Systematic Development Testing for Engine Structural Integrity Assurance

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The primary objectives of General Electric's development test programs are to verify the basic design and then demonstrate that the engine, including the individual components, has adequate life and integrity under all operating conditions to which it could be exposed in customer service. The successful attainment of these objectives requires balanced test programs. The programs must consider all phases of testing from the initial preliminary design models through flight testing of the engine. Emphasis is placed on real-life operating environment and accelerated life testing. The paper discusses General Electric's approach to systematic test planning. Examples of these programs from preliminary design components through engine life and reliability demonstrations are provided.

Introduction

THE reliability and life requirements of jet engines have increased tremendously over the past few years. Today's design objectives for commercial engines are to achieve in-flight shutdown rates of not more than one every 30,000 hr at maturity, engine removal rates of not more than one every 8,000 hr at maturity, and an engine design life of approximately 35,000 hr is required. In addition, parts must be repairable and be highly resistant to environmental factors (damage from foreign objects, corrosion, erosion, etc.) and meet weight/performance, economical, and ecological requirements.

The release of an FAA-certified or military-qualified engine to production usually occurs after approximately 10,000 hours of engine testing. It is this amount of full engine testing, backed by material and component testing, that assures the meeting of the design objective and enables prediction of future engine characteristics. The development of an aircraft engine that meets this high reliability and long life requires very sophisticated design analysis, supported by sound engine design experience and verified by a systematic test program. The manner in which such a test program is conducted becomes increasingly more important as costs rise and technology advances. This paper is a discussion of typical test planning for assurance that all requirements including structural integrity have been satisfied. The required test methods and facilities to support such a test plan are extensive.

Testing to assure structural integrity can be categorized in the following three main areas: 1) metallurgical and material testing; 2) component testing; and 3) engine testing. Metallurgical and material testing starts first. A large portion of this testing is completed prior to engine design initiation. Component testing starts during design and follows through the total development phase. Initiation of engine tests occurs somewhat later in the development cycle since a design must be established and hardware manufactured prior to the start of engine testing. These tests identify the need for design improvements which are introduced into the development process. The introduction of these design improvements represents a reiteration process which goes through the test cycle again to assure its structural integrity. Because of the incorporation of these design improvements, testing on a given engine program will occur concurrently in all three areas throughout the total engine development. Figure 1 shows the typical effort in terms of material, component, and engine test hours.

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Metallurgical and Material Testing

The main objective of metallurgical and material testing is to provide design engineering detailed information on material behaviors in their respective operational environment. The testing covers a wide variety of tests and test conditions. Table 1 gives a listing of a number of these tests. In addition to those listed there are special tests conducted to establish material behavior for unique applications such as wear characteristics, abradability and welded joint strength. Some of the material tests are of a more recent development and are of special interest relative to high structural reliability.

Low-Cycle Fatigue Testing

This is of special interest because it provides information on the material capabilities to withstand the load or stress cycles which occur a finite number of times (less than 100,000 cycles) during the life of the engine. These load cycles are those associated with such events as engine speed, temperature and/or pressure cycles, thrust and reverse thrust cycles, and maneuver loading. In this testing, test specimens are subjected to cyclic loading in a temperature environment representative of that expected dur-

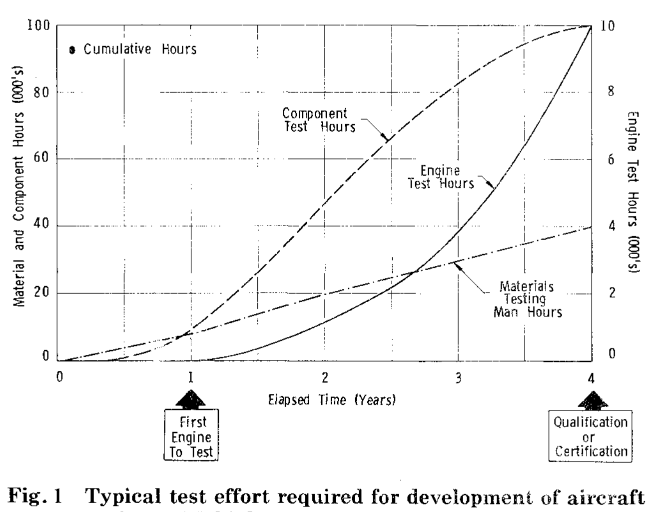

Fig. 1 Typical test effort required for development of aircraft engines with high structural integrity.

