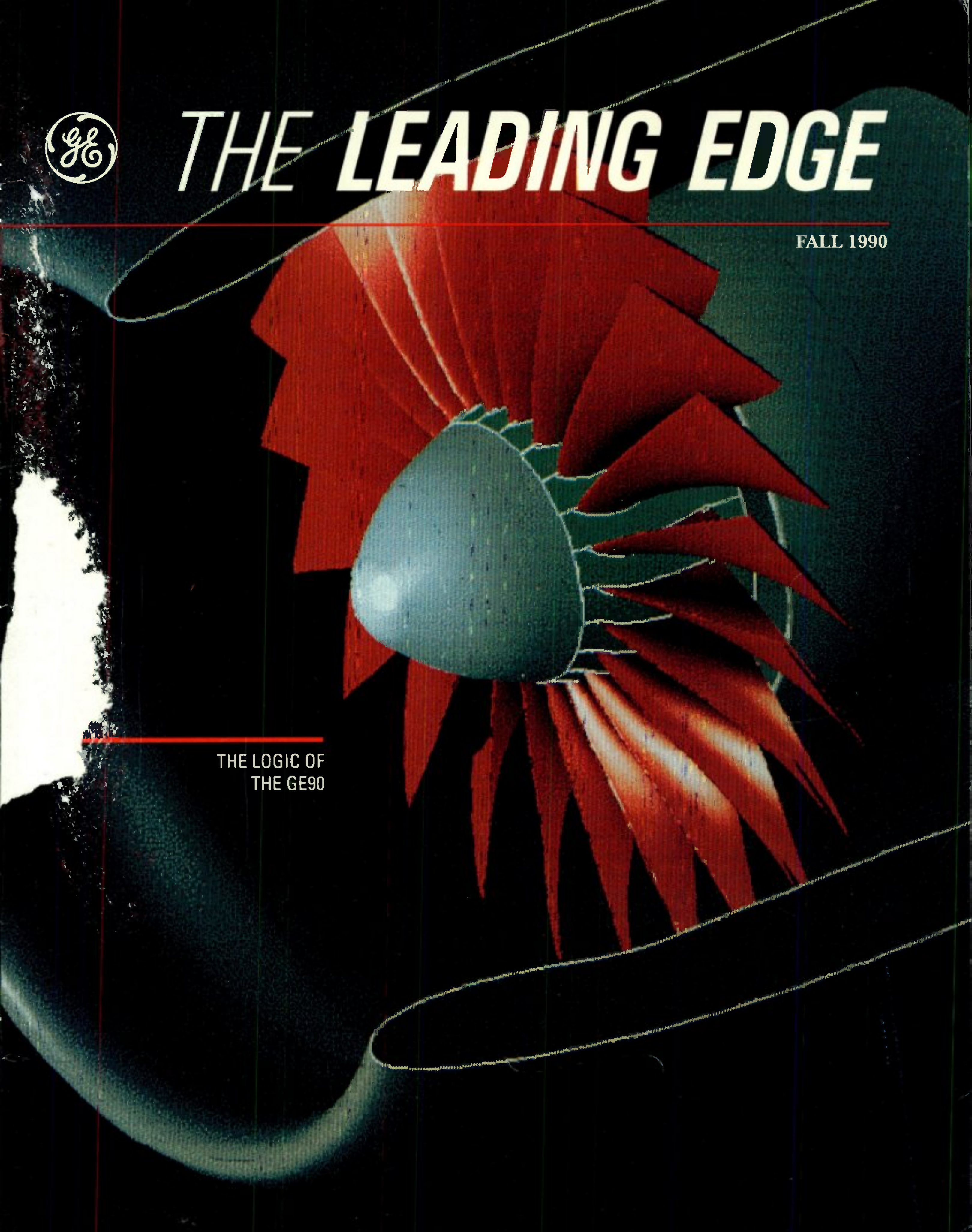
THE LEADING EDGE

FALL 1990



THE LOGIC OF
THE GE90

Photoelastic analysis is used to detect and evaluate stress concentrations in jet engine parts such as the F404 low pressure rotor turbine disk shown here. See the article on page 18 for a discussion of new developments for testing rotating parts.

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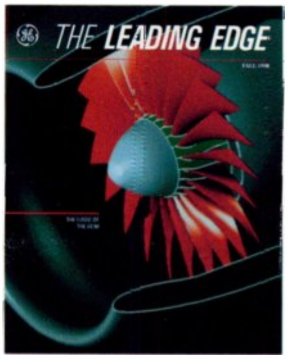

The Leading Edge reports information of interest to GE Aircraft Engines' technical community. It provides recognition for individuals and teams who have made significant technical contributions to the business.

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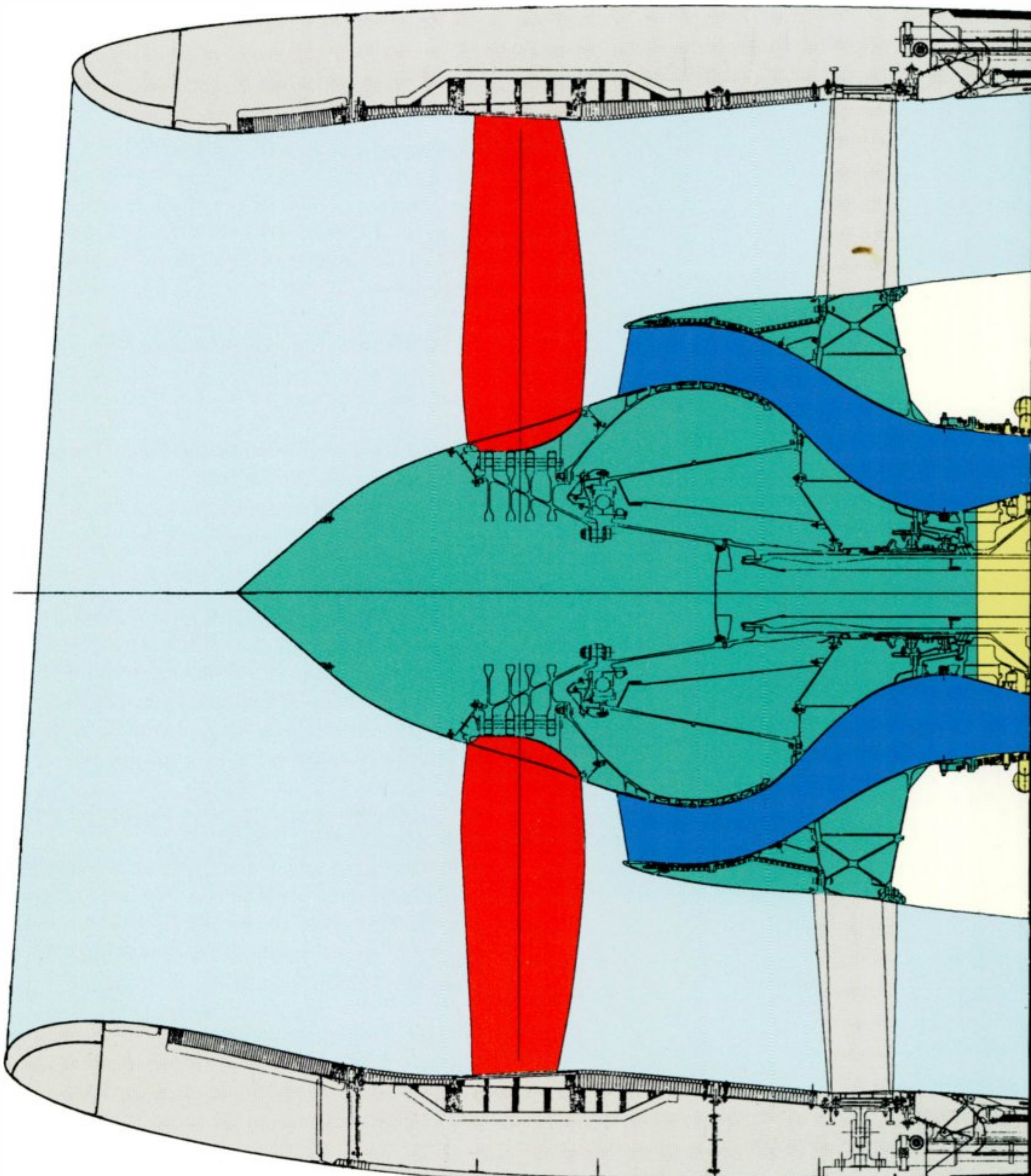
The Logic

