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August 23, 1992

Captain Ed Miller
4416 Randon Court
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Dear Ed:

Enclosed is the latest version (final I hope) of the paper to be published (see Tom's letter). This information is not proprietary and you can use it with the pictures you already have.

Z. J. Przedpelski
Principal Engineer
Accident & Incident Investigations

Enclosure

mlb222

FIRST INTERNATIONAL SYMPOSIUM ON VOLCANIC ASH AND AVIATION SAFETY

Mr. Zygmund Przedpelski
General Electric Corp. Maildrop J-60
Evendale, OH 45215

August 12, 1992

Dear Zyg,

Your manuscript for the volume has been reviewed and is accepted for the Proceedings Volume. I am returning it to you now for final revision. The principal reviewer of the paper made only minor suggestions for changes which I am sure you will want to consider. One area where almost all papers have needed work is to minimize jargon. This can easily be done by simply providing an explanation when a term or concept is used initially in the paper. There are a number of terms about engine operation (e.g. "rollback", "stopcock", FADEC, "compressor bleed", etc.) that most readers will be unfamiliar with. Please try to add some explanation for these terms. When I receive the manuscript back from you I will add references to other Symposium papers as appropriate.

Please do the following.

1. Revise your paper taking into consideration the comments by the reviewers.

2. Return to me the ***reviewer's copy*** together with ***one (1) copy of your printed revised manuscript, together with a floppy disk with your document.*** **We will be preparing this volume using Microsoft Word ver. 5.0A.** We can convert your document from most MS-DOS compatible word processing software.

3. Include camera-ready copy of your Figures.

4. Return your revised manuscript to me by August 30.

Zyg, thanks very much for your cooperation. I know your retirement date is fast approaching and I would feel badly if I didn't get this to you in time for revisions. Please contact me if you have any questions or problems with either the reviewer comments or with the deadline.

Sincerely yours,

Tom

Thomas J. Casadevall

U. S. Geological Survey, Box 25046, MS 903, Denver Federal Center, Denver, CO 80225 phone: 303 236-1080, fax: 303 236-1414

IMPACT OF VOLCANIC ASH FROM REDOUBT VOLCANO ERUPTION ON GE CF6-80C2 TURBOFAN ENGINES

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Evendale, OH, and T.J. Casadevall, U.S. Geological Survey,
Denver, CO

ABSTRACT

The 1989-1990 eruptions of Redoubt Volcano, Alaska, and the near tragedy of KLM Flight 867, a Boeing 747-400 aircraft powered by General Electric CF6-80C2 engines, on 15 December 1989 underscore the threat to aircraft safety from volcanic ash clouds.

An eruption of Redoubt at 10:15 A.M. Alaskan Standard Time (AST) produced an ash-rich eruption column which climbed to approximately 40,000 feet altitude. Wind speeds at high altitudes at the time were 100 knots from south-southwest. At 11:46 A.M. KLM Flight 867 entered the volcanic ash cloud at approximately 25,000 feet altitude, 150 nautical miles northeast of Redoubt. Immediately the aircrew increased power and attempted to climb out of the ash cloud. Within one minute the four engines decelerated below idle. The aircraft descended approximately 13,000 feet before the crew restarted the four engines and resumed flight to Anchorage. While there were no injuries to passengers, the damage to engines, avionics, and aircraft structure from this encounter was significant. Similar engine thrust loss and engine and aircraft damage was experienced by two Boeing 747 aircraft during 1982 volcanic eruptions of Galunggung Volcano in Indonesia.

The primary cause of engine thrust loss in the volcanic ash ingestion events in Indonesia in 1982 and at Redoubt in 1989 was the accumulation of melted and resolidified ash on the stage 1 turbine nozzle guide vanes (NGV's). These deposits reduced the effective flow area causing the compressor to stall.[1] Compressor airfoil erosion contributed to the loss of stall margin.

(1) Compressor stall is an airflow discontinuity resulting in loss of thrust and internal temperature increase.

Reduction of thrust level (combustor temperature and compressor rotational speed reduction) while in an ash cloud significantly reduces the rate of engine performance degradation.

STATEMENT OF PROBLEM

The loss of thrust on all engines during an approximately one-minute exposure to the Mt. Redoubt volcanic ash cloud could have resulted in a major tragedy. Fortunately the alert flight crew was able to restart all engines and make a safe landing at Anchorage.

The events preceding and subsequent to the cloud encounter and the engine's response and physical conditions were analyzed to identify procedures which would reduce the probability of future occurrences of similar flight safety threatening events.

METHODS OF STUDY

The following data sources were used to reconstruct the event, to establish the specific cause(s) of thrust loss and to recommend appropriate preventive/corrective actions:

- Interviews with and statements from the flight crew of KLM Flight 867.
- Tape recordings and transcripts of radio communications between air traffic controllers and KLM Flight 867 and other flights in the Anchorage area prior to and during the event.
- Forecasted and recorded wind aloft data.
- Digital Flight Data Recorder (DFDR), Aircraft Condition Monitoring Systems (ACMS) and the Non-Volatile Memory (NVM) of the engine Full Authority Digital Electronic Controls (FADEC).
- Event descriptions and findings from other aircraft-volcanic cloud encounters.

- CF6-80C2 engine steady state and transient operating characteristics with normal and degraded component efficiencies.
- On-site (Anchorage) external inspection of the aircraft and all engines and borescope inspection of engines number 1 and 2.
- Complete analytical disassembly and inspection of engine No. 1 at the KLM maintenance facility at Schiphol Airport, Amsterdam.
- General Electric experience with engines exposed to sand/dust environment in the field and during controlled factory tests.
- Analysis of samples of the volcanic ash recovered from various locations of the four engines.

RESULTS AND OBSERVATIONS

The time sequence of events is shown on the annotated aircraft flight path in Figure 1.

Based on seismographic records, major eruption of Mt. Redoubt Volcano occurred at 1015 A.M. AST and lasted for about one hour.

At 1146 A.M. AST, while leveling off at an altitude of 25,000 feet, KLM867 entered a heavy volcanic cloud. Maximum power climb was selected and approximately one minute later all engines decelerated. Engines 1 and 3 decelerated to sub-idle core rotor speed (N2) while engines 2 and 4 settled down at ~80% N2 for approximately 20 seconds before decelerating to sub-idle N2. Aircraft and engine response during that period is shown in Figures 2 and 3.

The location of the ash cloud (154 nautical miles from Mt. Redoubt on 217° true heading) was consistent with the forecasted and pilot reported winds aloft, and with the ash release at the beginning of the eruption cycle.

Prior to the encounter, the exact location of this cloud was not known by the crew of KLM867.

Pilot Reports (Pireps) and radar data available to Anchorage Air Traffic Controllers indicated either the presence of more than one ash cloud and/or a large dispersion of the main cloud resulting from the high velocity gradient of winds aloft as a function of altitude.

The fire warning bell and the displayed message "CARGO FIRE FWD" occurred shortly after engine deceleration and was interpreted by the Captain to be a false message. This was confirmed by inspection which showed no evidence of compartment fire.

