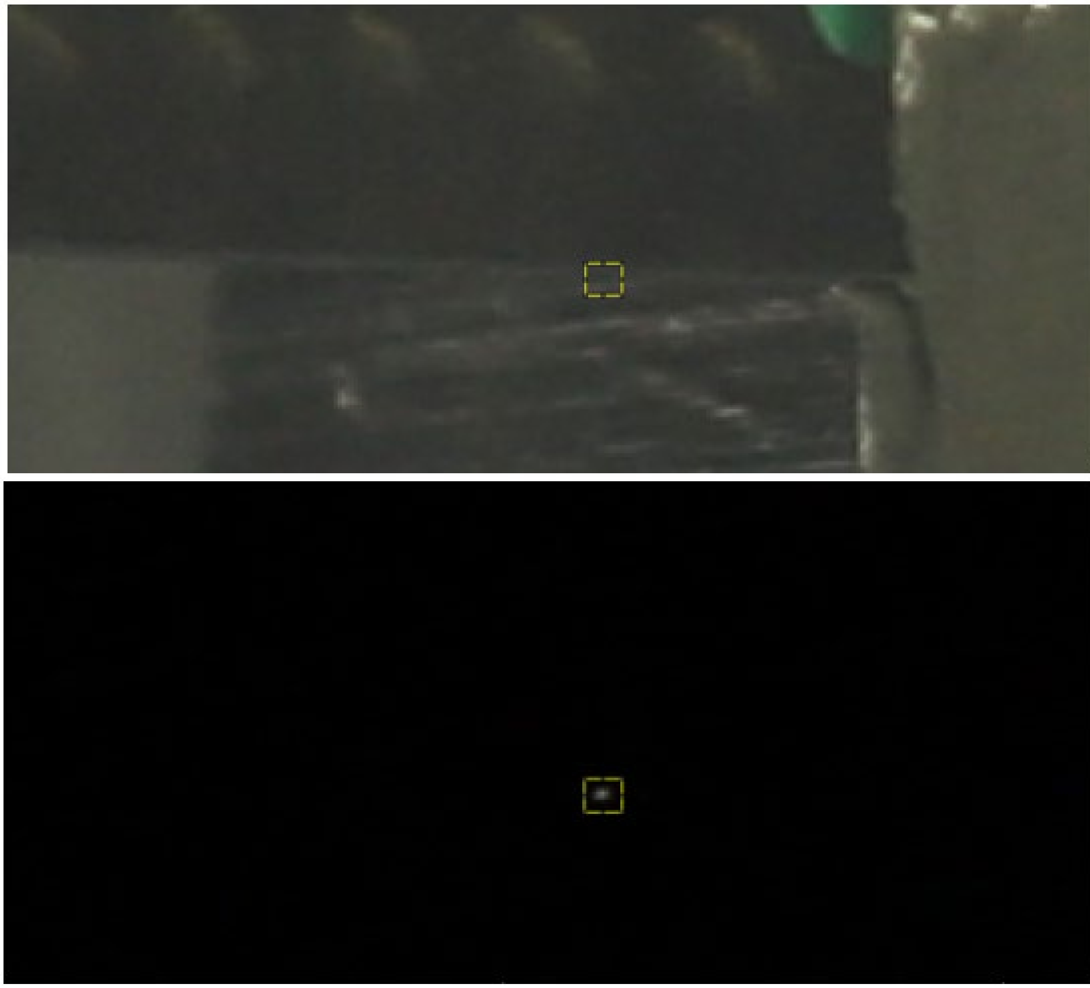
Test Article Description	Test Photo and Hue Histogram
Round Robin Back View Strip 5 (1 ply plain weave, 7 plies unitape)	 
Further Studies Front View CFRP Strip (1 ply plain weave, 7 plies unitape, cut at 45	 
Further Studies Front View CFRP Strip (1 ply plain weave, 7 plies unitape, cut at 45	 

Test Article Description	Test Photo and Hue Histogram
Further Studies Front View CFRP Strip (1 ply plain weave, 7 plies unitape, cut at 0 degree orientation)	 

5.4.5 Issues with test data:

5.4.5.1 *Ignitions due to contact sparking or undetected ignition source*

Some test shots were noted with no visible edge glow spots occurring in the image, but an ignition of the flammable gas mixture did occur. All but one of these test photos show no visible light in any region of the photo, which could be detected by the brightness based photographic method or the incandescent method. All of these tests occurred on the same test article during subsequent current application tests. In one case, an ignition was not detected by the incandescent method, but was detected by the brightness based photographic method, shown in Figure 38.



(a)

(b)

Figure 38. Test that ignited the flammable mixture, not detected by incandescent method, though detected by the brightness based method. (a) Illuminated test setup for location reference on CFRP coupon edge and (b) single light source occurring in the image.

The light detected was a spark of 4x3 pixels occurring at the edge of the test article. This spot could be responsible for the ignition of the flammable mixture, but since this particular case occurred on the same test sample as the ignitions with no detected visible light. This case may be a true ignition source on the test article, or a contact spark within the test chamber that caused a false failure. If it is a true ignition source, this case calls the effectiveness of the incandescent method into question.

One explanation for these undetected ignitions is contact sparking at the clamp area from generator to the CFRP coupon. The clamp area was shielded from view from the cameras, which would make any sparking at this location difficult to detect by the camera.

The second possible cause of these dark ignition photos is that an incandescent ignition source was present, but was too small to be sufficiently resolved by the camera. The possibility that very small light sources undetected by the camera could act as ignition sources is a concern for the effectiveness of not only the incandescent method, but the photographic method as well, since the same cameras are used producing the same variety of test image.

The example of contact sparking displayed in Figure 39 is from preliminary testing and is only intended for visualization of contact sparking. This case clearly demonstrates that the source of the sparking is due to poor clamp contact and not due to incandescence of the test article. The test cases of concern for the further studies testing did not show any visible light or sparking from any region in the photo, which makes the question of identifying if and where the ignition source occurred more challenging.


(a)
(b)

Figure 39. (a) Sample test image of contact sparking at the clamp area and (b) corresponding illuminated test setup for location reference.

5.4.5.2 *Ignition source size and camera resolution*

Images from the further studies testing were evaluated to determine which cases had few visible edge glow spots, or spots that were difficult to detect with the incandescent method. The ignition case identified with the smallest, fewest, and dimmest edge glow spots (excluding the case in Figure 38) is displayed in Figure 40. The hue signature of this image did not display a continuous hue range consistent with the other ignition cases for this test article with this camera. The largest illuminated spot in the image is 4x7 pixels. Other spots in this image measure as small as 3x3 pixels, indicating that light was only detected on one pixel, and was then expanded into a 3x3 area when the Bayer pattern interpolation was done by the camera's JPEG conversion (see section 2.1 . Because it is not possible to determine which spot(s) caused ignition, it should be assumed that any of these very small edge glow spots could have been the cause. This is a concern, because light sources falling within a 1-pixel area are at risk of being undetected by the camera entirely. The possibility that smaller light sources than these could be ignition sources is a concern for the effectiveness of not only the incandescent method, but the photographic method as well.

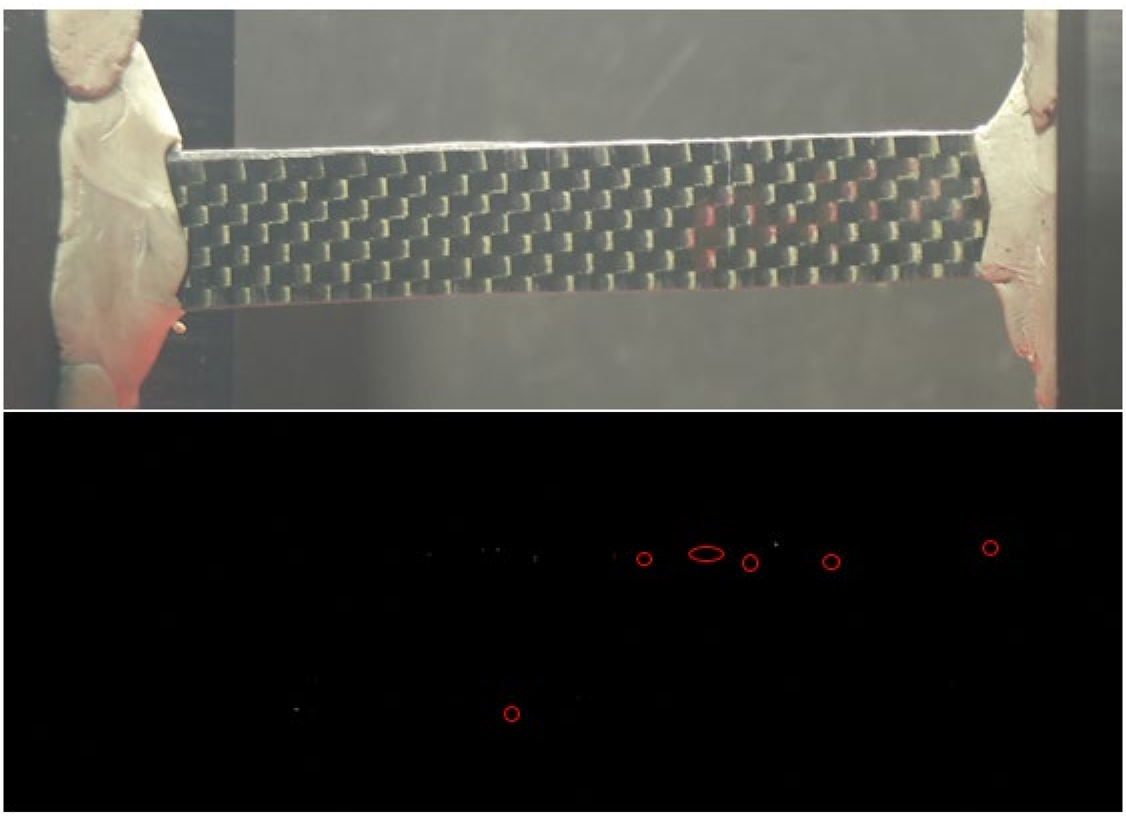


Figure 40. Sample photo of smallest detected incandescent edge glow sources resulting in ignition, outlined in red for visualization.

5.4.5.3 *Small datasets*

Other concerns from the further studies phase of testing stem from the small datasets collected. Initial planned dataset sizes were limited due to materials and time availability for additional testing. The sample set sizes further decreased after multiple test points resulted in invalid tests with the flammable mixture. The invalid tests resulted from post-test ignition verifications failing to prove that the test mixture was ignitable unsuccessful for multiple test cases (7 out of 48 non-ignition cases).

The invalid test cases occurred first with a gas mixture of 6.25% Hydrogen and air, which had been verified successfully with 9/10 ignition verifications prior to testing. During testing, after two unsuccessful post-test ignitions with the 6.25% Hydrogen mixture, the gas mixture was increased and verified 9/10 times at a higher hydrogen concentration of 6.75%. With the 6.75% hydrogen mixture, the gas failed to ignite post-test with the 200 μJ voltage spark, resulting in two additional invalid test cases.

