AIRSTART PERFORMANCE OF A DIGITAL ELECTRONIC ENGINE CONTROL SYSTEM ON AN F100 ENGINE

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SUMMARY

The ability to achieve reliable and rapid airstarts is an important feature of an engine. Engine shutdowns may occur as a result of nonrecoverable stalls or overtemperatures. The airstart logic in the engine control system meters fuel to the combustor to achieve combustor light off, and then to accelerate the compressor. If the fuel flow is too high, the compressor will stall, resulting in a hot start. If the fuel flow is too low, the compressor will not accelerate, resulting in a hung start. The allowable fuel flow range between the hot start and the hung start may be very small, particularly for turbofan engines. Most engine control systems have an open-loop airstart system in which the fuel flow is preprogrammed as a function of time. Due to the normal variations between engines, the control system tolerances, and differences in fuel characteristics, these airstarts are not always successful.

The NASA Ames Research Center's Dryden Flight Research Facility (DFRF) has recently tested the digital electronic engine control (DEEC) system installed on an F100 engine in an F-15 airplane. The DEEC incorporates a closed-loop airstart feature, in which the fuel flow is modulated to achieve the desired rate of compressor acceleration. With this logic, the DEEC-equipped F100 engine is capable of achieving airstarts over a larger envelope. This paper describes the DEEC airstart logic, the test program conducted on the F-15, and the results.

AIRSTART LOGIC

In the event of an engine shutdown or flameout, the DEEC monitors several parameters to ensure a successful airstart. A simplified block diagram of DEEC airstart logic is given in the following figure. An open-loop fuel scheduling routine is used until the burner "light" (fuel mixture ignition) is indicated by a rise in the fan turbine inlet temperature (FTIT) signal. Once the burner light has been detected by the DEEC, fuel flow (WF) and the compressor bleed control switches to the closed-loop logic shown in the figure. This logic attempts to maintain a desired core rotor speed (N2) rate by varying fuel flow. The desired N2 rate is a function of fan inlet static pressure (PS2), fan inlet total temperature (TT2), and N2. If the fuel flow is too high, the compressor will stall, resulting in a hot start. If the fuel flow is too low, the available energy will not be sufficient to overcome the losses in the engine and the accessory power drain, resulting in a hung start. The DEEC airstart logic maintains the optimal N2 rate subject to a bias if FTIT exceeds a limit of approximately 760° C. The minimum fuel flow set by a stop in the fuel metering valve is approximately 115 kg/hr. The compressor bleeds are held open until 56 percent N2 is attained.

The jet fuel starter (JFS) may also be used to assist in airstarts. The JFS is an auxiliary power unit that may be connected to the N2 rotor via a gearbox. It is normally used for ground starting and may also be used for airstarts below 6100 m. For JFS-assisted airstarts, the DEEC uses a higher scheduled N2 rate and a higher FTIT limit.

DEEC Airstart Logic

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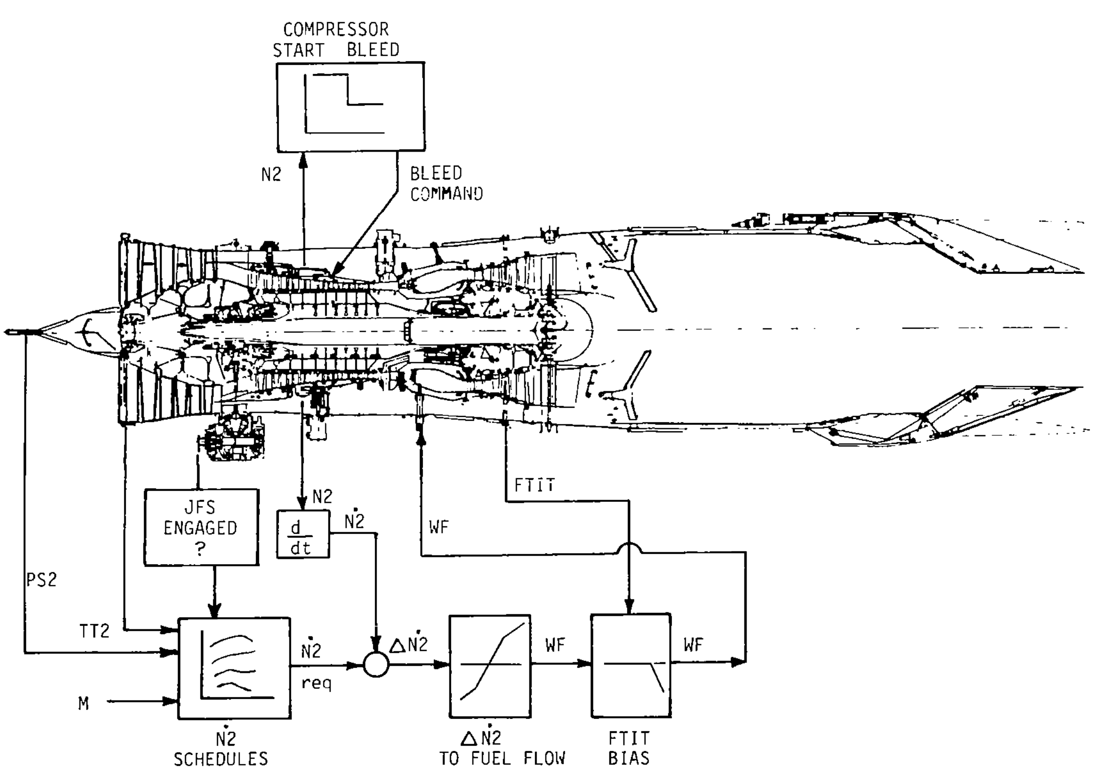

