THE LEADING EDGE

FALL 1992

The GE90 Story

The GE90 dual-annular combustor undergoing full-scale component tests to develop gas temperature profile and pattern factors. This dual-annular combustion system offers improved operability, significant reductions in emissions and reduced engine length.

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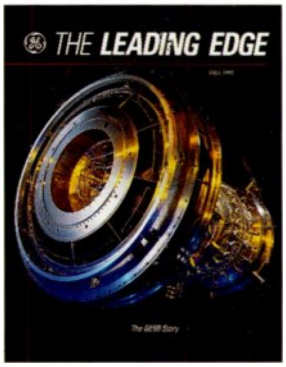

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On the cover: *The first GE90 core engine is prepared for compressor and turbine aeromechanical tests.*

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The commercial customer has changed significantly in recent years, and this trend will continue into the foreseeable future. Lee Kapor reflects on those changes and on the actions we must take to position ourselves for an eventual recovery in the commercial engine market.

GE90:

The Right Combination

By James W. Tucker

GE90 full-scale model

J. W. Tucker

The rapid pace with which change occurs in our global society today can make obsolete, in very short order, yesterday's technology. The large scale economics and deregulation of the commercial aviation business make it particularly dependent on evolving technologies, especially those that produce significant economic advantage.

In early 1990, GE Aircraft Engines launched the GE90, a high-thrust engine which combines proven technology in a totally new engine cycle concept for meeting tomorrow's advanced engine needs. The GE90 will power the next generation of widebody twin-engine aircraft, with growth versions to meet the needs of super-jumbo jets being considered for the year 2000. The engine provides airlines with the answers for meeting increasingly stringent economic, competitive and ecological pressures.

The GE90 turbofan engine addresses these difficult and somewhat conflicting needs through judicious selection of the engine cycle. The design incorporates advanced technologies which provide sufficient present and future payoff potential for SFC, weight, cost, emissions and reliability. Where the improvement potential for incorporating advanced technologies is small, the GE90 takes advantage of the proven reliability of today's technology.

The engine features a 123-inch diameter fan which increases the bypass ratio from the 5:1 typical of today's engines to 9:1 for the GE90, the highest bypass ratio of any ducted fan engine committed to development to date. The overall pressure ratio will exceed 40:1. This combination of increased bypass and pressure ratios reduces specific fuel consumption by more than 9% compared to conventional high bypass turbofan engines. In addition to improved performance and growth potential, significantly reduced emissions and noise signatures can be achieved.

However, the GE90's superior technology is only part of the story. These technologies were successfully integrated using a state-of-the-art design approach which relies on concurrent engineering, with early supplier partnerships and airline input. Another key to the program's success was integrating the manufacturing and design activities of the GE90's revenue sharing participants with the concurrent engineering plan.

Our revenue sharing participants include SNECMA, which is responsible for the high pressure compressor and booster; IHI, which is responsible for the low pressure turbine rotating parts and fan shafts; and Fiat, which is responsible for low pressure turbine static parts and gearboxes. GE Aircraft Engines has responsibility for systems engineering and overall program management, and is designing the fan, high pressure turbine and combustor components.

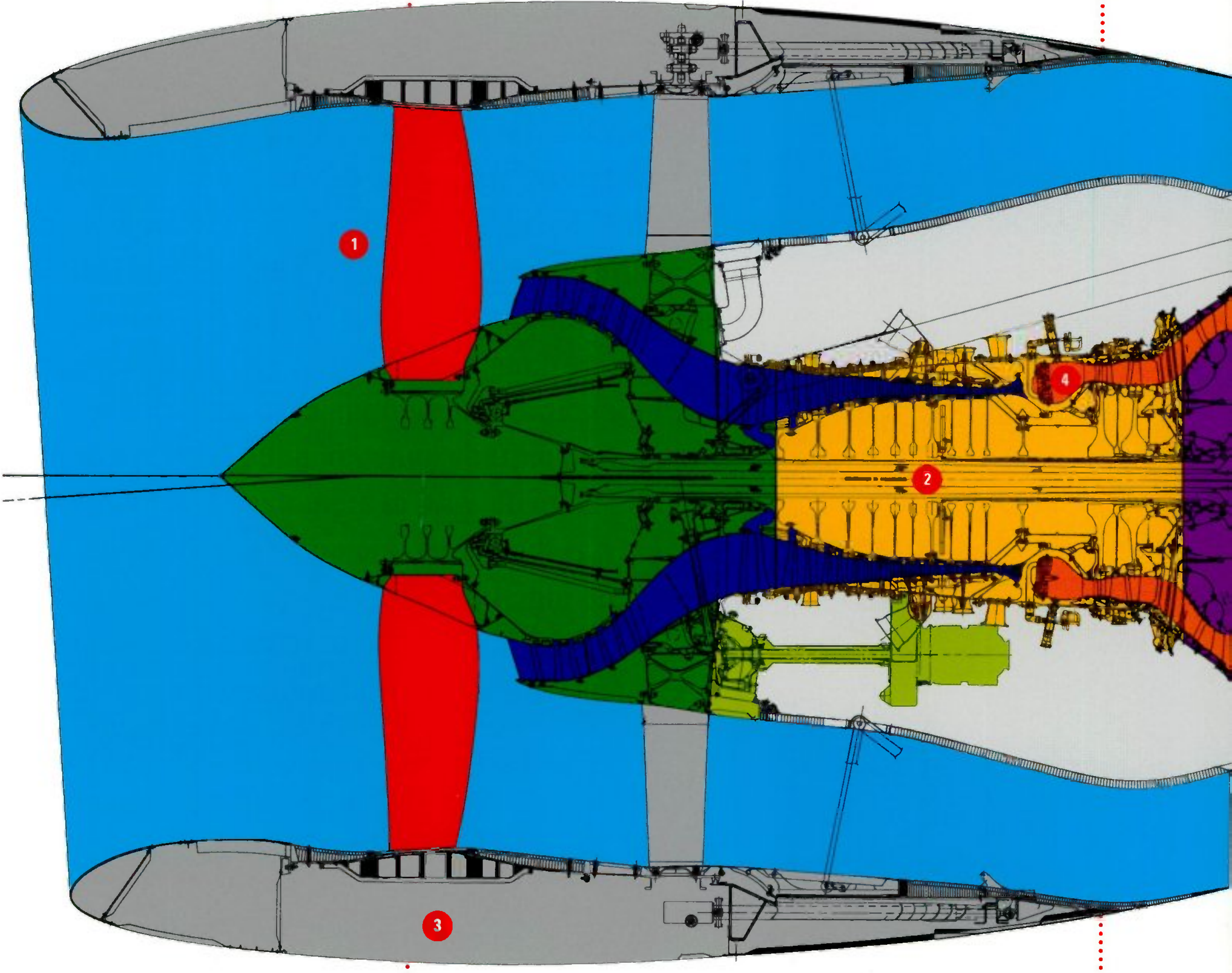
Representatives from design, manufacturing, marketing, product support, sourcing, suppliers and customers are co-located to facilitate boundary-less interaction. These groups work in concert with one shared goal: produce an engine that is highly reliable, economical, durable, maintainable, efficient and environmentally friendly. The primary focus is to make a positive impact on the customer's bottom line.

This combination of advanced technology, proven experience and concurrent engineering is being used to produce the GE90. This engine will provide the core for a family of engines that will meet the demanding needs of a broad spectrum of aircraft planned for well into the next century.

Jim Tucker is General Manager, GE90 Engineering Operation

Defining an Advanced Cycle Engine

By Ambrose A. Hauser



The GE90 provides a unique opportunity to optimize cycle parameters for both growth and low specific fuel consumption (SFC) by using key proven technologies (Figure 1). Compared to a conventional turbofan of today, the GE90 offers an SFC reduction of more than 9% due to its thermodynamic cycle, in addition to inherent improvements in the efficiency of individual components.

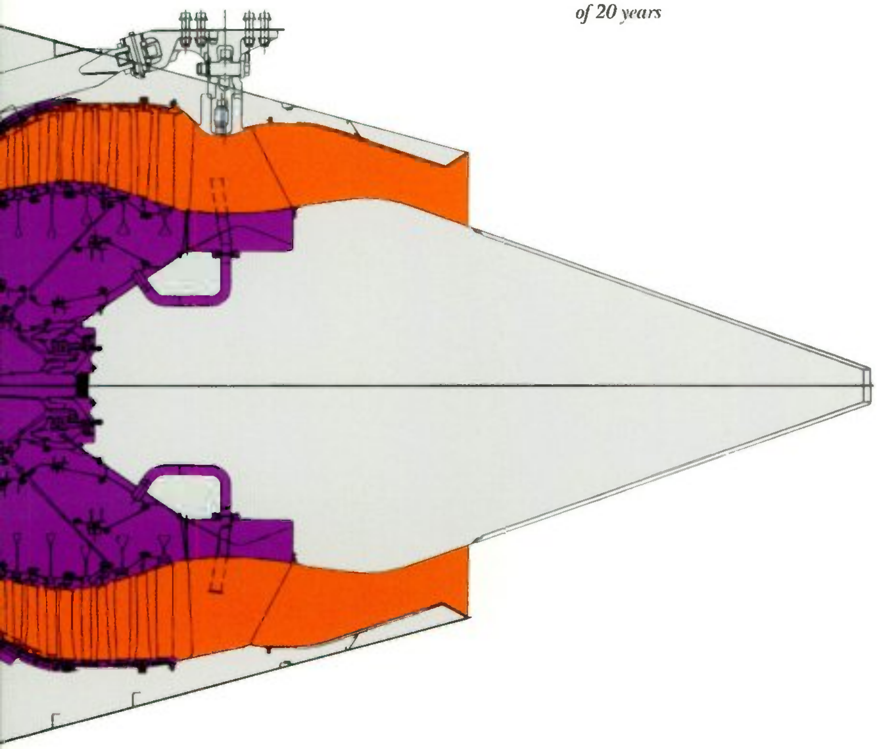
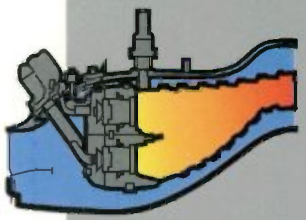


Figure 1: *Technologies key to the GE90 were jointly developed and successfully proven by GE in cooperation with NASA over the course of 20 years*

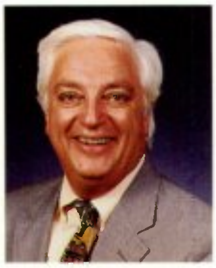
① **NASA/GE UDF**: *Wide-chord composite fan blade evolved from GE36*

② **NASA/GE E^3**: *Scaled core featuring short, durable 10-stage HPC aerodynamics*

③ **NASA/GE QCSEE**: *Composite nacelle and fan blades*



④ **NASA/GE ECCP**: *Rugged dual-dome combustor*



A. A. Hauser

Advanced

As the curves in Figure 2 illustrate, we began by defining a cycle with the lowest practical fan pressure ratio (FPR), consistent with a fixed fan nozzle area to yield a high propulsive efficiency. The GE90's low SFC is achieved by combining high propulsive efficiency with high thermal efficiency and high transfer efficiency (Figure 2a). High thermal efficiency is driven by the GE90's high overall pressure ratio. High transfer efficiency relates to the low pressure system's conversion of propulsor energy to thrust (established by the GE90's low fan tip speed and FPR in conjunction with lower low pressure turbine loading).

Benefits of low fan and gas horsepower

A calculation to determine the level of fan horsepower required to deliver a pound of thrust is shown in Figure 2b. Lower FPRs require significantly less fan horsepower to generate a given level of thrust. This is the key benefit of high propulsive efficiency.

This lower level of required fan horsepower can be used to:

- Reduce core size, which will cut weight and further improve the bypass ratio (BPR) advantage of the cycle.
- Select engine operating temperature levels consistent with prudent use of cooling flow and material strength capabilities.
- Use the airflow and temperature flexibility provided by the low FPR cycle to assure significant and reliable thrust growth capability for future applications.

These factors are illustrated in Figure 2c, which shows a 160°F reduction in cycle temperature, $T_{4.1}$, as a result of optimization at a lower FPR. This reduction in $T_{4.1}$ provided the flexibility we needed to size the GE90 core to fulfill program needs. These needs call for an engine core which can deliver growth levels of thrust (100,000+ lbs) using today's modern single-crystal turbine materials. The engine will be certified at thrusts of 87,000 lbs or greater using an earlier generation of these materials. The configuration will enter service at a level of thrust (76,000+ lbs) obtained with today's (CF6-80C) levels of metal temperature, with the greater capacity of single-crystal materials which provide growth without change.

Another benefit of the GE90's optimized design is that lower FPR means that lower levels of propulsor gas horsepower are needed to deliver a level of defined thrust (Figure 2d). This lower level of required gas horsepower will enable growth models to use the basic core engine with the current fan size (123-in diameter). Significantly greater growth can be achieved by increasing the fan size.

Figure 2 a through d: *High propulsive efficiency through low fan pressure ratio provides the GE90 with an overall efficiency advantage for transferring core gas horsepower into deliverable fan thrust*

