The F109-GA-100 Engine Designed Specifically for Trainer Use

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ABSTRACT

The F109-GA-100 (F109) engine, originally developed by Garrett under contract to the U.S. Air Force, is a state-of-the-art powerplant designed specifically for trainer use. The engine has been designed and demonstrated to be fully aerobatic capable, without limitations throughout the training envelope. To minimize student pilot workload, the engine features a full-authority digital electronic fuel control with automatic start and restart, automatic overspeed/temperature-limiting, simple power management with no restrictions in operation and automatic thrust trim. Maintenance features include extensive built-in test and data logging to support effective life management. Designed for an 18,000-hour life to a duty cycle with a mission severity comparable to that of a fighter, the F109 has demonstrated exceptional durability and high reliability. This durability—coupled with excellent fuel efficiency that rivals a turboprop—resulted in extremely low life-cycle-cost (LCC) as demonstrated in accelerated mission testing.

This paper describes the design features of the F109 that establish this engine as a trendsetter for the 1990s and beyond.

F109-GA-100 ENGINE DEVELOPMENT HISTORY

Development of the F109-GA-100 (F109) engine can be traced to the mid-1970s, when Garrett began independent funding of cycle studies, component development, and engine development. Engine sizing at that time was based on retrofitting the T-37B aircraft, which required approximately 1500-pounds (6.67 kN) of thrust per engine. To gain early engine running experience, Garrett funded a program to test a prototype F109 engine (designated the TFE76) which initially ran in November of 1981. All engine systems performed satisfactorily and the predicted thrust and thrust specific fuel consumption (TSFC) were achieved.

Using the TFE76 engine as a baseline, changes were incorporated, as required, to meet U.S. Air Force (USAF) design and performance requirements. The USAF wanted the lowest LCC, requiring low operating and support costs over an 18,000-hour service life, and fuel economy and performance meeting the Air Training Command mission. In July, 1982 Garrett was awarded a full-scale engine development program (FSED) that included unique requirements in two areas. The first involved the implementation of the Engine Structural Integrity Program (ENSIP), making the F109 the first primary propulsion engine to incorporate the ENSIP philosophy from its inception. In addition to providing a more disciplined and complete approach to engine development, ENSIP required significant attention directed at damage tolerance. As a result, the F109 engine was designed to stringent crack propagation criteria, with qualification testing conducted to verify analytically determined inspection intervals. The second unique requirement was the implementation of a three-step qualification program. Endurance testing included use of the actual mission duty cycle, accelerating the damage accumulation, and using reliability/ maintainability/safety and LCC requirements as pass/fail criteria.

During the FSED program, more than 12,700 actual test hours were accumulated on thirteen development and qualification test (QT) engines. Three T-44A aircraft logged 285 flights, accumulating 439 flight hours and 1415 engine hours. The F109 program was successfully concluded with the completion of qualification through initial service release (ISR) and delivery of Lot I production engines.

The key driver for the engine's development was the need for an advanced propulsion capability to specifically meet the demanding requirements of the abusive USAF primary trainer environment. As such, the F109 engine is a leading candidate in the joint USAF/Navy Joint Primary Aircraft Training System (JPATS) competition and is the only modern engine designed specifically for trainer use.

Development of the F109 engine has continued, with the TFE109 commercial family of engines spanning a thrust range of from 1330 to 1600 pounds (5.92 to 7.12 kN). Additionally, the TFE109 was selected for the Squalus aircraft, demonstrating its viability on a single-engine trainer application.

Integrated logistic support packages are available worldwide. The TFE109 engine was developed with strong emphasis on support and maintainability. A complete and up-to-date logistic support analysis, per MIL-STD-1388, is available. Ground support equipment was designed, fabricated, and compatibility verified. USAF Technical Order manuals were written and published, and training aides were designed. Moreover, spare part and provisioning data were computerized to aid further in early receipt of parts for timely customer support.

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ENGINE DESCRIPTION

Component Arrangement

The Garrett F109 engine, shown in Figure 1, is a twin-spool, nonaugmented, fixed geometry, medium-bypass-ratio (5:1) turbofan engine. The engine configuration includes a single-stage fan driven by a two-stage axial low-pressure (LP) turbine, and a high-pressure (HP) compressor driven by a two-stage axial turbine through a shaft that is concentric with the LP rotor shaft. The first-stage turbine stator and rotor are internally air-cooled. The combustor is an annular, reverse-flow design incorporating piloted airblast fuel nozzles.

