Validation Ice Crystal Icing Engine Test in the Propulsion Systems Laboratory at NASA Glenn Research Center

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The Propulsion Systems Laboratory (PSL) is an existing altitude simulation jet engine test facility located at NASA Glenn Research Center in Cleveland, OH. It was modified in 2012 with the integration of an ice crystal cloud generation system. This paper documents the inaugural ice crystal cloud test in PSL—the first ever full scale, high altitude ice crystal cloud turbofan engine test to be conducted in a ground based facility. The test article was a Lycoming ALF502-R5 high bypass turbofan engine, serial number LF01. The primary objective of the test was to validate the PSL ice crystal cloud calibration and engine testing methodologies by demonstrating the capability to calibrate and duplicate known flight test events that occurred on the same LF01 engine. Additional objectives were to generate engine data to support fundamental and computational research to investigate and better understand the physics of ice crystal icing in a turbofan engine environment while duplicating known revenue service events and conducting test points while varying facility and engine parameters. Lacking internal flow path cameras, the response of thermocouples embedded in hardware along the LF01 flow path was interpreted as ice building up during cloud on operation. Using this interpretation, a strong correlation between total water content (TWC) and a weaker correlation between median volumetric diameter (MVD) of the ice crystal cloud and the rate of ice buildup along the instrumented flow path was identified. For this test article the engine anti-ice system was required to be turned on before ice crystal icing would occur. The ice crystal icing event, an uncommanded reduction in thrust, was able to be turned on and off by manipulating cloud TWC. A flight test point where no ice crystal icing event occurred was also duplicated in PSL. Physics based computational tools were successfully used to predict ambient temperature settings required to induce ice buildup along the low pressure compression system flow path for several test points at incrementally lower altitudes, demonstrating that development of ice crystal icing scaling laws is potentially feasible. Analysis of PSL test data showed that uncommanded reduction in thrust occurs during ice crystal cloud on operation prior to fan speed reduction. This supports previous findings that the reduction of thrust for this test article is due to ice buildup leading to a restricted airflow from either physical or aerodynamic blockage in the engine core flow path.

Nomenclature

AD	=	Advisory Directive
AEST	=	Atmospheric Environment Science Technologies
ARMD	=	Aeronautics Research Mission Directorate
CAA	=	Civil Aviation Authority
CFR	=	Code of Federal Regulations
CNRB	=	Called No Roll Back
CRB	=	Called Roll Back
DI	=	Deionized
DOE	=	Design of Experiment
EHWG	=	Engine Harmonization Working Group
EIWG	=	Engine Icing Working Group
FAA	=	Federal Aviation Administration

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FAR	=	Federal Aviation Regulations
FT	=	Flight Test
HPC	=	High Pressure Compressor
HMU	=	Hydro Mechanical Unit
HPT	=	High Pressure Turbine
IBUA	=	Ice Build Up Apparent
ICC	=	Ice Crystal Consortium
IGV	=	Inlet Guide Vane
IMC	=	Instrument Meteorological Conditions
IWC	=	Ice Water Content
LPC	=	Low Pressure Compressor
LPT	=	Low Pressure Turbine
LWC	=	Liquid Water content
MVD	=	Median Volumetric Diameter
N1	=	Fan Rotational Speed
N2	=	High Pressure Compressor Rotational Speed
NTSB	=	National Transportation Safety Board
PLA	=	Power Lever Angle
P_s	=	High Pressure Compressor Inlet Static Pressure
PSL	=	Propulsion Research Laboratory
PSL-3	=	Propulsion Systems Laboratory Test Cell Three
PSL-4	=	Propulsion Systems Laboratory Test Cell Four
RB	=	Roll Back
RS	=	Revenue Service
Tavg	=	Average Temperature
T/C	=	Thermocouple

I. Introduction

THE Propulsion Systems Laboratory (PSL) at NASA Glenn Research Center (Cleveland, OH) is a direct connect jet engine test facility utilized primarily for research and development. In 2012, a spray nozzle system was integrated into PSL test cell three (PSL-3) to produce ice crystal clouds at simulated altitudes during full scale turbofan engine tests. The goal of this modification was to develop a full scale engine test and research facility to better understand the physics of ice crystal icing in turbofan engines. The development of this facility capability was a direct result of a technology plan developed by an international consortium of manufacturers, researchers and regulatory agencies investigating ice crystal icing in turbofan engines. This paper documents the first full scale, high altitude, ice crystal icing test conducted in a ground based engine test facility. The test article was an engine that experienced an uncommanded reduction of thrust or engine core roll back (RB) event during a flight test campaign while operating in high altitude ice crystal conditions. During this event both engine operating and environmental flight conditions were recorded and documented.

The following paragraphs of this introduction are intended to give a concise historical perspective of ice crystal icing in turbofan engines and how events occurring over the last half century plus led to the PSL-3 ice crystal cloud modifications and the inaugural full scale, high altitude ice crystal icing engine test conducted in February 2013.

A Historical Perspective of Ice Crystal Icing in Turbofan Engines

Britannia Event

The oldest significant reference to ice crystal icing in turbofan engines known to this author dates back to 1956. In his autobiography, Dr. Stanley J. Hooker [1] describes a high altitude RB event occurring on a Britannia 102 descending through clouds in 1956. He attributed the cause of these events to a buildup and shedding of ice due to operation in ice crystals at altitudes in the tropics where the ambient temperature was at or below freezing. He surmises that the tropical sea level temperatures are significantly warmer than standard day temperatures allowing for the air to hold much more water vapor. Ice crystals would form as water vapor condensed out of rising humid air and would freeze at altitudes where the ambient temperature became freezing. He specifically noted that the environmental conditions were not the same as those that caused ice buildup on the aircraft wings. The ice buildup and subsequent shed would cause compressor stall, combustor flame out or both simultaneously.

The engines would fully recover at lower altitudes (below the freezing line). The issue was resolved by flying at lower altitude when these environments were encountered and ultimately resulted in a series of modifications for the particular engine affected. Investigation and quantification of the environment surrounding Britannia events was conducted and documented by McNaughton[2].

BAe 146 Events

In the 1990's, a situationally similar series of events occurred on several BAe 146 aircraft powered by AlliedSignal ALF502-R5 turbofan engines. Pilots experienced uncommanded thrust reductions during cruise operation in instrument meteorological conditions (IMC) at high altitude in the vicinity of convective thunderstorms. Full power was always restored by descending out of the storm conditions to altitudes where the ambient air was above freezing temperature. Ultimately, these events resulted in an advisory directive (AD) issued by the Federal Aviation Administration (FAA) [3] which limited the altitude at which these planes could operate. This AD led to an extensive investigation that included both ground and flight testing to determine a cause and resolution of the engine thrust reduction. A proprietary report issued to the FAA, CAA and the Transport Canada in 1998, documents the entire investigation and resolution process which included a series of flight tests with the objective to duplicate a RB event while recording engine parameters and environmental flight conditions. The Investigations and Resolutions report led to a lifting of the AD for all ALF502-R5 engine models that implemented a field modification kit. This rendered the unmodified versions of the engine obsolete. The flight test engine serial number LF01 that experienced the uncommanded reduction of thrust during the flight test campaign remains unmodified and instrumented as it was for the 1997 flight test. LF01 was prepared and readied for testing by Honeywell Engines [4] and provided to NASA for use in the inaugural ice crystal icing validation testing conducted in PSL-3 during February 2013.

Engine Harmonization and Power Installation Harmonization Working Group

A joint committee made up of the Engine Harmonization and Power Plant Installations Harmonization Working Groups, the Engine Harmonization Working Group (EHWG), developed a database of engine icing related events between1989-2003. Based on this database the joint committee developed an ice crystal icing technology plan, advisory material and a threat envelope. This committee was also tasked by the National Transportation Safety Board (NTSB) to develop draft rules for Mixed Phase/Glaciated Engine Icing. This led to a proposed draft Appendix D to Title 14 Federal Aviation Regulations (FAR) Part 33 (Code of Federal Regulations CFR) in 2005 which, if implemented by the FAA, would define fully glaciated and mixed phase certification conditions. As of this writing, this has not yet been implemented.

The Theory of Ice Crystal Icing

In 2006 Mason, Chow and Strapp, presented a paper to the 44th AIAA Aerospace Sciences Meeting in Reno, NV that documented 46 uncommanded thrust reduction events suspected to be related to high altitude operation near convective storms[5]. At that time, the authors presented what has become the current ice crystal icing theory. The theory is that ice crystals are ingested into low pressure compression systems of turbofan engines operating at high altitudes in the vicinity of convective storms. The ingested ice crystals impinge upon warmer than freezing flow path surfaces and cool them down to the point where ice accretes. The ice accretion and or subsequent shedding can affect normal engine operation.

Engine Icing Working Group, Ice Crystal Consortium and NASA

In 2009 the Engine Icing Working Group (EIWG) was formed to foster discussion, partnerships and provide guidance for the technology plan outlined by the EHWG which was disbanded in 2007. The participants in the EIWG are comprised of international manufactures, research organizations and regulatory agencies. In addition, a small group of engine and airframe manufacturers formed a consortium, the Ice Crystal Consortium (ICC), to pool resources to address the problem. Together these groups, EIWG and ICC, form an international engine icing community comprised of representatives from both government and industry who are working collaboratively to address ice crystal icing. NASA is a participant in this collaboration via efforts in the Atmospheric Environment Safety Technologies (AEST) Project.

The AEST Project has an Engine Icing Characterization and Simulation Capability Technical Challenge Area that has three research areas[6]: Flight Characterization[7], Classical Research[8,9] and Computational Research[10]. This paper documents the NASA ice crystal icing research validation testing specifically the efforts to develop full scale turbofan engine ice crystal icing capabilities in PSL-3 to meet the Engine Ice-Particle Test Facility Development within the Classical Research area.

Inaugural Ice Crystal Engine Test in PSL-3

In February 2013, LF01 was tested in PSL-3 under high altitude ice crystal icing conditions and a RB was achieved. The targeted test point calibrated in PSL-3 for this ground test was the same altitude, temperature and measured environmental conditions recorded during the 1997 flight test campaign when LF01 experienced an uncommanded thrust reduction. This paper documents this inaugural ice crystal icing validation test conducted using LF01 in PSL-3 during the month of February 2013.

II. PSL Facility

The Propulsion Systems Laboratory (PSL) is located at NASA Glenn Research Center in the Cleveland Ohio Metropolitan Region (Brook Park), Figure 1. There are two test cells contained within the main building; test cell 3 (PSL-3) and test cell 4 (PSL-4), Figure 2. Both test cells are 24 feet in diameter and 39 feet in length and use common supply and exhaust supplied from a central equipment facility. The maximum altitude achievable in the facility is in excess of 90,000 feet. Cooling air can be supplied at a mass flow rate of 100 lbm/s. Various configurations of these test cells are capable of simulating direct connect or free jet testing environments for continuous run times.

PSL-3 is a lower Mach number cell and can handle temperatures up to 600°F or the equivalent of Mach 3 while PSL-4 is designed to simulate higher speeds and can reach temperatures corresponding to Mach 4 (Mach 6 in free jet configuration with auxiliary heating) with an inlet plenum designed to 1200°F at 150 psig.

Figure 1. The Propulsion Systems Laboratory, NASA Glenn Research Center, Cleveland, OH.

PSL includes three turbo expander units each capable of supplying 110 lbm/sec for a maximum supply of 330 lbm/sec of cold combustion air for engine testing. The PSL-3 combustion air can be as cold as -50F and PSL-4 can be supplied at -90F for optimized running conditions. The inlet air can also be heated with a pair of J57 engines that run their exhaust through two shell and tube heat exchangers to supply up to 280 lbm/sec of 1200°F air. Inlet air and exhaust pressures are set by facility valves that can be run in a manual mode or in an automatic mode with the distributed control system.

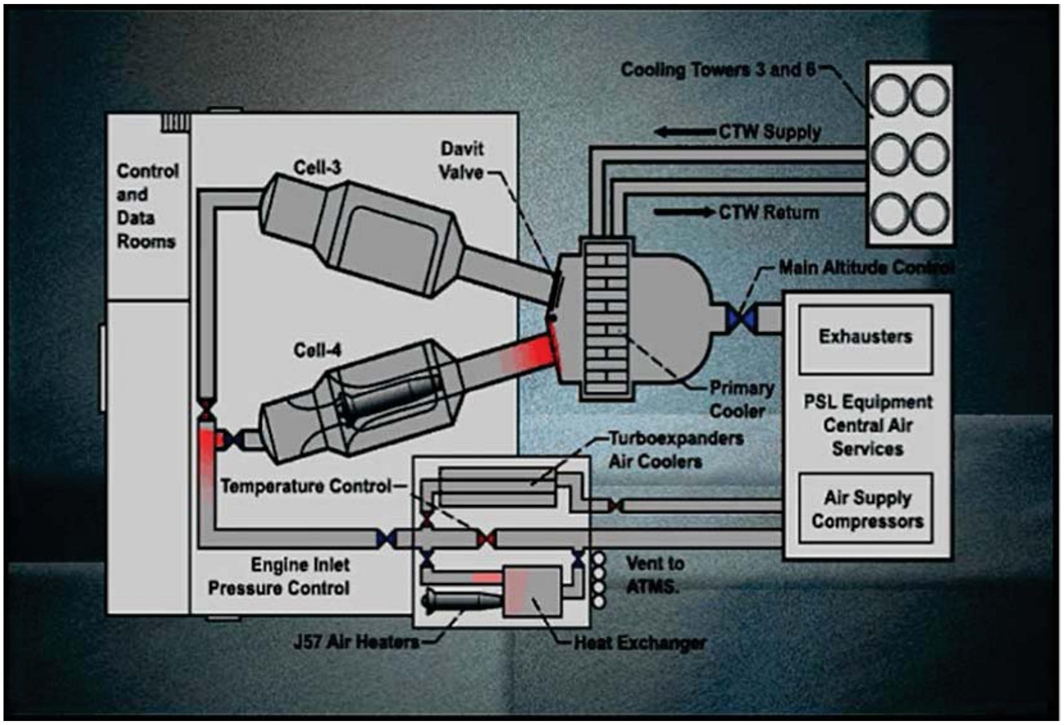

Figure 2. Schematic of the PSL.

Figure 3. Water injection spray bars installed into the PSL cell three.

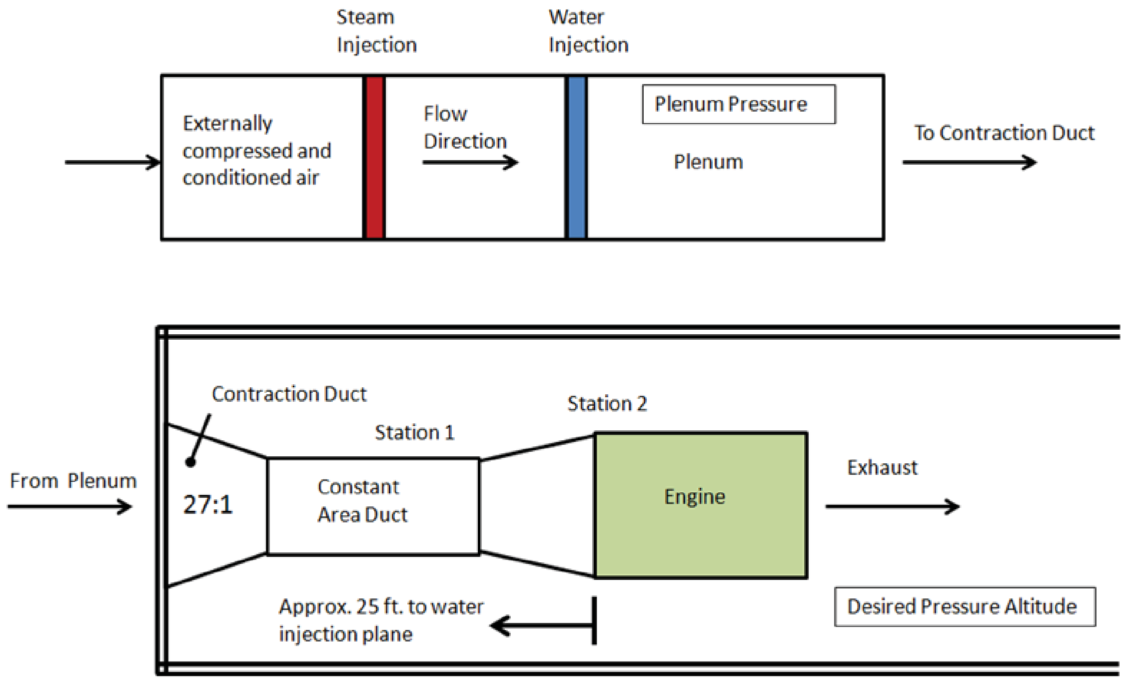

Figure 4. Schematic of the PSL-3 Engine Icing Test Configuration

Table 1. Comparison of PSL Facility Parameters for non-icing and icing configurations.