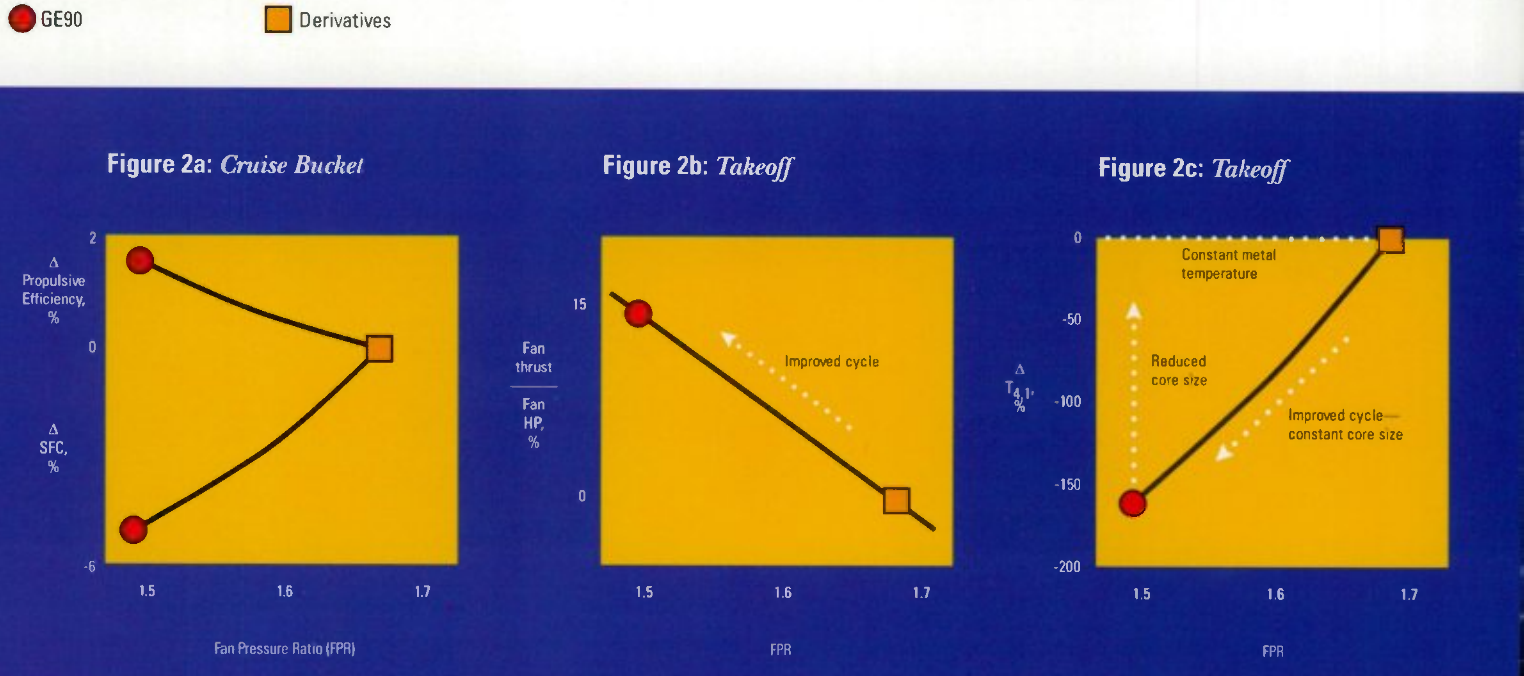


Figure 2a: *Cruise Bucket*

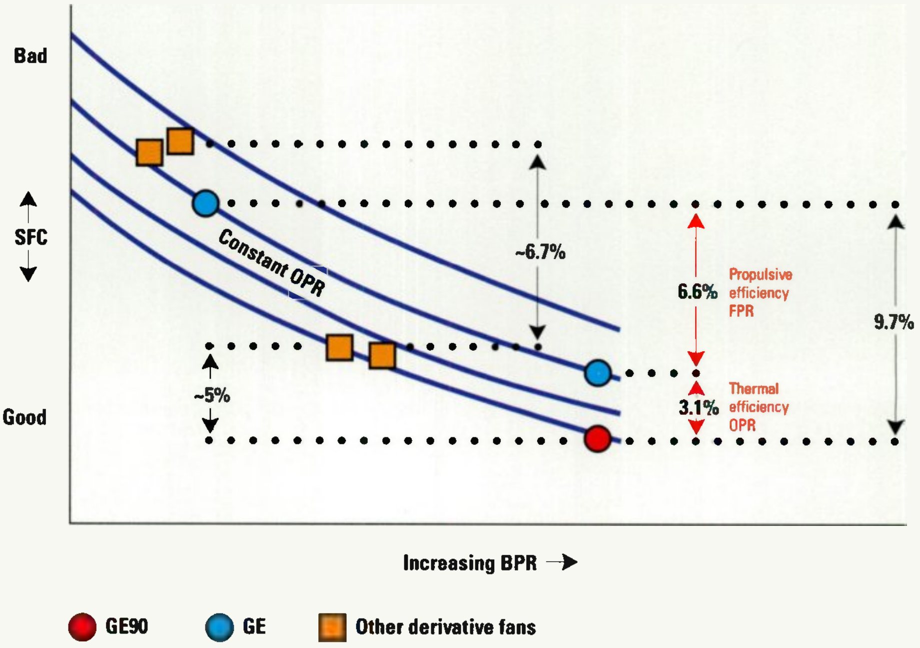
Figure 2b: *Takeoff*

Figure 2c: *Takeoff*

Total cycle benefits

The combination of improved propulsive efficiency and thermal efficiency, together with the benefit of higher transfer efficiency, yields the total cycle benefits shown in Figure 3. As this figure indicates, SFC can be reduced by more than 9% without any improvements in the component efficiency technology. However, the parametric study also assumes no variation in cooling flows with cycle overall pressure ratio. Operating at the elevated high pressure compressor discharge temperatures and high pressure turbine inlet temperatures that are found in a higher pressure ratio cycle would require either additional cooling flows or improved materials to meet life goals for hot parts. The GE90 satisfies hot parts creep, rupture and oxidation life goals primarily by using improved materials without sacrificing performance due to higher cooling flow usage.

Figure 3: *GE90's total cycle benefits include reduced SFC, lowest operating temperatures, best growth capability and reduced deterioration*



Reduced fan pressure ratios yield improved fan adiabatic efficiencies (lower loading) at reduced tip speeds, which also reduce noise signatures. Improvements of 1.5% and 2 to 2.5 dB, respectively, are being demonstrated, as well as improved bird ingestion capability.

The limited bore diameter of existing or derivative cores often curtails the potential torque carrying capability of these engines, even with a new low pressure system and upgraded high pressure power output. Consequently, current derivative engines are incapable of achieving levels of efficiency and/or thrust growth comparable to the GE90 engine. Derivatives of current engine models are also limited in FPR reduction for the same reasons, thereby reducing their ability to achieve the same cycle-related fuel-burn benefit.

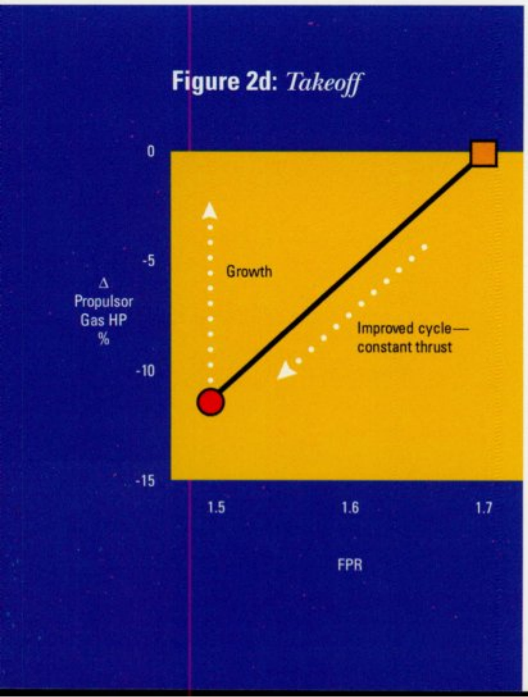
In order to achieve the full performance potential of high bypass ratio and lower fan tip speed, the GE90 was designed to accommodate elevated levels of low pressure shaft torque. The high pressure compressor and turbine disk bore size selected for the GE90 core enable a low pressure shaft diameter capable of torque transmission at thrust levels substantially exceeding 100,000 lbs.

Combined together, these cycle selection decisions provide airline customers a high-thrust engine with dramatic increases in performance, reliability, maintainability and operating efficiency.

Ambrose Hauser is Manager, GE90 Systems Engineering

Cycle

Figure 2d: *Takeoff*



Concurrent Design Approach

By Fred W. Tegarden and Lou M. DiBari

One of the most advanced technologies being applied to the GE90 engine program is its state-of-the-art design approach. Gone are the days when designers threw issued drawings "over the wall" to production or to suppliers. Instead, GE90's concurrent engineering design strategy brings all players in the new product introduction cycle together, from day one. This approach enables representatives from engineering, manufacturing, sourcing, marketing, revenue sharing participants, suppliers and customers to provide input early in the product's development. The result is a quicker cycle time for a top-quality, producible product that meets customer expectations in which problems are designed out rather than found in the development cycle.


F. W. Tegarden


L. M. DiBari

Then and now

Traditionally, engine design has been a serial process, with each step completed before the cycle progressed. Designers would complete their work and issue drawings with some inputs from manufacturing or potential suppliers.

Once a drawing was issued the production division or a supplier would determine if the part could be made to the drawing requirements using the current manufacturing capability. If the requirements exceeded the manufacturing process capability, a request for tolerance relief or process change was usually made. In many cases the part couldn't accommodate the changes required by manufacturing. Thus a merry-go-round of iterations with the product source would begin.

This inconsistency between drawing requirements and manufacturing capability could increase part discrepancies, scrap and costs. Design intent was achieved later in the cycle and costs mounted for all parties involved.

By contrast, concurrent design greatly reduces this problem by having manufacturing/suppliers work with GEAE engineers in a parallel process, rather than in a serial process. Revenue sharing participants (SNECMA, Fiat, IHI), which were selected early in the engine's development, also contributed significantly to the GE90's concurrent design approach.

The early involvement of manufacturing sources with engineering teams enables early prototyping to determine true part process capability. The teams may also study alternate manufacturing methods that can lower cost and increase part quality. There is ample time to investigate tooling concepts that speed throughputs and provide earlier hardware deliveries.

The GE90 concurrent engineering process deals with all components of the engine and the propulsion system. This process involves revenue sharing participants, domestic supplier participants (Precision Castparts, Wyman Gordon, Howmet, Rohr, Woodward

Engineering

Governor, Parker Hannifin and Argo-Tech), Boeing Commercial Airplane Group and British Airways, which has selected the GE90 to power its fleet of B-777 aircraft. The following are examples of how concurrent engineering is paying off on the GE90 in the work being pioneered with customers and suppliers.

Working Together

Traditionally, the aircraft company/engine company interface has not been a concurrent process. This can be illustrated by a scenario involving the design of engine external piping configuration. Typically, the engine company would select the best location for the engine components, often with little input from the aircraft manufacturer. The airframer, in turn, would develop a design to wrap the engine build-up and nacelle around the engine. This approach often produced a propulsion system that was neither optimized nor user-friendly.

For example, using the traditional approach, a design might evolve in which components such as borescope ports are covered with other piping and components. Thus, the components or piping would have to be removed before borescoping. These additional steps would increase customer repair time and cause costly flight delays. This past process represents the antithesis of concurrent engineering.

However, an initiative by leaders from GEAE and Boeing has led to a new precept, which has guided the interaction between the GE90 and the B-777 design teams. The key objective is to produce a product that is the best for the airline customer regardless of the individual company's position on a particular technical matter. Figure 1 shows the basic organization of this initiative.

The two companies first agreed on critical interaction areas where concurrent engineering would be required to assure that the "best product" is designed and produced. Each of the identified critical interaction areas has focal points, or team leaders, selected to head up the effort. Following the British Airways order of the GE90-powered B-777, their representatives also joined the concurrent engineering process.

The core of the initiative is the "Working Together Team (WTT)," a group of senior technical managers from Boeing, British Airways and GEAE. The mission statement of the WTT is to "Identify and remove roadblocks, facilitate team solutions and ensure decisions that 'bring to life' the preferred B-777/GE90 product." The term "make decisions" was purposely left out. Instead, the Boeing/BA/GEAE concurrent design process seeks to empower the teams at the lowest possible level to make technical decisions.

The critical initiative team leaders focus the resources of each company to produce the proper concurrent design and report to the Working Together Team. Experience has shown that when a critical interaction team can't arrive at a mutually agreeable decision it's generally an internal rule, policy or design practice of either Boeing or GEAE that is blocking a solution. The WTT assists the critical interaction team by removing or modifying the roadblock so that a solution agreeable to both companies is achieved.

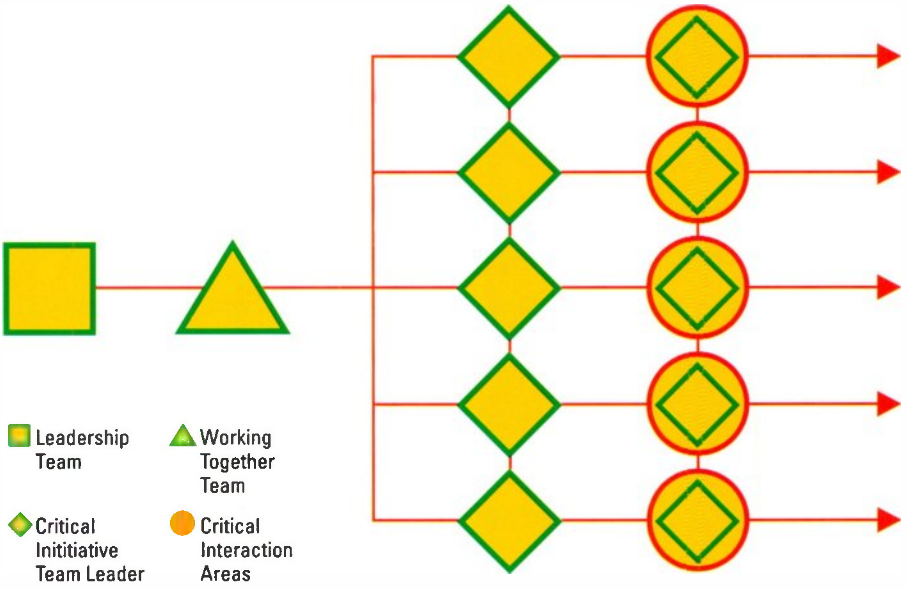
Periodically, the WTT reports to a leadership team, which consists of the highest levels of B-777/GEAE management. This report provides an update of the program and an opportunity to address any roadblocks that the WTT can't handle. Because the lowest level teams are empowered to make decisions, very few non-resolvable problems have been presented to the leadership team.

Sample results

The following example is evidence of how the Working Together concept is facilitating the concurrent engineering process.

When an engine is installed on a new application, a structural model of the engine is developed. Generally this model is developed about two years or more into the program. Because of the

Figure 1: *The Working Together Team structure developed by GE Aircraft Engines and Boeing Commercial Airplane Group has improved interaction on the GE90-powered B-777*



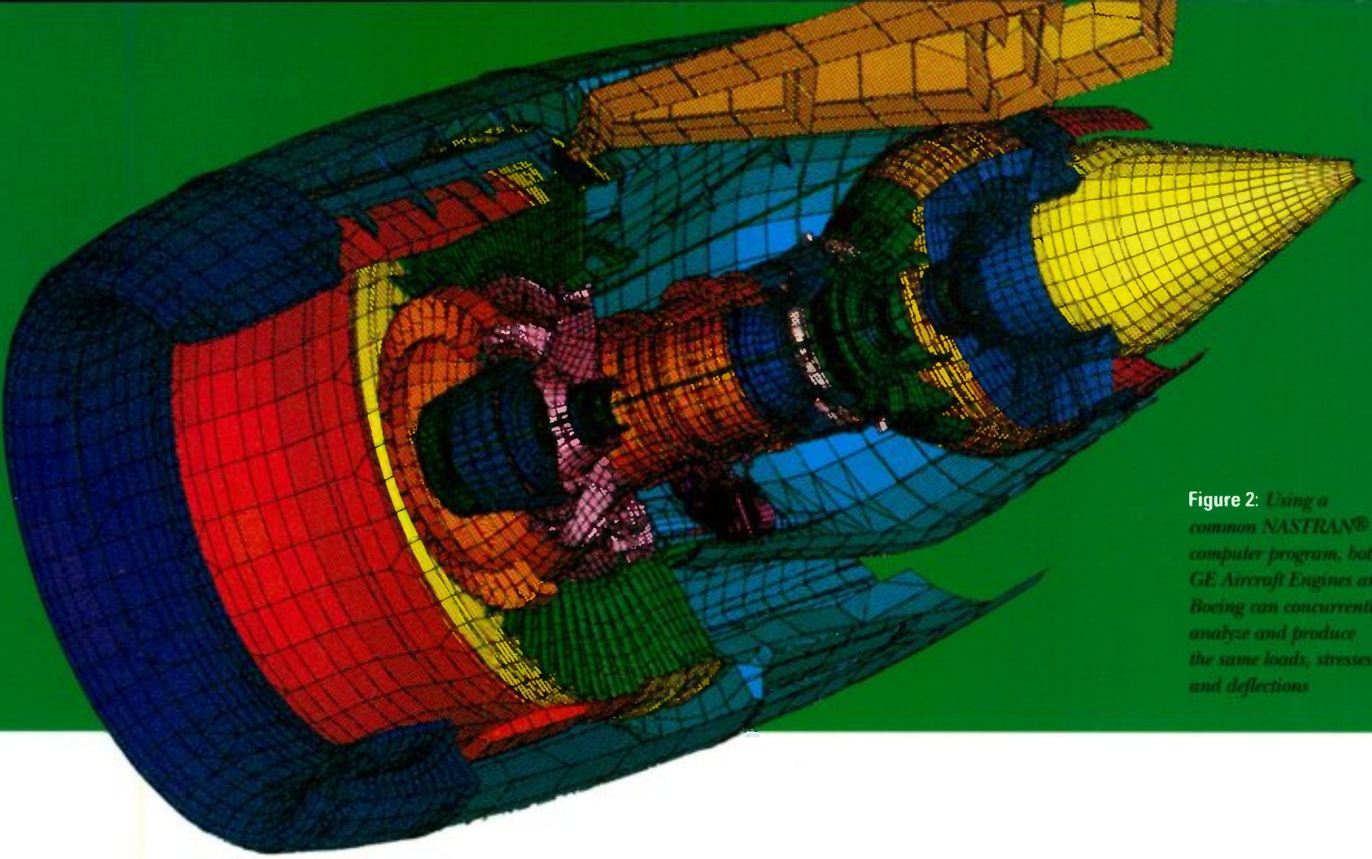


Figure 2: *Using a common NASTRAN® computer program, both GE Aircraft Engines and Boeing can concurrently analyze and produce the same loads, stresses and deflections*

importance of proper structural integration, a critical interaction team was formed in late 1989 to develop an integrated model of the GE90 and the Boeing nacelle components.

Through the use of the NASTRAN® computer program, this highly sophisticated model (Figure 2) was concurrently developed by GEAE and Boeing. Each company supplied models of their respective components to each other. The use of the common NASTRAN® computer program enabled each company to run the model. This meant each company could analyze and produce the same loads, stresses and deflections concurrently. Thus, there were immediate benefits gained from sharing load information, solving mutual problems and, more importantly, establishing a common technical data base.

The complete propulsion system model enabled GEAE designers to optimize the structural arrangement and mounting system of the engine. The selected arrangement minimized static-to-rotating relative deflection. This will produce significant benefits because the higher initial performance and better on-wing deterioration margins of the GE90 will not be lost by engine distortions that result in rotating blade tip rubs throughout the engine.

