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Federal Aviation Administration
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The FAA's Center of Excellence for UAS Research
ASSURE
Alliance for System Safety of UAS through Research Excellence

Annex C to Task A17: Airborne Collision Severity Evaluation – Engine Ingest Test Report

9-6-2022

Final Report

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U.S. Department of Transportation
Federal Aviation Administration

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LIST OF ACRONYMS

ARF – Aerophysics Research Facility
CG – Center of Gravity
FAA – Federal Aviation Administration
FE – Finite Element
FEA – Finite Element Analysis
FEM – Finite Element Model
KE – Kinetic Energy
NAS - National Air Space
NIAR - National Institute for Aviation Research
OSU – The Ohio State University
RSESC – Rotorcraft Systems Engineering and Simulation Center
SMDC – Space and Missile Defense Command
sUA – Small Unmanned Aircraft
TIM – Technical Interchange Meeting
UAH – University of Alabama in Huntsville
WSU – Wichita State University

1. SCOPE

1.1. Research Tasks

The University of Alabama in Huntsville's (UAH) role in the Task A17 project was to provide experimental high-speed impact test results to Wichita State University's (WSU) National Institute for Aviation Research (NIAR) for calibration of small unmanned aircraft (sUA) component and aircraft LS-DYNA™ finite element (FE) models.

Task B:

Task B was to conduct individual components (camera, motors, battery, and possible shell material) and full quadcopter model collision testing with titanium wedges, and update an existing UAS quadcopter model[1] accordingly. Impact tests were conducted in the range of 425-710 knots on an angled titanium plate to obtain contact conditions similar to an engine ingestion. Fully charged batteries were used in this study to provide some insight on potential fire hazards during an ingestion. FE models developed in the previous FAA project[1] for individual components and the full quadcopter model will be used in this research project. An appropriate mesh size to be used for FE simulations of the ingestion will also be suggested based on the experiments and computational modeling. Simulations to confirm integration of the UAS model with the fan model developed in Task A will also be conducted.

1.2. Research Questions.

Research Questions:

a. What modifications are needed for the quadcopter component (the motor, camera, or battery) and full quadcopter models for higher speed slicing impacts into titanium?

b. What range of rotational velocities would be experienced by the fan modeled in this project?

c. What velocities should be used in the experiments, to capture the relative velocities in an ingestion event (considering the fan rotational velocity, airspeed of the airplane, and velocity of the quadcopter)?

d. How can the full quadcopter be accelerated to the desired speed and should the quadcopter components be tested at a higher speed?

Assumptions and Limitations:

a. Procurement of materials and manufacturing of titanium wedges will be dependent on initial fan design.

b. Fan model from Task A will be completed for integration with the UAS model.

[1] Gerardo Olivares, et al., "Volume II - UAS Airborne Collision Severity Evaluation - Quadcopter," Washington D.C.: U.S. Department of Transportation Federal Aviation Administration, 2016.

1.3. Objectives

The goal of UAH's research was to conduct testing to that enabled calibration and validation of NIAR's FE models.

During FAA ASSURE TASK A3 – Airborne Collision Severity Research, quadcopter and fixed-wing models were validated at lower speeds from 100 to 250 knots with blunt force impacts against thin aluminum plates that were representative of the skin of an airplane, as well as aluminum plates that represent a rigid impact structure. The research focused on large commercial aircraft and business jets, but sUA mostly operate at lower altitudes and …

This was accomplished in two steps. First, UAH conducted impacts of sUA components like motors, camera payload and batteries with target velocities of 563 and 711 knots against machines titanium blades that are representative of intake bypass fan blade structures at the 50% and 80% radial spanwise positions. Based on g-loading and deformation during launch acceleration in the gun tube, it was not possible to reach 711 knots with the batteries. Second, UAH conducted impact tests by launching full sUA (DJI Phantom 3s) at approximately 425 knots at the representative intake bypass fan blades. This work was intended to identify how an sUA will damage intake bypass fan blades and if the damage caused can be separated in categories similar to what was developed during Task A.3.

Table 1. Test, Test Conditions, and Test Outputs

Test	Test Conditions	Key Output(s)
sUA Components High-Speed Impacts with machined titanium blades	sUA Battery, Motors, and Camera impacts at 563 and 711 knots against machined titanium blades that represent the 50% and 80% radial spanwise positions of an intake bypass fan blade	Damage Assessment, High Speed Videos, Strain and Load measurements, Still Images, 3D Scan Cloud Data, and Digital Image Correlation System outputs
sUA High-Speed Impacts with machines titanium blades	DJI Phantom 3 sUA, with camera and legs removed, impacted against machined titanium blades at approximately 425 knots	Damage Assessment, High Speed Videos, Strain and Load measurements, Still Images, and Digital Image Correlation System outputs

1.4. Relation of UAH's Efforts with Other Universities on the Task A17 Team

UAH's impact testing and the resulting video, still images, Digital Image Correlation System data, load cell signals, and strain gage signals were used by NIAR's modelers to calibrate aircraft component models. The component-level model calibration supported modeling full aircraft impacts by enabling a progressive buildup of the full aircraft model from its constituent parts. Full aircraft impact test data was used to enable calibration of representative titanium intake bypass fan blade models by NIAR and OSU.

2. UAH IMPACT TESTS

2.1. Tests Location

All tests were performed at the US Army Space and Missile Defense Command (SMDC) Aerophysics Research Facility (ARF) which is located on Redstone Arsenal. This facility operates three two-stage light gas gun systems. ARF Researchers designed and built two custom gas guns for FAA Tasks A16 and A17. The component testing was accomplished using a single-stage gun, and the full aircraft testing was conducted using a gun with potential to function as either a single or dual-stage gas gun, based on shot requirements. Table 2 provides examples of several existing dual and single-stage guns at the SMDC ARF.

Table 2. Representative ARF Gas Guns

UAH ARF Launcher Systems	Pump Tube Length	Pump Tube Inside Diameter	Launch Tube Length	Available Launch Tube Inside Diameters	Primary Impact Chamber	Projectile Launch Mass Range	Projectile Velocity Range
	(m)	(mm)	(m)	(mm)	Diam x Length (m)	(gm)	(km/sec)
Large	38.13	254	22.88	56, 57, 68, 70, 75, 78, 86, 100, 152	3 x 12.5	150 - 12,000	1 - 7.5
Intermediate	18.3	133	15.25	18, 29, 35	2.4 x 6.7	40 - 250	1 - 7.5
Small	13.42	108	7.47	19, 29	1.8 x 4.3	10 - 130	1 - 7.5
Single Stage	NA	NA	9.9	19, 32, 90	2.4 x 6.7	5 – 30	0.1 – 1.1

2.2. Test Apparatus

2.2.1. sUA Components Test Gas Gun System

An existing single stage compressed gas gun was modified for accelerating the motor, camera, and battery components of the sUA to the desired equivalent impact velocity. This gun utilized a 38 ft long, 90mm inside diameter barrel adapted to an impact test section configured with orthogonal and Digital Image Correlation System camera ports, a scrubber system for hazardous gas removal, cable feed throughs for load cell, strain gauge, and lighting power cables (Figure 1). The full system consists of a bulk gas manifold, which provides nitrogen or helium storage and supplies gas to the pressure reservoir. Between the bulk gas manifold and the reservoir is a gas pressure booster pump for pressurization of the reservoir. The gas pressure in the reservoir is directly proportional to the capacity of the gun system to do work on and accelerate a projectile in the barrel. The reservoir is connected to the barrel via an adapter and ball valve (Figure 2). The ball valve is used to discharge gas from the reservoir to the barrel and fire the projectile. While the magnitude of the pressure in the reservoir represents the maximum capability of the gun to accelerate a projectile, the timing or rate of opening the valve provides control over the rate of acceleration of the projectile. Based on the requirement to fire the sUA battery which is significantly larger and heavier than the sUA motor and camera, an alternate gas pressure reservoir and larger ball valve were installed in the system at the end of the component test period to accelerate the larger, heavier, and more compliant batteries and mitigate battery deformation. The barrel was mounted and aligned on a heavy I-beam structure using adjustable stanchions. Stanchions mounted on the I-beam to support the barrel enabled barrel alignment and have roller interfaces with the barrel that allow for barrel movement up and down range to adjust the projectile and sabot fly-out distance. Fly-out distance, in conjunction with projectile velocity and sabot design, was critical to provide enough flight time for air loads to separate the sabot from the projectile in flight. Based on the wide range of projectile velocities that were used in the study, the ARF personnel used both reservoir pressure and breach position of the projectile to control muzzle velocity. Breach position of the projectile refers to its location within the barrel prior to firing. The barrel is connected to the reservoir and extends through a port into the impact tank (Figure 3). The barrel is aligned with the desired impact point for the projectile on the intended target using the adjustable stanchions. The Task A17 component targets are mounting to a support frame using a steel tabletop and stainless-steel brackets (Figure 4). Load cells are beneath the tabletop mounted on the four studs that protrude up through the tabletop surface in Figure 4. The load cells are in compression prior to the test, so that tensile loads can be calculated based on the decrease in the static compressive force.

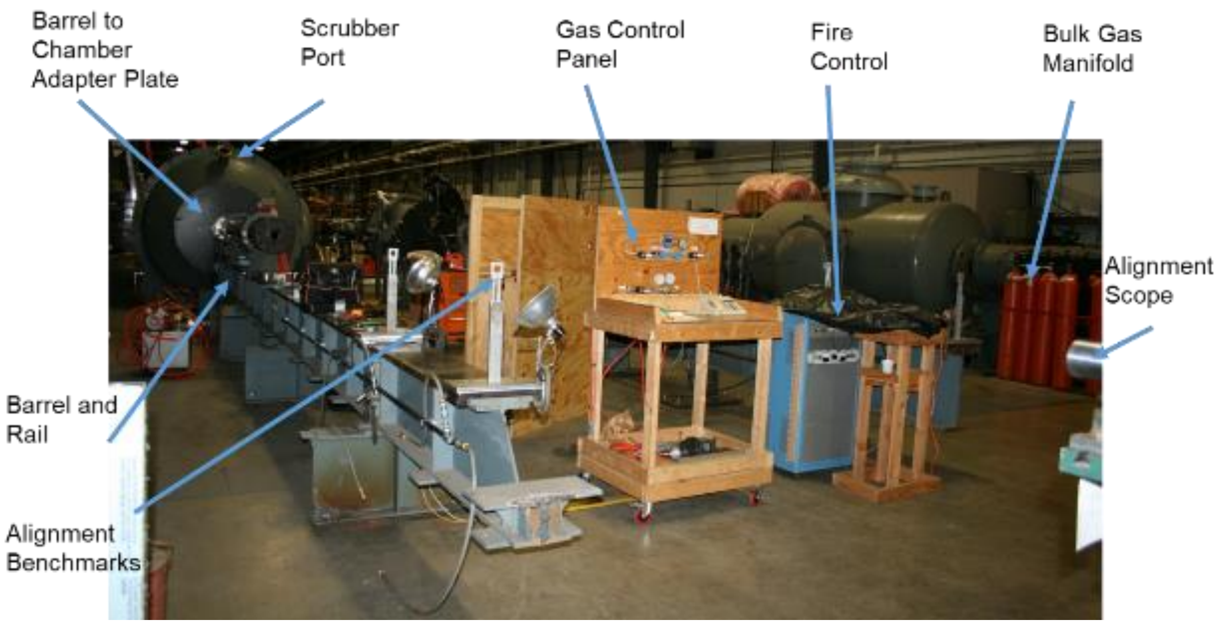


Figure 1. sUA Component Impact Test Range Setup (Reservoir Not Shown)

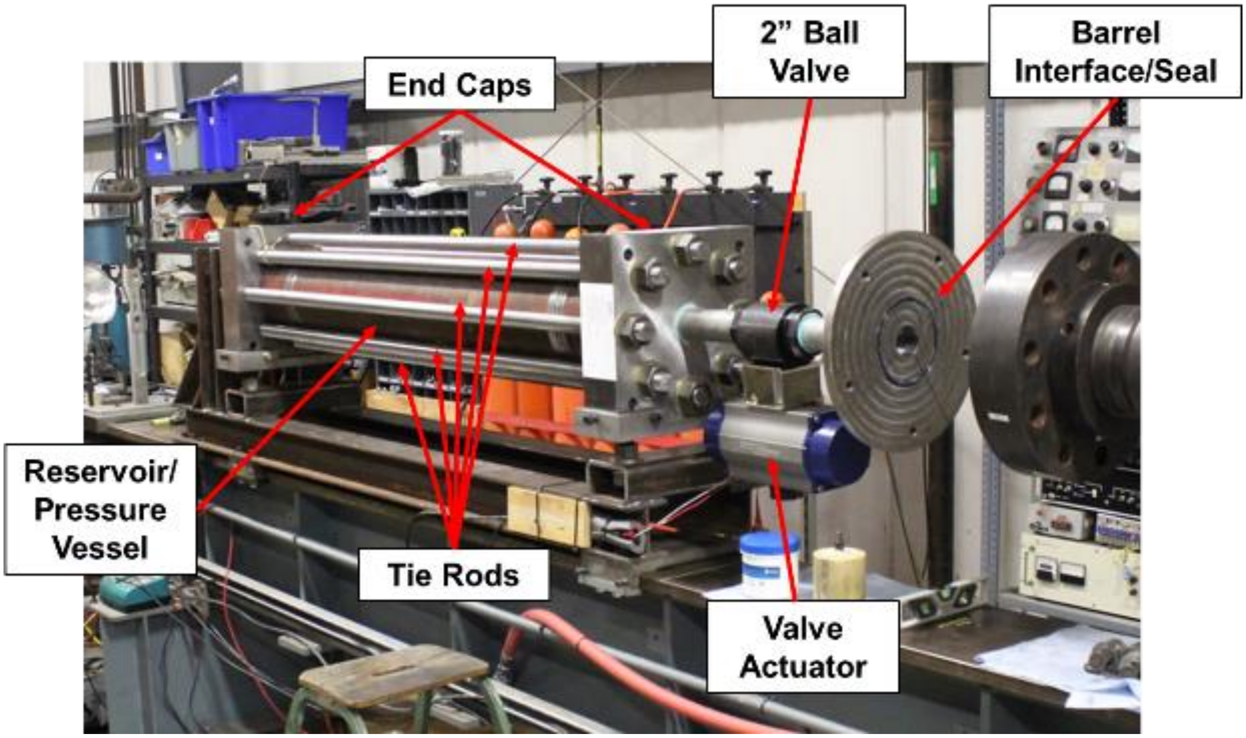


Figure 2. Pressure Reservoir, Valve and Barrel Adapter

Figure 3. Barrel Extension with Supporting I-beam Structure and Alignment System

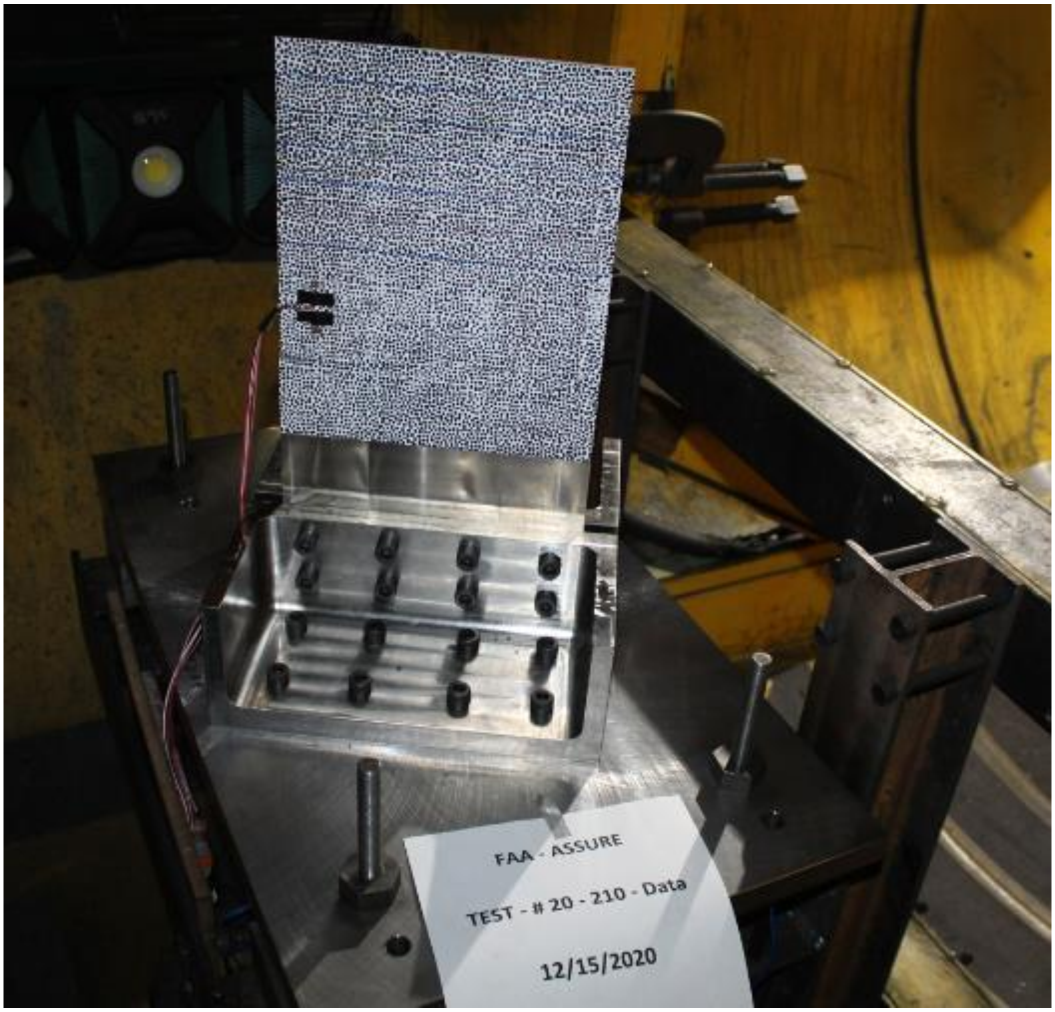


Figure 4. Task A17 Titanium Blade Target, Stainless Steel Bracket, and Tabletop Mount

Given that the full DJI Phantom 3 is a uniquely shaped projectile, a new range and launching system was designed by SMDC ARF personnel to conduct these impact tests. This range has a proprietary design and images are not included in this document to protect the nature of the full sUA range design. The full aircraft impact test range was designed to be a vacuum environment to prevent aerodynamic-induced tumbling of the full aircraft following release from the sabot. The projectile (aircraft and sabot) is launched using a track system in order to decouple the aircraft from the gun barrel. The design also allows for firing a wider range of aircraft since different sabots can be designed for the track system, versus having to purchase large diameter gun barrels (in excess of 12” diameter) for testing with larger aircraft.

2.2.2. Projectiles

sUA components (camera, battery, and motors) and full sUA are the projectiles used for this research purpose. The specifications of these projectiles are summarized in Table 3.

Table 3. Projectiles Description used in Task A17 Component Tests

Projectile	Dimensions [in]	Mass [oz.]	Quantity Needed
Battery	4.85x2.25x1.38	12.80	6
Motor	1.28x1.11x1.11	1.80	5
Camera	1.44x1.65x1.34	1.83	6

2.2.3. Targets

For the sUA component and full aircraft impact tests, two different targets were used. The two targets were representative of an impact at the 50% and 80% spanwise positions on an intake bypass fan blade. Still images of the two types of representative fan blade test articles are shown in Figure 5 and Figure 6. Manufacturing prints for both test articles are provided in Appendix A. Stock manufacturing heat treatment information for the titanium test articles is provided in Appendix B. Impact test article dimensions, material, and instrumentation are outlined in Table 4.