Since the further studies tests were primarily intended to be relative comparisons between camera factors, the sample set sizes were not intended to be large enough to train and test the data to determine incandescent signatures for each of the four cameras. The relative comparisons for test were achieved by photo-to-photo comparison. Hue signature, brightness, sharpness and other image qualities were compared to evaluate the various camera factors in corresponding ignition photos from each camera. These individual photo histogram comparisons allow for a more in-depth visualization of a case-by-case difference in appearance of ignition sources. For the purpose of this study, this is acceptable.

5.5 Results

5.5.1 Camera resolution

In the case of the comparison of the Canon T6i and the Canon 6D, the resolution made little to no difference on the size of the edge glow spots, while the brightness was not significantly affected.

5.5.2 Camera lens type

Comparison of a variable zoom lens versus a prime lens showed a minor difference in sharpness at edge of the images at the distances typically used for photographic method testing (distances of 1 meter or less). This difference in sharpness did not affect the appearance of the continuous incandescent hue range for this testing. The more important factor that determines sharpness than lens construction type is using lenses of the correct focal length at appropriate distances from the test article to ensure that the lens allows for sharp focusing on the test article. In other words, do not use a long focal length lens too close to the test article, or vice versa.

5.5.3 Camera distance

Camera distance results in a linear change in effective resolution of the test article and potential ignition source. Because of this, the recommendation is to minimize the distance from camera to test article to maximize the resolution in pixels per inch of the region of interest on the potential ignition source. Due to limited camera equipment, brightness and color effects of distance were not evaluated. This would have required duplicate cameras of the same model viewing the same lightning test case simultaneously, which was not feasible.

5.5.4 Best material to determine incandescent camera signature

Multiple materials were investigated throughout the course of this work though the preliminary studies, round robin, and further studies tests. Each of the CFRP coupon configurations produced somewhat differing appearance based on quantity, size, hue, and brightness of edge glow spots prior to and at ignition level of edge glow from one layup configuration to the next. Because of the variable nature of edge glow production between samples, it is recommended to repeat the "incandescent signature verification" for each composite material being tested using a sample of the test material (layup, fiber orientation at cut edge, edge finish qualities, and sealant) that the test article is made of.

5.5.5 Issues and limitations of method

Because of the concern regarding minimum camera resolution, in addition to the cases of ignition with no visible light in the test photos, more study is required to determine smallest possible incandescent ignition source. The ignition case without a detectable incandescent signature from Figure 38 also raises concern about the effectiveness of the incandescent method when applied to edge glow, though this case may have been a false failure due to contact sparking.

There is concern regarding the size of incandescent ignition sources relative to the resolution of the camera sensor. The smallest possible edge glow spot may not be large enough or bright enough to be detected by digital cameras depending on how it is positioned on the pixel grid of the camera sensor. This cannot be permitted, and may be an issue affecting both the incandescent method and the brightness-based photographic detection method.

When multiple incandescent edge glow spots occur in an image, the photo-based test method cannot determine which specific spots are responsible for causing ignition. The incandescent signature takes into account all light sources within the image as part of the hue signature. In the case of multiple edge glow locations, it can be difficult or impossible to pinpoint which specific region is causing ignition, which may be of value if test article redesign is needed.

Based on the comparisons of edge glow appearance and incandescent signature for multiple evaluated test materials, it is recommended to repeat the "incandescent signature verification" procedure for each unique test material. This is detrimental due to the time associated with this procedure before testing can begin. This verification procedure also requires sample composite material that matches the test article.

6. Future work and recommendations

This method shows promise for reliable and repeatable incandescent ignition source detection on simple CFRP coupons, however more study is recommended before this method be implemented for the purpose of ignition source detection for aircraft certification. A draft of the recommended test procedure for the incandescent ignition-source detection method is available in Appendix B of this document.

For more complex test articles, the method requires extensive additional evaluation to prove that it can be consistently implemented to detect incandescent ignition sources. Further testing on simple CFRP coupon configurations should include at minimum additional materials and layup variations outside of what has been tested to date. The position of the camera relative to the cut edge of the fibers can also be considered, since all testing in this work has used a camera orientation, which does not directly face the cut edge of the test coupons.

Additionally, this method has not been evaluated for use on parts containing metallic structure, fasteners, sealant, lightning strike protection or parts with splices. Any of these factors can introduce uncertainty of the source of light emitted in the photos, which would require the brightness-based photographic method to be used if metallic sparking is considered as a possible source of light emission.

As a result of this work, integration of obtained test data and developed methods into ARP documents within the framework of SAE International will be proposed with the purpose of supplementing or superseding the existing standard.

Other related topics that may warrant future investigation include characterization of ejected incandescent particles from sparking locations, use of IR imaging for detection of thermal sources like incandescent edge glow on composites, and/or hot surface ignition detection on metallic or composite parts, possibly with thermal imaging.

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A. Appendix A: Round Robin Test Procedure

Test and Image Analysis Procedure for Characterization and Detection of Incandescent Ignition Sources

Table of Contents

Executive Summary

At the request of FAA and industry, a research program was conducted by NIAR to investigate the ability of edge glow light emitted by CFRP to act as an ignition source. As a result, a new detection method has been proposed to supplement existing test guidelines. This method involves analyzing the images from the current camera procedure in order to characterize emitted light based on the hue signature produced by the camera.

Current test standards define any detected light above a determined threshold as an ignition source. The NIAR investigation determined that edge glow spots can far exceed the brightness threshold without causing ignition in the flammable gas test defined in ARP 5416A. The study showed that ignition can be predicted by analyzing the hue histogram of the detected light emission source. Thus, based on the research findings to date, a hue signature has been observed to be coincident with ignition of standardized gas mixture for several investigated materials. This hue signature is defined as the incandescent heat signature, consisting of a range of continuous red-orange-yellow hue, colors typically associated with thermal radiation.

With the purpose of augmenting the existing SAE ARP 5416A *Aircraft Lightning Test Methods* standard section 7.7 *Methods for Detection of Ignition Sources*, the launch of a round robin test has been proposed with the purpose of validating this approach for predicting the ignition conditions of the standardized flammable gas mixture imposed by an incandescent heat source.

The validity of the proposed approach is to be validated by several laboratories including NIAR/WSU, Boeing, DNB, and NTS (LTI) in the United States, and Cobham, LCOE, and DGA laboratories in Europe. This document outlines summary of the research findings and a test procedure for the round robin investigation written in accordance with the SAE ARP 5416A format. NIAR is to supply all the required materials for testing including tinned copper (Sn-Cu) wires, carbon fibers, carbon fiber reinforced polymer (CFRP) laminate.

Introduction

A 200 µJ energy value serves as a commonly accepted minimum ignition threshold for Jet A fuel. It is a standard for calibration of gas for the flammable gas detection method. Photographic ignition detection has also been utilized as an accepted alternative method of sensing the ignition threshold to provide economical means for testing, based on the brightness of the light emitted by the 200 uJ spark. Unfortunately, the photographic method applied to CFRP test articles provides too many false failures. This is because not all light emitted by carbon fiber composites is capable of acting as an ignition source, as in the case of carbon fiber edge glow. The goal of this work is to augment the existing photographic method with additional image analysis to limit the number of false failures occurring due to carbon fiber edge glow. This method distinguishes between light emissions that present a threat of ignition, and those that do not.

This work will retain the photographic method and the 200 µJ source from SAE ARP 5416A and supplement it with additional color-based evaluation of the image to determine ignition thresholds. Image analysis is carried out in ImageJ [1], an open source image processing software. Hue-based image analysis determines if significant thermal ignition sources are present in the image by characterizing the color signature of emitted light.

The color characterization is based on the "hue" channel of the image, after the red, green, blue (RGB) image is converted to the hue, saturation, brightness (HSB) color model. Each camera must be calibrated to determine its incandescent hue signature of ignition. The incandescent signature is defined as a continuous range of pixels in the red-orange-yellow hue range, approximately corresponding to hue values 0-42 (bins) based on the 0-255 total bins for an 8-bit image in the HSB color space.

The hue value 0 indicates red hue, transitioning to orange as hue value increases, with yellow at hue value 42. The incandescent signature will not necessarily span the entire 0-42 range, so the continuous hue range must be defined during the incandescent signature calibration of the camera. The upper bound of this continuous range indicates whether or not ignition conditions exist because it represents the highest temperature area of the test article. This upper bound is defined as the critical yellow hue. Ignition is marked by the occurrence of both components of the incandescent signature, the continuous spectrum, and the critical yellow hue.

A typical example of the incandescent signature hue histogram is shown in Figure 1. The incandescent signature and the corresponding image analysis technique can be considered the primary finding of this research, because it consistently predicts ignition conditions in the standard ignitable gas mixture for edge glow of carbon fiber composites while maintaining use of the existing digital photography sensor.

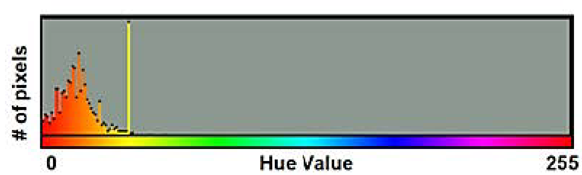


Figure 1: Sample incandescent hue signature displaying continuous spectrum in red-orange region and upper bound (peak) at yellow hue value 42.

Background - Preliminary study

During the course of this research, nine different systems of materials were investigated to further define the incandescent signature and confirm its occurrence regardless of test material. Investigated materials include tinned copper, nichrome, nitinol, steel, and aluminum wires, as well as bundles of carbon fiber, bundles of pre-cut carbon fibers, CFRP laminate, and CFRP-Lightning Strike Protection (LSP) laminate. The rationale for materials selection was driven by utilizing a method allowing high repeatability of experimental results, for which metal wires provided a suitable choice. With the purpose of addressing aircraft structural materials, CFRP laminates were investigated. The CFRP-LSP combination was utilized to examine effects of incandescence occurring at the interwoven metal wire-resin interface. Finally, partial pre-cutting the carbon fiber bundles allowed investigating influence of air-material dissociation/ionization on gas ignition.

Only several materials out of all investigated systems were selected for the proposed round robin experimentation, the test matrix of which is summarized in Table 1. All materials for the Round Robin industry validation testing will be provided by NIAR.

During the preliminary investigation, all investigated materials were subjected to resistive heating induced by the conducted lightning current Component A with the purpose of inducing incandescence at temperatures of visible light emission. Current magnitudes for these tests ranged from ~100 A to 9.1 kA for all investigated materials. Approach to experimentation followed the standardized procedure outlined in SAE ARP 5416A sections 7.7.1 and 7.7.2 [2]. Experiments were carried out in both air and an ignitable mixture of dry air and approximately six volume percent hydrogen.

During Joule heating of these systems, light emissions were observed caused by the following:

(1) thermal radiation of wires and fibers,
(2) air-material dissociation/ionization glow at the tips of carbon fibers,
(3) formation of vapor clouds around wires, fibers, and at the CFRP edge, and
(4) resin outgassing accompanied by ejected matter in CFRP material.

As a result of this work, CFRP ejections causing ignition were observed. Since the appearance of ejections always resulted in ignition, the thermal energy of these characteristic ejections can be viewed equivalent to or greater than the 200 μJ energy in terms of ability to ignite the flammable gas mixture. Additionally, due to complexity of characterization of ejections and to their strong propensity towards causing ignition, presence of ejected matter was jointly decided to characterize as a design failure.