SPOOLDOWN AIRSTART AT 250 KNOTS

The next figure is a time history of a DEEC 40-percent spooldown airstart at an airspeed of 250 knots and an altitude of 9100 m, which also illustrates the use of closed-loop airstart logic. The power lever angle (PLA) was moved to the on/off position to shut down the engine at time (t) = 10 sec. Immediately after shutdown there was a corresponding drop in core speed (N2), fan turbine inlet temperature (FTIT), and fuel flow to the engine. The pilot initiated the ignition sequence by moving the throttle up over the idle detent to the idle power setting at t = 22 sec as the core rpm reached 40 percent. At this point the fuel flow began at the minimum value of 115 kg/hr. At t = 31 sec, the fuel mixture was ignited (light) as noted by the increase in FTIT. The DEEC closed-loop logic modulated the fuel flow to achieve the desired rate of acceleration of the engine core. N2 increased uniformly to t = 45 sec, then increased more rapidly. Idle speed was reached at t = 77 sec. FTIT varied between 450° C and 520° C during the airstart. The time required for the airstart, defined as the difference between idle and pressurization times, was 55 sec.

DEEC Airstart

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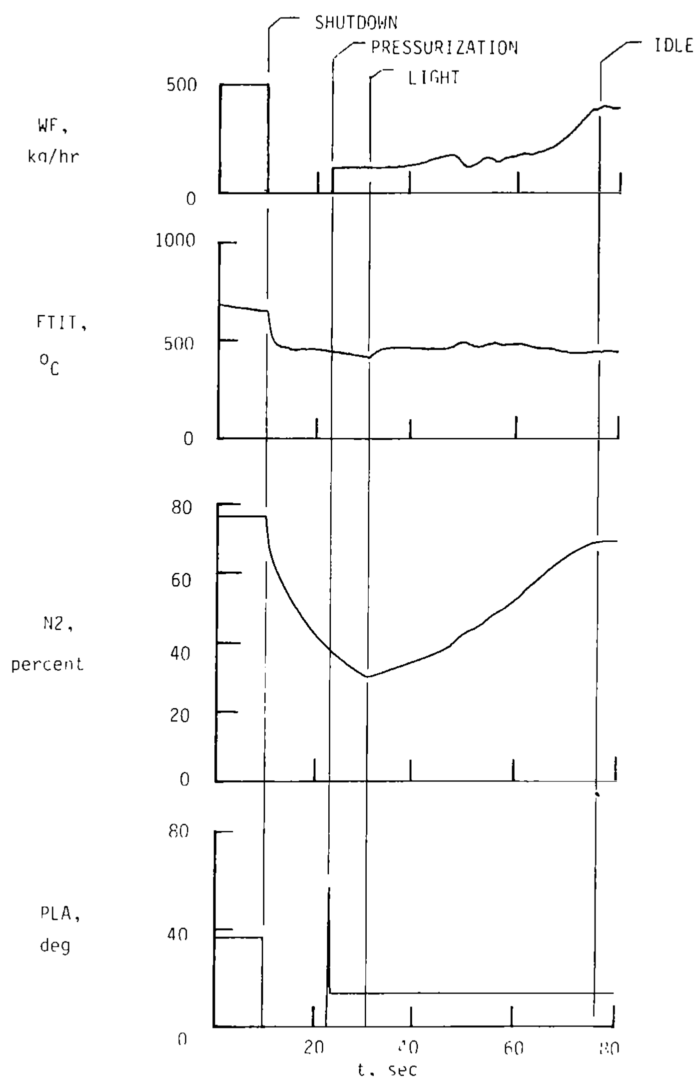
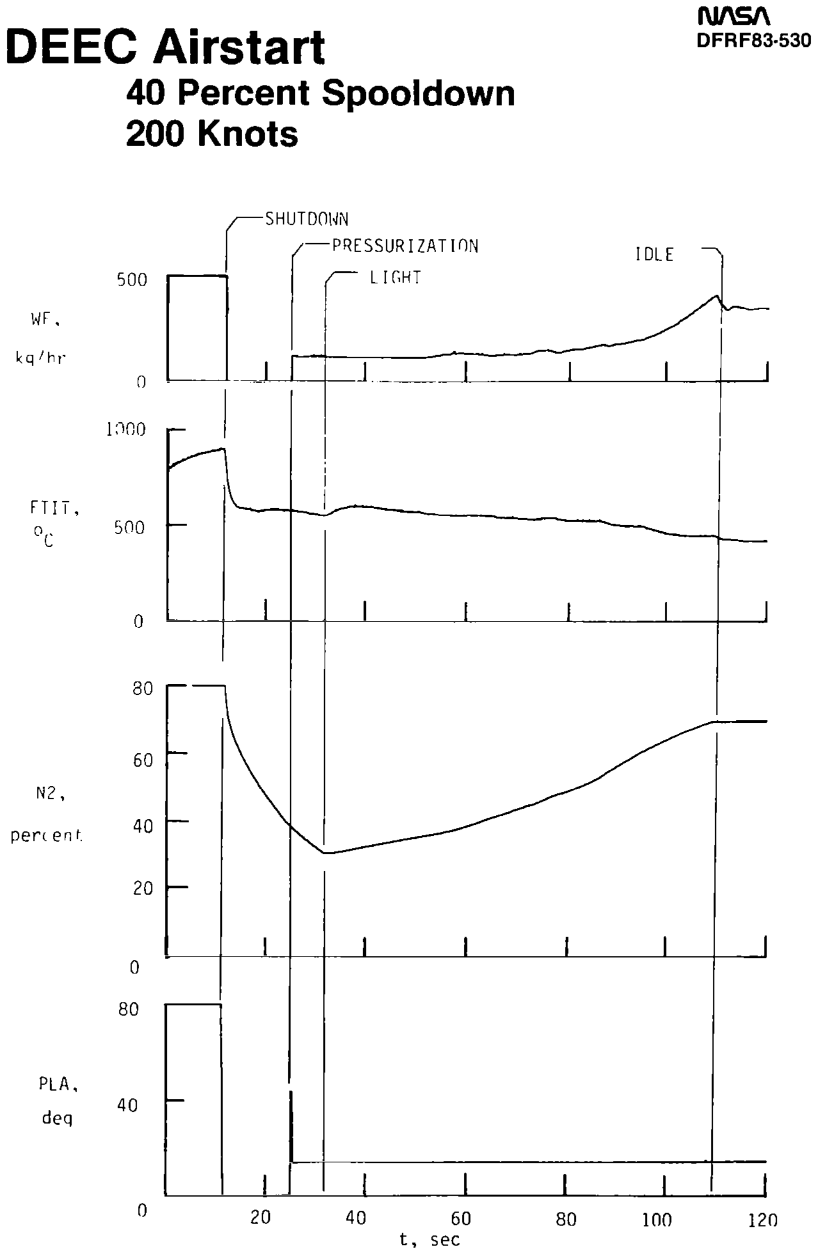
40 Percent Spooldown
250 Knots