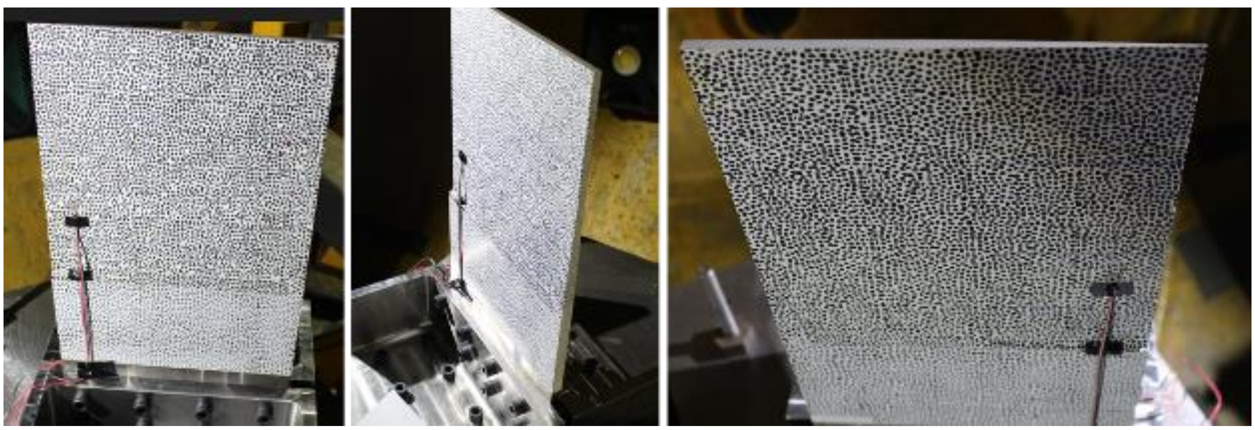


Figure 5. 50% Span Blade Test Article (Still Images)

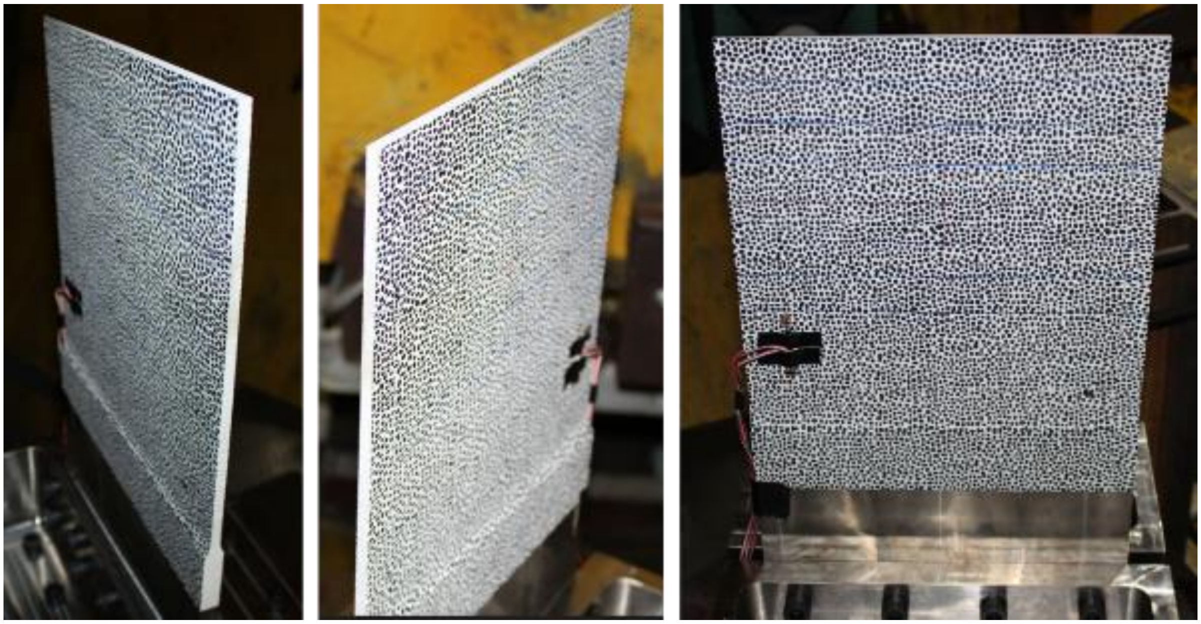


Figure 6. 80% Span Blade Test Article (Still Images)

Table 4. Test Article Descriptions

Target Description	Material	Target size [in]	Instrumentation	Quantity Needed
Titanium Blade Opt A-2 (for 80% radial impact)	Ti-6Al-4V	10x18 (including 3'' extension for bolts connection)	Linear Strain Gauge and DIC	9
Titanium Blade Opt B-5 (for 50% radial impact)	Ti-6Al-4V	10x18 (including 3'' extension for bolts connection)	Linear Strain Gauge and DIC	8

2.2.4. Projectile Sabot

A sabot is required to support the projectile in the middle of the barrel and provide a uniform loading surface during launch. A sabot trap, or stripper, is positioned at the end of the barrel to capture the sabot and allow the projectile to continue on in free flight. The sabots for the motor and camera component projectiles were 3D-printed using ABS plastic. Figure 7 shows the sabot used for motor launches.

Figure 7. Motor A Sabot

For the camera component, Figure 8 shows the sabot part made of 4 sabot leaves that separate in flight due to dynamic pressure and allow the projectile to continue down range toward the target.

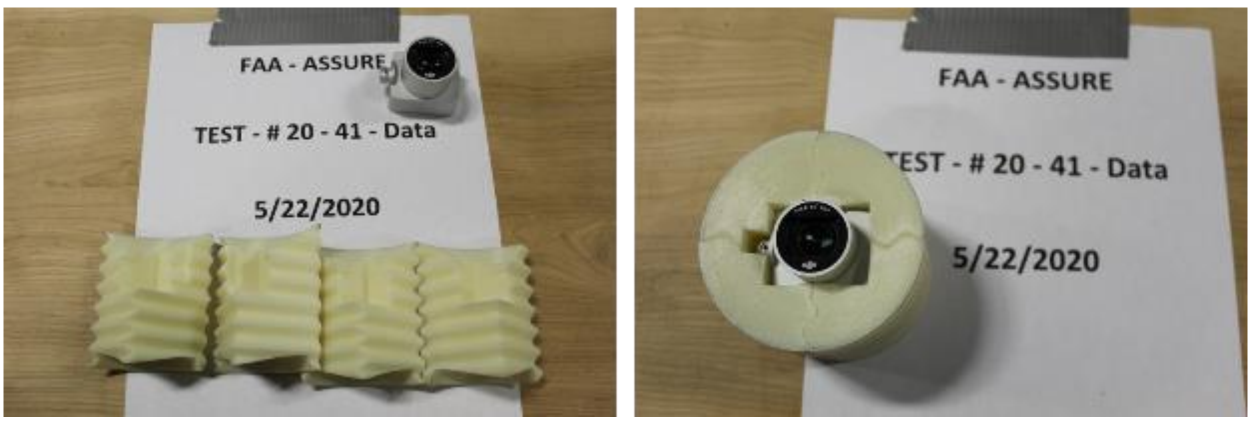


Figure 8. Camera Sabot

For the battery component, Figure 9 shows the sabot part made of a fiberboard cylinder filled with hard foam and cut into two halves with the battery held between the two halves.

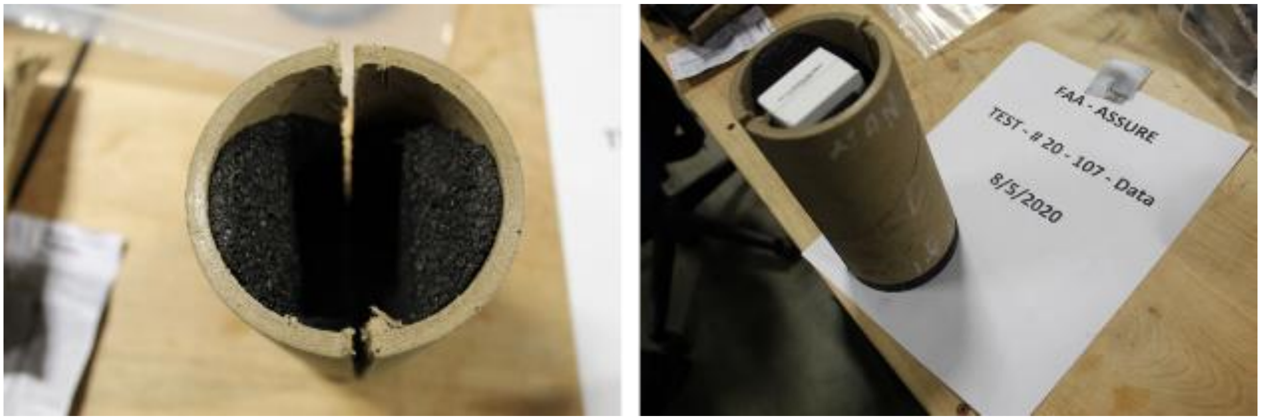


Figure 9. Battery Sabot

2.2.5. <u>Load Cells</u>

The force transferred to the target frame due to the high-speed impact of the projectile on the target is recorded by four uniaxial load cells located at the corners of the target frame. A set of four ICP® quartz force ring, PCB Piezotronics 204C, with a 40,000 lbf compressive capacity and an upper frequency limit of 55,000 Hz was used for all the tests. They were preloaded to approximately 8,000 lbf before testing and allowed to discharge. This allowed for the measurement of tension as a negative voltage and compression as a positive voltage. A 4-channel, line powered, ICP® sensor signal conditioner, PCB Piezotronics 482C24, was used to process load cell measured signals to readout or recording devices. A Yokogawa DL750 ScopeCorder which can measure signals up to 10 million samples per second was used to record the load cells data. Figure 10 shows an image of the PCB Piezotronics ICP® 204C Quartz Force Ring and 482C24 Signal Conditioner, respectively. Figure 11 shows a schematic of the load cell connection to the ScopeCorder via the Signal Conditioner. Figure 12 shows the relative positions of the four load cells held between the steel "table top" and the interface to the larger steel frame impact test fixture. The same corner-mounted load cell arrangement was used in the full sUA impact testing.

Figure 10. (L) PCB Piezotronics 204C ICP® Quartz Force Ring, (R) PCB Piezotronics 482C24 ICP® Signal Conditioner

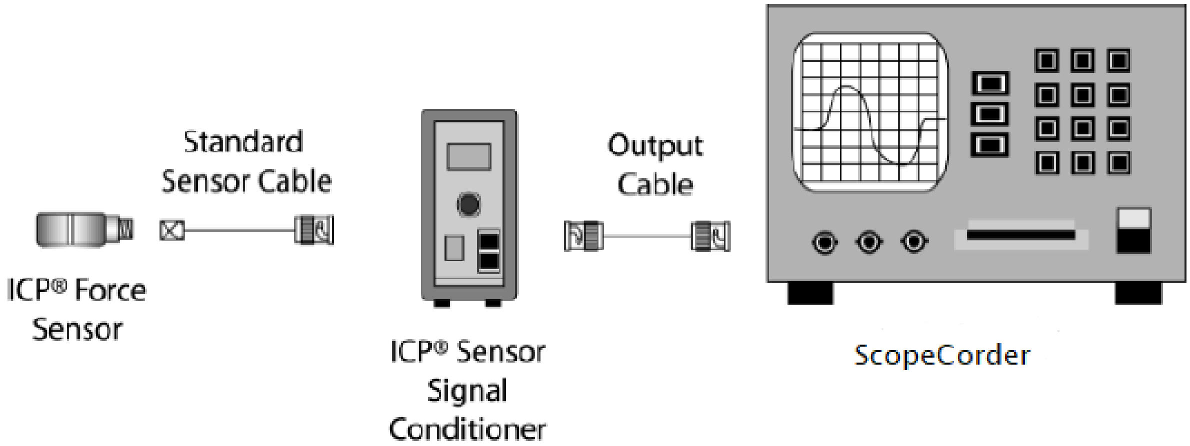


Figure 11. Load Cells Sensor System Schematic

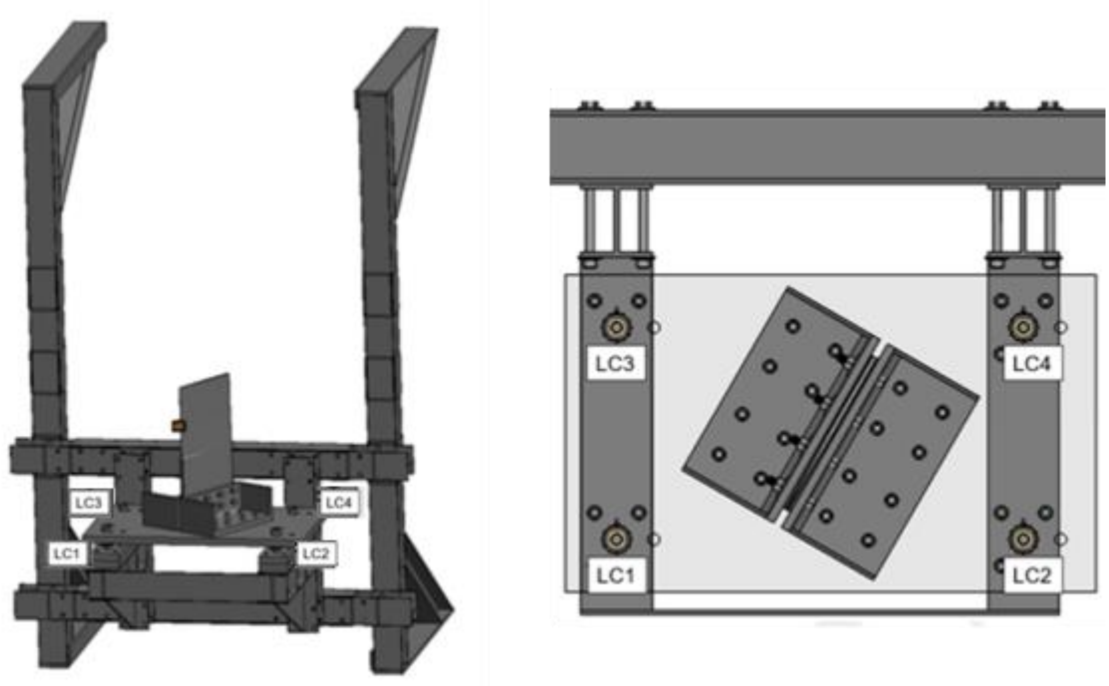


Figure 12. Load Cell Positions on the Titanium Blade Impact Test Fixture (Isometric and Top-Down Views)

2.2.6. Strain Gauges

The strain gauge data acquisition was recorded at 1 MHz, or one data point every microsecond. UAH used MMF003247 linear strain gauges from Micro-Measurements for measurement of local strain values on the titanium blade targets during component and full aircraft impact tests. These gauges have a 350 (± 0.3%) ohm standard elongation strain with a gage factor of 2.155 (± 0.5%) and are 0.25" (±5%). A Hi-Techniques Synergy Universal Input Amplifier SY6216-4D-VC was used to receive data from the strain gauges and store it at 1 MHz. Strain gauge locations for all of the Task A17 titanium blade impact tests were specified in the NIAR test plan REV E.

2.2.7. High-Speed Video Cameras and Digital Image Correlation System

High-Speed Video Cameras were used to record the projectiles in flight and the resulting impact on the target. Photron FASTCAM SA-Z high speed cameras were used. These cameras can provide a one-megapixel (1024x1024) image resolution at 20,000 frames per second or frame rates beyond 2 million fps at reduced image resolution. The Task A17 impact testing used two sets of Digital Image Correlation System cameras to measure surface strain fields on the up range and downrange sides of the titanium blade targets (Figure 13). A speckle pattern was applied to both sides of the test articles in order to allow use of Digital Image Correlation for visual strain field measurement (Figure 5 and Figure 6). There was also a pair of orthogonal cameras used in the testing, which were Cameras 1 and 6 in Figure 10. The Photron FASTCAM Viewer 4 software was used to perform post-processing of the raw files. Projectile velocity was measured using FASTCAM Viewer 4, too. The data from Cameras 1 and 6 were used to measure velocity. Markers were placed on the projectile and the movement of the markers over 10 frames was observed in the software during velocity estimation. A scale factor for each projectile was measured prior to any testing and applied to each high-speed video to determine impact velocity. Digital Image Correlation System files were processed using GOM Correlate software.

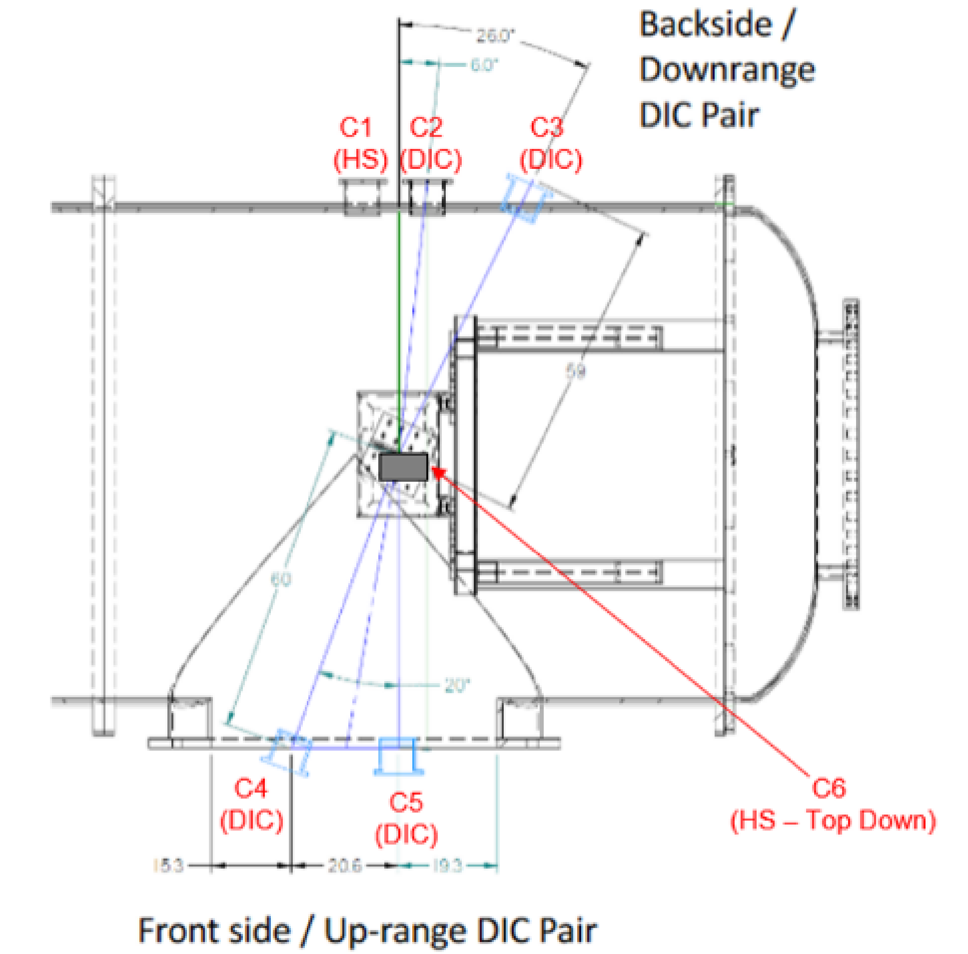


Figure 13. High-speed Cameras Location inside the Test Chamber

2.2.8. Pre and Post Pictures

Before and after a test was conducted, a high resolution, still images of the test setup and test articles were captured using a Canon DSLR camera.

2.2.9. Permanent Deformation Damage Documentation

A 3D scan of the three target types used in the component impact tests was performed prior to test execution. Later, the 3D scan of each target, for every test, was performed after each impact test to record the permanent deformation of the target specimen. UAH used a Metra Scan 750 Elite handheld optical CMM 3D scanner. This scanner has an accuracy of 0.0025 inches. The scans were performed with the test articles suspended from a small-diameter polymer line. The cloud data of the scans, before and after impact, were given to NIAR for further evaluation.

2.3. Component Test Matrix Overview

A total of 17 component tests were conducted. The original test plan included 18 component tests, however, one test was eliminated because of test article damage during manufacturing. Table 5 provides an overview of specifications of the projectiles, targets and the impact test conditions.

Table 5. Component Level Test Matrix

Test Case	Projectile	Span [%]	Relative angle [deg]	Impact Location	Velocity [knots]	Target
M80L7-001	Motor	80	25	LE	710.98	Titanium Blade Opt A-2
M80L7-002	Motor	80	25	LE	710.98	Titanium Blade Opt A-2
M80L7-003	Motor	80	25	LE	710.98	Titanium Blade Opt A-2
M50L5-004	Motor	50	30	LE	562.85	Titanium Blade Opt B-5
M50L5-005	Motor	50	30	LE	562.85	Titanium Blade Opt B-5
B80A5-006	Battery (Charged)	80	25	5 inches aft of LE	562.85	Titanium Blade Opt A-2
B80A5-007	Battery (Charged)	80	25	5 inches aft of LE	562.85	Titanium Blade Opt A-2
B80A5-008	Battery (Charged)	80	25	5 inches aft of LE	562.85	Titanium Blade Opt A-2
B80A5-009	Battery (Charged)	50	30	LE	710.98	Titanium Blade Opt B-5
B50L7-010	Battery (Charged)	50	30	LE	710.98	Titanium Blade Opt B-5
B50L7-011	Battery (Charged)	50	30	LE	710.98	Titanium Blade Opt B-5
B50L7-012	Camera	80	25	LE	710.98	Titanium Blade Opt A-2
C80L7-013	Camera	80	25	LE	710.98	Titanium Blade Opt A-2

C80L7-014	Camera	80	25	LE	710.98	Titanium Blade Opt A-2
C80L7-015	Camera	50	30	LE	562.85	Titanium Blade Opt B-5
C50L5-016	Camera	50	30	LE	562.85	Titanium Blade Opt B-5
C50L5-017	Camera	50	30	LE	562.85	Titanium Blade Opt B-5

*Note 1. Batteries were fully charged

2.4. Component Impact Test Method

The component impacts test matrix and requirements were provided by NIAR-WSU and UAH developed the test setup and conducted the tests. These tests involved high speed impact testing of a commercial quadcopter's electric motors, cameras and batteries against representative titanium intake bypass fan blades.

The test preparation sequence inside the tank included target installation, sensor hookup, lighting checks, and camera setup. The titanium blades were prepared for testing by undergoing surface preparation (heat treatment, washing, and cooling cycles), strain gauge bonding, speckle pattern application, horizontal 1-inch spaced reference lines are drawn with marker, and signal line soldering to the strain gauges. Prior to testing, each fan blade was bolted into the fixture and the strain gauge wires were connected to the Synergy DAQ. The load cells were zeroed out and tightened to 8,000 lbf of preloading and then allowed to discharge to zero. This allowed the load cells to register both tensile and compressive loads. The orthogonal view high-speed cameras were calibrated and manually focused. A calibration of the four high-speed cameras used for the Digital Image Correlation System was also performed by taking capturing images of a calibration plate. A time-delay trigger was connected to the load cell DAQ, strain gages DAQ, high-speed cameras, Digital Image Correlation System cameras, and the gas gun valve. A transistor-transistor logic (TTL) signal was sent from the time-delay generator to all the equipment to capture data at the same time. The entire equipment and sensors were calibrated in the mornings on days when tests are performed. Just before testing begins, the gas gun was cleaned and prepared. Initially, simulated masses were shot at dummy targets to validate projectile alignment, projectile impact velocity, projectile impact angle, gun settings (reservoir pressure, valve actuation time) and gun alignment (error between actual impact and desired impact location & offset impact angle).