The engines' operation during the high power climb was consistent with rapid reduction of the stage 1 nozzle flow area and associated high pressure turbine (HPT) efficiency reduction. Approximately one half of the maximum deterioration was still present following the successful restarts. Visual inspection of the number 1 engine (ESN 702-131) revealed thick deposits of melted and resolidified ash material on some of the stage 1 NGV's(Figure 4). These deposits were brittle at room temperature and many pieces fell off during the engine transportation and disassembly (Figure 5). The remaining deposits could be easily removed by hand. It was inferred that these deposits built up to maximum just prior to engines' deceleration and gradually became dislodged during the start attempts and during the subsequent engine operation. Based on borescope inspections conducted at Anchorage, approximately 40% of the NGV's were still covered by thick deposits after landing (Figure 6).

Engine fuel levers were moved to off position and air restarts were initiated immediately after the loss of power. Engines 1 and 2 were successfully started at an altitude of 17,200 feet (after five or six attempts). Engines 3 and 4 were successfully started at an altitude of 13,300 feet (after eight or nine attempts). Autostart mode was used and at least one start appeared to have been correctly terminated by the FADEC start/stall logic just before being terminated by the crew. The windmilling N2 was in excess of 30% and the entire start sequence varied from approximately 30 seconds to 60 seconds during each attempt.

Engines did not overtemperature during the deceleration or during the subsequent aborted starts. The highest exhaust gas temperature (EGT) of 930°C was recorded on engine Number 1 during the initial deceleration. There was no unusual thermal distress observed during the disassembly of this engine.

The general condition of all hardware in engine No. 1 was consistent with the performance level recorded prior to landing. In addition to the remains of the heavy stage 1 nozzle deposits, the following performance related observations were made:

- No measurable erosion or other damage to the low pressure system (Fan, Booster and Low Pressure Turbine (LPT).
- Minor compressor erosion, most pronounced in the mid and aft rotating stages.
- Stage 1 High Pressure Turbine (HPT) blade tips were "ground off" (approximately .060 inches of tip material was missing).
- Buildup of hard material on stage 1 HPT shrouds.
- Thin but hard deposits on stage 1 HPT blade pressure surfaces.

Engine No. 1 inspection indicated that there was no significant plugging of any of the HPT cooling circuits; however, there was a heavy fine powdery ash buildup within the HPT rotor cavities (Figure 7).

The general physical conditions (distress and presence of ash deposit) of all four engines were very similar.

The Compressor Discharge Pressure (Ps3) sensing line on engine No. 1 was unobstructed. The Ps3 readings obtained from the ACMS system during and after the deceleration indicated that Ps3 signals to the engine electronic controls were unrestricted.

The DFDR was not recording for two minutes and 5 seconds after the initial engine deceleration when all four electrical generators dropped off the line. The engine FADEC remained powered and were controlling the engines during that time and provided valuable information stored in the NVM.

CONCLUSIONS

Specific

Engines' deceleration from high power to below idle was initiated by high pressure compressor (HPC) stall. The stall margin loss was caused by Stage 1 HPT nozzle effective flow area restriction and associated HPT efficiency loss.

The Stage 1 HPT bucket clearance increase was caused by local hard buildup of melted/resolidified ash material on the shroud surface (Figure 8) which grinded off the bucket tip material.

The Stage 1 nozzle effective flow area restriction was caused by resolidification and buildup of melted ash particles on the leading edges and on the pressure surfaces of the individual NGV's. This effective flow area restriction was estimated to be 8%. This buildup also resulted in an increase in pressure loss across the nozzle and a reduction in HPT efficiency. Total HPT efficiency loss, including the stage 1 HPT blade clearance increase was estimated to be 7%.

High Pressure Compressor (HPC) erosion (Figure 9) caused by ingestion of the ash particles resulted in minor stall margin decrease and compressor efficiency loss estimated to be 1%.

The lowering of the temperature following manual fuel supply cut-off increased the viscosity and brittleness of the built up material. The thermal and pressure/velocity transients associated with the fuel off/on/off cycle dislodged some of the nozzle deposits. The density of these deposits was low and consequently there was no downstream airfoil damage. Successful starts were achieved after a portion of these deposits were dislodged.

During the starts, autostart mode was used and at least one start appeared to have been correctly terminated by the FADEC start/stall logic. Most of the starts, however, were terminated by the crew overriding the autostart sequence and thus negating the adaptive automatic restart features of the control system while, in some of these cases, the engine or engines appeared to be on the way to a successful start (Figure 10).

Continued engine operation, following successful restarts, dislodged additional Stage 1 deposits. Permanent engine performance degradation was the result of compressor erosion and the Stage 1 HPT blade clearance increase.

The absence of any thermal damage to the engines was the result of the combination of decisive and skillful actions of the crew and the responsiveness and built in protection in the FADEC system.

The presence of ash particles set off the cargo fire warning bell and displayed the "CARGO FIRE FWD" message (the cargo compartment fire detector is a smoke/particle detector unlike the engine compartment detector which is activated by temperature).

The ash concentration at the 25,000 foot altitude was estimated at 2 gm/m^3 based on the rate of nozzle deposit build-up compared to the rates measured during the Calspan conducted engine tests (Dunn & Wade, this volume).

Ash particles exiting the fan air stream ranged in size from 10-100 microns and most closely represented the size of particles encountered by KLM867 in flight. The particles found within HPT passages, which were believed to be representative of the size distribution entering the combustor, were typically 6-10 microns in size.

The ash contained some volcanic glass material with a melting point of ~1,200°C. This material is considered to be responsible for rapid build-up of deposits on the stage 1 NGV's; however, higher and lower melting point components of the ash were also present in the NGV deposits. The unmelted particles adhered to the semi-molten layer of the glassy material on the stage 1 NGV's. (Casadevall, Meeker & Przedpelski, this volume)

GENERAL

Relatively "new" (within hours of eruption) volcanic clouds contain concentrations of ash which can cause complete engine power loss (in approximately one minute) when the engine is operating at combustor discharge temperatures in excess of the melting temperature of the ash.

The primary mechanism of engine power loss during these high engine power and high ash concentration exposures is the buildup of melted and resolidified ash material on the stage 1 NGV's resulting in flow area reduction, turbine efficiency loss and compressor stall. Permanent damage to the engine under these conditions is limited if the engine is not exposed to overtemperature during the stall or subsequent restart attempt(s).

Time, altitude and airspeed permitting, the engine can be restarted by the fuel off/on/off cycles breaking up the deposit material which is brittle at low temperatures. FADEC with built-in start/stall/overtemperature logic in the autostart mode simplifies and speeds up the restart sequence and prevents further engine damage.

Reduction of engine power to flight idle upon inadvertent entry into a volcanic cloud will eliminate the stage 1 NGV buildup since the combustor discharge temperature at idle is below the melting point of volcanic ash compounds.

Operation in an ash cloud will result in compressor airfoil and flowpath erosion and eventual compressor stall. The time to reach this condition is at least an order of magnitude longer than the time to produce significant ash accumulation on the NGV's at the high power level (assuming same ash concentration). The compressor erosion is permanent and engine operability and available thrust will be adversely affected. Compressor erosion rate can be significantly reduced by decreasing the core engine rotational speed (N_2).

Longer term damage mechanisms are the restriction of HPT cooling circuits which may result in hot section distress, and the contamination of the lubrication system which may result in premature bearing(s) distress. Another possible damage mechanism is the restriction of the air flow passages around the fuel nozzles leading to poor fuel atomization and inability to start the engine.

Cloud ash entry can be recognized by St. Elmo's Fire/corona discharge (night or day), dust and smell in the cockpit/cabin and outside darkness (day time only).

