U.S. Customs and Border Protection
Office of Air and Marine

Aircraft Mishap Report

Class A Incident

Date of Incident: January 27, 2014
Asset: General Atomics MQ-9 Guardian
Asset Number: CBP159
Location of Incident: 20NM West of Point Loma, CA
Branch Name: NASOC-Corpus Christi

Incident Report: 20131003ZQ0001
Publication Date: February 14, 2014

U.S. Customs and Border Protection

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Executive Summary

On January 27, 2014, at approximately 11:18 p.m. Pacific Standard Time (PST), a U.S. Customs and Border Protection (CBP) MQ-9 unmanned aircraft system (UAS) registered as CBP159 was involved in a ditching mishap 23 miles west of Point Loma, California. The aircraft experienced a generator failure approximately one hour prior to the ditching. The National Air Security Operations Center - Corpus Christi (NASOC-CC)-based crew elected to ditch the aircraft upon determining there was insufficient battery power to transit the aircraft to the nearest recovery site at Fort Huachuca, Arizona. This action was in accordance with Office of Air and Marine (OAM) Headquarters direction and flight termination procedures specified in the Certificate of Authorization (COA). The crew conducted the flight under instrument flight rules inside Warning Area (W-291) and visual meteorological conditions. No injuries occurred as result of this mishap.

The Assistant Commissioner, OAM has determined that the most probable cause of this mishap was:

Intentional controlled ditching of the aircraft due to failure of the starter generator supplying electrical power to the aircraft.

Contributing Factors:

1. The aircraft was configured with two generators mounted to a single driveshaft creating a single point of failure for both generators, with no redundant power supply source other than the one-hour emergency battery backup system.

2. No divert capability within range of the emergency battery power supply was available.

3. The crew elected to ditch the aircraft in a safe and predictable manner in accordance with the COA.

Recommendations:

1. Identify and resolve the root cause of the MQ-9 aircraft starter/generator failures in collaboration with General Atomics (GA).

2. Equip the MQ-9 fleet with a permanent redundant electrical power supply source.

3. Equip the MQ-9 fleet with Automatic Take-off and Landing Capability (ATLC).

4. Identify and coordinate alternate recovery options within the range of flight using the installed emergency batteries as the sole source of aircraft power.

5. Develop and employ a system to effectively monitor the health and trends of the electrical power supply system.

6. Implement procedural changes to the MQ-9 flight manual and checklist to correct deficiencies discovered during the mishap sequence.

7. Modify MQ-9 crew training to incorporate lessons captured from this mishap.

8. Develop a national, federated UAS mishap plan.

9. Provide Marine Interdiction Agents emergency response training for possible recovery of OAM aircraft. Training should include hazards associated with exposure to jet fuel and carbon fiber, safety precautions, personal protective equipment (PPE) requirements, and handling procedures.

1. Factual Information

1.1 History of Flight

On January 27, 2014, at 8 p.m. Mountain Standard Time, CBP159, an MQ-9 Guardian maritime variant UAS, departed Fort Huachuca Army Airfield, Arizona (KFHU), commanded by an OAM-based crew at the National Air Security Operations Center – Sierra Vista. Approximately 50 minutes later, an OAM crew from the National Air Security Operations Center - Corpus Christi assumed control of the aircraft and completed the transit to W-291 off the coast of southern California. . The crew consisted of a pilot, Sensor Operator (SO), and Radar Operator.

At approximately 10:15 p.m. PST, the aircraft was transiting through W-291, near San Diego, en route to assigned operational areas at 28,000 feet Mean Sea Level (MSL). An audible alarm sounded followed by the "battery-sourcing current, 28 V bus - voltage approaching lower limit, and "power system/fault- payload shed" warnings. These are all indications of a generator failure. The pilot immediately reversed course and called for the Dual Generator Failure Checklist. The checklist was completed without restoration of generator operation. Throughout the remainder of the flight, the pilot attempted multiple unsuccessful generator resets. The crew analyzed the power supply options and determined that the aircraft lacked sufficient backup battery power to sustain flight for the time required to return to base. The aircraft could not be safely recovered without a risky transit across populated areas. In accordance with the procedures specified in the COA, the crew proceeded to the Flight Termination Point (FTP) on the eastern side of W-291 to complete an intentional ditching of the aircraft. The aircraft was being controlled via Ku satellite communication (SATCOM) and the crew elected to leave most of the electrical equipment on to ensure sufficient electrical power was available to control the aircraft throughout the ditching evolution.