Table 1 Various material tests conducted to support structural design[a]

Test description	Results obtained
Tensile testing	Yield and ultimate strength, percent elongation and reduction in area
Creep-rupture testing	Rupture life and creep rate
Thermal expansion testing	Coefficient of thermal expansion as function of temperature
Modulus of elasticity testing	Dynamic modulus of elasticity as function of temperature
Low-cycle fatigue	Life, effective K_t
Sustained peak load low-cycle fatigue testing	Fatigue life with effects of creep and rupture included
Fracture mechanics testing	Fracture toughness, crack growth rate, and critical crack length
Simulated engine thermal shock testing	Material and geometry comparison with simulated turbine blade and vanes leading and trailing edges
High-cycle fatigue	Stress range diagram information
Oxidation and corrosion testing	Resistance to oxidation and corrosion of material and coatings

[a] Testing conducted at temperatures representative of the operating environment.

ing engine operation. A sinusoidal load (or strain) spectrum is normally used with a cyclic load (or strain) rate of 15 to 20 cycles per minute. Low-cycle fatigue data are developed especially for the materials used in rotating disks and blades, pressure vessels, and the mounting systems.

Sustained Peak Low-Cycle Fatigue (SPLCF)

SPLCF is very similar to low-cycle fatigue testing. The only difference is in the load spectrum. In SPLCF testing, the load on the specimen is held (sustained) at the maximum value for some specific period of time. This testing is required because at elevated temperatures parts subjected to cyclic loads can exhibit a shorter life than can be accounted for by either low-cycle fatigue or stress rupture analysis. The sustained peak low-cycle fatigue material behavior is defined by conducting tests at different temperatures and hold times.

Fracture Mechanics Testing

Fracture mechanics testing provides a slightly different approach in establishing structure reliability. This analysis and testing are based on the assumption that there may be undetected material defects present even in new high-quality parts. This is probably a good assumption based on state-of-the-art limitation of present nondestructive inspection techniques. The testing done here is for the purpose of establishing: 1) crack growth rates; and 2) critical crack length in operational environments of the respective part. The critical crack length is the size of a crack or defect that will result in instantaneous or brittle failure in the operating stress field of the part. This testing provides information for designing parts with long life and assures that a critical part will not fail prematurely from some minute undetectable defect.

Simulated Engine Thermal Shock Testing (SETS)

SETS consists of testing where simulated turbine blade leading and trailing edges are subjected to thermal cycles. Heating is accomplished with gas flames and cooling with air jets. The specimens are mounted on a table which indexes the specimens through the heating and cooling cycle. Information is obtained for qualitative thermal fatigue screening of materials and geometry comparison.

Component Testing

The initial component tests are those required to support design where analysis alone does not provide sufficient confidence needed to establish a final design. These tests can occur in any of the structural design areas and are usually conducted on specially made models. In almost all cases the objective of structural integrity component tests is to demonstrate the adequacy of the component to perform in its operational environment (temperature, vibration, and load). In component testing, it is possible to do extra severity margin testing, purposely loading parts beyond those loads induced during engine operation. In cyclic testing, a much higher cyclic rate can be used than experienced in service thereby condensing time and accelerating experience. It is also possible to focus concentrated attention on a specific detail of a component to establish an in-depth understanding.

Table 2 is a listing of typical component tests that are conducted for structural integrity assurance and are listed