SAFETY RECOMMENDATIONS

Crew Actions

If a volcanic ash cloud is inadvertently entered, disconnect the autothrottle, reduce power to flight idle, increase compressor air bleed(2) to maximum possible and exit the cloud as quickly as possible. There is no universal "best" procedure for exiting the cloud; however, generally a 180° turn will result in the fastest cloud exit. Avoid rapid throttle movements (up or down) to prevent a possible compressor stall.

If power reduction to flight idle is not possible, reduce power to the lowest level consistent with other requirements and exit the cloud as quickly as possible. Monitor EGT as the primary engine instrument indicating ash accumulation at the stage 1 HPT NGV's. If EGT exceeds the red line or increases rapidly, throttle should be closed and fuel levers moved to "OFF" to minimize engine thermal damage and increase the probability of successful restart.

Restarts should be initiated immediately. More than one attempt may be required to obtain a successful start. Autostart should be used (if available) since it simplifies starting the procedure and provides engine overtemperature protection. Compressor bleed should be turned on during restarts and during subsequent engine operation to maximize stall margin. Following restart, the engine performance/stall margin/EGT may improve with time, but it will not reach the pre-ash encounter level. Rapid throttle movement and maximum power operation should be avoided, if possible, since stall margin is decreased and some cooling circuit plugging may be present.

(2) Air extracted from the compressor for use in various aircraft systems. Increased extraction increases stall margin.

REGULATORY AGENCIES

The greatest threat to aircraft and engines is presented by "new" clouds (within hours of eruption) which contain large concentrations of ash particles. The communication network between volcanic activity monitoring agencies and air traffic control agencies should be improved so that volcanic activity of the type which can result in substantial release of ash into the atmosphere can be communicated immediately to the effected air crews. In the early phases, following the eruption, the cloud position should be continuously tracked at all altitudes utilizing winds aloft, pilot reports and other available means. Appropriate air traffic control measures should be taken to provide aircraft/cloud separation.

The ash particle size distribution and concentration in volcanic eruptions should be documented. This combined with updated dispersion and fallout theoretical models can establish when an ash cloud ceases to be a flight hazard.

Engine and/or combustor tests should be sponsored by FAA to establish the "safe" ash concentration and combustor temperature range. This data, when combined with better definition of ash fallout rates and improved cloud tracking, will enhance aviation safety and reduce air traffic delays resulting from volcanic activity.

ACKNOWLEDGEMENTS

During this investigation many GE engineers contributed to the hardware reviews and engineering analysis. The following individuals, outside the GE organization, provided background data and constructive suggestions making this report possible:

Captain K.F. van der Elst, KLM Flight 867 Commander

Mr. Roy C. Daw, NTSB, Anchorage Regional Office, Alaska

Mr. Michael G. Dunn, Arvin/Calspan, Buffalo, New York

In addition, special thanks go to the KLM maintenance personnel at Schiphol Airport who performed the disassembly and inspections of the engines involved in this event.

<u>TABLES AND FIGURES</u>

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Figure 5	Stage 1 HPT Nozzle Guide Vanes Leading Edge Deposits Dislodged During Disassembly
Figure 6	Sketch of Stage 1 HPT Nozzle Guide Vanes Deposit Based on Borescope Inspection of Engine No. 1
Figure 7	Accumulation of Ash in the HPT Rotor
Figure 8	Hard Ash Material Deposits on Stage 1 HPT Shrouds
Figure 9	HPC Blade Leading Edge and Tip Erosion
Figure 10	Engine Parameters During First Recorded Start Attempt