While en route to the FTP, the pilot descended the aircraft from 28,000 feet MSL to 5,000 feet MSL. The pilot descended the aircraft to 500 feet to get below a marine overcast layer that was approximately 2,000 feet to ensure the intended FTP was clear. Once it was determined that the ditch area was clear of maritime traffic, the pilot positioned the aircraft to the south of the FTP and initiated a descent. At approximately 600 feet MSL, the crew lost link with the aircraft due to a low voltage condition that caused an automatic reset of the Interim Link Manager Assembly (ILMA). After approximately two minutes, the crew was able to re-establish return link. The aircraft was climbing through 2,000 feet MSL on its lost link profile (last set to 5,000 feet MSL). The crew re-established the command link and positive control. The pilot maneuvered the aircraft back towards the FTP, actuated the condition lever to stop the engine and completed the ditching. The aircraft impacted the water approximately 1.7 miles north of the FTP, destroying the aircraft. The majority of the fuselage sank to the ocean floor to a depth of approximately 4,200 feet.

EVENT DESCRIPTION WITH TIMELINE:

Time	Event
0616Z	CBP159 experiences generator failure
0619Z	Generator is lost and CBP159 is on battery power
0627Z	Crew declares an emergency with Beaver Control due to insufficient battery power to return CBP159 to launch site Sierra Vista.
0718Z	CBP159 is intentionally ditched

1.2 Injuries to Persons

There were no aircrew injuries as a result of this event.

Injuries	Crew	Passengers	Others	Total
Fatal	0	0	0	0
Serious	0	0	0	0
Minor	0	0	6	6
None	0	0	0	0
Total	0	0	6	6

1.3 Damage to Aircraft

The aircraft impacted the water in a nose down attitude at 175 knots with a decent rate of 4,005 feet per minute with the engine stopped and propeller feathered. The aircraft sustained a total break-up of the airframe as a result of the severe impact forces from the high-speed ditching. No major assemblies were discovered intact.

1.4 Other Damage

No other damage occurred as a result of the mishap.

1.5 Personnel Information

1.5.1 Pilot in Command

The Pilot in Command (PIC) holds an Airline Transport Pilot Certificate with airplane multi-engine land, airplane single-engine land, and instrument airplane with a P-3-type rating. The pilot has logged 8,327 hours total time. The pilot holds a current second class medical certificate. His last medical exam was in March 2013.

The PIC's recent flight time is depicted in the matrix below:

	Past 30 Days	Past 60 Days	Past 90 Days
MQ-9	4	15	18
P-3	54	55	58
Total Flight Time	58	70	76

1.5.2 Sensor Operator

The SO holds a current MQ-9 Sensor Operator designation, as well as P-3 Flight Engineer designation with over 18,000 hours flight experience in all aircraft to date. The SO holds a current second class medical certificate. His last medical exam was in December 2013.

The SO's recent MQ-9 flight time is depicted in the matrix below:

	Past 30 Days	Past 60 Days	Past 90 Days
MQ-9	10	15	15

1.6 Maintenance History

The aircraft's home station is the Sierra Vista Air Unit at Fort Huachuca Army Air Field, Arizona (KFHU). The aircraft was maintained in accordance with Federal Aviation Administration (FAA) regulations and OAM policy. Following the review of the logbook records and on-scene wreckage, the investigation team determined there were no pre-existing maintenance issues that may have contributed to the accident.

1.7 Aircraft Information

The gross weight and center of gravity were within the limits, as stated in the Aircraft Operator Manual.