Figure 1. F109 Design Combines High Performance With Excellent Durability.

In keeping with USAF requirements, the engine was designed to operate at a gyroscopic moment up to 3.5 rad/sec at maximum engine power. The HP spool, therefore, is straddle-mounted to minimize rotor deflections caused by gyroscopic moments. Dual bearing systems on the front and aft end of the LP spool provide the support for the cantilevered fan and LP turbine. This arrangement provides the engine with the ability to withstand loading from severe aerobatic aircraft maneuvers.

An accessory drive gearbox, driven by the HP spool, is located on the bottom of the engine, with provisions for mounting engine and airframe accessories. The gearbox-mounted permanent magnet generator provides primary power for the ignition system and the electronic fuel control unit (EFCU).

The lubrication system is fully self-contained and capable of operating with MIL-L-7808 (or MIL-L-23699) oil at ambient temperatures of 125°F (51.7°C). As a result, the engine incorporates two air/oil coolers in addition to a fuel/oil cooler.

Both HP and LP customer bleed air is available.

To simplify maintenance, we designed the engine as a modular assembly that can be easily replaced at the intermediate maintenance level.

Electronic Fuel Control Unit

The engine is controlled by a remotely mounted EFCU and an engine-mounted hydromechanical fuel metering control. The design functionally separates the EFCU into two essentially independent sections: a fuel control section and a monitoring and communications section. Each section is controlled by a single microprocessor.

The control software features are:
- "No-trim" for automatic thrust maintenance
- Automatic ignition, start, and blowout/restart
- Accurate acceleration and blowout fuel schedules
- Spool-speed and temperature-limiting
- Linear thrust relationship and unrestricted power-lever motion without "dead travel" for all flight conditions
- Automatic fuel specific gravity adjustment
- Automatic switch to hydromechanical backup mode in event of critical faults

Built-in-test features include:
- Computer, sensor, and output faults
- Selective fault accommodation
- Intermittent fault logging
- Fault history maintenance
- Fault isolation to line-replaceable units (LRUs).

The monitoring section of the EFCU circuitry contains the non-fuel-control-related requirements. These ancillary features include:
- Data logging
- Performance trend monitoring
- Airborne data recorder output
- Automatic standard data collection unit interface

Design Criteria

We designed the F109 engine to meet the mission severity of a a fighter aircraft, with the extended life requirements of a transport. Figure 2 defines the design mission duty cycle. This cycle, based on T-37B aircraft flight surveys, requires a total of 20 percent time at maximum power and 2.9 tactical aircraft cycles (TACs) per hour. The mission severity, as shown in Figure 3, is comparable to a typical fighter mission.

In contrast to a typical fighter engine, the F109 engine was developed for a design life of 18,000 hours for the cold engine components and 9,000 hours for the hot engine components (i.e., those in contact with the hot gas stream). The combination of the USAF design duty cycle and 18,000 hours lifetime
resulted in 14,550 zero-max-zero power excursions and 148,800 idle-max-idle power excursions, or an equivalent of 51,750 TACs.

The F109 engine durability and structural safety are controlled by the implementation of Military Standard 1783, ENSIP. ENSIP resulted from the combined efforts of the USAF and industry to establish an updated engine development specification.

ENSHIP is an organized and disciplined approach to the design, analysis, development testing, quality assurance, and life management of an engine. The benefits of ENSIP are many:
- Rigorous design validation and verification
- Higher engine maturity at production
- Improved reliability/durability/availability
- Unparalleled safety
- Lower operating costs.

A key element of ENSIP is application of damage tolerance as a basic design concept, which adds the consideration of inherent and induced defects in fracture-critical components to traditional durability considerations.

Performance and Operability

The F109 engine cycle resulted from extensive trade-off studies. These studies were aimed at minimizing TSFC at part-power conditions consistent with thrust requirements.

Review of the various Air Force training missions resulted in selection of the design-point flight condition as maximum-continuous power at 25,000 feet (7.620 km), Mach 0.35, ISA. Single-engine aircraft rate-of-climb requirements at 5,000 feet (1.52 km), Mach 0.192, 100°F (37.8°C) day conditions required a contingency power rating (CPR) which automatically boosted engine power by 8 percent in the event that one engine became inoperative.