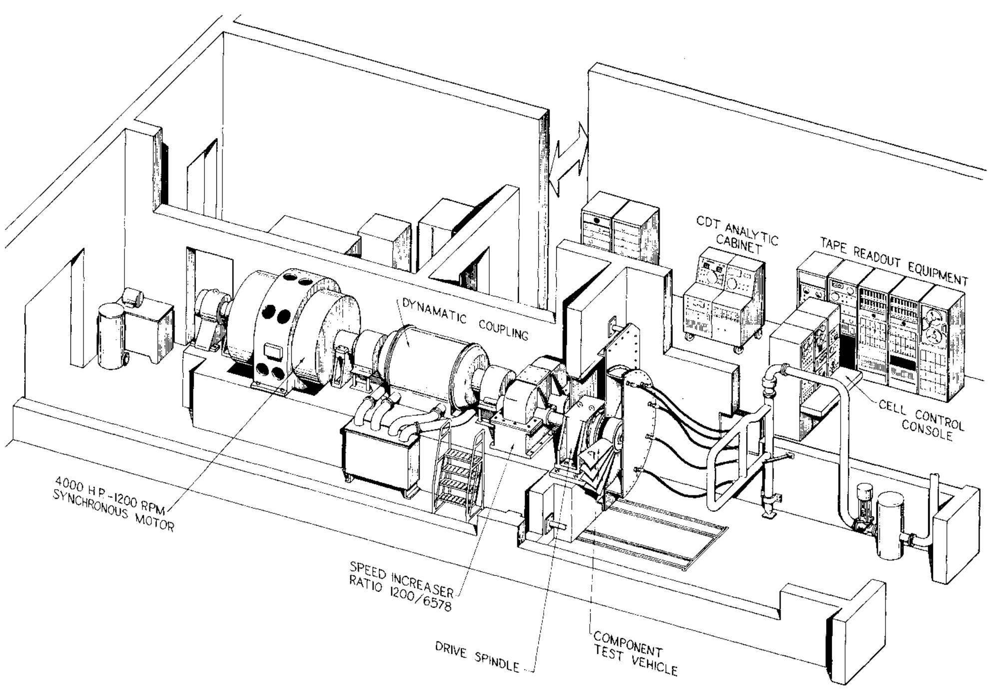

Fig. 2 Rotating blade test setup in whirligig test facility.

Table 2 Typical structural integrity assurance component tests[a]

Environment	Test description	Facility	Results obtained
Elevated temperature (may include pressure loading)	Turbine blade & vane cooling effectiveness & thermal cycling	Flame tunnel	Heat transfer, temperature distribution & thermal cyclic life
	Combustor liner cooling & thermal cycling	Flame tunnel	
Vibration	Blade vibratory characteristics and stress distribution	Electromagnet	Frequencies, nodal pattern, cord & span stress distribution
	Blade fatigue (tested at elevated temperature where appropriate)	Shake table plus controls & heater	Mean endurance strength and statistical scatter
	Air seal vibration	Electromagnet	Frequencies & nodal pattern
	Tubing vibration & fatigue	Electromagnet & large shake table	Frequencies & endurance capabilities
	Static structures vibration & fatigue	Electromagnet & large shake table	Frequencies, ring modes, damping
(including centrifugal loading)	Blade/disk vibration characteristic (vibration & centrifugal load)	Whirligig facility	Vibration characteristic as function of speed
Cyclic loading (centrifugal, pressure, thermal, thrust, and maneuver) and endurance	Static load testing of both static & rotating components and subcomponents	Adaptation & loading fixturing	Stiffness & stresses
	Cyclic load testing of both static & rotating components and subcomponents	Same as for static testing plus cyclic load controls	Cyclic life capability repair procedures, development
	Hydrostatic pressure testing of pressure vessels such as bearing support frames, combustor casing, etc.	Adaptation of fixturing with seals	Deflections & stresses
	Cyclic pressure testing of pressure vessels	Same as for hydrostatic plus cyclic pressure control	Cyclic life capability and repair procedure development
	Bolt torque/clamping loads and fatigue	Special fixturing and fatigue test stands	Torque/clamping force bolt endurance data
	Rotor high speed spin test	Spin pit facility	Centrifugal load stresses
	Rotor cycle speed spin test		Rotor life
	Gearbox dynamatic endurance testing	Dynamometer test cell	Demonstrate the gearbox load capability including overloads
Ultimate load (one-time safety requirements)	Rotor overspeed	Spin pit	Demonstrate rotor overspeed
	Engine mount system static load test	Same as static load tests	
	Hydrostatic test of pressure vessel (up to 2× plus temperature correction)	Same as hydrostatic testing	
Foreign object ingestion and impact testing	Bird & FOD ingestion testing	Impact test cell	Impact capability for static parts and ranking of rotating parts
		Rotating impact test stand	Impact capability for rotating parts

[a] Listed as function of the operational environment.

by the environment in which the test was designed to demonstrate the adequacy of the part. The tests listed are typical as the test plan for a new design is tailored to the specific and unique requirements of that design. Following are some comments on each type of component testing to illustrate the part it contributes to assuring a design with high structural integrity.