PSL Facility Parameter	Non-Icing Capability	Icing Capability
Pressure Altitude (ft) Min/Max	Sea level / 90,000	4,000 / 45,000
Static Temperature (F) Min/Max	-90 / 1,200	-60 / 15
Mach Number Min/Max	0.15 / 6.0	0.15 / 0.8
Air Mass Flow Rate (lbm/s) Max	480	330
Thrust Stand Capacity (lbf) Max	50K	50K
Test Cell Dimensions (ft) (∅ x length)	24 x 39	24 x 39
Ice Particle Size (microns)	n.a.	15 to 80
Ice Water Content (g/m^3)	n.a.	0.5 to 9

In 2012, PSL-3 was retrofitted with an ice cloud generation system[11]. The major upgrades included a water spray nozzle system, Figure 3, a steam injection system, and a demineralized or deionized (DI) water supply system. There were various additional mechanical and control components[11]. Figure 4, shows a schematic of the PSL icing system configured for direct connect engine testing. The objective of the retrofit was to produce conventional (super cooled liquid water droplet), fully glaciated (ice crystal) or mixed phase cloud testing conditions to gain capability to conduct engine icing and other aviation safety research and development. The icing configuration does have some limitations compared to the non-icing configuration. Predominantly the restrictions are related to the capacity to cool the air mass flow rate. Table 1 displays a high level PSL capabilities comparison between non-icing and icing configurations. One note is that Table 1 depicts the originally targeted design criteria for the icing modification. The icing system's operational envelope could be expanded to include higher altitudes and lower temperatures if needed for future research missions.

III. Test Article

Engine

The test article for this PSL inaugural test period is an original unmodified, high bypass (5.3:1), geared turbofan engine model ALF502-R5, serial number LF01, Figure 5. The ALF502 was originally developed at the Lycoming Turbine Engine Division in Stratford, CT and is currently owned by Honeywell Engines. It was certified in 1980 and a modified version of the original ALF502-R5 engine is currently used on the British Aerospace 146 (BAe 146) and Bombardier Challenger 600 aircraft. The engine has a fan diameter of 40 inches, is 64 inches long and has a maximum thrust of approximately 7K lbf. It has a single stage geared fan and low pressure compressor (LPC) powered by a two stage low pressure turbine (LPT). The core is comprised of a seven stage axial to single stage centrifugal high pressure compressor (HPC), annular combustor powered by a two stage high pressure turbine (HPT)[12].

This particular engine (LF01) was chosen as the inaugural/validation PSL test article because during a 1997 flight test campaign it experienced an uncommanded in-flight reduction in thrust event while the aircraft environmental operating conditions and key engine and flow path data were being recorded. This coincident information provided a unique set of known data and test results by which the NASA PSL could target and validate its first calibration window. This is an important consideration. The aircraft and engine operational conditions for all the known documented ice crystal icing related events are only generally known. To date there is no other specific data set characterizing both the aircraft and engine operating environment and parameters for any other ice crystal icing related field event.

LF01 was instrumented with thermocouples and pressure sensors along the regions of the flow path where ice crystal icing was suspected to be occurring for the flight test campaign. For the PSL-3 testing, this same instrumentation remained installed. The exact measured engine parameter responses that occurred during the flight test RB event were compared with measured PSL responses in order to quickly determine the cloud on RB conditions in the PSL validation testing. This reduced impact of experimental uncertainties associated with the flight test and the PSL facility and facilitated the ability to duplicate the targeted event in PSL.

Figure 6 shows a sanitized flow path/schematic of the unmodified low pressure compression system for ALF502-R5 engine. In LF01 there were five instrumented planes of interest, Plane 1(P1), Plane 2(P2), Plane 3(P3), Plane 4(P4) and Plane 5(P5). Each plane is instrumented with four thermocouples installed at clockwise positions A, B, C and D aft looking forward. The thermocouples were embedded into the metal at flow path locations of interest for the flight test campaign. This same instrumentation remained installed in LF01 for the February 2013 PSL-3 validation testing. Figure 6 also shows the path of splitter lip and inlet guide vane (IGV) anti-ice air flow from the HPC exit. P1 and P4 thermocouples are installed on the pressure side of the airfoils and P2 and P3 are installed on the suction side.

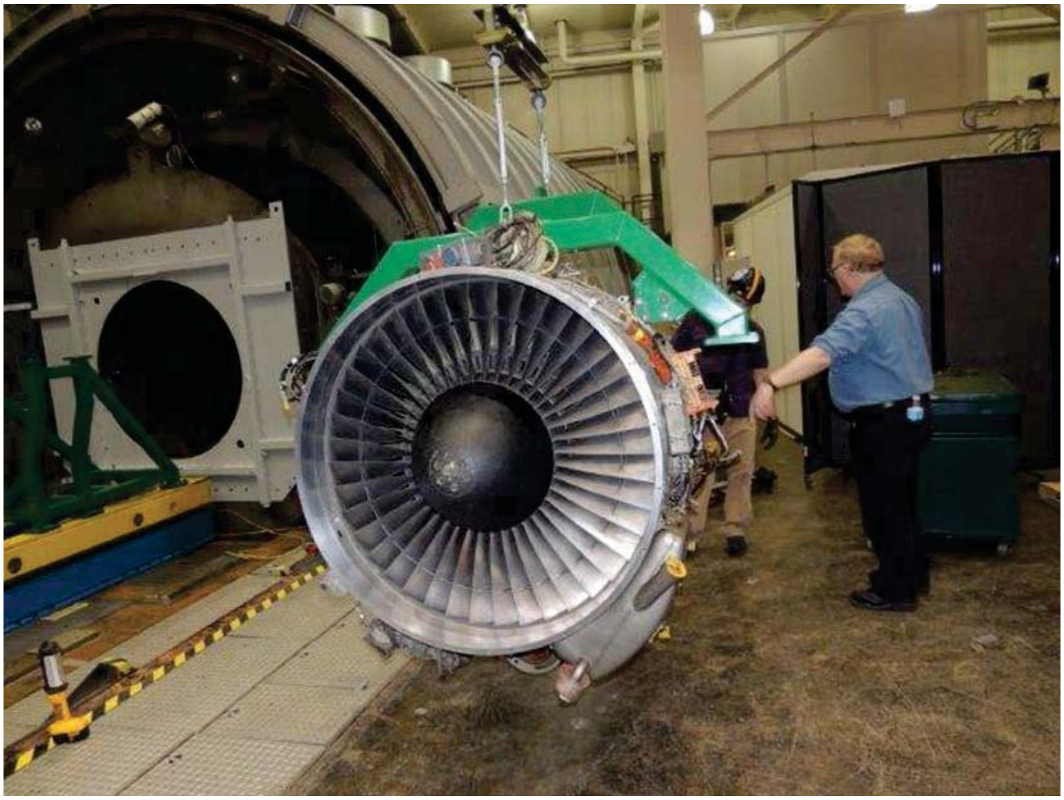

Figure 5. The ALF502-R5 (S/N LF01) engine being installed into PSL-3

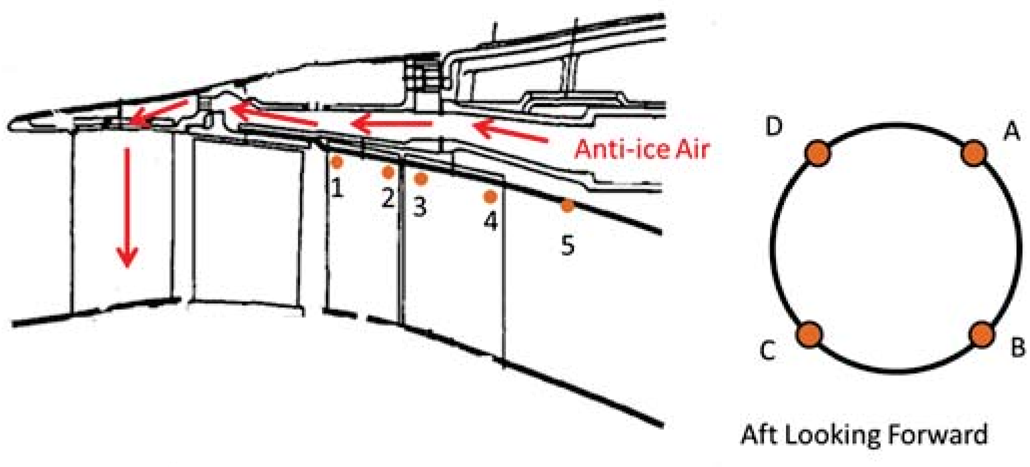

Figure 6. Schematic showing instrumented engine planes (1-5) with circumferential location (A-D) of thermocouples installed at each plane in LF01 for the 1997 flight test campaign. This instrumentation remains installed in LF01 for the PSL testing.

IV. Test Objectives and Results

PSL is the first ground based facility in the world to build the capability and attempt a full scale high altitude ice crystal icing turbofan engine test. The unmodified ALF502-R5 engine from the 1997 flight test campaign is the only known instrumented engine on which an ice crystal icing event and the operating flight conditions it occurred in were coincidently recorded. Using this engine as the inaugural test article for the PSL testing provides a unique opportunity to develop a test plan to validate the calibration techniques and test methodologies using a known set of operating conditions and a known expected result. The following section will discuss the flight test campaign, calibration envelope, test objectives and results of this validation testing.

1997 Flight Test Campaign

A flight test campaign was conducted in 1997 to investigate a series of ice crystal icing related events that resulted in uncommanded loss of thrust for several revenue service flights powered by the unmodified ALF502-R5 engine. Two key test flights from this test campaign were used as validation test points for the PSL testing; Flight Test Flight 850 (FT FLT850) and Flight Test Flight 855 (FT FLT855). For clarity, an FT will precede all references to 1997 flight test points. If there is no FT preceding the test point name that exists for both the flight test and the PSL test it refers to a test point conducted in PSL simulating the FT test point conditions of the same name. FT FLT850 is the flight test that coincidentally documented both engine and environmental parameters during an uncommanded in-flight reduction of thrust event. FT FLT855 was operating in a similar environmental condition compared to FT FLT850 but the engine did not roll back. During FT FLT855 the aircraft was operating in a warmer ambient temperature at a lower altitude. Figure7, shows a sanitized version of the roll back event that was recorded during FT FLT850. It is clear that both fan speed (N1) and High Pressure Compressor or Core Speed (N2) decrease as the flight test point ensues prior to the commanded shutdown of the engine by the pilot. In contrast, there is no decrease in either speed for FLT855 (not shown). These two FT test points were conducted within an envelope defined by several revenue service events leading up to the flight campaign. The FT test points and the revenue service events were used to define the test envelope for the validation testing in PSL.

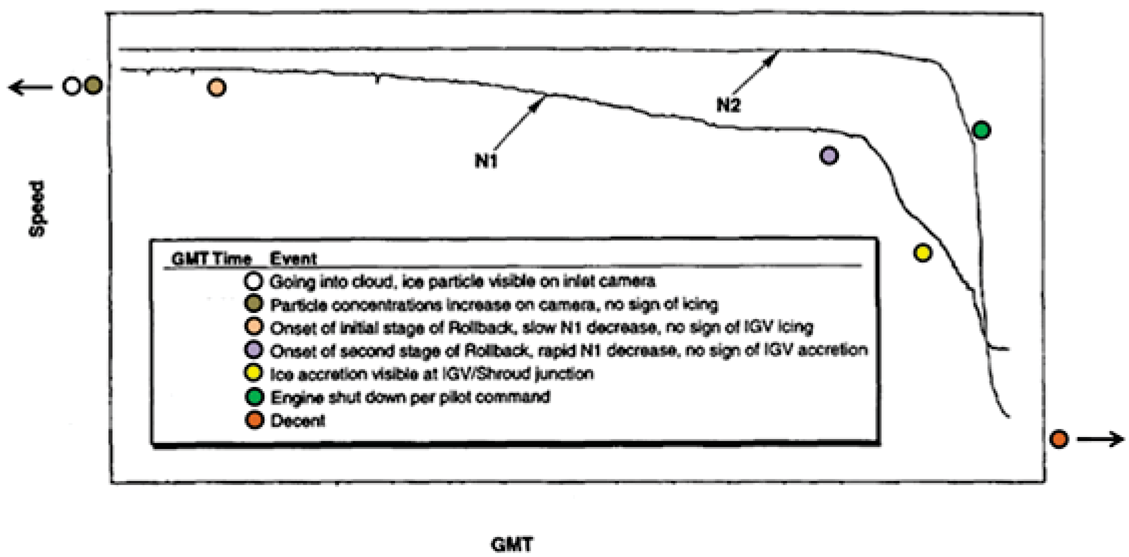

Figure 7. N1 and N2 plots for the ALF502-R5 LF01 engine showing an uncommanded reduction in thrust event recorded during a 1997 flight test.

Calibration of the Test Envelope

Once the new PSL-3 cloud generation system was installed and functional, a validation test envelope was calibrated. This calibrated test envelope was centered on the documented engine operational parameters and environmental conditions measured during the uncommanded reduction of thrust event that occurred during FT FLT850. This calibrated test envelope included conditions for the FT FLT855 test point from the same campaign as well as several documented revenue service uncommanded reduction of thrust field events. Figure 8 shows a sanitized altitude and ambient temperature chart of uncommanded reduction in thrust field events suspected of being related to ice crystal icing. The slanted lines are constant pressure altitude lines. The temperature and pressure altitude is colder and higher moving to the right and upward, respectively. FT FLT850 (red dot) and FT FLT855 (yellow dot) and the revenue service (orange dots) (RS) marked points were tested in PSL-3 during the validation testing.

The following parameters were considered in the PSL-3 calibration test plan: pressure (altitude), Mach number at the calibration plane - matched to Mach number at the fan face, and total temperature - matched to the static temperature at the fan face. Given these conditions, the characteristics of cloud uniformity were optimized for a circular area centered on the engines projected splitter lip. Spray bar atomizing air pressure and water pressure were mapped to total water content (TWC) and particle size measured as median volumetric diameter (MVD)[13]. TWC is the summation of liquid water content (LWC) and ice water content (IWC). For fully glaciated conditions LWC is equal to zero.

Primary Objective

The primary objective for the inaugural PSL-3 ice crystal icing validation testing was to demonstrate that the newly modified PSL-3 test cell could be calibrated and tested at known flight test conditions. Validation of this capability was based on calibrating, testing and duplicating the FT FLT850 and FT FLT855 test points. FT FLT850 and FT FLT855 flight test results were repeated throughout the month long test period. FT FLT850 was repeated three times and FT FLT855 was repeated four times.