Concurrent design has also been a driving force for cooperation between Boeing and GEAE in other disciplines including acoustics, installed aerodynamics, Extended Twin Engine Operations (ETOPS), configuration and engine build-up design, cross-cabin noise and development testing. The success of the GE90 program is likely to ensure similar partnerships on future programs.

Supplier teams

Supplier teams are also playing a key role in the successful design and manufacture of components for the GE90 engine application. Since inception of the program, several key suppliers were selected to provide their expertise and the enabling technologies needed to produce the most reliable components for the GE90.

Supplier concurrent engineering teams include cross-functional representatives from Precision Castparts (PCC), Wyman Gordon, Howmet, Rohr, Woodward Governor, Parker Hannifin and Argo-Tech. Objectives of these teams include incorporating "lessons learned" into the design, reducing development cycle time, increasing the technological base and developing a producible and reliable component. In addition, supplier teams working with their GEAE counterparts

Figure 3: *Because of early involvement on supplier teams, Precision Castparts was able to ship this turbine rear frame — the largest investment casting in the world — two months ahead of schedule*

are stressing teamwork and process improvements, as well as maximizing resources to achieve internal and external customer satisfaction. The following are a few highlights of the supplier teams' successes:

Precision Castparts' early involvement with supplier teams resulted in complex castings being delivered on time or earlier than GEAE/PCC promise dates. A case in point is the shipment of the largest investment casting in the world (75 inches in diameter) for the turbine rear frame two months ahead of GEAE/PCC promise dates (Figure 3). To resolve issues up front, supplier teams have developed reviews with GEAE counterparts to cover all notes and dimensions on drawings for producibility. This proactive approach will dramatically reduce case record items at first-article layout. To date, cycle times have been reduced on the initial hardware by three to eight weeks.

Howmet's early participation in the program significantly reduced long development lead-times for airfoil castings by developing prototype castings months ahead of the first production components (Figure 4). The early casting yields and dimensional data for the complex monocrystal blades show production yields and process controls normally associated with years of development activity. Howmet's internal teams continue to work on advanced casting development programs for the GE90 aimed at reducing costs and improving the service-ready performance of the engine.

Rohr's supplier team has been significantly involved with integration issues associated with the aircraft and propulsion system. Working together with GEAE and Boeing representatives, the team was successful in developing plans for interchangeability of the fan stator module with record short changeout times. The supplier team was also heavily involved in the design and development of a titanium exhaust system (a first in the GEAE commercial engine program). Like the GE90 team, Rohr's team is co-located to improve integration.

Woodward Governor's dedicated GE90 team has been instrumental in the design, development and production of the hydromechanical unit (HMU) (Figure 5). In March 1991 we determined that the HMU baseline design was not capable of packaging all the functions in a single casting. Working with GEAE, Woodward's team designed the envelope with a two-piece casting and successfully delivered the first HMU in June 1992 for "Wet Rig" testing (i.e., with fuel). This concurrent effort will reduce development cycle time by three to six months. The Woodward team, in conjunction with GEAE, has been actively involved in design/producibility reviews to ensure design parameters meet requirements and components are producible before the first chip is cut.

Figure 4: *Supplier Howmet significantly reduced long development lead times for airfoil castings by developing prototype castings like this one months ahead of production components*

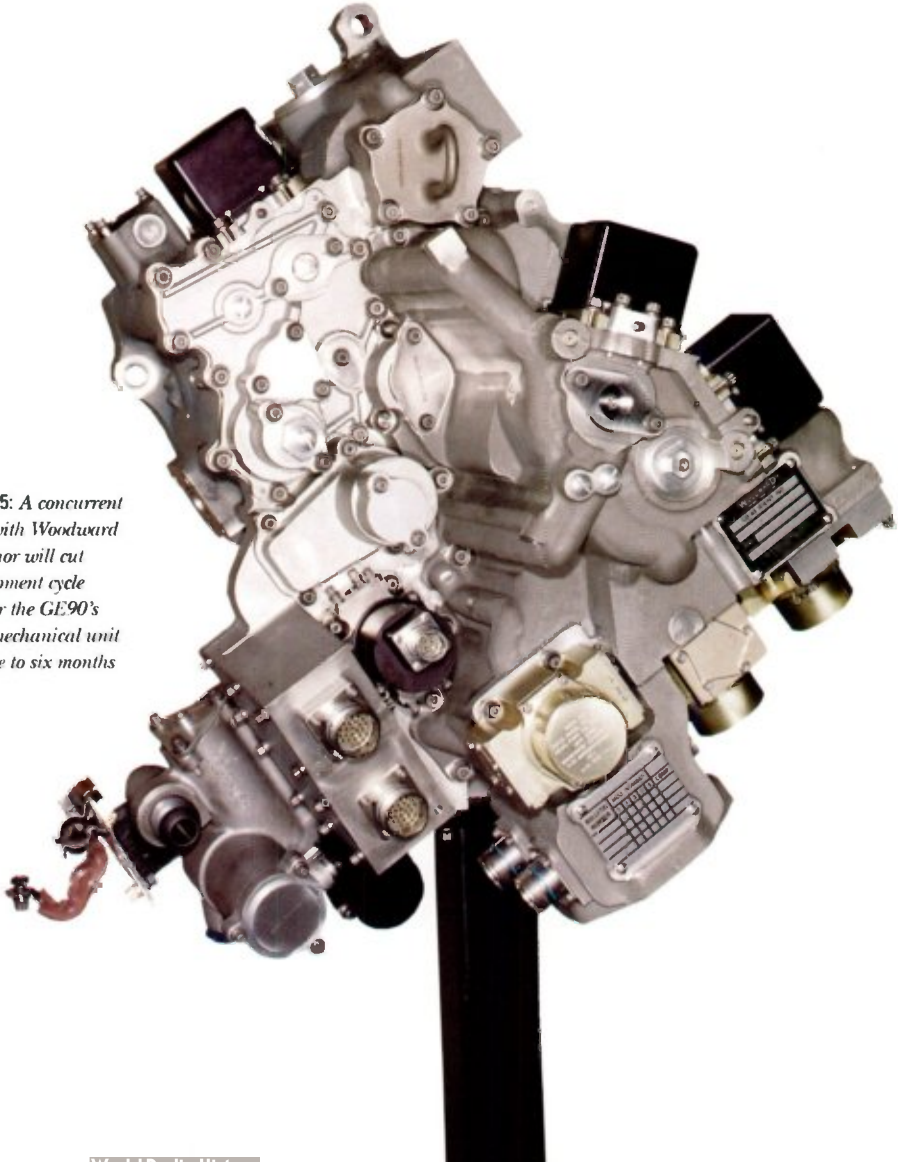


Figure 5: *A concurrent effort with Woodward Governor will cut development cycle time for the GE90's hydromechanical unit by three to six months*

Fred Tegarden *is Manager, GE90 Propulsion Systems Programs*

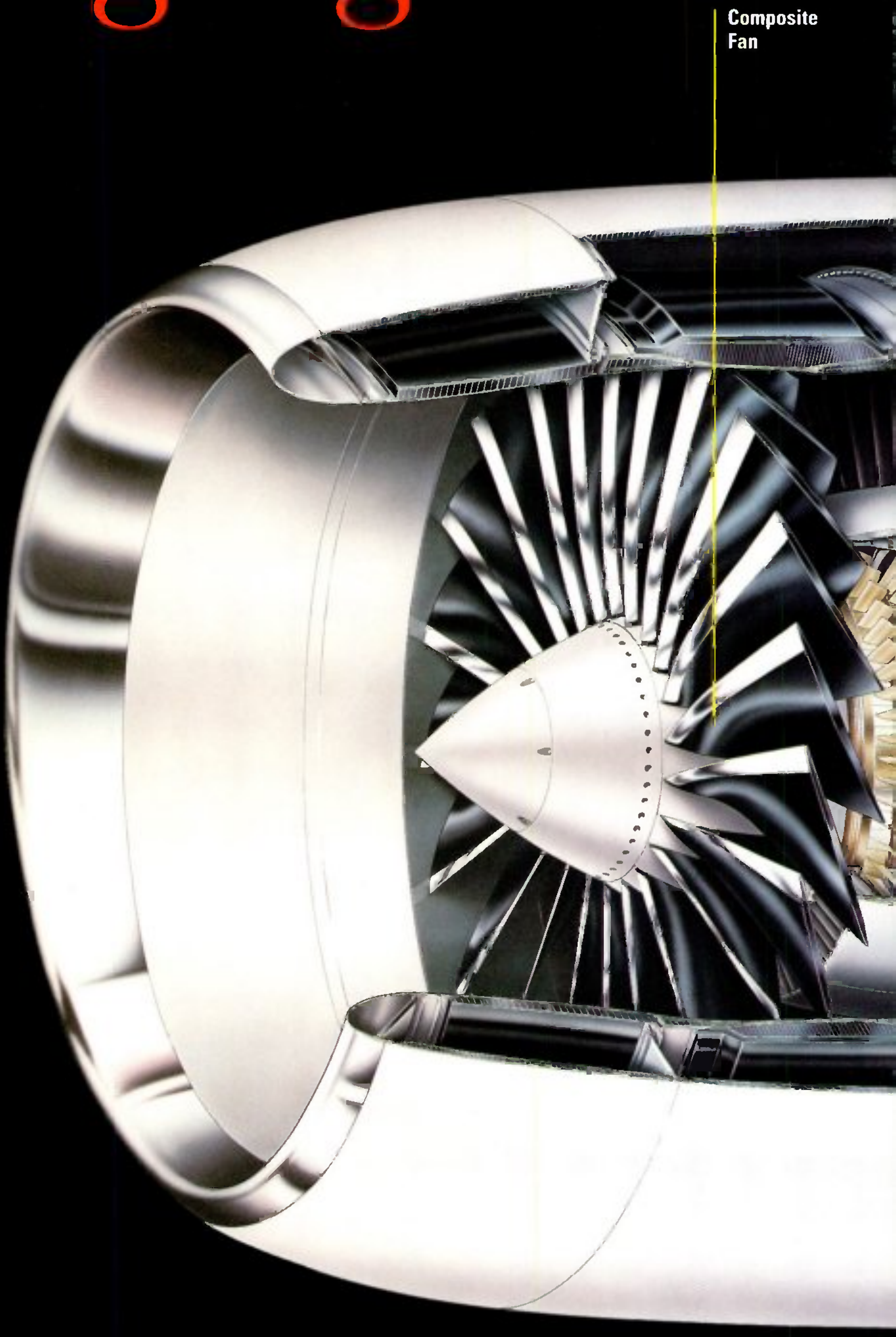
Lou DiBari *is Domestic Sourcing Manager*

Technology Highlights

Introduction

The concept of an all-new design for the GE90 has made it possible to deliver an engine which will be unsurpassed in fuel efficiency, emissions, acoustics and growth capability — all without sacrificing the proven reliability of today's engines. Cycle optimization has been unconstrained by derivative engine torque limitations on fan size, rotor speed or maximum thrust and is based on demonstrated component efficiency technology.

To achieve these goals the GE90 relies on key technologies which have been demonstrated well in advance of the first engine to test. Light weight, high durability composite fan blades, a dual-annular combustor with low emissions and improved operability, and efficient high pressure ratio cycles made possible by durable new single-crystal and powder-metal alloys combine to set the standard for the next generation of engines.



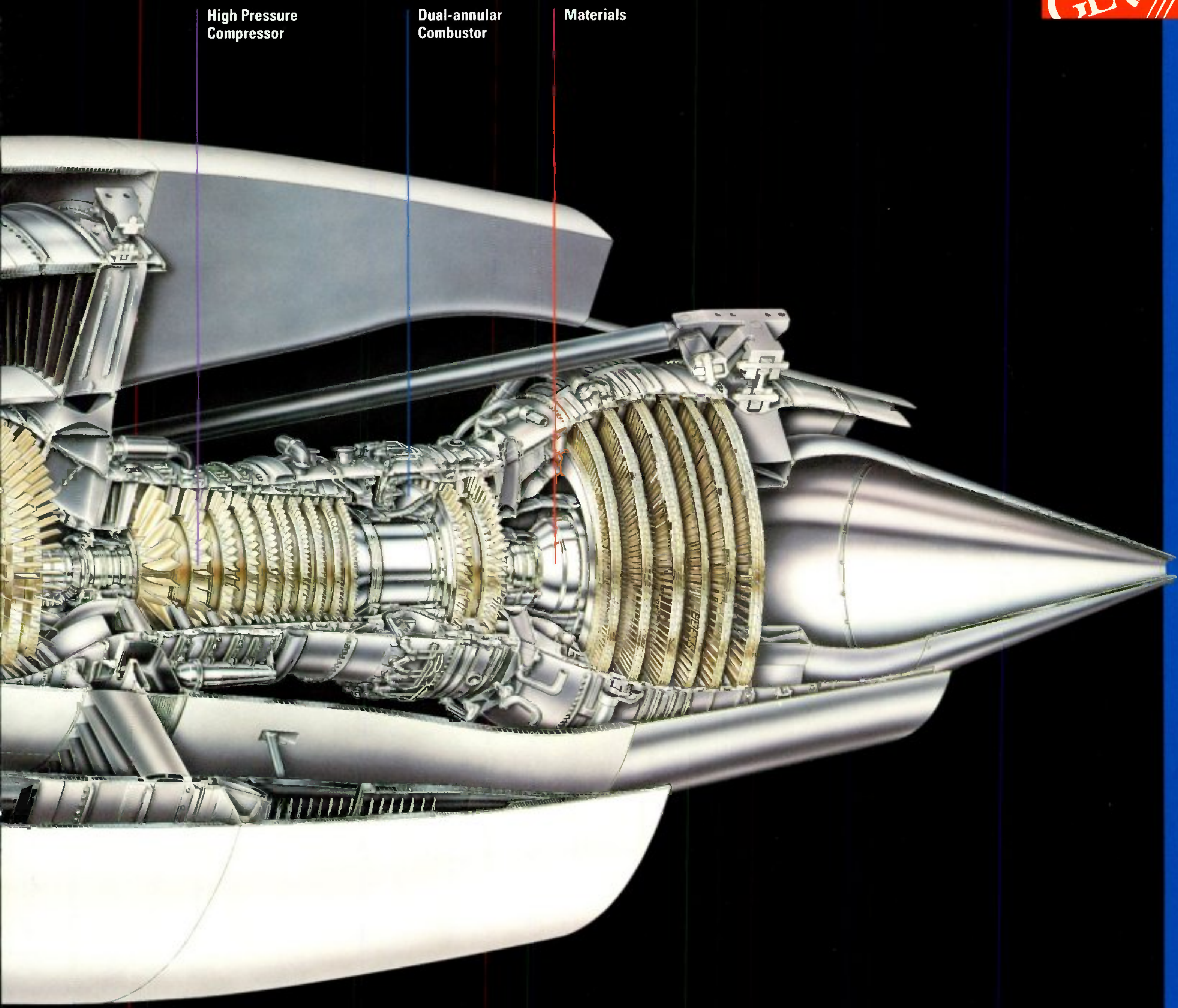


Figure 1: *The GE90 engine relies on proven, key technology advances that have been demonstrated well in advance of the first engine to test*

Technology
Highlights

Evolution of the GE90 Composite Fan

by Sidney B. Elston III

Engine designers have long been limited in their ability to increase bypass ratio and propulsive efficiency by the substantial engine weight penalties associated with larger fan diameters. The GE90's ultra-lightweight composite fan blade and fan case eliminate that obstacle.

S. B. Elston

As the GE90 trade studies evolved to configure and ultimately size the GE90 fan, it became apparent that the fan would require large blades with relatively low tip speed to achieve high propulsive efficiency. Composite materials in a wide-chord configuration provided an ideal solution to this design requirement that also increases durability levels, improves fan component efficiency and reduces noise.

Engineering trade study results showed that none of the desirable engine parameters that set performance, weight, durability and acoustics had to be compromised. The composite fan would enable these key engine operating parameters to be optimized. Perhaps most notable among the advantages realized through large, light-weight and slow-turning composite fan blades are their inherent damage tolerance. This tolerance provides substantial margins of reliability to both engine and aircraft.

Early work

Since the early 1970s, composite fan work has been part of GEAE development programs for the TF39 engine, F103 engine, QCSEE engine and, most significantly, the GE36 UDF® engine (Figure 2). These programs provided the engineering expertise needed to ensure the reliability of the GE90 composite fan.