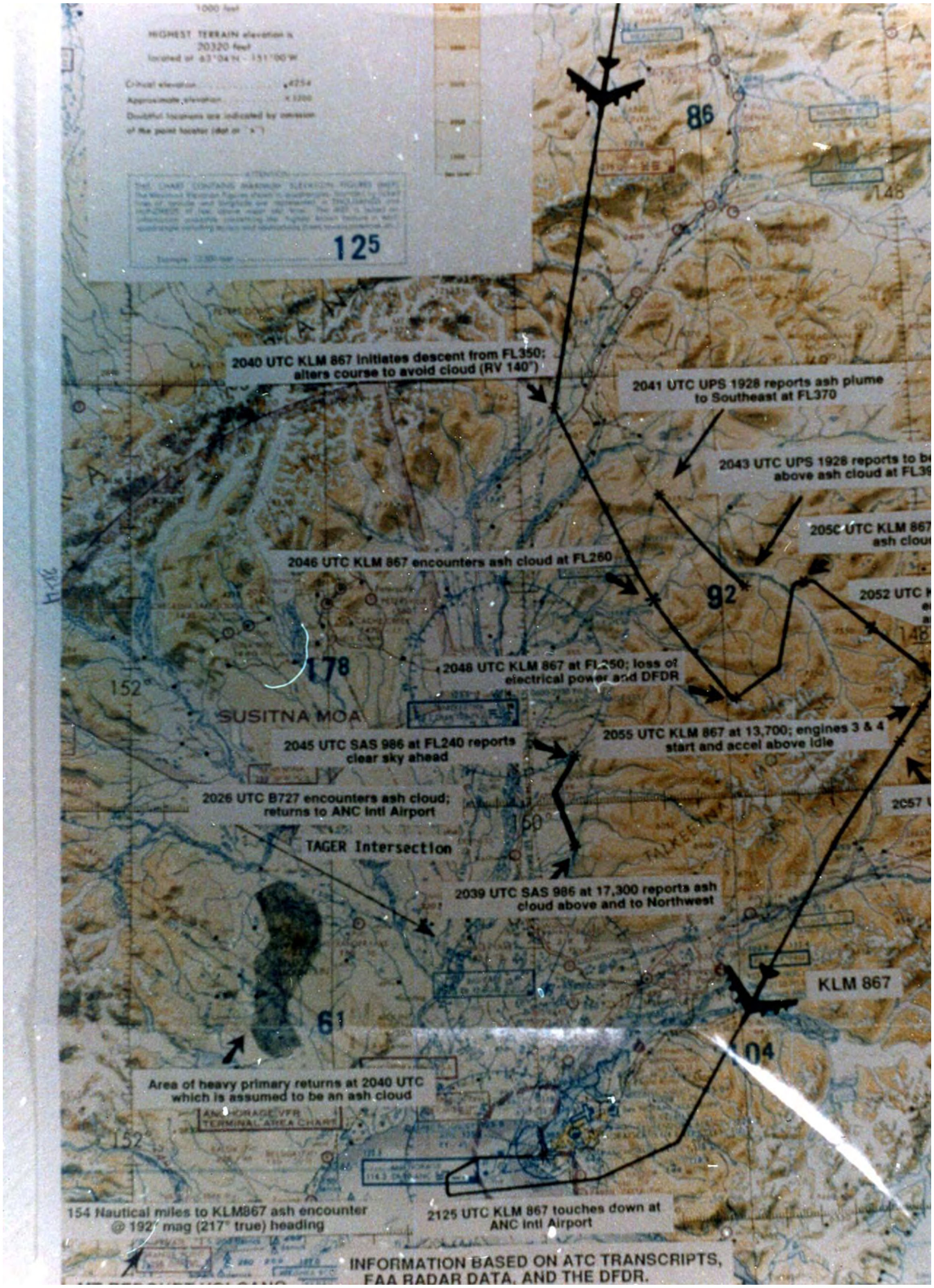


Figure 1 KLM Flight Path

THIS WILL BE SIMPLIFIED BY REMOVING MOST OF THE BACKGROUND MATERIAL

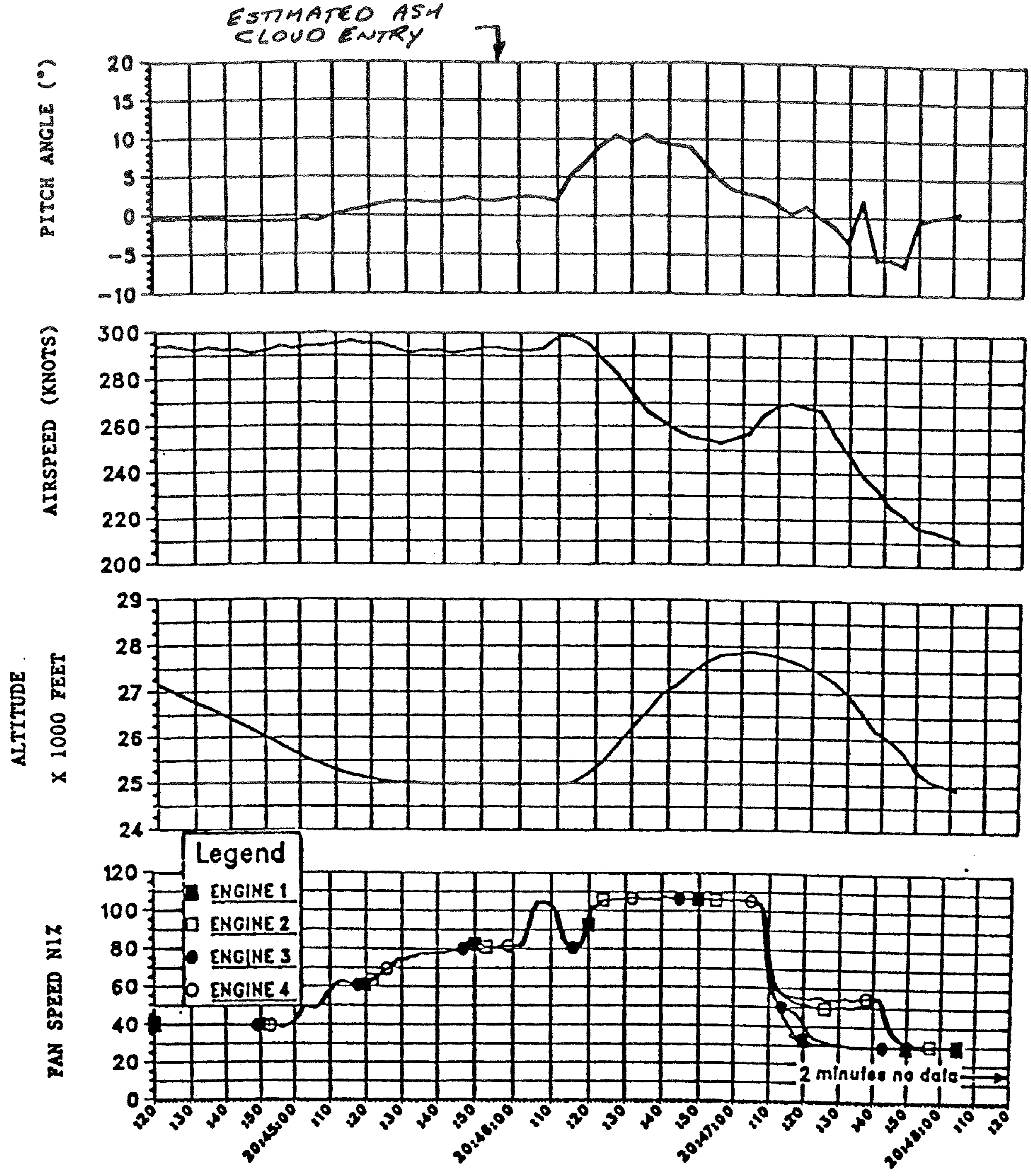


Figure 2 Engine and Aircraft Parameters From Cloud Entry To ENGINE SPOOL DOWN ✓

REMOVE EVERY SECOND GRID LINE VERTICAL AND HORIZONTAL ✓

has this been done?