S. ELSTON

Increasing air traffic, particularly in the long-distance markets of the emerging economic entities (the Pacific Rim, Western Europe '92, and South America), has dictated the need for the GE90. Both domes-



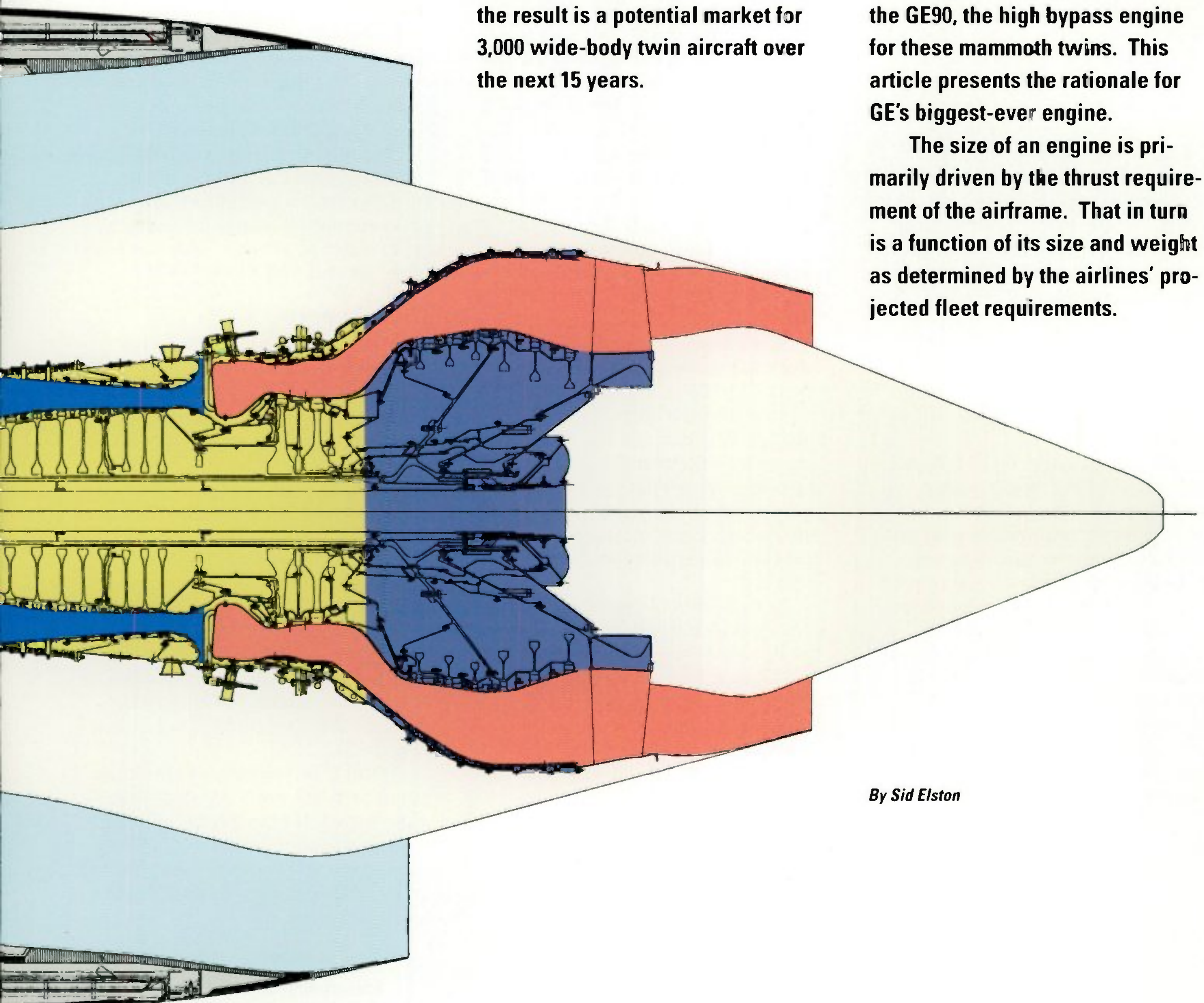
of the GE90

tic and overseas passenger rates are predicted to increase an average of 5% through the year 2000.

With the skies increasingly crowded and airports teeming with travelers, airlines are being forced to buy ever-larger planes. Packed ground facilities, jammed airways, and the staggering cost of new airplanes argue for wide-body twin-engine planes as a successor to the current generation of wide-bodies other than the 747. As the airlines must also replace their aging fleets, the result is a potential market for 3,000 wide-body twin aircraft over the next 15 years.

This new family of aircraft will be designed to transport up to 300 passengers beyond 6600 nautical miles (up to 440 at shorter ranges), while meeting the most stringent standards ever for cost effectiveness, extended range reliability, and environmental responsibility. Enter the GE90, the high bypass engine for these mammoth twins. This article presents the rationale for GE's biggest-ever engine.

The size of an engine is primarily driven by the thrust requirement of the airframe. That in turn is a function of its size and weight as determined by the airlines' projected fleet requirements.



By Sid Elston

Figure 1. *Boeing Commercial Airplane Group is offering its proposed new 767-X twinjet to prospective customers. Boeing will name the aircraft the 777 when it is launched into production. Initial deliveries are targeted for the first half of 1995.*

Once the fuselage is sized to transport the right amount of passengers and cargo, the next issue is wing design. The Boeing 767-X (to be renamed the Boeing 777 as soon as the first orders are received), which is the primary application of the GE90, will have a 197-foot wing span with optional folding wing tips to permit docking at congested airports. This wing is optimized for range and take-off performance. It must maintain acceptable approach speeds, yet provide lift permitting reasonable thrust levels to get the airplane off the ground from a runway no longer than 10,000 feet. With the wing structure designed, useful fuel capacity and airframe maximum takeoff gross weight (MTGW) are set. This allows the basic thrust required for takeoff to be determined.