1.8 Meteorological Information

The flight was being conducted under instrument flight rules with visual meteorological conditions prevailing. Meteorological conditions were not a factor in this mishap.

1.9 Communications

Communications were not a factor in the mishap.

1.10 Aerodrome Information

Airport facilities were not a factor in this mishap.

1.11 Airport Stops En Route

No intermediate stops were made en route. No adequate facilities existed along the aircraft's flight path to initiate a stop nor an emergency divert while returning to originating airfield.

1.12 Wreckage Information

The aircraft was recovered in two phases. Several hours after the mishap, Marine Interdiction Agents from the San Diego Air and Marine Branch retrieved the parts of the aircraft located at the ditch site that were still floating. This resulted in the recovery of approximately 20 percent of the aircraft including pieces of the wings, some panels, and assorted small pieces of debris.

OAM and the U.S. Navy coordinated and conducted a formal maritime salvage effort using U.S. Navy assets from the Advanced Ocean Technology Program Engineering and Expeditionary Warfare Center on February 6, 2014, resulting in recovery of the engine, propeller and spinner assemblies, various fuel lines, electrical cables, one embedded GPS/INS unit and one ATC communication radio. The engine was also recovered from a depth of approximately 4,200 feet. The failed starter/generator unit was recovered on the engine, intact. The Generator Control Unit (GCU) was recovered, but had collapsed under the extreme pressure at depth.

All initial wreckage recovered from the ocean surface was first moved to the U.S Coast Guard Air Station in San Diego, California, and then to the aircraft manufacturer's (General Atomics) facility located in Poway, California, for further examination.

1.13 Medical and Pathological Information

There were no aircrew injuries as a result of this mishap. The crew was sufficiently rested prior to the mission. There was no evidence that the pilot was fatigued, or suffering from any human factor issues that would have adversely affected his ability to perform crewmember duties. Investigators did not find evidence of adverse medical history or chronic or acute ailments during the course of the investigation.

Marine agents sustained minor injuries due to inhalation/exposure to jet fuel and lacerations from handling carbon fiber shards without proper PPE. All crewmembers involved were released and advised to follow up for any possible residual long term effects of the exposure.

1.14 Fire

No fire occurred in this mishap.

1.15 Survival Aspects

There were no survival aspects to this mishap.

1.16 Tests and Research

General Atomics engineering has undertaken all the tests and research related to the failure analysis and root cause analysis of the starter/generator failures. At the time of this writing, multiple tests are being conducted to determine the root cause and to test design improvements to the starter/generator components. Additionally, General Atomics completed a ground test and evaluation of a re-designed Permanent Magnetic Alternator and the units have been placed in service as a temporary solution to a redundant power supply until the design, production, and testing can be completed on a secondary, independent engine-mounted brushless generator.

1.17 Organizational and Management Information

The Command Duty Officer properly dispatched this flight in accordance with branch and OAM policies. A written record is on file.

1.18 Additional Information

The investigation team determined that the emergency battery backup power supply system performed to specifications supplying approximately one hour of power.

2. Analysis

2.1 General

Between April 2013 and January 2014, 18 starter/generator failures occurred among all the operators of the MQ-9 aircraft, three of which resulted in Class A mishaps. Prior to April 2013, starter/generator failures were infrequent. The standard configuration for all series of the MQ-9 aircraft consists of one engine-mounted starter generator which powers the entire system, and an emergency battery backup system that provides power for approximately one hour in the event that the starter/generator goes offline. The system is configured so that the starter/generator cannot charge the backup batteries; they must be recharged in between each flight.

Before the widespread failures began, there was little need for redundancy in the power supply system. Although the single starter/generator was considered a design weakness, it was generally assumed that the starter/generator was reliable enough that the design was acceptable. One operator of the MQ-9 developed additional battery packs to extend the range of the emergency system, but this was never a production modification that was offered to other customers.

