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Preliminary Flight Evaluation of F100 Engine Model Derivative Air-start Capability in an F-15 Airplane

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INTRODUCTION

The ability to achieve reliable airstarts is crucial to the safe operation of modern jet aircraft. The NASA Ames Research Center's Dryden Flight Research Facility has tested protoype F100 engine model derivative (EMD) engines in an F-15 airplane. The F100 EMD has a thrust increase of approximately 15 percent over the standard F100 engine. It incorporates a redesigned fan, improved materials in the hot section, and a redesigned augmentor fuel distribution system. The F100 EMD also incorporates the digital electronic engine control (DEEC) system, which features a closed-loop airstart logic that significantly improves the airplane airstart envelope. An airstart evaluation of the DEEC-equipped F100 engine was conducted in an F-15 airplane previously (ref. 1). An objective of the F100 EMD testing is to determine the new engine's airstart characteristics. This report presents the flight evaluation of the EMD airstart capability.

SYMBOLS AND ABBREVIATIONS

BUC	backup engine control
CIVV	compressor inlet variable vanes
DEEC	digital electronic engine control
EMD	engine model derivative
FTIT	fan turbine inlet temperature, ^{o}C
HP	pressure altitude, m
JFS	jet fuel starter
M	Mach number
N1	engine fan speed
N2	engine core speed, percent (100 percent is 14,000 rpm)
PB	main burner pressure, kN/m^2
PLA	power lever angle, deg
PS2	engine inlet static pressure, kN/m^2
PT6M	mixed turbine discharge pressure, kN/m^2
RCVV	rear compressor variable vanes

SDT	spooldown time, time to spool down from intermediate power N2 to a given N2, sec
T	airstart time, time from pressurization to idle N2, sec
TT2	engine inlet temperature, ^{o}C
WF	engine fuel flow, kg/hr

DESCRIPTION OF APPARATUS

The F-15 aircraft (fig. 1) is a single seat, high performance, all weather air superiority fighter capable of Mach 2. It is a twin-engine airplane with a high-mounted sweptback wing, twin vertical stabilizers, and large horizontal stabilizers. The F-15 airplane has been modified to be a general test bed aircraft. During Phase I of the flight test program, the left engine was replaced with an F100 EMD engine. During Phase II, the EMD engine used in Phase I replaced the right engine, and another F100 EMD engine was installed in the left side.

The F100 EMD engine (figs. 2 and 3) is a twin spool, low bypass ratio augmented turbofan. It has a 3-stage fan driven by a 2-stage low pressure turbine. The fan has 5 percent greater airflow capability and 7 percent more pressure rise than the standard F100 fan. The 10-stage high pressure compressor is driven by a 2-stage high-pressure turbine. The turbines incorporate single crystal blades and vanes, allowing a higher operating temperature than the standard F100 engine. Compressor bleed is used only during starting. The variable camber inlet guide vanes and rear compressor variable vanes allow for higher performance over the operating flight envelope. Variable augmented thrust is provided by a mixed flow, sixteen-segment afterburner. The mixed flow is exhausted through a variable area convergent-divergent nozzle. During Phase I, engine serial number P680350 was used, and for Phase II, engine serial number P680585 was added. Both engines are pre-production test models. All airstarts were conducted with P680350 except a flight-check airstart for P680585.

An important feature of the EMD engines is the DEEC unit. The DEEC is a full-authority digital electronic control system with a simple integral hydromechanical backup engine control. The DEEC replaces the functions of the supervisory electronic engine control and hydromechanical unified fuel control on the F100 engine. The DEEC system, shown in figure 4, receives inputs from (a) the airframe through throttle position (PLA) and Mach number (M); (b) the engine through pressure sensors PB, P6TM, and PS2, temperature sensors TT2 and FTIT, and rotor speed sensors N1 and N2; and (c) the control system through feedback resolvers that indicate variable vane (RCVV, CIVV) positions, metering valve positions (fuel flow for primary and augmented thrust modes), and exhaust nozzle positions. This information is used by the DEEC controller to (a) schedule the compressor bleeds and position the variable vanes through actuators in the open-loop system; (b) control the primary and augmented fuel flows in a closed-loop system; and (c) control the nozzle in a closed-loop system.

The DEEC computer is a 16-bit, 1.2-microsec-cycle-time microcomputer with 10.5 kilobytes of available memory. The entire electronic unit is fuel cooled and is engine mounted.

The jet fuel starter (JFS) is a small auxiliary gas turbine power unit which can be coupled to the F100 engine. The JFS is used to accelerate the high compressor for engine starting on the ground. It may also be used in flight at altitudes below 7000 m. The JFS disengages automatically when 50-percent N2 is achieved.

Pressures, temperatures, rotor speeds, fuel flow, and positions of variable geometry are measured at various stations in the F100 engine. Engine parameters important to this report are PLA, N2, FTIT, and WF. All parameters are input into a pulse code modulation (PCM) system during the test flights. The digital PCM data are recorded on an onboard tape recorder and also telemetered to the ground for real-time display in the control room.

DEEC AIRSTART LOGIC

In the event of an engine shutdown or flameout, the DEEC monitors several parameters to insure a successful airstart. An open-loop fuel scheduling routine is used until the burner "light" (fuel mixture ignition) is indicated by a rise in the FTIT signal. Once the burner light has been detected by the DEEC, fuel flow and compressor bleed control switches to the closed-loop logic shown in figure 5. This logic attempts to maintain a desired N2 rate by varying fuel flow. The desired N2 rate is a function of PT2, TT2, and M. If the fuel flow is too high the compressor will stall, resulting in a "hot start." If the fuel flow is too low, the energy available 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. At airspeeds below approximately 200 knots, the DEEC airstart logic is designed to light the burner and maintain N2, but not to accelerate the engine to idle.

The logic discussed above was incorporated into the DEEC logic package P. D. 4.2.1.

The jet fuel starter may also be used to assist in airstarts. For JFS-assisted airstarts, the DEEC uses a higher scheduled N2 rate and a lower FTIT limit. Compressor bleeds are held open until 56-percent N2 is achieved.

TEST PROCEDURE

This report documents the ability of the DEEC-equipped F100 EMD engine to perform airstarts with and without a JFS assist. The three types of airstarts examined are 40-percent spooldown, 25-percent spooldown, and JFS assisted. For all airstarts the normal F-15 power requirements for the engine and accessories were present.

The spooldown airstart is achieved in a four-step procedure: (1) engine shutdown, (2) pressurization, (3) light, and (4) acceleration of the engine to idle speed. The engine shutdowns were mostly performed from the intermediate power setting. The compressor rotor is then allowed to wind down (spool down) to a predetermined percentage of maximum core speed. For the evaluation of EMD airstart capability, values of 40-percent N2 and 25-percent N2 were used. The pressurization step is accomplished when the pilot returns the throttle to the idle power setting to begin the start cycle. This pressurizes the fuel system and fuel begins to flow to the combustor. Approximately 10 seconds later, the fuel reaches the combustor nozzles and is ignited (light). The fuel flow is modulated by the DEEC to maintain the scheduled N2 rate until the scheduled idle speed is reached and the airstart sequence is completed. Airstart time is calculated from pressurization to the time when idle N2 is reached in the above procedure.

The JFS-assisted airstart is accomplished by coupling the jet fuel starter to the high compressor rotor through a gearbox. The JFS may be engaged at any N2 speed from 0 to 30 percent. It accelerates the core rotor to approximately 30 percent. The pressurization step may be initiated at a core speed of 12 percent or greater. The JFS disengages automatically at 50-percent N2.

During the airstart tests, the pilot used the right engine of the F-15 aircraft to maintain the desired airspeed and altitude. Airspeed was held within 4 knots and altitude within 30 m of the desired test conditions. Test day temperatures varied as much as $\pm 10^{\circ}$ C from standard-day temperatures. More details of the test procedure can be found in reference 3.

RESULTS AND DISCUSSION

Of the 23 primary EMD airstarts attempted during the flight tests, 13 were 40-percent spooldown, 8 were 25-percent spooldown, and 2 were JFS assisted.

Spooldown Airstarts

Figure 6 is a time history of an EMD airstart at 225 knots calibrated airspeed and an altitude of 10,700 m. The pilot initiated the airstart procedure by shutting down the engine at t = 10 sec. The core speed, N2, immediately began to spool down with a rapid drop in fan turbine inlet temperature (FTIT). The core reached 40-percent rpm at t = 28 sec, at which time the pilot moved the throttle to idle, which pressurized the fuel system and initiated the airstart sequence. The fuel began to flow through the fuel manifold; however, FTIT and core speed continued to drop until t = 41 sec, when the fuel reached the combustor and was ignited as indicated by the increase in FTIT. The DEEC closed-loop logic then modulated the fuel flow to achieve the desired rate of acceleration of the engine core. Core speed, N2, increased uniformly until t = 72 sec, then increased its acceleration slightly until idle rpm was reached at t = 100 sec. The FTIT remained below 400° C. The airstart time, defined as the time from pressurization to idle N2, was 72 sec.

Figure 7 shows an airstart at the same flight conditions of 225 knots and 10,700 m, but for a 25-percent spooldown. The pilot shutdown the engine at t = 10 sec. Fuel flow quickly went to zero, while core speed and FTIT dropped rapidly for the first few seconds, then more slowly. The engine reached 25-percent N2 at t = 51 sec, at which time the throttle was moved to pressurize the fuel system. Engine rpm and FTIT continued to drop, reaching 20 percent and 278° C, respectively, at t = 63 sec, when the fuel mixture ignited. The core increased speed uniformly until reaching idle at t = 140 sec. The airstart took 89 sec compared to 72 sec for the 40-percent spooldown airstart.

Airstarts at lower airspeeds took longer because of the reduced energy of the inlet flow, lower burner pressure, and lower stall margin. Figure 8 shows a 40-percent spooldown airstart at an airspeed of 200 knots and an altitude of 10,700 m. The pilot shut down the engine at t = 10 sec and pressurized at t = 28 sec. Engine rpm and FTIT dropped to 27 percent and 377° C respectively at t = 41 sec, when the burner lit. The engine reached idle at t = 121 sec. The airstart time was 93 sec compared to 72 sec for the 225 knot airstart at the same altitude.

Airstarts were performed at different altitudes to test the effect of altitude on airstart times. Figure 9 is a 40-percent spooldown airstart at 225 knots and an altitude of 7600 m. The pilot shut down the engine at t = 2 sec and pressurized at t = 17 sec. The engine spooled down to 27 percent rpm, and FTIT was at 458° C, when the fuel ignited at t = 27 sec. The engine reached idle speed at t = 80 sec. The total airstart time was 63 sec; compared to the airstart at an altitude of 10,700 m which took 10 sec longer.

JFS-Assisted Airstarts

The JFS was utilized to test for faster airstart times at conditions within the JFS envelope. Figure 10 shows a time history of a JFS-assisted airstart at an airspeed of 170 knots and an altitude of 7000 m. The pilot shut down the engine at t = 11 sec and engaged the JFS at t = 43 sec, when N2 was at 17 percent. The JFS accelerated N2 to approximately 25 percent, and the pilot advanced the PLA to idle at t = 55 sec. The light occurred at t = 71 sec and the engine quickly accelerated to 50 percent. When the JFS disengaged, the N2 rate dropped off for a few seconds, then increased again, and idle was reached at t = 115 sec. The airstart time was 60 sec compared to a 25-percent spooldown airstart at similar conditions of 175 knots and 7600 m, which took 133 sec.

Figure 11 shows another JFS-assisted airstart at an airspeed of 170 knots and an altitude of 3050 m. The shutdown was at t = 10 sec, and the pilot engaged the JFS at t = 31 sec, pressurized at t = 39 sec, and the light occurred at t = 52 sec. As in the previous example, the N2 rate was reduced at 50-percent N2 when the JFS disengaged. The start proceeded, and the engine achieved idle at t = 89 sec. The airstart time was 50 sec, whereas an airstart of 175 knots and 3050 m for a 40-percent spooldown resulted in a hung start, as is shown later.