The thrust required to take off and climb during single engine operation, and the maximum continuous thrust required to maintain a suitable single engine cruising altitude, establish the thrust requirement of the engine. Boeing plans to enter service in 1995 with an "A Market" airplane weighing 506,000-515,000 lb MTGW (see Figure 1). This model will require 72,300 lbs sea level static takeoff (SLST) thrust per engine. The later "B Market" airplane with increased range weighing 580,000 lbs MTGW will require 84,600 lbs SLST thrust, and ultimately the growth version of the GE90/B777 will require upwards of 90,000 lbs near the end of this decade (Figure 2).

The CF6-80 will not fill the bill. The CF6, which was originally designed for the 40,000 lb. thrust class category, is currently reaching 72,000 lbs in the form of the CF6-80E1, but has nearly run out of growth margin. In order to achieve this maximum thrust rating and maintain competitive fuel consumption, the highest bypass ratio that the core engine can deliver — limited primarily by material temperature capability at compressor discharge and turbine inlet locations — sets the fan diameter at 96 inches. This diameter fan, due to maximum area specific fan flow of 45 lbs/sec/ft^2, limits the engine thrust to around 75,000 lbs with the fan blade tips running as fast as safe foreign object ingestion design limits will allow.

To deliver even more thrust, a larger fan is needed. But the torque required to drive a larger fan requires a bigger shaft than can fit through the center of the CF6 core. To produce the additional torque at the core engine's airflow rate, improvements in the temperature capability of our latest commercial disk and HPT blade alloys would be required.

Both Rolls and Pratt face similar problems with their current engines, the Pratt & Whitney 4082, and the Rolls Royce Trent 800. Each may be able to provide the 84,000 lbs of thrust required for the "B Market" airplane, but neither appears capable of powering the later "C Market" model.

Faced with the prospect of a huge market, GEAE is developing the GE90. Since there exists the opportunity to configure the GE90 from a clean sheet of paper, and bring all of our hard-earned technology to bear for a clear advantage over competitive derivative engines, the intent is to design an engine which will serve as the core for an entire family of engines, just as the CF6 core did a generation ago.

GEAE's Preliminary Design Department completed an extensive series of studies to evaluate the relative fuel burn, weight, and cost of several potential configurations for the GE90. Included in the studies were a variety of large fans, multiple spool designs, and more conventional high and low bypass ratio fans. What ultimately emerged as the most competitive choice in terms of maximum thrust with minimum fuel burn, weight, and cost was a cycle that combined high propulsive efficiency, like the UDF® engine, with high thermodynamic efficiency, like the Energy Efficient Engine (E^3).

Propulsive efficiency generally pertains to the fan and is the measure by which a given level of velocity (V_j) is imparted to a given mass of air in order to achieve a desired level of thrust and flight speed (V_o):

$$\text{Thrust} = \text{Air Mass}\,(V_j - V_o)$$

$$\eta_p = \frac{2}{1 + (V_j/V_o)}$$

As evident by the terms of the expressions, it is more efficient to generate thrust by moving large amounts of air at lower jet velocities as opposed to low amounts of air at high jet velocities. Turbofans move more air mass at lower velocities; turbojets move smaller amounts at higher exhaust velocities. The so-called "bypass ratio" indicates what proportion of air is passing around the core (at low velocities) compared to the lower amount of air passing through the core (at high velocities) (Figure 3).

In high bypass ratio engines, the core's primary purpose is not to generate thrust directly, but to efficiently convert the chemical energy of fuel into pressure and temperature (thermodynamic) energy for driving the fan:

$$\eta_{th} = \frac{\text{Energy available from core}}{\text{Energy input from fuel}}$$

Figure 2. *Major Airline Markets*

GE90

	MAX TAKEOFF GROSS WEIGHT (LBS)	SEATS	RANGE (STATUTE MILES)
A	506,000-515,000	350 (TRI-CLASS)	4800
B	580,000	285-300 (TRI-CLASS)	7600
C	580,000+	285+	VERY LONG RANGE

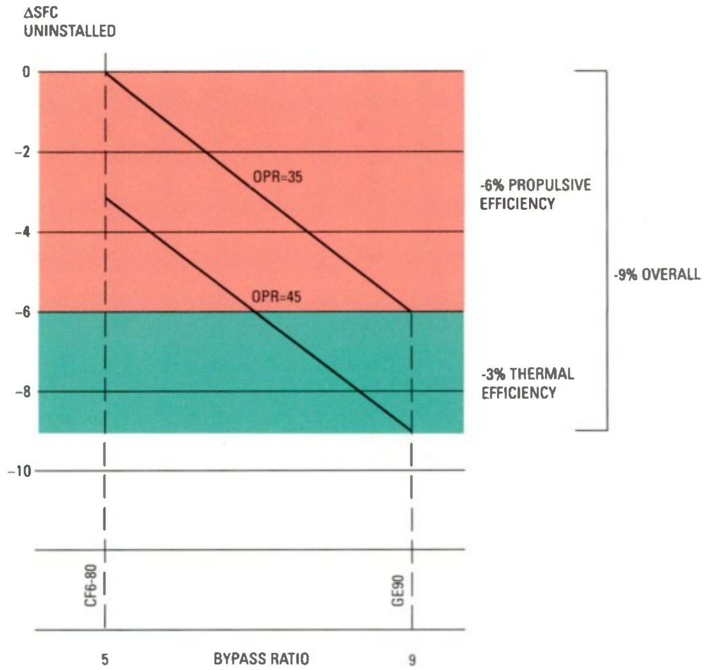


Figure 3.
Theoretical benefit on fuel consumption of increasing fan diameter

When high thermodynamic efficiency is achieved, not only is the energy conversion performed with minimal loss but also the physical size of the core — for a given amount of energy needed to drive the fan — can be smaller. Hence, a higher bypass ratio and thus higher propulsive efficiency can be achieved for a given diameter and thrust of engine. That all adds up to a highly efficient design, with one big problem — the increased weight of the larger diameter fan.

A limit to the practical size of a fan has been posed by the weight of metal blades; they usually weigh enough so that not all the fuel burned benefits are realized. However, thanks to several key technologies developed on prior GEAE engine programs, namely the UDF® engine and E^3 engine, the weight barrier which would ordinarily limit the high bypass ratio of the GE90 can be overcome.

Composite blades are one key. They weigh much less than any metal blades, even hollow titanium blades. Because the high bypass ratio fan delivers thrust with lower blade tip speeds, the composite blades are also able to comply with the corresponding foreign object ingestion requirements. The wide chord configuration also helps with foreign object and particle ingestion, and the low tip speed minimizes noise as well.