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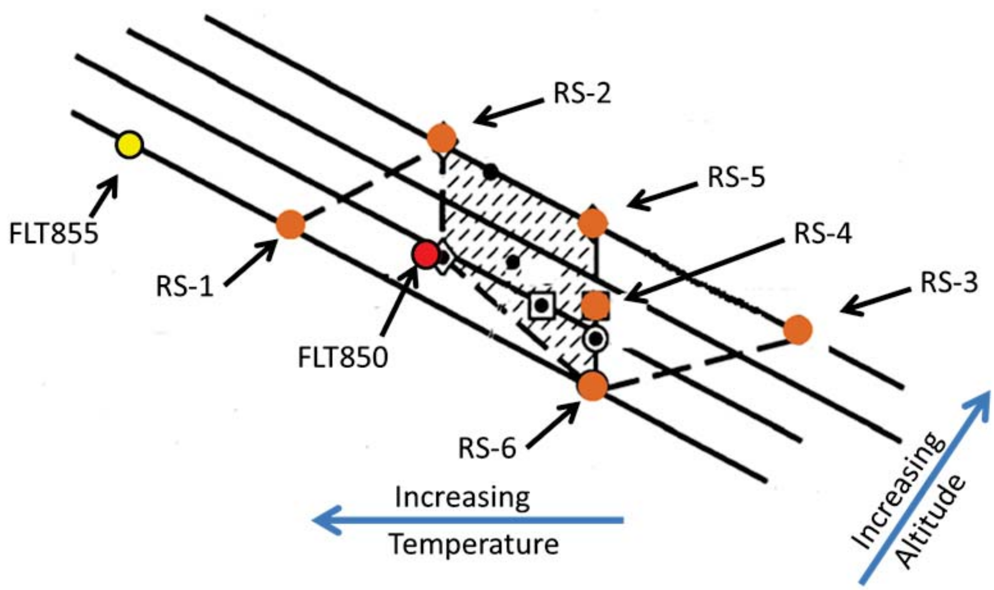

Figure 8. Envelope of uncommanded reduction in thrust flight test and field events.

<u>FLT850</u>

The FT FLT850 test point is represented by the red dot in Figure 8. To date this is the first and only flight test that both the environmental operating conditions and engine operating parameters were being measured and recorded on a partially instrumented engine and aircraft when an uncommanded reduction in thrust event occurred related to ice crystal ingestion. The engine operating parameters, aircraft flight altitude and instrumented plane thermocouple measurements, Figure 6, were all known with good confidence for FT FLT850. However, due to subsequent analysis by atmospheric scientists who collected the original FT FLT850 environmental/cloud data, an uncertainty existed as to the correct cloud parameters of MVD and TWC experienced during FT FLT850.

Cloud Sweeps

Due to flight test environment measurement uncertainties, in an effort to efficiently ascertain whether a PSL-3 test point was a roll back viable test point, a cloud parameter sweep methodology was implemented. The one minute cloud sweeps varied the key cloud parameter of TWC, while holding MVD, and monitored the response of the thermocouple measurements in the LF01 flow path to the cloud on conditions. If the LF01 thermocouples responded to the cloud on conditions in a similar fashion as the flight test, the test point parameters were deemed viable as roll back test conditions. Using this methodology a set of viable FT FLT850 roll back test conditions were quickly identified for the FLT850 testing in PSL-3.

Full Rollback Test Points

Implementing these test conditions in PSL-3 led to a full roll back test point closely duplicating FT FLT850 in both sensor response and time to roll back. Figure 9 shows a comparison between the thermocouple readings at P4, from FT FLT850 and P4 measurements from a PSL-3, FLT850 full roll back test point. The charts are sanitized, have the same axis scales and a single tick mark on the temperature scale represents the same temperature for both. Note how the thermocouple traces for the PSL chart (lower) drop immediately when cloud on operation commences.

Based on documented information and flight test data these thermocouple traces drop to a certain value initially at the cloud on condition and subsequently drop to a lower value as the test point ensues if a roll back event is going to occur. In general for all roll back test points conducted in PSL within the primary test envelope the thermocouple traces dropped to a similar certain initial value and then lowered to a similar second value prior to the roll back event occurring. For test points where no roll back occurred the initial drop in the thermocouple traces was to a higher temperature than that for the RB test points and the no roll back test points did not demonstrate the trend of a secondary thermocouple drop.

The initial temperature drop is likely the surface embedded thermocouples measuring either the temperature of surface water or cooling due to evaporation (i.e. a wet-bulb temperature effect as water evaporates from the surface to bring the air passing immediately over it to saturation[14]). Since air outside of the engine is quite cold and likely saturated with a given humidity ratio, as the air enters the engine and heats up the humidity ratio remains similar for the warmer air which increases the potential to evaporate or sublimate water/ice on the surface. The thermodynamic wet-bulb temperature of dry air would be significantly lower than the ambient static temperature which explains the rapid decrease in cloud on thermocouple measurements along the LPC flow path. The second temperature drop is interpreted as the result of the ice forming on the surface and cooling as ice sublimates into the air flowing over it. Due to the lack of internal cameras to identify and characterize ice buildup, this interpretation of the thermocouple response as equating to ice buildup is used for all subsequent roll back test points.

After identifying several viable FLT850 cloud test parameters based on flow path thermocouple response, duplication of a full roll back event was attempted. Figure 10 shows percent of maximum fan (%N1) and core (%N2) engine speeds for the first ever high altitude, ice crystal ingestion test point resulting in an uncommanded full roll back event, PSL-3, FLT850-1. The time axis of Figure 10 is similar to the time axis for the FT FLT850 engine speeds shown in Figure 6. Note that the PSL-3 plot in Figure 10 shows a roll back that occurred in nearly 1/3 the time of FT FLT850 in Figure 6. Figure 11 shows test point FLT850-2 with cloud TWC reduced by half. The cloud TWC was reduced to better match the RB time of FT FLT850. Note that the FLT850-2 roll back time in Figure 11 is similar to FT FLT850 in Figure 6. This indicates that cloud TWC is a key contributing factor to the time between cloud on and the occurrence of roll back for this test article. The power lever angle (PLA) or engine throttle and the cloud on indication are also shown in both Figures 10 and 11.

Cloud-on Exit procedure

Once the full roll backs shown in Figures 10 and 11 occurred, the engine needed to undergo a recovery process. The first step in the recovery process is to exit the cloud on condition. Two methods were tried. In Figure 10 it is seen that the PLA was reduced prior to the cloud turning off. In Figure 11 the cloud is turned off simultaneously with the PLA being reduced. This was an effort to develop a procedure to exit the cloud on condition in as safe a manner as possible to the engine.

In the first case, Honeywell Engines speculated that upon turning the cloud off there would be an increased probability to shed ice that accreted during cloud on operation while the engine rotating hardware was at higher speed and therefore more susceptible to mechanical damage should shed ice impact the rotating hardware. To minimize this risk the engine speed was reduced prior to turning the cloud off. However, this method resulted in heavy ice accretion on the IGV as the cloud on operation engine speed was reduced and the anti-ice air became cooler. Subsequently the engine became sub-idle and did not respond to PLA input for several minutes. This method was accompanied by a long recovery time.

The second method ceased ice buildup at roll back, resulted in a significantly shorter recovery time and did not experience the lack of response to PLA changes seen in method one. The second method was implemented for the remainder of the test as the preferred cloud exit procedure.

Called Roll backs

A "called roll back (CRB)" procedure was developed to minimize the risk of critical damage to the engine due to ice buildup and subsequent shedding. In order to develop this procedure, plots of several parameters measured during two separate full RB test points were analyzed: FLT850-1 and FLT850-2. Figures 12 and 13a show the RB indicating parameters plotted and analyzed for these test points. Note that the X and Y-axis scales are identical for both figures and TWC for the Figure 12 test point is 2 times that of the Figure 13a test point.

The plot trace labeled LOAD in the roll back indicator charts throughout the paper is an average of two load cell measurements made on the engine thrust stand. In Figures 12 and 13a LOAD is shown to increase at cloud on conditions and then begin decreasing as the RB test point ensues. This LOAD decrease occurs prior to the %N1 decrease in both figures. Note that the measured HPC inlet static pressure (Ps) also begins to drop before the %N1 decrease. This suggests that significant ice buildup has occurred and that RB is imminent. The LOAD increase at cloud on is due to an increased momentum change occurring as the engine ingests cloud particles entrained in the air flow.

Using LOAD as the key roll back indicator parameter, a CRB decision was made to end test points when a pre-established LOAD decrease threshold was reached during cloud on testing. No decrease in the LOAD parameter indicates a test point that is a called no roll back (CNRB). There were 86 CRB and 37 CNRB during the month long PSL validation testing.

During the RS and flight test RB events, the BAe 146 pilots became aware of the ice crystal icing induced roll back only by noticing N1 on the flight deck instrument panel reading was lower than expected/commanded. This alerted them that they were in an uncommanded loss of thrust situation. Testing in PSL-3 with the ALF502-R5 mounted on a thrust stand revealed that LOAD begins to decrease prior to the N1 reduction. PSL-3 testing showed that both LOAD and measured HPC inlet static pressure decrease simultaneously. Figure 13b shows this for the PSL-3 FLT850-2 test point. Note the LOAD, airflow and N1 perturbation. The static pressure would decrease by conservation of mass if a given air mass flow required by the core was trying to get through the LPC through a reduced area and was picking up speed. This suggests that a physical or aerodynamic blockage is occurring in the LPC. For a typical RB test point no ice is visible on the inlet guide vanes. In Figure 13a, the plane average thermocouple values trend as P5< P4 <P3 <P2<P1. This suggests that ice buildup initiates at P5 and grows forward towards P1. This suggests that the physical or aerodynamic blockage that initiates restricted flow leading to a roll back occurs along this path. This means the ice blockage is occurring downstream of the LPC and upstream of the HPC. Evidence is shown in Figure 35 that liquid water rivulets on the IGV appear to travel from the TE to the LE for the full roll back test points. This could be caused by the stalling of the LPC due to a downstream blockage or to secondary flows on the suction side of the IGV due to mismatched velocity triangles as N1 decreases throughout the RB test point. At any rate a choked flow between the LPC and HPC and a reduced change of momentum of air flowing through the core shows as a reduction of measured LOAD. This became the leading RB indicator that allowed reliable implementation of a CRB procedure to both lessen the risk of ice shed damage to the test article and to make efficient use of valuable test time.

Referencing Figure 8, in the range of RB events based on ice buildup and RB time for given cloud on conditions, FT FLT850 and points near it seem to be near the center of a highly probable RB operating condition for this test article. As the temperature and altitude move away from this region the ice buildup time for a given condition appears to increase. Near to the boundaries of the test event envelope it is required to manipulate the TWC or PLA during testing in order to influence the onset of ice buildup leading to RB or CRB. RB/CRB is able to be turned off and on (RS-1, Figures 15, 16 and RS-3 Figures 18, 19 for example) by small incremental changes in either TWC or PLA. The TWC effect is more obvious to explain since more or less surface cooling capacity of impinging cloud particles increases or reduces respectively the potential for ice buildup and the subsequent RB/CRB event. Changing the PLA is less obvious of an effect since it changes fuel flow most directly but the impact via the control system, a hydro mechanical unit (HMU) for this test article, is more difficult to assess.

Engine Recovery

The thermocouple plots in Figures 12 and 13a show delayed recovery or return to pre-cloud on values at cloud off. This is evidence that ice buildup occurred and remains on and/or around the flow path embedded thermocouples. The thermocouple traces return to pre-cloud on values after an engine recovery period in which this ice sheds. Note that in Figure 13a the full recovery is cut off to make the axis scale identical to Figure 12. In general the longer the time required for RB/CRB to occur, the longer the time required for engine (thermocouple) recovery to occur. Though the recovery time varied for different test points, this cloud off engine recovery period is typical for all RB and CRB test points conducted in PSL-3.

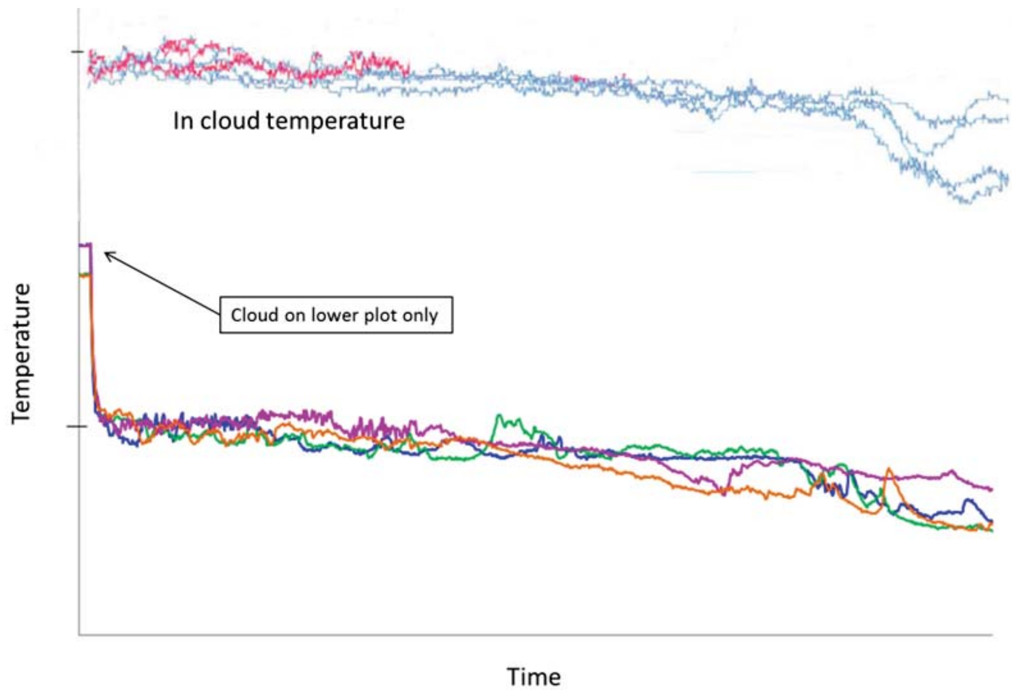

Figure 9. Plane 4 LF01 thermocouple plots recorded during the FLT850 1997 flight test (top) and PSL testing (bottom) at the same conditions.

<u>FLT855</u>

The FT FLT855 test point is represented by the yellow dot in Figure 8. It is the single documented NRB event from the 1997 flight test campaign within the PSL-3 cloud calibration envelope. It is interesting because it falls outside of but close to the grouping of the FT FLT850 and the documented RS RB events. Figure 14 shows the RB indicating parameters chart for test point PSL-3, FLT855-1. Note that there are no decreases in LOAD, Ps, N1 or N2 for this test point. The target TWC for this test point is identical to that of FLT850-2, Figure 13a. This PSL-3 test point was called as a no roll back test point after a certain time frame elapsed while observing minimal if any changes in the roll back indicators. Note that both the X and Y axis scales of Figure 14 are identical to those of Figures 12 and 13a. The only targeted difference beyond the Figure 8 location is that the FLT850-1 test point, Figure 12, has twice the TWC of the other two test points, FLT850-2 and FLT855-1. The average cloud on thermocouple measurements for the NRB point in Figure 14 are significantly higher than both the RB test points of Figure 12 and 13a for all instrumented planes. In Figure 14, it is shown that immediately upon cloud off all the average thermocouple measurements from P1 to P5 returned to pre-cloud on conditions. The engine required zero recovery time for this test point. The roll back indicators chart of PSL-3, FLT855-1, Figure 14, is typical for test points that are CNRB test points. This is indicative that little to no firmly accreted ice buildup occurred at these instrumented planes of the engine. For NRB test points, Figures 14, 15 and 18 unsteady thermocouple behavior was observed. This may indicate loosely accumulating and shedding ice buildup for NRB test points vs. firmly accreted ice buildup for RB/CRB test points.