Before the simulated masses or the actual components are fired, a triggering test was performed to verify that the trigger causes all the equipment and sensors to record data at the same time. The trigger causes the valve on the gas gun to open, however, there is no gas or projectile during triggering tests. The lights in the chamber turn on momentarily and the high-speed cameras capture data. The quality of the high-speed cameras is verified. The strain gage wires were gently shaken to verify that the wiring connections were good prior to testing.

After verifying that the pre-test procedures were completed and all checks completed, the actual component was placed inside the sabot and fired on the target. The data capture by the equipment and sensors was verified. The titanium blade was removed from the fixture and a 3D scan was performed. The chamber was then cleaned and prepared for the next test.

2.5. Full Aircraft Test Matrix Overview

UAH conducted a total of six full sUA impact tests. Table 6 provides an overview of specifications of the projectiles, targets and the impact test conditions.

Table 6. Full sUA Impact Test Matrix

Test Case	Projectile	Span [%]	Relative angle [deg]	Impact Location	Velocity [knots]	Target
D80L7-001	Full sUA*	80	25	LE	425	Titanium Blade Opt A-2
D80L7-002	Full sUA*	80	25	LE	425	Titanium Blade Opt A-2
D80L7-003	Full sUA*	80	25	LE	425	Titanium Blade Opt A-2
D50L5-004	Full sUA*	50	30	LE	425	Titanium Blade Opt B-5
D50L5-005	Full sUA*	50	30	LE	425	Titanium Blade Opt B-5
D80A5-006	Full sUA*	50	30	LE	425	Titanium Blade Opt B-5

(*) Remove legs, gimbal, camera and propellers. **Batteries were fully charged prior to the tests.**

2.6. Full sUA Impact Test Method

UAH prepared for individual full sUA impact tests by moving the component test fixture and instrumentation from the component impact test range to the full aircraft impact test range. In order to determine gun conditions (reservoir pressures) ARF personnel conducted developmental shots prior to the actual record tests. Gas gun, instrumentation, data acquisition and lighting triggering were executed in the same manner during full sUA testing as during component-level impact tests.

3. RESULTS

3.1. sUA Components Impact Testing

All 17 sUA component tests were performed. 16 of the 17 tests provided full data collection. During Test C80L7-015, the orthogonal cameras and one Digital Impact Correlation System camera did not record video.

3.1.1. Results Overview

Table 7. Task A17 Component Impact Test Results (Shown in Order of Completion)

Test #	Projectile	Target	Des Vel (kts)	Act Vel (kts)	Result
M50L5-004	Motor A	B-5	562.86 (289.56 m/s)	569 (292.72 m/s)	Plastic deformation in blade leading edge without loss of material
M50L5-005	Motor A	B-5	562.86 (289.56 m/s)	569 (292.72 m/s)	Plastic deformation in blade leading edge without loss of material
C50L5-016	Camera	B-5	562.86 (289.56 m/s)	571 (293.75 m/s)	Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact
C50L5-017	Camera	B-5	562.86 (289.56 m/s)	569 (292.72 m/s)	Plastic deformation in leading edge with a single horizontal fracture/tear that splits into two vertical fractures
C50-L5-018	Camera	B-5	562.86 (289.56 m/s)	568 (292.4 m/s)	Impact created a petal-shaped section that partially tore off away from the point of impact
M80L7-001	Motor A	A-2	710.98 (365.76 m/s)	716 (368.34 m/s)	Impact broke >4” section of material off from the leading edge of the blade
M80L7-002	Motor A	A-2	710.98 (365.76 m/s)	713 (366.8 m/s)	Impact created a 3” horizontal tear/fracture in the blade
M80L7-003	Motor A	A-2	710.98 (365.76 m/s)	715 (367.83 m/s)	Impact broke a crescent-shaped section out of the leading edge of the blade
C80L7-013	Camera	A-2	710.98 (365.76 m/s)	722 (371.43 m/s)	Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact
C80L7-014	Camera	A-2	710.98 (365.76 m/s)	711 (365.77 m/s)	Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact
C80L7-015	Camera	A-2	710.98 (365.76 m/s)	719 (369.89 m/s)	Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact
B80A5-007	Battery	A-2	562.86 (289.56 m/s)	547 (281.4 m/s)	Blade bent away from the impact in vicinity of the base at the fixture grip.

B80A5-008	Battery	A-2	562.86 (289.56 m/s)	550 (282.94 m/s)	Blade bent away from the impact in vicinity of the base at the fixture grip.
B80A5-009	Battery	A-2	562.86 (289.56 m/s)	549 (282.43 m/s)	Blade bent away from the impact in vicinity of the base at the fixture grip.
B50L7-010	Battery	B-5	710.98 (365.76 m/s)	533 (277.29 m/s)	Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 7" high and >3" wide crescent-shaped section of material from the leading edge.
B50L7-011	Battery	B-5	710.98 (365.76 m/s)	539 (277.29 m/s)	Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 8" high and >4" wide crescent-shaped section of material from the leading edge.
B50L7-012	Battery	B-5	710.98 (365.76 m/s)	532 (273.68 m/s)	Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 6" high and >3" wide crescent-shaped section of material from the leading edge.

3.1.2. Aircraft Component Impact Test Results Summary

A total of 17 test were performed during sUA Components Impact testing. The test conditions and result summaries of each of these tests are described below.

3.1.2.1. M50L5-004

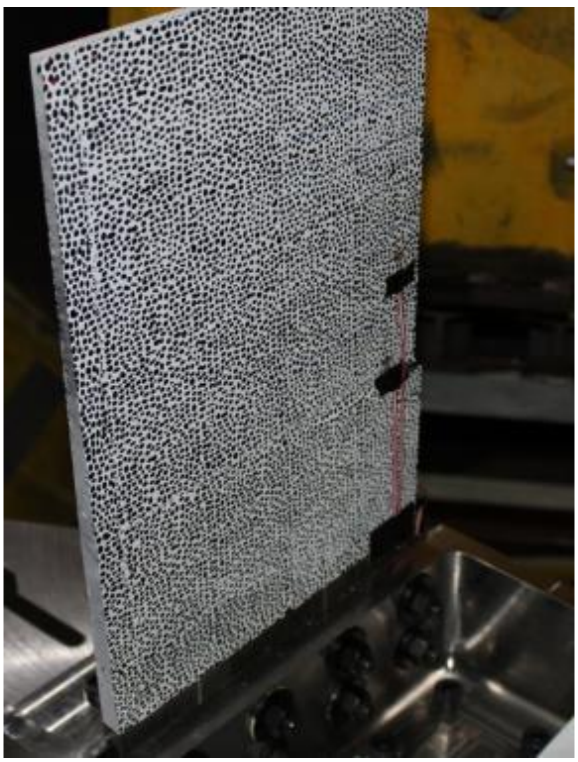
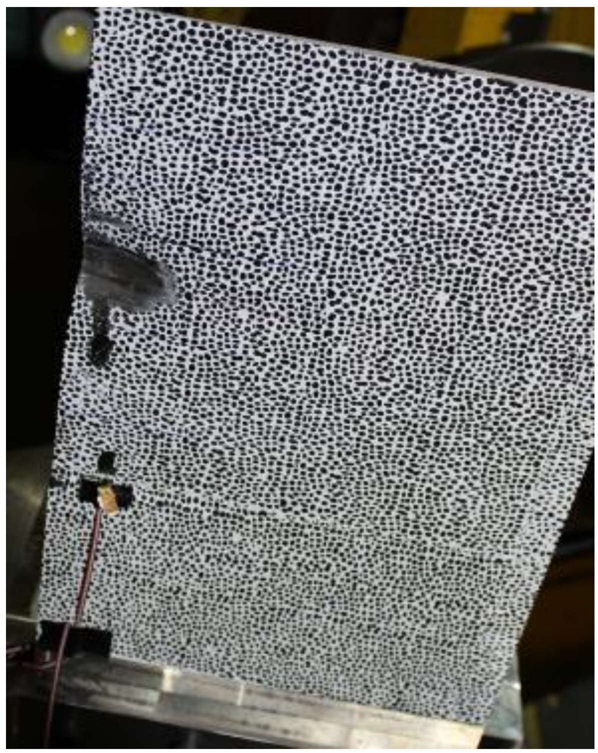
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**10-30-2020**
ARF Test ID Number	**20-183**	NIAR Test ID Number	**M50L5-004**

Test Description	Motor A impact at 569 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Motor A	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	1.8 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	569 (292.72 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary	Plastic deformation in blade leading edge without loss of material

Photos	
FAA - ASSURE TEST - # 20 - 183 - Data 10/30/2020	FAA - ASSURE TEST - # 20 - 183 - Data 10/30/2020
	

3.1.2.2. Test M50L5-005

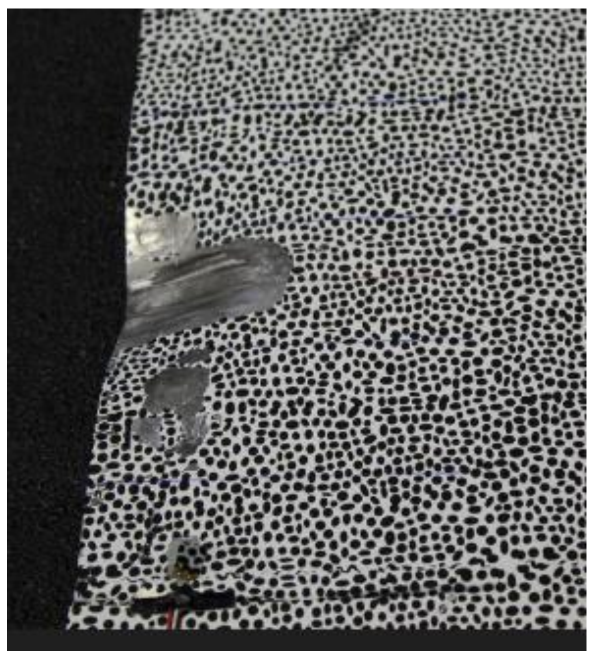
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**10-30-2020**
ARF Test ID Number	**20-184**	NIAR Test ID Number	**M50L5-005**

Test Description	Motor A impact at 568 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Motor A	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	1.8 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	569 (292.72 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary	Plastic deformation in blade leading edge without loss of material

Photos	
FAA - ASSURE TEST - # 20 - 184 - Data 10/30/2020	FAA - ASSURE TEST - # 20 - 184 - Data 10/30/2020
FAA - ASSURE TEST - # 20 - 184 - Data 10/30/2020	

3.1.2.3. C50L5-016

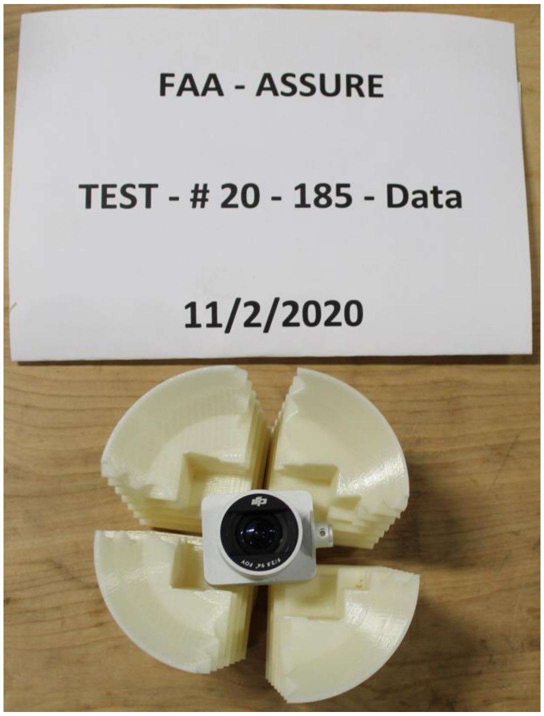
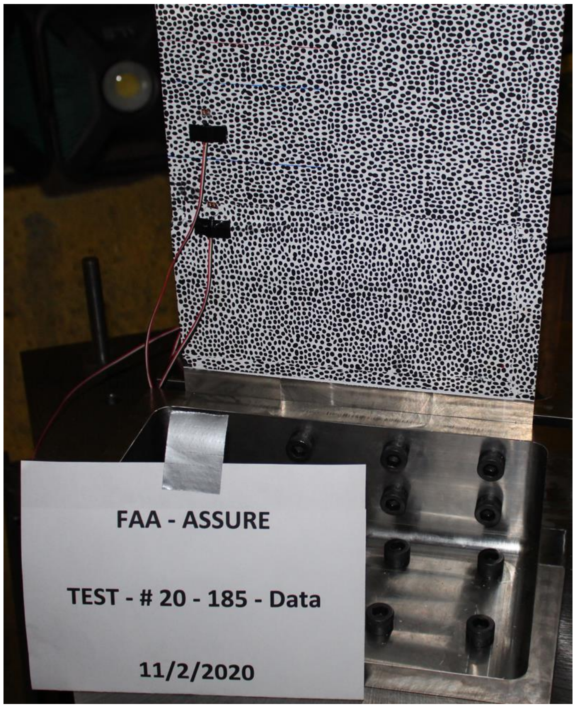
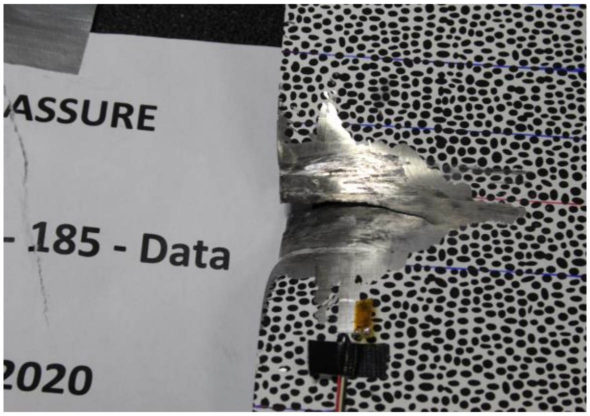
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-2-2020**
ARF Test ID Number	**20-186**	NIAR Test ID Number	**C50L5-016**

Test Description	Camera impact at 568 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	571 (293.75 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact

Photos	
FAA - ASSURE TEST - # 20 - 185 - Data 11/2/2020	FAA - ASSURE TEST - # 20 - 185 - Data 11/2/2020
	ASSURE - 185 - Data 2020

3.1.2.4. C50L5-017

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-2-2020**
ARF Test ID Number	**20-186**	NIAR Test ID Number	**C50L5-017**

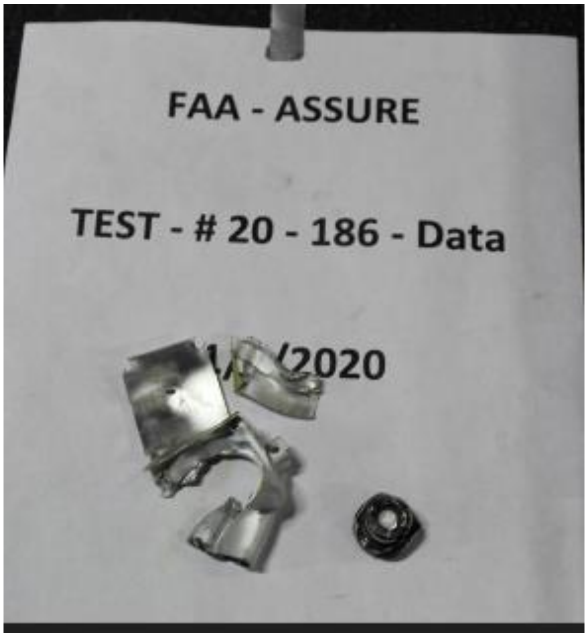
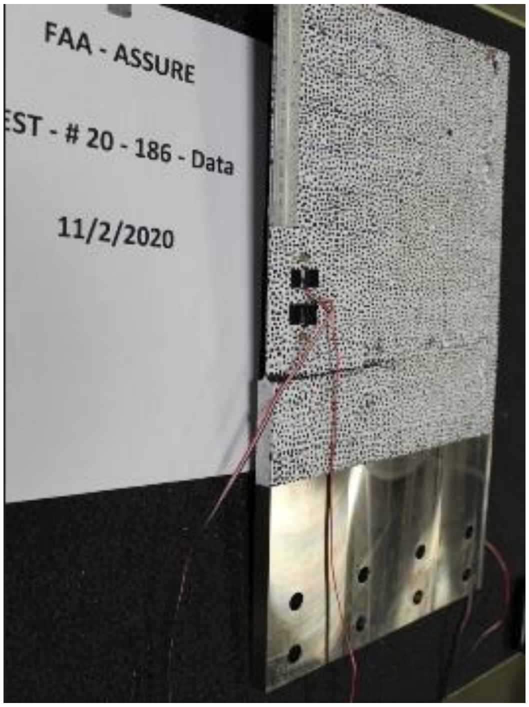
Test Description	Camera impact at 568 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	569 (292.72 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Plastic deformation in leading edge with a single horizontal fracture/tear that splits into two vertical fractures

Photos

 FAA - ASSURE TEST - # 20 - 186 - Data 11/2/2020	 FAA - ASSURE TEST - # 20 - 186 - Data
 FAA - ASSURE 11/2/2020	

3.1.2.5. C50L5-018

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-3-2020**
ARF Test ID Number	**20-187**	NIAR Test ID Number	**C50L5-018**

Test Description	Camera impact at 568 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	568 (292.4 m/s)

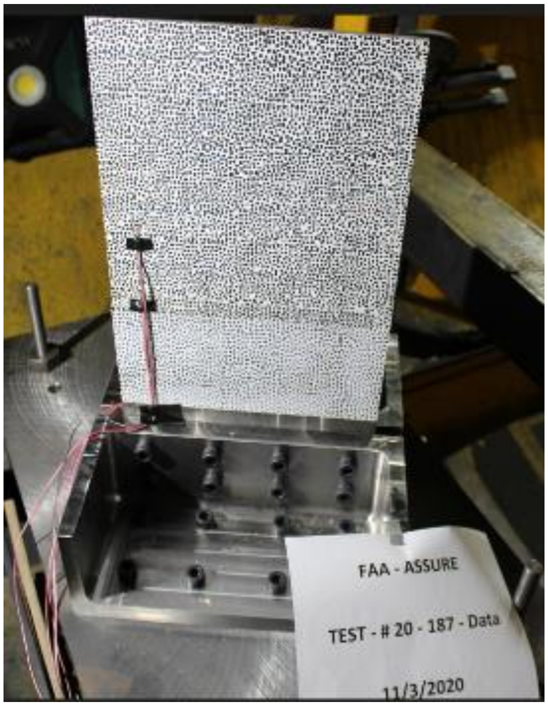
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Impact created a petal-shaped section that tore off away from the point of impact

Photos


FAA - ASSURE
TEST - # 20 - 187 - Data
11/3/2020


11/3/2020


FAA - ASSURE
TEST - # 20 - 187 - Data
11/3/2020

3.1.2.6. M80L7-001

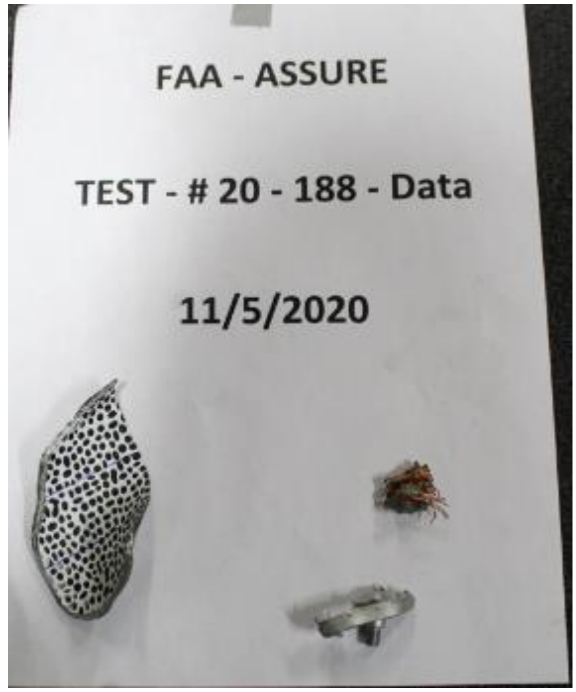
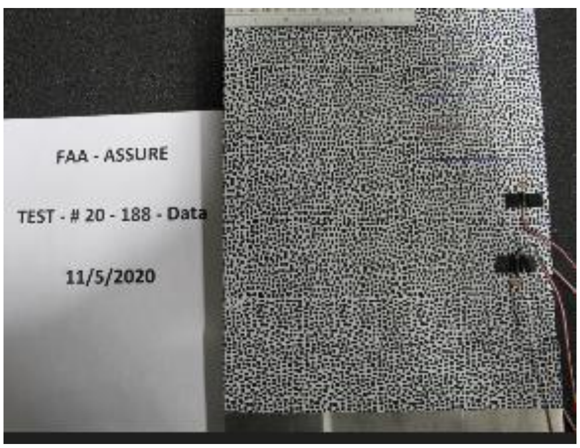
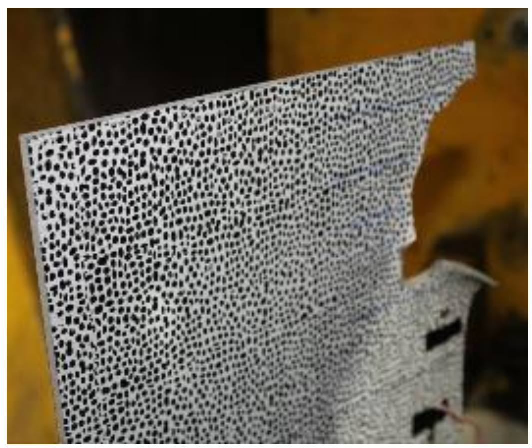
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-5-2020**
ARF Test ID Number	**20-188**	NIAR Test ID Number	**M80L7-001**