Early in the program, we decided to set the maximum turbine inlet temperatures approximately equal to CF6-80 levels in order to reduce the need for new turbine blade alloys and cooling technologies. These temperatures, combined with the high (23:1) pressure ratio, 10-stage E^3 compressor (Figure 4), will provide the overall core pressure ratio and the desired level of thermodynamic efficiency. René 88 powder metal disk alloys developed on our CT7 and advanced military engine programs will be used to address the relatively high discharge temperatures of the E^3 compressor. This

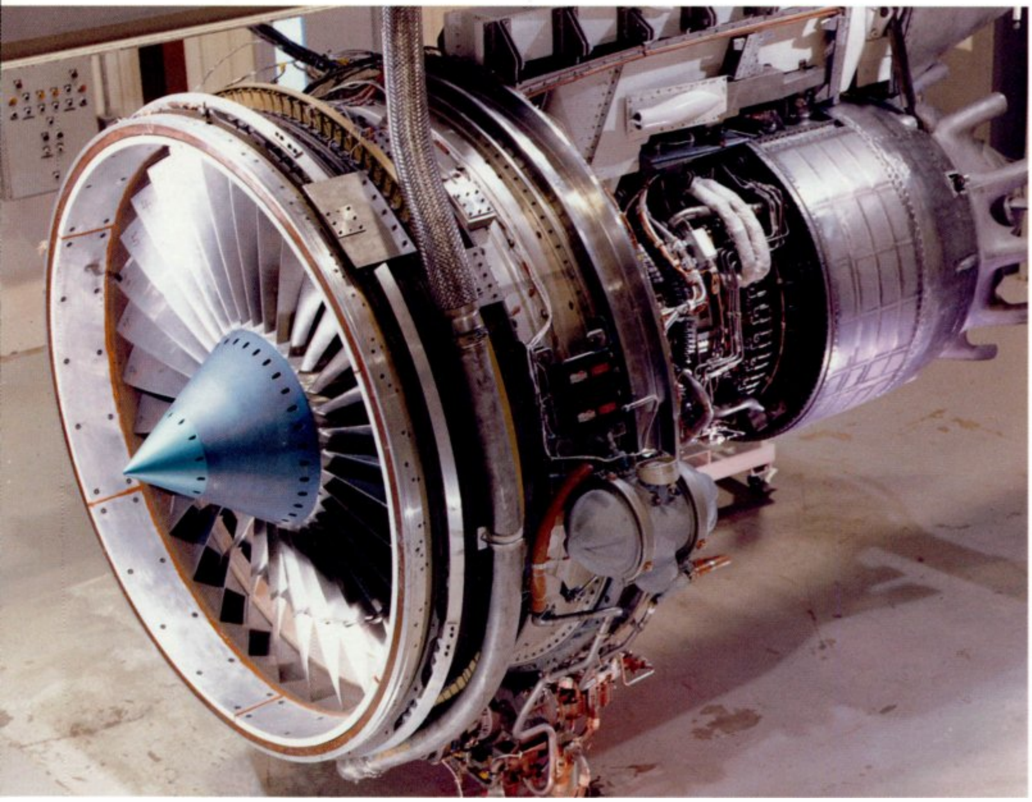


Figure 4.
The E^3 engine provides the compressor concept for the GE90

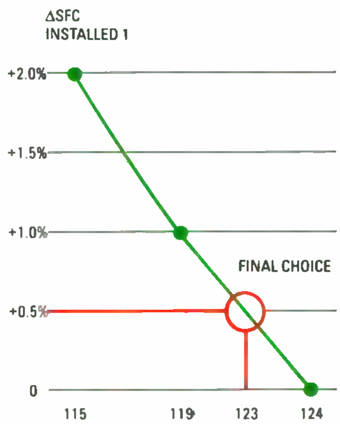


Figure 5.
Cycle Advantage of Increasing Fan Diameter, "SFC INSTALLED 1"

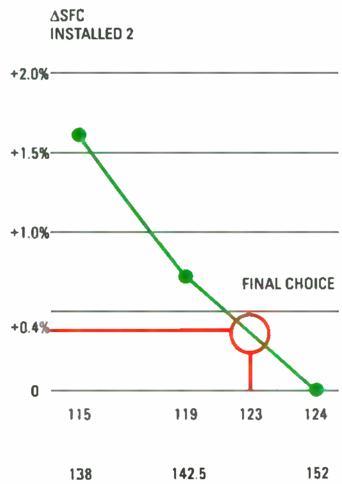


Figure 6.
Nacelle Diameter Impact on Fuel Burn, "SFC INSTALLED 2"

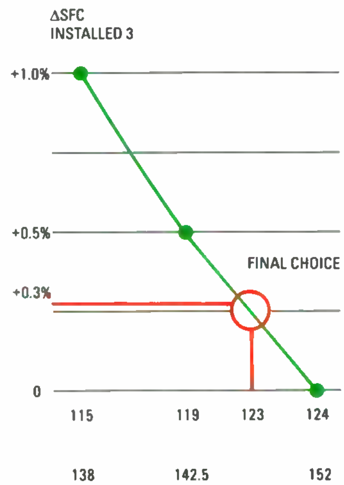


Figure 7.
Weight Impact, "SFC INSTALLED 3"

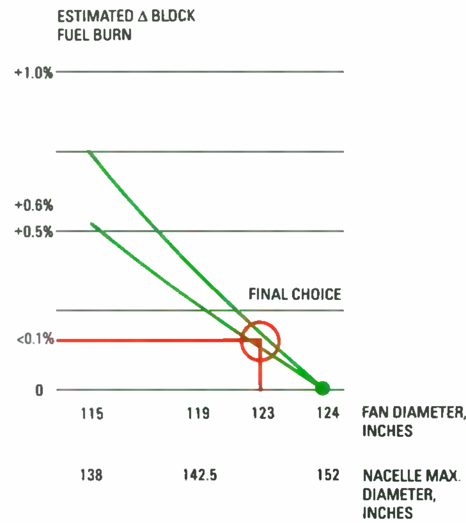


Figure 8.
Predicted Boeing Interference Drag Scenario, Prior to Wind Tunnel Test

application will provide adequate rim creep lives in the aft compressor and HP turbine disks.

Once several fundamental characteristics of the engine are established, and the effects that the size of the engine has upon the airframe are understood, the process for selecting precise engine size is straightforward. In the case of the GE90, the desire to stay below a particular compressor discharge and turbine inlet temperature implies a fixed relationship between core energy requirement and core physical airflow. Over the range of fan sizes studied, the fan tip speed was held constant within the composite blades' impact capability regime. Across the range of fan sizes studied, the fan pressure ratio was varied as needed at this constant tip speed to maintain the desired thrust.

In order to deliver competitive fuel burn, the fan diameter for the GE90 had to fall somewhere between 115 and 124 inches. Since in principle, bigger is better from a performance viewpoint, the question at hand was really just how big could we make the fan before nacelle drag, weight, installation drag, and the difficulties in transporting spare parts or subassemblies became too great.

So, consistent with our key engine fundamental characteristics, the relationship of fan size vs. pure cycle efficiency was developed by varying core airflow to hold temperature constant and by varying fan pressure ratio while holding tip speed constant. LP Turbine efficiency was also a variable which increased with increasing RPM as fan tip speed remained constant at reduced diameter.

Figure 5 shows a 2% cruise fuel consumption benefit for the larger diameter fan. No surprise there, but how much would the aerodynamic scrubbing drag of the larger nacelle diameter offset that 2% Specific Fuel Consumption (SFC) advantage? As seen in Figure 6, plotted as "SFC INSTALLED 2," the 2% advantage reduced slightly to about 1.7%, but still "bigger was better."

The increased weight of a larger fan also had an offsetting effect on the SFC benefit. Plotted as "SFC INSTALLED 3," Figure 7 shows that the original 2% cycle benefit had now been cut to 1.0%, but bigger was still better.