The F109 engine boasts a sea-level, ISA, maximum power, minimum performance engine TSFC of 0.396 lb/hr/lb [11.22 (mg/S)/N], putting the engine in a class by itself.

Unlike commercial engines, which restrict operation at maximum power and maximum climb, the F109 has no such restrictions.

F109 performance and operability were verified at the Arnold Engineering Development Center (AEDC) as part of the USAF QT program.

The engine flight envelope, start envelope, and qualification test conditions are illustrated in Figure 4. Testing determined performance, engine stability, and acceleration/deceleration times at these rating points. In addition, functional tests, which consisted of steady-state and transient characteristics at the extremities of the operating envelope, with and without inlet distortion, were demonstrated. Finally, start and restart capabilities, and CPR for one-engine-out operation were demonstrated.

The following altitude characteristics were demonstrated:
- Performance - F109 fuel consumption was better than the specification model at maximum power. Measured turbine interstage temperature (T4.5) met all requirements.
- Operability - Operability is reviewed in three categories: functional operation, starting, and contingency power operation.
  - Functional Operation - All steady-state and transient operation throughout the flight envelope was successful in automatic mode (electronic control), as shown in Figure 5.
  - Starting Operation - Manual-mode (back-up control) was demonstrated to be a safe mode of operation. Manual-mode operation is unrestricted.
  - Contingency Power Operation - Automatic mode tested at the operating conditions, as shown in Figure 6. Throughout the flight envelope, the engine demonstrated surge-free and unrestricted throttle movement at all test conditions. Surge schedules were developed from results of prior tests where compressor surges were intentionally induced to define the compressor surge line at different altitude conditions.

Worst-case inlet distortion screens were tested at the operating conditions, as shown in Figure 6. Throughout the flight envelope, the engine demonstrated surge-free and unrestricted throttle movement at all test conditions. Surge schedules were developed from results of prior tests where compressor surges were intentionally induced to define the compressor surge line at different altitude conditions.

Manual-mode (back-up control) was demonstrated to be a safe mode of operation. Manual-mode operation is unrestricted.
except for operation during maximum power hot-day conditions, which may require the pilot to manually adjust power lever angle (PLA) to maintain interturbine temperature (T4.5) below redline limits. Manual-mode operation provides at least 90 percent maximum auto mode thrust.

- Starting - All JP-4 and JP-5 auto-mode and manual-mode altitude starts were successful with simulated cross-bleed temperature (T4.5) and bleed controls. The engine also demonstrated automatic restart capability. The F109 start test results are summarized in Figure 7.

**COMPONENT QUALIFICATION TESTING**

Component qualification tests were performed to verify the environment in the engine under steady-state and transient conditions and to verify damage tolerance and durability. These tests are summarized in the following paragraphs.

A fan foreign object damage (FOD) test was run to verify the ability of the fan rotor assembly to continue operation following FOD. This test cycle consisted of six 1-hour cycles to demonstrate high-cycle-fatigue capability at the resonant points of the fan, where maximum dynamic loads occur. These conditions induced no vibratory stress cracking or failure.

Other tests, such as the large bird ingestion test and airfoil containment tests, verified the engine’s ability to contain internal damage without causing damage to the airframe.

Damage-tolerance tests were conducted on both rotating and static ENSIP critical components to verify the adequacy of the ENSIP inspection intervals, which were based on analytical predictions. Flaws were machined into the high stress regions of the components, and the engine operated by cyclic loading. The predicted crack growth rates and test data were in excellent agreement. Prior to component testing, a total of 122 test specimens were machined from component forgings and were tested to investigate the effects of mission loading, geometric features, stress fields and gradients, residual stress, and temperature on cyclic crack growth rates. Engine damage-tolerance testing of the second-stage HP compressor impeller and first-stage HP turbine disk verified crack growth rate predictions in an engine accelerated mission endurance test environment. Again, crack growth test data correlated well with analytical predictions.