Summary of Airstart Times

Summaries of 40-percent spooldown airstarts and 25-percent spooldown airstarts are shown on figures 12 and 13. The results show an inverse relationship between airspeeds and airstart times. In figure 12, for 40-percent spooldown airstarts, airstart times varied from approximately 55 sec at 250 knots to 132 sec at 175 knots. Also shown is the average airstart time for the DEEC-equipped F100 engine (ref. 1). The F100 EMD results are very similar.

The 25-percent spooldown airstart results shown in figure 13 show airstart times ranging from 55 to 170 sec. Although the 175-knot airstart was successful, it is obvious that the long start time would be unacceptable for inflight use. It does show that the DEEC control is capable of lighting the engine at this condition and maintaining rpm until the pilot can increase airspeed. Again, the DEEC-equipped F100 engine results from ref. 1 are shown, and good agreement is seen.

The difference between the 40-percent and 25-percent spooldown airstarts is shown in figure 14 for an altitude of 10,700 m. The 40-percent spooldown airstarts are 10 to 20 sec faster than the 25-percent spooldown airstarts.

Unsuccessful Airstarts

The F100 EMD engine experienced two unsuccessful airstarts at 175 knots during flight tests. This is not surprising since at low speeds the DEEC logic is designed only to light the burner and maintain the rpm until the pilot can increase his airspeed. One unsuccessful airstart was a hot start, in which the engine lit normally, but the FTIT exceeded the engine starting temperature limit. The other was a hung start, in which the engine lit, but N2 hung at a value below idle.

Figure 15 shows the time history of the hot start at an airspeed of 175 knots and an altitude of 10,700 m. At t = 12 sec, the pilot pulled the throttle to the off position, and pressurized at t = 29 sec. The light occurred at t = 37 sec and N2 initially showed a sign of accelerating. However, even with the fuel flow on the minimum stop the FTIT continued to increase. When the FTIT reached 750° C at t = 75 sec, the pilot discontinued the test and pushed the nose of the plane over to increase the airspeed, eventually reaching 300 knots. The fan turbine inlet temperature, FTIT, then quickly dropped and N2 accelerated back to idle. This hot start was not typical because the compressor did not show evidence of a stalled condition with FTIT rising and N2 falling.

Figure 16 shows the time history of the hung start at 175 knots and 3050 m. The shutdown was at t = 11 sec and pressurization at t = 19 sec. The burner lit at t = 31 sec, but FTIT increased only 50° and remained around 500° C. Core speed, N2, stopped its deceleration but stayed at the value of 19 percent. When the hung start was apparent at t = 100 sec, the pilot discontinued the test and increased the airspeed to 270 knots, which caused the N2 to quickly accelerate to idle.

Summary of Spooldown Airstart Success

Figure 17 summarizes the successful and unsuccessful spooldown airstarts. The airstarts at airspeeds of 200 knots and above were all successful. For lower airspeeds, both 25-percent and 40-percent spooldown airstarts at VC = 175 knots and 7600 m were successful, but the 40-percent spooldown airstarts at 10,700 m and at 3050 m were unsuccessful. These results agree very closely with the DEEC-equipped F100 engine (ref. 1), indicating that the redesigned fan of the F100 EMD has only a small effect on the airstart characteristics.

Comparison of F100 EMD Engines P350 and P585

Figure 18 shows a 40-percent spooldown airstart with F100 EMD engine P350 performed at 250 knots and 7600 m. Shutdown occurred at t = 5 sec, pressurization at t = 21 sec, light at 30 sec, and idle at t = 71 sec. The airstart time was 52 sec.

Figure 19 shows the time history of the flight-check airstart for F100 EMD engine P585 tested at the same conditions as above. Shutdown occurred at t = 6 sec, and pressurization was at t = 21 sec. Ignition occurred at t = 29 sec, 8 sec after pressurization. Comparatively, P350 ignited 9 sec after pressurization. The core reached idle rpm at t = 72 sec for an airstart time of 51 sec compared to 52 sec for P350. The close comparison of the two F100 EMD engines shows that the engine-to-engine variation was small.

Spooldown Time

Spooldown time, defined as the time elapsed between shutdown and the point at which a specified N2 percentage is reached, does not have a direct effect on airstart times. It does, however, indicate how long a pilot has to initiate a spooldown airstart at various flight conditions. Figures 20 and 21 show the spooldown times.

Figure 20 shows the time required to spool down to various values of N2 at VC = 200 knots, at three altitudes. The time required to spool down to 40-percent N2 varies between 8 sec at the lower altitude and 17 sec at the higher altitude. For the 25-percent spooldown, the time required varied from 15 to 35 sec. It is evident from figure 20 that raising the altitude from 3050 m to 10,700 m more than doubles the time to spool down to a given N2.

Figure 21 shows the spooldown time results as a function of airspeed at an altitude of 7600 m. The time required to spool down to 40-percent N2 is only slightly affected by airspeed, but the time to spool down to 25 percent is more strongly affected.

CONCLUDING REMARKS

A series of airstarts was conducted in an F-15 airplane with two prototype F100 engine model derivative (EMD) engines equipped with digital electronic engine control (DEEC) systems. The airstart envelope and time required for airstarts were defined. The success of an airstart is most heavily dependent on airspeed. Spooldown airstarts at 200 knots and higher were all successful. Spooldown airstart times ranged from 53 sec at 250 knots to 170 sec at 175 knots. JFS-assisted airstarts were conducted at 175 knots at two altitudes, and airstart times were 50 sec and 60 sec, significantly faster than unassisted airstart. The effect of altitude on airstarts was small. In addition, the airstart characteristics of the two test engines were found to closely resemble each other. The F100 EMD airstart characteristics were very similar to the DEEC-equipped F100 engine tested previously. Finally, the time required to spool down from intermediate power N2 to a given N2 was found to be a strong function of altitude and a weaker function of airspeed.

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Edwards, California 93523, June 11, 1984

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3. Burcham F.W., Jr.; Myers, L.P.; Nugent J.; Lasagna, P.L.; and Webb, L.D.: Recent Propulsion System Flight Tests at the NASA Dryden Flight Research Center. AIAA Paper 81-2438, Nov. 1981.