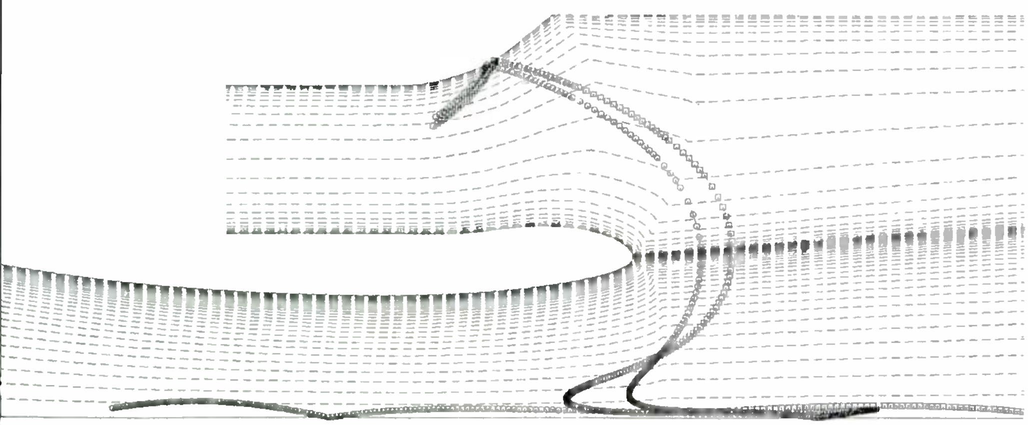
The final factor affecting the choice of engine size was an approximation of the engine nacelle-to-wing interference drag for the GE90/Boeing 777 installation (subsequent wind tunnel testing showed the interference drag to be negligible). Figure 8 combines this and all prior factors into the relative net fuel burned on a typical 2000 nautical mile mission for a 115-inch to 124-inch diameter fan.

Reasonable though challenging fan nacelle inlet thickness contours were chosen that minimized interference drag, yet still ensured that the fan inlet would not separate and stall the remaining fan during the airplane yaw of single engine operation. Taking all of the "installed" effects into account, the "bigger is better" argument still held up — and the fuel burn advantage compared to the competitors' derivative engines is significant.

One study also included the scenario for a growth Airbus Industrie A330 airplane, another potential application for the GE90. The results on the A330 were similar, except for the installation drag, which reflected penalties from the fixed wing and gear configuration of the A330.

Finally — with one last check to ensure that the fan diameter did not pose transportability difficulties for our airline customers — the 123-inch fan was chosen, with a corresponding core engine airflow of 215 lbs/second.

Figure 9.
Computer study of trajectory followed by 1,000-micron particles from runway surface.

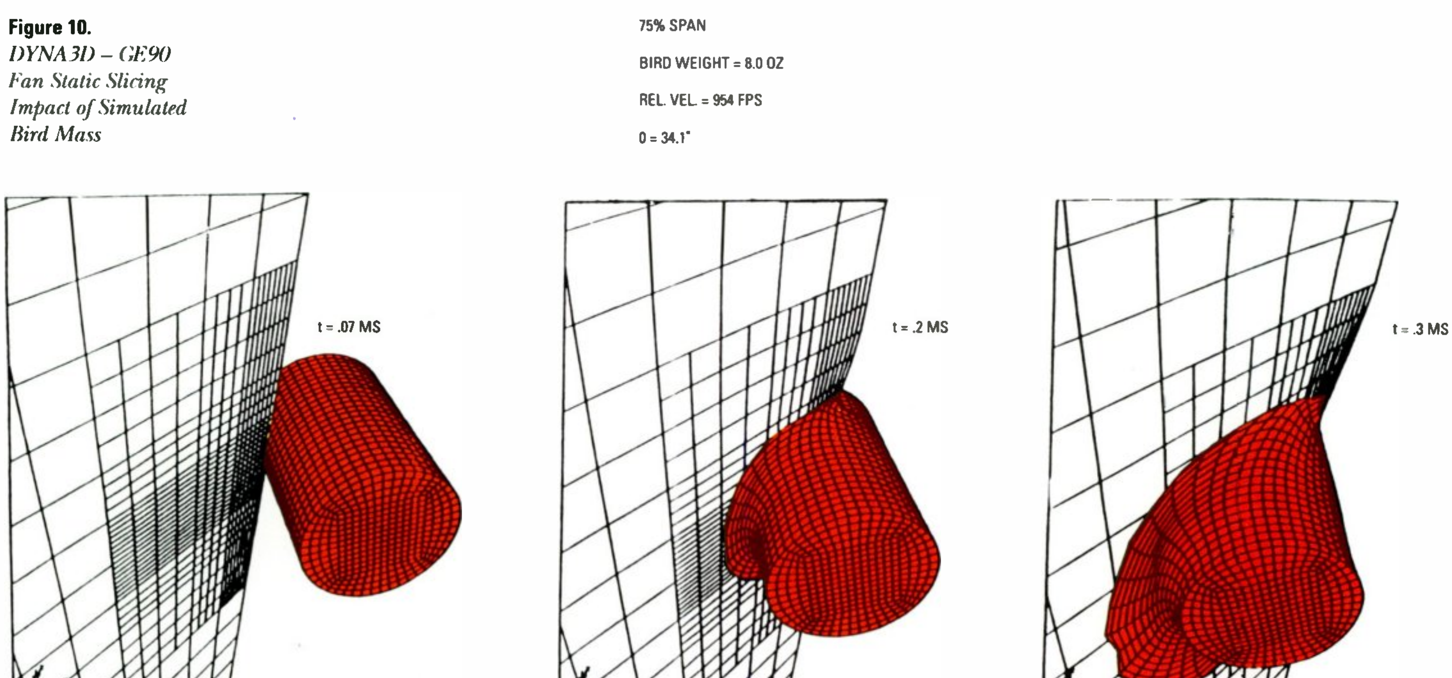


All in all, the GE90 makes excellent sense as the engine of choice for the Boeing 777 and the other wide-bodied twins of tomorrow. But other issues must be dealt with before this new engine becomes a reality.

Reliability, for example, is a key issue. Early authorization for extended twin operations (ETOPS) is needed; this necessitates inflight shutdown rates of no more than .02 per thousand flight hours (one shutdown in 250,000 hours of operation), a value normally associated with mature engines.

Using previously-demonstrated technology helps meet this goal. So do "lessons learned" reviews beginning at design conception and continuing through development, as well as a component and engine test program which will include far more endurance testing (15,800 cycles) and smarter testing than has ever been done before. For example, lessons learned on the CFM56 are driving intense efforts to configure the engine inlet so as to minimize the amount of hail and water ingestion and thus avoid flameout difficulties.