The following summarizes the observed effects produced by investigated materials in relation to incendivity of the gas mixture:

(1) Ejections *ignite* gas,

(2) Edge glow without incandescent signature observable in CFRP and carbon fibers *does not* ignite gas,
(3) metal wires and carbon fiber with continuous spectrum but without yellow hue *do not* ignite gas,
(4) metal wires and carbon fibers with continuous spectrum and with yellow hue *ignite* gas.

Interpretation of Hue Data from Digital Images

This research has demonstrated that, based on 0-255 total bin count for an 8-bit image in the HSB color model, occurrence of gas ignition coincided with appearance of the critical yellow hue value along with a continuous distribution of pixels falling in the 0-42 (red-orange-yellow) hue range. However, in certain circumstances, erroneous hue values can occur in test photos, affecting the incandescent signature. This can include hue introduced by light leaks or reflections in the test chamber. The movement of the light source can affect the resulting hue values, since light was not able to integrate in the same pixel location for the full duration of the test.

Keeping the test article stationary in the test chamber during testing is essential for proper light integration. For example, if the wire expands when heated, causing it to bend or shift location within the chamber, the light will not have integrated at the same particular pixel area on the camera sensor. All efforts should be taken to keep the specimen from moving or shifting during the test, including limiting wire length, reducing slack in the wire, and ensuring that each test article is securely mounted in the test chamber.

The accuracy of the histogram data can be affected by noise pixels in the dark background area of test photos. In dark box photos, these slight variations in hue are artifacts of the way the camera senses and reproduces color. Brightness and saturation of the pixels in the dark background area are very low, so the corresponding hue data of the background region is not as meaningful as the hue data in regions illuminated directly by the ignition source. These very dark regions can skew the hue histogram, so they should be excluded from analysis if possible. One method to exclude background noise pixels from analysis is cropping around the ignition source to remove most of the background area. Another method to remove noisy background pixels from analysis is to threshold the image based on brightness so that the hue data from the darkest pixels is not included in histograms.

It is a requirement that the camera settings remain the same for all images that will be directly compared or evaluated with this method. This includes keeping the light integration time the same for all images. The shutter time must be long enough to capture the entire light emission event. The light emission events themselves must be the same or similar in time duration. Consider two wires, each emitting the same amount of light at any instant in time. The first wire, glowing for 10 microseconds, does not have the ability to integrate light on the camera sensor that the second wire, glowing for 1 second, does.

Light emitted during combustion of flammable gas can introduce color to the test photos. It is important that all testing be conducted in hydrogen, or a similar gas that burns without producing visible flames. Any hue data added by the combustion of fuel gases will skew hue histogram results. An effort must be made to keep the test chamber free of dust, which can introduce hue into the test photographs if ignition occurs and dust particles are ignited.

Test Equipment

Sensor

In this document, the term 'camera' includes light sensors, lenses, image data recording, and associated controls and settings. The camera must allow manual control of the settings to ensure that sensitivity remains the same for all test photos. The resulting output value is the observed hue signature obtained in the test image.

The camera, lens, and camera settings should be treated as a set of calibrated equipment which should be calibrated every 12 months in accordance with SAE AE-2 Lightning Committee White Paper: Recommended Camera Calibration and Image Evaluation Methods for Detection of Ignition Sources [3]. This calibration process will ensure that the peak pixel value of detected light will fall approximately in the middle of the camera's dynamic range, keeping the ignition sources from oversaturating the sensor. Incandescent signature verification process should also be completed at this time, or at least every 12 months. Incandescent signature verification must be repeated whenever the distance from camera to test object changes.

Flammable Gas

The recommended ignitable mixture is hydrogen in dry air at the suggested starting concentration of six volume percent of hydrogen. Calibration of the flammable gas mixture utilizing the standard 200 uJ voltage spark source according to ARP 5416A will be performed prior to testing. Potential adjustments to the hydrogen concentration may be necessary in order to achieve at least nine out of ten ignitions prior to testing.

Hydrogen is recommended as the test gas because it burns with a nearly invisible flame, which will not affect hue histograms of test images when gas ignition occurs. Other flammable mixtures may be utilized if it is not possible to test in a hydrogen and air mixture, but will require all tests to be repeated twice, once using the flammable gas method and once using the incandescent photographic method. This is not ideal due to the increase in time required for testing, and because it assumes that the two test instances are identical, which may not be the case.

Light Source for Incandescent Signature Verification

Incandescent signature verification is necessary for each camera due to the variations in both hardware and software available in digital cameras, and because digital photography utilizes the device dependent RGB color space. Color output varies between devices, meaning the incandescent hue signature defined for one camera will not be applicable to other cameras.

A consistent and repeatable incandescent light source emits a representative incandescent light signature. The purpose is to photograph the light signature produced by an incandescent source of a fixed geometry and temperature in order to characterize the incandescent hue signature produced by the camera. The same incandescent source will be utilized by all participants in the round robin test.

A resistively heated copper wire is used to generate a representative incandescent light emission for characterizing the incandescent signature produced by the camera. The wire, provided by NIAR to ensure consistency across all labs, is installed in a test fixture designed to control the geometry of the wire installation. A suggested test fixture design is shown in Figure 2. The test fixture serves the purpose of keeping the wire and other test materials in place at a fixed length and position to avoid wire movement during the test. The fixture must sufficiently prevent sparking at the contact area from escaping into the flammable mixture, causing a false ignition. Care should be taken to avoid damaging or creating bends in the wire. Damage will reduce the cross sectional area, leading to possible failure of the wire due to higher current densities at this location.

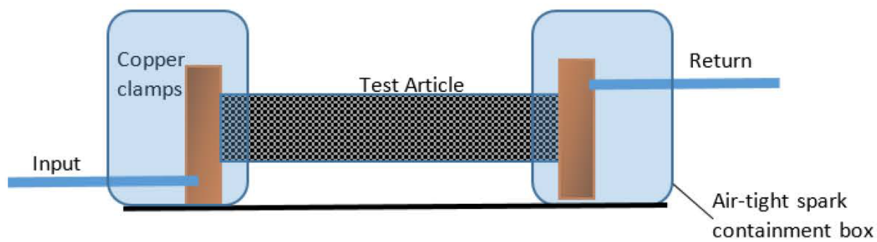


Figure 2: **Suggested Test Fixture and Test Article Installation Drawing**

Test Waveforms

Incandescent signature verification will be performed using Waveform 5A as defined in ARP 5412B [4]. Suggested test levels, listed in Table 1, are defined by the action integral, peak current, rise time, and time to 50% decay. All test levels are based on Waveform 5A being conducted through the test articles.

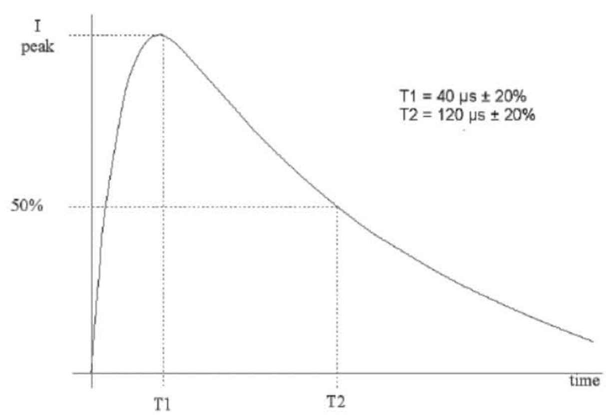


Figure 3: Exponential Current Waveform 5A

The sample test setup shown in Figure 4 was used for preliminary testing at NIAR. Any circuit that produces the desired waveform parameters is acceptable for use. The primary goal is light emission from the test article. Some variability in the waveform is acceptable, but Waveform 5A is recommended to allow direct comparison of results between labs.

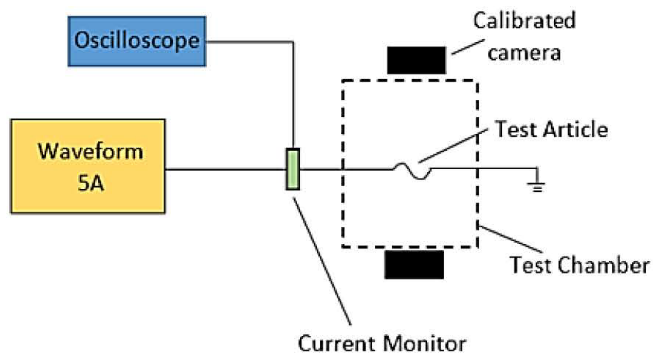


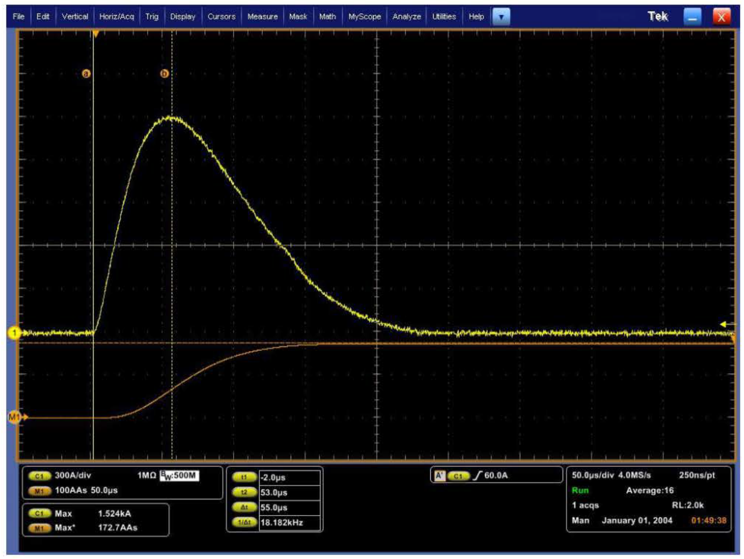
Figure 4: Sample Test Setup and Circuit Diagram

Recommended test levels and waveform parameters are listed in Table 1. These test levels are based on the levels used during preliminary testing which successfully produced a faint glow from each test material. To increase or decrease the intensity of light emission throughout the test, the test levels will have to be adjusted. Suggested increments to adjust the test level are also provided in Table 1. Additional information about the test materials is provided in the "Test Material Specifications" section on page 23.

Table 1 – Example Experimental Matrix

<table>
<tr><th colspan="2">Suggested Test Level Range</th></tr>
<tr><th colspan="2">Copper wire:</th></tr>
<tr><td>Length of exposed wire between electrodes: 2" ± 0.25" (pulled tight)

Peak current: 1.524 A,
Time to peak current: 55 µs,
Time to 50% decay: 119 µs,
Action integral: 172.7 AAs.