Since April 2013, General Atomics has been very proactive in investigating the root cause of the failures and designing a redundant power supply that will become a permanent modification. The root cause, however, is still under investigation. In CBP159's starter/generator, investigators found three areas of mechanical failure (known as failure modes) stemming from design deficiencies. These failure modes are consistent throughout many of the other failed units that were recovered and examined. The problem is, the components worked as designed for so long, but some factor that is likely external to the starter/generator has changed. This unknown factor is common to all the operators, and is exploiting the design deficiencies, causing the components to fail.

At this time, no correlation has been found between operating locations or conditions. No correlation has been found between payloads or aircraft configuration. Initially, it was believed the failures were limited to units that had been rebuilt by the manufacturer, but that theory has now been discarded because several units failed that had never been rebuilt, to include CBP159's. The starter generator unit has a 1,000-hour time before overhaul (TBO) cycle. No correlation has been found in service life or in units not making it to TBO. Failures have occurred between 3.5 to 925 hours. CBP159's failure occurred at 522 hours.

General Atomics launched a thorough investigation into the manufacturer of the starter/generator, Skurka Aerospace. They identified several quality control deficiencies in the manufacturing and rebuild process and issued recommendations to have them corrected. None of the deficiencies, however, were significant enough to be considered to be the root cause. It was also discovered that the starter/generator's brushes and commutator are not manufactured by Skurka Aerospace, but sourced from other manufacturers who are also being investigated by General Atomics.

2.2 Failure Modes

Investigators found three failure modes related to minor design deficiencies in the starter/generator unit recovered from CBP159. All of the failed units that have been recovered have shown at least one of these three failure modes; usually they have two. CBP159's was unique in that all three could be identified.

It is unknown if there is an order by which these failure modes occur; in effect, any one failure can trigger the others. This "domino effect" of damage continues until the starter/generator is either mechanically destroyed or the voltage output becomes so low that the GCU takes it offline and locks out a generator reset. As damage increases, the heat build-up increases, which accelerates the failures.

2.2.1 Excessively Worn and Broken Brushes

The starter/generator utilizes 16 individual carbon brushes. The brushes are arranged in 4 assemblies of 4 brushes each and are positioned at the 12, 3, 6, and 9 o'clock positions around the commutator. Each brush in the assembly is attached to a common contact point by a braided copper wire that is fastened to the brush by a single copper rivet.

Figure 1. An intact single rivet brush assembly

Carbon brushes are fragile and prone to breaking if subjected to excessive heat, vibration, uneven pressure, and electrical arcing. All of the brushes in CBP159's starter generator were excessively worn, likely caused by uneven contact with the commutator. Many of the brushes were broken, with the break line running through the rivet hole. Single-rivet design brush assemblies have displayed a weak point around the rivet. Arcing and excessive heat cause the rivet to loosen. Once loose, the rivet causes cracks in the brush material it comes in contact with, leading to eventual breakage. An intact single rivet brush assembly that was not removed from CBP159 is shown above (Figure 1). The picture clearly shows discoloration and evidence of arcing on the rivet heads.

The actual brushes removed from CBP159 are shown below (Figure 2). The picture shows the break that runs through the rivet hole as well as the uneven wear and missing material on the bottom of the brush. The brush assemblies are not made by Skurka Aerospace. General Atomics engineers also noted design and minor quality control deficiencies with the brush manufacturer in their investigation and addressed those issues directly.

Figure 2. Brushes from CBP159's starter/generator

2.2.2 Broken and Missing Spring Guides

When the brush assemblies are installed in the starter generator, the four brushes are aligned in pairs in their holders. Constant down pressure is required to maintain proper contact with the commutator to keep the brushes from moving and to prevent electrical arcing. The spring guides are the contact point where the spring rests that provides the alignment of the springs and the brushes. If the spring guide fails, uneven pressure causes one brush to wear more than the other which creates a gap. Arcing occurs in the gap and the brush is free to move in its guide, and the brush eventually breaks.