Whirlpool low-cycle-fatigue (LCF) and static component load tests were run to verify structural integrity. LCF testing verified that LCF life-limiting components could successfully complete one full mission life without cracking. Static load tests were completed on all engine static components and demonstrated the absence of permanent deformation under limit loading and no structural failure at ultimate loads (1.5 times limit loads).

Lubrication system components were tested in an attitude rig to demonstrate the integrity of the lubrication system at various attitudes that may be experienced in flight. The test rig utilized the complete engine lubricating system and related components, including supply and scavange pumps, oil reservoir, oil coolers, main rotor shafts, bearings, accessory gearbox, tower shaft, oil seals, and interconnecting plumbing. The rig was externally powered with the speeds, oil temperatures, bearing thrusts, and seal buffering pressure controlled to required engine conditions. A total of 12 test points were completed at various attitudes and times of operation. All operating conditions remained within the specified limits. Posttest inspection revealed no evidence of mechanical or impending damage that could affect engine life or operation.

Engine controls and accessories component tests verified structural and operational characteristics of these components. The EFCU successfully underwent various endurance tests and demonstrated full operational capabilities following environmental tests. These included exposure to humidity, sand, dust, sustained acceleration, impact, vibration, salt/fog, and electromagnetic interference (EMI). Fire tests were successfully completed for the oil tank, hydro-mechanical fuel control, fuel pump, fuel flow divider, oil coolers, and lubrication system.

**ACCELERATED MISSION TESTING (AMT) ENGINE TESTS**

The F109 engine was qualified to the USAF AMT requirements, an innovative approach in engine development. AMT has several unique facets. These include:

- Contingency Power Rating - The engine demonstrated the required 8 percent thrust increase for one-engine-out operation at the 5,000 feet (1.52 km), Mach 0.192, 100°F (37.8°C) ambient temperature condition. The electronic control automatically provided CPR during engine-out conditions and with aircraft wheels down and locked. In addition, when CPR is commanded, idle HP speed was raised to allow the running engine to carry the additional aircraft loads.

- Component qualification tests were performed to verify the environment in the engine under steady-state and transient conditions and to verify damage tolerance and durability. These tests are summarized in the following paragraphs.

- Damage-tolerance tests were conducted on both rotating and static ENSIP critical components to verify the adequacy of the ENSIP inspection intervals, which were based on analytical predictions. Flaws were machined into the high stress regions of the components, and the engine operated by cyclic loading. The predicted crack growth rates and test data were in excellent agreement. Prior to component testing, a total of 122 test specimens were machined from component forgings and were tested to investigate the effects of mission loading, geometric features, stress fields and gradients, residual stress, and temperature on cyclic crack growth rates. Engine damage-tolerance testing of the second-stage HP compressor impeller and first-stage HP turbine disk verified crack growth rate predictions in an engine accelerated mission endurance test environment. Again, crack growth test data correlated well with analytical predictions.

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The modular design of the F109 engine results in ease of servicing and maintenance. The engine was designed for on-condition maintenance using a reliability-centered maintenance analysis (MIL-STD-1843). Engine health parameters, required to support the on-condition maintenance concept, were recorded by the EFCU. Engine parts were designed to fit-and-function, with new parts for up to a lifetime of use.

As part of the FFR qualification program, the F109 engine underwent a two-phased maintainability demonstration.

The goal of Phase I was to verify the requirements of the prime item development specification with demonstrated maintenance man-hours per task applied to required action frequencies. Its specific objectives were:

- To demonstrate the time and procedures needed to assemble and disassemble the engine, including removal and replacement of engine modules and engine components
- To demonstrate the suitability of field support equipment, maintenance tooling, and fixtures
- To demonstrate engine technical manual procedures, including removal and replacement of frequently removed components

Accurate timing of all maintenance actions during the demonstration test verified that all maintenance requirements were successfully met.

The requirement for a 2.5-hour mean-time-to-repair (MTTR) at the organizational maintenance level was successfully demonstrated. A maximum-time-to-repair (MAX TTR) of 5.0 hours at the 90th percentile and the requirement for maintenance man-hours per engine flight hour (MMH/EFH) of 0.173 was also successfully demonstrated.

Tasks performed during the demonstration verified that F109 maintainability features were adequate for frequently removed service items, component and module replacement, and engine disassembly and reassembly.