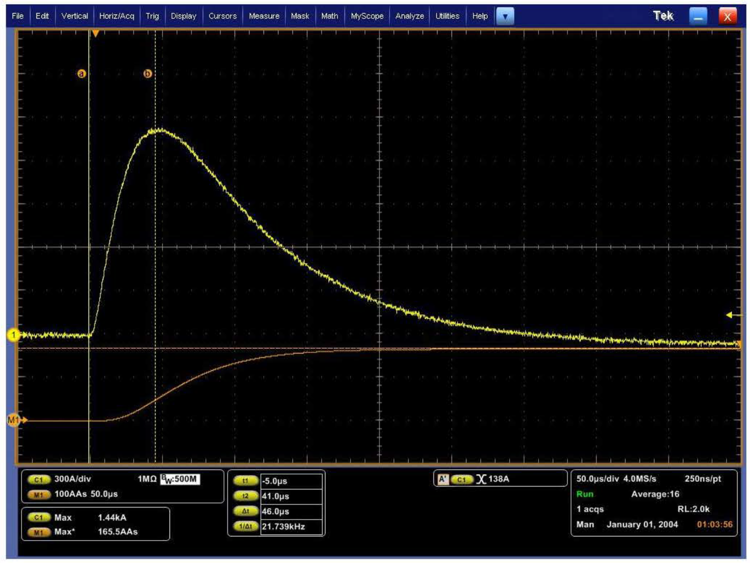
Increase peak current by ~75A until yellow glow/ignition level is reached.</td><td>
</td></tr>
<tr><th colspan="2">Carbon fibers:</th></tr>
<tr><td>Tightly twisted bundle of multiple fibers

~ 0.01" ± 0.0025" diameter

Length of exposed fiber bundle between electrodes: 2" ± 0.25" (pulled tight)

Peak current: 276 A,
Time to peak current: 43 µs,
Time to 50% decay: 115 µs,
Action integral: 6.17 AAs.

Increase peak current by ~10 A until yellow glow/ignition level is reached.</td><td>
</td></tr>
</table>

CFRP laminate strip	
Peak current: 1.44 kA, Time to peak current: 46 µs, Time to 50% decay: 117 µs, Action integral: 167 AAs. Increase peak current by ~200 A until yellow glow/ignition level is reached.	

Procedure

The following steps describe the procedure for incandescent signature verification:

Setup

1. Set up the generator, test equipment, and test fixture as depicted in Figure 4. The setup for preliminary testing at NIAR is pictures in Figure 5 and Figure 6.
    a. The test sample and the ignitable gas mixture shall be contained in an enclosure that:
        i. prevents external light sources or reflective surfaces from appearing in the recorded camera image. Any external light leaks will affect the hue data.
            1. The use of a witness light/reference light to verify that the camera shutter opened during the test (as described in ARP5416A) is not advisable since it will introduce hue values into the image that are unrelated to the test article. If it is necessary to use a reference light, it should be excluded from the image analysis if possible (by cropping or by other means).
        ii. is sealed to prevent flammable gas leakage with a safety blow out panel. [2]
        iii. Sufficiently isolates the contact/clamp area of the test article from the flammable mixture to prevent contact sparking from causing a false ignition.

Figure 5: Overall Test Setup

Figure 6: Test Fixture with Composite Strip in Copper Clamps

2. Perform calibration of ignitable mixture to achieve at least 9 out of 10 ignitions with a 200 uJ voltage spark source as described in ARP 5416A.
3. Set up the camera(s). Ensure the test object is in focus and within the field of view.
   a. If the camera is located outside of the test volume, the enclosure will contain a transparent window with minimal attenuation over the 400-800 nm range of visible light in order to seal the gas chamber while allowing test photos to be collected.
   b. Record the camera specifications, including: manufacturer, model number, lens model, and lens manufacturer. Record all camera settings including: F-Stop, ISO, shutter speed, white balance, noise reduction, exposure bias, distance from the camera to the to the test object, and any other applicable settings. Acquire images in a high quality JPEG image format at the cameras sensor native resolution.
   c. Ensure that the potential ignition source on the object under test takes up a significant number of pixels on the sensor in order to produce adequate data for analysis. The minimum image resolution is at least 30 pixels per centimeter of length of the test article.

Incandescent Signature Verification

Determine test level – No flammable gas

4. Install wire in the photo chamber and connect to the generator. Use Table 1 as a guide for suggested starting test amplitudes.
   a. Electrically insulate test article to electrode attachment points to prevent contact sparking from escaping into the test chamber by sealing/covering the area with high voltage putty, corona dope or similar.
   b. **NOTE:** The wire sample must be replaced between test shots. Further study of wire degradation is desired.
5. Take a pre-test open-box picture to establish the location of the test article.

6. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings as used during calibration. Use these camera settings for the duration of testing.
7. Apply Waveform 5A at the suggested test level in Table 1 to create a visible glow of the wire. Open the camera shutters to capture all light emitted during the test.
8. If the wire does not glow in step 7, repeat the application of Waveform 5A, adjusting the current level accordingly until the wire glows, using the levels in Table 1 as guidance. Ensure that the camera shutter is open for duration of each test.
    a. Continue to repeat this step until a test level is established that provides a visible orange/yellow glow without causing explosion of the wire.

Determine Test Level in Flammable Mixture

9. Install new wire into the photo chamber and connect to the generator. Use the test level determined in step 8 as the starting test amplitude.
    a. Electrically insulate test article to electrode attachment points to prevent contact sparking from escaping into the ignitable mixture by sealing/covering the area with high voltage putty, corona dope or similar.
    b. **NOTE:** The wire sample must be replaced between test shots while the test level for gas ignition is being determined. Further study of wire degradation is desired.
10. Take a pre-test open-box picture to establish the location of the test article.
11. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings used during calibration.
12. Begin testing in gas in accordance with ARP 5416A. See "flammable gas" section above.
13. Starting at the test level determined in Step 8, apply Waveform 5A to create a visible glow of the wire. Open the camera shutters to capture all light emitted during the test. The goal of this step is to determine the lowest test level that will cause repeatable ignition of the flammable mixture.
    a. If the flammable gas ignites, repeat the test at a lower test level, decreasing by increments suggested in Table 1, repeating until the threshold of ignition/no ignition is discovered. When the ignition threshold test level is discovered, repeat the test once more at this level to verify that ignition is repeatable. Save all test photos at every test level, record waveform parameters and whether or not ignition occurred.
    b. If the flammable gas does not ignite, repeat the test, increasing the test level by increments suggested in Table 1 until the threshold of ignition/no ignition is discovered. When the ignition threshold test level is discovered, repeat the test once more at this level to verify that ignition is repeatable. Save the test photos from each test level, record waveform parameters and whether or not ignition occurred.
14. Repeat Step 13 until the minimum current level is established that provides a visible orange/yellow glow of the wire, ignites the flammable gas, and is repeatable at least two consecutive times.
15. In **air**, repeat the application of Waveform 5A at the current level determined in Step 14 eight more times, collecting test photos each time. (This step is done in air to reduce testing time.)
    a. The 10 photos obtained during Steps 14 and 15 at this test level serve as the "ignition photos" from which the camera specific incandescent signature is obtained.

16. Take a post-test open-box picture of the illuminated test article to observe any damage and to establish the location of the wire in the box.

Obtain Incandescent Signature

17. Analyze photos collected in Step 13-15 according to the "Image Analysis" procedure below. The hue signature obtained in this step through image analysis defines the "camera-specific incandescent signature" that represents ignition.
    a. Note should be taken of pixels falling in the hue range 0-42 (continuous spectrum), with emphasis on the hue value at the upper bound of this range (critical yellow).
        i. Due to variations between digital cameras, the continuous spectrum may not span this entire range, or the range may not fall between 0-42. Instead, make note of any span of hue bins containing a nonzero pixel counts within the red/orange/yellow range. Record the upper and lower bound of this range. The continuous range must be present in <u>all</u> ignition photos. This continuous hue range is now defined for this camera.
        ii. The critical yellow hue of ignition might not fall exactly at hue 42. Instead, look for the highest hue value at the upper bound of the continuous spectrum that is present in <u>all</u> ignition photos. This value is defined as the critical yellow hue. This value must appear in every photo of ignition. The critical yellow hue value is now defined for this camera.
        iii. Observe and record any other characteristics of the hue signature that indicate ignition or no ignition. Hue values outside the red/yellow/orange range do not represent incandescent sources, so do not need to be considered.

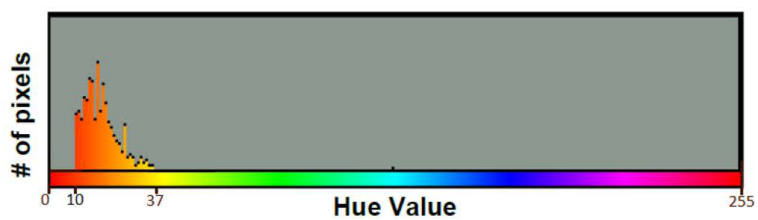


Figure 7: Example histogram of ignition, with the continuous spectrum spanning 27 bins, bounded by hue value 10 and 37.

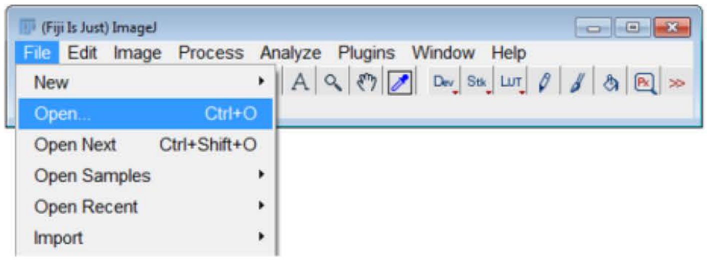
    b. Compare the hue signatures of the non-ignition photos with the defined incandescent signature (continuous spectrum and critical yellow hue) to determine whether there are distinguishing hue characteristics between ignition and non-ignition photos.
    c. Future test photos containing the defined continuous spectrum range in addition to the presence of the critical yellow hue will be characterized as an ignition.

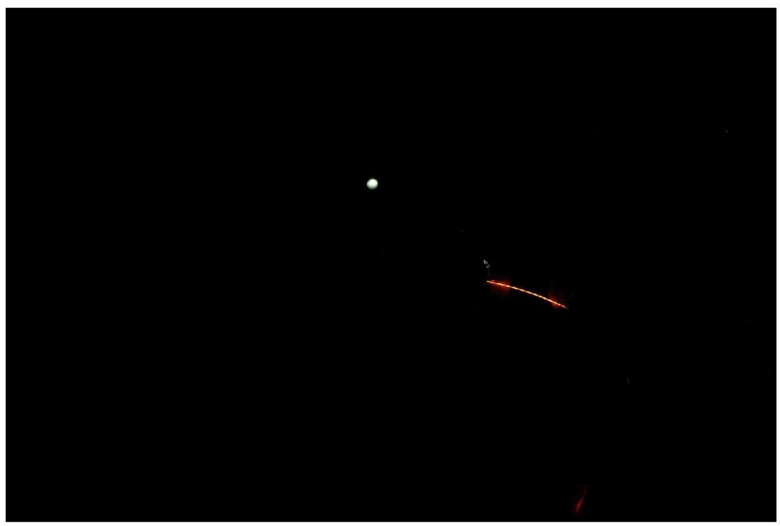
Test Article Testing

18. Begin testing test articles from Table 1.
19. Install the test object in the photo chamber and connect to the generator. Use Table 1 as a guide for suggested starting test amplitudes.
    a. Electrically insulate test article to electrode attachment points to prevent contact sparking from escaping into the ignitable mixture by sealing/covering the area with high voltage putty, corona dope or similar.
    b. **NOTE:** Test samples may be reused for consecutive test shots as the test level is increased. When the test amplitude is high enough to ignite the flammable mixture or cause visible ejected matter or damage to the test sample, the test article must be replaced.
20. Take a pre-test DC resistance measurement across the test article.
21. Take a pre-test open-box picture to establish the location of the test article.
22. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings as used during calibration.
23. Begin testing in gas in accordance with ARP 5416A. See "flammable gas" section on page 7.
24. Begin testing at the suggested starting amplitude in Table 1.
25. Open the camera shutters during the test to capture all light emitted during the test.
26. Repeat steps 22-24, adjusting the test level by increments suggested in Table 1 until the threshold of ignition/no ignition is discovered. Refill flammable gas between each experiment.
    a. Save the test photos from each test level, record waveform parameters and whether or not ignition occurred.
27. Take a post-test open-box picture of the illuminated test article to observe any damage.
28. Take a post-test DC resistance measurement across the test article.
29. Perform "Image Analysis" steps to determine whether the hue signature matches the incandescent signature of ignition.