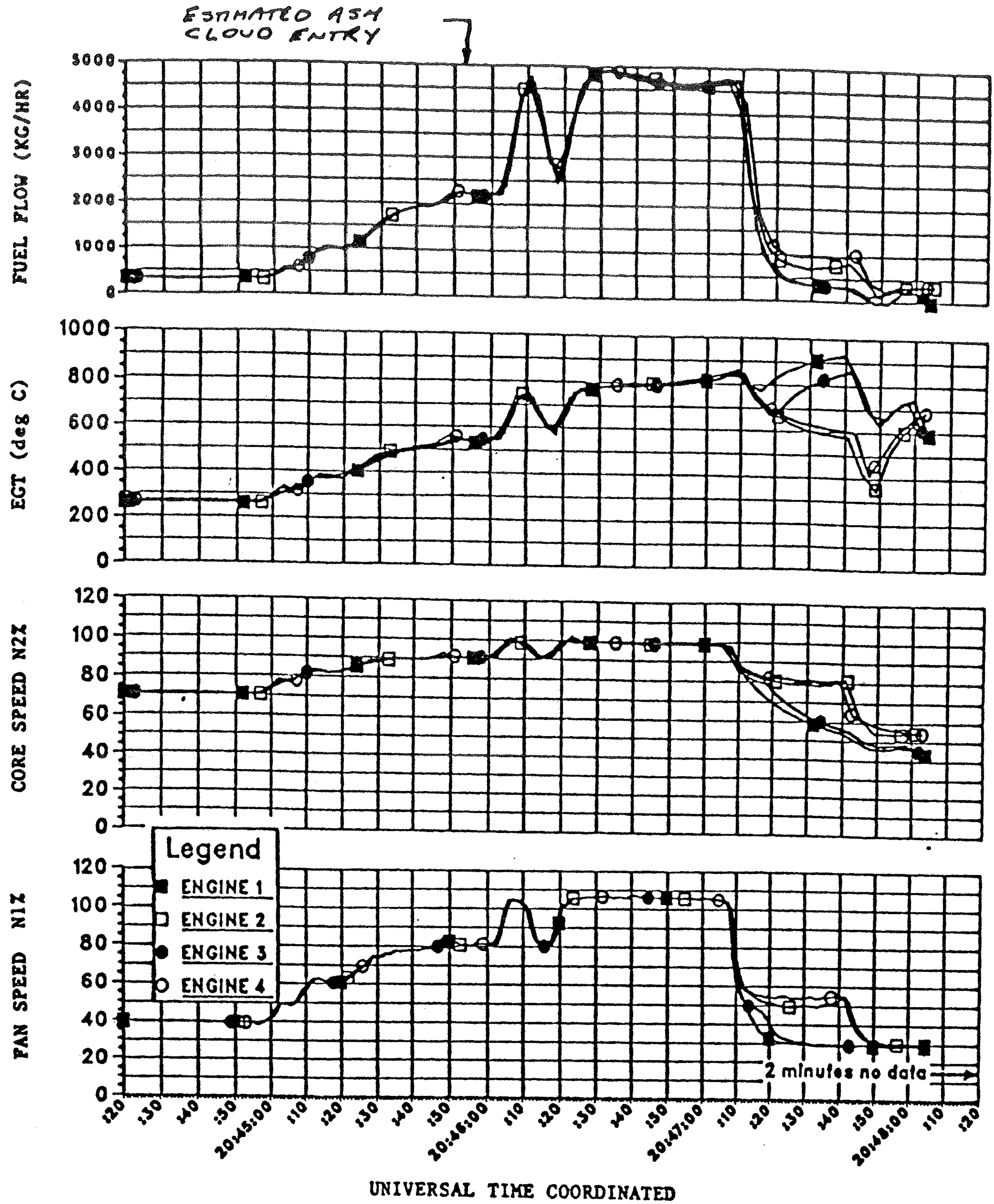


Figure 3 Engine Parameters From Cloud Entry To ENGINE SPOOL DOWN

CHANGES SAME AS FIG 2

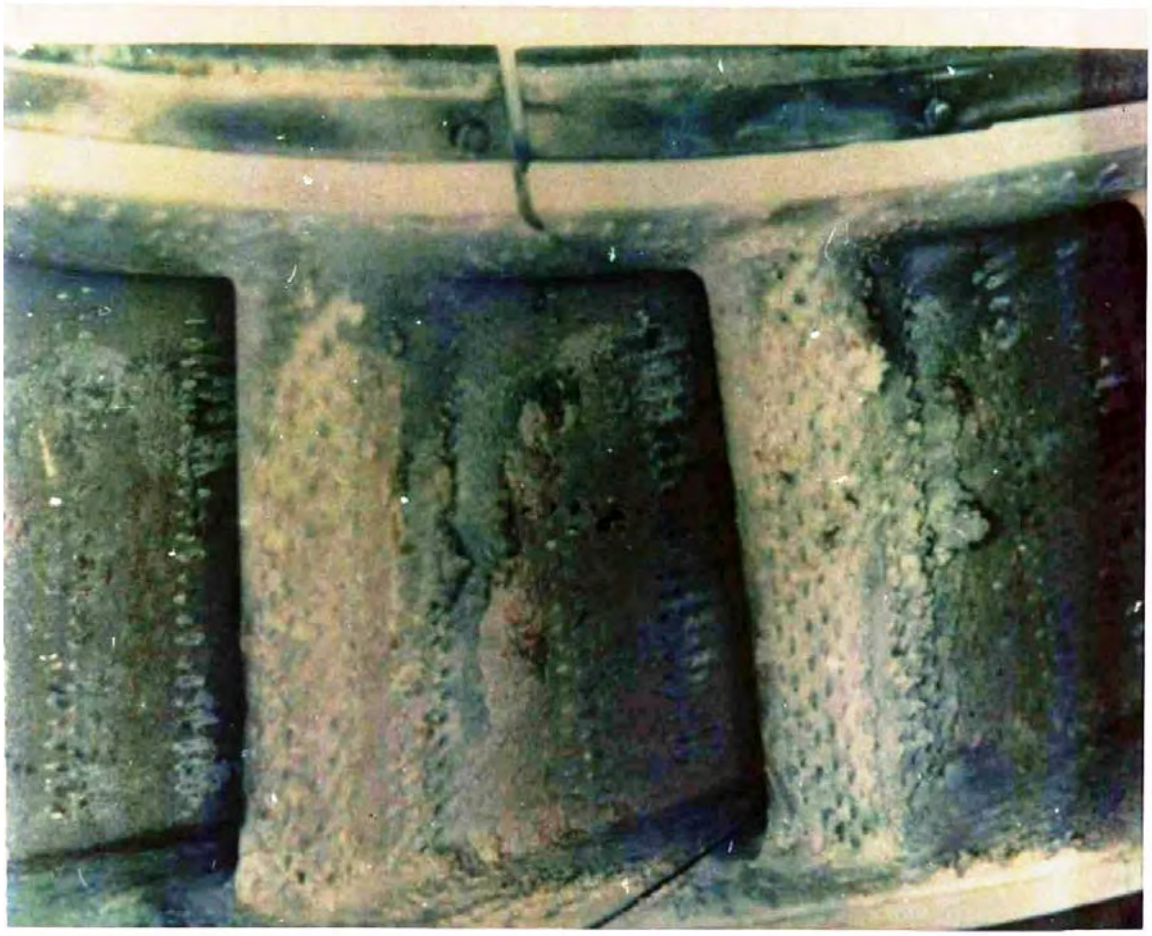


Figure 4

Stage 1 HPT Nozzle Guide Vane Leading Edge Deposit

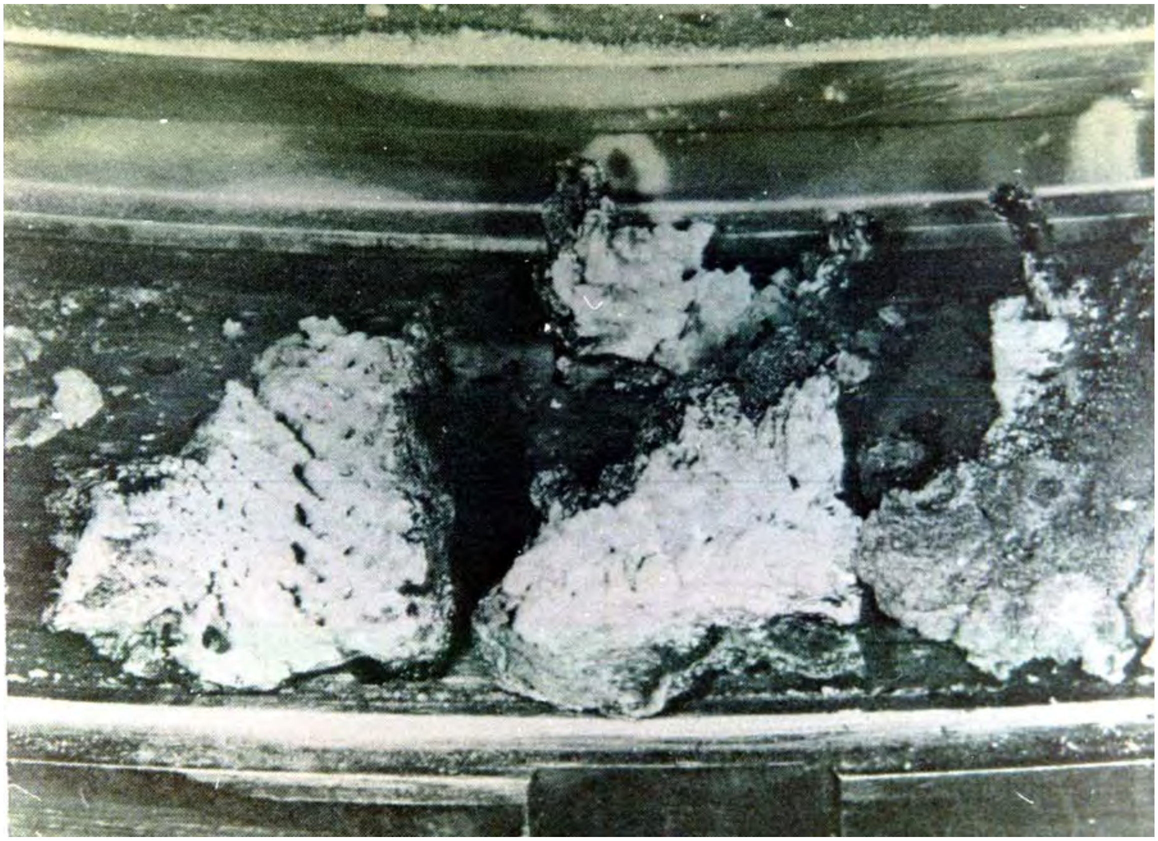


Figure 5