The spring guide is a flat piece of copper that is bent 90 degrees and is attached to each of the brushes by a single rivet (Figure 3). The bend permits the end of the guide to overlap the other brush in the assembly. General Atomics engineers found that the bend radius is too tight, which causes a weak point in the metal. Very small stress cracks develop over time. The rate and severity of the cracks depend on how much excessive heat the part has been subjected to. Heat in that area weakens the bend area until it fails. Once the spring guide fails, the spring makes contact with the brush, causing damage, and constant down pressure is lost. CBP159's starter/generator had four of its eight spring guides broken.

Figure 3. Spring guides

2.2.3 Raised Commutator Bars

The commutator, also known as the armature, is also outsourced by Skurka Aerospace. Skurka spot welds the commutator to a winding assembly that it produces to make the rotor assembly. The commutator is made up of 40 individual bars arranged on a common shaft that turns (Figure 4). The bars make contact with the brushes, which are stationary.

Two of the commutator bars on CBP159's starter generator were found to be raised .004 inch and .007 inch above the rest. They were positioned exactly 180 degrees opposite each other. Once a bar becomes raised it causes excessive wear to the brushes every time it passes one. Again, this leads to uneven brush wear that has the same result as encountered with a broken spring guide. As the brush is worn down, arcing increases, and the commutator has the tendency to deteriorate the most from the excessive heat build-up. CBP159's commutator is one of the only examples intact enough to be examined. In past examinations, the majority of commutators are found with the bars melted together or burnt beyond recognition.

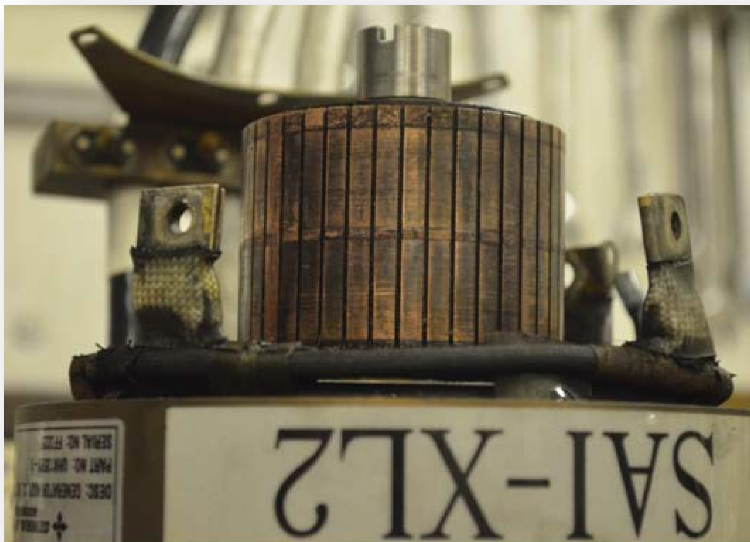

Figure 4. Commutator

The two potential causes of the raised bars are excessive heat build-up that loosened the bars or what is known as "magnetic sticking" during the start sequence. For this to occur, the bar would have had to come to a stop directly under a brush after the previous shutdown. When the starter is actuated the magnetic field builds rapidly to turn the starter generator. The starter must carry a load of 500 amps in order to overcome the torque of turning the cold engine. If the bar was directly underneath a brush, the magnetic stress could potentially pull the bar out of place. If the commutator was still hot from previous operation or the bars were already loosened by heat, the magnetic forces would have a greater effect.

At the time of this report, General Atomics is investigating the manufacturer of the commutator, conducting hardness testing on CBP159's commutator, and conducting research on the start sequence.

2.3 Link Interruption

As CBP159's crew prepared to ditch the aircraft, it was controlling it with the Ku-band satellite link. The Ku-band system draws significantly more power than the Line of Sight (LOS) control system (used for launch and recovery) but since the crew was beyond LOS range and landing at an airfield was not an option, the crew elected to keep the Ku powered up to safely ditch the aircraft while it had full functionality.