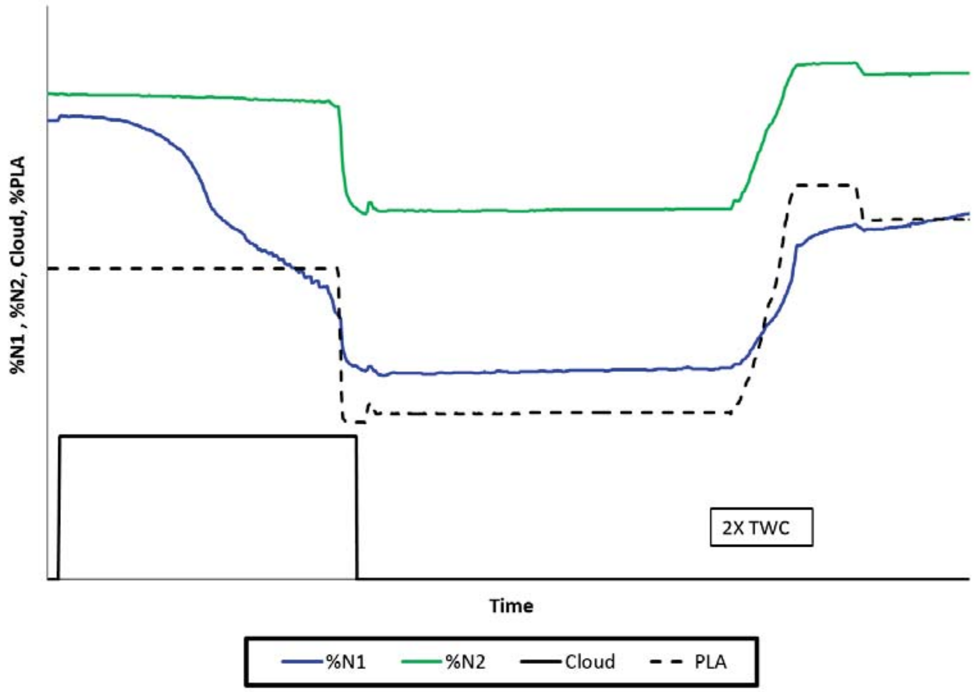

Figure 10. Fan Speed (%N1) and Core Speed (%N2) Chart showing uncommanded roll back for the first ever FLT850 test point in PSL-3.

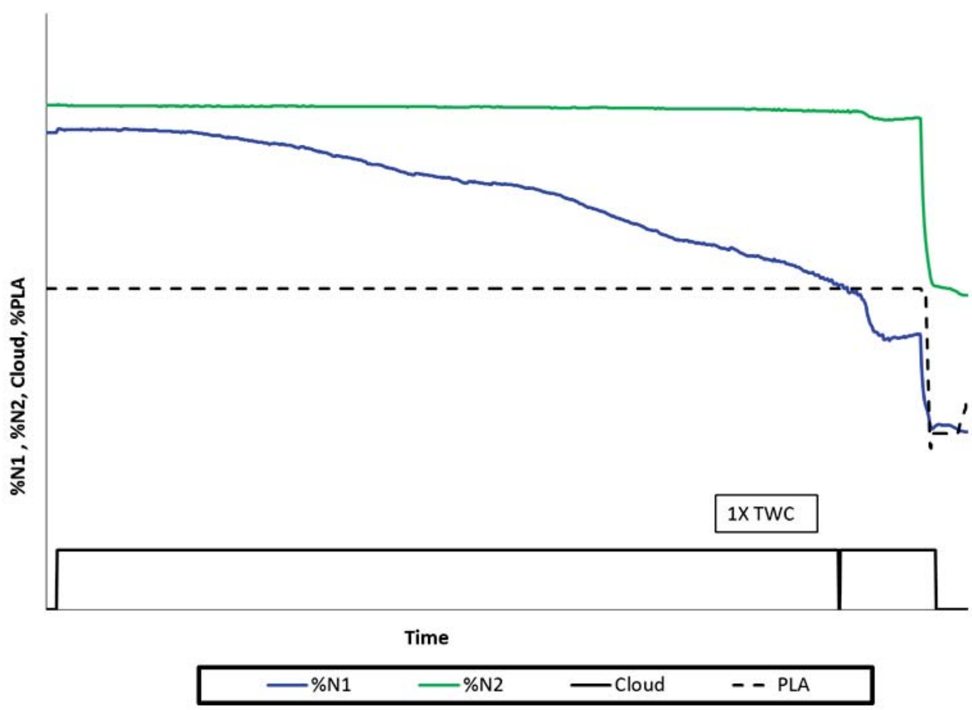

Figure 11. Fan Speed (%N1) and Core Speed (%N2) Chart showing uncommanded roll back for the second ever FLT850 test point in PSL-3.

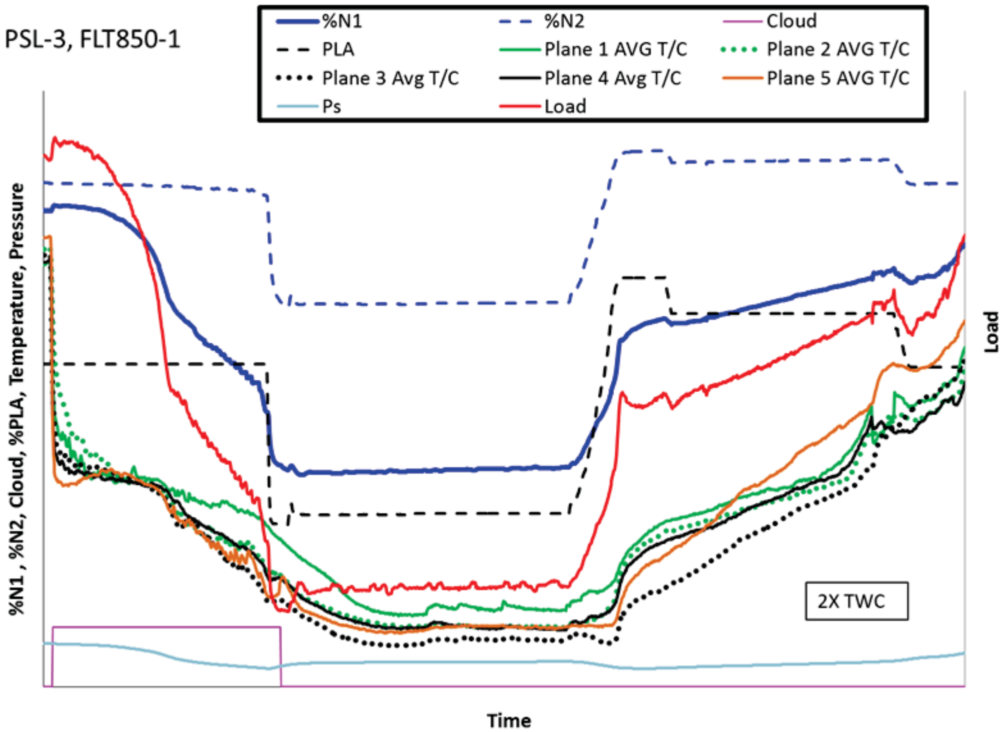

Figure 12. Roll back indicators chart for first PSL-3 FLT850-1 full roll back test point

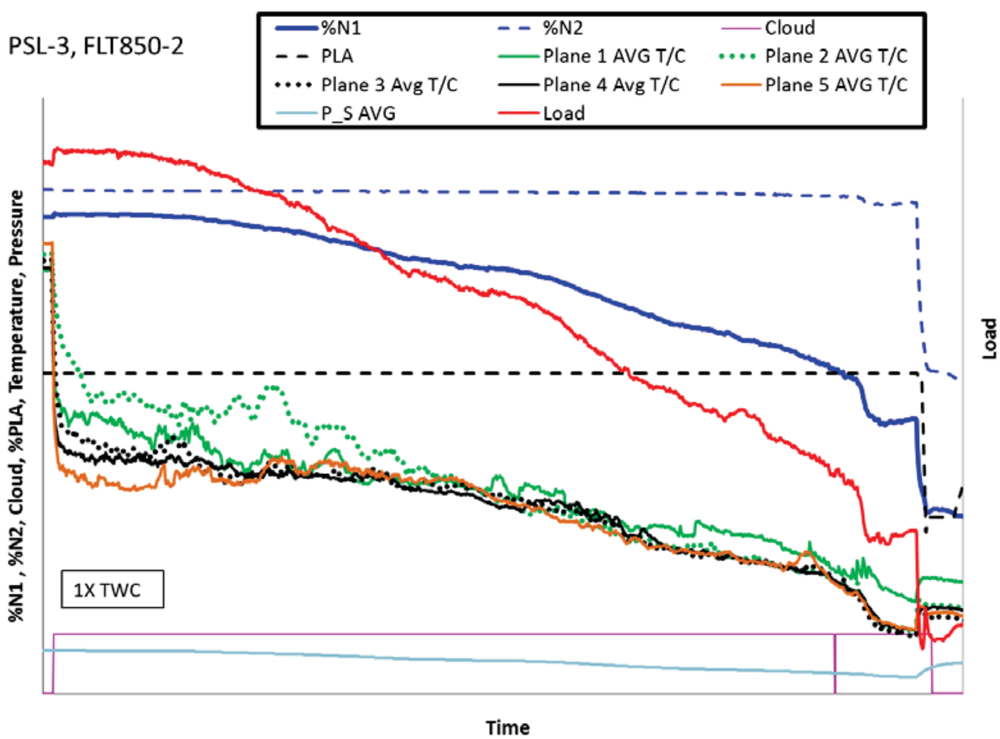

Figure 13a. Roll back indicators chart for FLT850-2 full roll back test point

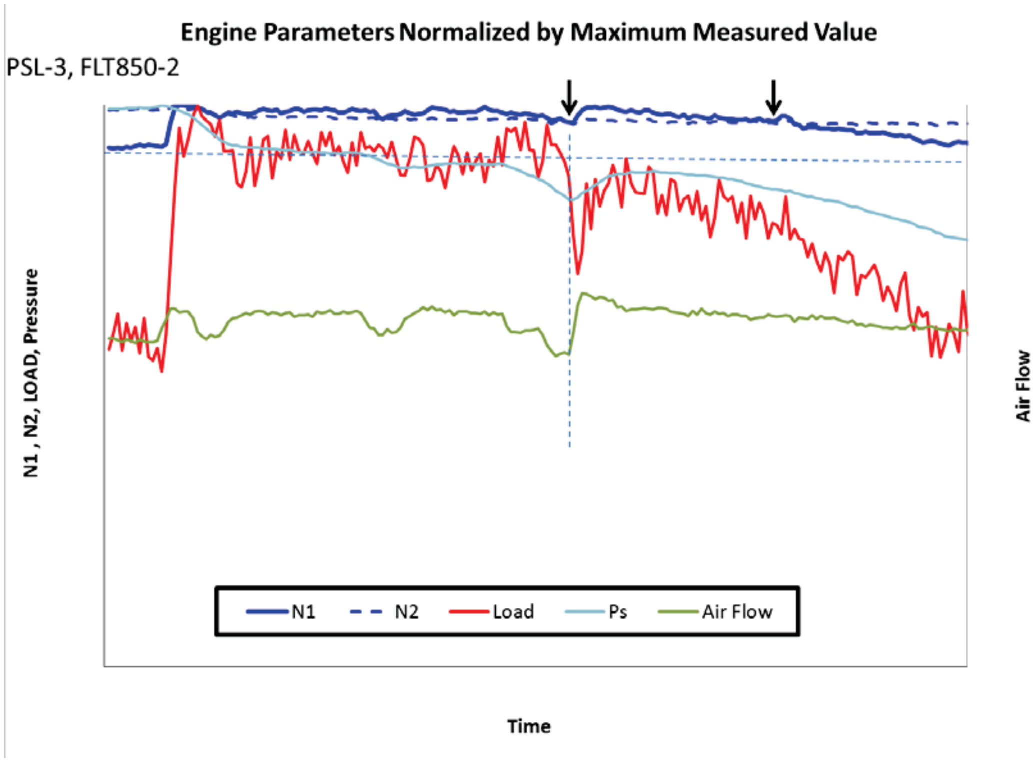

Figure 13b. Roll back indicators chart Zoomed View for FLT850-2 full roll back test point

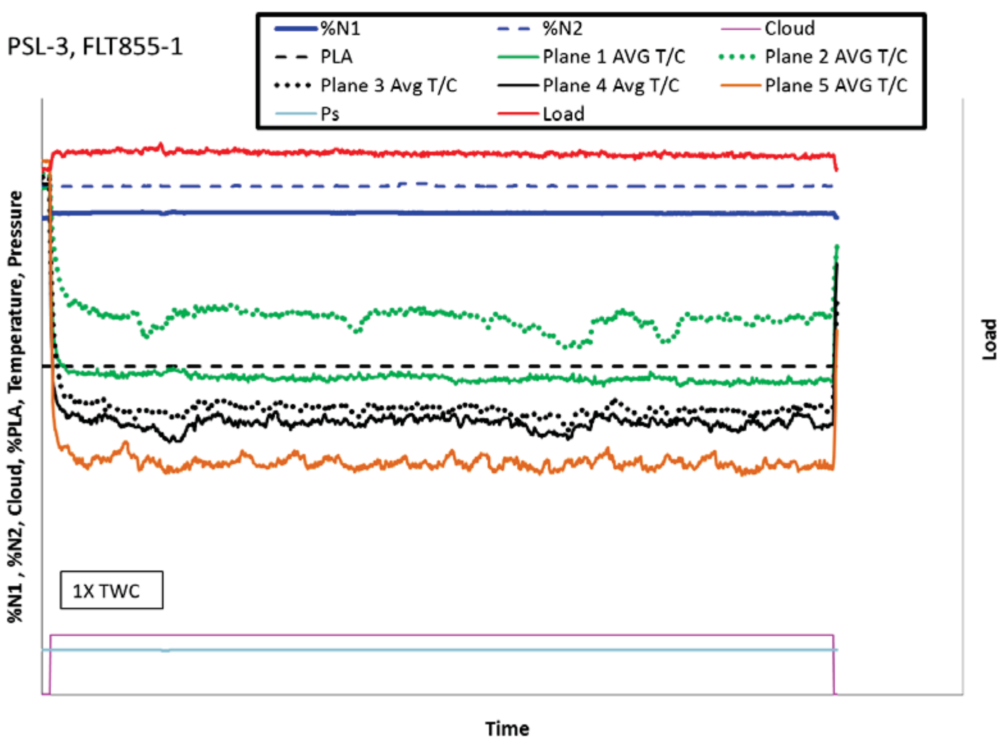

Figure 14. Roll back indicators chart for PSL-3 FLT855-1 no roll back test point

Secondary Objective

The secondary objective for the inaugural testing was to duplicate documented uncommanded reduction of thrust field events that occurred during revenue service within the PSL-3 cloud calibration envelope. The technical difficulty in these test cases is that both the environmental and engine operational characteristics were not well documented for any of these field events. NASA worked with Honeywell Engines to estimate the engine operational parameters for these events based on an engine performance deck and an expanded window of environmental conditions centered on those measured during PSL-3 test FLT850. The secondary objective was successfully demonstrated. A PSL-3 RB test point was successfully achieved for each revenue service field event tested.