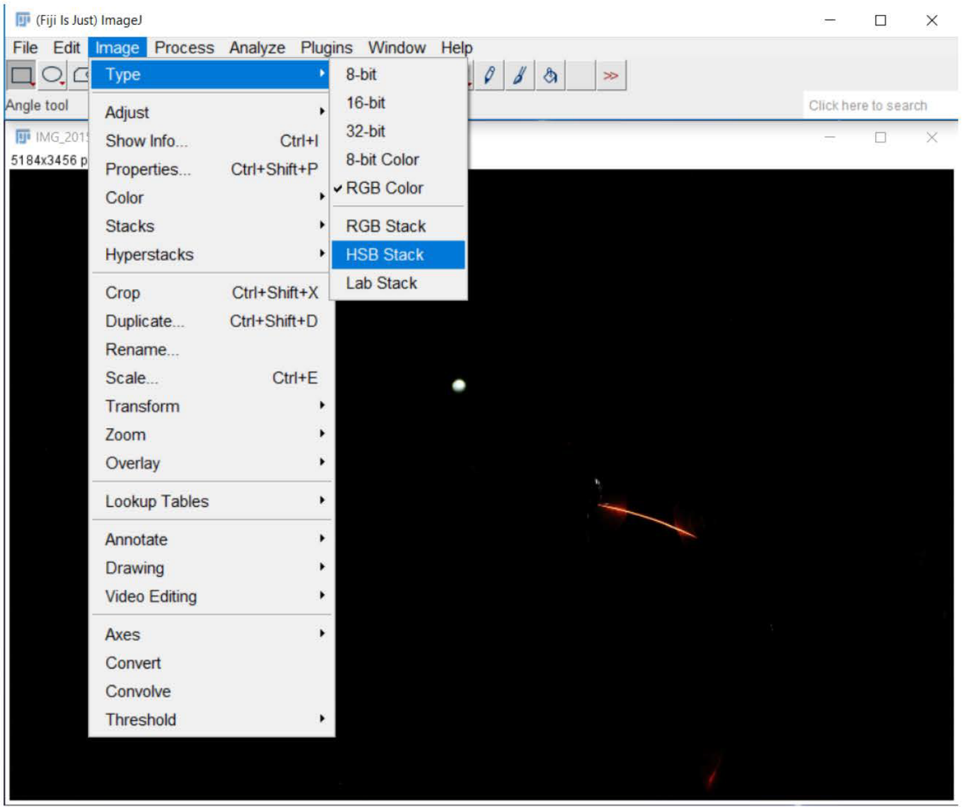
Image Analysis with ImageJ Software:

a. Download ImageJ software at https://imagej.net/Fiji/Downloads. Equivalent image processing software can be used if ImageJ is unavailable.
b. To ensure that original image test data is not overwritten during the image analysis process, perform all image processing on a duplicate copy of the original image file.
c. Open a test photo in ImageJ (drag/drop an image or File > Open.):

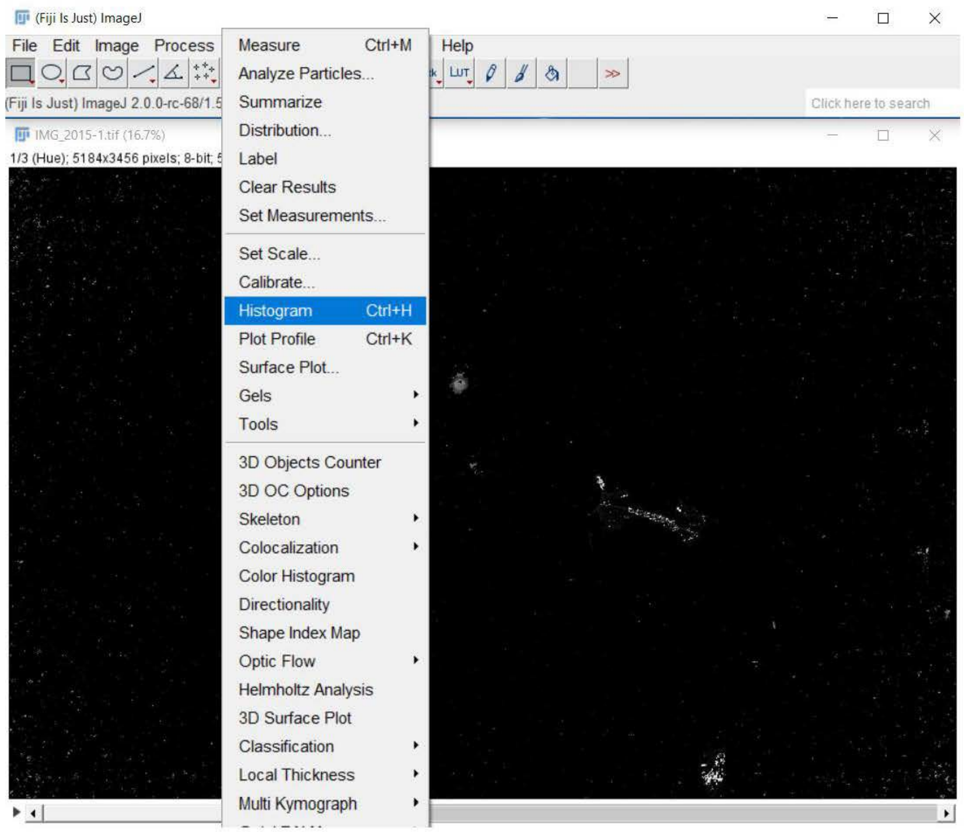




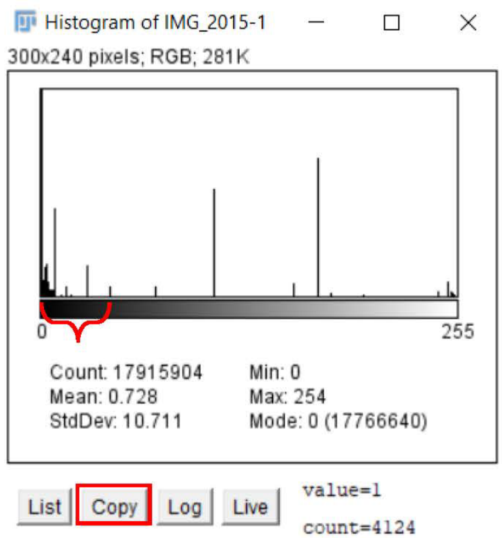
d. Convert the image from RGB Color to HSB stack: Image > Type > HSB Stack:



e. Create histogram of the "hue" channel: Analyze > Histogram:

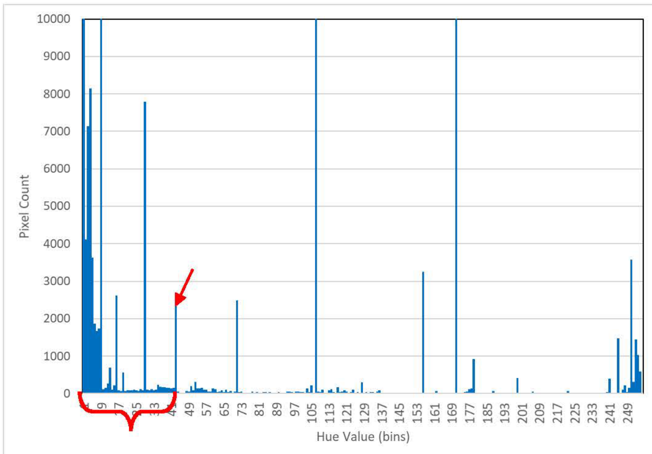


f. Observe the hue signature of the photo. The histogram will display pixel counts when the cursor is hovered over it. To more clearly see the histogram plot it is preferable to plot the values in Excel.



g. Click "Copy" on the histogram. This copies all histogram data to the clipboard. Paste the resulting data in a spreadsheet, making note of which test the image corresponds to, and whether or not ignition occurred.

h. Plot the histogram data as a column graph. Determine if the incandescent signature is present, and if the results of the hue analysis match up with the ignition of the flammable gas. Both components of the incandescent signature, the continuous spectrum and the critical yellow hue, must be present to represent ignition.



- The Excel-plotted histogram above shows that all bins from hue 0-42 contain non-zero pixel counts. For this particular camera this indicates ignition based on the presence of this continuous spectrum combined with the critical yellow hue 42.

Data to be Returned

1. All original photos - Labeled with material tested, test level, pre-test/test/post-test, and ignition/no ignition. Photo labels/descriptions can be kept in a spreadsheet with the corresponding image file names.
2. All histogram data from the analyzed test photos, in the form of Excel spreadsheets, labeled with test material, test level, ignition/no ignition, and corresponding test photo numbers (if applicable).
3. Waveform screenshots for each test, including peak current amplitude, action integral, time to peak, and time to 50% decay.
4. Pre and Post-test DC resistance measurements.
5. Information about test setup:
    a. Camera manufacturer, model number, lens model, lens manufacturer, F-Stop setting, ISO, shutter speed, white balance setting.
    b. Camera pass/fail brightness threshold (determined during AE2 white paper validation).
    c. Distance from camera body to test article.
    d. Type of protective window used in front of camera (If applicable, i.e. glass, acrylic).
    e. Flammable gas mixture used (percent by volume) and atmospheric conditions (temperature, relative humidity, pressure).
    f. Photos of test setup.

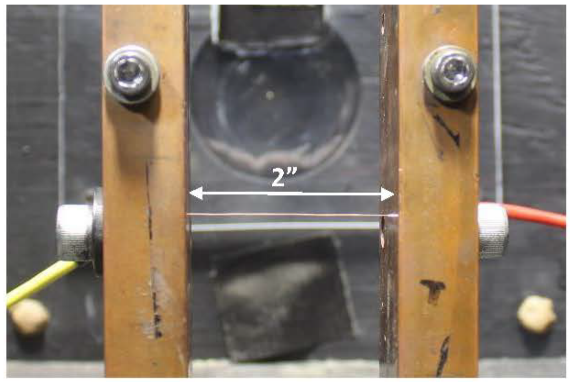
Optional Additional Sensitivity Studies

1. Wire reuse – How many times (if any) can a wire be retested before suffering enough material degradation to cause a change in results?
2. Wire size variation – Will a larger diameter wire require a lower peak temperature to cause ignition?
3. Zoom – Does a fixed zoom lens provide better/different results than a similar variable zoom lens? How does the sharpness compare?
4. Distance – Does distance between camera and sensor affect histogram results?
5. Resolution – How does sensor resolution affect the results or reliability of the method? What is the minimum resolution (pixels per centimeter) required for consistent results?
6. Wire to wire sensitivity – Does replacing the length of wire under test with another length of wire (from the same spool) affect the energy required to cause glow/ignition?