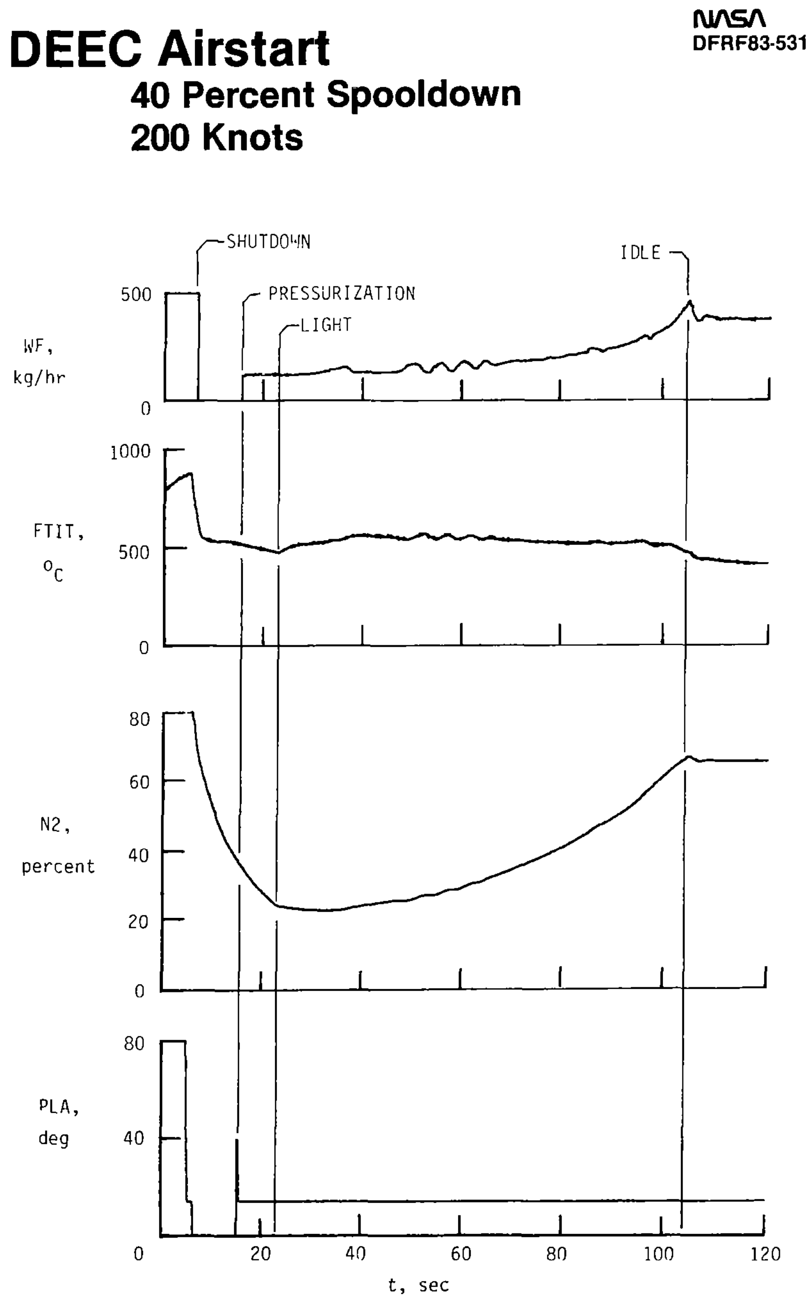
AIRSTART AT 200 KNOTS AT 9250 METERS

Airstarts at lower airspeeds took longer, due to the reduced energy of the inlet flow and lower burner pressures. The figure below shows a 40-percent spool-down airstart at an airspeed of 200 knots and an altitude of 9250 m. Shutdown time was t = 12 sec, pressurization at t = 23 sec, light at t = 32 sec, and idle at t = 108 sec. Airstart time was 86 sec. The FTIT reached 600° C at t = 38 sec, with the fuel flow on the minimum flow stop.



AIRSTART AT 200 KNOTS AT 4600 METERS

A DEEC 40-percent spooldown airstart at 200 knots, at an altitude of 4600 m, is shown below. Shutdown occurred at t = 9 sec, pressurization at t = 15 sec and light at t = 23 sec. Following the light, the N2 continued to decrease for 10 sec as fuel flow was increased. At t = 40 sec, a positive N2 rate was achieved and fuel flow was cut back as FTIT reached 600° C. In the time between t = 50 sec and 70 sec, oscillations in N2, FTIT, and WF occurred indicating that the gains in the closed-loop control logic were slightly high. The airstart continued and idle was reached at t = 104 sec, for an airstart time from pressurization to idle (T) = 89 sec, slightly longer than the 86 sec time from the previous figure at the higher altitude but a similar airspeed.



JFS-ASSISTED AIRSTARTS

For more rapid airstarts at altitudes below 6100 m, the jet fuel starter was used for assisted airstarts. The figure below shows a time history of a JFS-assisted airstart at calibrated airspeed (VC) = 255 knots at an altitude of 6100 m. Shutdown occurred at t = 11 sec and the JFS was engaged at t = 33 sec at an N2 of 25 percent. The N2 increased as a result of the JFS assist and stabilized at N2 = 32 percent. The pressurization was delayed for this test until stable JFS motoring speed was observed at t = 68 sec. After the light at t = 79 sec, N2 increased rapidly and idle was achieved at t = 106 sec for an airstart time of 38 sec.