During the initial ditching attempt a low voltage condition caused an automatic reset of the ILMA, which explains why the crew lost Ku command and return links. This resulted in the aircraft attempting to fly its Lost Link Emergency profile automatically. Upon regaining the Ku-band link, the crew elected to complete the ditching with a redundant control system, which uses relatively little power. In retrospect, the only thing the crew could have done to improve its situation and avoid the unexpected link interruption would have been to enable the redundant control system right away instead of depleting the batteries by using the Ku system.

2.4 Emergency Procedures Checklist

Several steps in the published Emergency Procedures Checklist were found to be incorrect, given the conditions that existed. The checklist is written in a way to conserve the electrical power of the batteries and, ideally, recover the aircraft. To do this, the checklist directs the crew to turn off most of the equipment. When the crew regained link and used the redundant control system, it was never able to re-establish video and was forced to fly blind. The lack of usable video resulted from execution of the Dual Generator Failure Checklist. This checklist directed the crew to turn off the airborne router, which supplied the path for the pilot’s video when using the redundant control system. In executing the emergency procedures the crew had eliminated the use of equipment and video despite having sufficient power available.

To make the checklist more applicable to the different emergency situations a crew could face, the checklist responses were immediately reviewed and revised to read “off, as required” instead of “off.” This change now allows the crew to use discretion and keep on some equipment that is appropriate to the control link in use.

2.5 Ditching

The Crew Resource Management during this mishap was outstanding. The crew did an excellent job in communicating the situation to the Air and Marine Operations Center (AMOC), which alerted the San Diego Air and Marine Branch and the USCG to assist with the recovery of CBP159 as the crew executed the ditching in accordance with the COA. Had the crew attempted to transit back to KFHU it would likely have resulted in a destroyed aircraft during an offsite landing and posed a considerable risk to residents in populated areas.

3. Conclusions

3.1 Findings

- The PIC was trained and qualified in accordance with current FAA and OAM policy and was appropriately designated by the Director, Air Operations in the MQ-9 Guardian aircraft.

- The pilot was sufficiently rested prior to this mishap. There was no evidence that he was fatigued, or suffering from any human factor issues that would have adversely affected his ability to perform his duties.

- The flight was properly dispatched, and a written record is on file.

- The aircraft was certified, equipped, and maintained in accordance with FAA and OAM policies.

- Three failure modes of the starter generator have been identified by OAM; however, the root cause is still under investigation by General Atomics.

- The investigation team determined that there were no practical divert options available within range of the emergency battery power supply system:
  - Flight routing transited two major population centers
  - Battery capacity preformed to specification, offering approximately one hour of flight time
  - There was no option to recover the aircraft without incurring undue risk and violating the provisions of the COA

- The investigation team determined that the crew did an exemplary job in dealing with the emergency by managing their resources and mitigating risk. No adverse human factors issues were discovered as a result of this mishap.

- The investigation team identified several steps in the Emergency Procedures Checklist that were incorrect, given the conditions.

- No UAS subsystem was available to the crew to effectively monitor the electrical power supply system that would have alerted them to the impending failure

3.2 Probable Cause

The Assistant Commissioner, OAM has determined that the most probable cause of this mishap was:

Intentional controlled ditching of the aircraft due to failure of the starter generator supplying electrical power to the aircraft.

3.3 Contributing Factors

1. The aircraft was configured with two generators mounted to a single driveshaft shaft creating a single point failure of both generators, with no redundant power supply source other than the emergency battery backup system.

2. No divert capability within range of the emergency battery power supply was available.

3. The crew elected to ditch the aircraft in a safe and predictable manner in accordance with the COA.

4. Recommendations

1. Identify and resolve the root cause of the MQ-9 aircraft starter/generator failures in collaboration with General Atomics.

2. Equip the MQ-9 fleet with a permanent redundant electrical power supply source.

3. Equip the MQ-9 fleet with Automatic Take-off and Landing Capability (ATLC).

4. Identify and coordinate alternate recovery options within the range of flight using the installed emergency batteries as the sole source of aircraft power.