Test Description	Motor impact at 715 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Motor A	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	716 (368.34 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Impact broke a >4” section of material off from the leading edge of the blade

Photos	
FAA - ASSURE TEST - # 20 - 188 - Data 11/5/2020	FAA - ASSURE TEST - # 20 - 188 - Data 11/5/2020
FAA - ASSURE TEST - # 20 - 188 - Data 11/5/2020	

3.1.2.7. M80L7-002

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-6-2020**
ARF Test ID Number	**20-189**	NIAR Test ID Number	**M80L7-002**

Test Description	Motor impact at 713 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Motor A	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	713 (366.8 m/s)

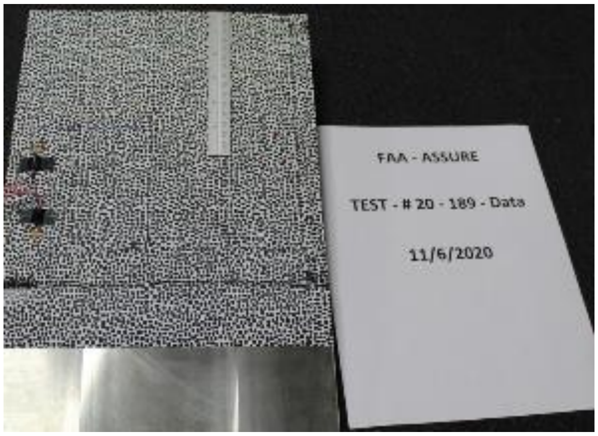
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

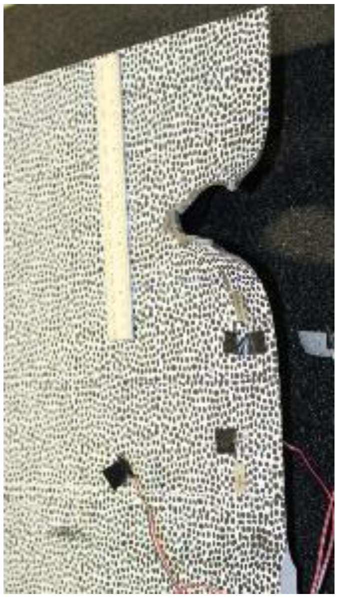
Test Results Summary Impact created a 3” horizontal tear/fracture in the blade

Photos


FAA - ASSURE
TEST - # 20 - 189 - Data
11/6/2020


FAA - ASSURE
TEST - # 20 - 189 - Data
11/6/2020


FAA - ASSURE
TEST - # 20 - 189 - Data
11/6/2020



3.1.2.8. M80L7-003

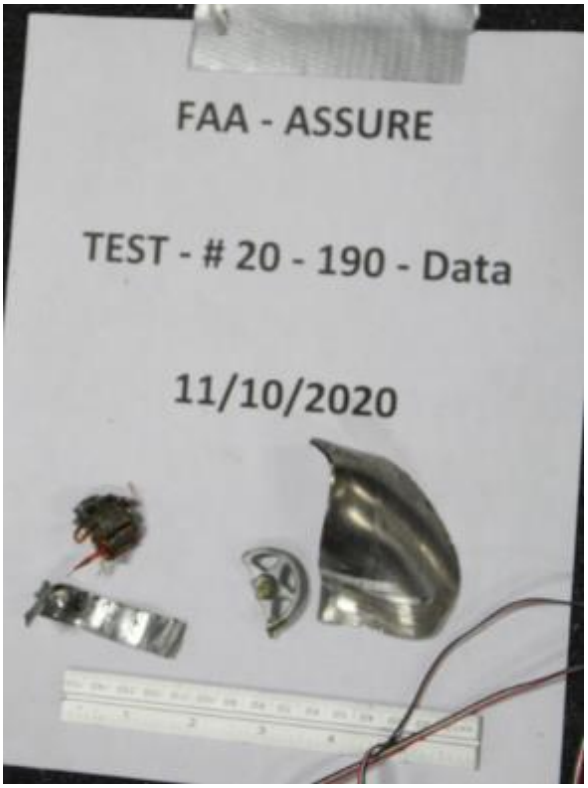
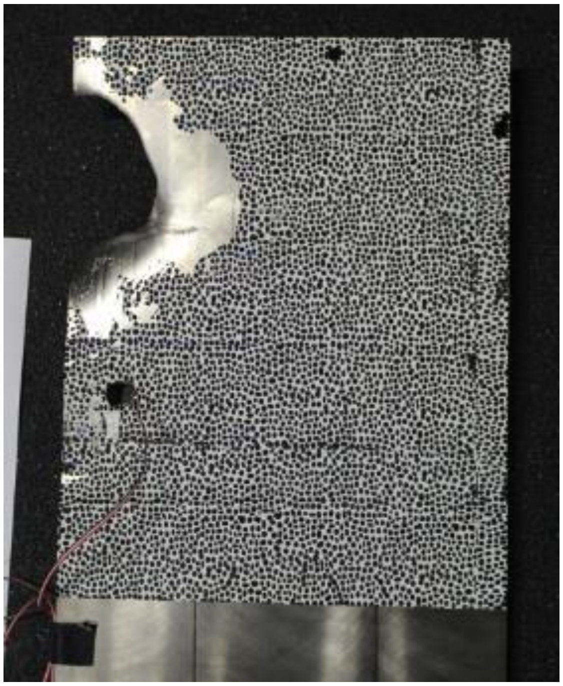
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-9-2020**
ARF Test ID Number	**20-190**	NIAR Test ID Number	**M80L7-003**

Test Description	Motor impact at 714 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Motor A	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	715 (367.83 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Impact broke a crescent-shaped section out of the leading edge of the blade

Photos	
FAA - ASSURE TEST - # 20 - 190 - Data 11/10/2020	FAA - ASSURE TEST - # 20 - 190 - Data 11/10/2020
	

3.1.2.9. C80L7-013

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-10-2020**
ARF Test ID Number	**20-191**	NIAR Test ID Number	**C80L7-013**

Test Description	Camera impact at 721 kts to the leading edge of test article design A-2 (80% span representative blade section

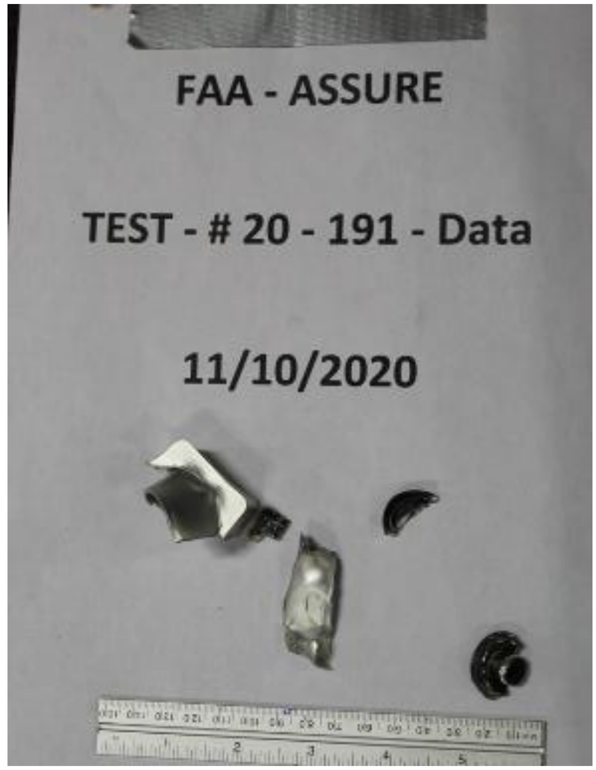
Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	722 (371.43 m/s)

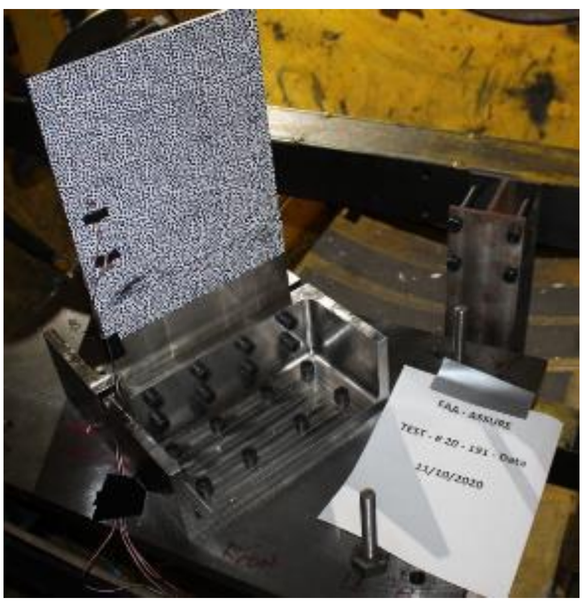
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

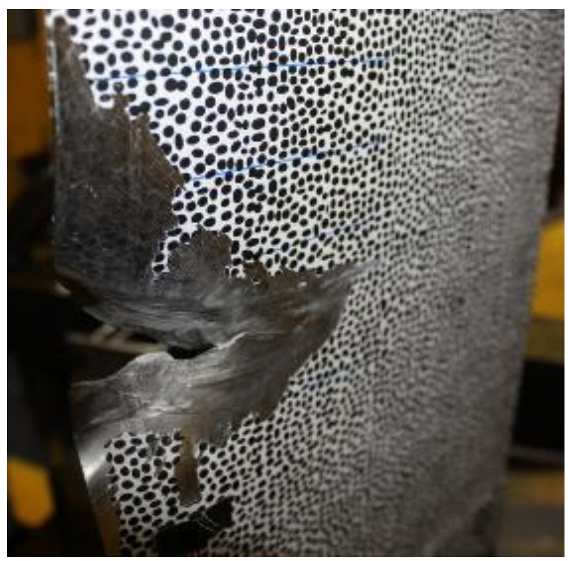
Test Results Summary Plastic deformation in leading edge with a single fracture/tear extending approx. 3" back from point of impact

Photos


FAA - ASSURE
TEST - # 20 - 191 - Data
11/10/2020


FAA - ASSURE
TEST - # 20 - 191 - Data
11/10/2020


FAA - ASSURE
TEST - # 20 - 191 - Data
11/10/2020



3.1.2.10. C80L7-014

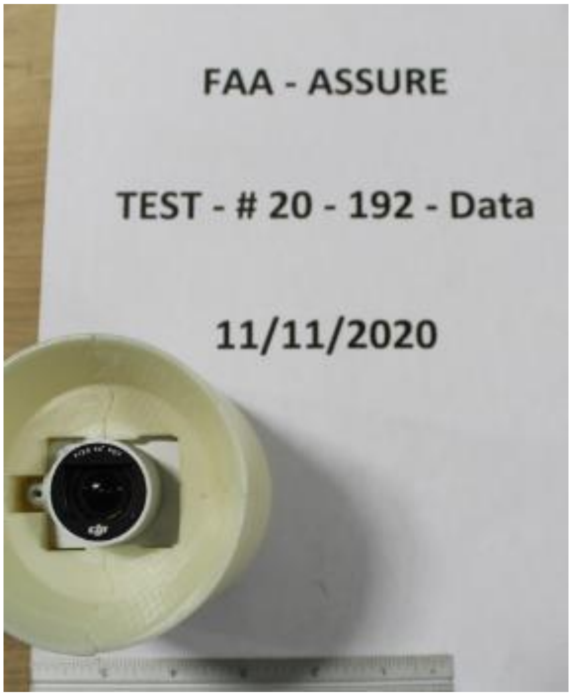
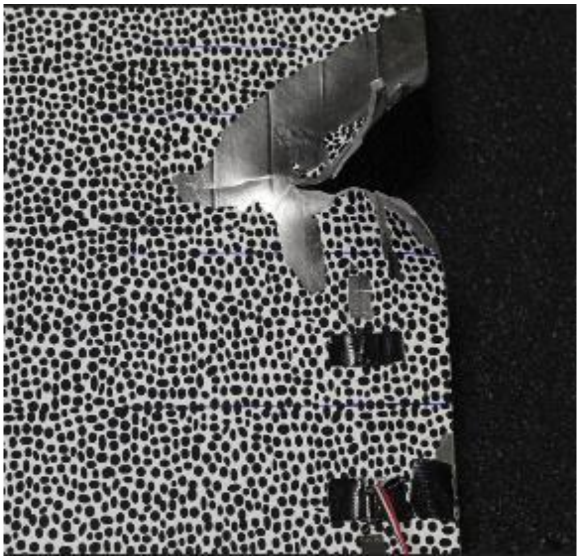
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-11-2020**
ARF Test ID Number	**20-192**	NIAR Test ID Number	**C80L7-014**

Test Description	Camera impact at 711 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	711 (365.77 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Plastic deformation in leading edge with a single fracture/tear extending approx. 3” back from point of impact

Photos	
FAA - ASSURE TEST - # 20 - 192 - Data 11/11/2020	FAA - ASSURE TEST - # 20 - 192 - Data 11/11/2020
FAA - ASSURE TEST - # 20 - 192 - Data 11/11/2020	

3.1.2.11. C80L7-015

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**11-12-2020**
ARF Test ID Number	**20-196**	NIAR Test ID Number	**C80L7-015**

Test Description	Camera impact at 718 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Camera	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	1.83 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	719 (369.89 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	N
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	N		

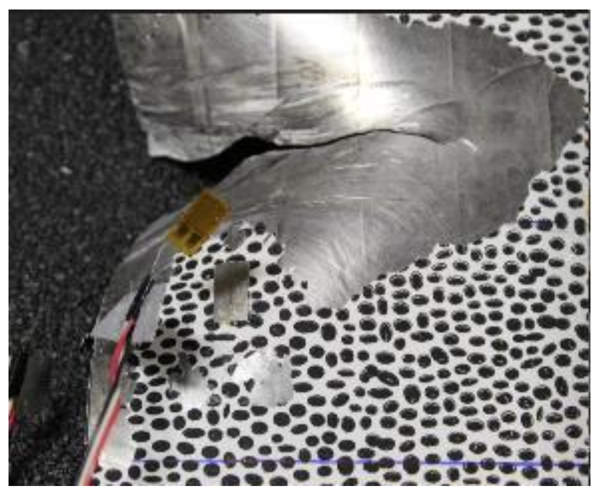
Test Results Summary Orthogonal cameras and the right DIC cameras did not trigger properly. No usable visual strain data for the right side or orthogonal video could be gathered. Plastic deformation in leading edge with a single fracture/tear extending approx. 3" back from point of impact.

Photos


FAA - ASSURE
TEST - # 20 - 196 - Data
11/12/2020


FAA - ASSURE
TEST - # 20 - 196 - Data
11/12/2020


FAA - ASSURE
TEST - # 20 - 196 - Data
11/12/2020



3.1.2.12. B80A5-007

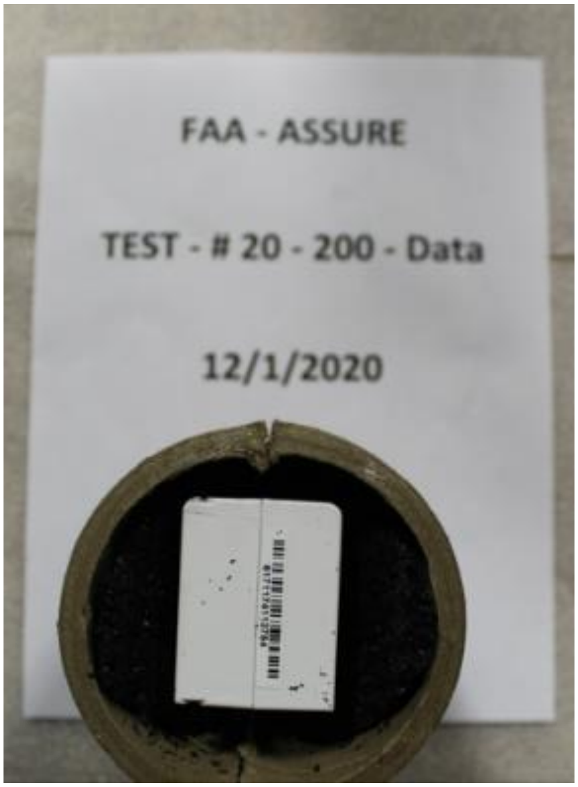
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-1-2020**
ARF Test ID Number	**20-200**	NIAR Test ID Number	**B80A5-007**

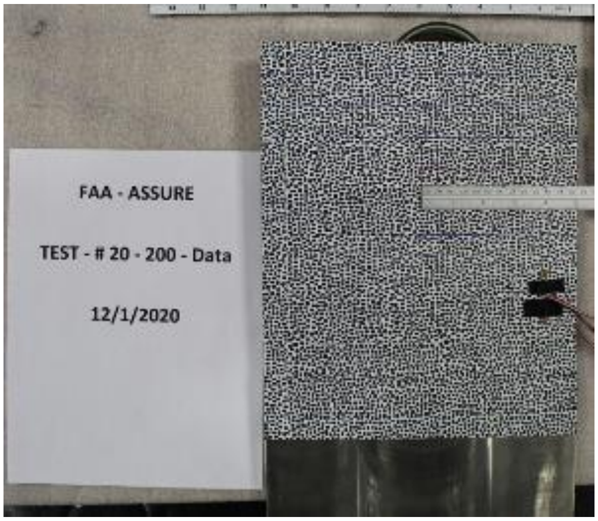
Test Description	Battery impact at 563 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	547 (281.4 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Blade bent away from the impact in vicinity of the base at the fixture grip. Battery broke apart into plastic parts, pieces of film, and Lipo dust.