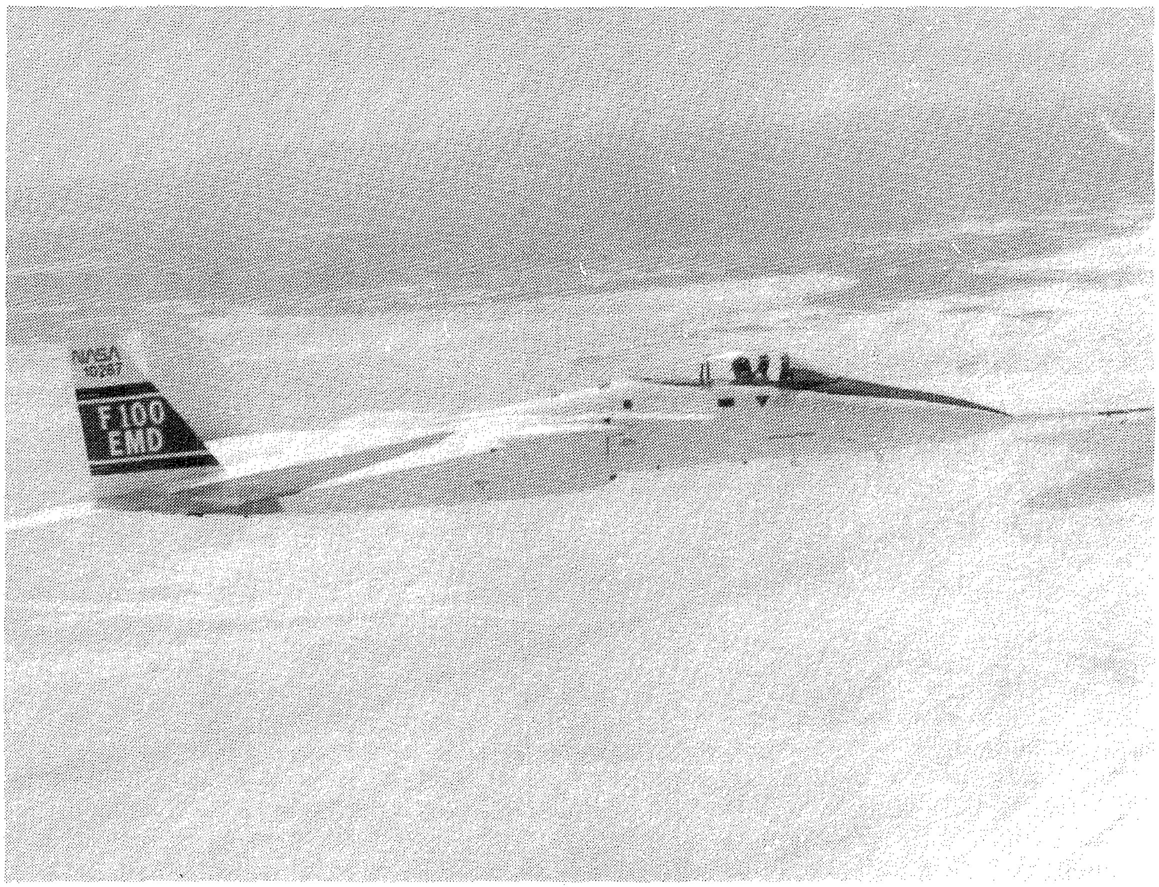

Figure 1. Photograph of the F-15 airplane

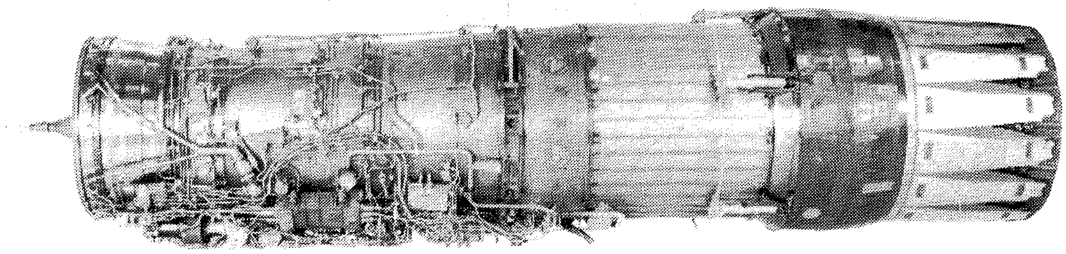

Figure 2. Photograph of the F100 EMD test engine

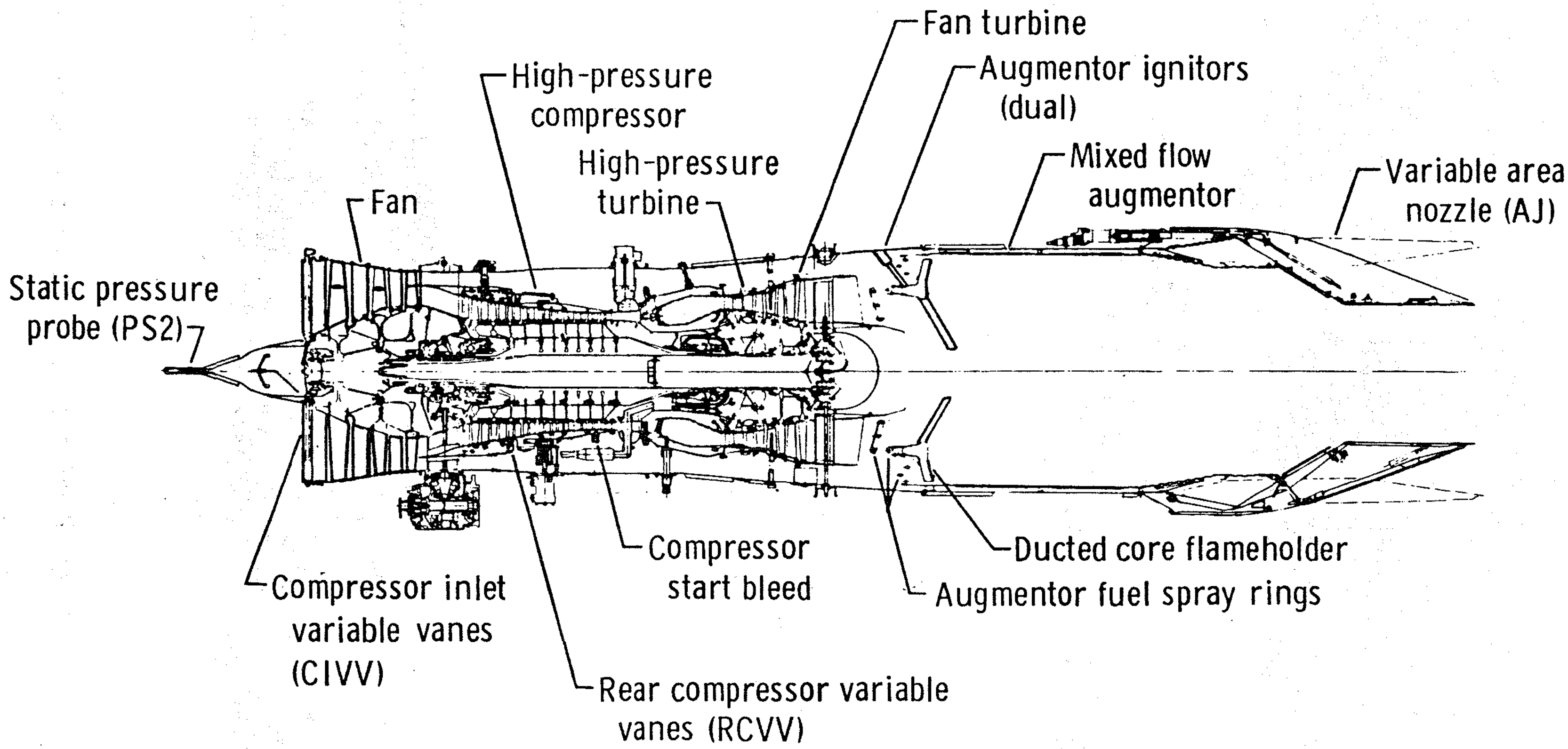

Figure 3. Cutaway view of the F100 EMD engine

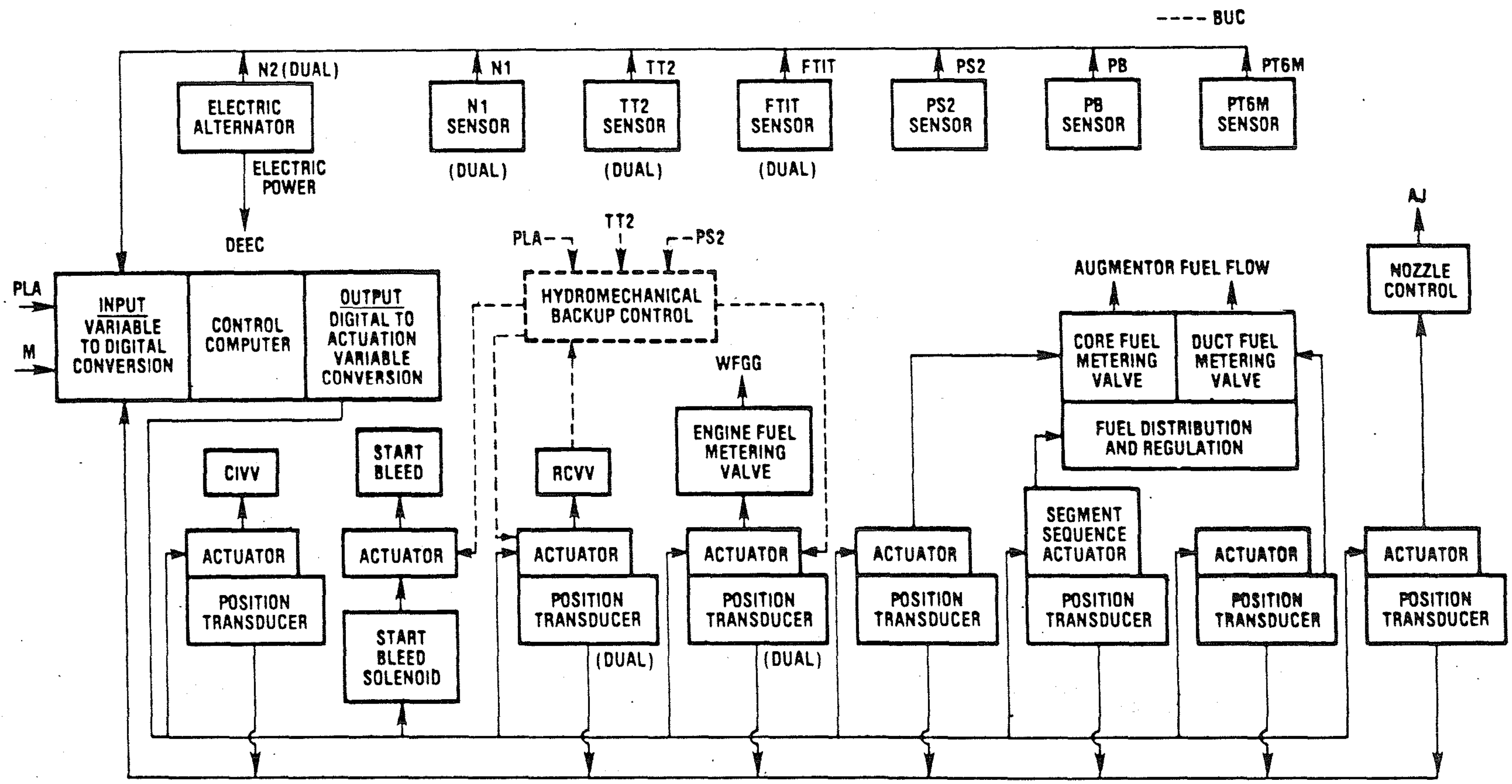

Figure 4. Block diagram of the F100 EMD/DEEC control system

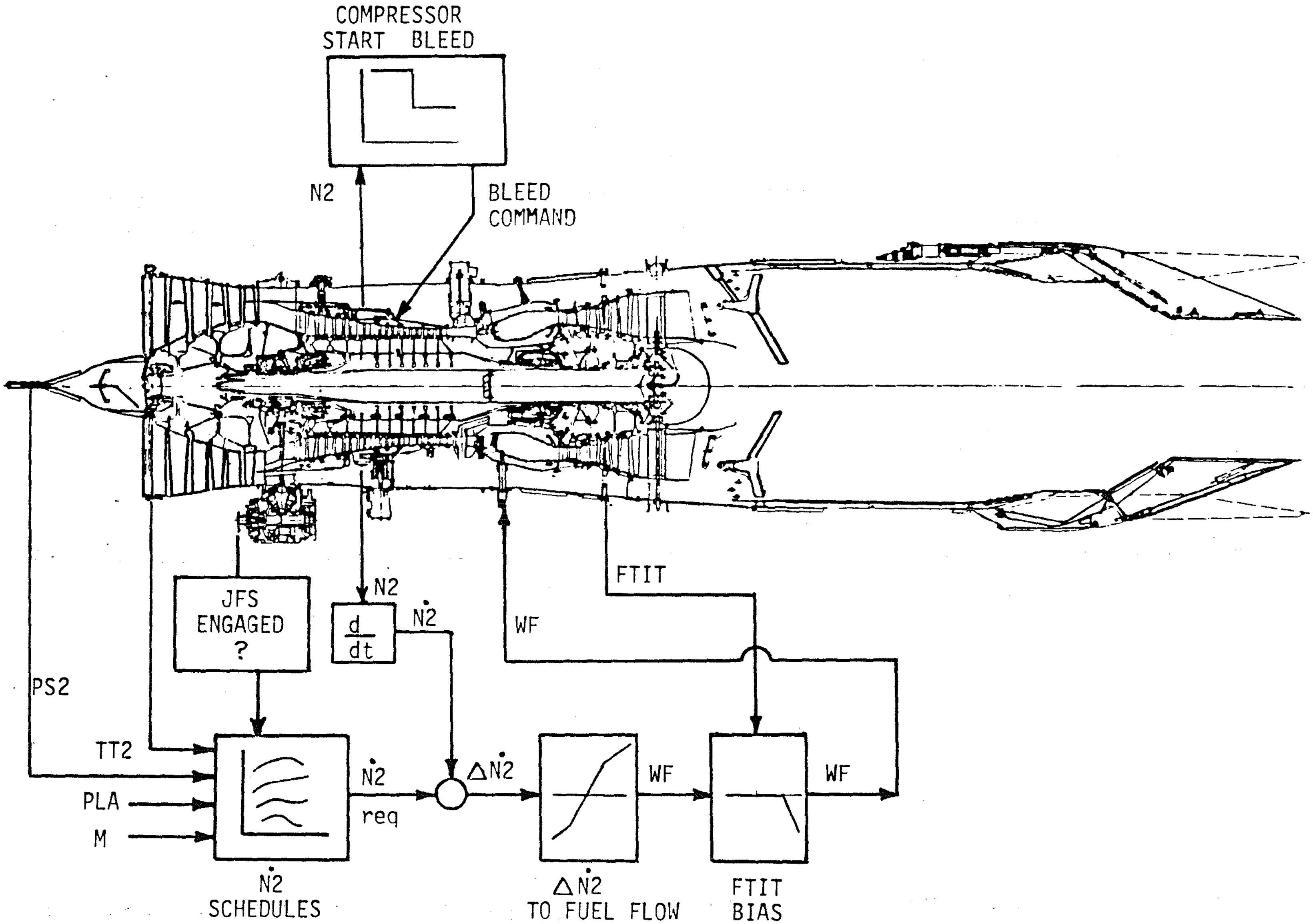