Elevated Temperature Testing

Elevated temperature testing provides a method of establishing the effectiveness of the cooling system for turbine blades and vanes and combustor liner early in the design phase. This also includes information on thermal cyclic life capability. This reduces redesign reiterations on engine hardware thereby saving time in the total development cycle.

Vibration Testing

Vibration testing is usually conducted to provide data for one of these three objectives: 1) vibration characteristic data to determine if conditions of resonance exist with potential engine sources of excitation that would cause premature failure; 2) fatigue capability data to demonstrate that the component parts themselves meet the design objective and will operate satisfactorily in the expected environment; and 3) vibration information to be used for monitoring early development engine tests so as to avoid engine failures. The complexity of vibration testing varies over a wide range from simple bench vibration characteristic studies using an electromagnetic facility for excitation to complex rotating vibration tests which require rather extensive drive facilities as shown in Fig. 2.

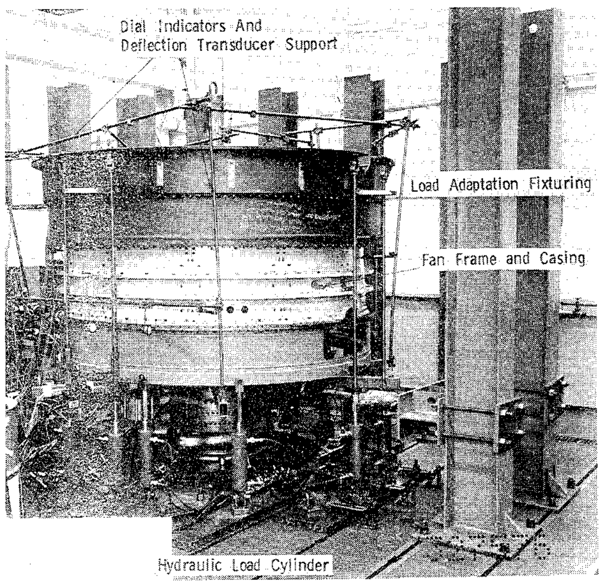

Fig. 3 Static load test setup.

Cyclic Loading

Cyclic loading occurs to some degree with each change in engine speed, thrust, and maneuver of the aircraft. Also associated with the engine speed change is corresponding change in pressures and temperatures. Of course, the more extreme the change, the higher the amplitude of the cyclic load. Static and cyclic load, hydrostatic and cyclic pressure, and high-speed component tests are conducted to verify design adequacy and the component's capability to withstand cyclic loading. Static load (Fig. 3) and hydrostatic tests provide data on stresses, load paths, and structural stiffness. Structural stiffness data are used in vibration analysis of the engine system to make certain that the major modes of vibration are satisfactory.

Cyclic load and pressure tests are conducted on both components and subcomponents. Testing on many of the small components and subcomponents, such as turbine disk dovetail parts and blade dovetails, is conducted at operational temperatures. Testing of the larger components, such as combustion cases, frames, and mount systems, is performed at room temperature with the load adjusted upward to compensate for the difference in material strength between the test and operational temperature. These tests are used to demonstrate the cyclic life capability of the respective component. Cyclic load and cyclic pressure testing provides information on crack growth rate and assures that the defect size required to cause an instantaneous brittle type failure is large and easy to detect, so that there is more than adequate opportunity to identify any defect prior to the existence of any real problem. Rotor high-speed and cyclic-speed spin tests serve a similar purpose for evaluating the effect of centrifugal loading on rotors as the static load (hydrostatic) and cyclic load (pressure) tests do on static components.

Gearbox Dynamometer Endurance Testing

This is conducted with the gearbox driven by a variable speed drive with each of the accessory pads loaded with the respective accessory or with a water dynamometer. This test setup provides a method of endurance testing gearboxes with all the pads loaded to their design rating including those output pads used to provide power to the aircraft.