The test points labeled as RS-xx in Figure 8 are revenue service field events that were tested in PSL during the test period. They represent field events that span the altitude, temperature and engine operation calibration envelope of the PSL-3 cloud generating system for this inaugural ice crystal icing test. Since none of these events had similar data measured as that of FT FLT850, NASA and Honeywell Engines worked to develop a test methodology based on the ALF502-R5 cycle deck to determine engine operation at the specified ambient temperature, pressure altitude, cloud variation (centered on the FLT850 cloud parameters) and documented knowledge of the RS events. In general during testing, all RS test points started with the identical MVD and TWC as FLT850-2. Cloud TWC was increased incrementally as necessary to produce a CRB event for a given RS test point. Cloud MVD adjustment was not performed for any RS test point to produce the CRB event. The RS test points near the colder/higher as well as warmer/lower boundaries of the temperature, altitude envelope shown in Figure 8 required incremental TWC adjustments to produce a CRB. The CRB events that occurred near FT FLT850 conditions were characteristically similar to FLT850-2 with similar ice buildup rates, CRB and recovery times and cloud parameters. The roll back indicators for selected RS test points are shown in Figures 15 to 19. Figures 15/16 and 18/19 show how incremental adjustment of TWC caused the CRB event to occur. For RS-1b (Figure 16), 3b (Figure 19) the cloud TWC was targeted to be 1.3 times and 2 times respectively compared with RS-1a (Figure 15), 3a (Figure 18) to produce the CRB event.

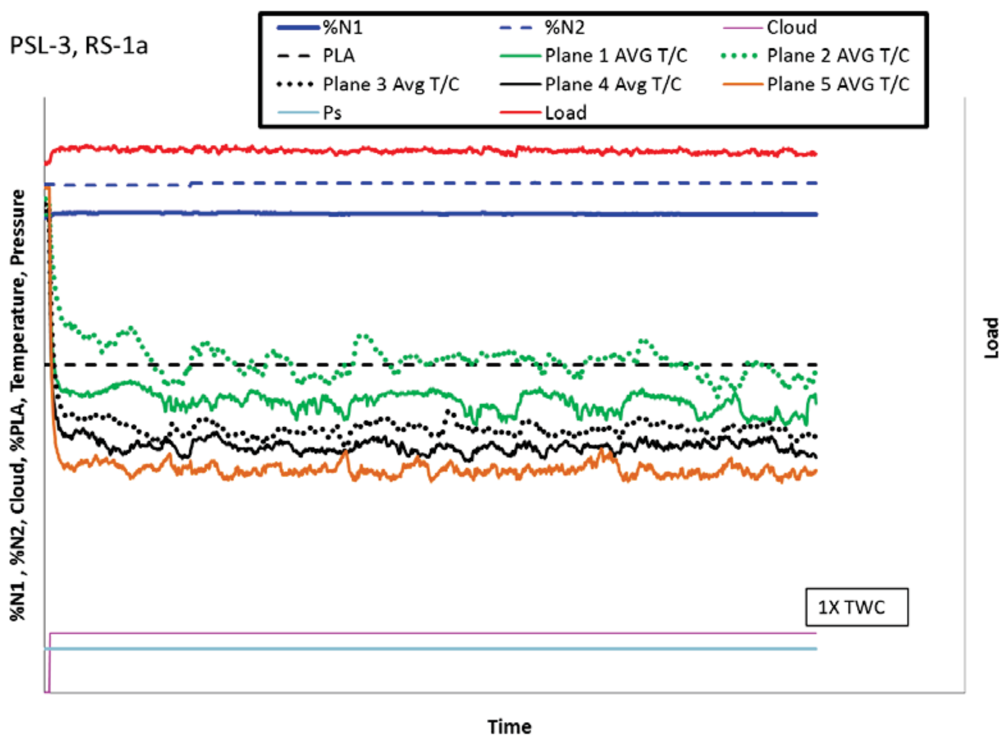

Figure 15. Roll back indicators chart for test point RS-1a, relative to Figure 16.

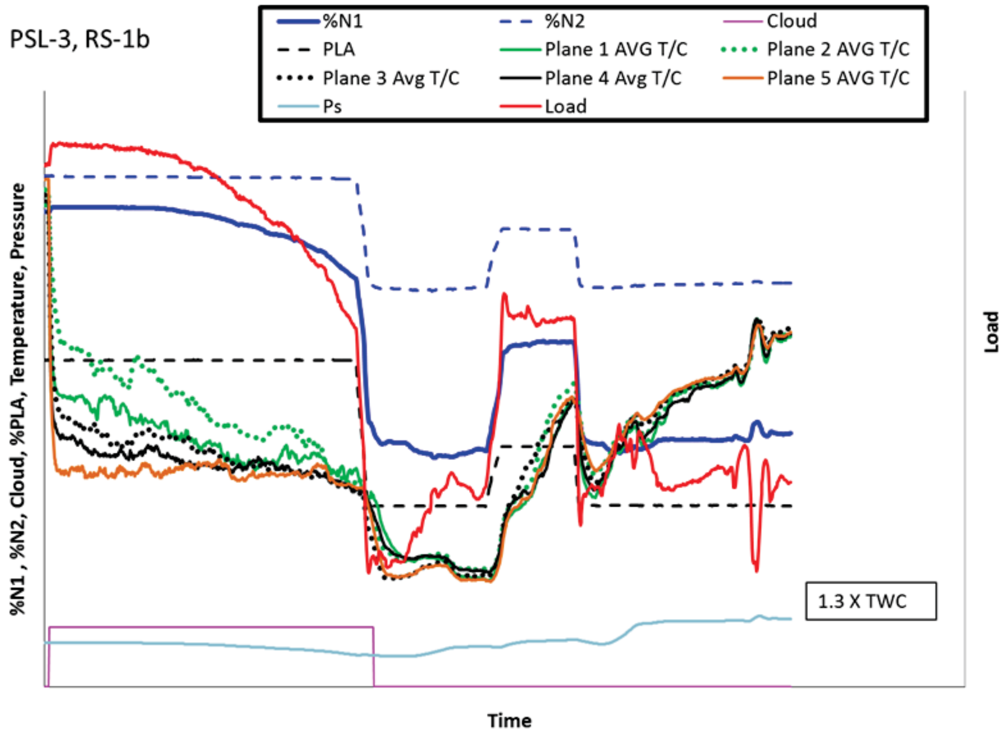

Figure 16. Roll back indicators chart for test point RS-1b relative to Figure 15.

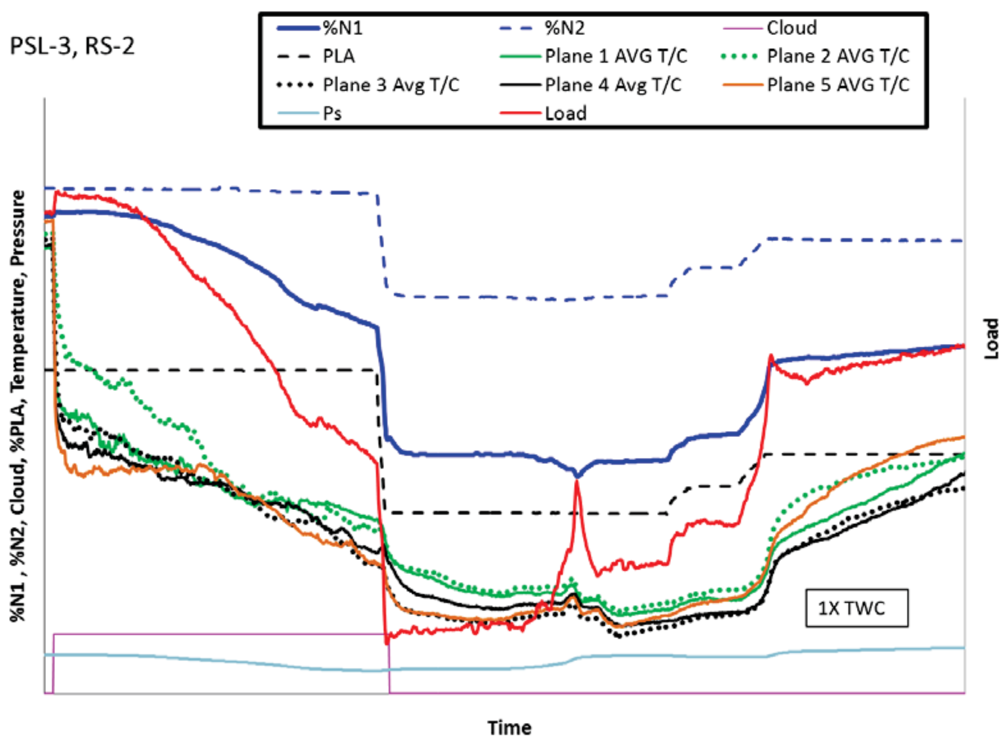

Figure 17. Roll back indicators chart for test point RS-2

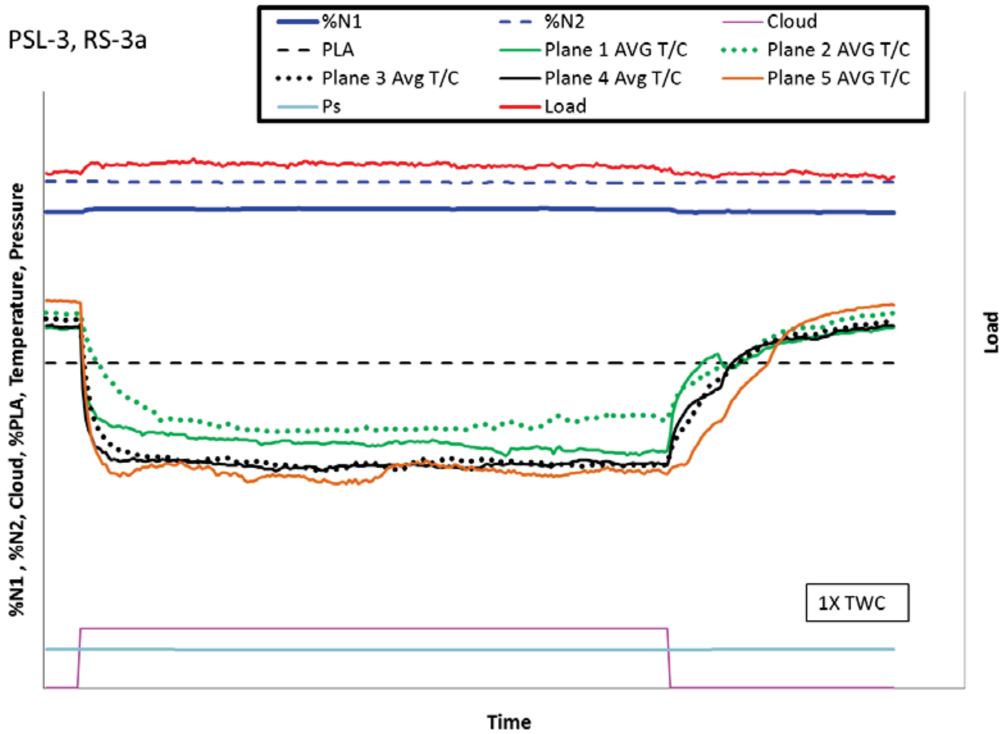

Figure 18. Roll back indicators chart for test point RS-3a, relative to Figure 19.

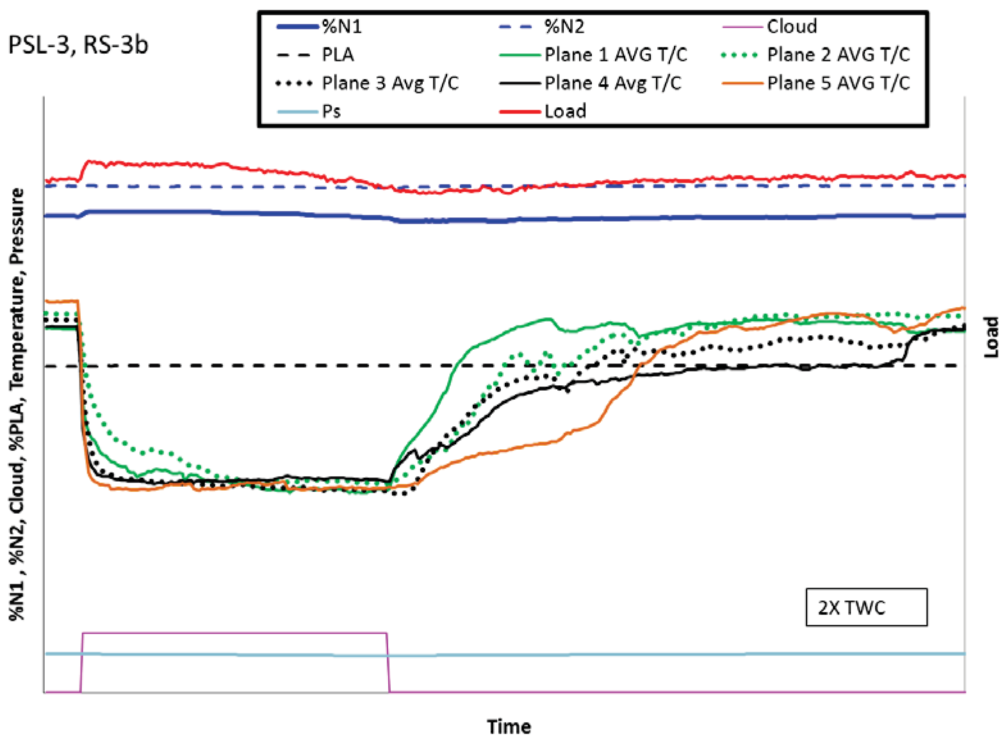

Figure 19. Roll back indicators chart for test point RS-3b, relative to Figure 18.

Additional Objectives

The additional objectives of this inaugural testing were to demonstrate repeatability of the PSL facility, to explore the individual parameters controllable in PSL-3 and the engine and characterize the resulting effects on the operation of the LF01 engine. Repeatability was demonstrated by repeating test point FLT850-1 on several occasions throughout the month long test program, Figure 20. To achieve the facility, engine and cloud parameter effects, anti-ice system on/off, various parameter sweep and design of experiment (DOE) test points were performed. Figures 21-24 show results of these parameter test points. Qualitatively, the additional objectives were successfully achieved. However, several of the test points fell outside of the calibrated test envelope used in achieving the primary and secondary objectives. Future calibration efforts could work to extend the calibration envelope to include these test point conditions for further analysis.

PSL-3 Repeatability

The results of the PSL-3 repeatability test points, Figure 20, show test point FLT850-1 conducted at various times through the test series. Inspection of the chart shows that the measured average LOAD for all the test points was within one percent of the nominal value. The measured average P2 temperature is within 2% of the nominal value. Both variations are within expected ranges. The variation in LOAD is due primarily to variation in repeating the exact PLA position for each repeated test point. Note that the LOAD parameter begins to decrease at the same time for the various test runs. This location is labeled as ice buildup apparent (IBUA) since roll back is initiated by flow restriction due to a buildup of ice.