After completion of the maintenance demonstration, engine performance, vibration, and thermal characterization tests were conducted, followed by a demonstration of several engine transients.

A Phase II demonstration test was conducted to demonstrate EFCU fault detection and isolation to the LRU level, including all organizational replaceable units not tested under Phase I.

A minimum of one simulated fault per LRU was demonstrated. Failures were simulated sequentially, with verification of proper detection and isolation by the EFCU prior to performing the next fault simulation. A portable computer and printer generated a printout of the fault code.

Stop watches were used to obtain accurate timing for each fault simulation, with only hands-on time recorded. Accurate and complete data were maintained during the demonstration, with record sheets used to record all tasks, times, manpower, and equipment used during the demonstration.

ENGINE MAINTENANCE MANAGEMENT SYSTEM (EMMS)

An engine maintenance management system was developed and qualified for the F109 utilizing the EFCU data logging feature.

This feature provides for engine diagnostics with the following functions available:

- Engine parameters NL, NH, T4.5, and PLA are available at a single terminal for continuous recording by an air vehicle flight-data recorder.
- Engine data logging capability, as shown in Table 1.

These data are stored in the EFCU and can be retrieved with a portable hand-held terminal or similar equipment using communication standard R422A. The EFCU digital readout feature provides for engine diagnostics with the following functions available:

- Engine parameters NL, NH, T4.5, and PLA are available at a single terminal for continuous recording by an air vehicle flight-data recorder.
- Engine data logging capability, as shown in Table 1.
Table 1. EFCU Data Logging Summary.

<table>
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<tr>
<th>Documentary</th>
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<tbody>
<tr>
<td>Engine Serial No.</td>
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<td>EFCU Serial No.</td>
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<th>Individual Flight Counting</th>
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<td>Time Above Selected NL (4 values)</td>
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<tr>
<td>Time Above Selected NH (4)</td>
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<tr>
<td>Time Above Selected T4.5 (4)</td>
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<tr>
<td>Time Above Start Temperature (4)</td>
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<td>Engine Starts</td>
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<tr>
<td>Time Over Start Temperature (4)</td>
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<tr>
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<th>Performance Trending of Last 10 Flights</th>
<th>&quot;Max Power Snap-Shot&quot;</th>
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<tr>
<td>PTO, Total Pressure, psia</td>
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<tr>
<td>AP/P, Dynamic Pressure Divided by Total Pressure</td>
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<tr>
<td>AT4.5, T4.5 Temperature Margin, F</td>
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</tr>
<tr>
<td>NL, Fan/Low-Pressure Turbine Rotor Speed, rpm</td>
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</tr>
<tr>
<td>NH, Compressor/High-Pressure Turbine Rotor Speed, rpm</td>
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<td>NHCREF, EFCU NH Corrected Set Point</td>
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<td>T4.5, Interturbine Temperature, F</td>
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</table>

has sufficient capacity to accommodate potential line losses, should the air vehicle contractor decide to provide a central, externally accessible readout capability on the aircraft.

GROWTH

The F109 was designed with growth in mind. Two commercial growth derivatives have been developed providing thrust growth to 1600 pounds (7.1168 kN). A building-block approach to growth has proven its cost effectiveness and low risk throughout development.

Significant development and prototype engine verification testing has been accomplished. Testing included temperature and vibration surveys, combustor rig testing, controls schedule verification, overspeed testing, and endurance testing. This development has culminated in the availability of both 1500- and 1600-pound (5.92 to 7.12 kN) engine prototypes for customer use. Currently, a 1600-pound (7.1168 kN) thrust prototype engine has been approved for flight evaluation.

CONCLUSION

The Garrett F109-GA-100 engine represents a significant advancement in small turbine engine technology that identifies it as a trend-setter in the world’s aircraft market.

Designed specifically for trainer use, the F109 combines the operational characteristics of a student pilot’s ultimate fighter bomber or transport jet engine with the economy of a turboprop.

The USAF design, development, and qualification philosophy as applied to the F109 resulted in an engine with demonstrated durability, reliability, safety, low operating costs, and flexible maintenance options.

Flight-test experience in both twin and single-engine applications further confirmed the F109’s capabilities.

Finally, preplanned growth capability is currently available in commercial derivatives of the F109 engine at thrust levels up to 1600 pounds (7.12 kN).