Foreign Object Ingestion and Impact Testing

This is accomplished in both rotating and static bench tests. The environment which results in the aircraft en-

Table 3 Typical full-scale/engine test conducted to assure structural integrity

Test Description	Facility Requirements	Results Obtained
Full-scale fan	Remote drive SLS cell with matched airflow	Fan component performance including stall margin Permits optimization of variable geometry schedule Blade/vane stress under both normal and stall conditions
Full-scale compressor	Remote drive SLS cell with matched airflow	Compressor component performance including stall margin Permits optimization of variable geometry schedule Blade/vane stress under both normal and stall conditions
Combined fan/compressor test vehicle	Dual drive SLS cell with matched airflow Telemetry capability	Overall compression system efficiency and stall characteristics Transfer characteristics
Engine mechanical evaluation	SLS and altitude facility cells	Vibration characteristics of structures, rotors and configuration hardware vs engine speed
Rotor stress and temperature distribution	SLS and altitude facility cells Telemetry/slip ring capability	Confirmation that stress and temperature are within allowable limits
Heat transfer verification	SLS and altitude facility cells	Confirmation that basic engine, as well as fluid system heat transfer, meet requirements
Anti-icing	SLS and altitude facility cells	Demonstrate that engine meets the in-flight anti-icing requirements
Foreign object damage	SLS facility cell with dropped chute	Demonstrate that engine will accept the normal runway or accidental nut, wrench, rag type of FOD without suffering a catastrophic failure
Ingestion—H_2O, sand, bird, ice, hail	SLS or outdoor/remote facility	Demonstrate or evaluate items such as gas path erosion, cooling hole plugging, containment, interlock disengagement
Extra severity tests	SLS, outdoor, and altitude facilities High speed photography, TV viewing, telemetry and slip ring capability	Demonstrate or evaluate effects of distortion, lube oil interruption, electrical failure consequences, crosswind or tailwind effect
Durability	SLS or outdoor facility	Allows conduct of accelerated service tests that evaluate LCF or stress rupture life (fleet leader program)

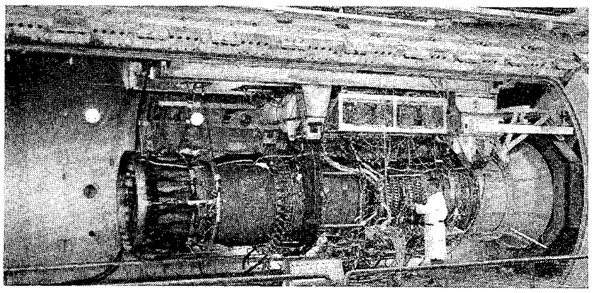

Fig. 4 Full-scale engine test altitude chamber.

gine ingesting foreign objects such as birds, rocks, ice, etc., is not completely of its own making as are many of the other environments. These are environments that an aircraft engine must be able to withstand. Component parts are tested in two basic test setups. In the simpler of these, the test part is mounted stationary and the foreign object is shot from a gas gun striking the test part at a specified high velocity. This test setup provides impact resistant information on static (nonrotating) components and gives a method for ranking or comparing designs. Rotating ingestion tests vary in complexity but can be representative of engine conditions.

Engine Testing

The basic objectives of a totally integrated engine test plan are directed toward: establishing performance and operational capability; establishing mechanical integrity, durability and reliability; development of maintenance techniques; development of growth and in-service maturity; refining and/or expanding maintenance techniques; providing operational support; and satisfying other specification requirements. Over the past 30 years, the Aircraft Engine Group of the General Electric Company has analyzed the test patterns of various engine development cycles. On the basis of known success and failure, an integrated engine test plan was designed that will assure the structural integrity expected of an engine designed to fly in the period 1970 through 1990. From initiation of engine testing up to the point of certification some 60%–80% of the total test effort will be directed toward endurance-durability testing. Some 50% of this total will be environmentally structured. Table 3 lists typical assurance tests. In general, this testing can be broken down into the following categories.

Aerodynamic and Mechanical Testing

This determines the adequacy of basic engine characteristics under normal and simulated operation and can be summarized as component performance evaluation. It

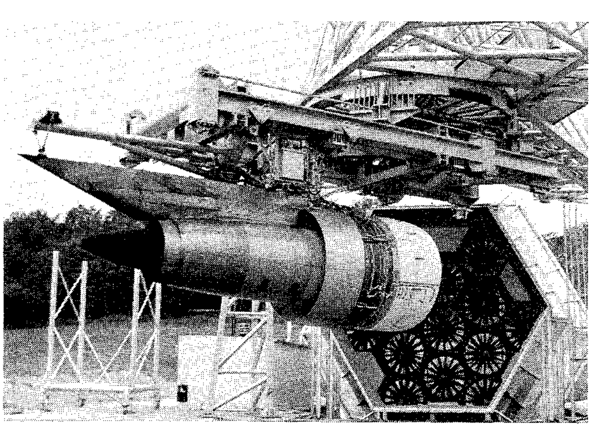

Fig. 5 Full-scale engine test crosswind facility.