Figure 5. F100 EMD/DEEC airstart logic

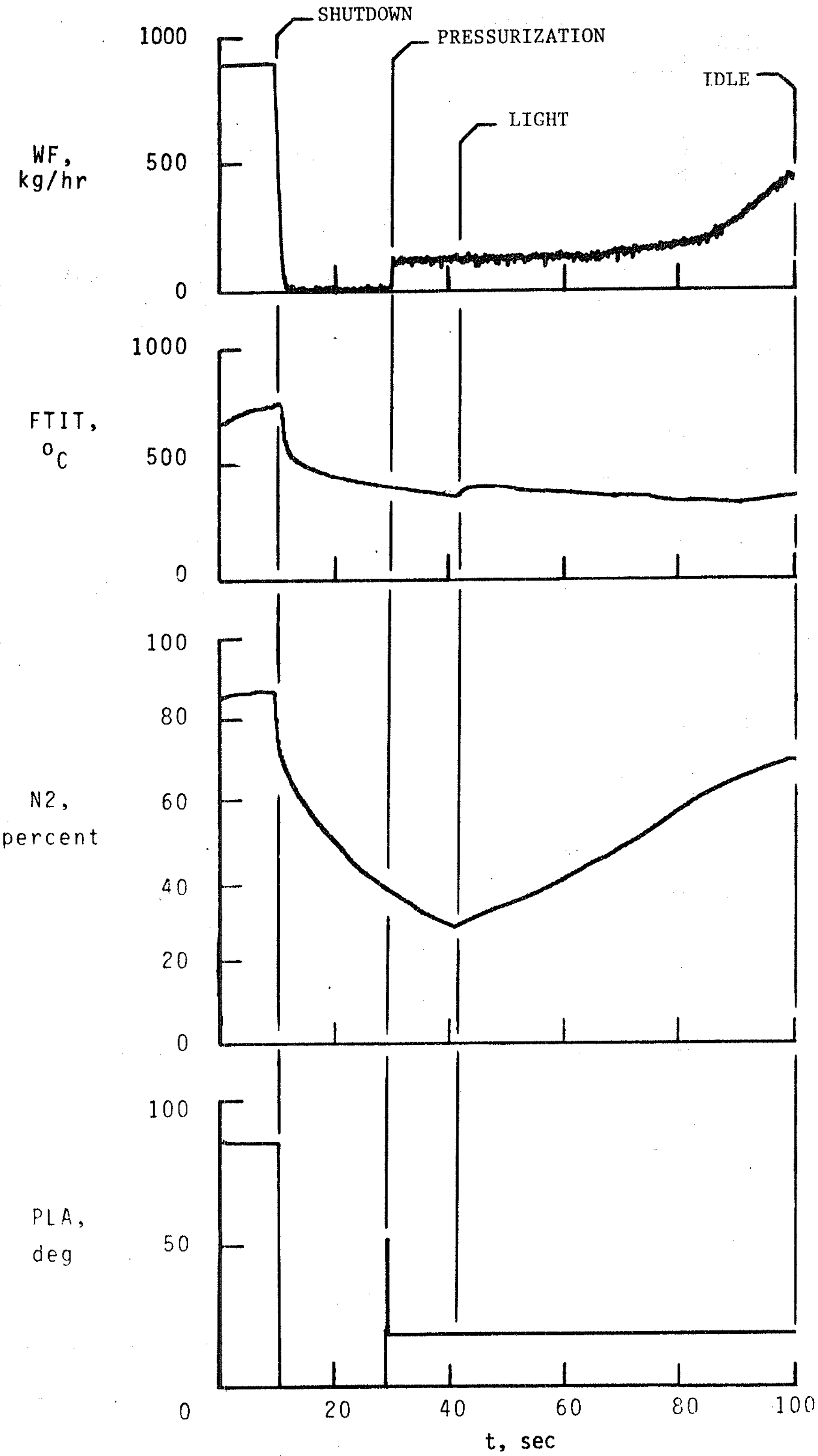

Figure 6. EMD 40-percent spooldown airstart.
VC = 225 knots, HP = 10, 700 m

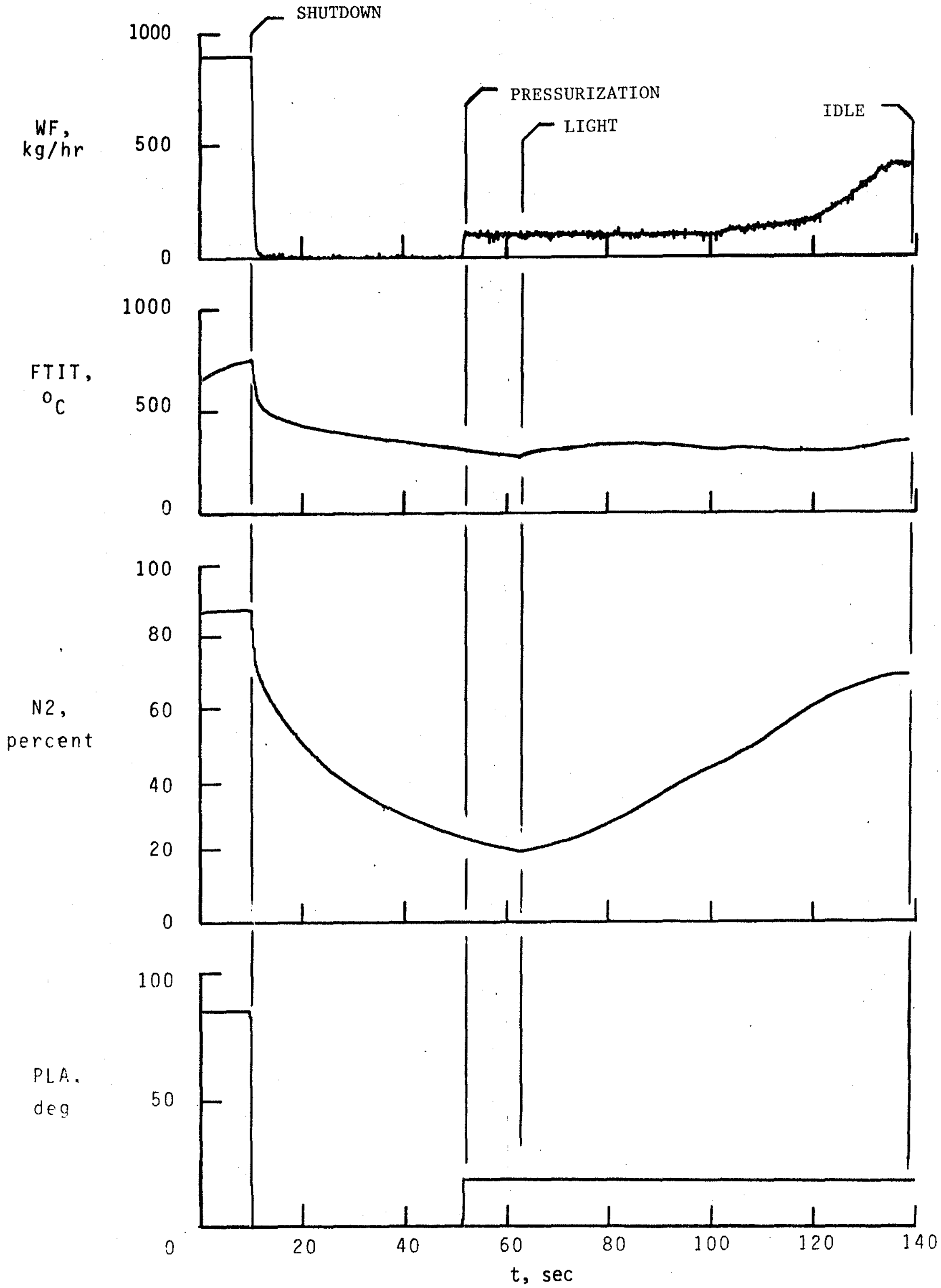

Figure 7. EMD 25-percent spooldown airstart.
VC = 225 knots, HP = 10,700 m

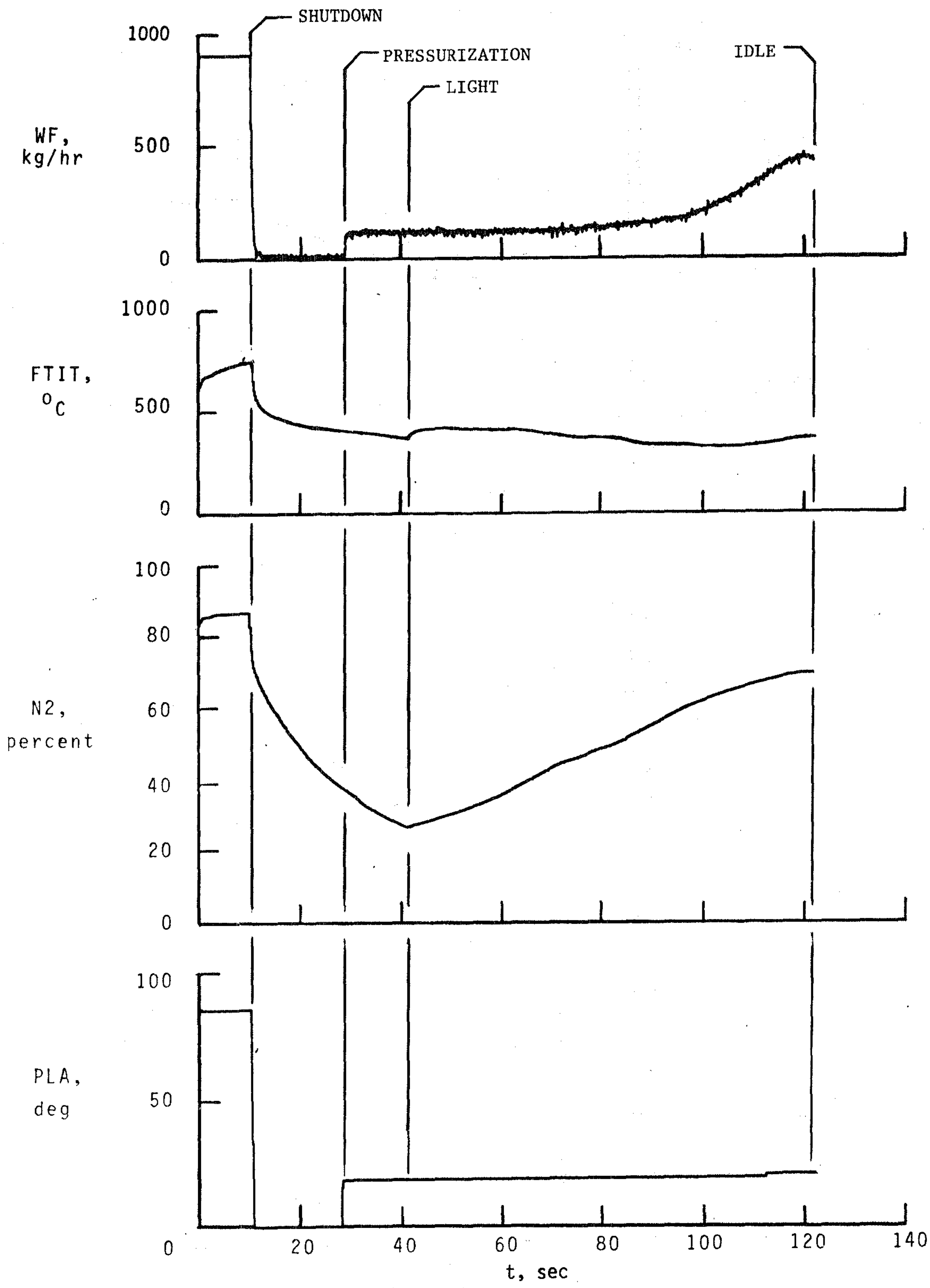

Figure 8. EMD 40-percent spooldown airstart.
VC = 200 knots, HP = 10,700 m

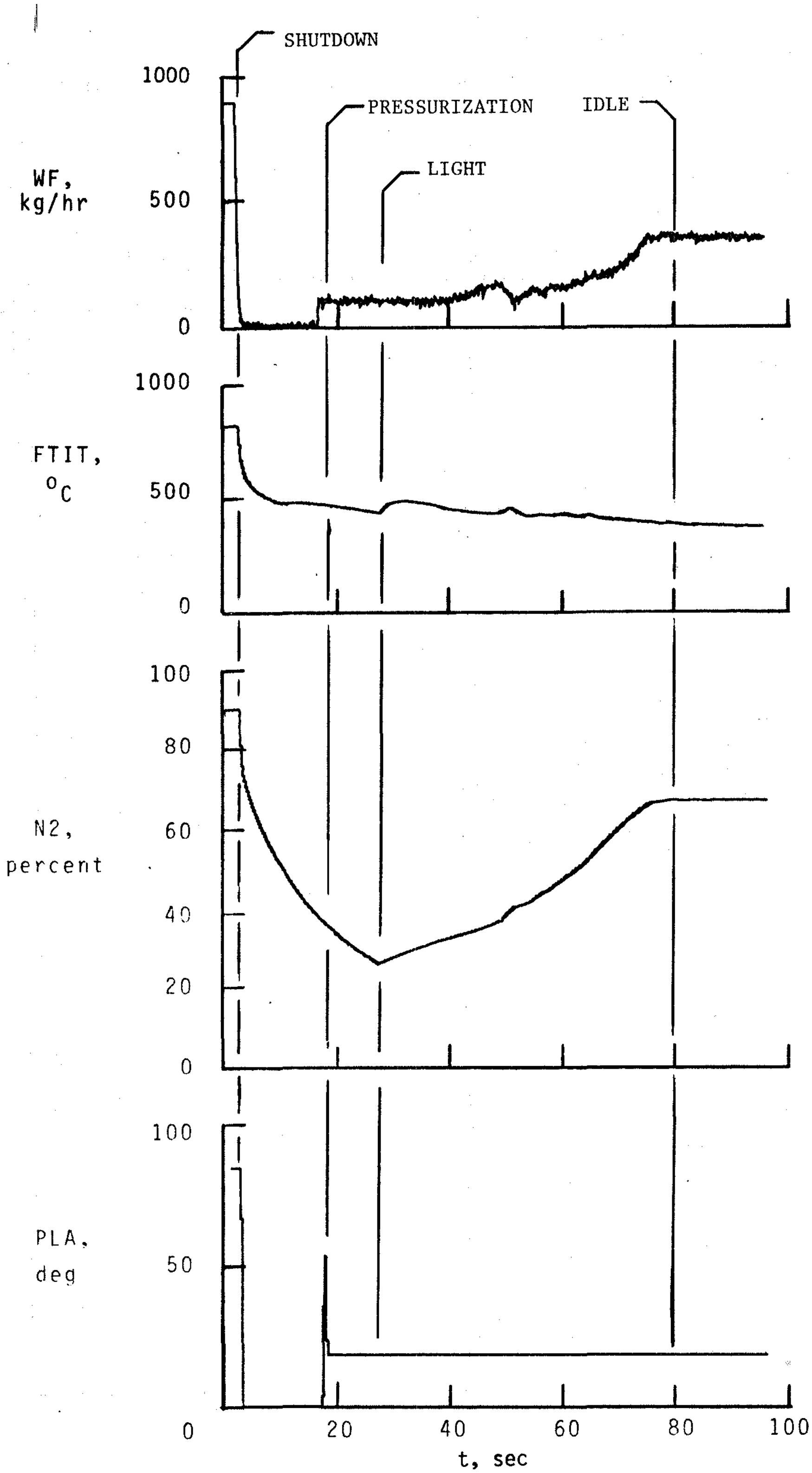