Anti-ice on/off

The result for a test point with FT FLT850 conditions conducted with and without the engine anti-ice system turned on is shown in Figure 21. The engine anti-ice system works by allowing hot air from the high pressure compressor exit region to flow into the annular area cavity that surrounds the low pressure compressor outer flow path and down through the inlet guide vane. The individual P1 to P5 thermocouples are mounted in or on vanes that are bonded directly to the outer flow path of the LPC, Figure7. From Figure 21 the cloud off P2 Tavg trace for the anti-ice on test point is shown to be higher than the anti-ice off trace. This is likely due to either anti-ice air heating the outer shroud from the back side, leaking into the flow path near the outer wall, air heating up as is it passes over the heated IGV or some combination of the three. Note that the anti-ice off trace falls immediately and levels off

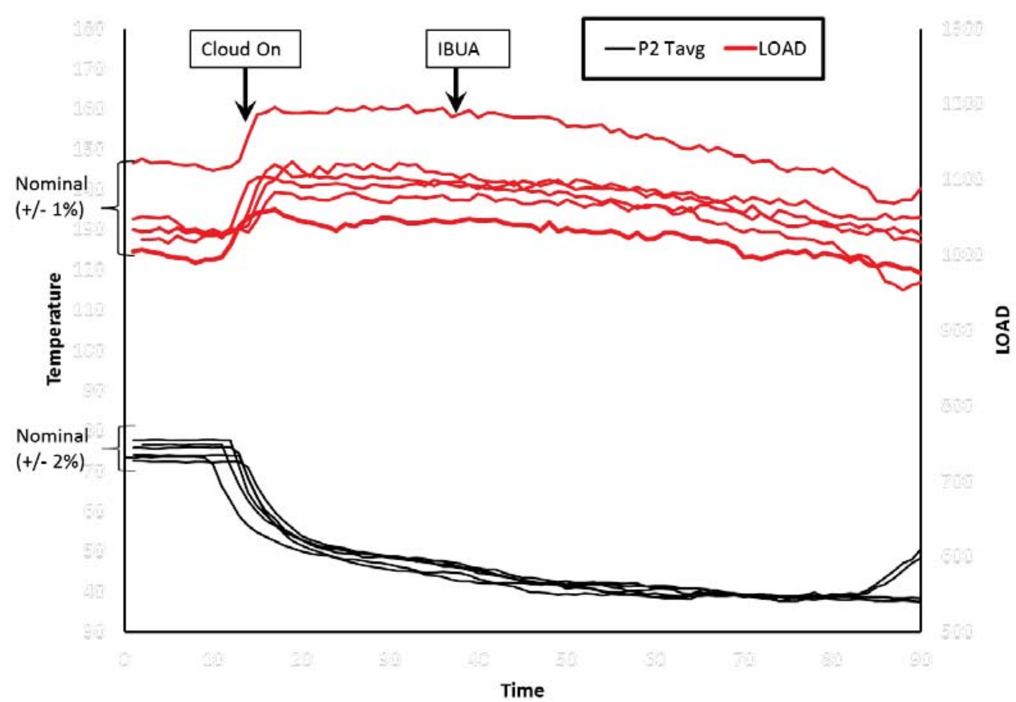

Figure 20. PSL-3, FLT850 test points conducted throughout the month long test

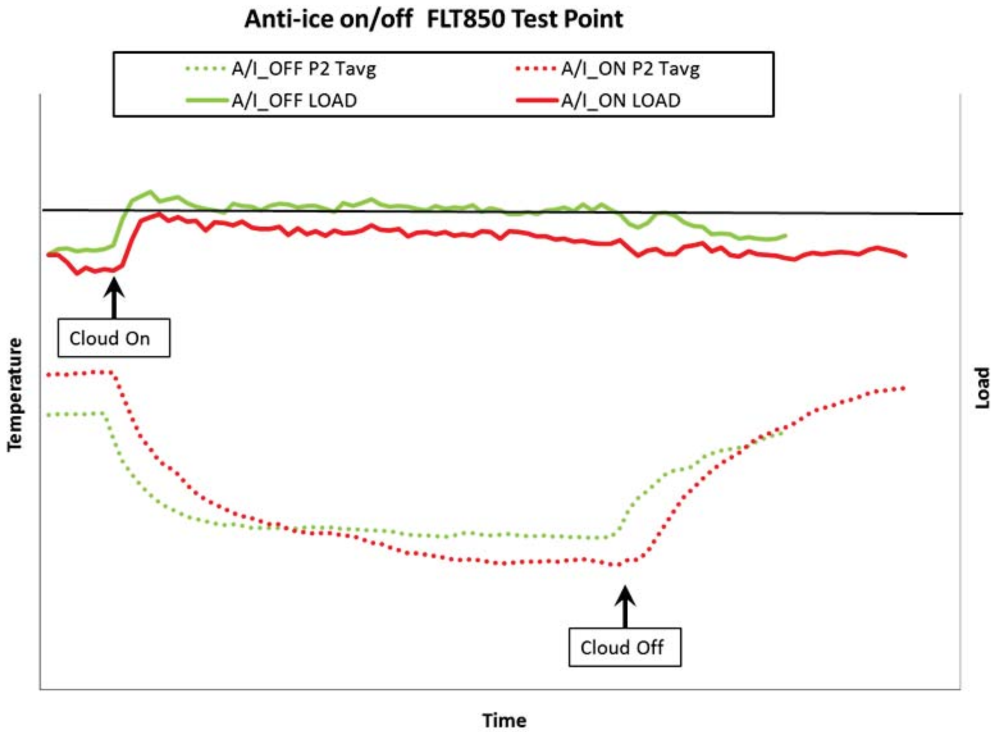

Figure 21. PSL-3, FLT850 test points conducted with the engine anti-icing system turned on and off

to a relatively steady value at cloud on condition and that there is no secondary temperature drop indicating ice buildup. The LOAD trace for the anti-ice off test point remains steady at the cloud on value. The P2 Tavg trace for the anti-ice on test point drops immediately to the same value as the anti-ice off test point at cloud on condition but undergoes a secondary temperature drop as the anti-ice on LOAD trace begins to drop. This is indicative of critical ice buildup and imminent RB.

MVD and TWC sweeps

MVD sweeps were conducted for both a RB RS test point and a NRB FLT855 test point. Note that each MVD was investigated as a separate test point. The objective was to investigate the influence of cloud particle size on one RB and one NRB condition. The RB indicator charts showing the results of an MVD sweep for the RS RB and NRB (FLT855) test points are shown in Figure 22 and 23 respectively. For the RS RB test point in Figure 22 the particle size does not appear to affect the on-set of IBUA. All loads appear to begin decreasing at a similar time after cloud on condition. Note that the rate of LOAD decrease is greater for the larger MVD cloud test point and is least for the smallest MVD cloud. For the NRB series of test points the only difference is a significantly warmer P5 Tavg trace. This is likely due to the larger MVD cloud not being fully glaciated. It appears that while cloud particle size does not influence the onset of ice buildup it does influence the rate of ice buildup if it is occurring for a given test point.

TWC sweeps were conducted for the FLT850 test point. The objective was to investigate the influence of cloud TWC on RB condition. The RB indicators chart showing the results of the TWC sweep is shown in Figure 24. It is clear that the largest TWC cloud produces the highest rate of LOAD decrease for this test point. Note that the largest TWC also produces the most rapid initial and secondary temperature drop at cloud on conditions. TWC has a major influence on both the rate of ice buildup and cooling of the flow path.

It should be noted that TWC is affected by the direct connect nature of the set-up. The PSL-3 facility ice crystal test configuration blocks the normally open test cell by-pass air flow to prevent this region from icing up during the icing tests. For non-icing configuration the airflow in the plenum chamber containing the spray bars would be constant throughout a test point. For icing configuration the airflow is regulated by maintaining the static pressure setting which is measured in the plenum chamber. This means that as ice begins to build up in the LPC of the test article and airflow becomes restricted and the engine desires less airflow, the airflow in the plenum actually decreases. For cloud on operation in this inaugural test, the water injection rate was not reduced as the airflow reduced. This leads to increased TWC for a given test point as ice buildup occurs. Since this does not occur until the ice buildup commences the cloud on condition is accurate up until the onset of ice accretion. In theory the TWC should be maintained by reducing the water injection rate to match the air flow rate as the test point continues beyond the onset of ice accretion and the facility airflow is reduced. Two discussion points can be made to address this issue:

1. Since the RB issue is occurring in the LPC and airflow through the LPC-HPC flow path is likely pulling in cloud particles that are entrained into it, the overall impact of leaving the water injection rate unadjusted may not be a one to one consideration i.e. TWC may not be effectively or significantly increasing in the region of interest. More work is required to better characterize the cloud that actually makes it beyond the fan and into the LPC-HPC flow path. Supporting this discussion point is that the full RB test points conducted in PSL-3 compare well to the FT FLT850 test point, Figure 9. This suggests that the TWC/facility airflow correction may not be a first order effect.
2. Adjusting the cloud water injection as the test point ensues makes it extremely difficult to calibrate accurately for a wide range of test points without being able to predict the reaction on a particular test article to ice buildup.

<u>Surge and Flameout Test Points</u>

In turbofan engine field events discussed in literature and documented by the ICC as suspected of being related to ice crystal ingestion, effects on the engine include both engine surge and flameout[5]. During the PSL-3 inaugural ice crystal icing test program both a surge (FLT850-3) and a flameout (DOE-1) occurred. The RB indicators charts showing the plane average thermocouple traces for these two test points are shown in Figures 25 and 26. Figure 28 shows the results of repeating the flameout test point (no flame out occurred for the repeated attempt). Figures 27 and 29 show the individual thermocouple traces for P1 and P2 to characterize the circumferential shedding of ice for the two test points.

Ice shed into the core of turbofan engine, made up of the HPC, Combustor and HPT, can cause both flameout and surge. In the case of a flameout the ice mass shed quenches or in some other way extinguishes the combustor flame and in the case of surge the ice mass shed causes a compressor stall resulting in reverse flow.

In Figure 25, the air mass flow trace shows a distinctive movement suggesting a sudden disturbance in the air flow. This is interpreted as an engine surge for this test. The facility airflow parameter is calculated using an averaged series of static pressure transducers in the PSL-3 plenum. These are not dynamic pressure sensors and the nature of how the pressure sensors function resulted in the “drawn out” representation of the surge as compared to a spike and return that would be expected as the engine surges and recovers. Note that the label for non-uniform ice shed in Figure 25 suggests an ice shed occurred in P1 prior to the surge behavior. Figure 26 shows the non-uniform behavior of the individual thermocouples in P1. This suggests that a non-uniform circumferential ice shed occurred and entered the HPC and resulted in the stall/surge.

The flameout test point was part of a design of experiment (DOE) series of test points to investigate sensitivities of the RB and ice build up to various parameters. In this particular case the CRB was made, the cloud was turned off and the ice shed occurred resulting in the flameout. Figures 27, 28 show the RB indicators chart for the flameout test point with average plane and individual thermocouple traces respectively. Figures 29, 30 show the RB indicators chart for the repeated flameout test point with average plane and individual thermocouples respectively. The repeated flameout point failed to produce another flameout. Inspection of the two RB indicator charts plotting the P1 and P2 measured thermocouples Figures 28 and 30, reveals a non-uniform ice shed at cloud off condition for the flameout point and a more uniform ice shed for the repeated flameout test point.

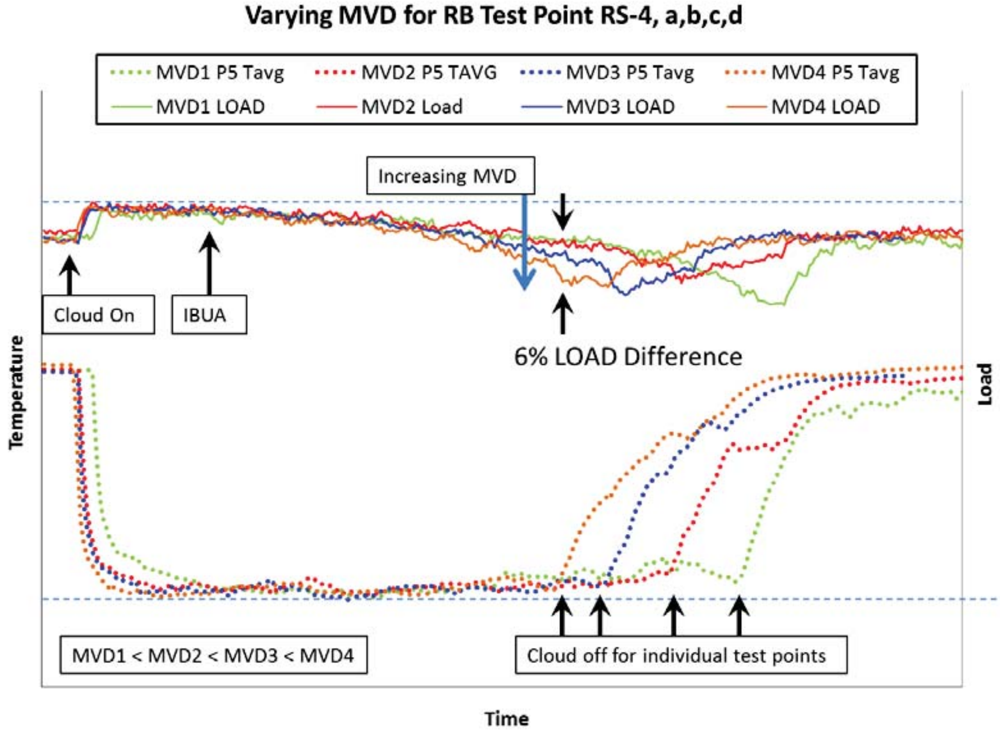

Figure 22. RS-4 RB test points conducted implementing a cloud MVD sweep.

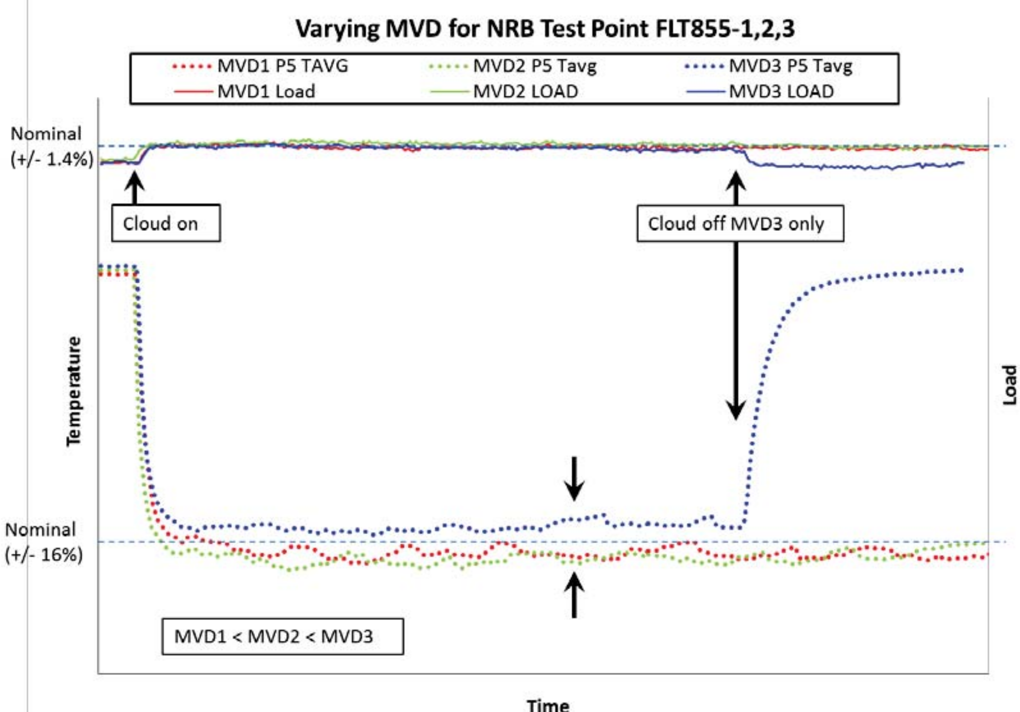

Figure 23. FLT855 NRB test points conducted implementing a cloud MVD sweep.