Figure 10.
DYNA3D – GE90 Fan Static Slicing Impact of Simulated Bird Mass



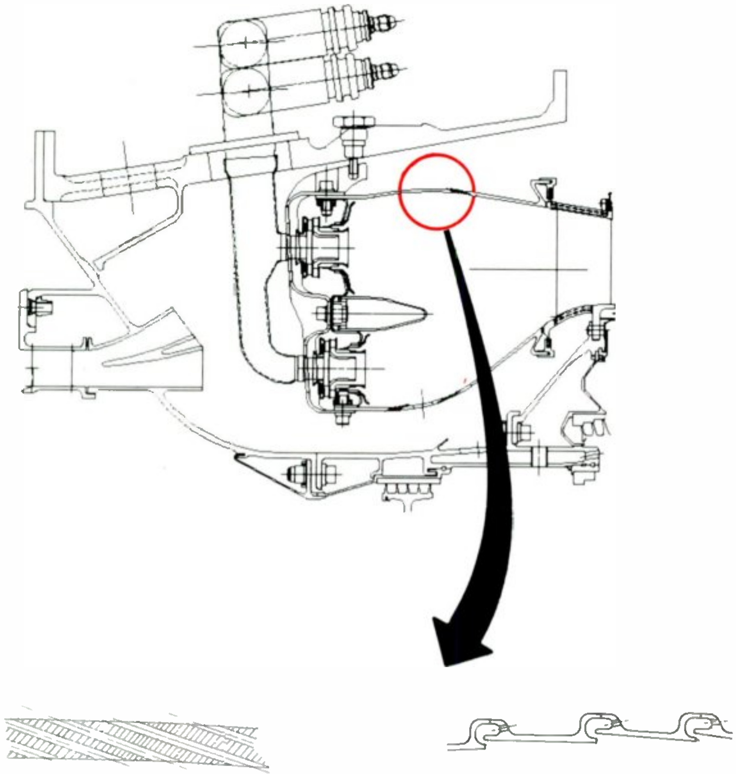


Figure 11. *The GE90 Dual Dome Combustor*

The slightly higher physical tip speeds of the scaled E^3 compressor (1600 FPS vs 1500 FPS on the CFM56) make it important to control erosion from dust and sand particles (Figure 9). The GE90 will feature a hybrid, conical/elliptical spinner shape to prevent ice build up and to reflect particles away from the booster splitter, and a particle and water separator located in front of the core. The wide-chord fan design will also help by reducing particle ingestion.

Another reliability issue is the impact resistance of the fan blades. Here the experience gathered on the UDF® engine comes into play, as does the use of DYNA3D, a program developed to predict the effects of bird strikes (See *The Leading Edge, Winter, 1989-90, pp 4-9*). (See Figure 10.)

The E^3 10-stage compressor with a 23:1 pressure ratio poses its own challenges. To put this compressor in perspective, the International Aero Engines consortium made two attempts to achieve 20:1 with their 12-stage design, but aeromechanical and stall difficulties forced them to the current 16:1 design. By comparison, the GE90 compressor is an aerodynamic scale of the successful E^3 compressor, with significant mechanical design improvements. These include stiffer aft stage casings with transient thermal matching to the rotor to control clearances, as we have done in HP turbines. Also, bleed air is extracted internally. This heats the rotor bores during acceleration and steady-state power settings to facilitate thermal matching, which maximizes stall margin and fuel efficiency while minimizing transient turbine inlet temperature overshoots during acceleration. As a result temperature margin is preserved, meaning longer on-wing life for the engine.

The dual-dome combustor of the GE90 (Figure 11), soon entering production on our advanced military engines, responds to environmental concerns by enabling increased thrust without increased NO_x emissions. The GE90-powered B-777 should produce 30% lower NO_x emissions per passenger seat-mile than current wide-body twins.

This improvement is obtained through optimization of the main (inner) dome for minimal emissions during takeoff and cruise by shaping the combustor so that combustion by-products spend less time exposed to very high temperatures, a variable that relates by the fourth power to the amount of nitrous oxides produced. Ordinarily, high through-flow velocity works against good flame-out margin and minimum relight time at altitude, but in the GE90 the pilot (or outer) dome can be optimized for this at low-power operation. Ordinary single-dome combustors must compromise each requirement and to guarantee operability will inevitably produce higher NO_x than a dual-dome design.

New materials strengthen the engine and preserve its life at high operating temperatures. For instance, defect-tolerant René 88 DT powder-metal disk alloy provides the rim creep strength required to withstand the red-line compressor discharge temperature.

Innovative cooling schemes make the bleed air work efficiently. The bores of the two HPT disks and the cavity that separates them are bathed in high-pressure, high-temperature midstage compressor air that first "heats" the disks, decreasing their response time for good thermal matching with the stator. Then the same air passes through to cool the stage two blade.

Finally, because the rotational speed of the LPT is lower than usual, the diameter of the LPT is large in order to get the high tip speeds associated with high turbine efficiency. LP rotor cavities will be pressurized and sealed effectively to passively transfer the turbine rotor's aerodynamic load to the static structure.

Technically innovative, yet relying on proven and demonstrated technologies, the GE90 presents a manageable challenge. With strong help from our partners and a major investment by GE, the GE90 should be ready when the Boeing 777 takes off in the second half of the decade. ≡

__Sidney Elston__ is Manager, GE90 LP Turbomachinery Systems

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HISTORICAL

By Calvin H. Conliffe

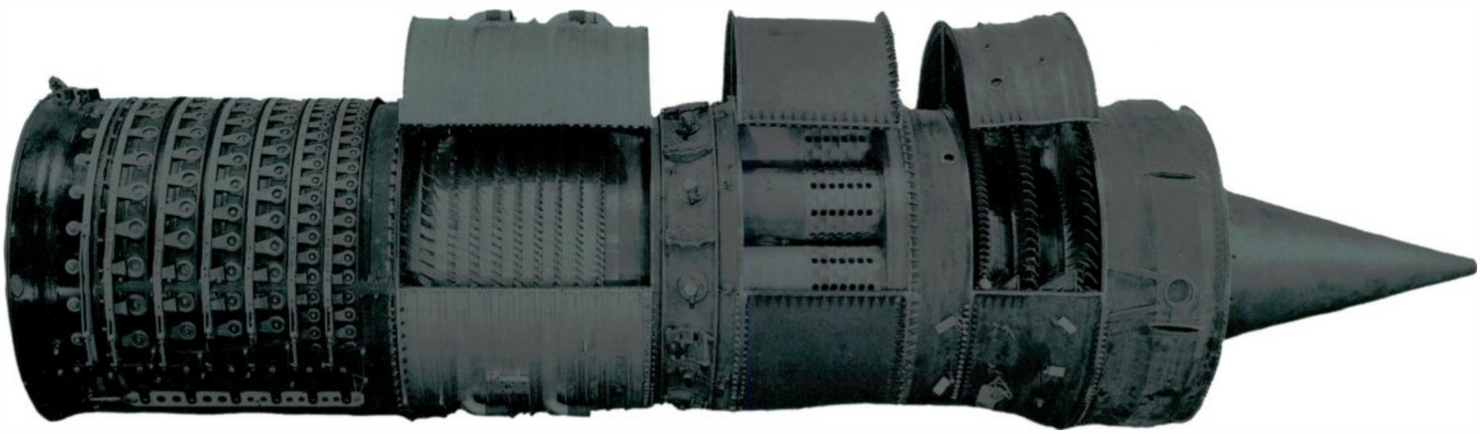
C. CONLIFFE

The Birth of the GOL-1590

In every business there are landmarks that give the company a leading edge. For GE Aircraft Engines, the variable stator concept, not the industry standard, was such a landmark.

Cal Conliffe, now responsible for identifying the technologies we'll have to have to make tomorrow's breakthroughs into product commercial engines, was a young engineer when the variable stator concept was first demonstrated on an engine, the GOL-1590. This is his recollection of the GOL-1590.

The GOL-1590 Team circa 1953



Gerhard Neumann, who went on to become the head of Aircraft Engines, had initially come up with the variable stator concept for improving the performance of compressors. This allowed the angles of the static blades (called stators) within a compressor to be adjusted relative to the rotating blades. This was needed because as the engine went up in speed, the matchup of the incidence angles of the rotating blades with the static blades was no longer optimum at every point. Efficiency fell off and the compressor would stall.