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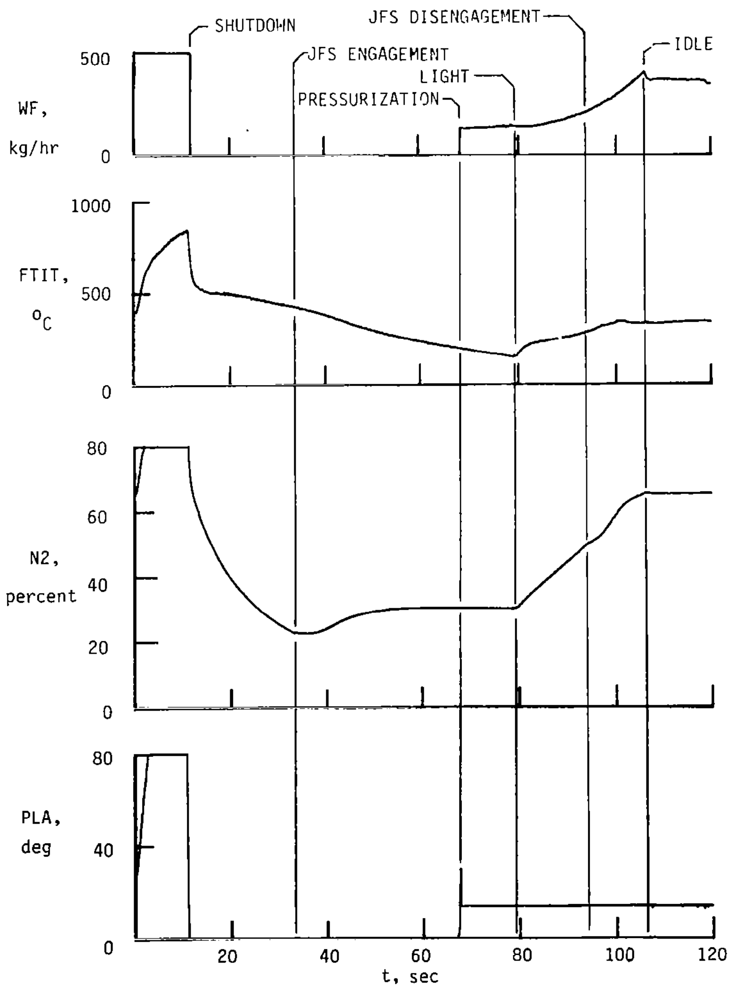
DEEC JFS Airstart
255 Knots



JFS-ASSISTED AIRSTART AT 210 KNOTS

A JFS-assisted airstart at a lower speed of VC = 210 knots and at an altitude of 6100 m is shown below. Shutdown occurred at t = 14 sec, JFS engage at t = 34 sec, pressurization at t = 36 sec, and light at t = 46 sec. The N2 rate was reduced to nearly zero at t = 65 sec prior to JFS disengage. Following the JFS disengage an increase in N2 rate occurred. The airstart was completed at t = 83 sec, for an airstart time of 47 sec.

All JFS-assisted airstarts attempted were successful from VC = 400 knots to 200 knots over a wide range of altitudes.

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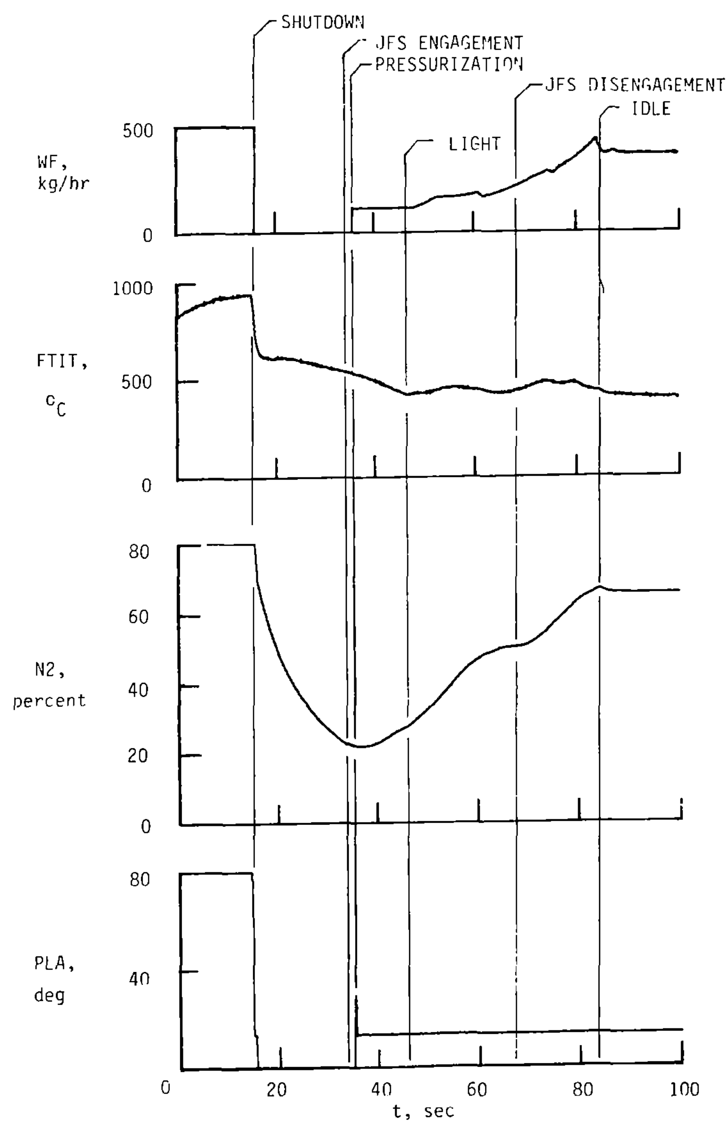
DEEC JFS Airstart
210 Knots



SUMMARY OF AIRSTART TIMES

Airstart times - T - for the DEEC airstarts are shown in the figure below for the 40-percent spooldown airstarts, for the 25-percent spooldown airstarts, and for JFS-assisted airstarts. Airstart times for the 40-percent spooldown airstarts were approximately 50 sec at VC = 250 knots, 85 sec at VC = 200 knots, and up to 192 sec at VC = 175 knots. For the 25-percent spooldown airstarts, times were approximately 65 sec at VC = 250 knots, and from 97 sec to 135 sec at airspeeds of 205 knots to 210 knots. It is clear that airstarts at VC = 200 knots are only marginally successful, due to the long start times.