Test Material Specifications

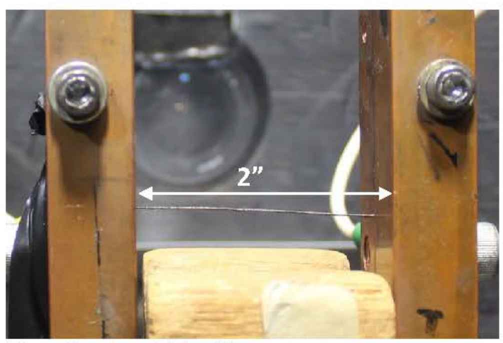
All test materials will be provided by NIAR. Current is conducted through each test article during the test to generating light emission. to be analyzed with the incandescent photographic method.

1. Copper wire:



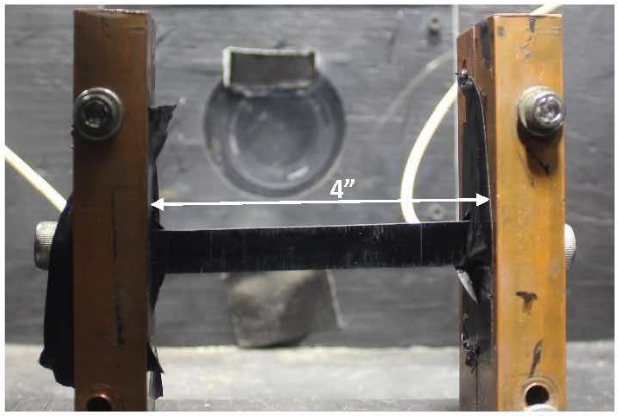
    - 30 AWG (0.01” diameter)
    - Length of exposed wire between electrode attachment locations: 2” ± 0.25” (pulled tight)
    - Manufacturer: Arcor Electronics

2. Carbon fibers:



    - Tightly twisted bundle of multiple fibers
    - ~ 0.01” diameter bundle (this is not strict, as long as glow is successful)
    - Length of exposed fiber bundle between electrode attachment locations: 2” ± 0.25” (pulled tight)
    - Manufacturer: A&P Technology Fibers removed from biaxial carbon fabric BIMAX-H-48

3. 8 ply CFRP laminate strips:



- Thin carbon fiber composite strip: 0.5" x 5" x 0.05"
- Ply 1-7: Cycom 5320-1 Unitape Prepreg (0°, 90°, 0°, 90°, 90°, 0°, 90°)
- Ply 8: Cycom 5320-1 PW Prepreg (0°/90°)

References

1. Schindelin, J, et al.,"Fiji: an open-source platform for biological-image analysis", Nature methods 9(7). June 28, 2012.
2. Society of Automotive Engineers (SAE) International Aerospace Recommended Practice (ARP) 5416A Lightning Test Methods. Revised 2013
3. "Recommended Camera Calibration and Image Evaluation Methods for Detection of Ignition Sources", SAE AE-2 Lightning Committee White Paper, Rev. NEW. January 2018.
4. Society of Automotive Engineers (SAE) International Aerospace Recommended Practice (ARP) 5412B Aircraft Lightning Environment and Related Test Waveforms. Revised 2013

B. Draft Incandescent Test Procedure for ARP5416A

Test and Image Analysis Procedure for Photographic Characterization and Detection of Incandescent Ignition Sources

June 2021

Table of Contents

Executive Summary

At the request of FAA and industry, a research program was conducted by the National Institute for Aviation Research (NIAR) to investigate the ability of edge glow light emitted by carbon fiber reinforced plastics (CFRP) to act as a fuel tank ignition source. As a result, a new detection method is proposed to supplement existing test guidelines. This method adds an analysis step for the test images from the existing camera procedure to characterize emitted light based on the hue signature of the image.

Existing test standards define any detected light above a determined threshold as an ignition source. NIAR investigations determined that edge glow spots can far exceed the brightness threshold without causing ignition in the flammable gas test defined in ARP 5416A. The study showed that ignition can be predicted by analyzing the hue histogram of the detected light emission source. Thus, based on the research findings to date, a hue signature has been observed to be coincident with ignition of standardized gas mixture for several investigated materials, including carbon fiber composites. This hue signature is defined as the incandescent heat signature, consisting of a range of continuous red-orange-yellow hue, colors typically associated with thermal radiation.

This document outlines a test procedure for the incandescent detection method written in accordance with the SAE ARP 5416A format.

Introduction

A 200 µJ energy value is a commonly accepted minimum ignition threshold for Jet A fuel. It is the standard for calibration of gas for the flammable gas ignition source detection method. Photographic ignition source detection is an accepted alternative method of ignition source detection to provide economical means for testing, based on the brightness of the light emitted by the 200 uJ spark. Unfortunately, the photographic method results in a large percentage of cases resulting in false test failures when applied to CFRP test articles. The false failures occur because light emitted by carbon fiber composites is not necessarily capable of acting as an ignition source, as in the case of carbon fiber edge glow.

In an effort to reduce the number of false failures from carbon fiber edge glow, the proposed ignition source detection method retains the photographic method and the 200 µJ source from SAE ARP 5416A and supplements it with additional color-based image analysis to determine ignition thresholds. This analysis distinguishes between light emissions that present a threat of ignition, and those that do not. The incandescent signature and the corresponding image analysis technique are the primary finding of this research, as it predicts ignition conditions in the flammable gas mixture for edge glow of carbon fiber composites while maintaining use of the existing digital photography sensor.

Image analysis is performed in ImageJ [1], an open source image processing software. Hue-based image analysis determines whether thermal ignition sources are present in the image by characterizing the color signature of emitted light. The color characterization is performed using the hue channel of the image. The hue is determined by converting the red, green, blue (RGB) image to the hue, saturation, brightness (HSB) color model. A particular hue signature has been noted in the image histograms, which coincides with ignition of the flammable gas mixture. This signature is the "incandescent signature" of ignition. Each test camera must undergo a verification procedure to determine its incandescent hue signature of ignition.

The incandescent hue signature is defined as a continuous range of pixels in the image falling within the red-orange-yellow hue range. The red-orange-yellow range approximately corresponds to hue values 0-42 (bins) based on the 0-255 total bins for an 8-bit image in the HSB color space. The hue value 0 indicates red hue, transitioning to orange as hue value increases, with yellow at hue value 42. The incandescent signature may not necessarily span the entire red, orange, yellow range, so the continuous hue range must be defined during the incandescent signature verification of each camera. The presence of light at the defined upper bound of this continuous range indicates whether ignition conditions exist, as it represents the highest temperature region of the test article. This upper bound of the continuous spectrum, which is present in all ignition photos, is referred to as the "defined upper bound hue value" of the incandescent spectrum. Ignition is marked by the occurrence of both components of the incandescent signature: the continuous spectrum, and the defined upper bound hue value.

A typical example of the incandescent signature hue histogram is shown in Figure 1.

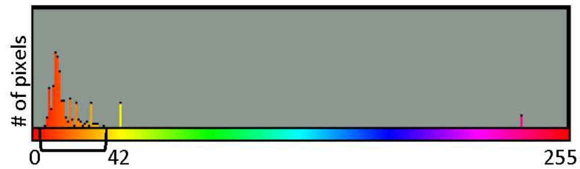


Figure 1: Sample incandescent hue signature displaying continuous spectrum in red-orange region (hue = 4 - 33) defined upper bound hue value at hue = 33.

Background - Preliminary study

The following summarizes the observed effects produced by investigated materials in relation to incendivity of the gas mixture:

(1) Ejections *ignite* gas,
(2) Edge glow without incandescent signature observable in CFRP *does not* ignite gas,
(3) Edge glow with presence of continuous spectrum but without defined upper bound hue value *do not* ignite gas,
(4) Edge glow with presence of continuous spectrum and with defined upper bound hue value *ignite* gas.

Recommendations for Hue Analysis of Digital Images

In certain circumstances, erroneous hue values can occur in test photos, affecting the incandescent signature. This can include hue pixels introduced by light leaks or reflections in the test chamber. The movement of the light source can affect the resulting hue values, since light was not able to integrate in the same pixel location for the full duration of the test. All efforts should be taken to keep the test specimen from moving or shifting during the test, by ensuring that each test article is securely mounted in the test chamber.

The accuracy of histogram data is affected by noise pixels in the dark background area of test photos. Brightness and saturation of the pixels in the dark background area are very low, so the corresponding hue data of the background region is not as meaningful as the hue data in regions illuminated directly by the ignition source. These very dark regions can skew the hue histogram and should be excluded from analysis if possible. One method to exclude background noise pixels from analysis is cropping around the ignition source to remove most of the background area. Another method to remove noisy background pixels from analysis is to threshold the image based on brightness so that the hue data from the darkest pixels is not included in histograms.

It is a requirement that the camera settings remain the same for all images that will be directly compared or evaluated with this method. This includes keeping the light integration time the same for all images. The shutter time must be long enough to capture the entire light emission event. The light emission events themselves must be the same or similar in time duration. Consider two light sources, each emitting the same amount of light at any instant in time. The first source, glowing for 10 microseconds, does not have the ability to integrate light on the camera sensor that the second source, glowing for 1 second, does.

Light emitted during combustion of flammable gas can introduce color to the test photos. It is important that all combined photographic/ignition testing be conducted in hydrogen or a similar gas that burns without producing visible flames. Any hue data introduced by the combustion of fuel gases will skew hue histogram results. The test chamber should be kept free of dust, which can introduce light/hue into the test photographs if ignition occurs and dust particles are ignited.

Test Equipment

Photographic Sensor

In this document, the term 'camera' includes light sensors, lenses, image data recording, and associated controls and settings. The camera must allow manual control of the settings to ensure that sensitivity remains the same for all test photos. The resulting output value is the observed hue signature obtained in the test image.

The camera, lens, and camera settings should be treated as a set of calibrated equipment, which should be calibrated every 12 months in accordance with SAE AE-2 Lightning Committee White Paper: Recommended Camera Calibration and Image Evaluation Methods for Detection of Ignition Sources [3]. This calibration process ensures that the peak pixel value of detected light will fall approximately in the middle of the camera's dynamic range, keeping the ignition sources from oversaturating the sensor. Incandescent signature verification process should also be completed at this time, or at least every 12 months. Incandescent signature verification must be repeated whenever the distance from camera to test object changes.

Flammable Gas

The recommended ignitable mixture is hydrogen in dry air at a concentration of seven volume percent of hydrogen. Calibration of the flammable gas mixture utilizing the standard 200 uJ voltage spark source according to ARP 5416A must be performed prior to testing. Adjustments to the hydrogen concentration may be necessary in order to achieve at least nine out of ten ignitions prior to testing.

Hydrogen is the recommended test gas because it burns with a nearly invisible flame, which will not affect hue histograms of test images when gas ignition occurs. Other flammable mixtures may be used if hydrogen and air mixtures are not available. Other test gases may introduce light into the test chamber during ignition. This requires all tests to be repeated twice, once using the flammable gas method and once using the incandescent photographic method. This is not ideal due to the increase in time required for testing, and because it assumes that the two test instances are identical, which may not be the case.