For example, NASA's original concept for the GE36 featured highly-swept propeller blades to reduce penalties in performance and noise at high subsonic aircraft speed. GEAE took the concept further by successfully testing an aeroelastically stable blade design that was light enough to be used on subsonic commercial aircraft. This was achieved by using computational

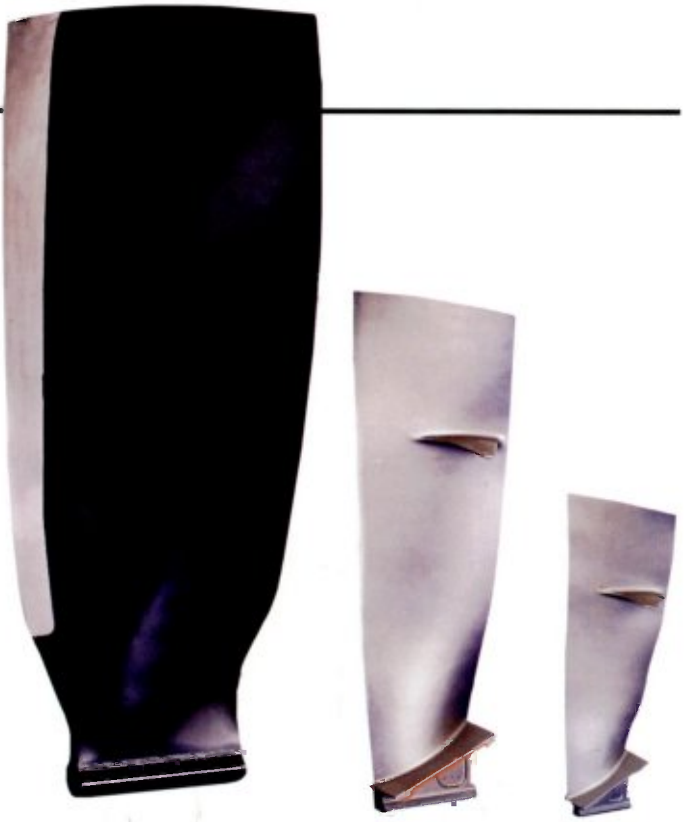


Figure 1: *Relative fan blade size of the GE90, CF6 and CFM56 engines*

Figure 2: *The GE90 fan combines 25 years of GE composites development with the advances achieved in materials and analysis technology*

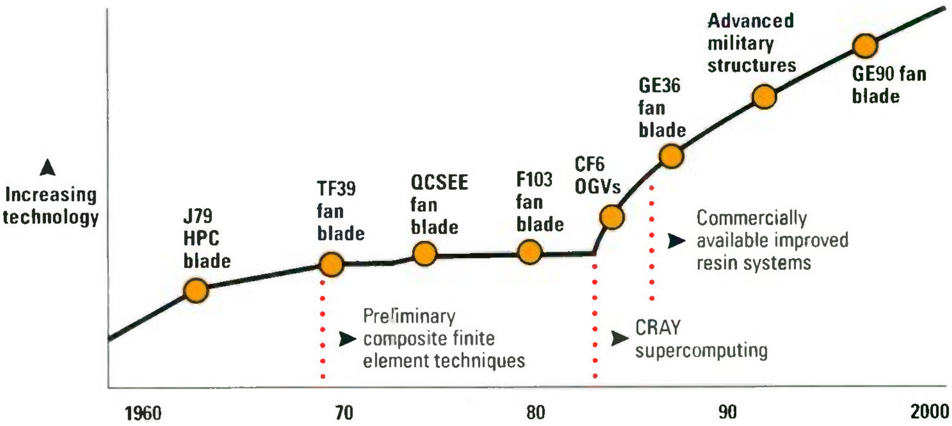


Figure 3: *Robotic techniques being adapted by GE Aircraft Engines and Cincinnati Milacron will replace manual manufacturing methods for GE90 fan blades*

structural analysis which enabled the full use of the directional stiffness variation characteristics of the composite material.

However, the GE90 engine required different technical considerations. Whereas aeroelastic stability was the key technical obstacle to overcome on the GE36 engine, bird impact at the higher tip speeds and incidence angles of a fixed-pitch fan blade were the main concern for the GE90. Thus, specific technology advances which had accrued since the trials of the GE36 engine in the 1980s were refocused for the GE90 engine composite fan. Highlights of two key advances follow.

Materials: Composite rotorcraft blades have been successfully used on helicopters and commuter aircraft for many years in the subsonic tip speed regime (< 750 feet per second). By comparison, the GE90 operates with engine tip speeds in the vicinity of 1200-1300 feet per second (the speed of sound at sea level is approximately 1100 feet per second).

Toughening agents in improved resin systems offer roughly three times the shear strain capability and delamination suppression of conventional "brittle" epoxy systems in service on existing rotorcraft. These resins permit hard-body impact-ruggedness and fatigue resistance equivalent to existing rotorcraft, but at GE90 engine tip speeds where impact forces, proportional to the square of the tip speed, are roughly three times higher:

$$\text{Force} \sim \left[\frac{1{,}250}{750}\right]^2 = 2.8\text{X}$$

As a result, the composite blade tests have demonstrated a dramatic capability for damage tolerance, even on blades inflicted with damage well in excess of expected service levels.

Manufacturing: Until recently, virtually all composite fan development in industry has been conducted with manually constructed blades. Plies are cut to shape from unidirectional sheets, placed in sequence to one another to achieve the full blade thickness, and then compacted in a vacuum bag to consolidate stacking. Traditionally, this work is all done by hand. This technique results in some blade-to-blade variation in the final placement and orientation of the composite plies.

The GE90 program is trying to minimize this variation by using robotic manufacturing techniques similar to those used to construct missile casings and large airframe structures. Cincinnati Milacron and GEAE are adapting these techniques for the GE90 engine fan blade. Figure 3 shows two blades being simultaneously constructed by the Cincinnati Milacron process. The robotic technique for fiber placement will eliminate the manual lay-up and vacuum compacting of previously manufactured blades, while reducing time and cost. This robotic technique is scheduled for introduction following the initial certification of the GE90 engine.

GE90 fan blade description

Unlike a conventional CF6 blade, the GE90 blade is a wide-chord design without a mid-span shroud. The fan blade is an all-composite design, with the exception of a titanium leading edge guard. It is made of a material system which consists of intermediate modulus fibers in a toughened resin system. The titanium leading edge guard is attached to the leading edge of the composite airfoil for erosion protection. A polyurethane coating is bonded to the surface of the airfoil for protection against erosion, ultra-violet light and aircraft fluids. The dovetail of the blade is also made of composite material with a single outer ply of dry bearing material to prevent wear; no dovetail coating or dry film lubricant is required.

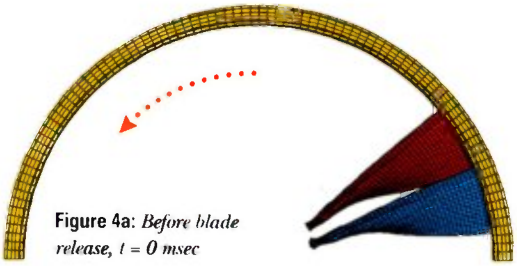


Figure 4a: *Before blade release, t = 0 msec*

Figure 4: *A thorough analytical approach with the use of DYNA-3D ensures predictable test results, with the lowest overall program costs and development cycle time*

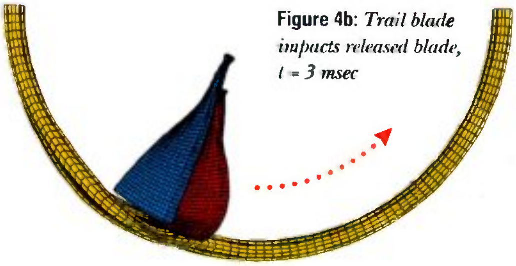


Figure 4b: *Trail blade impacts released blade, t = 3 msec*

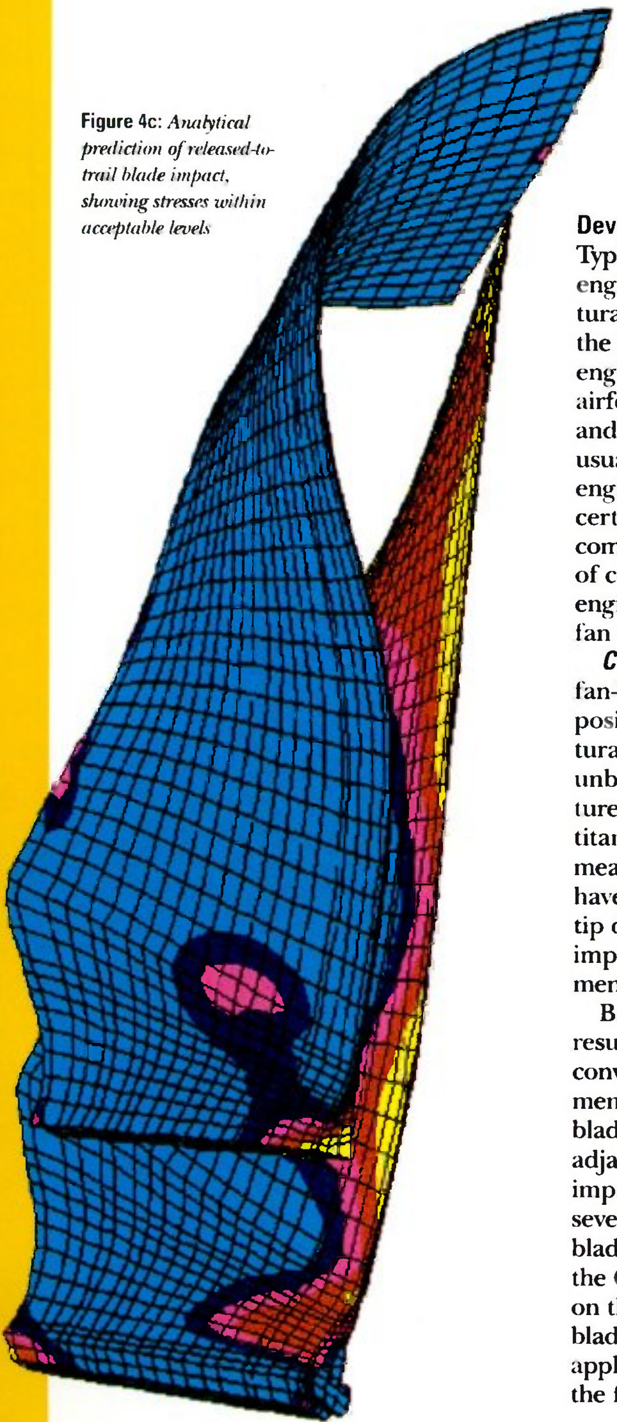


Figure 4c: *Analytical prediction of released-to-trail blade impact, showing stresses within acceptable levels*

Development status

Typical development cycles for fan engines include two major fan structural tests: 1) Fan containment, which the FAA requires to show that the engine structure will contain released airfoil parts and safely shutdown; and 2) Bird ingestion. These tests are usually conducted between the first engine to test (FETT) date and the certification date. However, the GE90 composite fan warrants a multitude of component tests prior to the actual engine certification tests to ensure fan success.

Containment capability: Successful fan-bladeout testing requires the composite blade design to provide structural assistance by transmitting rotor unbalance load into the casing structure after a blade is released. As with titanium blade requirements, this means that the composite blade must have adequate buckling strength and tip durability, as well as secondary impact resistance and overall containment system effectiveness.

Based on experience from test results for GE90 large-bird impact and conventional titanium engine containment, it is important to design the blade retention system to withstand adjacent blade root forces as they impact the released blade. In fact, several patentable design features for blade retention were introduced by the GE90 design team based purely on the sophisticated analysis of the fan bladeout event that was rigorously applied in the 18 months preceding the first test.

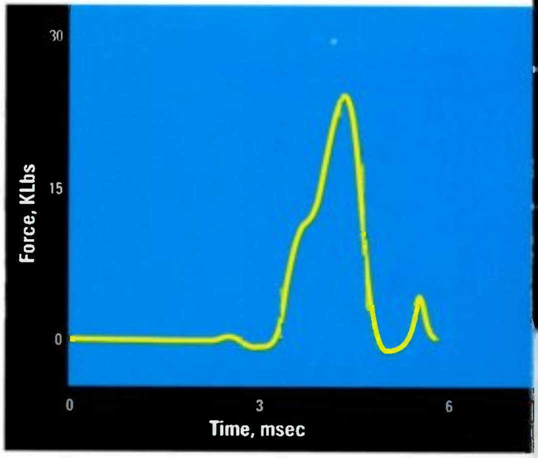


Figure 4d: *DYNA-3D prediction for trail blade root load, due to secondary impact, ensured successful blade retainer design*

This up-front scrutiny paid off: the composite containment tests have performed exactly as predicted (Figures 4 and 5). The blades met all the durability requirements established for minimal secondary damage and rotor imbalance forces. Furthermore, after testing, it was clear that the released blade had been reduced into relatively harmless debris. This demonstration of dramatically reduced fragmentation energy represents a significant improvement to both engine and airframe reliability.

Bird impact capability: The GE90 design team faced a significant challenge: designing the world's first successful composite fan while also adhering to the increased bird ingestion guidelines recently imposed by the FAA which essentially double the bird size of previous fan blade requirements. A key to the effort's success has been the recent introduction of composite finite element techniques coupled with super-computing capability. This combination enabled GE90 design engineers to identify and improve the blade and retention design features determined to be critical during impact events.

As a result of 2 1/2 years of iterative testing and analysis, GEAE has demonstrated that the GE90 composite blade can meet the new FAA medium (2.5 lbs.) and large (8.0 lbs.) bird ingestion requirements. More impact tests will be performed to verify the effects of impact locations, design improvements such as ruggedized leading edge guard designs and manufacturing processes.