5. Develop and employ a system to effectively monitor the health and trends of the electrical power supply system.

6. Implement procedural changes to the MQ-9 flight manual and checklist to correct deficiencies discovered during the mishap sequence.

7. Modify MQ-9 crew training to incorporate lessons captured from this mishap.

8. Develop a national, federated UAS mishap plan.

5. Appendices

Appendix 1 – Ground Control Station Data Log Trace of Electrical System

Figure 1 identifies failure of the aircraft power generation system and resultant operation on the emergency battery backup power supply.

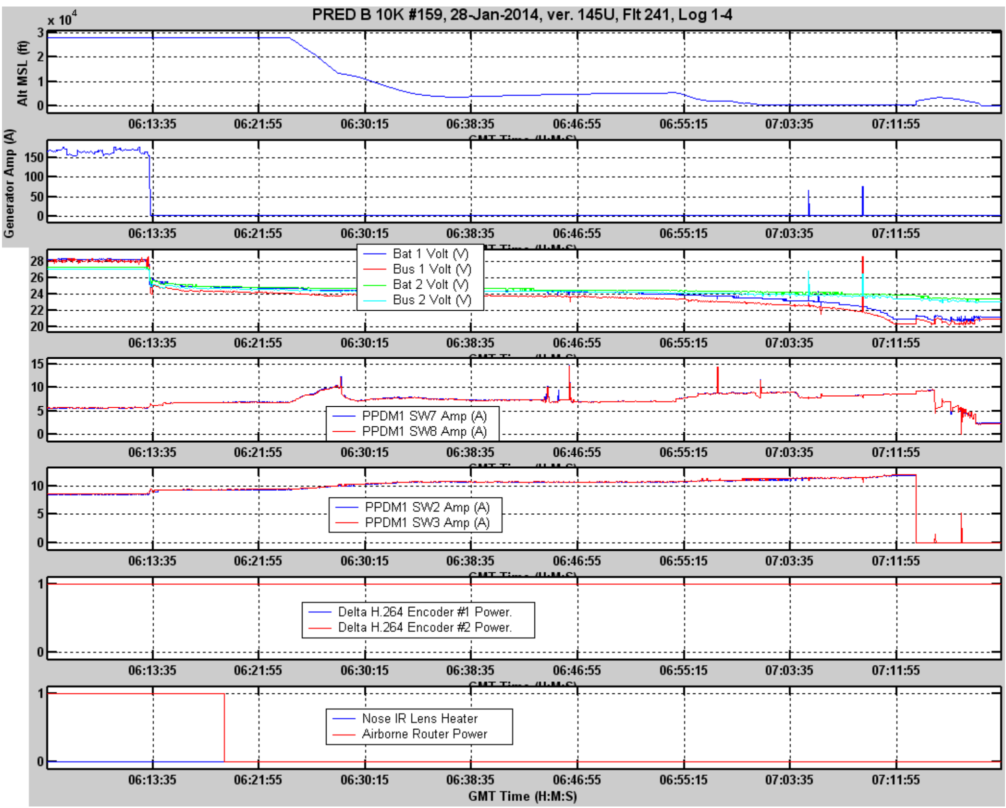

Figure 1

Note: Bus 1 operation maintains the highest load throughout the failure, and is the first to exhaust, resultant in SATCOM link interruption about time 07:11:55.