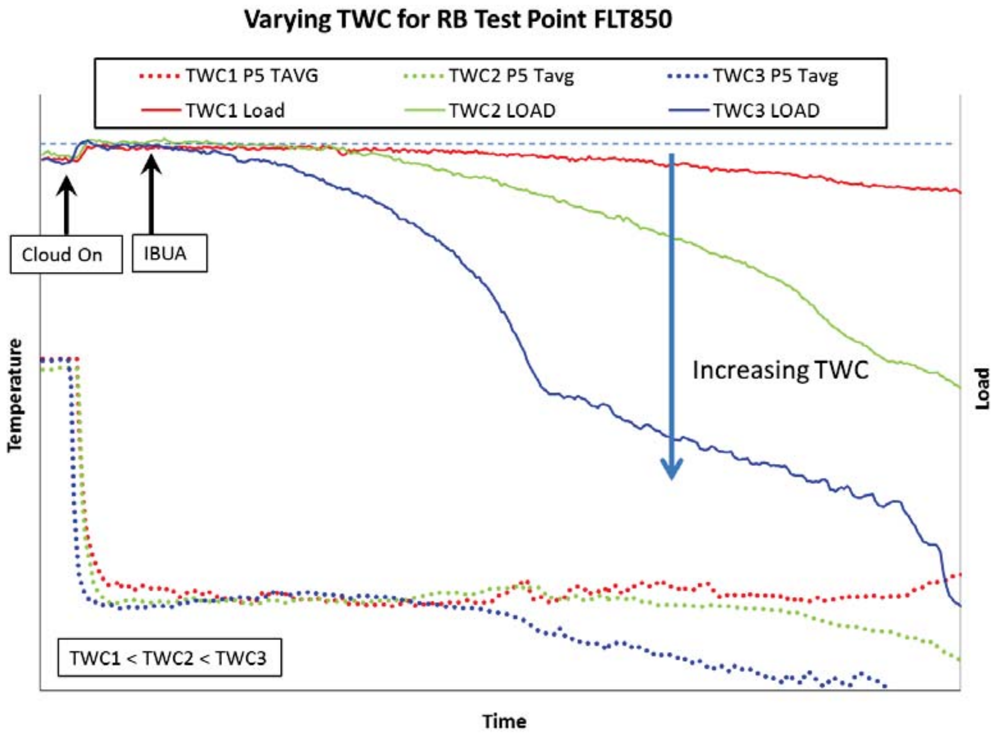

Figure 24. FLT850 RB test points conducted implementing a cloud TWC sweep.

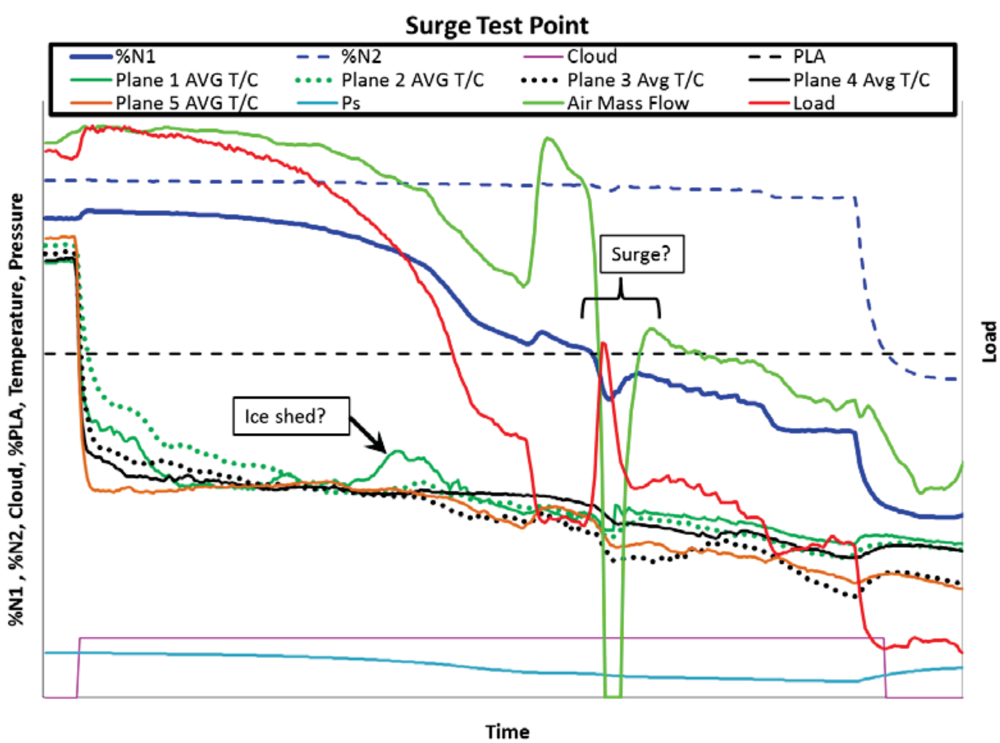

Figure 25. FLT850-3 full roll back test point RB indicators chart. The thermocouple traces shown are averages for each plane of interest.

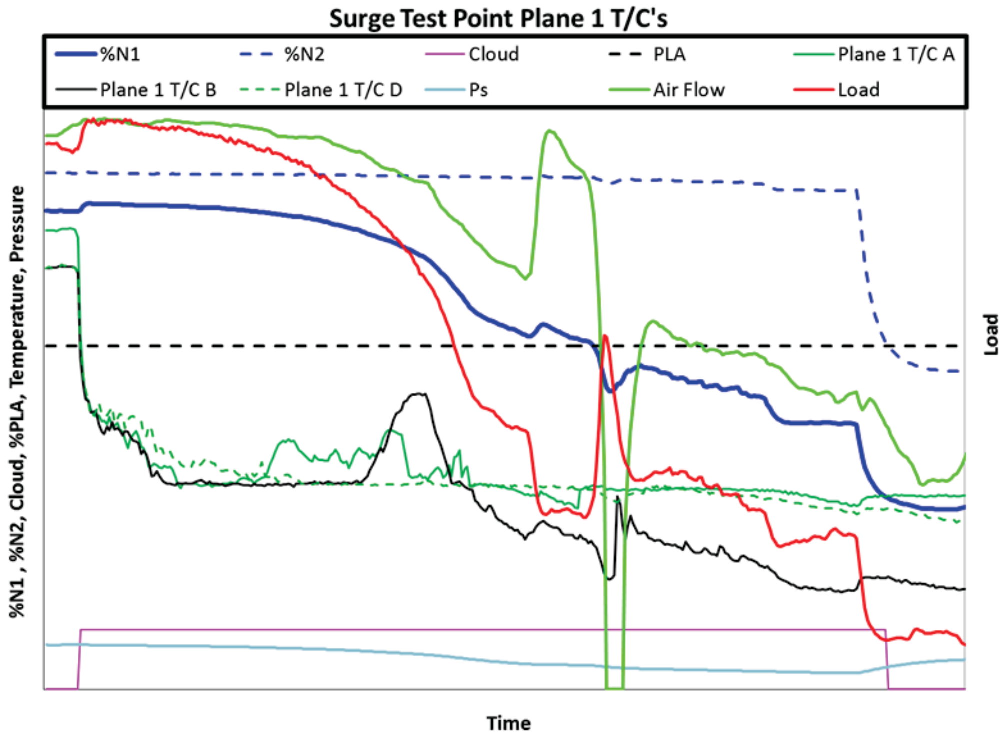

Figure 26. FLT850-3 full roll back test point RB indicators chart. The thermocouple traces shown are the individual traces for the instrumented plane 1-- labeled as "Non-uniform ice shed?" in Figure 25.

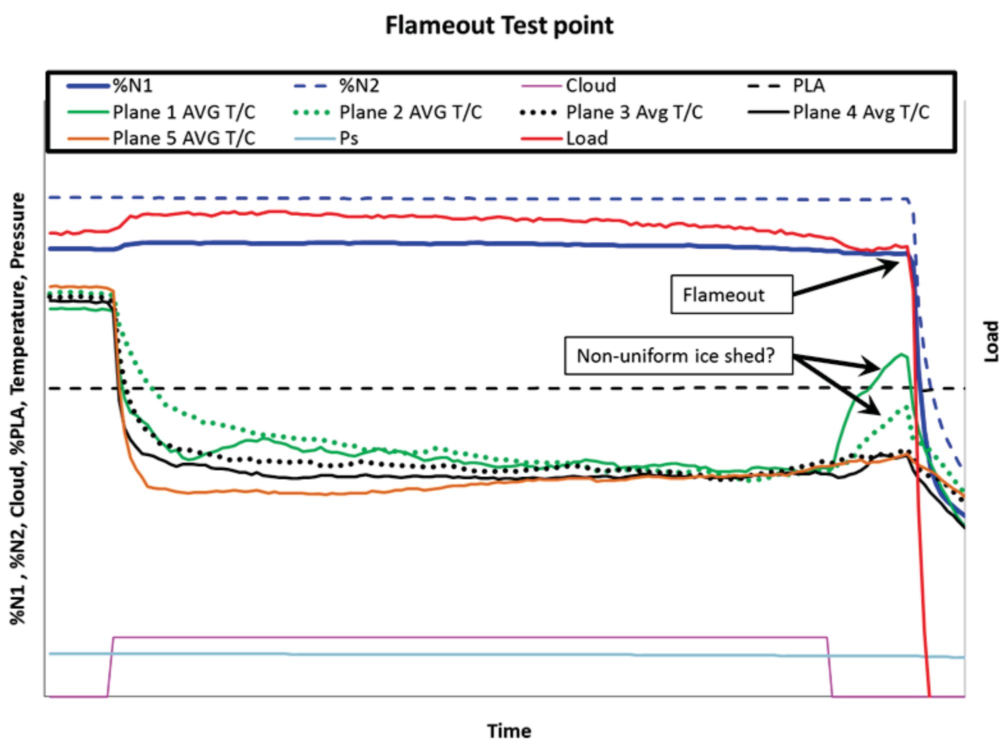

Figure 27. DOE-1 test point centered on FLT850—flameout. The thermocouple traces shown are average for each plane of interest.

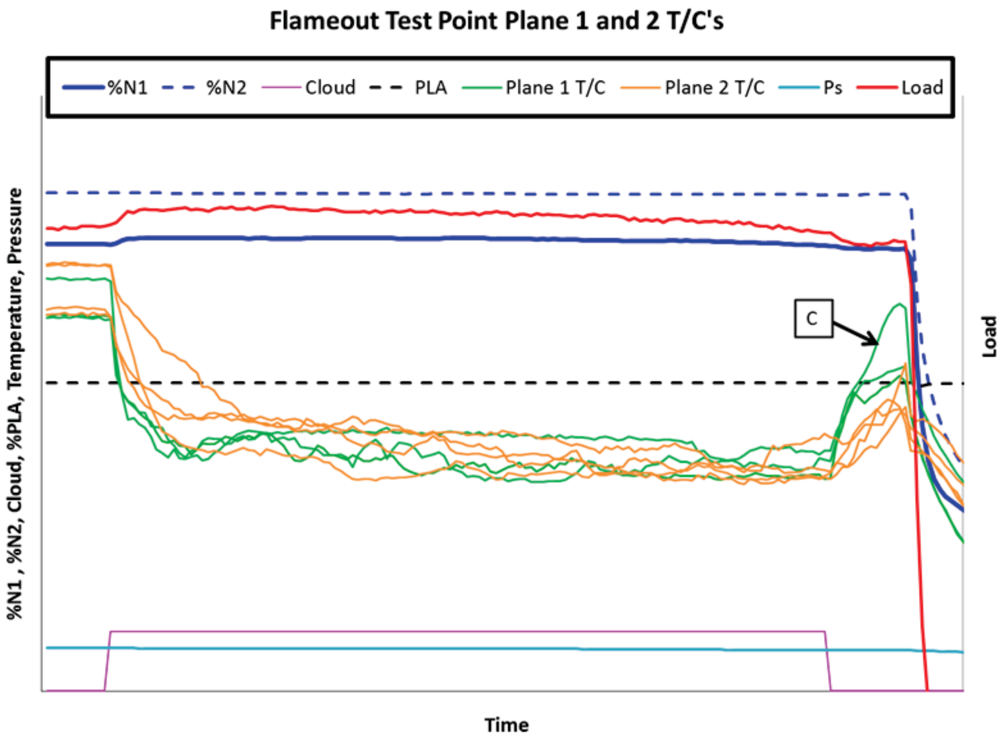

Figure 28. DOE-1 test point centered on FLT-850—flameout. The thermocouple traces shown are the individual traces for the instrumented planes 1 and 2 labeled as "Non-uniform ice shed?" in Figure 27.

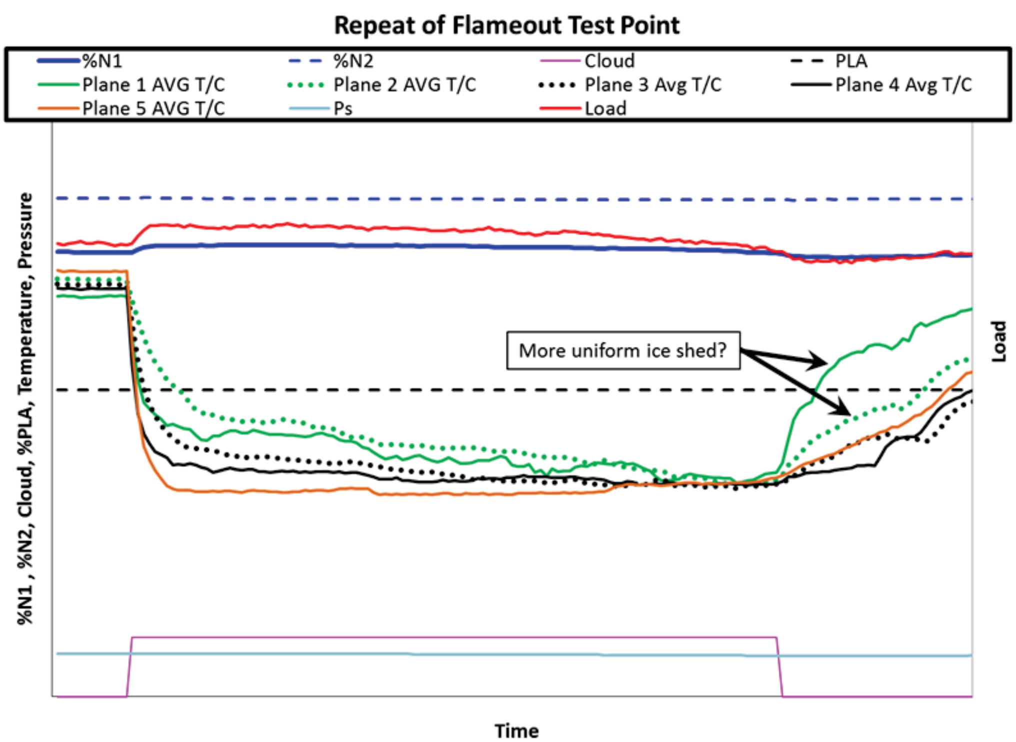

Figure 29. Repeat of DOE-1 test point centered on FLT850—no flameout. Thermocouple traces shown are average of each plane of interest.