Photos	
	


FAA - ASSURE
TEST - # 20 - 200 - Data
12/1/2020

3.1.2.13. B80A5-008

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-2-2020**
ARF Test ID Number	**20-201**	NIAR Test ID Number	**B80A5-008**

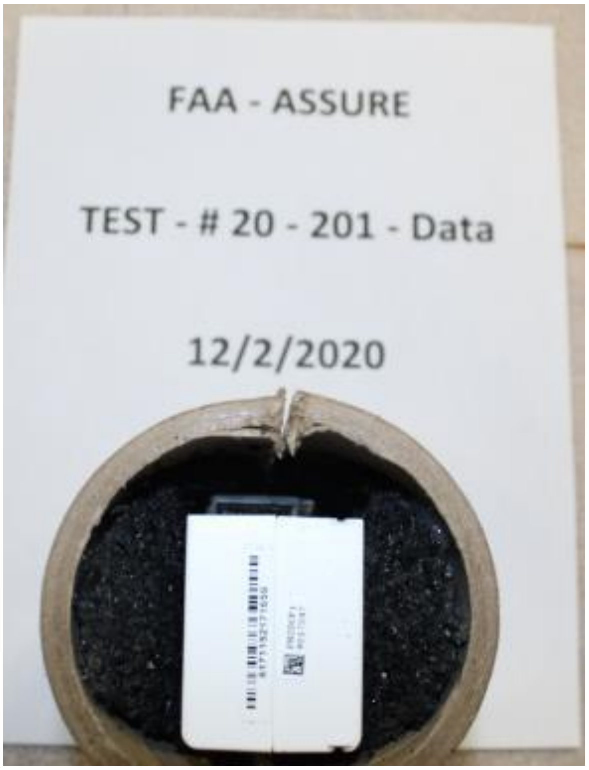
Test Description	Battery impact at 549 kts to the leading edge of test article design A-2 (80% span representative blade section

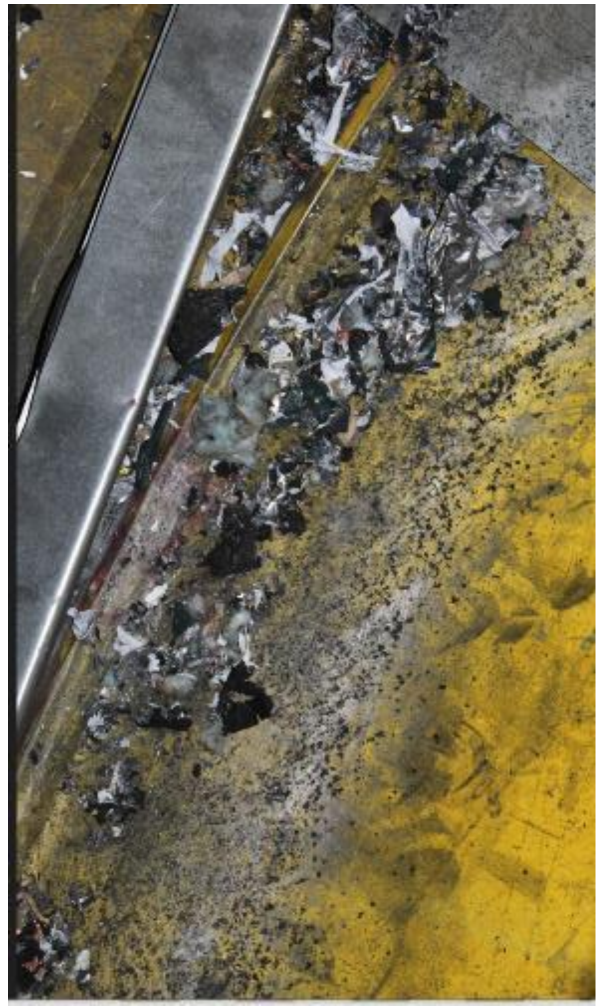
Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	550 (282.94 m/s)

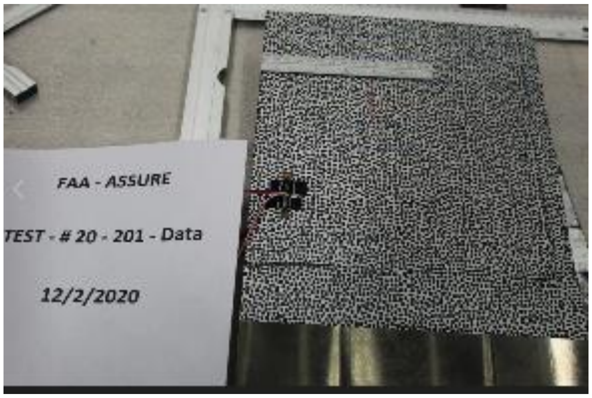
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

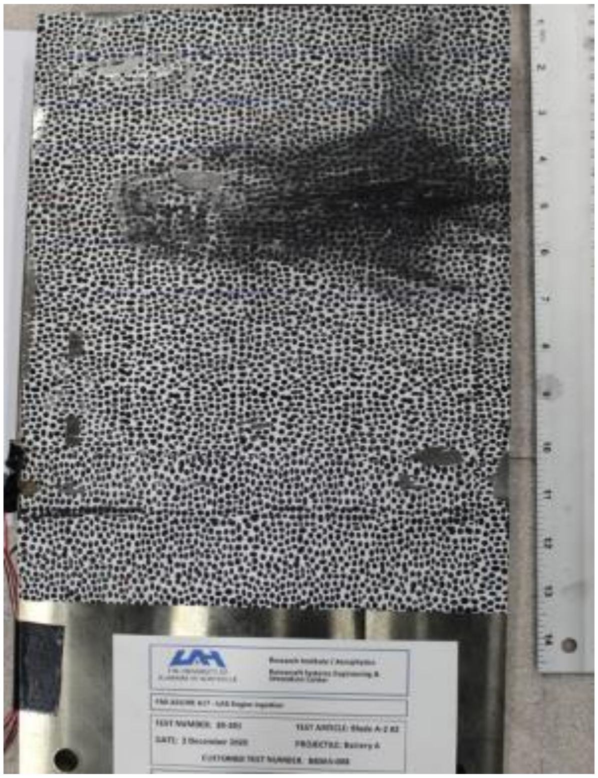
Test Results Summary Blade bent away from the impact in vicinity of the base at the fixture grip. Battery broke apart into plastic parts, pieces of film, and Lipo dust

Photos






FAA - ASSURE
TEST - # 20 - 201 - Data
12/2/2020



3.1.2.14. B80A5-009

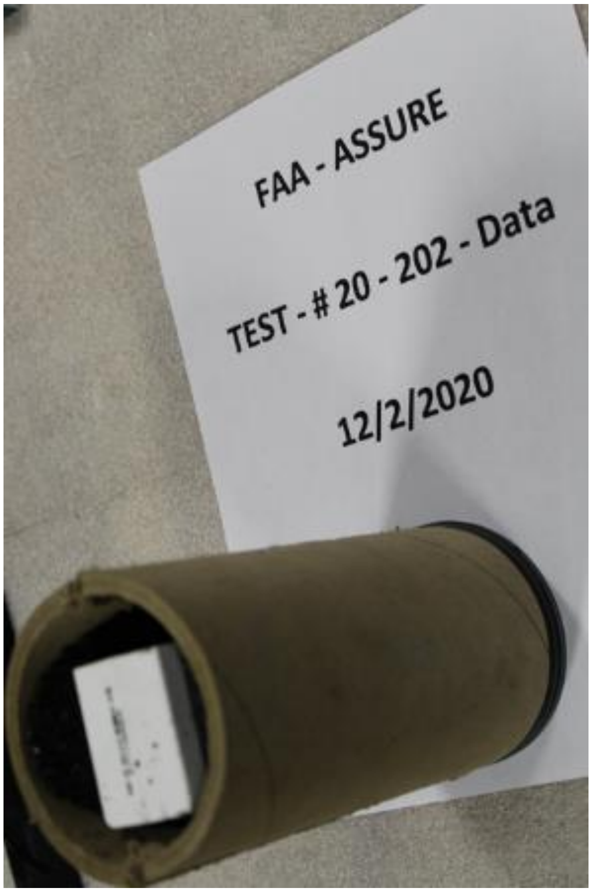
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-2-2020**
ARF Test ID Number	**20-202**	NIAR Test ID Number	**B80A5-009**

Test Description	Battery impact at 548 kts to the leading edge of test article design A-2 (80% span representative blade section

Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	562.86 (289.56 m/s)
		Actual Impact Velocity (knots)	549 (282.43 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Blade bent away from the impact in vicinity of the base at the fixture grip. Battery broke apart into plastic parts, pieces of film, and Lipo dust

Photos	
	

3.1.2.15. B50L7-010

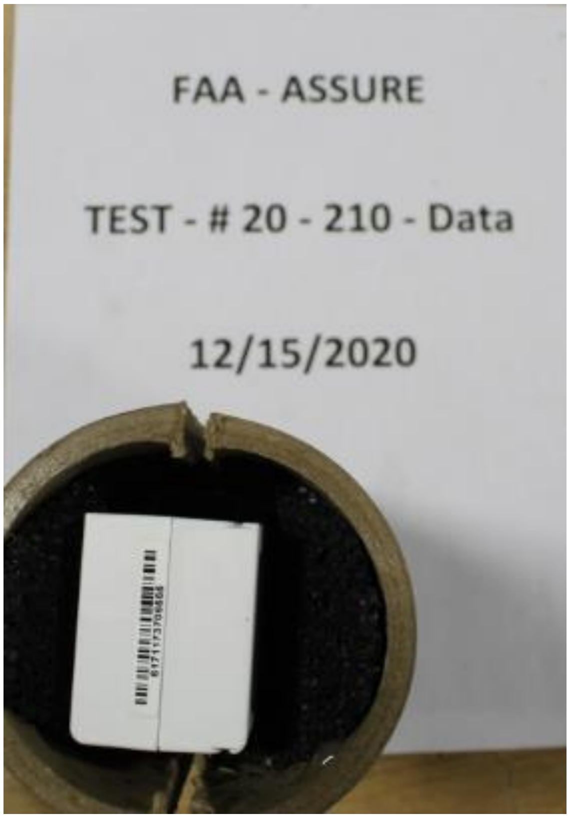
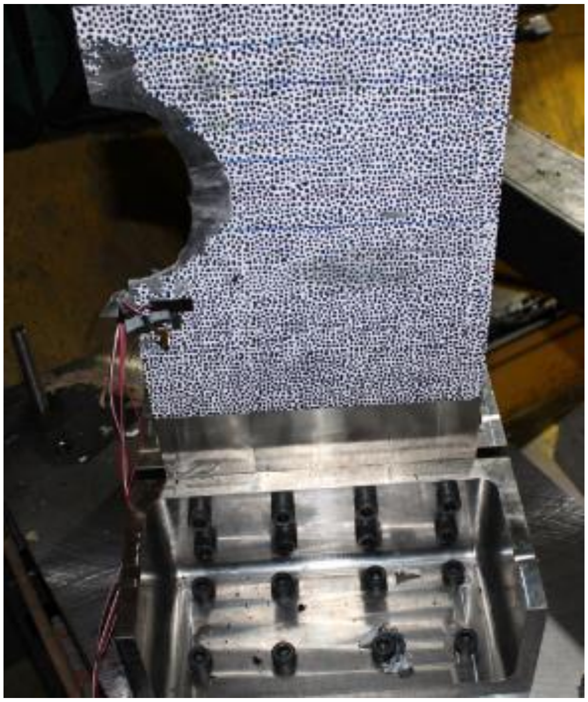
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-15-2020**
ARF Test ID Number	**20-210**	NIAR Test ID Number	**B50L7-010**

Test Description	Battery impact at 533 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	533 (277.29 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 7” high and >3” wide crescent-shaped section of material from the leading edge.

Photos	
FAA - ASSURE TEST - # 20 - 210 - Data 12/15/2020	
FAA - ASSURE TEST - # 20 - 210 - Data 12/15/2020	

3.1.2.16. B50L7-011

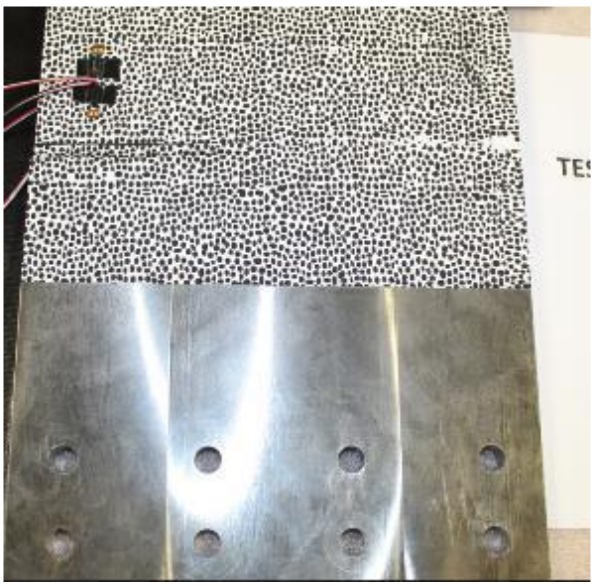
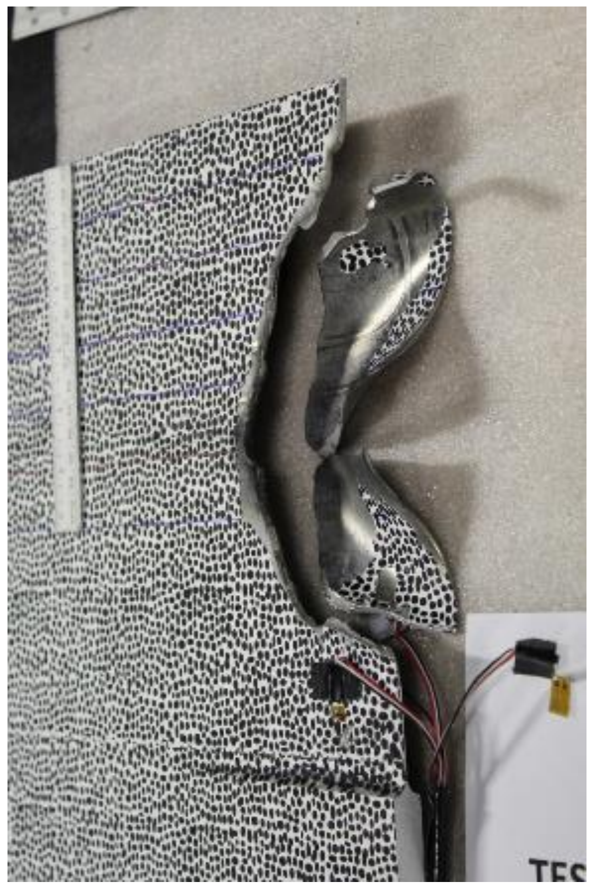
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-15-2020**
ARF Test ID Number	**20-211**	NIAR Test ID Number	**B50L7-011**

Test Description	Battery impact at 539 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	539 (277.29 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 8" high and >4" wide crescent-shaped section of material from the leading edge.

Photos	
	
	

3.1.2.17. B50L7-012

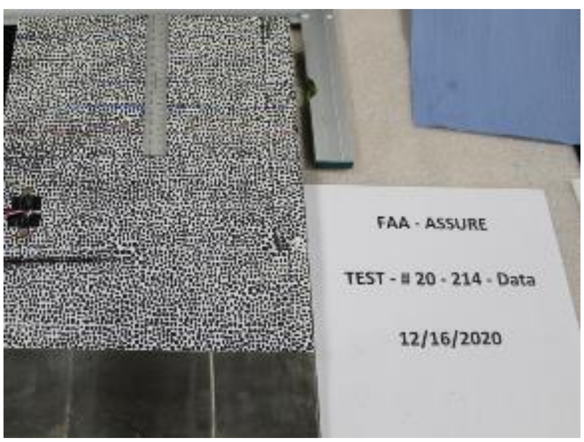
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**12-16-2020**
ARF Test ID Number	**20-214**	NIAR Test ID Number	**B50L7-012**

Test Description	Battery impact at 532 kts to the leading edge of test article design B-5 (50% span representative blade section

Test Conditions			
Projectile	Battery	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	12.8 oz.	Nominal Impact Velocity (knots)	710.98 (365.76 m/s)
		Actual Impact Velocity (knots)	532 (273.68 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary Velocity was reduced from 710kts because of battery deformation during acceleration. Battery impact removed an approximately 6" high and >3" wide crescent-shaped section of material from the leading edge.

Photos	
FAA - ASSURE
TEST - # 20 - 214 - Data	
FAA - ASSURE
TEST - # 20 - 214 - Data
12/16/2020	

4. Full sUA Impact Test Results

4.1. Full sUA Impact Testing

UAH conducted full sUA impact testing against helicopter components as shown in Table 8. UAH uploaded the full sUA impact test data sets that include strain gauge and load cell signal data, high speed videos, and still images to the NIAR ftp site for use in model calibration following each individual test.

4.1.1. Full Aircraft Impact Test Results Overview

Table 8. Full sUA Impact Testing Summary (as Executed)

Test #	Projectile	Target	Desired Velocity (kts)	Actual Velocity (kts)	Result
D80L7-001	DJI Phantom 3	A-2	425 (218.64 m/s)	406 (208.86 m/s)	The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.
D80L8-002	DJI Phantom 3	A-2	425 (218.64 m/s)	394 (202.69 m/s)	The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.
D80L7-003	DJI Phantom 3	A-2	425 (218.64 m/s)	434 (223.37 m/s)	The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.
D50L5-004	DJI Phantom 3	B-5	425 (218.64 m/s)	433 (222.75 m/s)	The aircraft impact created an approximately 6” bowed-out deformation in the leading edge of the blade. The impact did not appear to create any leading-edge fractures or tears.
D50L5-005	DJI Phantom 3	B-5	425 (218.64 m/s)	419 (215.55 m/s)	Left Side Digital Image Correlation System lighting did not trigger. Aircraft center body impact was right and aft of intended point on the leading edge, resulting in overall bending of the blade.
D50L5-006	DJI Phantom 3	B-5	425 (218.64 m/s)	428 (220.18 m/s)	The impact resulted in separation of an approximately 2.5” high and 1” wide rectangular section from the leading edge of the blade. The aircraft was reduced to debris and battery dust.

4.1.2. Full Aircraft Impact Test Results

4.1.2.1. D50L5-004

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**6-10-2021**
ARF Test ID Number	**21-52**	NIAR Test ID Number	**D50L5-004**

Test Description	405 kts impact test of DJI Phantom 3 against the leading edge of test article design B-5

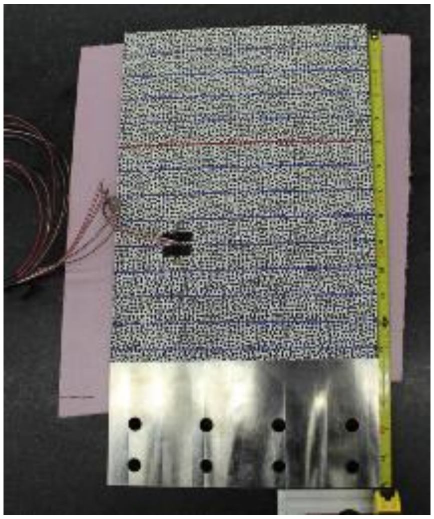
Test Conditions			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	2.04 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	10.35 lbs	Actual Impact Velocity (knots)	433 (222.75 m/s)

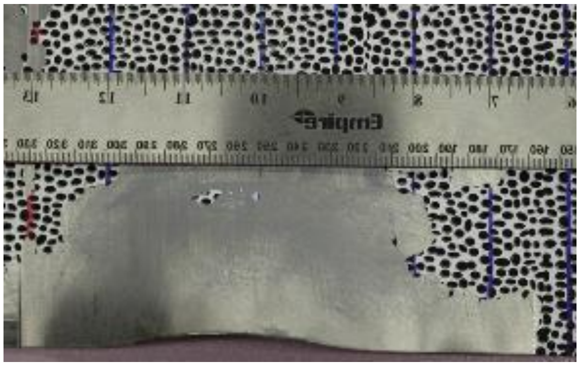
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

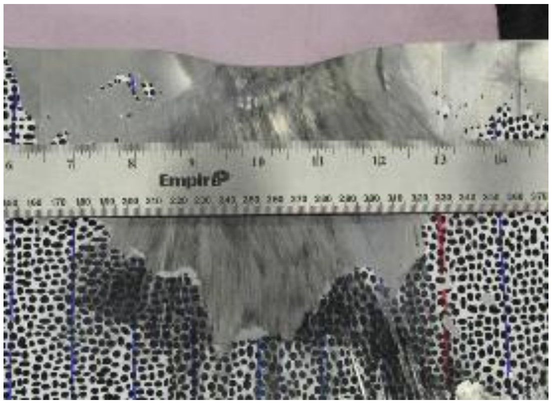
Test Results Summary The aircraft impact created an approximately 6” bowed-out deformation in the leading edge of the blade. The impact did not appear to create any leading-edge fractures or tears.

Photos

Post-impact aircraft pictures unavailable. Per discussion with ARF test personnel, the sUA was reduced to debris and battery dust during the impact.







4.1.2.2. D50L5-005

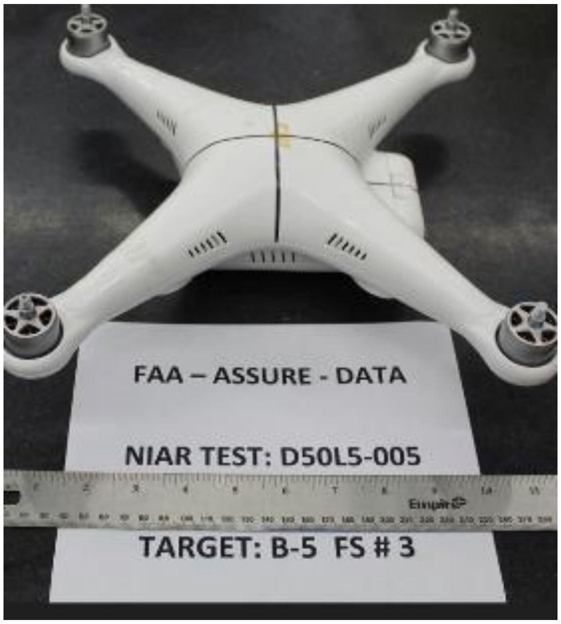
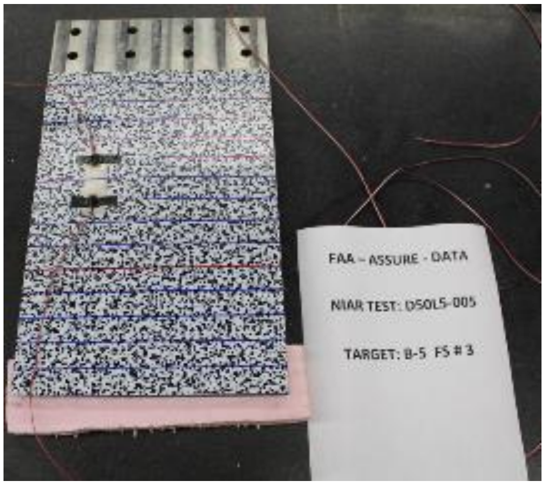
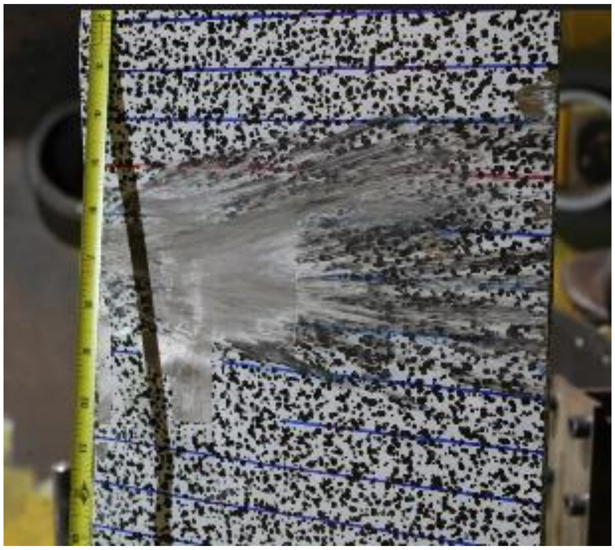
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**6-15-2021**
ARF Test ID Number	**21-55**	NIAR Test ID Number	**D50L5-005**