Appendix 2 – Ground Control Station Data Log Trace of Electrical System

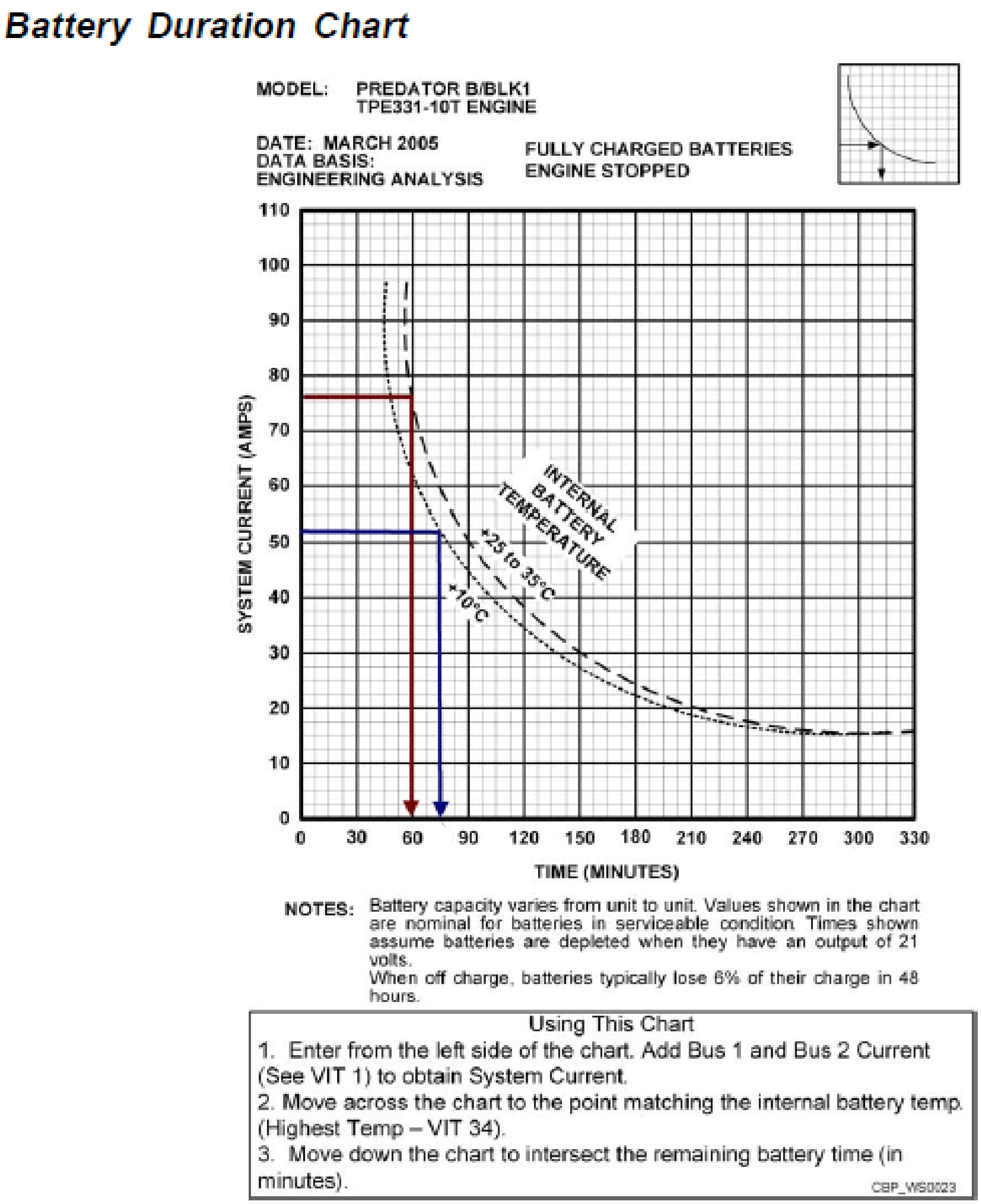

Figure 2 – Battery duration chart

6. Acronyms and Abbreviations

CBP	U.S. Customs and Border Protection
COA	Certificate of Authorization
FAA	Federal Aviation Administration
GCU	Generator Control Unit
ILMA	Interim Link Manager Assembly
INMARSAT	Brand name of communications device
KFHU	Fort Huachuca Army Airfield, Sierra Vista, Arizona
Ku	Radio band used for satellite communication
MSL	Mean Sea Level
OAM	Office of Air and Marine
PIC	Pilot in Command
PPE	Personal Protective Equipment
PST	Pacific Standard Time
SATCOM	satellite communications
SO	Sensor Operator
TBO	Time Before Overhaul
UAS	unmanned aircraft system
USCG	United States Coast Guard