Stage 1 Nozzle Guide Vane Leading Edge Deposits
Disclosed During Disassembly

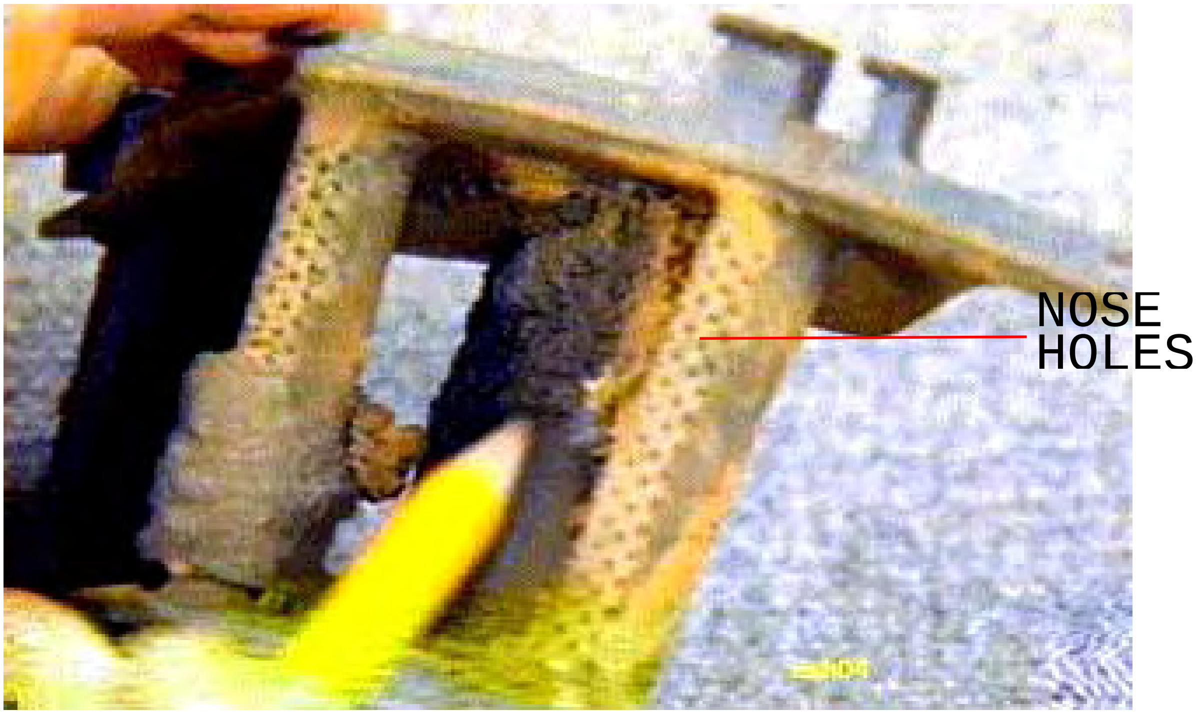


Figure 6

Sketch of the Stage 1 HPT Nozzle Based on Inspection of Engine No. 1

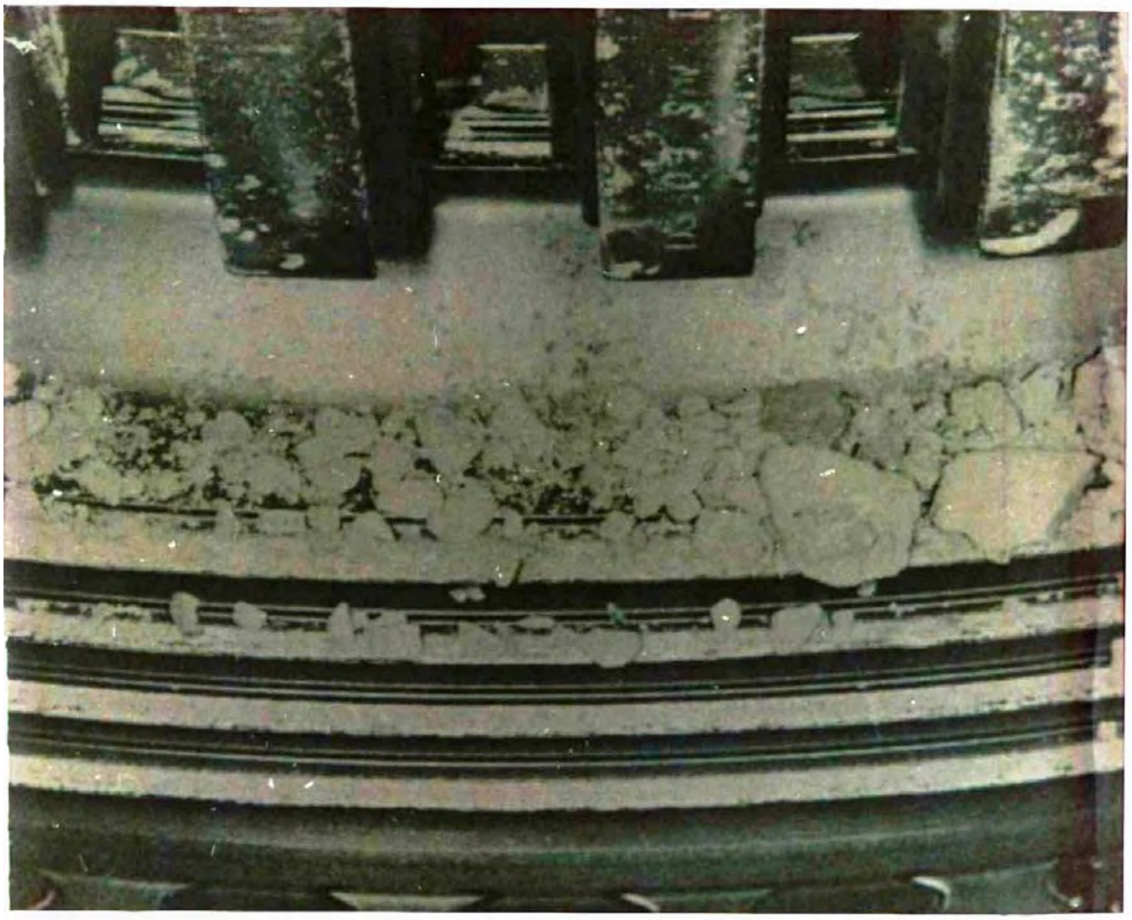
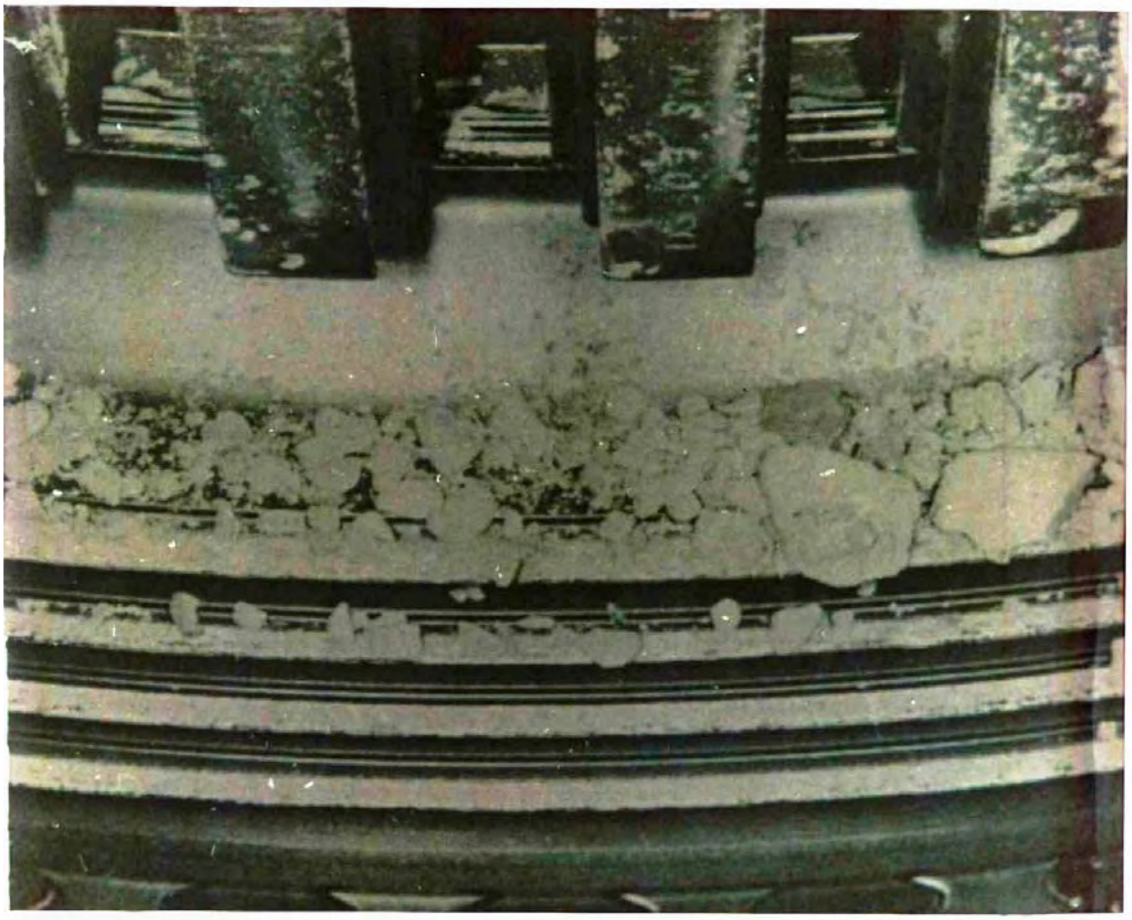