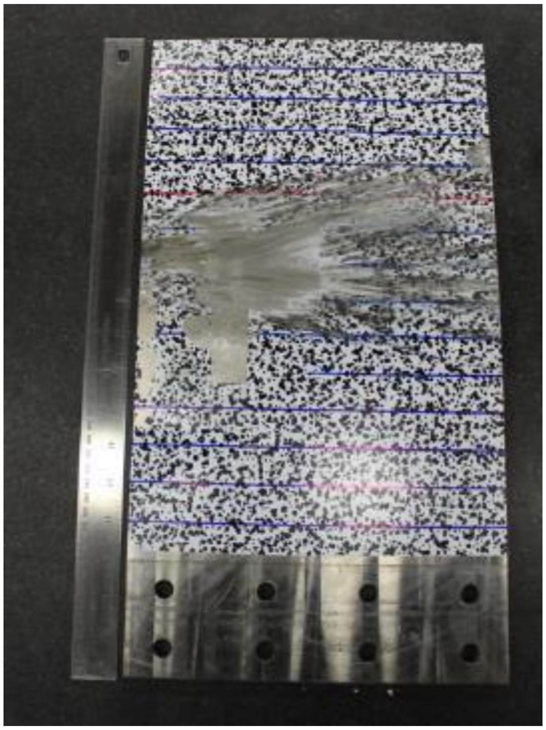
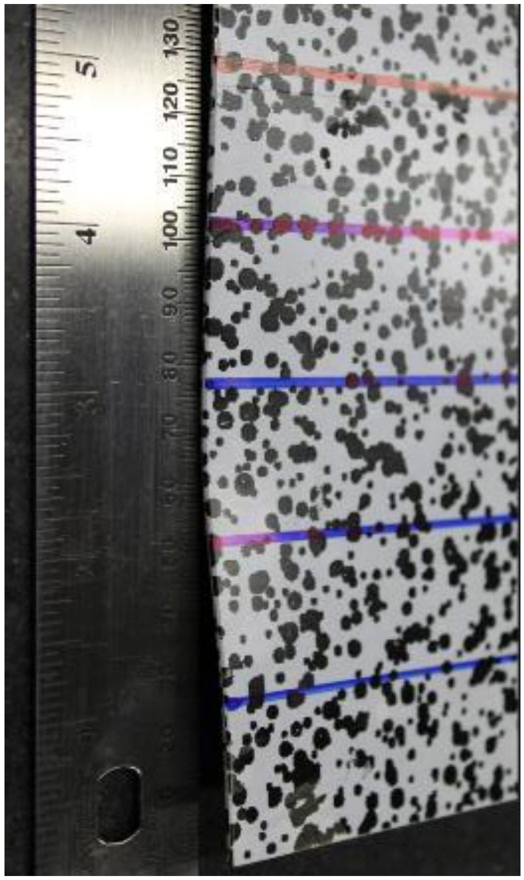
Test Description	419 kts impact test of DJI Phantom 3 against the leading edge of test article design B-5

Test Conditions			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	2.06 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	10.4 lbs	Actual Impact Velocity (knots)	419 (215.55 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	N
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	N		

Test Results Summary Left Side Digital Image Correlation System lighting did not trigger. Aircraft center body impact was right and aft of intended point on the leading edge, resulting in overall bending of the blade.

Photos	
FAA – ASSURE - DATA NIAR TEST: D50L5-005 TARGET: B-5 FS # 3	
FAA – ASSURE - DATA NIAR TEST: D50L5-005 TARGET: B-5 FS # 3	

	130 120 110 100 90 80 70 5 4

4.1.2.3. D80L7-002

General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**7-13-2021**
ARF Test ID Number	**21-82**	NIAR Test ID Number	**D80L7-002**

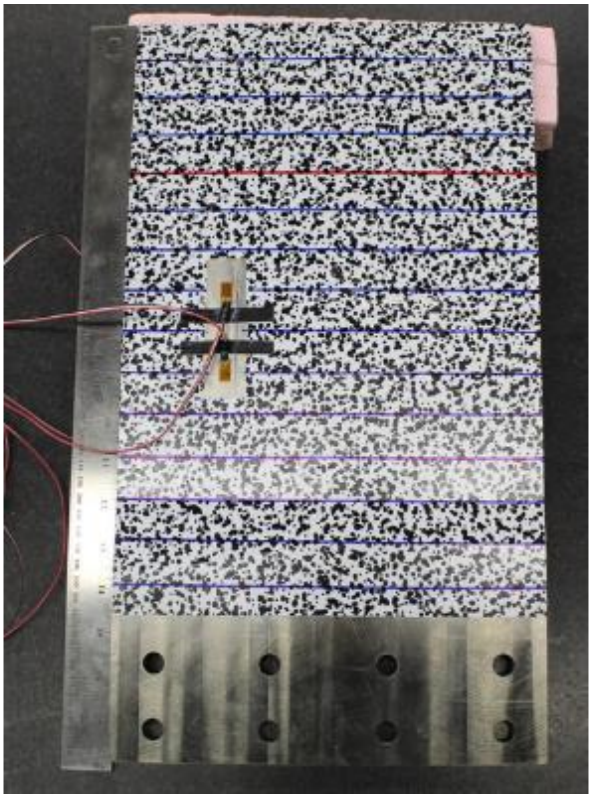
Test Description	394 kts impact test of DJI Phantom 3 against the leading edge of test article design A-2

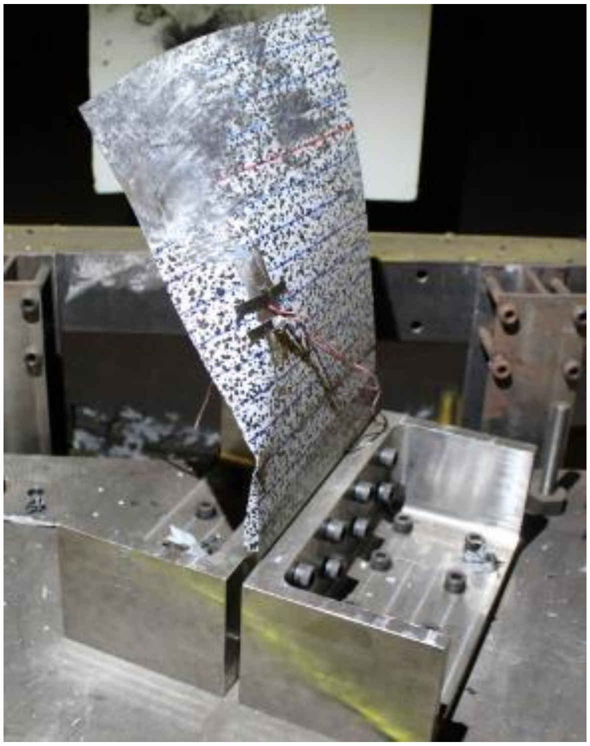
Test Conditions			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	2.02 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	8.25 lbs	Actual Impact Velocity (knots)	394 (202.69 m/s)

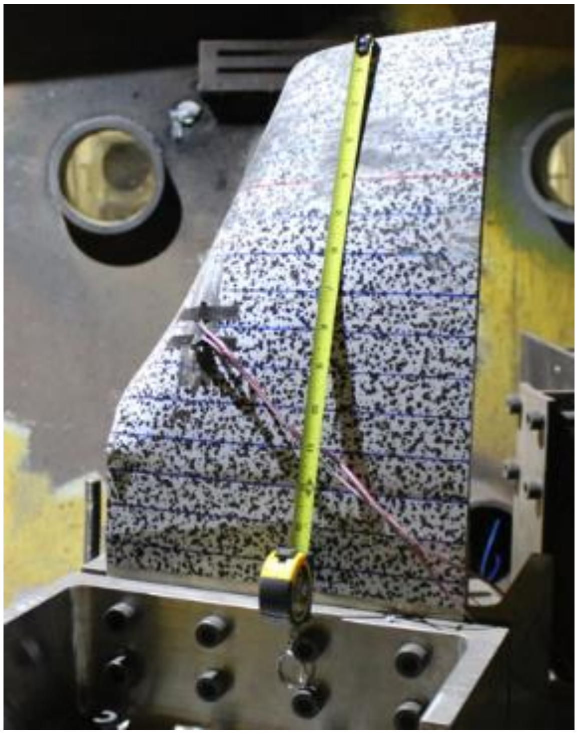
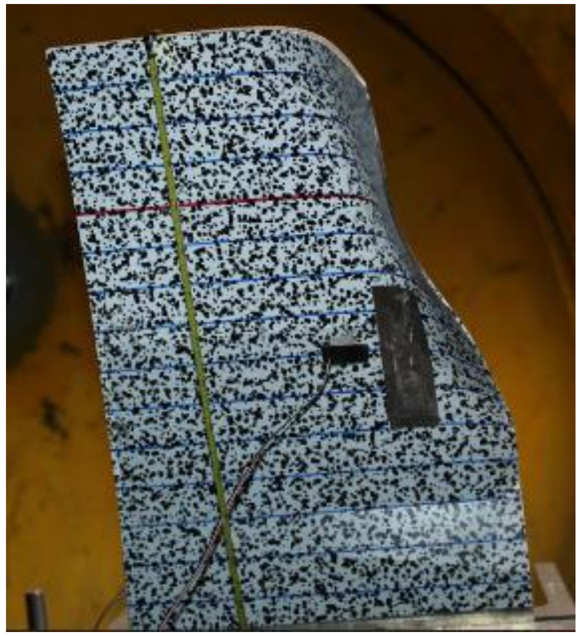
Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.

Photos





4.1.2.4. D80L7-001

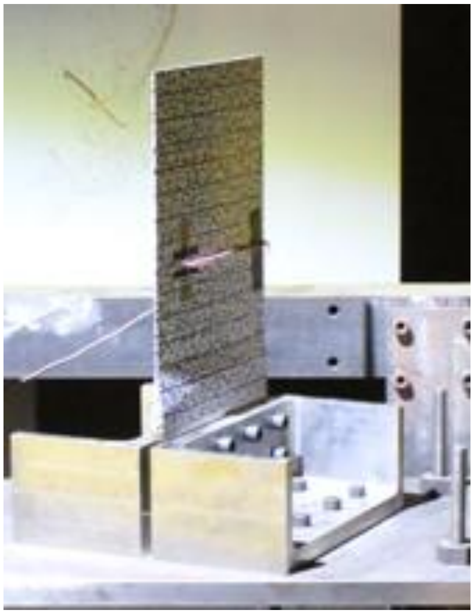
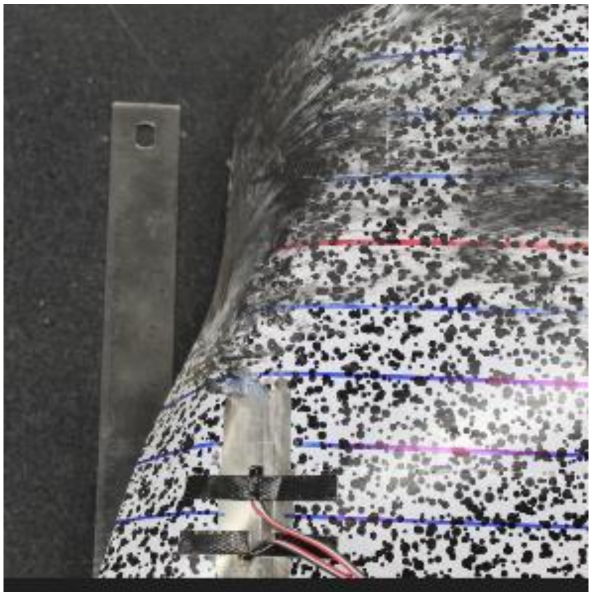
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**7-15-2021**
ARF Test ID Number	**21-82**	NIAR Test ID Number	**D80L7-001**

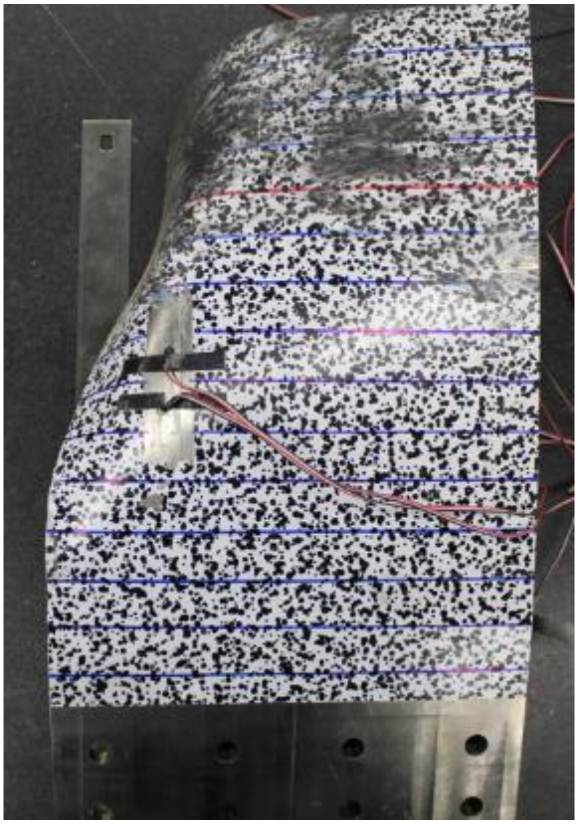
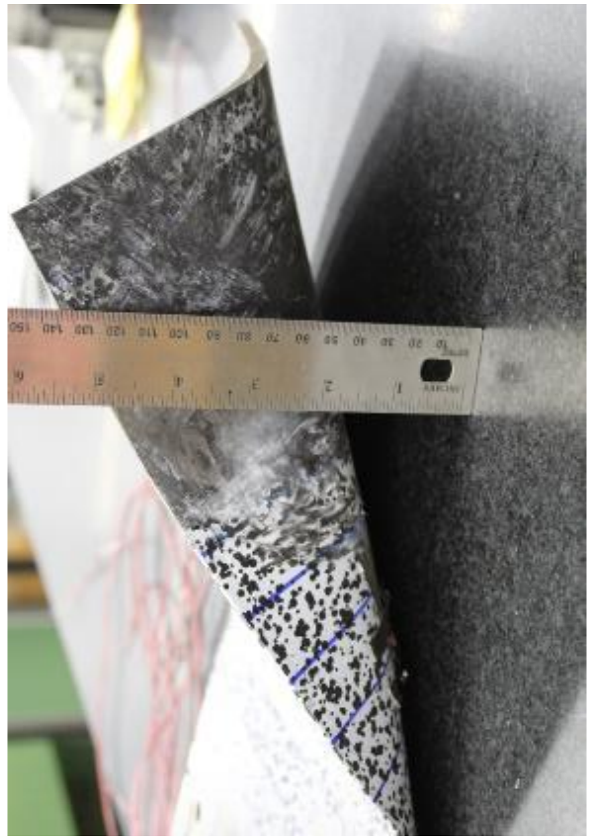
Test Description	405 kts impact test of DJI Phantom 3 against the leading edge of test article design A-2

Test Conditions			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	2.09 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	8.25	Actual Impact Velocity (knots)	406 (208.86 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.

Photos	
	There are no images of the aircraft after impact; however, ARF test personnel reported that the aircraft was reduced to debris and battery dust during the impact.
	

4.1.2.5. D80L7-003

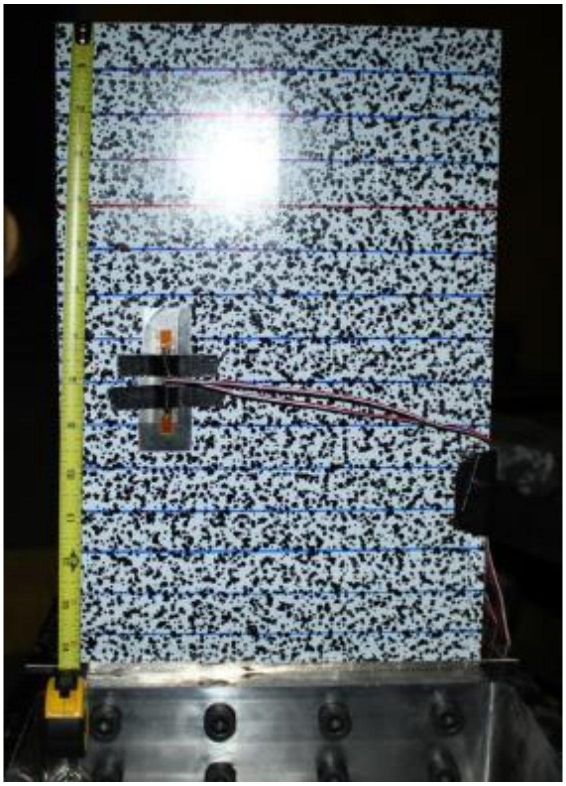
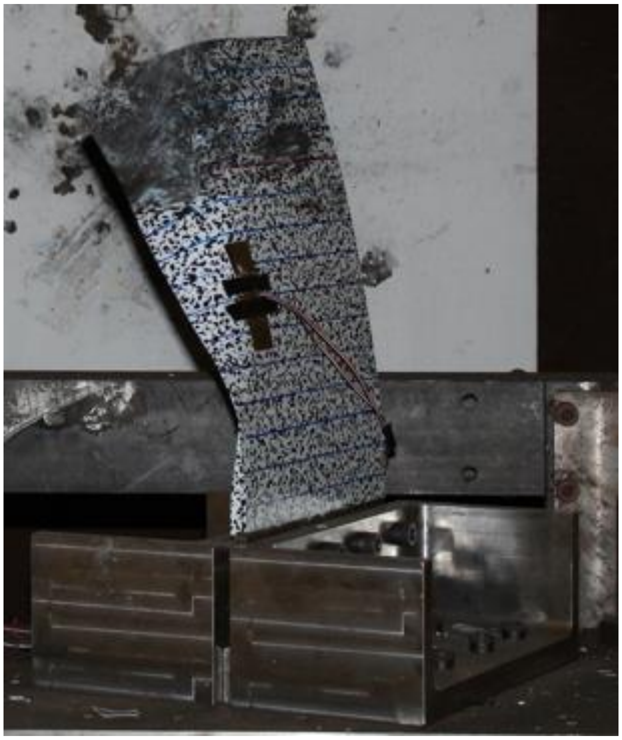
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**7-20-2021**
ARF Test ID Number	**21-84**	NIAR Test ID Number	**D80L7-003**

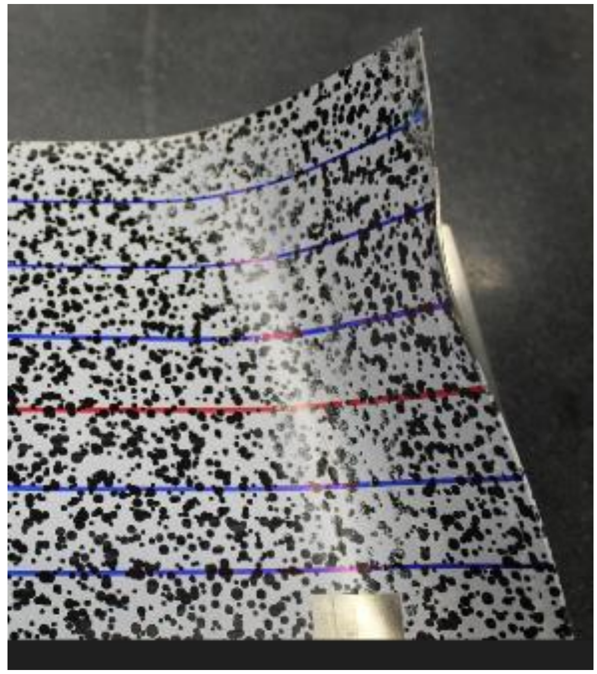
Test Description	434 kts impact test of DJI Phantom 3 against the leading edge of test article design A-2

Test Conditions The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3'' extension for bolts connection)
Projectile mass	2.02 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	8.35 lbs	Actual Impact Velocity (knots)	434 (223.27 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary The impact resulted in a significant plastic deformation in which the blade was bent away from the impact.

Photos	
	There are no images of the aircraft after impact; however, ARF test personnel reported that the aircraft was reduced to debris and battery dust during the impact.
	