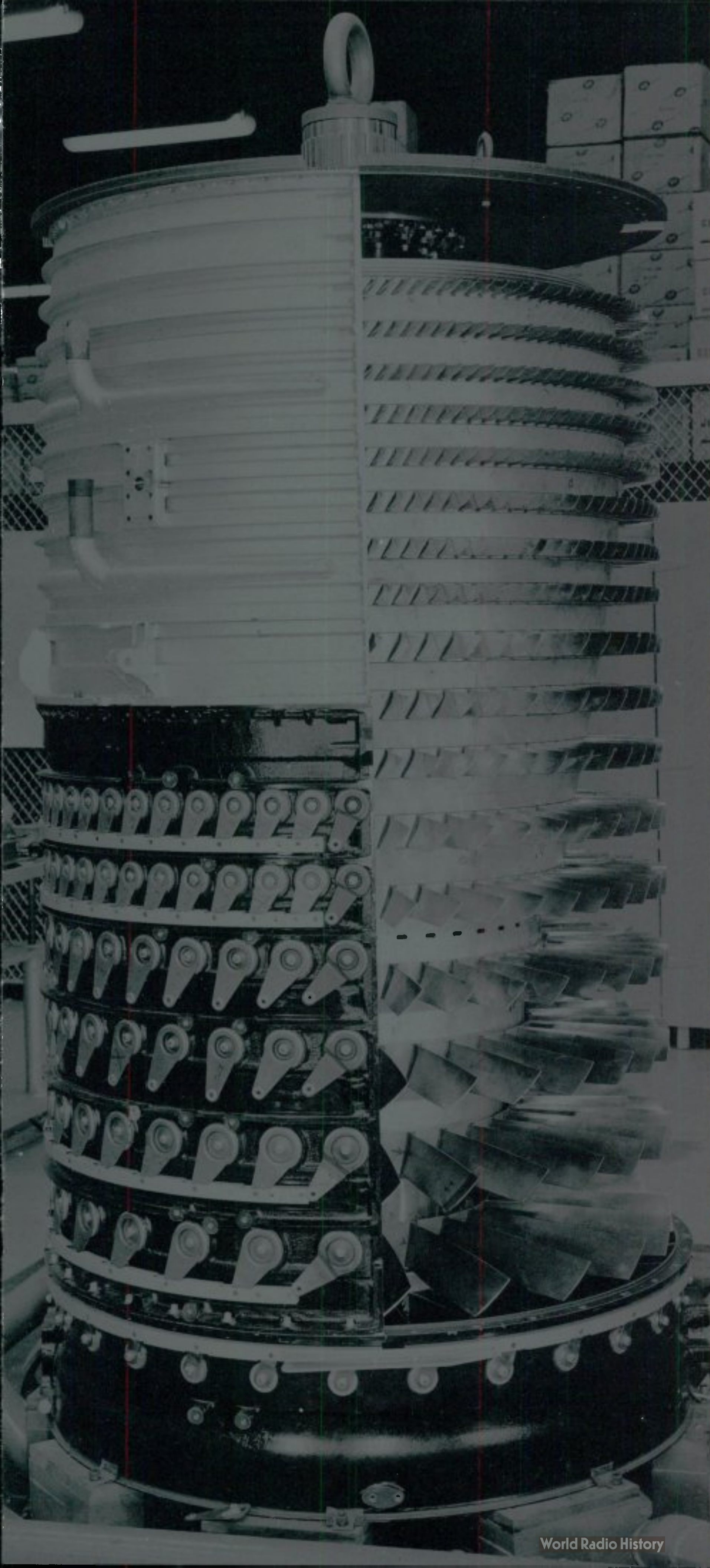
Gerhard came up with a working engine model with mechanically variable stator vanes to demonstrate the concept, and it performed flawlessly. It caught the attention of Jim LaPierre, who at that time was head of the aircraft engine business. Gerhard, who was working on GE's top secret nuclear powered aircraft engine called the Atomic Nuclear Propulsion (ANP) project, was given the responsibility to put a team together and make a design utilizing the variable stator principle. This team would compete head-on with another team that used the dual-spool approach, which maintained good performance over various speed ranges by dividing the compressor rotor into two sections and operating them separately at different relative speeds.

Gerhard's team was declared the winner, and he was commissioned to design and build a new demonstrator engine to incorporate the variable stator idea. He also had to pull together the team to do the whole job in about a year, starting from scratch.

At that time I was working in Vermont on my fourth assignment as a Test Engineer and was ready to go "off test," i.e., to go on a permanent assignment. So I set up an interview with visiting recruiters from GE Aircraft Engines in Lynn. I'd heard they might transfer most of their operation to a new plant that was opening near Cincinnati, but there would be plenty of work in Lynn.

When I arrived for the interview, the man who was supposed to interview me was a little late, but another chap walked in and struck up a conversation. He told me he was from a group called ANP. I asked what the hell does GE have to do with the A&P company (the grocery chain). Well, the fellow turned out to be Gerhard Neumann, and in about 15 minutes he had offered me a job in ANP. I was concerned about going too far South, but when I visited the Lockland plant, I found the work was interesting enough so I accepted the job for what I figured would be three to five years.

While I was waiting for my Q clearance from the Atomic Energy Commission (it took eons in those



days), Gerhard invited me to work on this new project he was heading. It turned out to be the GOL-1590 engine, which was to be the prototype of a powerful new military engine as well as serve as the core for the nuclear powered engine. GOL didn't stand for anything in particular — I think it was the General Office Ledger account number, GOL-1590.

I soon found the work so fascinating that I transferred out of ANP, which was good, because that project was disbanded shortly afterwards. So the GOL-1590 became my first true engineering assignment.

We were a very closely knit group. Everybody was under one roof — in fact, we were on one floor. That included the designers, manufacturing people, the purchasing people, everybody. And that meant that communications were quite effective. Today, we're gravitating back to that system, like on the GE90; it means time and money saved.

We also were given a lot of authority. Back in those days a design engineer had responsibility for his particular parts, from the cradle to the grave or production, whichever the result. You lived with those parts through every aspect from conception through putting it on paper, analyzing it, getting prototype parts made, evaluating, making changes, manufacturing, even field follow-up. It was a very important experience, especially to a young engineer like I was with practically no design experience.

The GOL-1590 Project was special because it had extraordinary talents. Even though we were part of a small, young industry we had a lot of darn good people with some good experience. Like Clarence Danforth, who could visualize and reduce to practical terms some very complicated theories, or develop blade design formulae with which engineers like me could actually calculate and predict excessive rotating blade vibrations, and avoid some problems.