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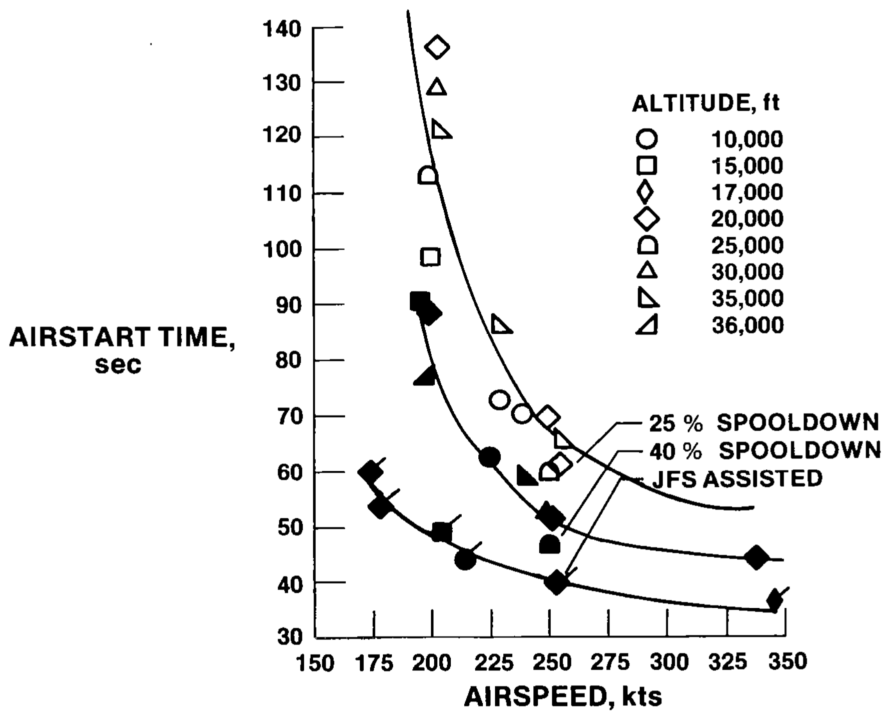
EFFECT OF AIRSPEED AND ALTITUDE ON AIRSTART TIMES



HUNG AIRSTART

At airspeeds below 200 knots, most of the spooldown airstarts were unsuccessful. The unsuccessful airstarts were mostly hung starts in which the N2 either decreased or did not increase. A typical example of a hung start, shown in the figure below, is a 25-percent spooldown airstart attempt at VC = 180 knots at an altitude of 7600 m. Following the light, N2 increased very slowly to 28 percent and then stabilized. The fuel flow remained on the minimum flow stop; FTIT initially exceeded 600° C and then slowly decreased.