4.1.2.6. D50L5-006

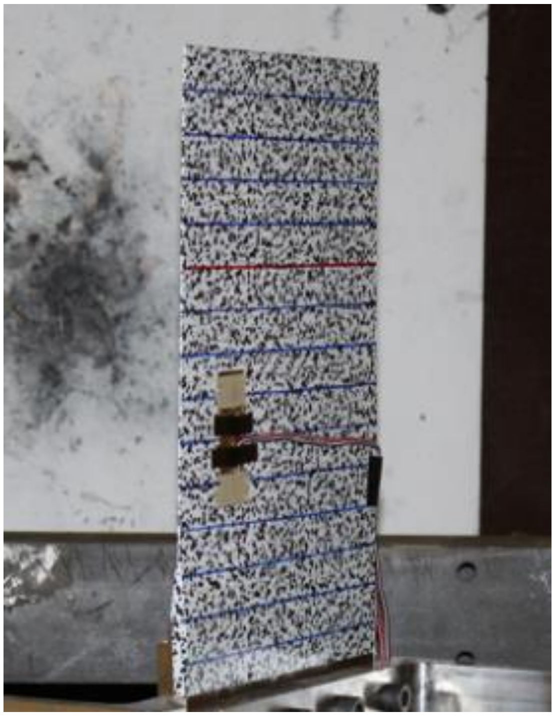
General Test Information			
Test Facility:	**SMDC-TC Aerophysics Research Facility**	Test Date	**7-22-2021**
ARF Test ID Number	**21-85**	NIAR Test ID Number	**D50L5-006**

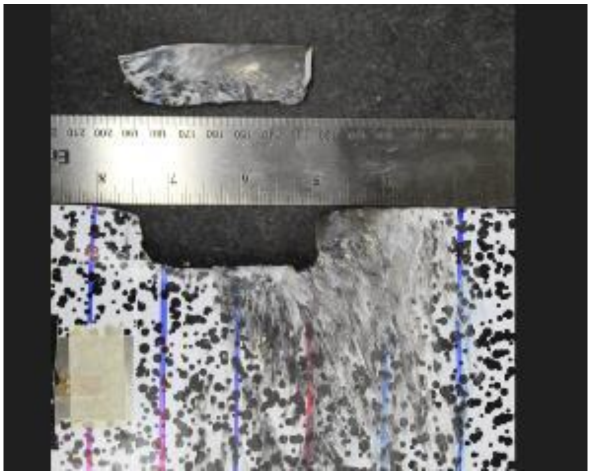
Test Description	427 kts impact test of DJI Phantom 3 against the leading edge of test article design B-5

Test Conditions			
Projectile	DJI Phantom 3 without legs or camera	Target Dimensions	10x18 (including 3’’ extension for bolts connection)
Projectile mass	2.1 lbs	Nominal Impact Velocity (knots)	425 (218.64 m/s)
Target	8.25 lbs	Actual Impact Velocity (knots)	428 (220.18 m/s)

Test Setup			
Target impact angle attained	Y	DIC system recorded properly	Y
Gun alignment in tolerance	Y	All load cells recorded data	Y
All still camera images captured	Y	All strain gages recorded data	Y
All high-speed cameras capture impact	Y		

Test Results Summary The impact resulted in separation of an approximately 2.5” high and 1” wide rectangular section from the leading edge of the blade. The aircraft was reduced to debris and battery dust.

Photos	
	
	

APPENDIX A – TEST ARTICLE MANUFACTURING PRINTS

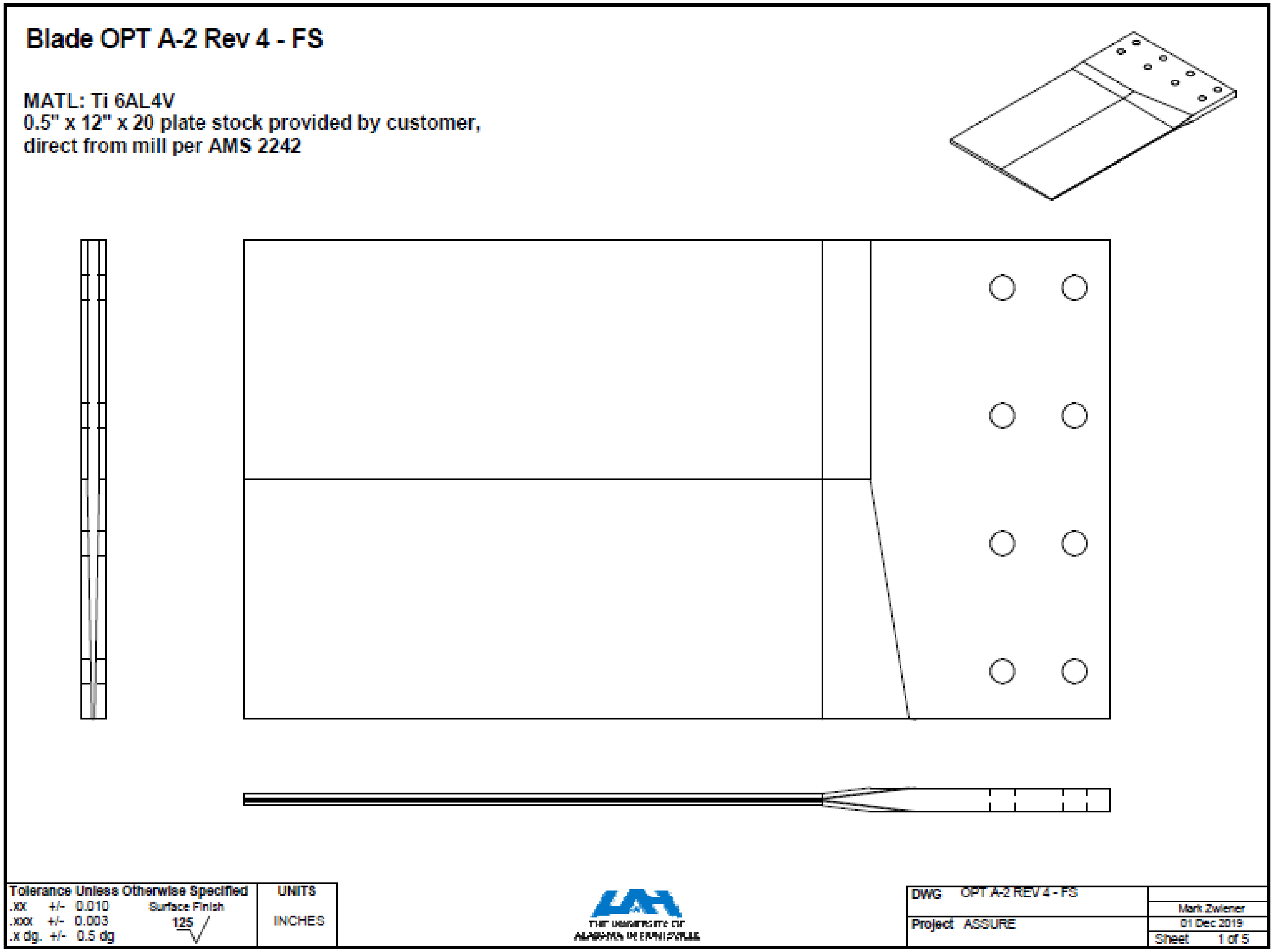


Figure A - 1 80% Span Test Article Manufacturing Print Page 1

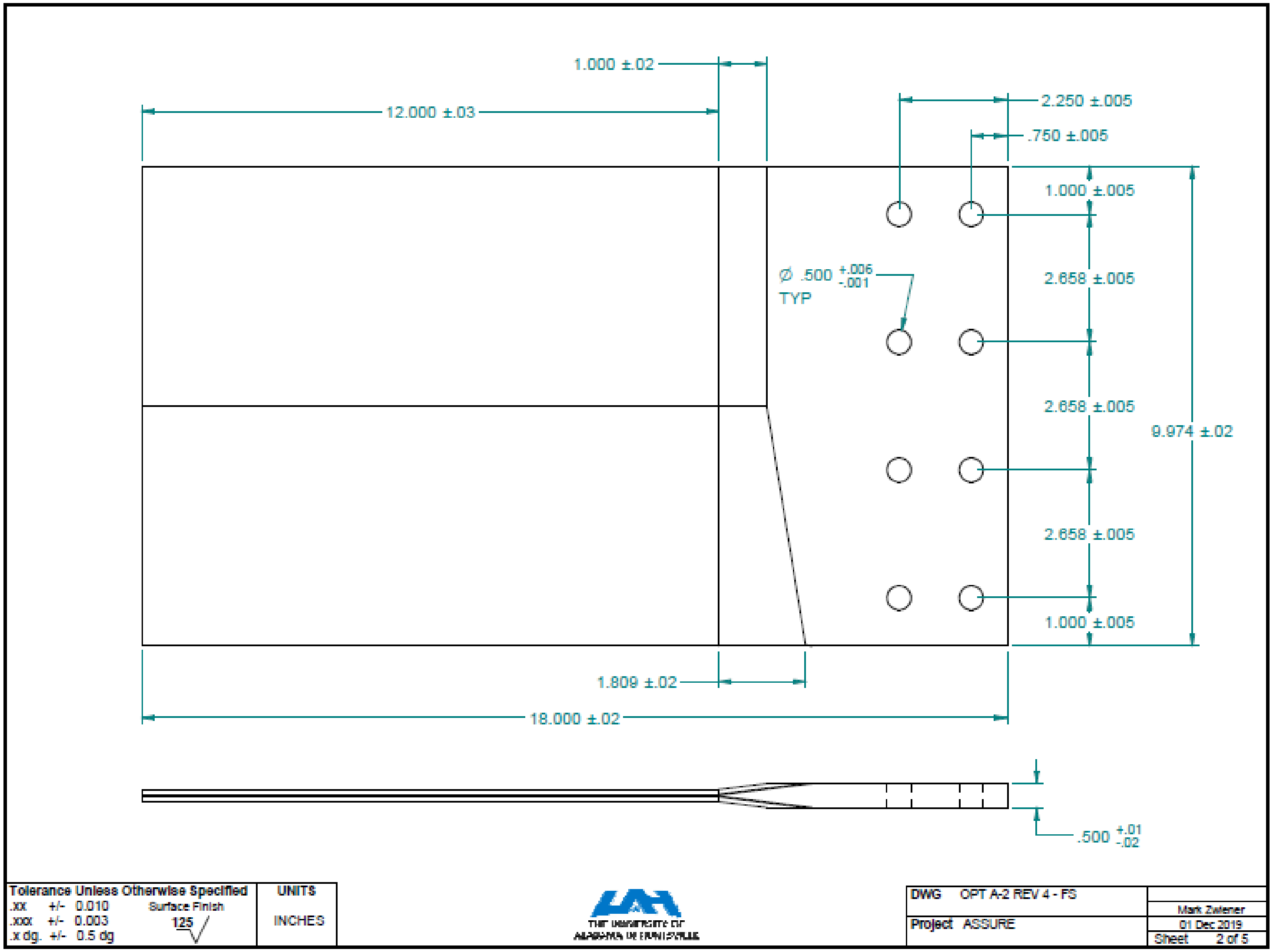
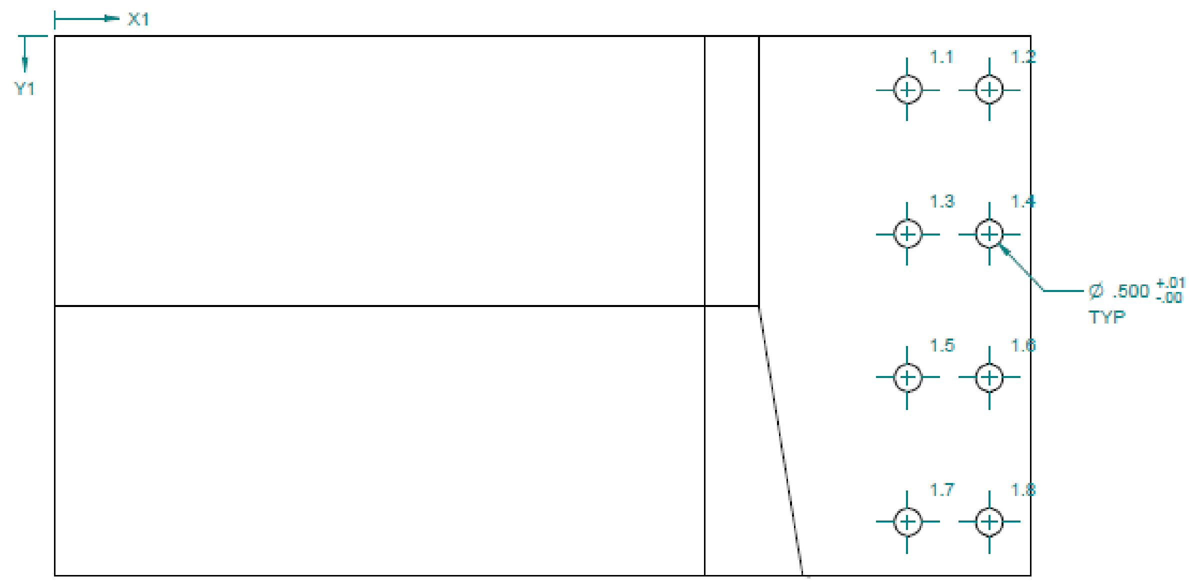


Figure A - 2 80% Span Test Article Manufacturing Print Page 2

Hole	X	Y	Size
1.1	15.75 in	-1 in	0.5 in
1.2	17.25 in	-1 in	0.5 in
1.3	15.75 in	-3.658 in	0.5 in
1.4	17.25 in	-3.658 in	0.5 in
1.5	15.75 in	-6.316 in	0.5 in
1.6	17.25 in	-6.316 in	0.5 in
1.7	15.75 in	-8.974 in	0.5 in
1.8	17.25 in	-8.974 in	0.5 in



Tolerance Unless Otherwise Specified
.xx +/- 0.010
.xxx +/- 0.003
.x dg. +/- 0.5 dg
Surface Finish 125