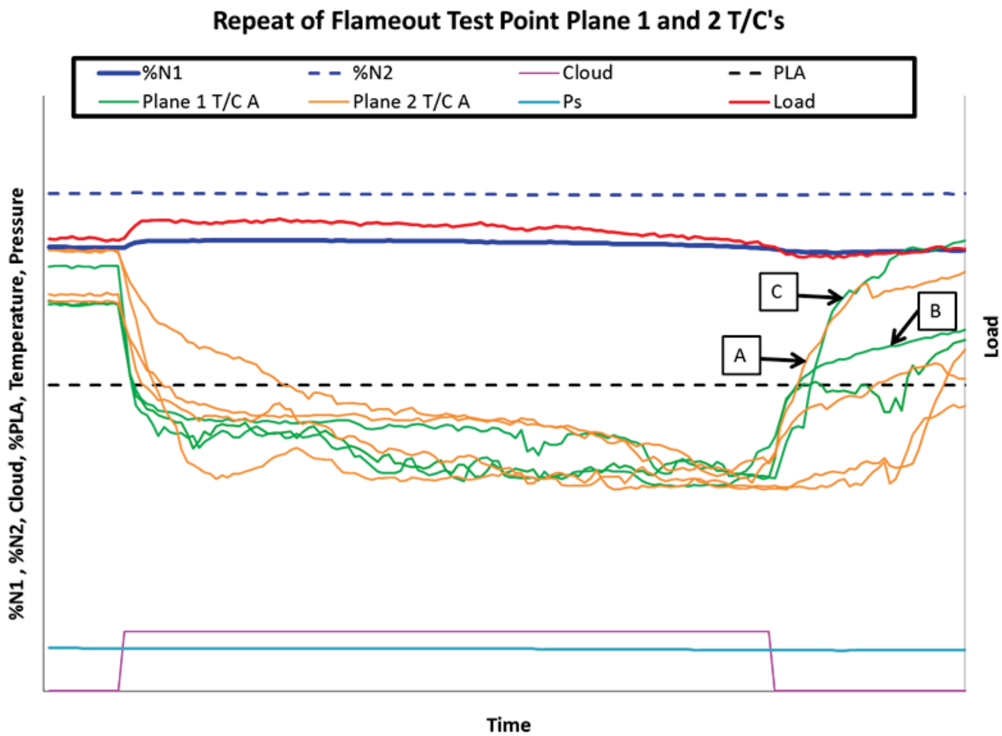

Figure 30. Repeat of DOE-1 test point centered on FLT850—no flameout. The thermocouple traces shown are the individual traces for the instrumented planes 1 and 2 labeled as "More uniform ice shed?" in Figure 29.

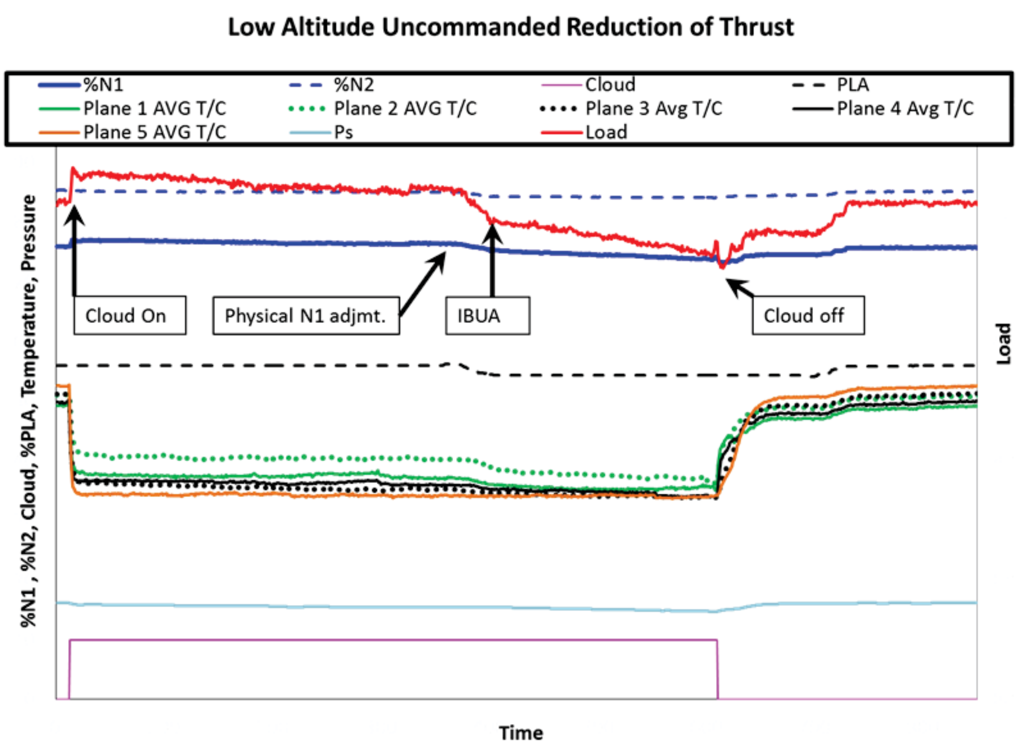

Figure 31. A PSL-3 low altitude test point Roll Back Indicator Chart showing an Uncommanded Reduction of Thrust.

Low Altitude Test Points

In an effort to generate engine data at lower altitudes the pressure altitude was incrementally reduced from the FLT850 test point conditions to conduct a series of low altitude test points. The goal of this work was to investigate the feasibility of reproducing or somehow scaling the high altitude test condition and duplicating it at sea level. The concept, if feasible, could help engine manufacturers to determine what ice crystal icing test conditions to run at their own sea level test facilities to simulate high altitude ice crystal icing scenarios. This could especially help the larger engine manufacturers whose products cannot run full scale in PSL.

Because the low altitude test points were outside of the calibration envelope a computer model developed by NASA to predict turbofan engine flow path icing risk was used as a starting point to successfully predict the PSL-3 low altitude ambient temperature conditions[10]. The physics based model was developed using the geometry of the ALF502-R5 engine and was calibrated using the FLT850 full RB high altitude test conditions prior to predicting the low altitude conditions. Figure 31 shows the RB indicators chart for a low altitude test point that successfully produced a CRB. This demonstrated that the concept of turbofan engine ice crystal icing altitude scaling is feasible.

The low altitude test point, Figure 31, shows that ice buildup similar to that at high altitude RB/CRB test points occurs. Note, the low altitude test points were not intended to be feasible operational flight conditions. They were conducted in an effort to investigate the feasibility of developing ice crystal icing scaling laws in a facility such as PSL-3 where non-realistic flight and operating parameters are easily tested to develop the physics or investigate the feasibility thereof for engine icing scaling. The ultimate goal is to develop scaling laws that are feasible and transferable to engine and air frame manufacturers to perform ice crystal icing testing at large scale, sea level turbofan engine test facilities. Without cameras in the flow path to specifically characterize and determine similarity or lack thereof of low altitude ice buildup compared to high altitude ice buildup there is no way to confirm or deny that low altitude ice buildup is the same or similar as high altitude ice buildup. Data was generated at incrementally lower altitudes and this data will be studied in detail. Future testing should include flow path cameras to characterize the ice between low and high altitude as well as the location of the buildup.

V. Additional Test Observations

Throughout the test period random information was gathered that was not a part of the original objectives of this validation testing. The following items are additional observations made about the engine and facility while conducting the test plan that the author thought interesting and worthy of a separate section to report on them.

Engine

1. There was chronic engine degradation (in the form of turbine exit temperature rise) throughout the test believed due to mineral deposits, Figure 32, from the use of filtered (not demineralized) city water for the ice crystal cloud. This was done to use small particulate in the city water as nucleation sites for ice crystal formation. This degradation would recover somewhat on low altitude high TWC cloud test points.
2. The heated spinner was a source of liquid water for all cloud on conditions, Figure 33. During anti-ice off test points this liquid water formed ice accretion on the lower third of the IGV, Figure 34.
3. Reverse flow of liquid water was observed on the LPC IGV for RB test points, Figure 35.
4. Flow path hardware was damaged during a full roll back test point. This is suspected to be a result of an ice shed impacting the rotating hardware during cloud off engine recovery, Figure 36.

Facility

1. Facility air flow is reduced during ice crystal icing test points. The cloud water injection is not adjusted accordingly and may result in elevated TWC clouds subsequent to ice buildup, Figure 25.
2. There is an MVD upper limit for fully glaciated cloud generation.
3. Current plenum static temperature sensors are slow to respond to a spike in plenum static pressure such as an engine surge. A dynamic plenum static pressure capability is required as a standard for future engine icing tests.
4. Descent operation was demonstrated. Both pressure and temperature were controllable for a simulated descent flight profile of 1000 ft/min. Note these results are not shown in this paper.
5. The cloud generation system demonstrated the ability to simulate flying into different clouds during the same test point.
6. The icing configuration for PSL-3 blocks the test cell bypass air flow and makes it very difficult if even possible to simulate rapid throttle movements.

7. The PSL-3 tunnel walls were all grounded to successfully prevent the static cling of ice crystals.
8. During integrated systems testing heated pitot tube probes were used during ice crystal cloud on operation. A rivulet of water ran back and froze to the tunnel side wall approximately 6 to 8 inches downstream of the heated probe, Figure 37.

Figure 32. Mineral deposits on LF01 engine core flow path hardware.

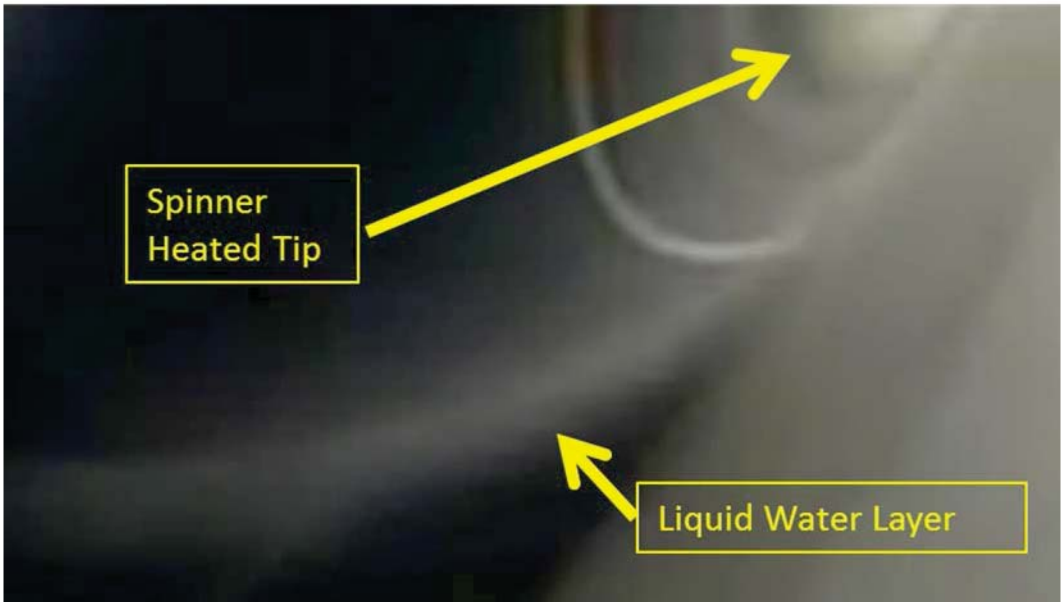

Figure 33. ALF502-R5 spinner during cloud on conditions.

Figure 34. Ice accretion forming on bottom leading edge of LPC IGV during anti-ice off cloud on conditions.

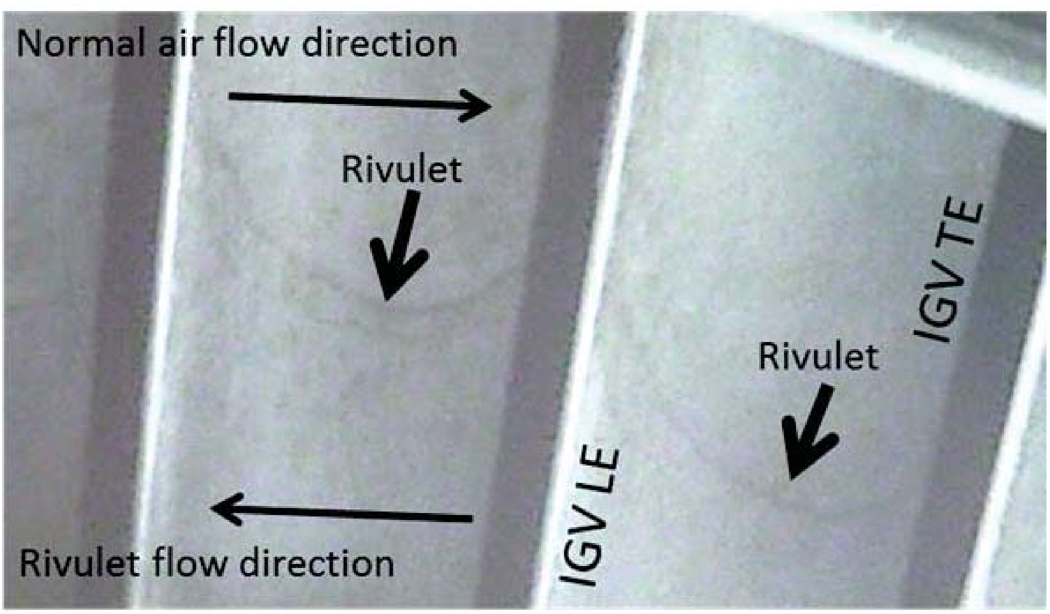

Figure 35. Reverse flow rivulet running from LPC IGV trailing edge to leading edge during a RB test point.


Figure 36. HPC Rotor 1 mechanical damage.

Figure 37. Ice mass accreting to side wall downstream of heated pitot probe.

VI. Conclusion

The Propulsion Systems Laboratory at NASA Glenn Research Center, an altitude simulation engine test facility, was modified to allow the ingestion of an ice crystal cloud during high altitude operation of a full scale turbofan engine. The test article for the inaugural engine icing test was the ALF502-R5 turbofan engine. The primary objective to validate calibration and engine test methodology by duplicating known flight test points in the PSL was successfully achieved. The cloud calibration techniques were successful which included droplet freeze out using nozzle over expansion coupled with a large contraction ratio duct. Methodologies for the engine test were successfully developed for cloud on, cloud off and recovery operations. The secondary objective of duplicating selected known high altitude revenue service ice crystal icing field events was achieved successfully.

Additional objectives of generating data for facility performance, scientific analysis and altitude scaling investigations were achieved. Based on test measurements and observation, the PSL facility is repeatable and can simulate descent flight and low altitude operation. Also, NASA tools were able to predict and PSL was able to generate low altitude test conditions that resulted in ice buildup in the engine flow path. This demonstrated that the concept of turbofan engine ice crystal icing altitude scaling is feasible. However, a lack of internal cameras for this test article prevented the direct comparison of the nature and location of ice buildup between low and high altitude test points.

Filtered city water used in the cloud generation nozzle system to provide ice crystal nucleation sites resulted in mineralization forming on flow path hardware that led to a chronic degradation of engine performance during the month long test.

Key engine observations and data analysis from this test conclude that cloud TWC is a major influence on both the onset and rate of ice buildup. The ice buildup leads to uncommanded thrust reduction in this test article which begins due to the restriction of core airflow and not from an N1 reduction. It was also shown that the induction system anti-ice airflow was required to be on for ice crystal icing to occur for the test points conducted. The heated spinner is a source of liquid water into the engine core air flow path during ice crystal cloud on conditions. Lacking internal flow path cameras, interpretation of thermocouple response suggests that ice builds and sheds on no roll back points within the calibrated test envelope. Though particle size appears to slightly affect the rate of ice buildup it does not appear to affect the onset of ice buildup for the tests conducted. Ice buildup similar to that at the higher altitude RB test points was inferred to occur at low altitude test conditions based on interpretation of thermocouple response. These insights will drive the development of the instrumentation and test plan for a planned follow on full scale test based on a similar, more robustly instrumented engine, ALF502-R5 (s/n LF11).

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