Figure 7
Accumulation of Ash in the HPT Rotor



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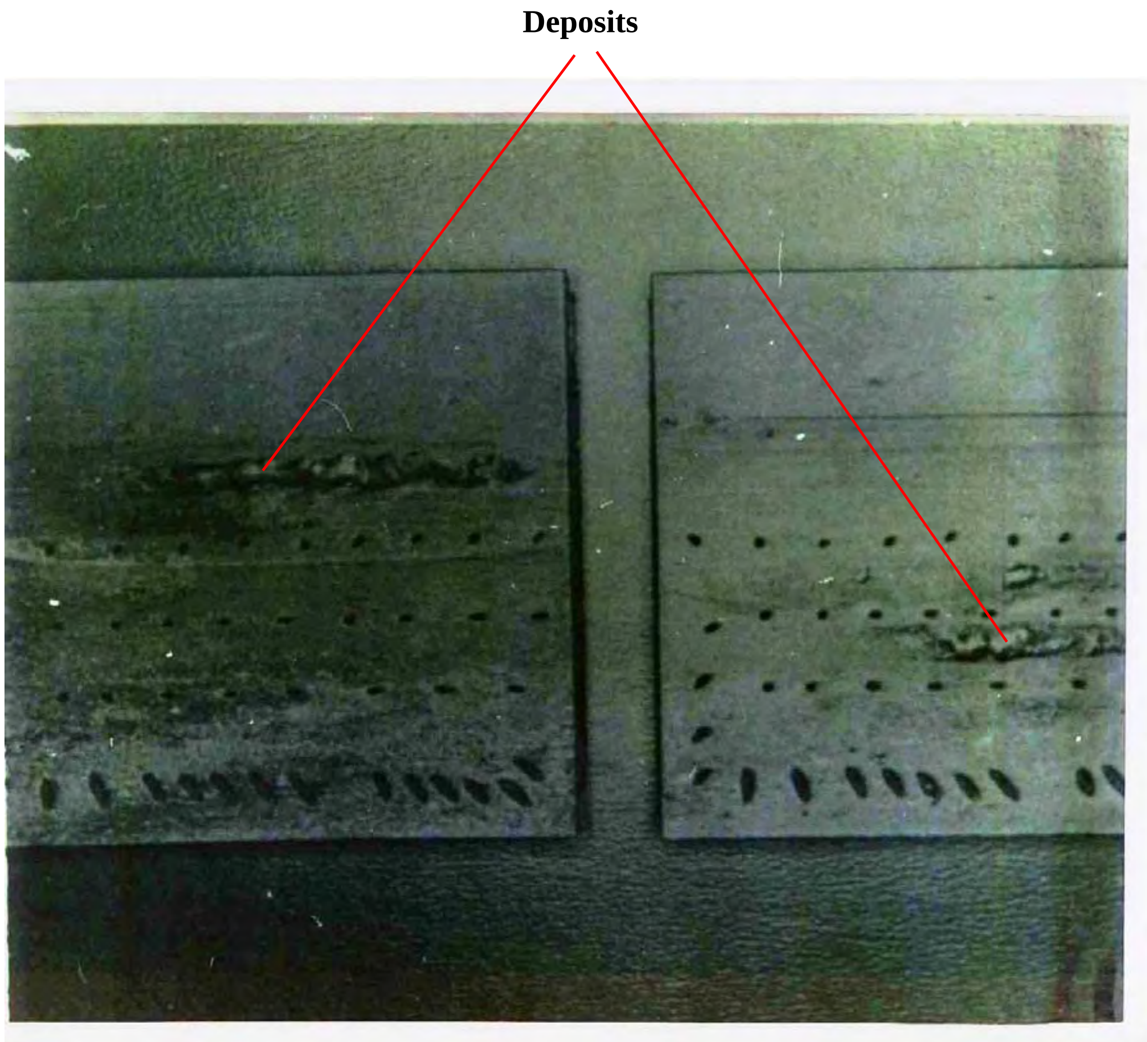