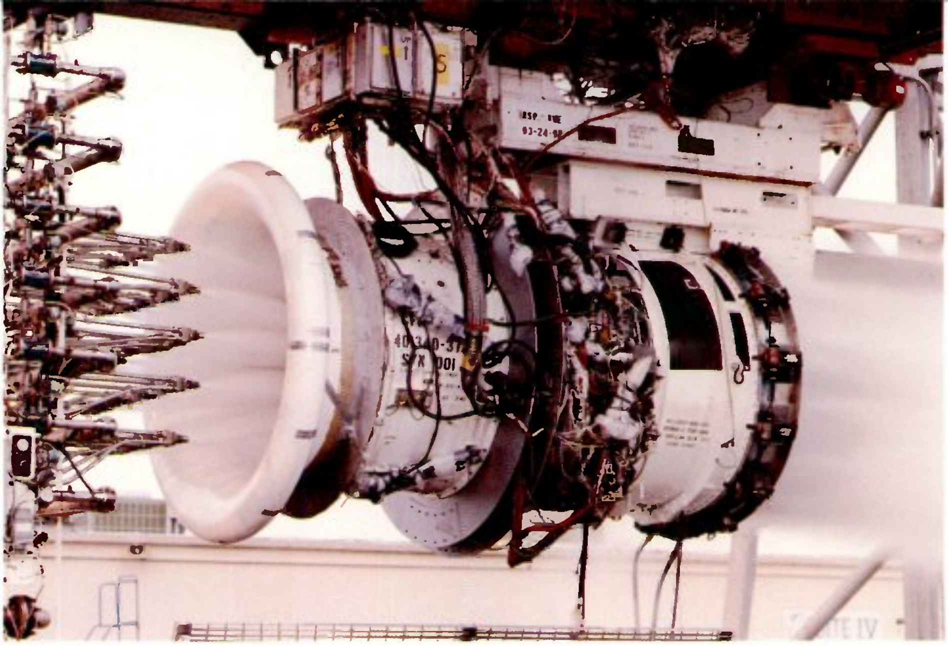


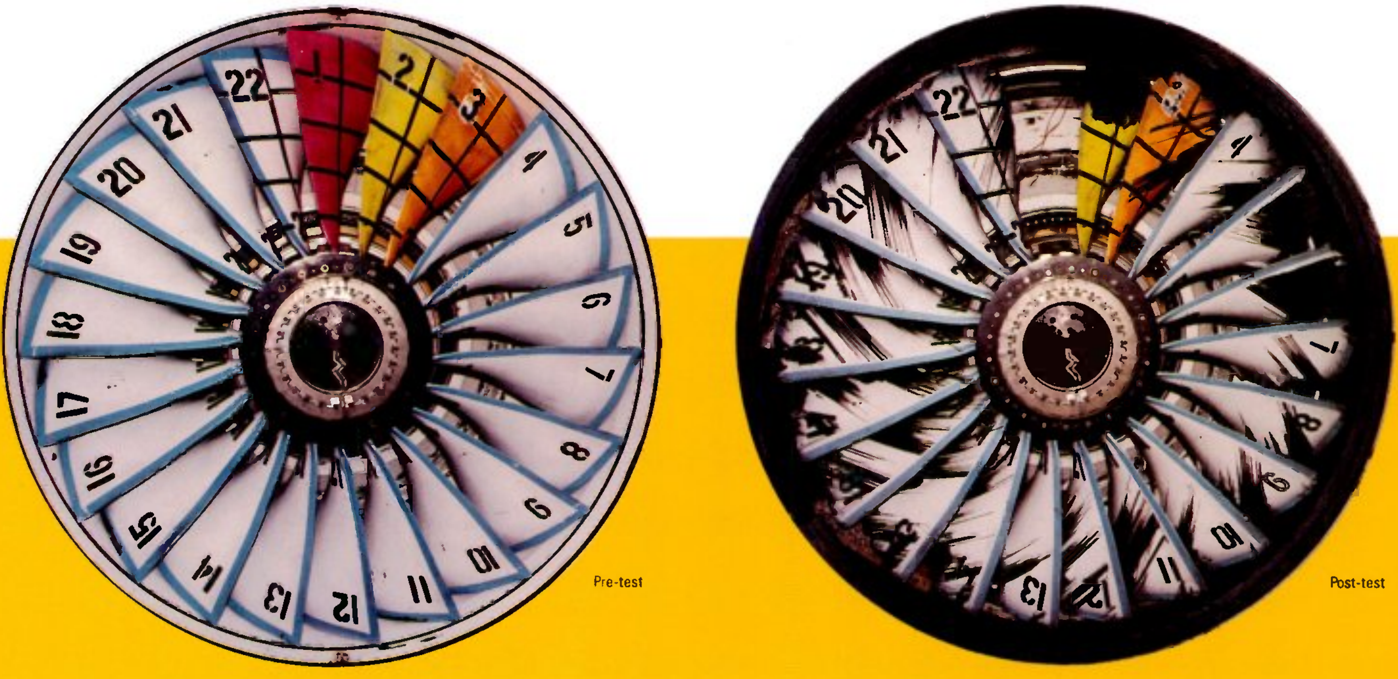
Figure 6: *Severe rain and hailstone ingestion tests demonstrate the composite fan blade's tolerance to inclement weather*

Additional tests to demonstrate inclement weather tolerance were performed at GEAE's outdoor test facility in Peebles, Ohio (Figure 6). In this series, a CFM56-3 engine was fitted with 22 wide-chord composite fan blades and subjected to severe rain and hailstone ingestion. The fan blades were constructed of the same leading edge and composite materials as planned for the production GE90 blade. After more than an hour of monsoon rain ingestion at takeoff (225 gallons per minute, exceeding five years of equivalent airline service), and 15 minutes of descent, idle and takeoff hailstone ingestion (1 lb/second, total 900 lbs. of hail), the blades were completely free of any damage or erosion whatsoever. The same engine will be fitted with a set of composite blades that more closely represents the final production design. This configuration is scheduled for cyclic endurance testing by SNECMA as part of their contribution to the GE90 development program.

To date, the GE90 composite fan blade has met or exceeded all of its design requirements. With additional verification testing planned, the same analytical techniques proven accurate by test are predicting continued success in this key technology program.

Sid Elston *is Manager, GE90 Low Pressure Turbomachinery Systems*

Note: *Safety equipment in Figure 3 may have been removed to illustrate the product and must be in place prior to operation*



Pre-test

Post-test

Figure 5: *Fan bladeout imbalance and secondary impact forces were within predicted levels, proving blade and retention design adequacy*

Technology Highlights

The Blended Design of GE90's Dual-annular Combustor

H. S. Roberts

By Hubert S. Roberts

Figure 1: *GE90's dual annular combustion system blends the characteristics of two different combustors, each optimized for different operating regimes*

The GE90 dual-annular combustion system offers significant reductions in emissions, improved operability and reduced engine length.

A conventional single-annular combustion system could have been designed for the GE90 to meet existing International Civil Aviation Organization (ICAO) emissions standards. However, GEAE believes social responsibility mandates the use of the most environmentally acceptable technology in its new engine and that airline customers will be inspired to select and use the most environmentally superior product. We believe that this fact will be recognized by the aviation industry even before government regulatory agencies mandate more stringent emissions requirements.

Based on component test data, significant emission reductions are predicted for the GE90 double-annular combustor as compared to a single-annular design. Reductions of more than 50% in unburned hydrocarbons (HC), carbon monoxide (CO), and smoke levels, as well as a reduction of more than 35% in nitrogen oxides (NOx) levels, are projected for the GE90 when compared to the current generation of high bypass fan engines.

The double-annular combustor will achieve these emissions reductions—and improve operability—by blending the characteristics of two different combustors, each optimized for different operating regimes. At low (idle) power conditions, only the outer (pilot) annulus (Figure 2) of the combustor is fueled, resulting in favorably high fuel-to-air ratios. This permits the outer dome to be tuned to minimize low power emissions, specifically CO and HC, and to operate with good starting, altitude relight and approach power flameout characteristics. These operability characteristics are further enhanced by designing the outer dome with low air velocities

At all high-power operating conditions both the outer (pilot) and inner (main) annuli shown in Figure 2 are fueled. Since the inner dome operates only at high power conditions, it is designed to minimize NOx and smoke emissions. This is accomplished by designing this dome with lean fuel-to-air ratios. The lean mixtures are obtained by introducing a large fraction of the total combustor airflow into this dome. The high airflow further reduces NOx levels by reducing residence (burning) time.

A burner staging valve (BSV) inside the engine's hydromechanical unit (HMU) controls staging of the combustor by turning the fuel flow to the inner annulus on and off. The BSV also controls the fuel flow splits to the outer and inner domes for optimum emissions control and operability. This BSV is controlled by the full authority digital electronic control (FADEC) unit. The

FADEC monitors parameters such as combustor inlet temperatures and pressures, engine speeds and throttle positions to determine the staging conditions for the combustor.

The dual-annular fuel nozzles are designed for reliable performance and operability. Hydraulically, the two systems within each nozzle are very similar to a fuel nozzle for a single-annular combustor with one exception. A portion of the fuel in the outer dome circuit flows through an internal heat exchanger designed to cool the stagnant fuel in the inner dome circuit during outer annulus only (idle power) operations. The cooling fuel then flows into the outer dome as scheduled. This design prevents the non-flowing fuel from coking in the small passages in the inner nozzle circuitry which would affect performance and emissions. The fuel nozzles were concurrently designed by GEAE and Parker-Hannifin and are manufactured by Parker-Hannifin.

Optimizing air flow

A key design feature of the low emissions combustor is the higher quantity of core air introduced through the two domes to reduce NOx levels. Increased availability of combustor airflow for this purpose has been achieved by combining a modern, long-life combustor liner material with an efficient multi-hole film cooling design to reduce the required liner cooling air flow (Figures 3 and 4).

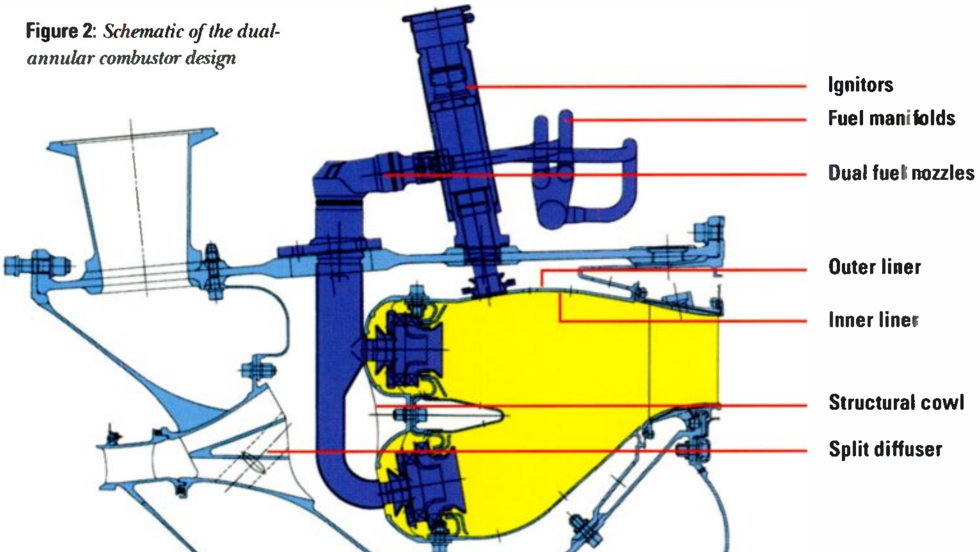
The liner material is GTD-222, a GE alloy. The material has enhanced castability, formability and weldability, making it easier to produce and repair the combustor liners. GTD-222 also provides superior yield and creep properties compared to conventional combustor alloys to avoid buckling problems.

Figure 3: *The GE90's long-life combustor liner is easier to cast, form, weld and repair*

The inner and outer liners are fully machined from centrifugally cast rings that have properties similar to forged material. The structural, investment cast cowl is also produced from GTD-222. This structure prevents axial buckling and collapsing of the double-annular dome due to high pressure loads from the compressor discharge air.

A multi-hole, film-cooling concept provides efficient cooling for the GTD-222 liners. The thin shell liners contain a large quantity of small holes that are laser-drilled at compound angles to the surface and engine axis. Staggered rows provide the best trade-off between cooling effectiveness and thermal gradients. Average cooling effectiveness for this design is 0.90 versus approximately 0.70 in a conventional design for a slot cooled liner.

Figure 2: *Schematic of the dual-annular combustor design*



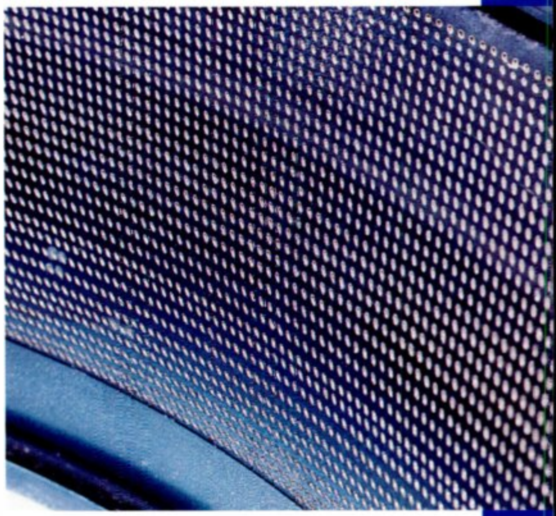


Figure 4: *Close-up of multi-hole film cooling design*

The acute angle to the surface produces a very long hole which, through the benefit of a large hole surface area, allows cooling to be achieved with a small amount of air. The surface-to-axial angle improves film spreading when the cooling air exits the holes onto the hot gas path surface of the liner. This gives a more uniform coverage and even film distribution than the early axial discharge configurations. This shape also reduces the stress concentration factor at the multi-holes, thereby enhancing the fatigue life of the liners.

Multi-hole cooling of the GE90 liners requires 40% less cooling air than the conventional liner designs. This air is used in the dome flow to reduce NOx emissions.

Development of dual-annular combustors technology began in the early seventies and is now fully ready for introduction into the GE90. The dual-annular combustion concept has been demonstrated in the Energy Efficient Engine (E^3) and an advanced military engine. Multi-hole film cooled liner designs have also been demonstrated in advanced military engines. These proven concepts have been combined to provide a combustor design that will significantly reduce emissions and improve operability in the GE90.

Hu Roberts *is Team Leader, GE90 Combustion Design*

Technology Highlights

88DT

RENÉ N5

Materials Development for the GE90

By Robert E. Allen

The performance benefits of high overall pressure and high bypass ratios led GEAE to develop second-generation powder-metal alloys for discs and single-crystal alloys for turbine airfoils in the early 1980s. These efforts resulted in the unique alloys named René 88DT and René N5, which are used, respectively, in the GE90 rotor disks and high pressure turbine (HPT) blading (Figures 1 and 2).

R. E. Allen

Figure 1: *In production since 1988, R88DT is the best high-temperature rotor material for today's engines*

Figure 2: *Experience in production military engines demonstrates that Rene' N5 is the most oxidation-resistant alloy for high pressure turbine airfoils*

Highly reliable R88DT

R88DT was designed to be defect-tolerant. The development program builds on 15 years of production and operation experience with powder metal for rotor hardware in both military and commercial engines. Currently more than 10,000 GEAE engines are in service with rotor parts made from powder metal.

R88DT alloy was designed to increase creep capability by 200°F over the conventional rotor alloy DA718, while improving defect tolerance over our first generation alloy, René 95. To reach this objective, 120 different alloy chemistries were screened by computer simulation of properties and 50 alloys were produced and tested to select the final chemistry for R88DT.

An extensive heat treatment study also was conducted. When the results of this study were applied to the selected alloy, the material yielded an outstanding combination of creep, defect tolerance, tensile strength and "hold time" crack-growth resistance (Figure 3). In fact, R88DT not only provides the capabilities required for the compressor discharge temperature for the baseline GE90 certification requirements, but also has the margin necessary for growth to higher thrust levels.

Reliable performance of R88DT has been assured through ultra-clean powder-processing methods recently developed and introduced into production. Reliability is further enhanced by a process which extrudes the ultra-clean powder into dense fine-grained billets followed by isothermal forging to produce the desired disk shape. This combination of chemistry, heat treatment and advanced metal-working processes enhances the reliability of R88DT. In production since 1988, R88DT is the best high-temperature rotor material for today's engines.

Unique chemistry of N5

The selection of N5 for HPT airfoils brings the most oxidation-resistant alloy ever used in turbine blades to commercial service. Experience in production military engines has given us confidence that the unique N5 chemistry is castable in the complex configurations found in today's airfoils.

Advancements in casting technology enabled the use of the element yttrium in the alloy. This element has demonstrated beneficial effects on both oxidation and hot corrosion resistance. However, it was precluded from turbine blade use because of its chemical reactivity with the SiO_2 ceramics used in the casting process. Now, yttrium can be used in N5 thanks to nonreactive casting ceramics that have been recently developed. This combination provides a significant 250-300°F increase in oxidation resistance over the DS R80H material used in early CF6 engines (Figure 4). Since oxidation of turbine blade tips is a key contributor to the deterioration of engine performance, this significant attribute of N5 will play an important role in GE90 durability.

In addition to its outstanding environmental resistance, N5 brings a 50°F increase in stress rupture and fatigue capability. This increase raises the operating temperature capability of the turbine inlet by 136°F. A comparison of the capability of GE directionally solidified and single-crystal alloys to withstand oxidation, low-cycle fatigue and stress rupture is shown in Figure 4.

The figure also shows N6, an alloy 50°F stronger than N5 which is currently being scaled up for production in advanced military turbine applications. Production readiness is scheduled for 1995. The chemistry of N6 is an extension of the technology developed in N5. The key strengthening element in N6, like N5, is Rhenium. Rhenium, which has a very high melting point and a large atomic radius, imparts excellent high-temperature strength and stability when added as a strengthener to these nickel base alloys.

N6 derives much of its improvement in strength from the fact that it contains almost twice as much Rhenium as N5. As in N5, N6 oxidation resistance originates from the addition of yttrium.