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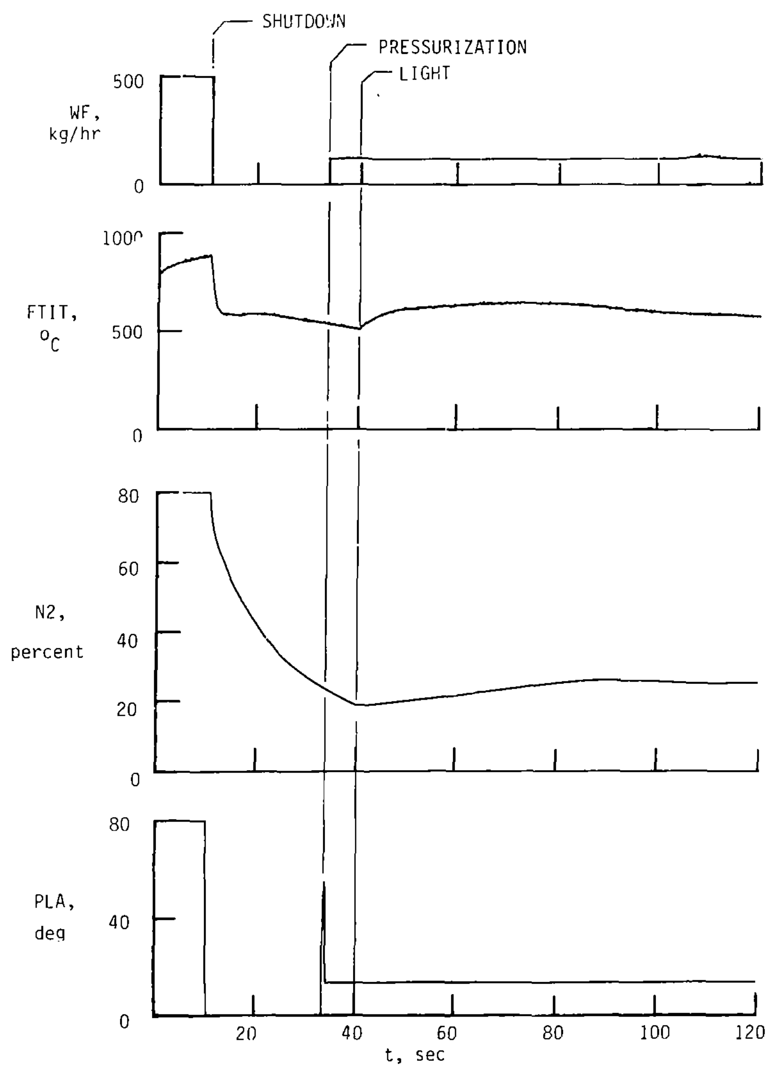
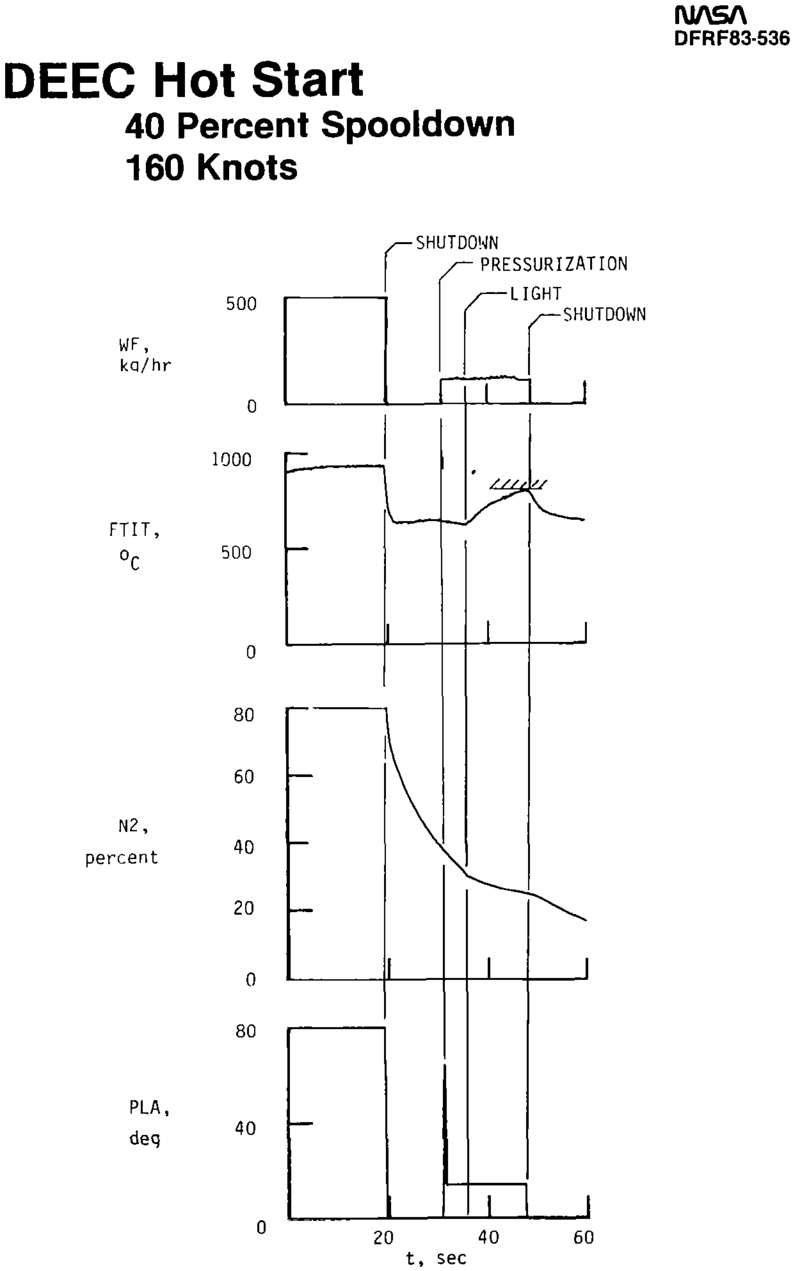
DEEC Hung Airstart
25 Percent Spooldown
180 Knots