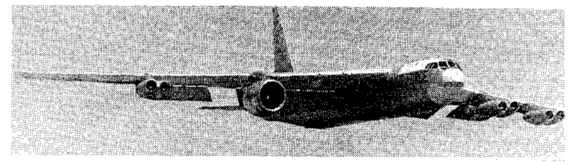

Fig. 6 B52 modified for use as flying test facility.

covers all testing using a specific engine model and is characterized by high quantities of instrumentation. These tests measure how well the design meets the technical requirements of aerodynamic performance and efficiency, stress margin, pressure drops, deflection, temperature profile and pattern, natural frequencies, strength margin, and vibration characteristics.

System Design Verification Tests

These tests are designed to measure interrelationships between components and performance measurements. Typical tests planned throughout a test program are: transient response rates, engine system stability, control system vibration survey, control system temperature survey, verification of system heat load, starting torque, fluid contamination effects, failure consequence testing, windmilling heat loads, stator and nozzle system operation, and engine diagnostic monitoring.

Environmental Testing

To ensure that the engine will operate safely under varying climatic conditions, environmental testing is devoted to simulated altitude/Mach number (Fig. 4), cold and hot starting, anti-icing, ingestion, installed crosswind, and tailwind effects (Fig. 5).

Aircraft Interface Tests

These help assure early compatible mating between the engine and the airframe. This includes investigatory or engineering testing directed toward horsepower extraction, nacelle effects on heat transfer/performance, and inlet distortion. At the same time, engine maintainability in terms of "on the wing" maintenance can be assessed.

Flight Test Status/Certification

Flight Test Status/Certification (Fig. 6) includes the unofficial and official tests specifically designed to clear the engine for flight or release to production.

Durability Testing

This is designed to accelerate detection of critical failure modes, and to develop life, safety, reliability, durabil-

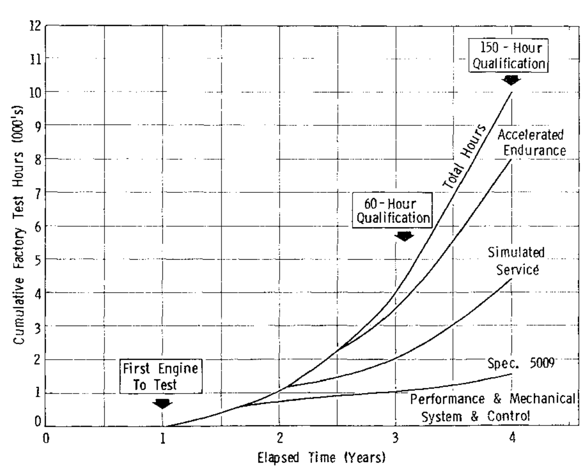

Fig. 7 Engine test plan.