Figure 3: *Rotor-alloy evolution*

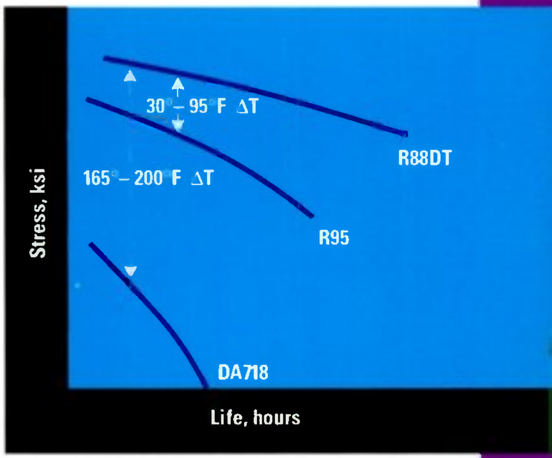
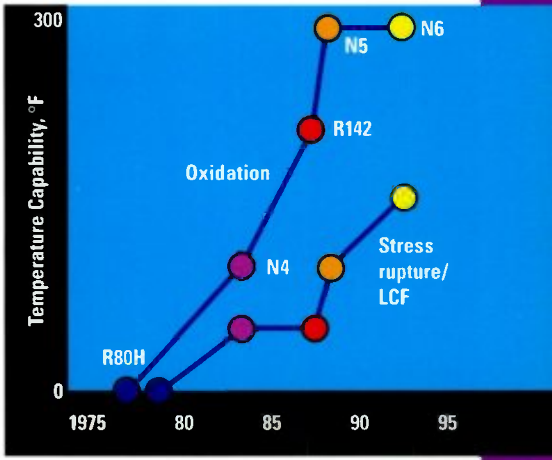


Figure 4: *Blade alloy evolution*



Development engine testing of N6 is in progress and, while still early, results to date are very encouraging. Growth versions of the GE90 will benefit from the additional increase in turbine inlet temperature enabled by this development. Both the original and the growth version of GE90 will benefit from the fact that N5 has been in production since 1988 and that both of these alloys are producible at the major turbine airfoil casting suppliers.

Bob Allen *is Department Staff Engineer, Engineering Materials Technology Laboratories*

Technology Highlights

Origins of the GE90 High Pressure Compressor

By Roger C. Walker

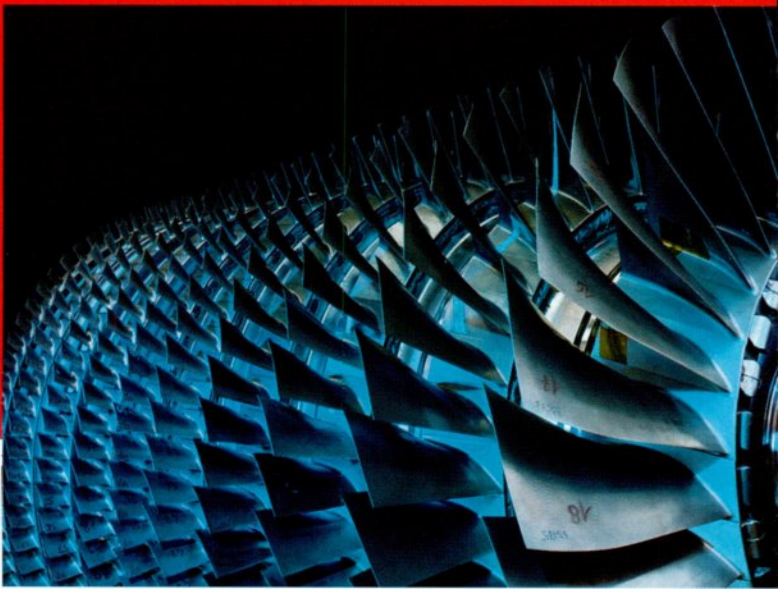


Figure 1: *Based on the E^3 engine, the GE90's high pressure compressor features a compact, 10-stage, single spool design*

The GE90 high pressure compressor (HPC) is based upon an aerodynamic scale-up of the compressor developed for the successful NASA/GE Energy Efficient Engine (E^3) and is being designed by SNECMA. This design continues to set the standard for high pressure ratio (23:1) with a compact, 10-stage, single-spool machine (Figure 1). The E^3 HPC was selected for the GE90 because of its high compression ratio and proven operability characteristics.

R. C. Walker

High core pressure ratio provides the GE90 with two important advantages. Limiting the amount of boost required for the cycle design overall pressure ratio means fewer booster stages are required. This will, in turn, result in lower operating temperatures in the low pressure turbine (LPT) due to the reduced demand for low pressure horsepower. Increased power extraction in the high pressure turbine (HPT) yields lower LPT inlet temperatures. Therefore, lower cost, uncooled LPT blades and vanes can be used, even at thrust levels greater than 100,000 lbs.

In more than 250 hours of component and engine testing, the E^3 compressor (Figure 2) has demonstrated satisfactory starting, stall free engine transients, 19% design speed stall margin, and excellent stator tracking. With high-speed, low aspect-ratio blading, the E^3 compressor achieved a respectable adiabatic efficiency, while meeting all of its pressure ratio, flow, capacity and aeroelastic stress and stability goals. The design and manufacture of the GE90 HPC is the responsibility of revenue sharing participant SNECMA. In addition, SNECMA is responsible for the booster, control and accessory components and configurations hardware.

Solid foundation

The E^3 HPC—a proven design—provided a solid foundation for the mechanical design of the GE90 HPC. Lessons learned from other engines such as the CF6 and CFM56 were also considered during the design cycle. The resulting mechanical design of the GE90 HPC is expected to demonstrate high reliability, long life and high efficiency in development engines. Advanced mechanical features in the GE90 HPC include clearance control in the aft stages, advanced sealing and roundness control, innovative bleed air systems, high-temperature rotor materials and ruggedized components.

The GE90 HPC blades and vanes are direct scale ups of the E^3 with minor changes for aeromechanical reasons due to small changes in maximum speed and temperature from the scaled E^3. The airfoils are electrochemically machined to obtain small airfoil toler-

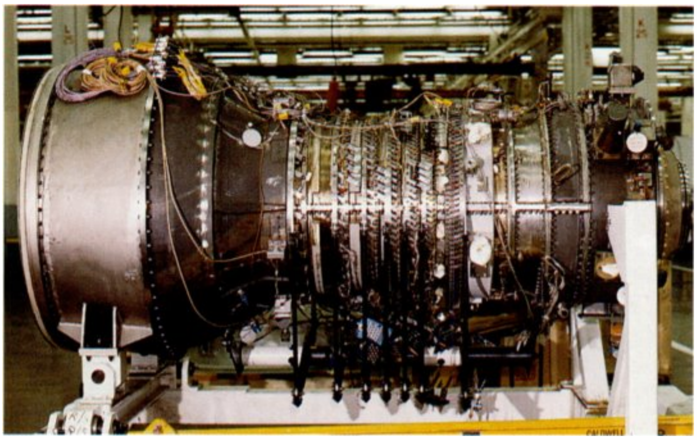


Figure 2: *The E^3 design, proven in more than 250 hours of component and engine testing, provided a solid foundation for the GE90's high pressure compressor*

Figure 3: *The high pressure compressor's stage one disk features a steel design to enhance durability*

ances and repeatable good performance. Aft stator vanes are a brazed construction similar to that of the CFM56 which has proven to be a durable design that provides excellent aerodynamic performance.

In order to ensure durability, a steel design was selected for the stage one disk (Figure 3) which incorporates lessons learned from other commercial engine programs. It was selected to ensure that the low-radius-ratio, wide-chord, high-tip-speed design of the stage one blade could achieve the required strength at the disk post and blade dovetail (Figure 4).

In addition to a steel stage one disk, the GE90 rotor has a titanium spool for stages two through six, an INCONEL® 718 alloy/R88DT spool for stages eight through 10, and a single bolted joint at stage seven. High-temperature titanium is used for the rotor structure and blades on stages five and six. Using high-temperature titanium eliminated the need for a second bolted joint forward of stage seven and significantly reduced the weight of the rotor structure. The aft two stages of the rotor feature R88DT disks and UDIMET® 720 alloy blades to ensure high-temperature capability.

The rotor structure has been carefully designed to minimize its weight and maximize its stiffness by positioning the spacers as far outboard as possible. This design ensures that all rotor loads have direct loading paths without discontinuities. Tapers are used to maximize stiffness and reduce stress in areas of high loads. The high bore diameter to spacer diameter ratio of more than 3:1 was achieved by improved production processes. This design reduces overall rotor weight beyond that achieved by the more typical 2:1 ratio.

Cooling

The forward stages of the HPC rotor spool are cooled by low pressure, low temperature air. This design is similar to that of CFM56 and CF6 engines. The aft rotor stages are cooled by higher pressure, higher temperature air. A series of rotor bleed slots (similar to production military engine designs) duct the air directly from the flowpath to the rotor bore aft of the stage seven blade. There are three important advantages to this rotor bleed arrangement:

1. Cooling air is delivered to the second stage turbine blade at a reduced cost to the engine cycle (lowest pressure air possible to cool the blade). Also, no labyrinth seal leakage occurs since no rotating seals are in the system.

2. The high temperature air in the compressor bore reduces the rim-to-bore thermal gradient, reduces mission stresses and increases the life and reliability of the rotor.

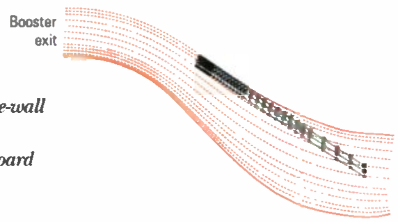
3. The high temperature, high pressure bore air increases the rotor temperature and speeds the thermal response of the disks. This enables improved thermal matching capability between the rotor and the stator, resulting in good clearance control at the blade tip.

The original E^3 demonstrated effective clearance control in the aft HPC stages, with measured HPC efficiency improvement for the system exceeding +0.5 points. The GE90 has enhanced this clearance control system by incorporating improved thermal matching that has been demonstrated on the CF6 and CFM56 high pressure turbines. The enhanced GE90 design increases operating efficiency, improves start/stall characteristics and reduces turbine inlet temperatures.

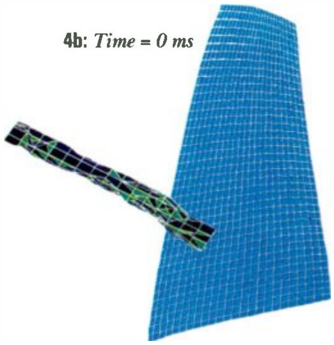
While the rotating machinery is controlled by seventh stage air, the casing design uses fourth-stage bleed air, which is directed across the aft inner compressor casing outer surface prior to being ducted aft to the low pressure turbine. By using bleed air already required for turbine cooling, HPC casing temperature can be controlled without penalty to the engine cycle due to air losses from parasitic bleed.

The fourth-stage bleed air controls the casing temperature, as well as its transient thermal response to achieve better thermal matching of the stator and rotor. The thermal matching achieves good blade tip clearances throughout the engine operating range. This design also protects the HPC from deterioration due to blade tip rubs during transient operation. The aft compressor inner and outer compressor casings are also full round (no split flanges) to minimize flowpath distortions and clearance loss.

Roger Walker *is Manager, GE90 Booster/HPC Participant Programs*



4a: *High slope-wall directs bird trajectory inboard*



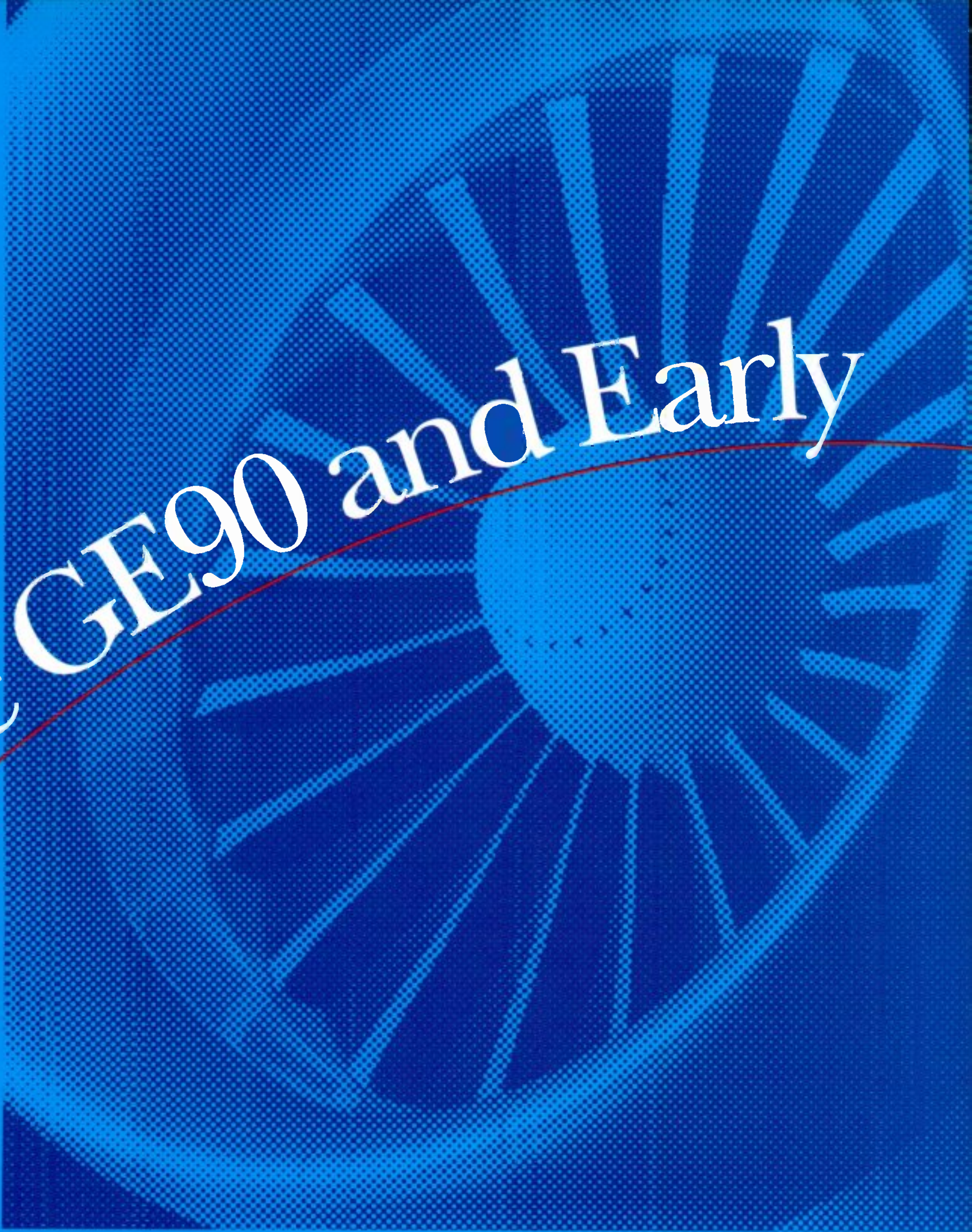
4b: *Time = 0 ms*

4c: *Time = 0.1 ms*

4d: *Time = 0.6 ms*

Figure 4: *The same analytical techniques proven on composite fan blade development also predict enhanced HPC blading durability*

The GE90 and Early



O

G. M. Pirtle

ETOPS 180

By George M. Pirtle

Building on its base of proven technologies and reliable experience, GEAE has developed an aggressive program to ensure the GE90/B-777 receives 180-minute Early-Extended Twin Engine Operations (E-ETOPS) approval at its entry into service. This type of approval, which will be a first for a new GEAE engine, will provide greater flexibility to the airline customers which purchase the GE90-powered B-777 aircraft.

ETOPS background

ETOPS approval must be granted before an airplane is allowed to operate on routes that might require more than 60 minutes flying time, with one engine inoperative, to the nearest suitable alternate airfield. Specific levels of demonstrated reliability, expressed in In-Flight Shutdowns (IFSDs) per 1,000 engine flight hours (EFH), are tied to specific levels of approval, expressed in minutes of diversion time to the alternate field.

These levels of reliability are derived from studies which assess the risk of total thrust loss of both engines due to independent causes as a function of reliability and diversion time. The resulting risk must be extremely remote for approval to be granted. For example, the FAA reliability requirements for approvals of less than or equal to 120 minutes is 0.05 IFSD/1,000 EFH. For approvals of greater than 120 minutes up to 180 minutes (the current maximum allowed by the FAA), the reliability requirement is 0.02 IFSD/1,000 EFH.

The approvals are further divided into Type Design Approval (TDA) and Operational Approval. Type Design Approval is based on the ability of the airplane/engine combination to maintain the appropriate reliability level. Operational Approval, which is airline specific, is tied to a specific airline's ability to maintain and operate the airplane consistent with ETOPS requirements.

ETOPS approval is currently based on demonstrated reliability; 250,000 hours of operation must accumulate before 120-minute approval is granted and one year of 120-minute operation must be accumulated before 180-minute approval is granted. The B-777/GE90 Early-ETOPS program initiative is unique in that the program is committed to obtaining 180-minute Type Design Approval for the airplane/engine combination and to assist British Airways in obtaining 180-minutes Operational Approval, both immediately upon entry into service (EIS).