Figure 8
Hard Ash Material Deposit on Stage 1 HPT Shrouds

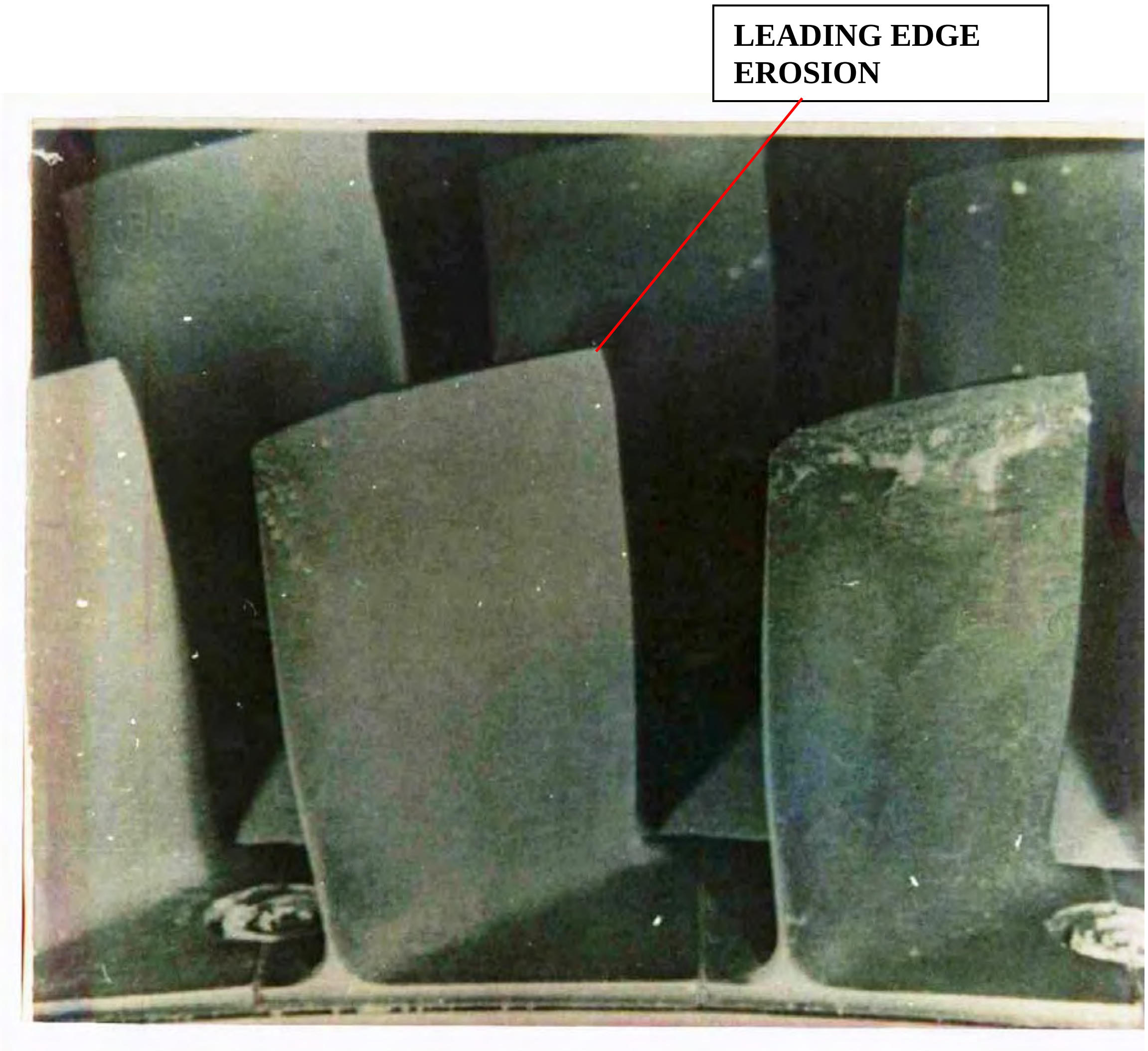

Figure 9
HPC Blades Leading Edge and Tip Erosion

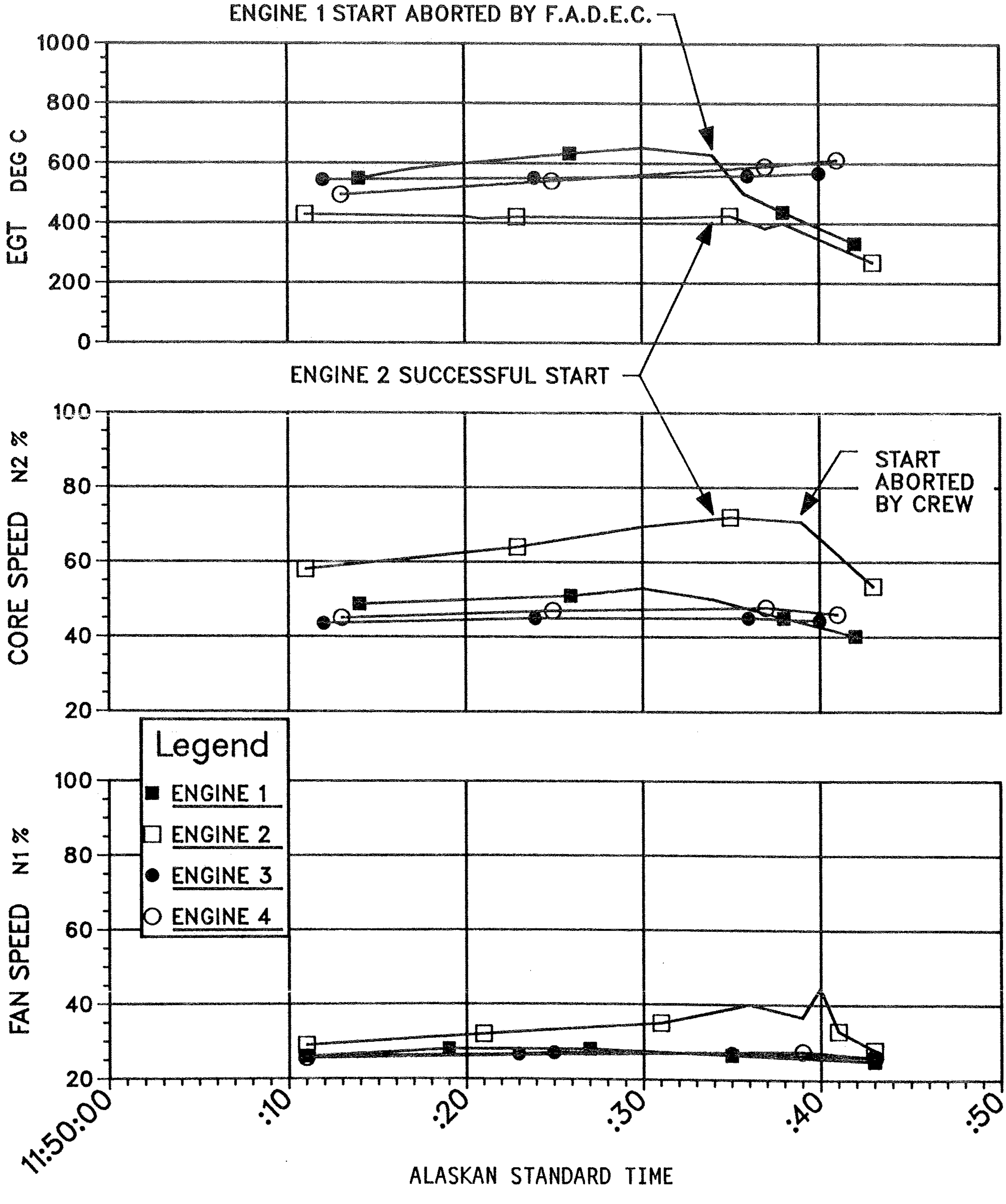

Figure 10 Engine Parameters During First Recorded Start Attempt