Figure 9. EMD 40-percent spooldown airstart.
VC = 225 knots, HP = 7600 m

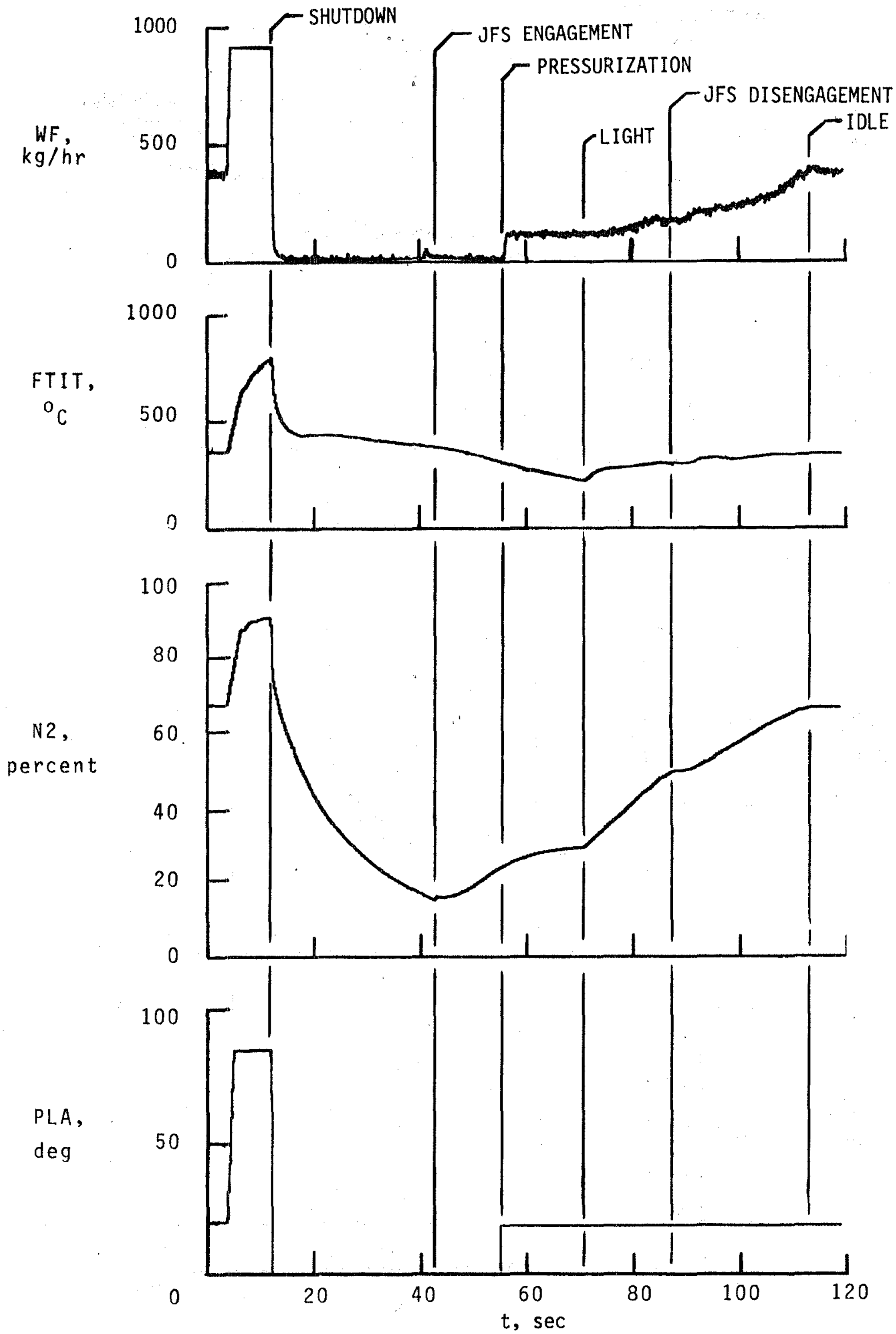

Figure 10. EMD JFS-assisted airstart.
VC = 170 knots, HP = 6100 m

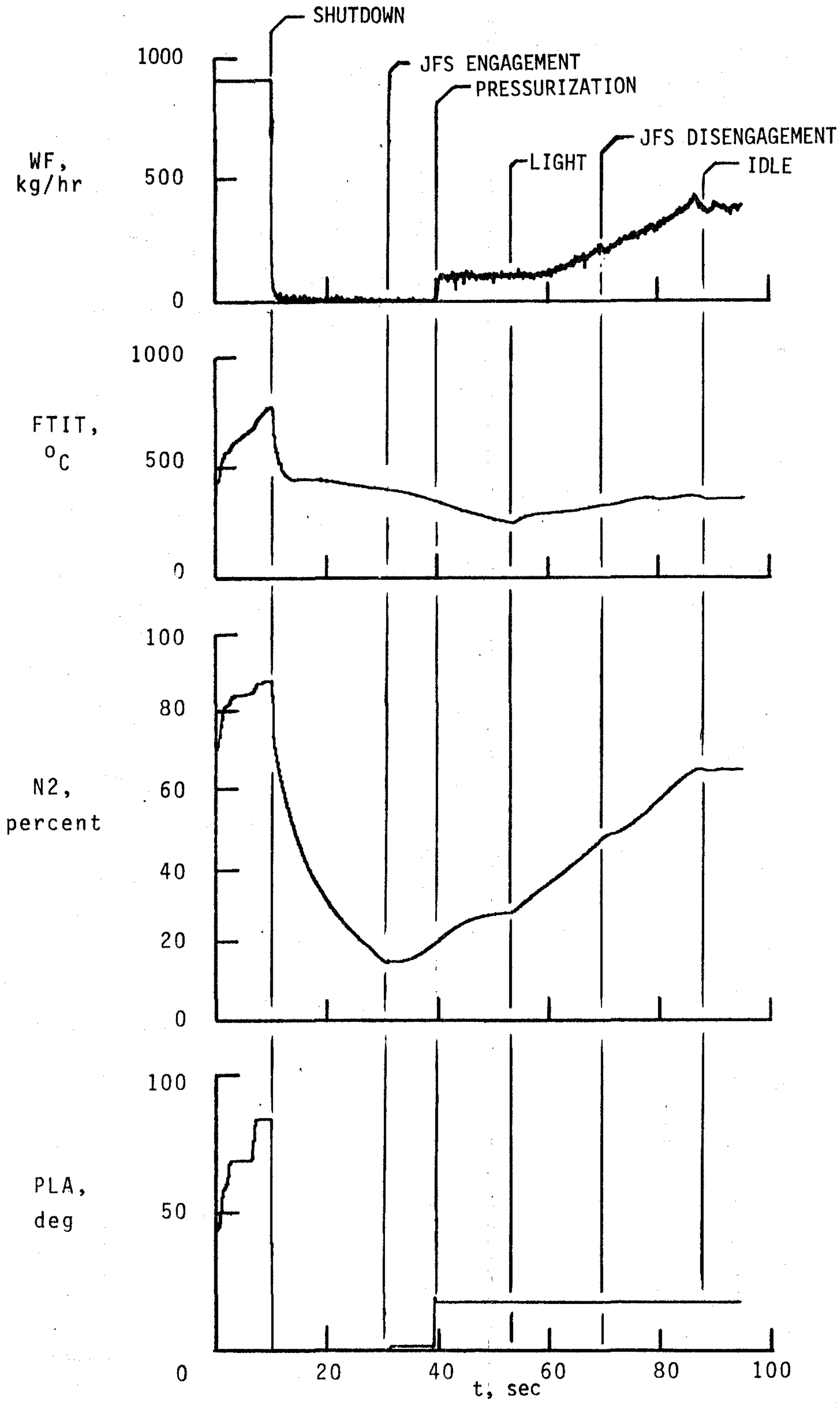

Figure 11. EMD JFS-assisted airstart. VC = 170 knots, HP 3050 m.

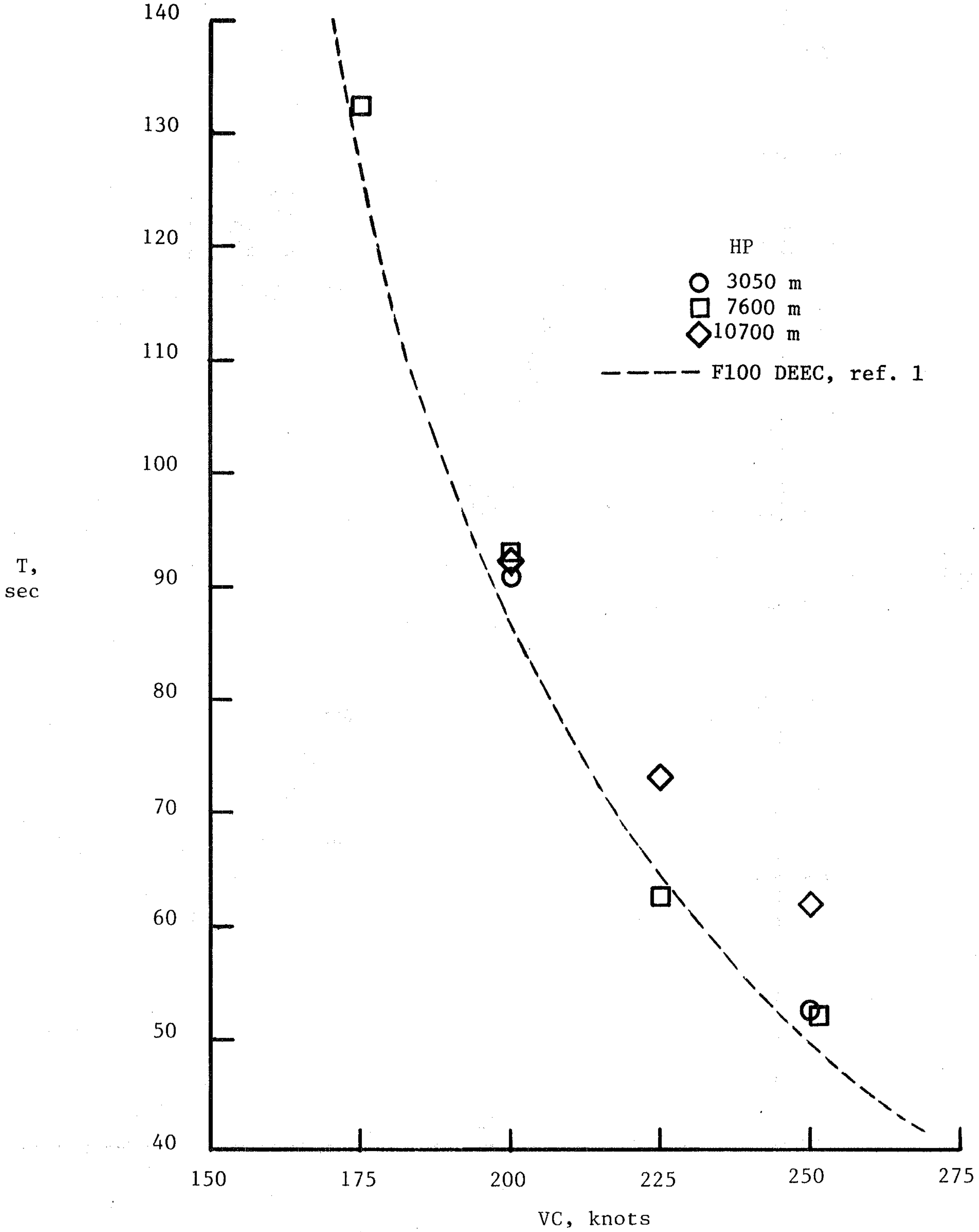

Figure 12. Effect of airspeed on airstart time for 40-percent spooldown airstart.