Getting there early

In order to achieve the E-ETOPS goal, adequate "compensating factors" must be substituted for in-service experience. One critical compensating factor unique for the GE90-powered B-777 is the inherent capability of current GEAE processes and procedures to produce an engine that meets the reliability requirements for 180-minutes ETOPS

The GE90 and Early ETOPS

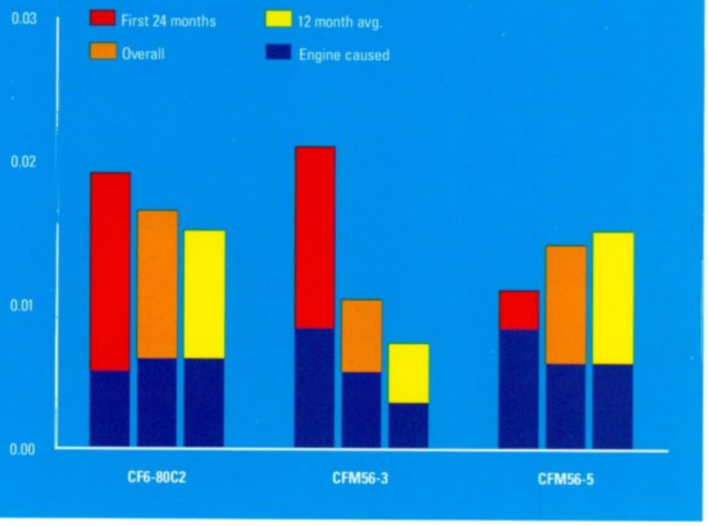


Figure 1: *Based on the GE90 approach, the CFM56-3 and -5 and the CF6-80C2 engines would have met the requirements for Early-ETOPS approval*

at EIS (Figure 1). Based on this approach, the CFM56-3 and -5 and the CF6-80C2 engines would have met the requirements for Early-ETOPS approval.

One of the basic requirements (and perhaps the most important) for Early-ETOPS approval is the ability to predict, to the satisfaction of U.S. and European regulatory authorities, an IFSD rate at EIS that is equivalent to that normally required to be demonstrated in-service.

To accomplish this, the GE90 program is developing a Reliability Assessment Manual. This manual will provide a disciplined and consistent approach to be used by GE90 engineering personnel to predict the EIS reliability of the components, sub-systems and propulsion system.

This approach will consider previous engine development and EIS experience, design analysis, testing, problem resolution and maintainability improvements. The basis for the analysis will be reliability growth modeling. Reliability growth occurs through systematic identification and resolution of problems. This is generally accomplished through a closed-loop corrective action procedure, commonly called Test, Analyze and Fix. Data for this loop are provided by the enhanced GE90 Development Problem Reporting System. Both the preliminary outline of the Reliability Assessment Manual and the basis of the GE90 analytical methods have been well received by regulatory authorities.

Data points to lessons learned

By focusing on "lessons learned," the GE90 can preclude repetition, through design and test enhancements, of IFSDs which occurred on previous programs. In order to accomplish this, IFSD root causes must be determined using GEAE and CFMI experience bases. Data were gathered on the CF6-50, -80A, -80C2, and the CFM56 engine families. All IFSDs, refused take-offs, and loss of thrust control events from 1970 to the present were analyzed.

For every relevant event, each design team:

- Determines the root cause
- Analyzes for applicability
- Determines GE90 corrective action
- Determines appropriate analytical and test verification
- Reviews all of the above at a Chief Engineer's Design Review

The teams will document the closure of all relevant events with an "Evidence of Completion" report. Results of this entire process will then be compiled and delivered to the regulatory agencies.

After reviewing the initial data, GEAE met with Boeing to determine, together, the root cause of IFSDs for early in-service experience with GEAE engines on Boeing airplanes. A study of this particular set of data indicates the need for extensive integrated full propulsion system testing (everything below the wing), as well as a comprehensive maintenance development program.

This need will be addressed with a maintenance development program which is thoroughly integrated into the GE90 development testing plan. A major point of this program is the requirement that all maintenance and service activity from the beginning of testing is to be completed "by-the-book" with the draft manuals and production configuration field tooling. This will enable experienced GEAE test technicians to provide significant input to the process. British Airways maintenance personnel have also been invited to participate in the maintenance development (Figure 2), thereby ensuring that the manuals and tooling are developed and verified consistent with the customer's needs.

Extensive testing

A highly vertical test plan that includes 6,000 hours of full propulsion system testing has been developed for the GE90. This plan includes considerably more hours of testing than in any previous GEAE engine development program. Five development engines will be equipped with all engine build-up (EBU) hardware, and will be run with complete electrical, hydraulic and pneumatic bleeds equipment, simulating in-service operation. Three of these will be full propulsion systems with operable reversers. In all, 17,400 low-cycle fatigue cycles and 4,850 long cruise cycles are planned prior to aircraft certification.

This test plan required a significant investment to upgrade test facilities. Four outdoor test sites at GEAE's Test Center in Peebles, OH, will be used by the GE90 program. Two of the four will be new sites and two will be modified or upgraded sites. All four will use the new advanced data acquisition system which will increase the data calculation throughput by as much as 20 times over the existing system.

GE90's revenue sharing participants —SNECMA, IHI and Fiat—will also conduct engine and component testing. SNECMA is constructing a new test cell that will include an advanced data acquisition system with digital data capabilities for monitoring the Full Authority Digital Engine Control (FADEC). IHI is modifying an existing test cell to accommodate the GE90 engine. Modifications to the test cell include new inlet stack lip, revised inlet silencer and exhaust stack. A large percentage of the GE90 engine cyclic endurance testing will be run at this facility. Fiat will conduct numerous component tests at their existing facilities in Turino, Italy.

In addition to extensive cyclic endurance testing, instrumented vibration characterization and stairstep endurance testing with high levels of imbalance will be conducted very early in the development cycle. These tests will help the team identify potential problems (especially with the engine externals) early in the program. Early identification will provide enough time to introduce and verify design improvements prior to aircraft certification.

An early production engine, dedicated to E-ETOPS verification, also has been added to the development test program. The engine will be configured as a full production propulsion system, including the production Boeing strut. This propulsion system will run 3,000 endurance cycles, simulating two years' in-service experience. The testing will include high levels of imbalance to simulate operation of an engine delivered at maximum production acceptance vibration limits. This propulsion system will also run simulated 180-minute diversions, with single engine loadings and bleeds.

Figure 2: *British Airways maintenance personnel have also been invited to participate in the maintenance development*

The 3,000-cycle E-ETOPS verification engine test will serve as a final test of the maintenance training, procedures and field tooling developed for the GE90 program. During this testing, we will remove and reinstall the engine from the test stand with production tooling and manuals, simulating an on-wing engine change. We will also perform a low pressure turbine module replacement, routine maintenance (including full borescope inspection) and servicing, and replace all line replaceable units, supplied by both GEAE and Boeing. These maintenance actions will be performed by trained GEAE, Boeing and British Airways personnel. The routine maintenance will be performed to published task times, simulating actual airline operations. The purpose of this activity is to verify that the performance of normal maintenance and servicing procedures will not adversely affect the reliability of the GE90 propulsion system.

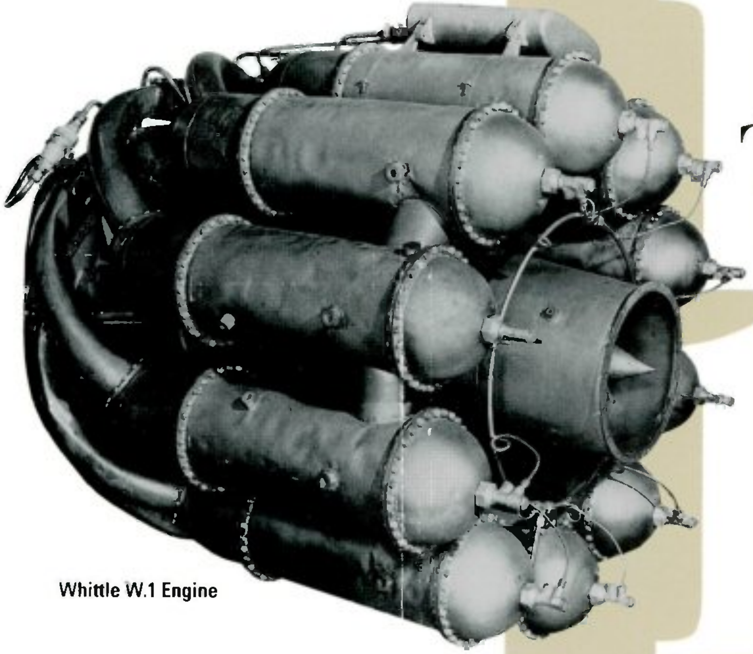
The culmination of the GE90 E-ETOPS program is the 1,000-cycle ETOPS Validation Flight Test. This testing simulates one year of in-service operation and is the final test leading to E-ETOPS approval. British Airways will operate and maintain the airplane for a portion of this testing (30 days, 90 flight sectors planned) over a representative route structure (Figure 3). This series, the first international flight test of its kind, will complete the aggressive test program for targeted E-ETOPS approval of the GE90/B-777.

George Pirtle *is Manager GE90 Aircraft/Propulsion System Integration*

Figure 3: *British Airways Sectors (E-ETOPS CVP Flight Test)*

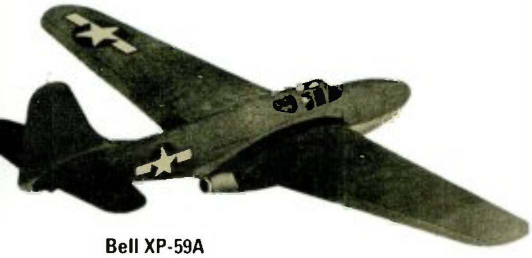
1942 1992

The 50th Anniversary of American Jet Flight



Whittle W.1 Engine

by David M. Carpenter



Bell XP-59A

In early October 1942, Bell chief pilot Bob Stanley made American aviation history with the inaugural flight of the highly secret XP-59A aircraft, powered by two GE Type I-A turbojet engines. Spurred by the pressures of war, this flight took place just one year after the prototype for the first American jet engine began its journey from England's Power Jets Ltd. facilities to GE's Lynn, MA, plant. There, a select team of GE engineers worked in secrecy to reproduce and improve the design developed by Royal Air Force officer Frank Whittle.

Initial advances in gas turbine propulsion for aircraft were made through separate developments in Germany and Britain. Hans von Ohain, an aerodynamics student, holds the first German patent for a turbojet engine design, granted in 1935. This engine design would eventually be proven in the world's first jet flight on August 27, 1939, in a remote airfield on Germany's north coast.

D. M. Carpenter

Centrifugal air compressor

Although Whittle patented his design in 1930, he faced a decade-long struggle against an uninterested British Air Ministry. Whittle's struggles paid off in 1935 when he was asked by a former RAF officer to join an effort that led to formation of Power Jets Ltd. Whittle's team faced recurring problems with the combustion and turbine sections, including several engine explosions. Finally, in July 1939, the Air Ministry officially awarded Power Jets a contract for an experimental jet engine to power an aircraft designed by the Gloster Aircraft Company. The engine, designated W.1, achieved a thrust level of 855 pounds.

Meanwhile, Japan had begun gas turbine work in 1937, when the Japanese Navy purchased Swiss Brown-Boveri engines to be adapted in aviation use. Italy started gas turbine studies in 1933, when engineer Secondo Campini proposed concepts for adapting current designs for aircraft jet propulsion.

In the US, gas turbine work in the 1930s was directed primarily toward turbosuperchargers, with relatively little focus on jet powerplants for aircraft use. However, it was in part due to the successful GE turbosupercharger experience that the US military turned to GE when it became interested in the concept of jet flight in the early 1940s.

America enters the jet age

A National Academy of Sciences report issued in January 1941 concluded that gas turbines were impractical for aircraft propulsion because they required 13 pounds of engine weight for every unit of horsepower delivered. By contrast, the current piston engines were approaching one unit of horsepower for every pound of weight.

However, intelligence sources at this time were receiving scattered information about German and British efforts in jet powered aircraft. In March, the chairman of the National Advisory Committee for Aeronautics, Dr. Vannevar Bush, established a Special Committee on Jet Propulsion, which initiated gas turbine contracts with three US manufacturers in July.

At the same time, negotiations were being conducted with the British to facilitate an exchange of information regarding gas turbine production. This effort followed a visit by Major General H.H. Arnold, deputy chief of staff for air, US Army Air Forces, to witness Britain's advances with the Whittle engine. Once the terms were successfully negotiated, the US effort was formally launched in Washington, DC, on September 4 at a meeting that included representatives of the US government, the military, and GE. It was decided that 15 engines and three airplanes would be produced as soon as possible. The contract for the engines, to be based on the Whittle design, went to GE. Bell Aircraft Corporation was selected to design the twin-engine plane.

Work begins

The two teams began simultaneous work on the engines and the aircraft. The Bell design team, known as the "Secret Six," consisted of six key engineers working at Bell's Buffalo, NY, site. The original group included specialists in aerodynamics, thermodynamics, structural design, development, stress analysis and weights. Working under extreme security from only a free-hand sketch of the engine, the group produced a proposal and a 1/20 scale model in just two weeks. The proposal was approved and a contract awarded for the XP-59A on September 30.

The GE effort began in earnest in early October with the secret arrival of the W.1X engine and a set of manufacturing drawings of the Power Jets' improved W.2B engine design. GE began by testing the W.1X in a special cell built within an existing building. For safety reasons, the test cell was built of reinforced concrete with entrance through a steel door. The only means of viewing an engine in the cell, which was dubbed "Fort Knox," was through a small observation slit. The initial run-ups of the Whittle engine were restricted to 10,000 rpm, and run only to 16,550 rpm after considerable test experience.

Using this experience and the improved W.2B drawings, the GE team under Donald F. ("Truly") Warner began their design work. However, their

The GE-I series engines

Model	Number of units	Thrust (lb.)
I	5	1,250
I-A1, 2	16	1,250
I-14 A,B	9	1,400
I-16A, B, C	241	1,600
I-20	Test units only	2,000

inspection revealed several shortcomings in the updated Whittle engine, and GE requested and received permission to make modifications to improve the design. The original GE Type I-A was run on March 18, 1942, just six months after the arrival of the first drawings. Eventually, 30 I-A engines would be produced for the XP-59A program.

The Type I-A was a dual, back-to-back, centrifugal, reverse flow, turbojet engine that delivered about 1,250 pounds of thrust. Initial problems with excessive exhaust gas temperatures were corrected with help from Whittle during his visit in June 1942. He remained in the US for several weeks, helping to iron out problems until the engine was ready for installation in early August.

The XP-59A engines were located as near as possible to the center of the airplane, almost touching each other. This arrangement helped reduce drag and avoid difficulties of single engine flight in case of an engine failure. This configuration caused concerns with the air inlet design due to the threat of boundary layer turbulence, which could hamper ram pressure recovery at the inlet. A high efficiency of ram air pressure recovery at the engine air intake is needed to reach maximum thrust at high flight speeds. Therefore, boundary layer turbulence generated along the fuselage sides can hinder clean airflow into the nacelle inlet. The problem was solved with a built-in boundary layer removal system, which was tested in wind tunnels at the Dayton Wright Base facility.

Bell XP-59A

First flight

By early fall, problems with the engines and aircraft design were resolved sufficiently to enable a first flight test. Again for security reasons, the military selected the remote Army Air Force Muroc Bombing and Gunnery Range (later renamed Edwards Air Force Base) in Kern County, CA, as the test site. The engine and aircraft arrived at the site in mid-September following an eventful six days of cross-country travel in specially guarded railroad cars. The airplane was reassembled and the first installed engine run-up took place on September 26.

Stanley's first flight occurred on October 1, 1942. In all, four flights were made that day, all with the landing gear down, and limited to altitudes of 100 feet. The "official" takeoff in front of military and civilian observers took place the next day. Stanley made two flights: one to 6,000 feet and the second to 10,000 feet. The third flight of the day was made by the first military jet pilot, US Army Air Force Colonel Laurence C. Craigie. Additional flights were not made until October 30, after repairs and modifications were made.