Light Source for Incandescent Signature Verification

Incandescent signature verification is necessary for each camera due to variations in both hardware and software available in digital cameras, and because digital photography utilizes the device dependent RGB color space. Color output varies between devices, meaning the incandescent hue signature defined for one camera may not necessarily be applicable to other cameras.

Ideally, a standard repeatable incandescent light source would be used to emit a consistent incandescent light signature. Photographs of this controlled geometry and temperature light source would be used to characterize the incandescent hue signature detected by the camera for a known incandescent source. Unfortunately, a standard repeatable incandescent light source is not readily feasible or obtainable. The best available representative light source for incandescent signature verification is a sample coupon of the same composite material being tested for ignition source detection testing. Conducted current is applied to this sample coupon to generate incandescent light near the threshold of flammable gas ignition. The light from the sample coupon is photographed to determine the incandescent signature.

A suggested test fixture design is shown in Figure 2. The test fixture serves the purpose of keeping the test sample in place at a fixed length and position to avoid movement during the test. The fixture must sufficiently prevent sparking at the contact areas from escaping into the flammable mixture, causing an ignition unrelated to the incandescent source.

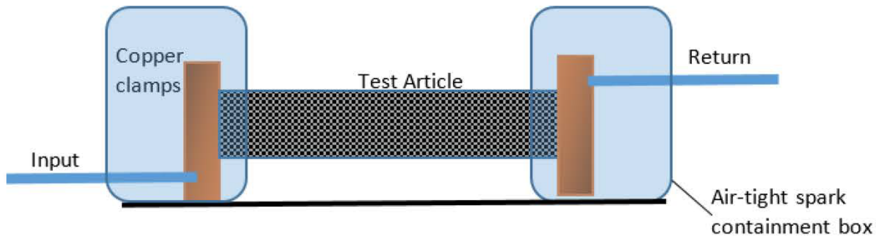


Figure 2: **Suggested Test Fixture and Test Article Installation Drawing**

Test Waveforms

Incandescent signature verification is performed using the same waveforms that will be utilized during testing. Waveforms are defined in ARP 5412B [4] with specific parameters for the action integral, peak current, rise time, and time to 50% decay.

A recommended sample test setup for incandescent signature verification is shown in Figure 3. Any circuit that produces the desired waveform parameters is acceptable for use. To achieve the goal of incandescent light emission from the test article.

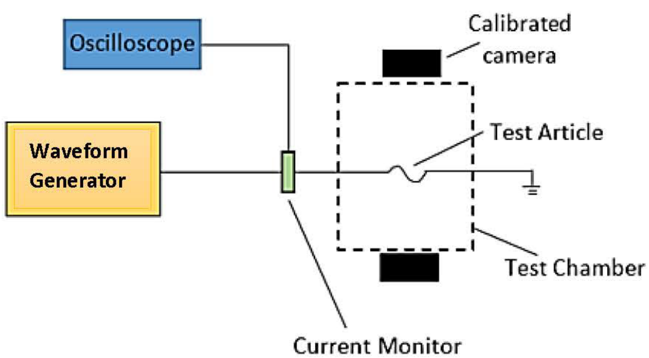


Figure 3: Sample Test Setup and Circuit Diagram

Recommended test levels should be based on the waveforms used during the ignition detection test itself, but the levels should be reduced to produce faint glow from each test material. To increase or decrease the intensity of light emission, the applied waveform amplitudes must be incrementally adjusted.

Procedure
The following steps describe the procedure for incandescent signature verification:

Setup

1. Set up the waveform generator, test equipment, and test fixture as depicted in Figure 3.
    a. The test sample and the ignitable gas mixture shall be contained in an enclosure that:
        i. prevents external light sources or reflective surfaces from appearing in the recorded camera image. Any external light leaks will affect the hue data.
            1. The use of a witness light/reference light to verify that the camera shutter opened during the test (as described in ARP5416A) is not advisable since it will introduce hue values into the image that are unrelated to the test article. If it is necessary to use a reference light, it should be excluded from the image analysis if possible (by cropping or by other means).
        ii. is sealed to prevent flammable gas leakage with a safety blow out panel. [2]
        iii. Sufficiently isolates the contact/clamp area of the test article from the flammable mixture to prevent contact sparking from causing a false ignition.
2. Perform verification of ignitability of flammable mixture to achieve at least 9 out of 10 ignitions with a 200 uJ voltage spark source as described in ARP 5416A.
3. Set up the camera(s). Ensure the test object is in focus and within the field of view.
    a. If the camera is located outside of the test volume, the enclosure will contain a transparent window with minimal attenuation over the 400-800 nm range of visible light in order to seal the gas chamber while allowing test photos to be collected.
    b. Record the camera specifications, including: manufacturer, model number, lens model, and lens manufacturer. Record <u>all</u> camera settings including: F-Stop, ISO, shutter speed, white balance, noise reduction, exposure bias, distance from the camera to the to the test object, and any other applicable settings. Acquire images in a high quality JPEG image format at the cameras sensor native resolution.
    c. Ensure that the potential ignition source on the object under test takes up a significant number of pixels on the sensor in order to produce adequate data for analysis. The minimum image resolution is at least 30 pixels per centimeter of length of the test article.

Incandescent Signature Verification

Determine minimum test level for edge glow– No flammable gas

4. Install CFRP material sample in the photo chamber and connect to the generator. Scaled down test waveforms are recommended for the incandescent signature verification. The rise time, decay time, and overall waveshape for the reduced waveforms should meet the same requirements as the full-scale test waveforms.
    a. Ensure a good electrical bond from test article to electrode attachment points. Sealing/covering the attachment/clamp area with high voltage putty, corona dope

or similar to prevent contact sparking from escaping into the test chamber and igniting the flammable mixture.

   b. **NOTE:** The sample must be monitored for degradation between test shots, and replaced as necessary. This may exhibit in visible physical material loss, damage, or other changes. It may also present as a significant change in light emission at similar applied waveform levels. Further study of material degradation/conditioning is desired.

5. Take a pre-test open-box picture to establish the location of the test article.
6. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings as used during the brightness-based whitepaper calibration. Use these camera settings for the duration of testing.
7. Apply test waveform to create a visible edge glow from the coupon. Open the camera shutters to capture all light emitted during the test.
8. If edge glow is not produced in step 7, increase the current amplitude and repeat the application of the test waveform. Ensure that the camera shutter is open for duration of each test.
   a. Continue to repeat this step until edge glow is produced.

Determine Test Level in Flammable Mixture

9. Install new CFRP material sample into the photo chamber and connect to the generator. Use the test level determined in step 8 as the starting test amplitude.
   a. Ensure a good electrical bond from test article to electrode attachment points. Sealing/covering the attachment/clamp area with high voltage putty, corona dope or similar to prevent contact sparking from escaping into the test chamber and igniting the flammable mixture.
   b. **NOTE:** The sample must be monitored for degradation between test shots, and replaced as necessary. This may exhibit in visible physical material loss, damage, or other changes. It may also present as a significant change in light emission at similar applied waveform levels. Further study of material degradation/conditioning is desired.
10. Take a pre-test open-box picture to establish the location of the test article.
11. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings used during calibration.
12. Begin testing in gas in accordance with ARP 5416A. See “flammable gas” section above.
13. Starting at the test level determined in Step 8, apply test waveform to create visible edge glow. Open the camera shutters to capture all light emitted during the test. The goal of this step is to determine the lowest test level that will cause repeatable ignition of the flammable mixture.
    a. If the flammable gas ignites, repeat the test at a lower test level, repeating until the threshold of ignition/no ignition is discovered. When the ignition threshold test level is discovered, repeat the test once more at this level to verify that ignition is repeatable. Save all test photos at every test level, record waveform parameters and whether or not ignition occurred.
    b. If the flammable gas does not ignite, repeat the test, increasing the test level until the threshold of ignition/no ignition is discovered. When the ignition threshold test level

is discovered, repeat the test once more at this level to verify that ignition is repeatable. Save the test photos from each test level, record waveform parameters and whether or not ignition occurred.

14. Repeat Step 13 until the minimum current level is established that provides visible edge glow, ignites the flammable gas, and is repeatable at least two consecutive times.
15. In **air**, repeat the waveform application at the current level determined in Step 14 eight more times, collecting test photos each time. (This step is done in air to reduce testing time.)
    a. The 10 photos obtained during Steps 14 and 15 at this test level serve as the "ignition photos" from which the camera specific incandescent signature is obtained.
16. Take a post-test open-box picture of the illuminated test article to observe any damage and to establish the location of the CFRP material sample in the box.

Obtain Camera Specific Incandescent Signature

17. Analyze photos collected in Step 13-15 according to the "Image Analysis" procedure below. The hue signature obtained in this step via image analysis defines the "camera-specific incandescent signature" that represents ignition.
    a. Note should be taken of pixels falling in the hue range 0-42 (continuous spectrum), with emphasis on the defined upper bound hue value of this range.
        i. Due to variations between digital cameras, the continuous spectrum may not span this entire hue range, or the range may not fall between 0-42. Instead, make note of any span of hue bins containing nonzero pixel counts within the red/orange/yellow hue range. Record the upper and lower bound of this range. The continuous range must be present in <u>all</u> ignition photos. This continuous hue range is now defined for this camera.
        ii. The defined upper bound hue value of the continuous spectrum may not fall exactly at hue 42. Instead, look for the highest hue value at the upper bound of the continuous spectrum that is present in <u>all</u> ignition photos. This value must appear in every photo of ignition. The defined upper bound hue value has now been determined for this camera.
        iii. Observe and record any other characteristics of the hue signature that indicate ignition or no ignition. Hue values outside the red/yellow/orange range do not represent incandescent sources, and do not need to be considered.

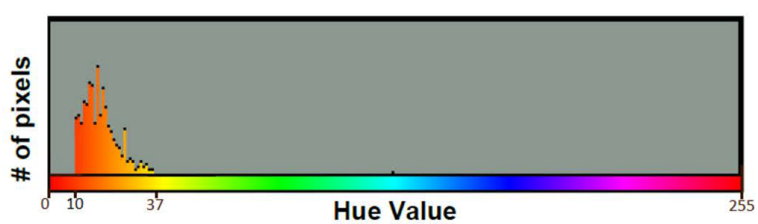


Figure 4: Sample histogram of ignition, with the continuous spectrum spanning 27 bins, bounded by hue value 10 and 37.

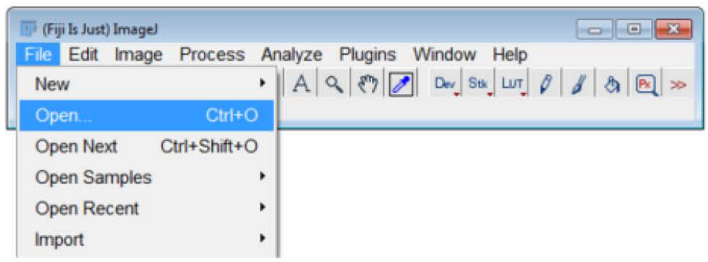
   b. Compare the hue signatures of the non-ignition photos with the incandescent signature (continuous spectrum and the defined upper bound hue value of the incandescent spectrum) to determine whether there are distinguishing hue characteristics between ignition and non-ignition photos.
   c. Future test photos containing the defined continuous spectrum range in addition to the presence of the defined upper bound hue value of the incandescent spectrum will be characterized as ignition.