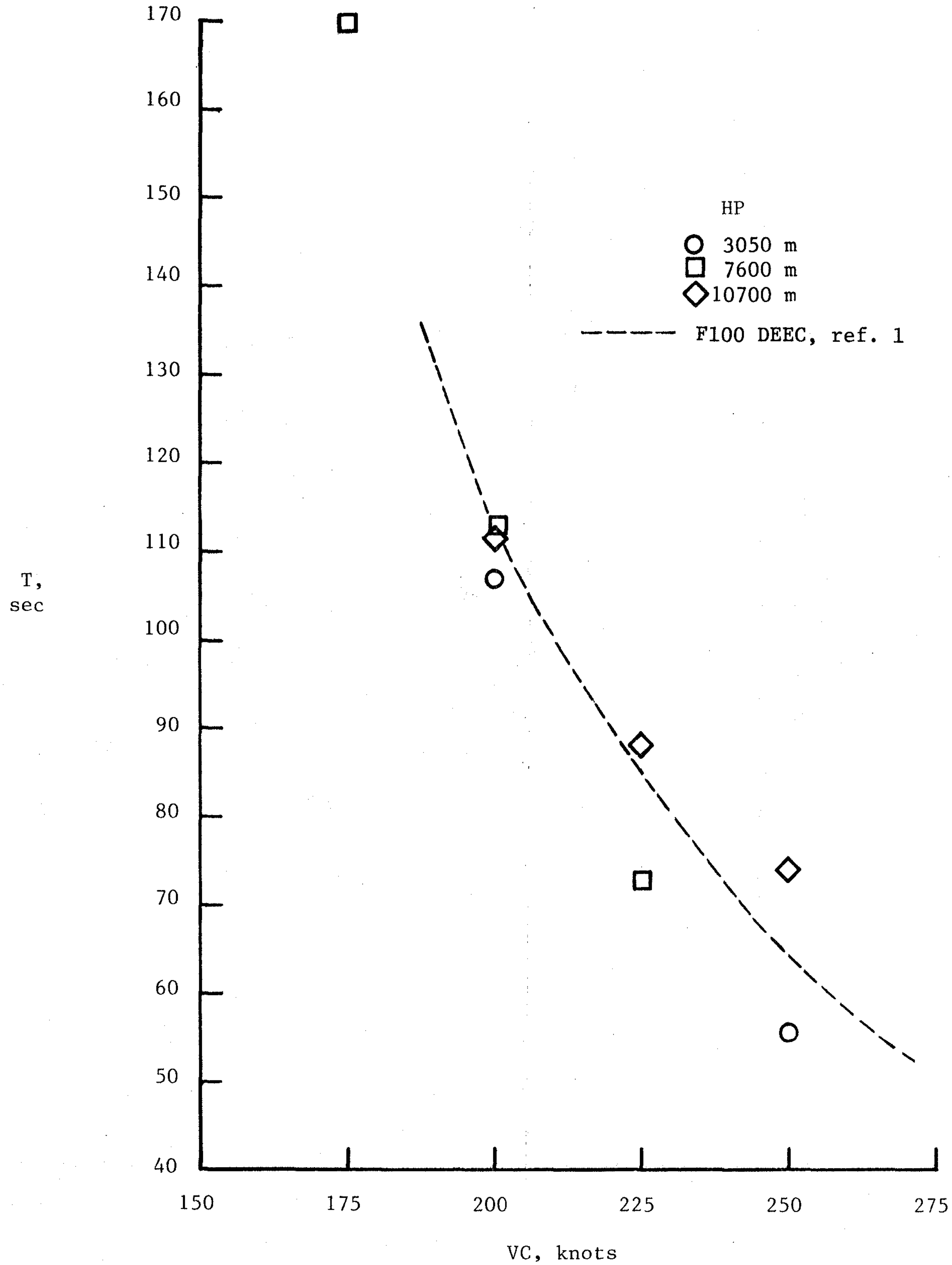

Figure 13. Effect of airspeed on airstart time for 25-percent spooldown airstart.

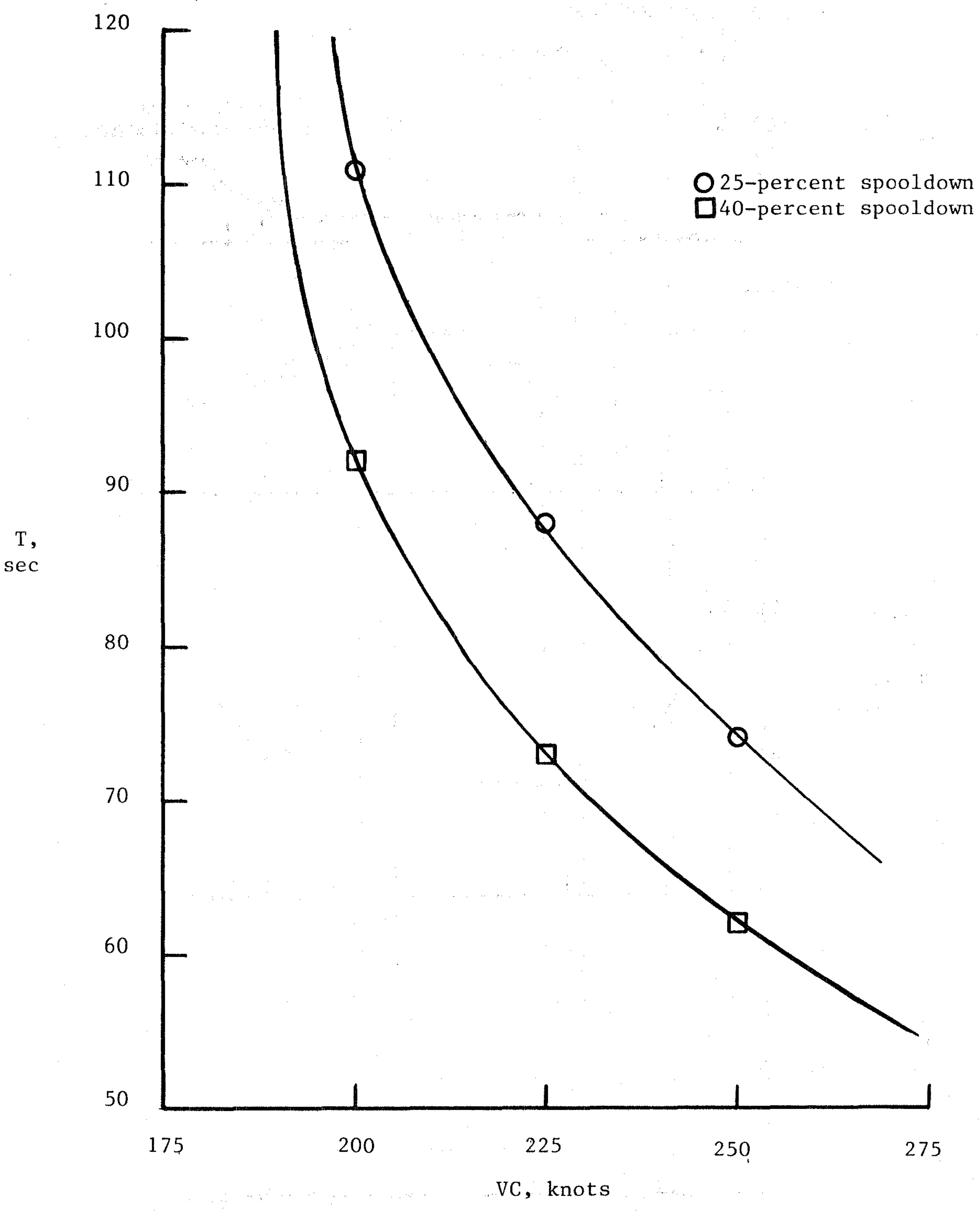

Figure 14. Comparison of 40-percent and 25-percent spooldown airstart times for HP = 10,700 m

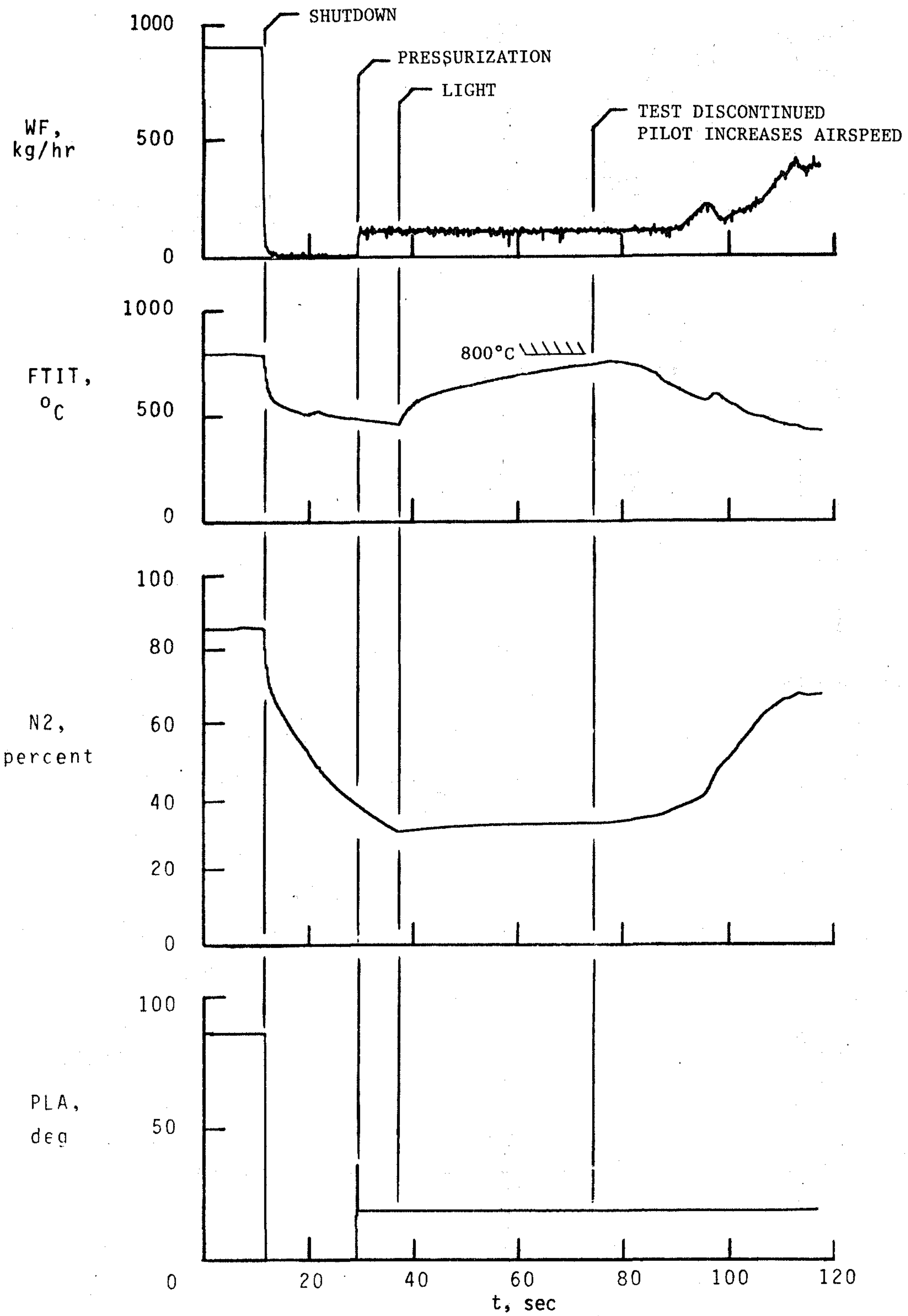

Figure 15. Unsuccessful 40-percent spooldown airstart (hot start). VC = 175 knots, HP = 10,700 m