EYEWITNESS ACCOUNTS

Floyd Heglund

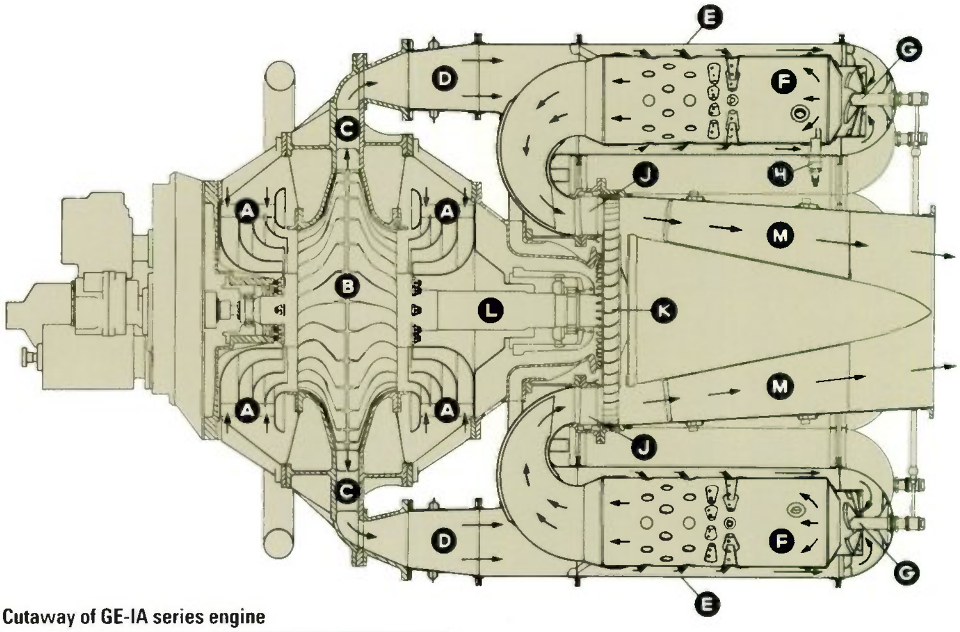
John Benson

The birth of the first American jet engine required parallel efforts from teams on both coasts—in Lynn, MA, and Kern County, CA. Two GE engineers who witnessed this historic event from opposite sides of the country recently shared their memories for a special project by the Jet Pioneers of America. The following excerpts are from that conversation with John Benson, who worked on the testing of the Type I-A engine in Lynn, and Floyd Heglund, who traveled to Muroc in March 1943 and remained until August 1946.

In addition to the initial model, 13 YP-59As, 20 P-59A-1s and 30 P-59B-1 aircraft were produced. Each model flew with an improved version of the I-A, with the top-line I-16/J31 engine reaching 1,600 pounds of thrust. Testing and improvements of the XP-59A and derivative models and the I-A and derivative engines continued through February 1944. Free of major mishaps, the program accumulated 242 1/2 hours of flight time.

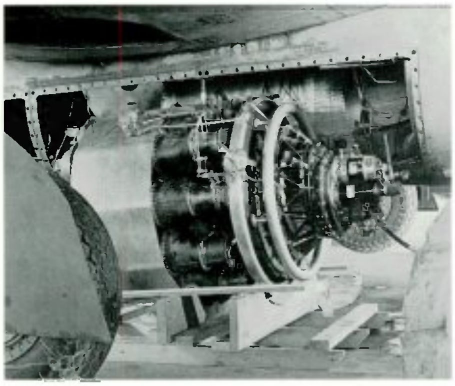
Even though a combat aircraft did not result from the development of the XP-59A, Bell played a key role in the preliminary design work that led to the XP-80 "Shooting Star." The P-80, powered by GE's I-40 engines, did see combat in Korea in the early 1950s.

***Dave Carpenter** is Manager, Spare Parts Sales, T700 Turboshaft*



Cutaway of GE-IA series engine

A. Air inlets
B. Impeller
C. Diffuser
D. Combustor inlet
E. Outer case
F. Combustor
G. Fuel nozzle
H. Spark plug
J. Nozzle
K. Turbine wheel
L. Shaft
M. Exhaust duct



I-A engine installation

Benson: "My first assignment on the I-A came in October 1941, having worked on superchargers since 1938. I was told I was being placed on a secret assignment and that I was to keep my mouth shut. I reported to Building 45 for my new job."

Heglund: "I began with GE in 1940, working on turbosuperchargers. I was moved to the I-A project the following year, and was originally sent to the flight test base on a three-month, rotating assignment. I wasn't allowed to tell my wife exactly where I was going or why. But when it turned out I would be staying much longer than three months, I was allowed to send for her."

Benson: "The first Whittle engine was different from anything we'd ever seen. It had long round ducts leading from the compressor to the combustion chamber that we nicknamed 'elephant trunks.' The turbine wheel was just beautiful. It was obvious from its appearance that this was an efficient design. However, the British engineers didn't have the opportunity to get too fancy with the early models. They needed to get something running to help with the war effort."

Heglund: "I was in Lynn for the first testing of the Whittle engine. After it was tested, we dismantled it and rebuilt it to see how it worked. Shortly after that, I went out to Muroc."

Benson: "We took turns going around the country, getting various companies to build parts. I even put my wife to work, making the chamois air filters for the first 10 or 12 engines. We had to work with what was available."

Heglund: "Out in the desert, they built this old wooden propeller that they used to hang on the front of the aircraft when they moved it from one field to another. It wouldn't fool anyone up close, but it might from a distance."

Benson: "The first test run of the I-A engine took place about 11 p.m. on our deadline night. I was the engineer in charge of test, and Truly Warner, Earl Auyer, Bob Santos and George Price were there. We didn't have the shroud ring on yet, because we were trying to meet the six-month deadline, so we knew we wouldn't make full temperature. But we got it ready and Truly pushed the throttle up and away she went. We couldn't get it up to more than half speed because it was running at maximum tailpipe temp. but everything else was ship-shape. We were very, very happy.

Later on, some engines were damaged in the test cell because compressor blades developed cracks where they joined the main disk. This problem also occurred in England with the same configuration. M.G. Robinson, an experienced GE compressor engineer, redesigned this area and then we had no further failures. Eight compressor impellers were shipped to England to fix the problem they were having."

TOWARD 2000

The Changing Face of the Commercial Customer

PERSPECTIVE

by Lee Kapor

The customer who buys commercial aircraft engines has changed in many ways since my early days in this business. When the industry was younger and the technology still evolving, we were essentially growing together. We tolerated each others' "growing pains" because all of us—airframer, airliner and engine maker—were learning about our businesses.

Today, we're all a little smarter, but we're also facing extreme financial pressures that leave little room for tolerance. Each player is expected to bring expertise to the table and to deliver on promises. Because their business is often on the line, our customers can accept no margin in performance and reliability. They will not buy engines that do not meet spec and stay on wing.

L. Kapor

Some of this change can be explained in what we've all seen in the media: the airline industry is currently going through the most difficult period in its long history. Even the largest and strongest carriers are struggling to deal with massive financial losses that have drained the industry of more than six billion dollars during the last two years.

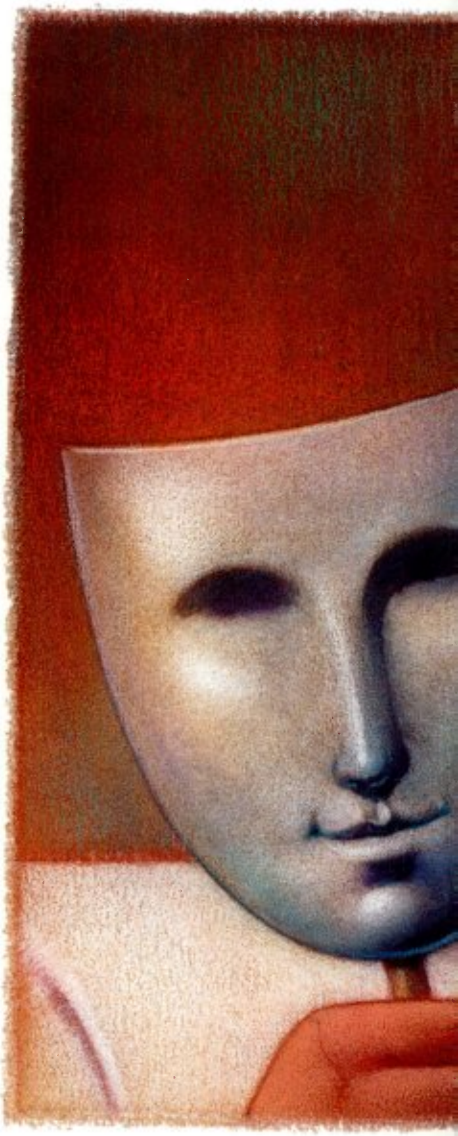
Bob Crandall, CEO of American Airlines, described it best when he said, "this business is intensely, vigorously, bitterly, savagely competitive." Fundamentally, the airlines are no different than any other business when it comes to the basic laws of economics.

Today the industry is trying to cope with a large surplus in capacity created by a fall off in airline traffic (traffic demand had a negative growth of almost -4% in 1991). Much of the excess capacity persists as a number of airlines currently in Chapter 11 continue to operate while they struggle to survive. The result is intense price competition that is taking its toll on the industry as a whole. While airline seats may be filled with highly discounted fares, the ticket yields are not sufficient to keep the airlines operating profitably.

GE Aircraft Engines is also feeling the effect of this dramatic change in the industry fortunes. Many airlines have revised their new equipment acquisition plans, deferring delivery of aircraft currently on order to a later day and, in some cases, cancelling orders. The change is very substantial.

During the growth period of the late 80s through 1991, the airlines took delivery of approximately 650 new aircraft per year. We expect this will come down into the range of 500 to 550 per year for the remainder of this decade. At the same time there will be further dramatic changes in the industry. The large international airlines will grow and become more global. We already see intense price competition among these international airlines in a market that once enjoyed premium ticket prices. There will be new alliances among airlines as they try to grow market share in an increasingly deregulated world.

All of this has large implications for GEAE. Our most immediate problem is to adjust our business to these new market realities. We have already experienced a reduction in sales for 1992 and 1993 as airlines have rescheduled deliveries. Also, spare parts sales are down as airlines reduce their inventories and only buy essential replacement parts. We expect this to continue at



least for the next two years. Much depends on a turnaround in the economy and the ability of the airlines to become profitable again.

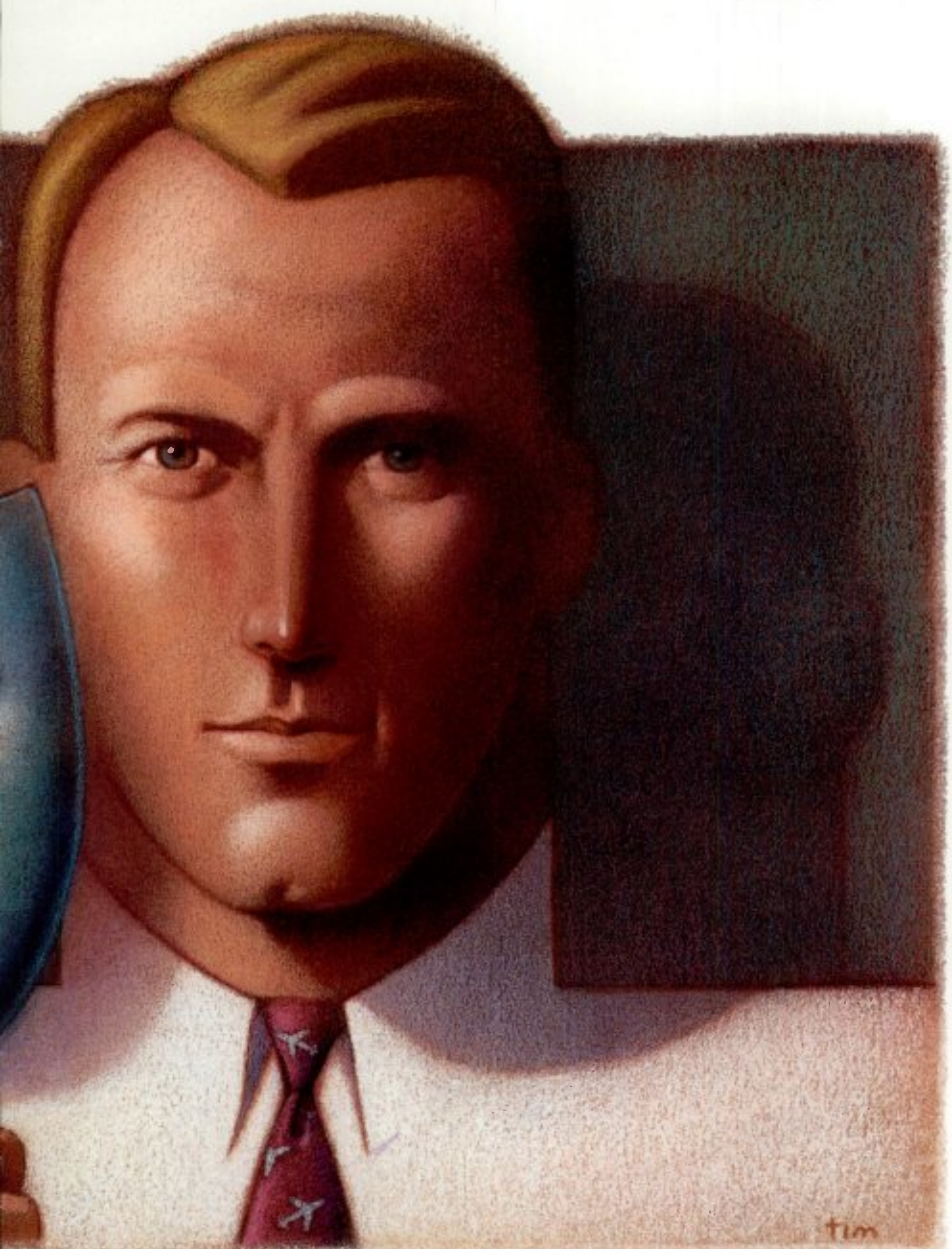
During this "pause" in the industry, we have a rare opportunity at GEAE to change the way we do things, to become more efficient and more productive. The many new initiatives we have under way that are focused on improving quality, reducing manufacturing and warranty costs, and improving customer support are all necessary. We must be successful in these efforts to maintain the strong investment we have in developing the technologies that are the backbone of our business.

At the same time, the Engine Development Cycle efforts will help us improve the way we design engines. This process, which focuses on concurrent engineering involving manufacturing, suppliers and customers, has already benefited the GE90 and F414 programs.

These efforts will have a high payoff when the market turns up again. We will have the strength and flexibility to compete and win our fair share of the market. However, this market will be even more competitive than we have seen so far. There is plenty of evidence of that already as our competitors work to keep their factories busy.

The long term prospects for GEAE's commercial engine business are excellent, provided we stay on our game plan of improving productivity and design processes in every corner of the business.

As world population and global economics continue to expand, the demand for air travel is expected to increase approximately 50% to 1.7 trillion revenue passenger miles flown (from today's level of 1.1 trillion revenue passenger miles flown) by the year 2000. There are about 8,700 operating commercial aircraft today. Approximately 3,000 of them will have to be replaced over the next 10 to 15 years because of age. So, there really will be a demand for about 5,600 new aircraft over the next decade to satisfy both traffic growth and aircraft retirement.



Airport and air traffic control constraints are creating the demand for higher capacity, widebody jets such as the Boeing 777, the Douglas MD11 and the Airbus A330/A340. In addition, all three of these aircraft manufacturers are studying new four-engine 600-passenger long range aircraft. Much of the growth in traffic will have to be served by these aircraft.

Our new GE90 high-bypass family of engines is being designed specifically for the new generation of widebody aircraft with the capability to grow from 75,000 to more than 100,000 lbs. of thrust. In addition to meeting the stringent noise and emissions requirements for future propulsion systems, the GE90 will have a clear competitive advantage in fuel consumption and cost of ownership.

The first core is scheduled to go to test in December and the first propulsion system will run early next year. Certification is scheduled in December 1994, so the next two years will be very challenging for the GE90 team.

Of course, the CFM56 and CF6-80C2 will be our "bread and butter" production engines over the next ten years, at least. The engines will continue to be improved, and as aircraft and the market require new derivative versions, they will be developed.

In all of this work we must continually "raise the bar of excellence" and re-earn the confidence of our customers day after day. This is what it takes to win and secure our future. While it's true that our customer is different than he was when I started in this business, we will certainly continue to anticipate and meet his needs…but we must be willing to make some changes of our own first.

Lee Kapor *is General Manager, Commercial Engine Operation*

GE Aircraft Engines

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