Test Article Testing

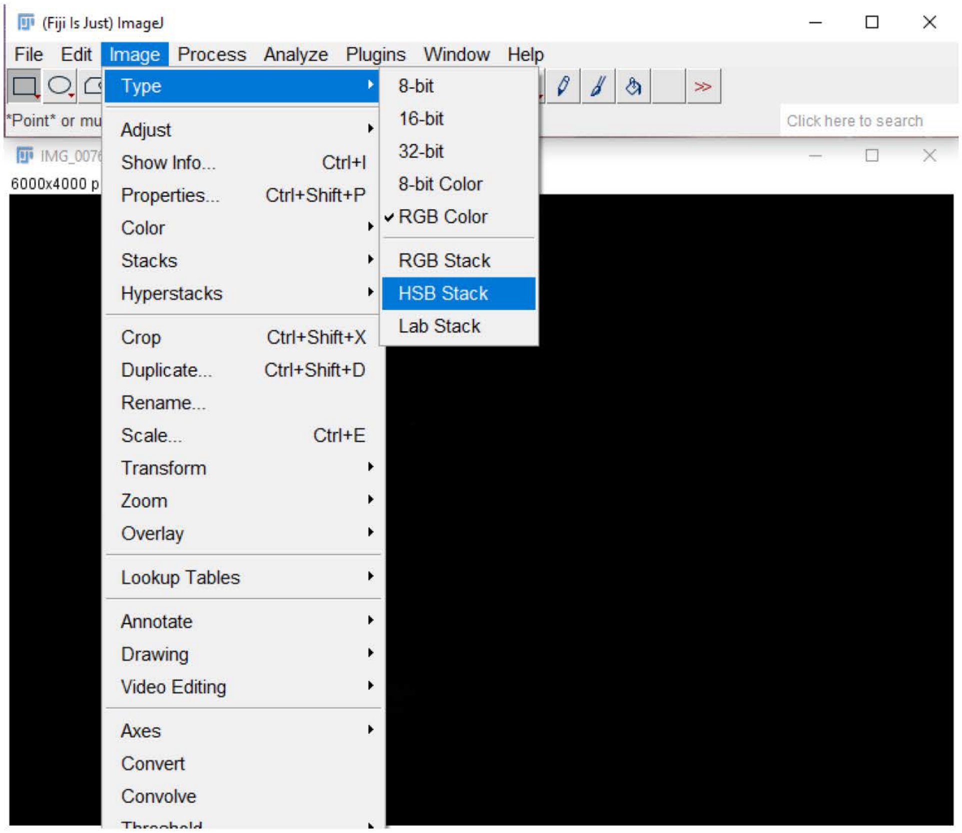
18. Install the test object in the photo chamber and connect to the generator. Begin testing CFRP test articles.
    a. Ensure a good electrical bond from test article to electrode attachment points. Sealing/covering the attachment/clamp area with high voltage putty, corona dope or similar to prevent contact sparking from escaping into the test chamber and igniting the flammable mixture.
    b. **NOTE:** For ignition source detection testing of actual test articles, it is recommended to replace the test article after each test shot. If this is not feasible, particular attention must be given to monitoring the test article for degradation between test shots. Degradation may exhibit in visible physical material loss, damage, or other changes. It may also present as a significant change in light emission at similar applied waveform levels.
19. Take a pre-test DC resistance measurement across the test article.
20. Take a pre-test open-box picture to establish the location of the test article.
21. Cover the box with the lid, verify no external light leakage into the chamber, and take a closed-box picture using the same camera settings as used during calibration.
22. Begin testing using the photographic ignition source detection method accordance with ARP 5416A.
23. Apply test waveform(s).
24. Open the camera shutters during the test to capture all light emitted during the test.
25. Take a post-test open-box picture of the illuminated test article to observe any damage.
26. Take a post-test DC resistance measurement across the test article.
27. Perform "Image Analysis" steps to determine whether the hue signature matches the incandescent signature of ignition. This determines whether ignition conditions were present and a resulting pass/fail test result.

Image Analysis with ImageJ Software:

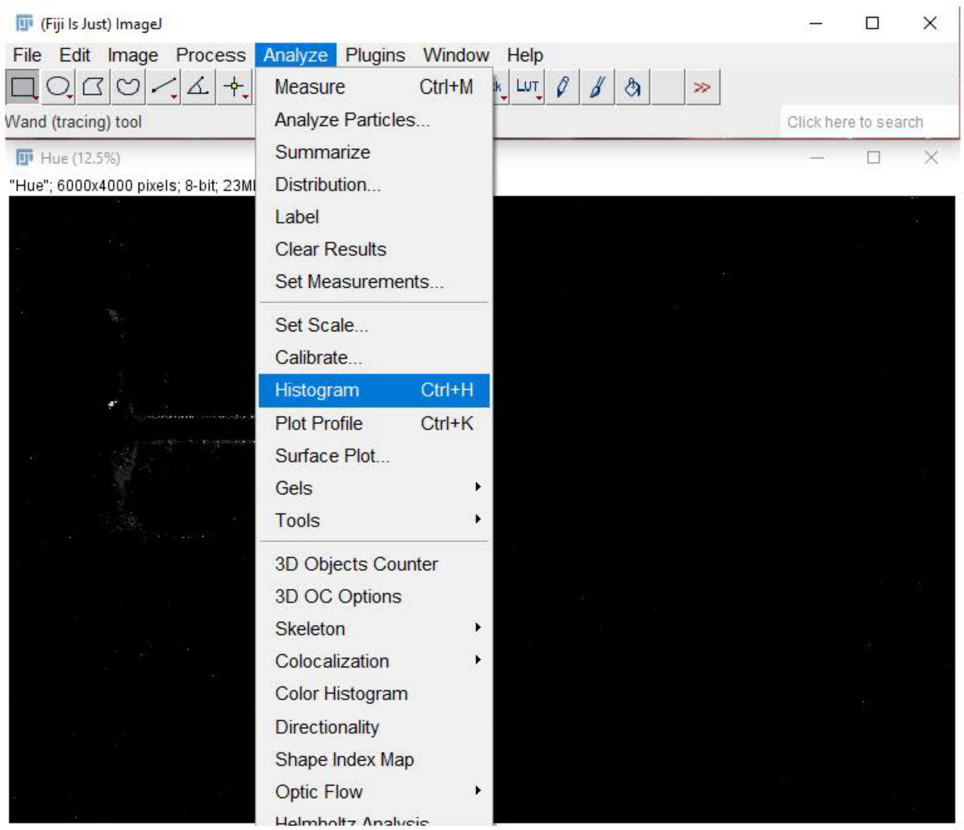
a. Download ImageJ software at https://imagej.net/Fiji/Downloads. Equivalent image processing software can be used if ImageJ is unavailable.
b. To ensure that original image test data is not overwritten during the image analysis process, perform all image processing on a duplicate copy of the original image file.
c. Open a test photo in ImageJ (drag/drop an image or File > Open.):



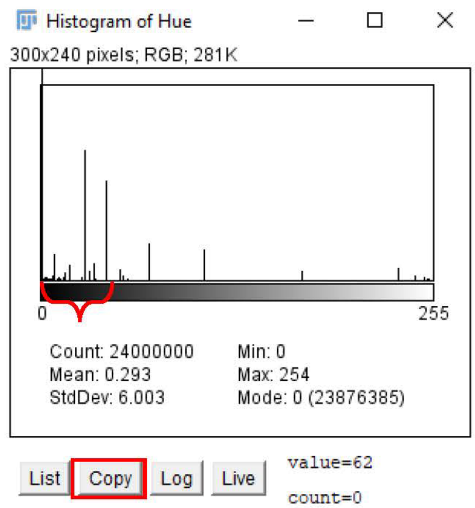
d. Convert the image from RGB Color to HSB stack: Image > Type > HSB Stack:



e. Create histogram of the "hue" channel: Analyze > Histogram:

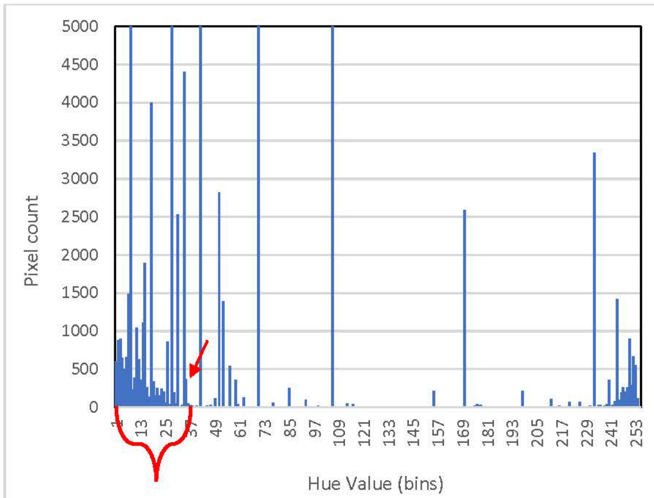


f. Observe the hue signature of the photo. The histogram will display pixel counts when the cursor is hovered over it. To better visualize the histogram plot it is preferable to plot the values in Excel.



g. Click "Copy" on the histogram. This copies all histogram data to the clipboard. Paste the resulting data in a spreadsheet file, making note of which test the image corresponds to, and whether or not ignition occurred.

h. Plot the histogram data as a column graph. Determine whether the incandescent signature is present, and if the results of the hue analysis match up with the ignition of the flammable gas. Both components of the incandescent signature, the continuous spectrum and the defined upper bound value of the incandescent spectrum, must be present to represent ignition.



- The Excel-plotted histogram above shows that all bins from hue 0-40 contain non-zero pixel counts. For this particular histogram, ignition is coincided with this continuous spectrum range combined with an upper bound hue value at hue=40.

Data to be Collected

1. All original photos - Labeled with material tested, test level, pre-test/test/post-test, and ignition/no ignition.
2. All histogram data from the analyzed test photos, in the form of Excel spreadsheets, labeled with test material, test level, ignition/no ignition, and corresponding test photo numbers (if applicable).
3. Waveform data for each test, including peak current amplitude, action integral, time to peak, and time to 50% decay.
4. Pre and Post-test DC resistance measurements.
5. Test setup details:
    a. Camera manufacturer, model number, lens model, lens manufacturer, F-Stop setting, ISO, shutter speed, white balance setting.
    b. Camera calibrated pass/fail brightness threshold (resulting from AE2 white paper camera calibration procedure).
    c. Distance from camera body to test article.
    d. Type of protective window used in front of camera (If applicable, i.e. glass, acrylic).
    e. Flammable gas mixture used (percent by volume) and atmospheric conditions (temperature, relative humidity, pressure).
    f. Photos of test setup.

References

1. Schindelin, J, et al.,"Fiji: an open-source platform for biological-image analysis", Nature methods 9(7). June 28, 2012.
2. Society of Automotive Engineers (SAE) International Aerospace Recommended Practice (ARP) 5416A Lightning Test Methods. Revised 2013
3. "Recommended Camera Calibration and Image Evaluation Methods for Detection of Ignition Sources", SAE AE-2 Lightning Committee White Paper, Rev. NEW. January 2018.
4. Society of Automotive Engineers (SAE) International Aerospace Recommended Practice (ARP) 5412B Aircraft Lightning Environment and Related Test Waveforms. Revised 2013