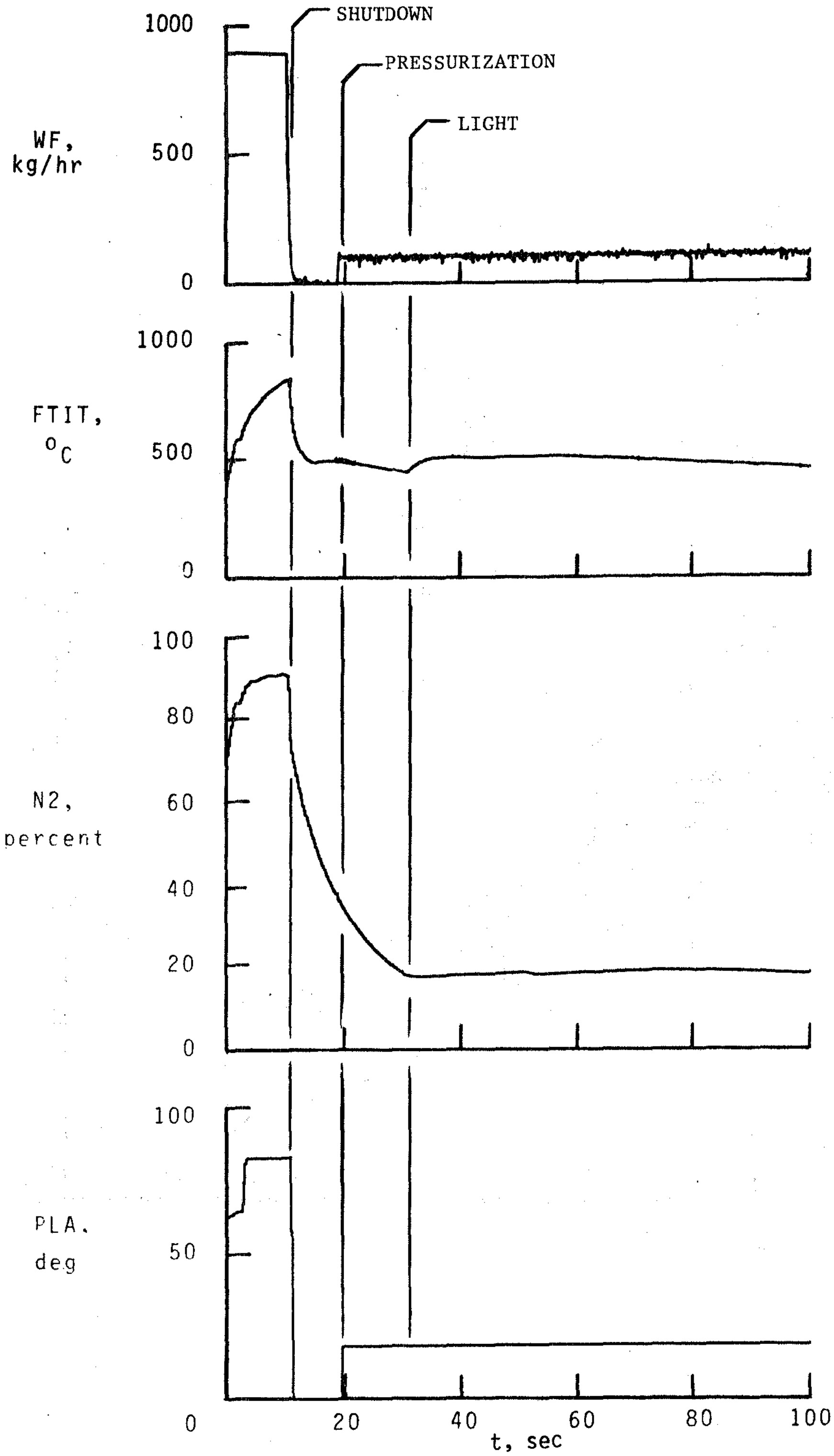

Figure 16. Unsuccessful EMD 40-percent spooldown airstart (hung start). VC = 175 knots, HP = 3600 m

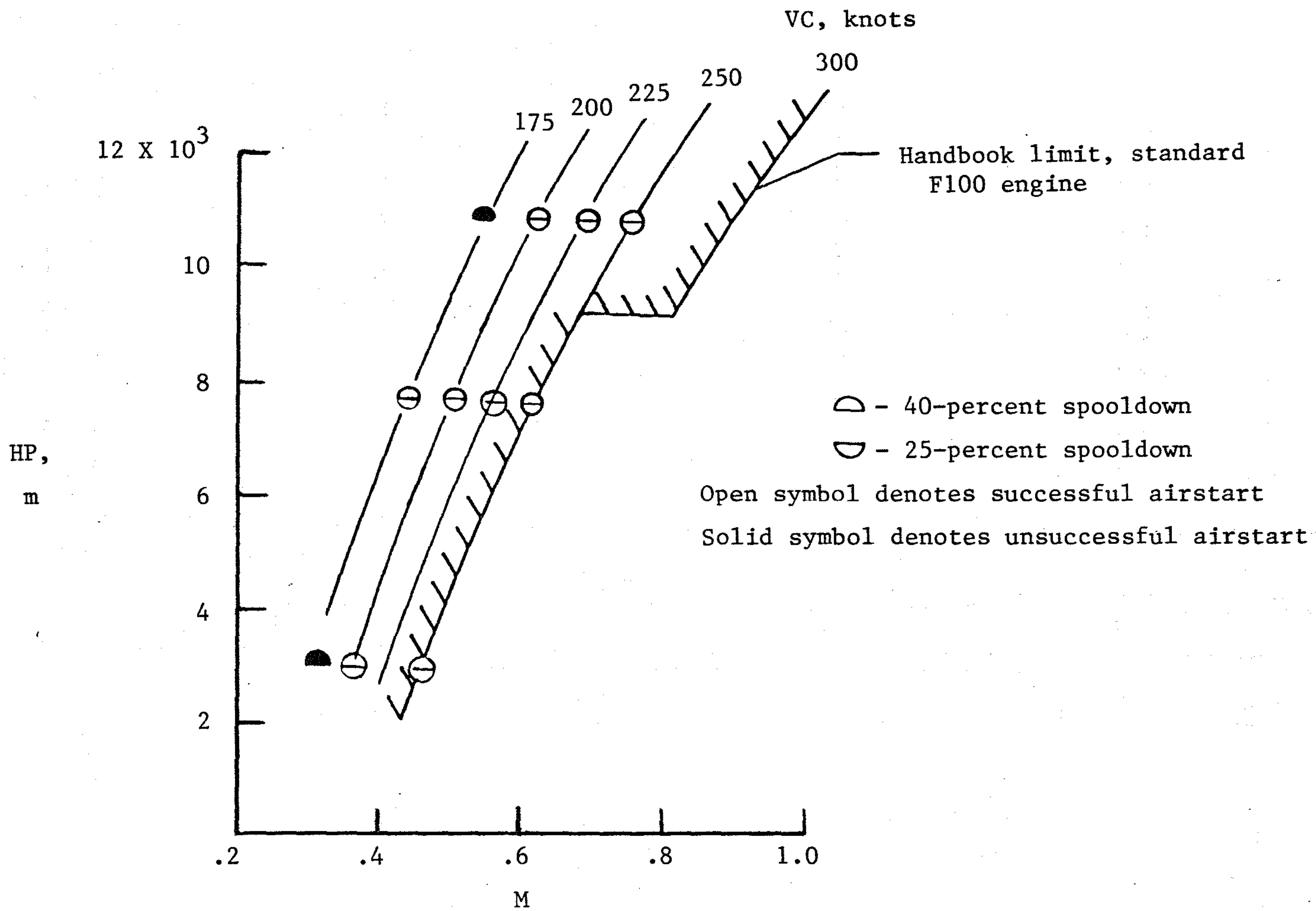

Figure 17. Summary of EMD spooldown test success

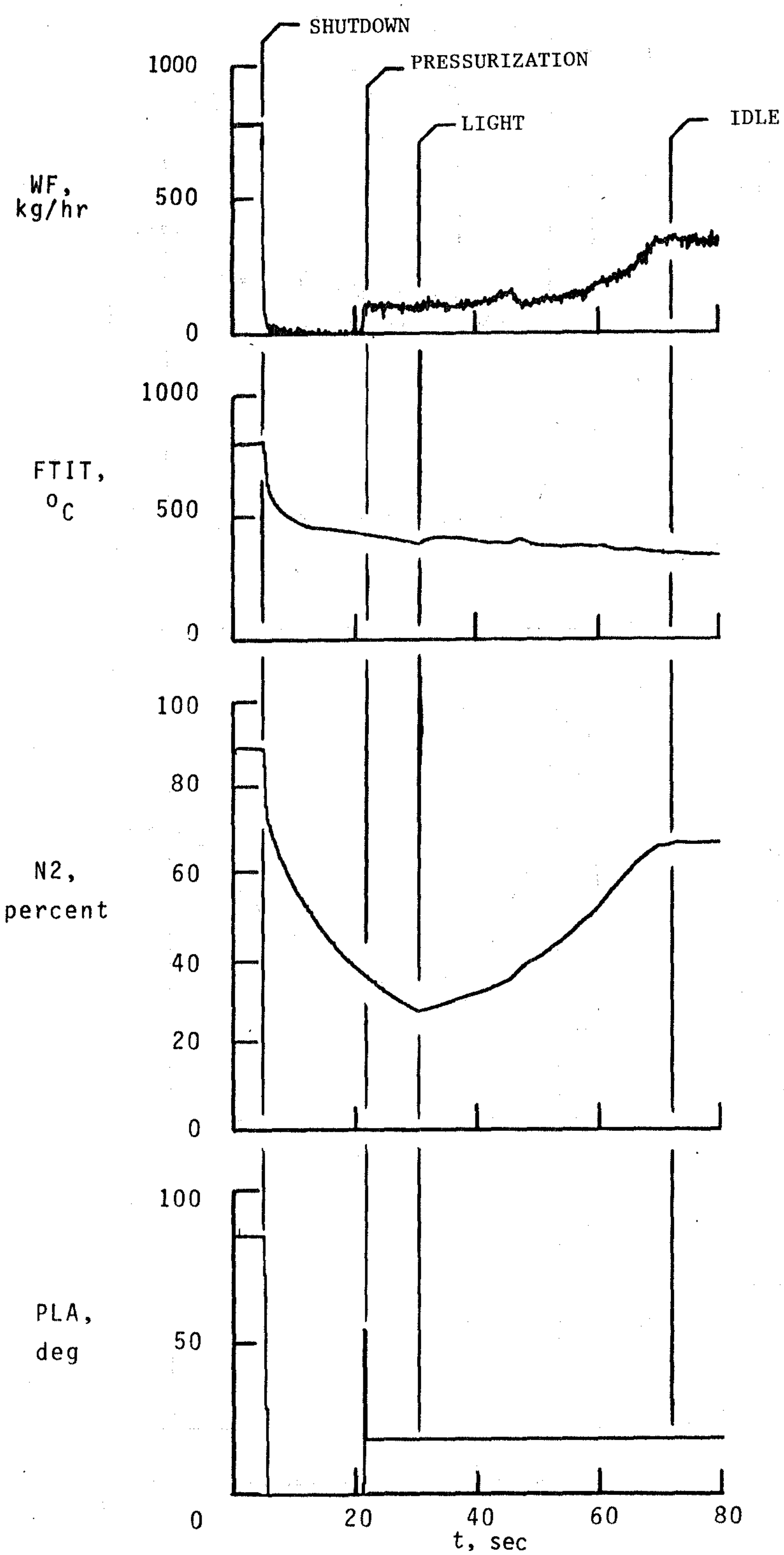

Figure 18. EMD P680350 40-percent spooldown airstart. VC = 250 knots, HP = 7600 m