UNITS
INCHES

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

DWG OPT A-2 REV 4 - FS
Project ASSURE
Mark Zwiener
01 Dec 2019
Sheet 3 of 5

Figure A - 3 80% Span Test Article Manufacturing Print Page 3

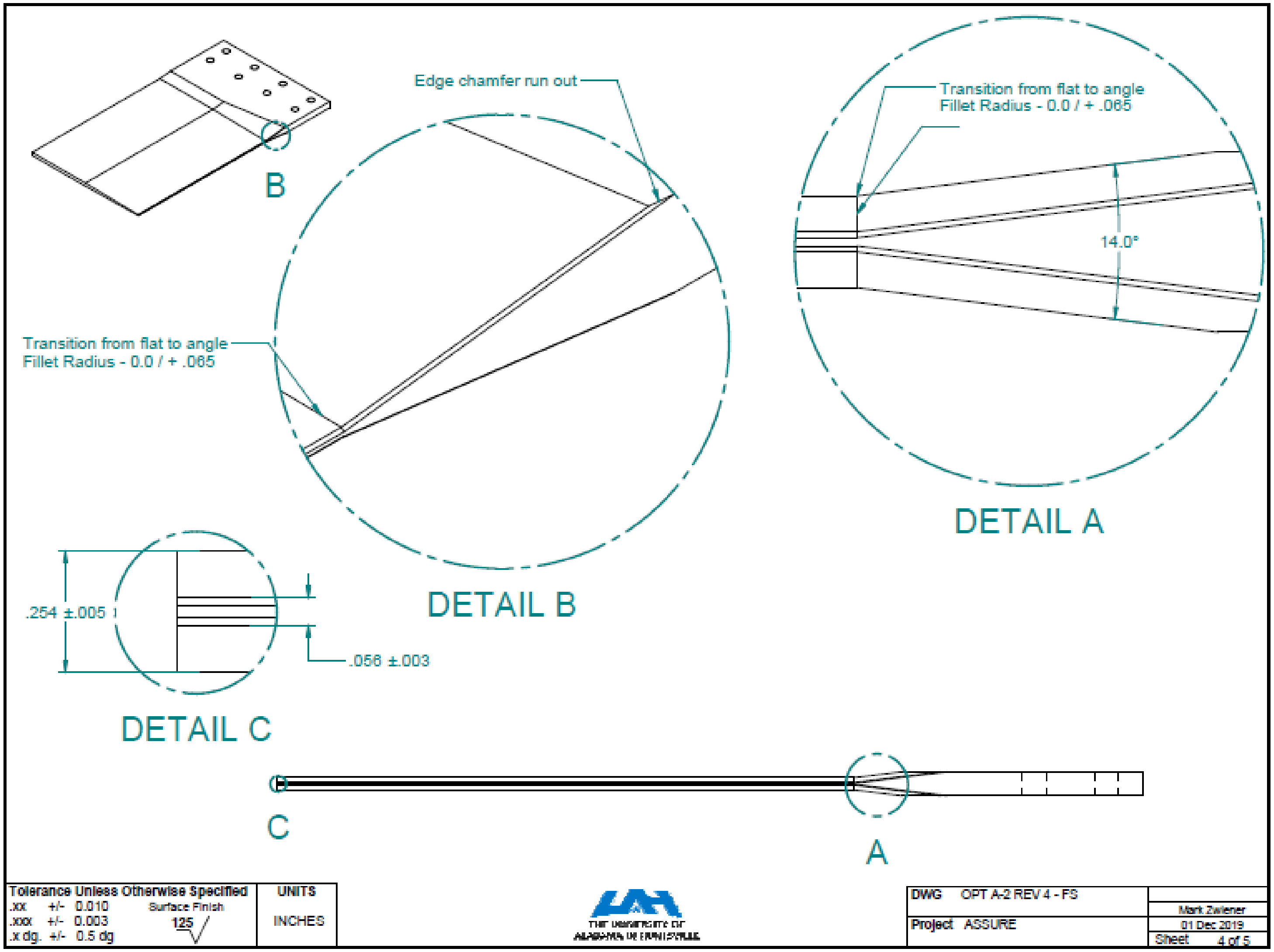


Figure A - 4 80% Span Test Article Manufacturing Print Page 4

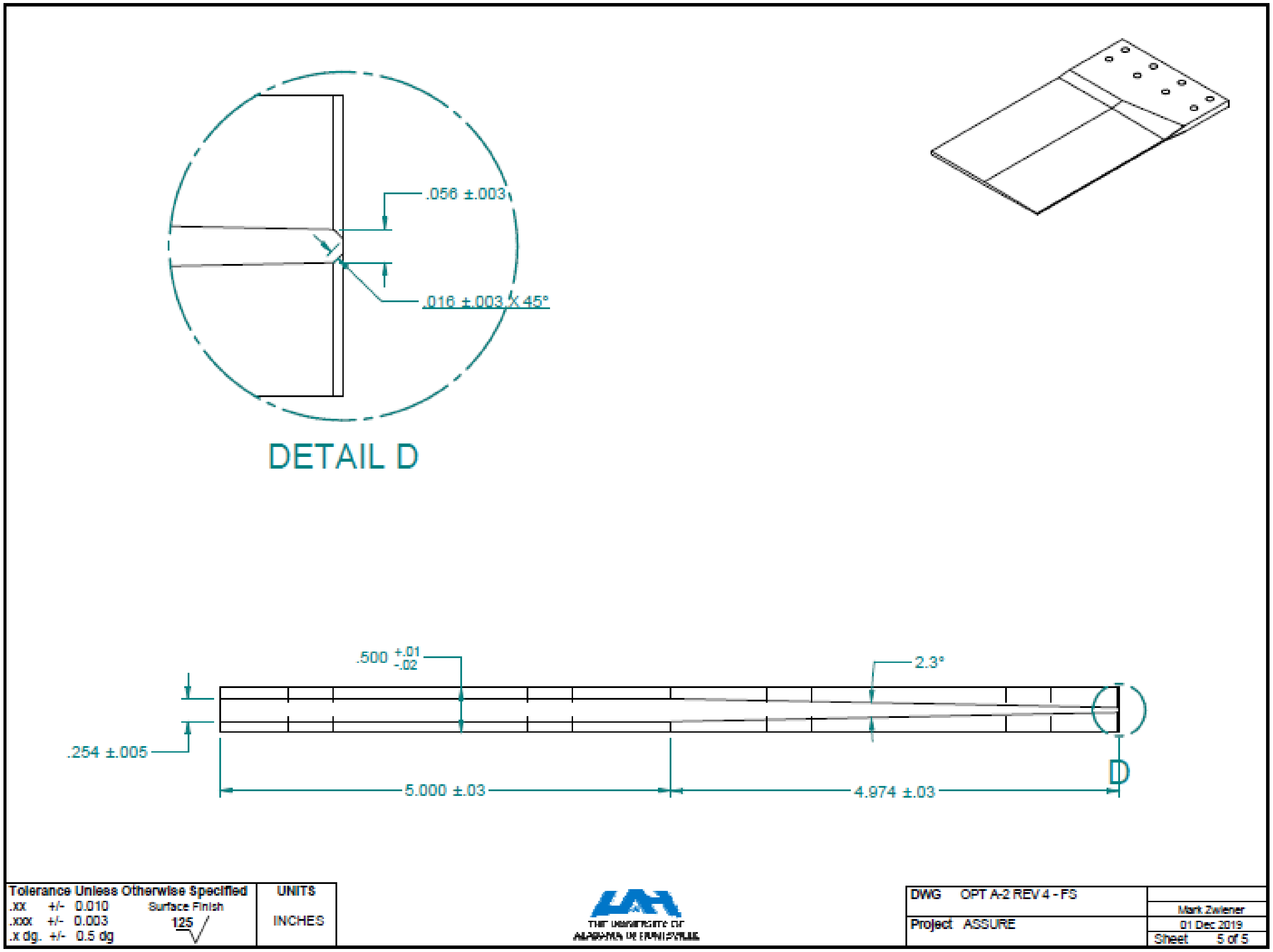


Figure A - 5 80% Span Test Article Manufacturing Print Page 5

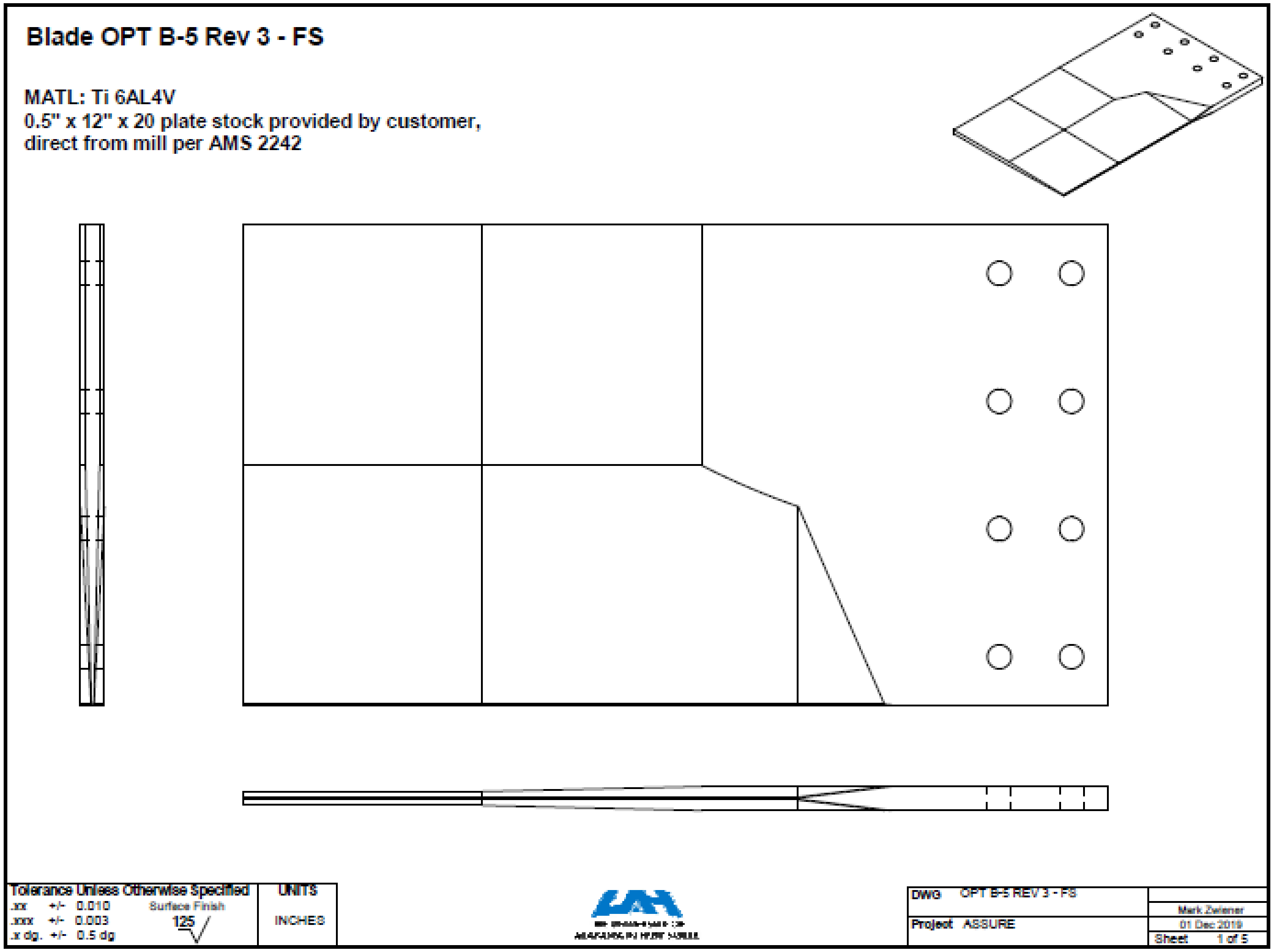


Figure A - 6 50% Span Test Article Manufacturing Print Page 1

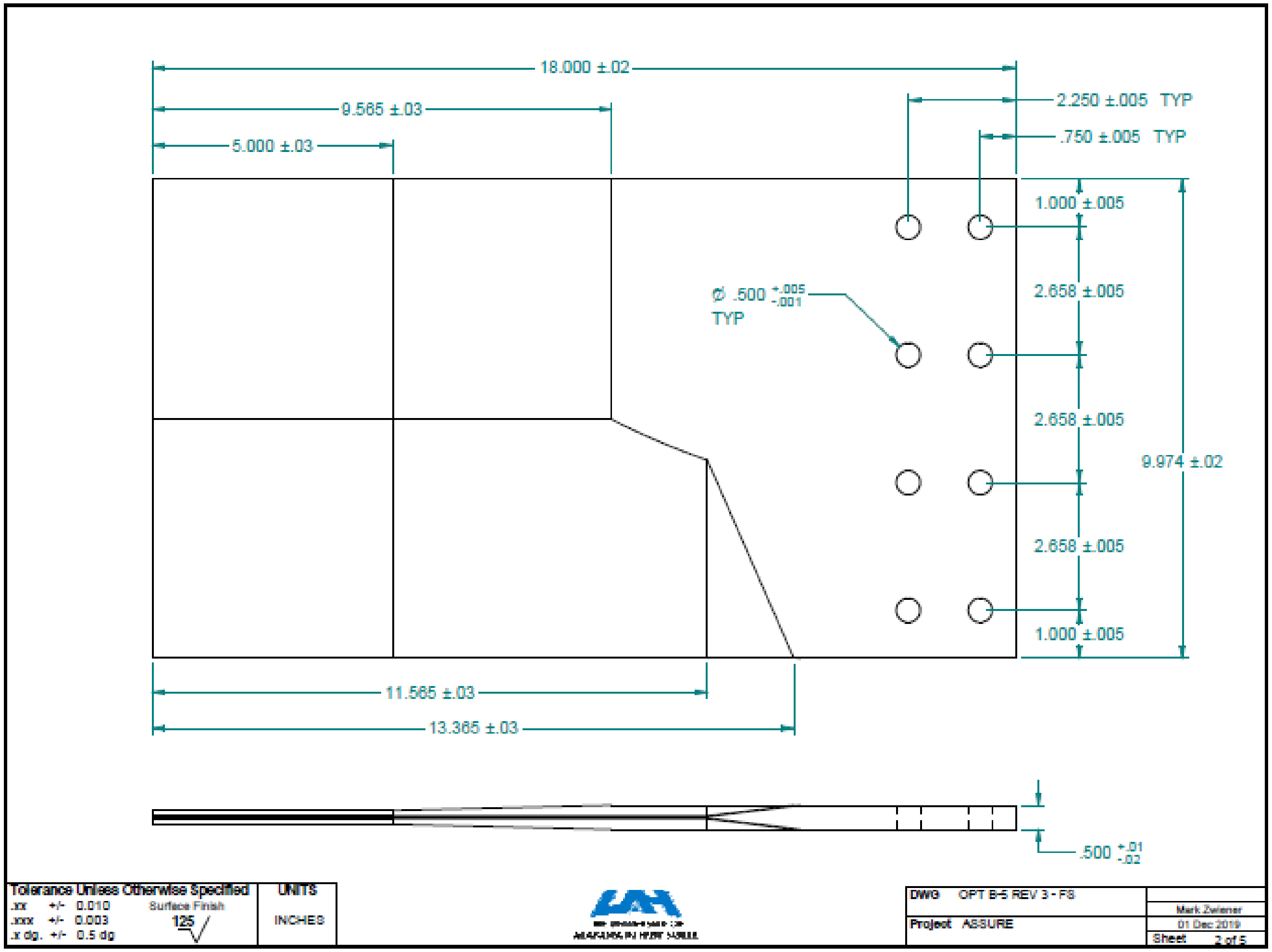


Figure A - 7 80% Span Test Article Manufacturing Print Page 2

Hole	X	Y	Size
1.1	15.75 in	-1 in	0.5 in
1.2	17.25 in	-1 in	0.5 in
1.3	15.75 in	-3.658 in	0.5 in
1.4	17.25 in	-3.658 in	0.5 in
1.5	15.75 in	-6.316 in	0.5 in
1.6	17.25 in	-6.316 in	0.5 in
1.7	15.75 in	-8.974 in	0.5 in
1.8	17.25 in	-8.974 in	0.5 in

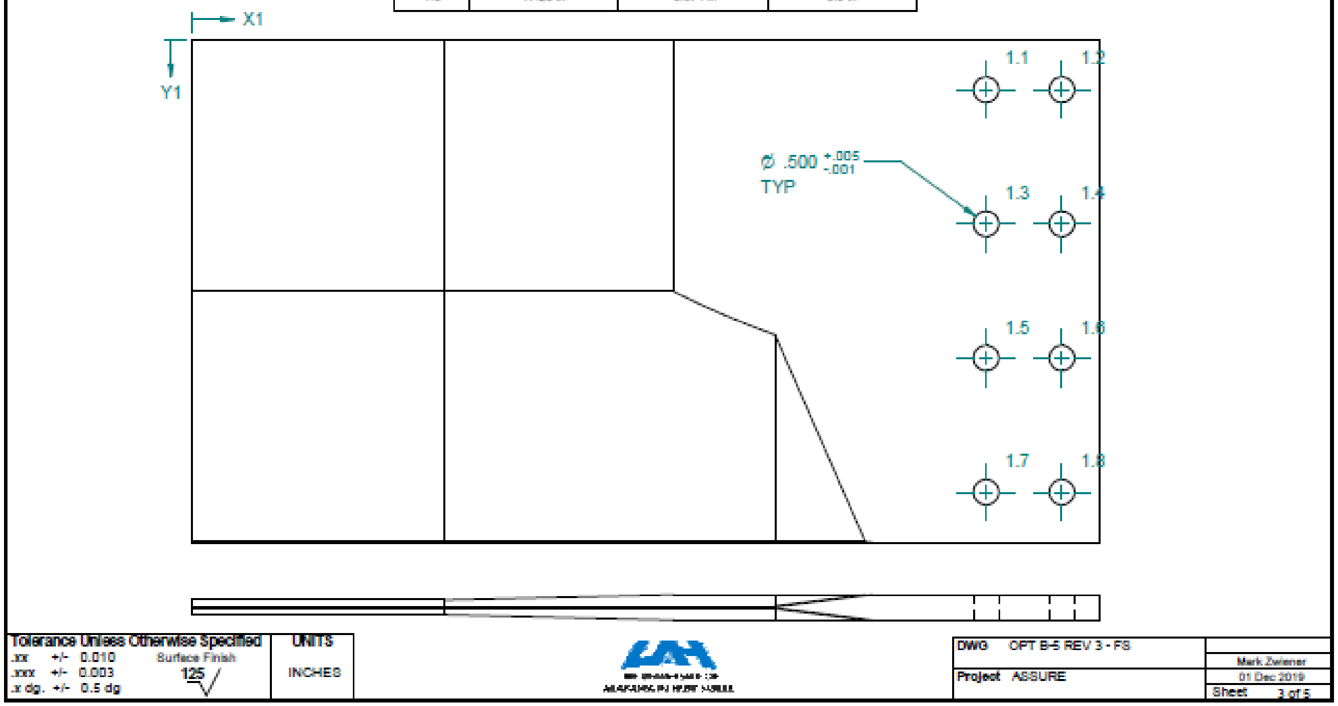


Figure A - 8 80% Span Test Article Manufacturing Print Page 3

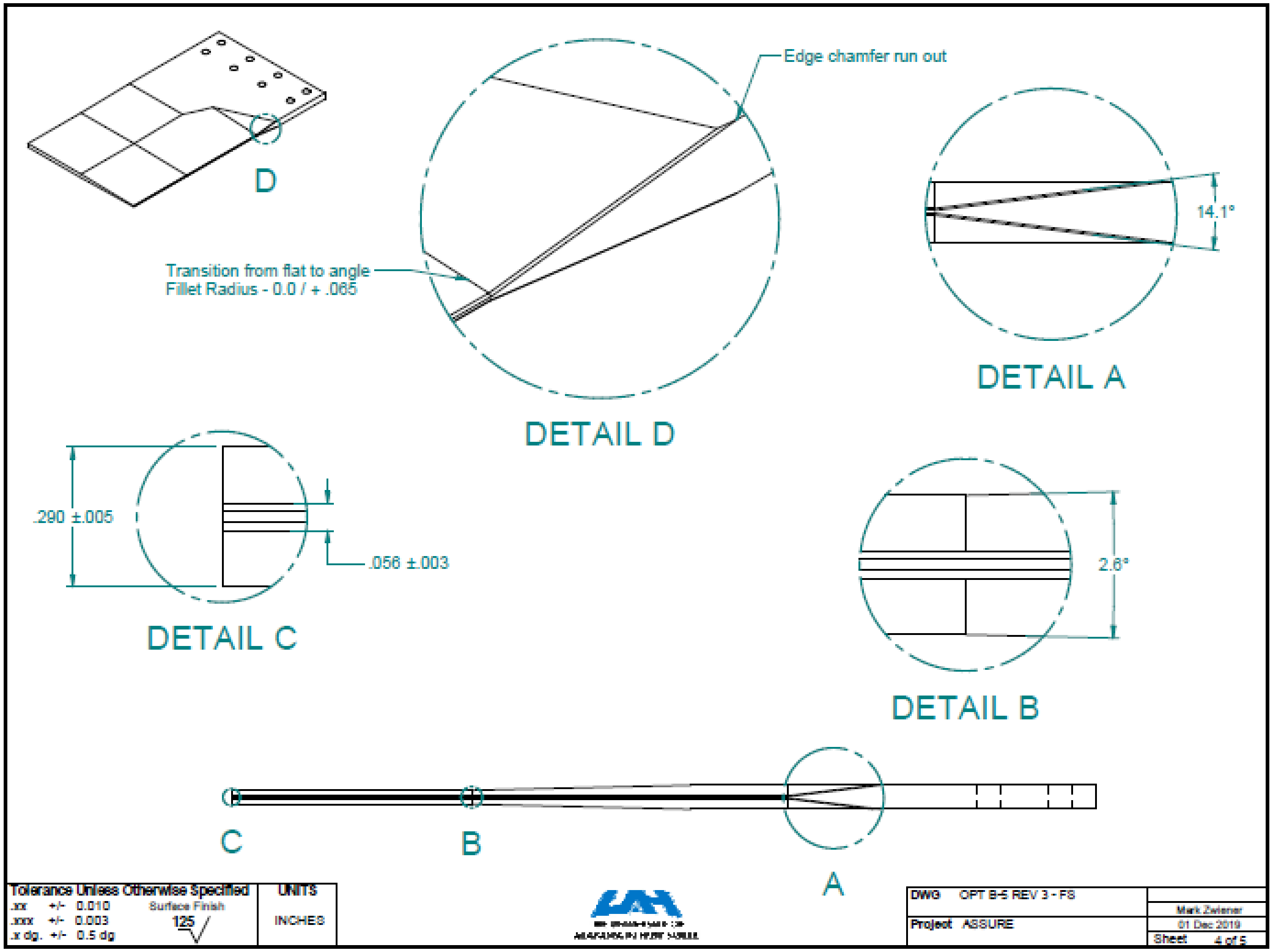


Figure A - 9 80% Span Test Article Manufacturing Print Page 4

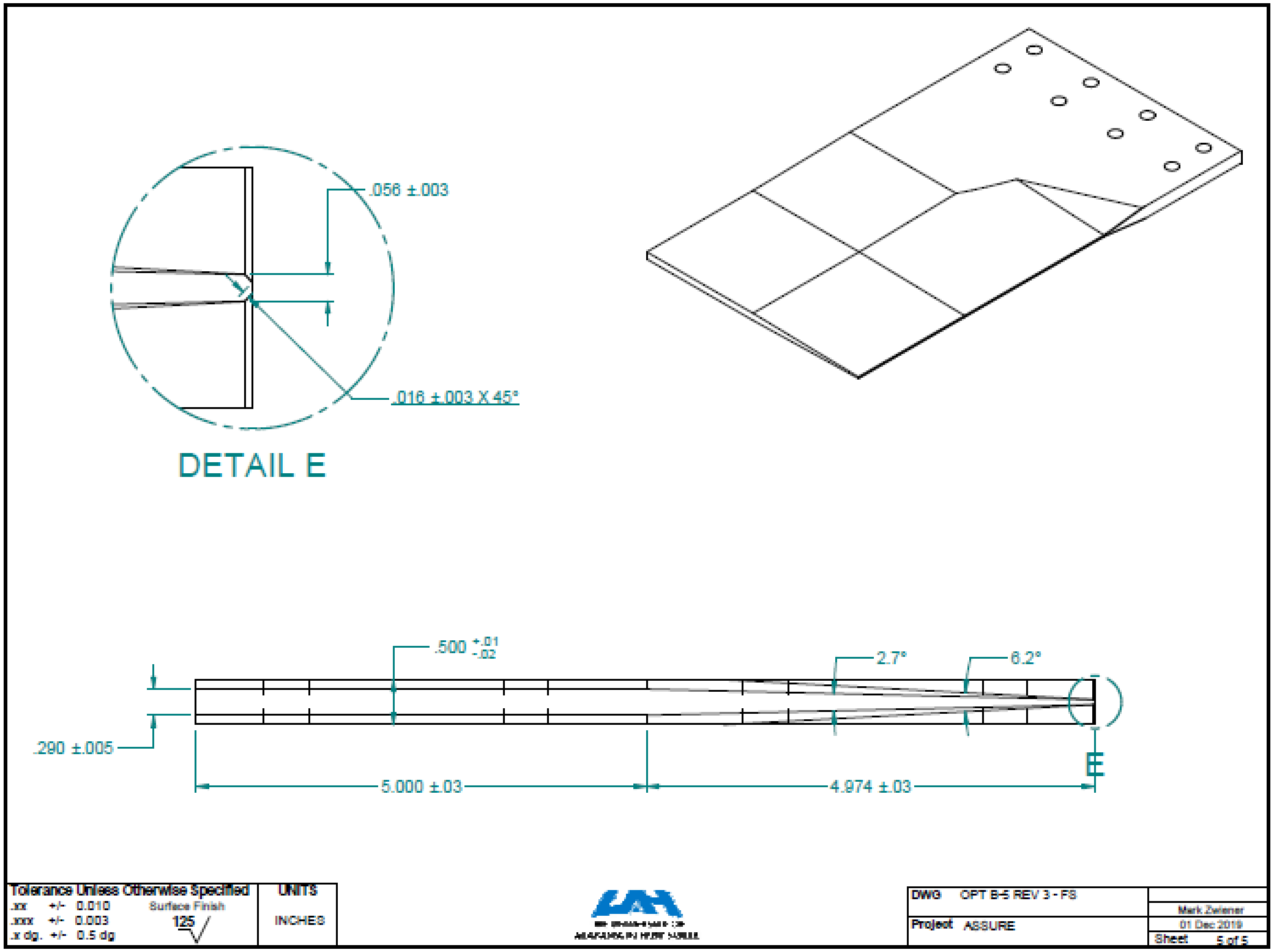


Figure A - 10 80% Span Test Article Manufacturing Print Page 5

APPENDIX B: TEST ARTICLE PACKING LIST WITH TI INDUSTRIES HEAT NUMBERS

Packing List

Packing List 296965-1
Shipment Dt 10/22/2019

Ship-To
UNIVERSITY OF ALABAMA HUNTSVILLE
SEE ORDER PROCESSING NOTES
HUNTSVILLE, AL 35899

Issued from
Titanium Industries
7373 Hunt Avenue
Garden Grove, CA
USA
92841

Sold-To
UNIVERISITY OF ALABAMA HUNTSVILLE
301 SPARKMAN DRIVE
HUNTSVILLE, AL 35899

Dlvy Mthd Our Carrier
Carrier Old Dominion Freight -CHG-
Dlvy Hours 16:00-18:00

To
Ref 33105111513

Vehicle No
Trailer No

Item | Product

Our Order 252355 Your PO P0091875 (10/4/2019)
Delivery Prepaid & Add

1-1 Titanium Plate 6AL-4V US
Titanium Plate .500" x 12" x 20"
TIMET MATERIAL ONLY

Heat	Tag	Lift	PCS
H32152-J20743	106665BA	7	18

Shp	MI	Certificate
1	0	Certificate of Conformance
1	0	Mill Test Cert

Total for the Shipment
1 Riser (7)

Gross	Tare	Net (LBS)
412	30	382

Inside Slp Chad Boan (904) 288-8300 (904) 288-0074
Taken-by Slp Chad Boan (904) 288-8300 (904) 288-0074

Received bySignature:______________________________Date:__________________

Archive Copy

Packing List

Packing List 298967-1
Shipment Dt 10/22/2019

Issued from
Titanium Industries
7373 Hunt Avenue
Garden Grove, CA
USA
92841

Ship-To
UNIVERSITY OF ALABAMA HUNTSVILLE
SEE ORDER PROCESSING NOTES
HUNTSVILLE, AL 35899

Sold-To
UNIVERSITY OF ALABAMA HUNTSVILLE
301 SPARKMAN DRIVE
HUNTSVILLE, AL 35899

Dlvy Mthd: Our Carrier
Carrier: Old Dominion Freight -CHG-
Dlvy Hours: 16:00-18:00
To
Ref 33105111521
Vehicle No
Trailer No

Item | Product

Our Order 252355 Your PO P0091875 (10/4/2019)
Delivery Prepaid & Add

2-1 **Titanium Plate 6AL-4V US**
Titanium Plate .500" x 12" x 20"
TIMET MATERIAL ONLY

Heat	Tag	Lift		PCS
H32152-J20743	106664BA	3-230623		6
H32152-J20743	106664DA	3-230623		1
H32152-J20743	106664EA	3-230623		1
			Total 8	8

Shp	Ml	Certificate
1	0	Certificate of Conformance
1	0	Mill Test Cert

Total for the Shipment	Gross	Tare	Net (LBS)
Wood Crate (3-230623)	188	26	162

Inside Slp Chad Boan (904) 288-8300 (904) 288-0074
Taken-by Slp Chad Boan (904) 288-8300 (904) 288-0074

Received bySignature:________________ Date:____________