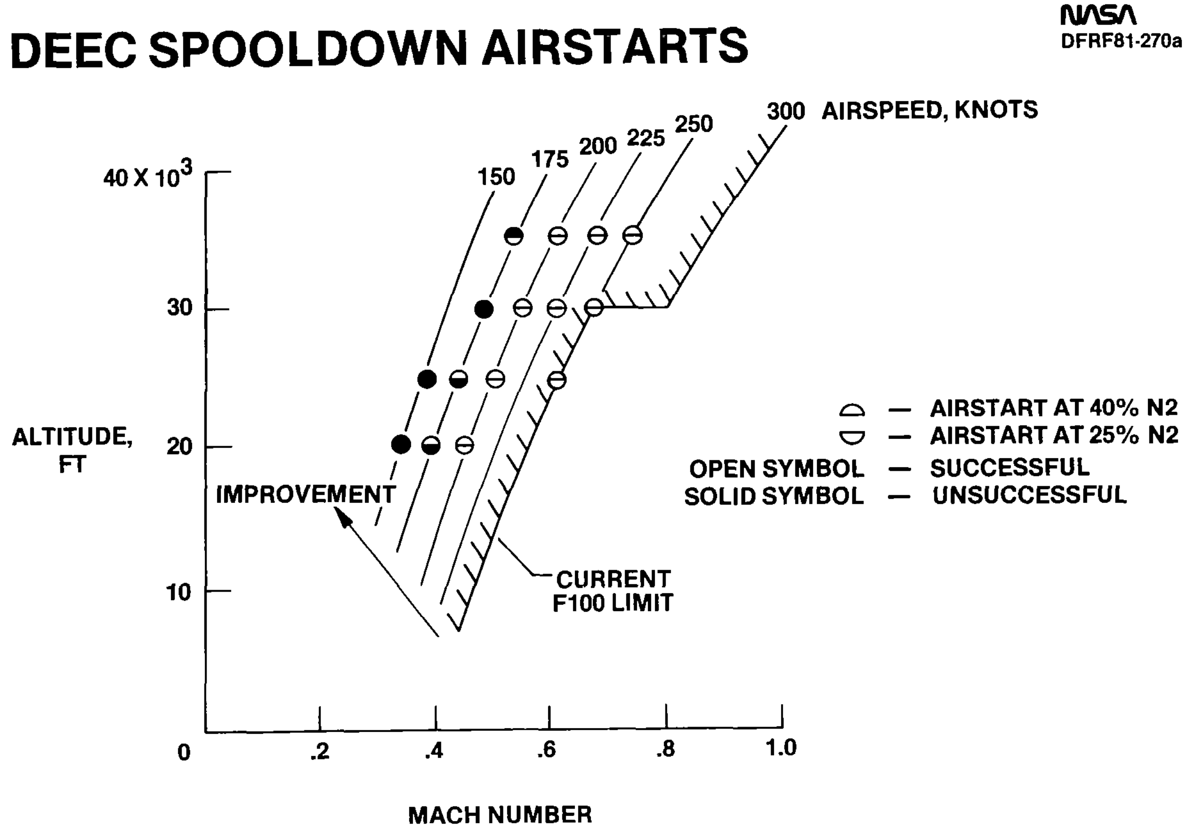
HOT START

Only one hot start occurred in the airstart test; it is shown in the figure below. It was a 40-percent spooldown airstart attempt at VC = 160 knots at 7600 m. Following the burner light at t = 35 sec, N2 continued to decrease, while FTIT increased rapidly, even with the fuel flow at the minimum value, indicating a stalled compressor condition. When the FTIT reached the maximum allowable value of 800° C, the pilot shut down the engine.



SUMMARY OF AIRSTART SUCCESS

A summary of the DEEC spooldown airstart success is shown in the figure below. All DEEC airstarts at and above 200 knots were successful, both for 25-percent and 40-percent spooldown airstarts. This capability represented a 50-knot to 100-knot improvement over the standard F100 engine handbook limit.



CONCLUDING REMARKS

The summary of the DEEC airstart capability of an F100 engine equipped with a DEEC is shown below. The DEEC airstart capability with the closed-loop control logic was very effective. All airstarts at 200 knots and above were successful, a 50-knot to 100-knot improvement over the standard F100 engine. Airstart times for spooldown airstarts ranged from 50 sec to 70 sec at 250 knots to 80 sec to 130 sec at 200 knots. All JFS-assisted airstarts were successful at airspeeds between 170 knots and 400 knots. At speeds below 200 knots, most of the airstarts were unsuccessful, as expected, due to hung starts.

Summary

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- DEEC closed-loop airstart logic effective
- All airstarts at airspeeds of 200 knots or greater were successful, 50 to 100 knot improvement over standard F100
- Airstart times between 50 to 70 sec at 250 knots and 80 to 130 sec at 200 knots
- All JFS-assisted airstarts were successful
- Unsuccessful starts at airspeeds of 175 knots and below, as expected