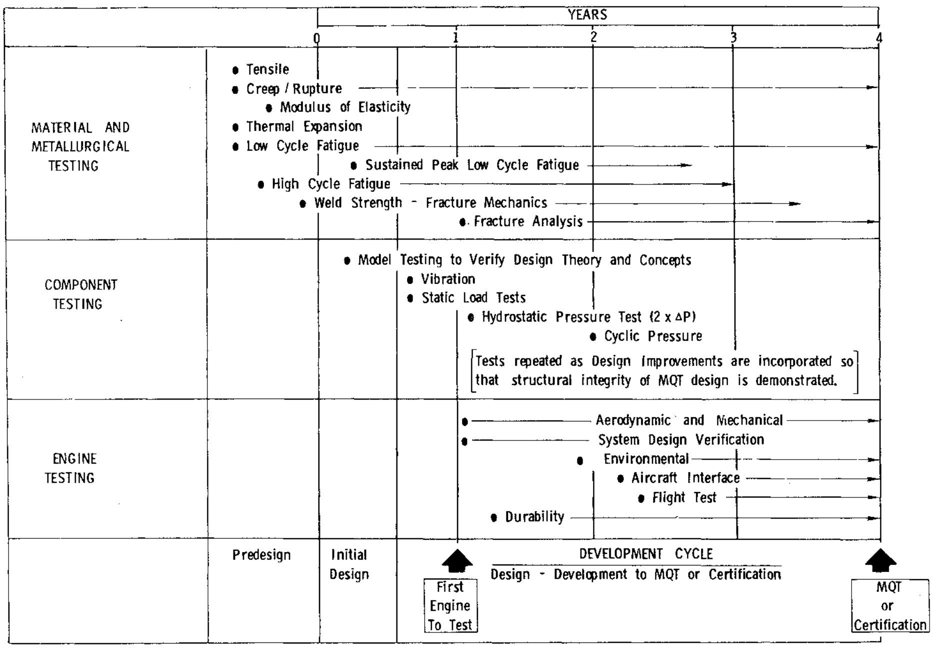

Fig. 8 Typical test program for structural integrity assurance for compressor rear frame and combustion casing.

ity and maintainability. Approximately 60%–80% of the total engine tests are devoted to durability. This includes the following.

Accelerated Cyclic Endurance

Sea-level cyclic endurance testing designed to accelerate experience in searching for failure modes such as thermal fatigue, low-cycle fatigue, and wear and tear on variable mechanisms.

Accelerated Service Endurance

Extra severity testing conducted under simulated mission conditions. These include testing at higher than rated turbine metal temperatures as well as testing the flight envelope boundaries including any overshoot conditions.

In terms of testing to assure adequate structural integrity it can be seen that although engine testing can be categorized there is much interrelation of one area to the other. The engine contractor must assure that his plan is time/sequence phased to allow adequate time from any initial demonstration to final product verification for incorporation of needed improvements (see Fig. 7). A typical test program for an engine component from initial material selection to final certification is shown in Fig. 8. Each phase of this cycle involves extensive testing and retesting as required to verify and substantiate design improvements.

Life/Reliability Prediction

One of the most challenging aspects of engine development involves the utilization of the development test hours as a basis for predicting future reliability and mechanical integrity of the engine. General Electric has been studying techniques for the prediction of gas turbine reliability growth for several years. Several techniques are utilized. Some of these involve rather complex math models—some are more straightforward. One such method is briefly described: by plotting data from several development and operational programs it has been observed that the characteristic of cumulative new failures versus cumulative equivalent hours of operation of a gas turbine plots as a straight line on log-log paper. The equation of such a line takes the form: $N = K(T)^{\beta}$ where N = number of cumulative failures, T = cumulative equivalent operating

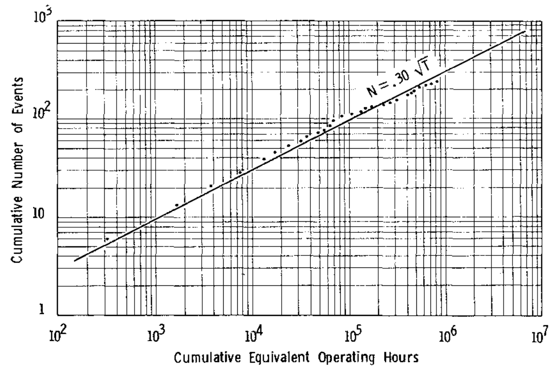

Fig. 9 Unscheduled gas turbine removal trend.

hours (i.e. adjusted for variation in test or operational severity), K = constant (intercept of log-log line), and β = constant (slope of log-log line)—observed to be approximately 0.5 for the surveyed data. Data have been collected for the TF39, CF6, LM2500 family of engines since the first development testing of the TF39 engine in 1965. These data have been reviewed for the purpose of identifying and trending the occurrences of *new* problems. The results of this review are presented as Fig. 9. It will be noted that a smooth trend is evident, fit by the equation given in Fig. 9.

This total problem prediction is comprised of various categories, including structural integrity which can be individually predicted. This ability to predict the life characteristics early in the development program and take the necessary corrective action is vital to the operational and economical success of the engine throughout its life cycle.

Conclusion

There are few, if any, shortcuts in an engine development program. It is the thoroughness of the test program and the prompt correction of faults detected that pay vast future dividends. Our objective must be to execute a more thorough job for less cost. Modern test facility equipment, better analytical techniques, and utilization of previous design and test experience should make this possible. It will only be possible if the development programs are systematic and well planned from the beginning, eliminating costly and unnecessary testing without compromising the necessary work.