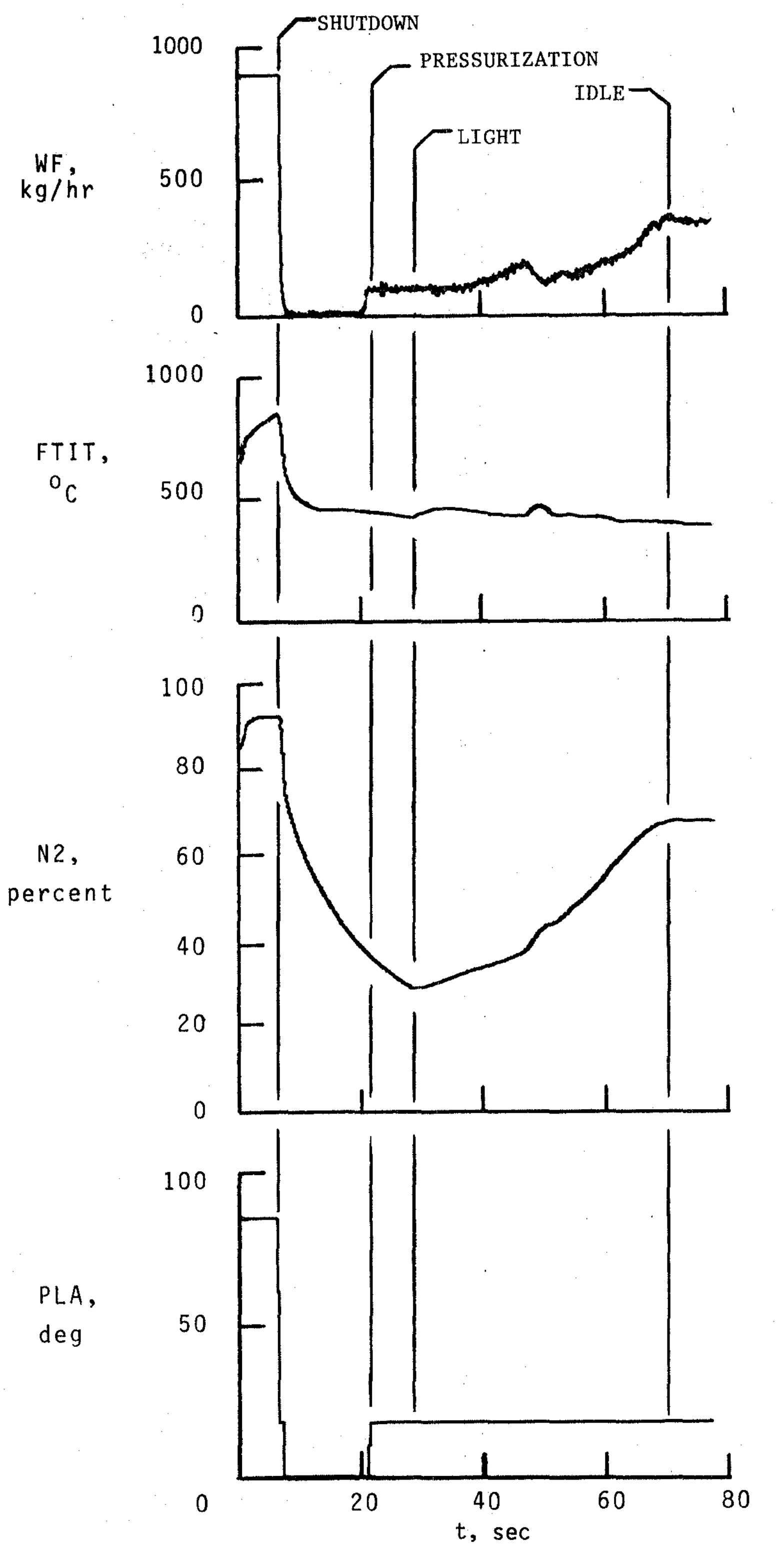

Figure 19. EMD P680585 40-percent spooldown airstart.
VC = 250 knots, HP = 7600 m

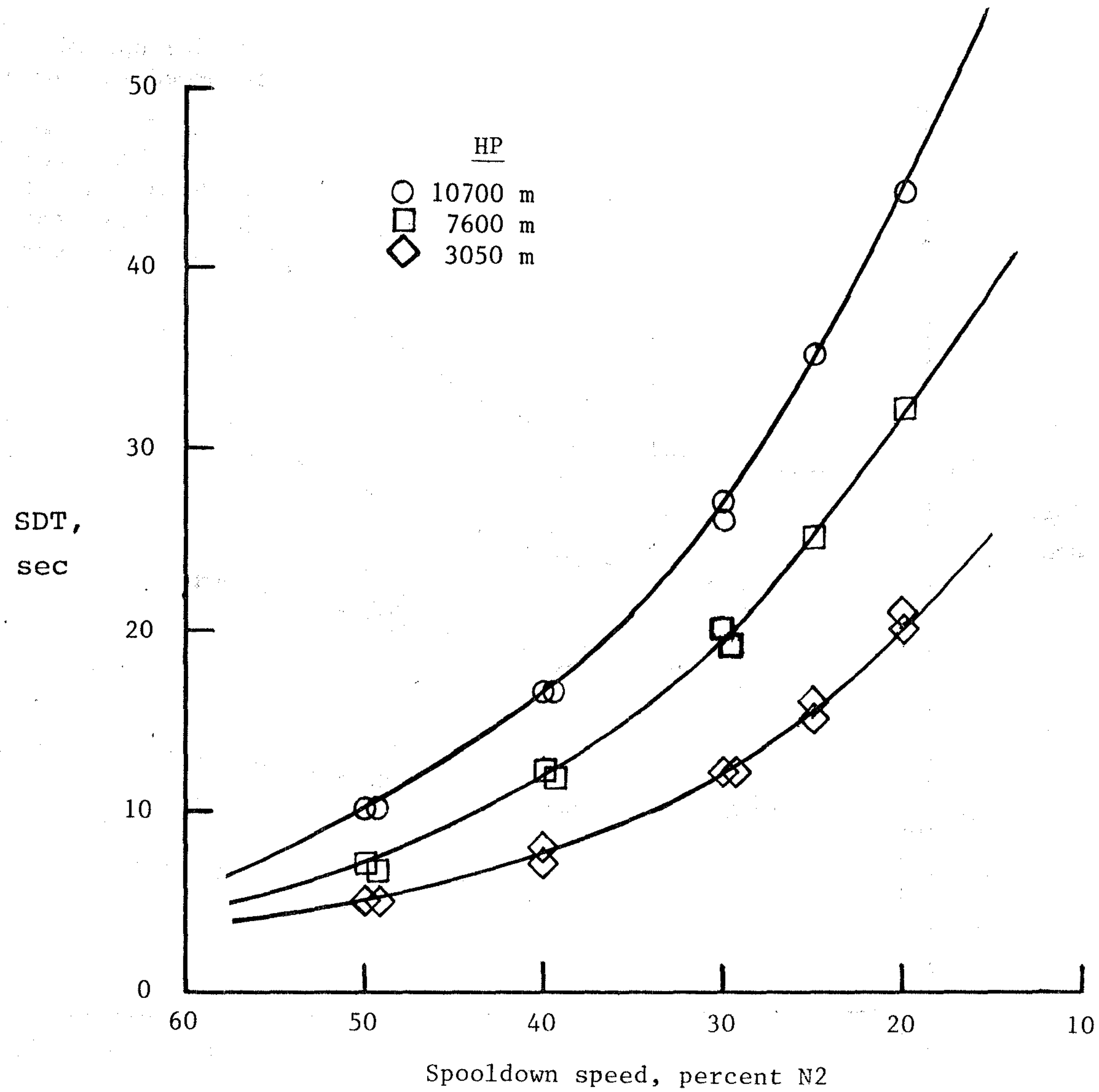

Figure 20. Spooldown times for VC = 200 knots.

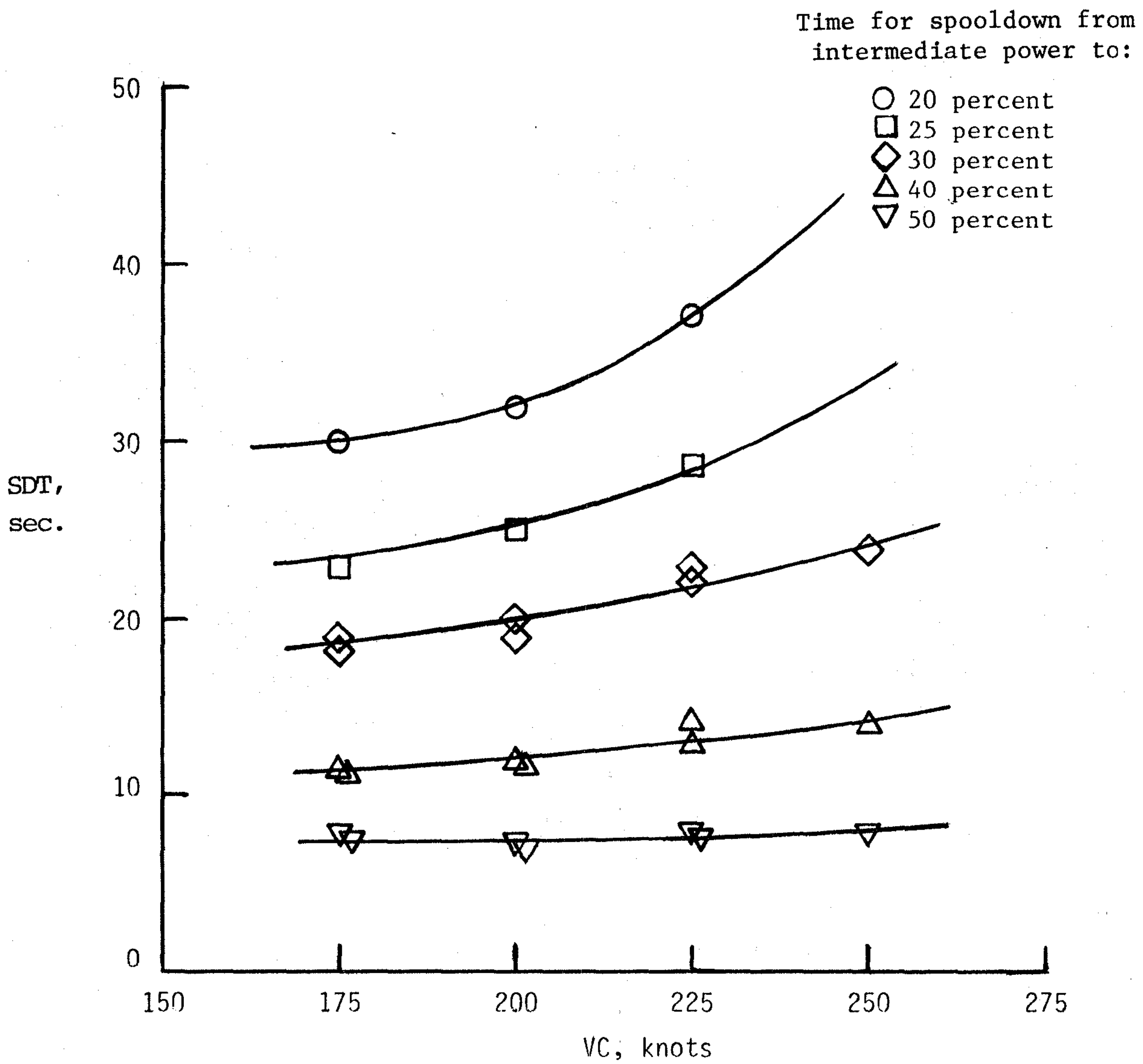

Figure 21. Effect of airspeed on spooldown time.
HP = 7600 m

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15. Supplementary Notes

16. Abstract

A series of airstarts was conducted in an F-15 airplane at the NASA Ames Research Center's Dryden Flight Research Facility with two prototype F100 engine model derivative (EMD) engines equipped with digital electronic engine control (DEEC) systems. The airstart envelope and time required for airstarts were defined. The success of an airstart is most heavily dependent on airspeed. Spooldown airstarts at 200 knots and higher were all successful. Spooldown airstart times ranged from 53 sec at 250 knots to 170 sec at 175 knots. Jet fuel starter (JFS)-assisted airstarts were conducted at 175 knots at two altitudes, and airstart times were 50 sec and 60 sec, significantly faster than unassisted airstart. The effect of altitude on airstarts was small. In addition, the airstart characteristics of the two test engines were found to closely resemble each other. The F100 EMD airstart characteristics were very similar to the DEEC-equipped F100 engine tested previously. Finally, the time required to spool down from intermediate power compressor rotor speed to a given compressor rotor speed was found to be a strong function of altitude and a weaker function of airspeed.

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