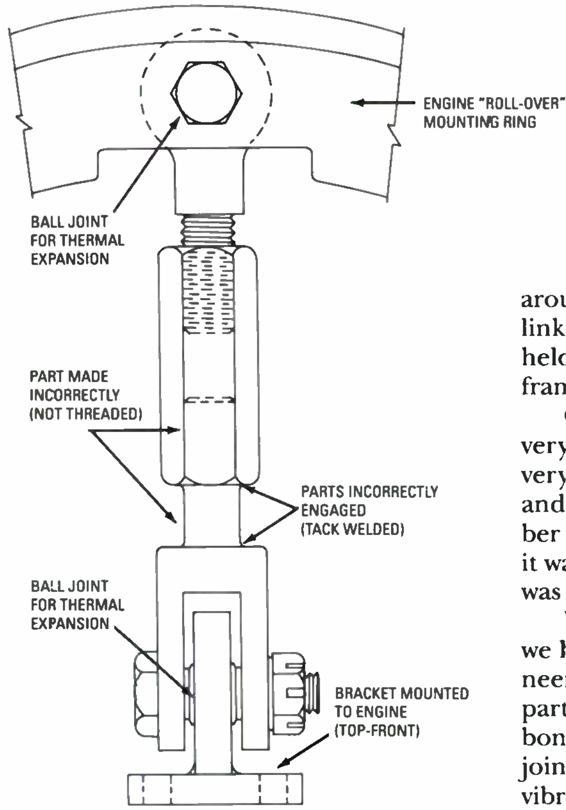
After Gerhard's team had won the competition he was allowed to pick the best personnel from both teams. At first we were kind of top-heavy, but it weeded down to a very close-knit group. There was Jim Krebs, who was Gerhard's right-hand man, Art Adinolfi, Bob Warren, and Jerry Macke, who became the father of photoelastic investigations here (see related article on page 18). We had Bob Ingraham, Marty Hemsworth, Don Keck, Bob Neitzel, Frank Driscoll, Bill Collier, Lee Jensen, and lots of others who subsequently made valuable contributions to GE's aircraft engine business. Bruce Roberts and Jim Krebs eventually went on to become vice presidents.

We had major challenges with the engine. First, it had to be reliable, able to operate over a wide range of conditions. It had to be lightweight, under 3000 pounds. It had to meet its thrust requirements in a much smaller frame than its predecessors.

One problem was figuring out how to actually test the engine. For example, just the matter of starting it was a challenge. It sounds simple, but it was more powerful than any engine we'd ever built before. We solved that one with an engine out of a Cadillac, rigged it up and actually coupled it to the GOL-1590 as the starter motor.

Another thing was that we had very crude analytical methods and tools. Small slide rules, no computers. When we went to test we had to use manometers to get pressure readings. Strain gauges were in their infancy, so we had to conceive, design, and apply a lot of new things to make it work.

Because we were given so much responsibility there was a lot of possessiveness, and because time was so



THE DOGBONE OF CONTENTION

short, we were very demanding of our co-workers. I remember vividly, I was having some parts machined, and a couple of the parts were messed up after I'd been up all night holding their hands to make sure it didn't happen. When I came in the next morning and was told what had happened, I went up one side and down the other of a couple of guys there. Another man came in and was trying to defend what had happened, and I chewed him out, too.

About an hour later I got called into Gerhard's office. "Officially, I have to reprimand you," he said, "for chewing out a division manager." Then he said, "Now that I've done that, good job!"

So there were some drawbacks to the way we did things in those days, but we got things done by treating each part with the respect and attention that it deserved.

There were some personal problems, too. I owned the compressor blades, and Gerhard told me one day that I was about to own the limiting part for the whole engine. He told me to get up to the vendor in Connecticut and not come back til I brought the parts with me.

When I got there I found out they were a shop in great turmoil. The plant manager said he was sympathetic but couldn't do anything because he couldn't even communicate with the guys on the floor. I was just a fledgling engineer, so I asked if it was OK to talk to them about making the parts.

I told them, "You're making parts for the first engine to test, and this program can be big. If it is big, the fact that you're making the first parts means that you would get a favored position to be considered to carry on. So it's to our mutual benefit to get these parts made and on time.

They asked how much time there was and I told them three weeks. They went off into a huddle and came back, saying they'd work the parts, but they wouldn't work with their management. Everything had to go through me. So for two weeks, there I was running that damn shop, passing on instructions, cajoling the guys, etc. But in two weeks I walked out of there with all my blades. They even made me a going away present, a machete they fashioned out of scrap. I still have it.

That taught me a big lesson about people, that is, if you treat people with the respect you'd like to be accorded, they'll break their necks for you. And those guys did.

Finally we were getting the engine ready for test. We went through a lot of preparation to be sure that we had it ready. We got the engine in the test cell, checked out the starter, to accelerate the engine. Back in those days, if you ran the engine for the first time and got it off the starter, that is, running by itself, why that was a great big thing! Getting to full speed might take you days or weeks. Now, of course, we expect predicted performance right away. Anyway, we started the engine and were going up in speed when the front end fell to the floor, spewing blades and chunks of casings around the test cell. The connecting link, called the "dog bone" — which held the front frame to the test cell frame — had failed.

Gerhard was livid. Gerhard, a very demanding person, could be very colorful in his actions, speech, and body language. I don't remember exactly what he said — most of it was in German — but the message was certainly clear.

What happened was that while we had spent all of our time engineering to perfection the engine parts, the people who made that dog bone had just welded it with a butt joint and so when the engine started vibrating a bit, the weld just let go.

That happened about two o'clock in the morning. We stayed up the rest of the night starting to look at the damage which had been done and saying, "Okay, if that hadn't broken, what else could have gone wrong?" We went back over everything we could to be sure that we hadn't missed something else. We got back on test in about six weeks, and went through a successful program. But it was replete with a lot of drama.

Running an engine for the first time, you didn't know exactly what to expect, and you gingerly walked up the operating lines and Bodie stalls, etc. watching the stresses. I had Clarence Danforth right with me, watching strain gauges and interpreting them. A lot of pressures, a lot of responsibility, because if a blade let go you were in deep, deep trouble. But we made it, then went on to adapt the GOL-1590 compressor to the J79.

The J79 went on to sell over 18,000 copies. But that's another story. ≡

__Calvin Conliffe__ is Manager, Commercial Engine Advanced Technology Programs

By Don Salyards and Jerry Macke

Photoelastic Analysis of Jet Engine Rotating Parts

D. G. SALYARDS

H. J. MACKE

Photoelasticity is often a relatively fast and economical way to evaluate potential problems arising from stress concentrations and stress distributions. At one time or another, photoelastic models of representative designs of virtually all highly-stressed jet engine components have been tested in various ways.

Recent advances in fixturing and instrumentation have improved the capability for stress-freezing assemblies during rotation. As a result, today's models more accurately represent hollow components, fasteners, and complete assemblies. We have chosen here to deal primarily with rotating parts tested by stress-freezing because both the models and the test procedures display the latest developments.

Stringent requirements for lightweight and high-strength designs have been the incentive for these developments.[1,2,3] In addition, failures emanating from stress concentrations such as fillets, holes, and dovetail slots must be avoided and the multiplying effect on the underlying (or nominal) stresses accurately assessed to achieve the required design life.

Briefly, as described in comprehensive reports,[4,5] the tests use a stress-freezing method which "locks in" the strains, which cause optical effects in the material. The model rotates in a precisely controlled vacuum oven, locking in the effect of rotational stresses (as opposed to dead weight static testing). Using laws of similarity, the stresses are then scaled to the rotational stresses in real metal parts, which determine the part life.

Application to Design

The Photoelastic Lab works closely with Design Engineering and the theoretical analyst to obtain shape, loads, estimated stresses, and variables to be included. First, designers use finite-element computer analyses to predict stresses. Photoelastic testing then provides greater stress accuracy in critical (but sometimes small) areas of complex stress concentrations by relating stresses in these regions to stresses elsewhere in the component.

While photoelastic testing may be used to verify computer results, there are often areas of intersecting concentrations, uncertain load distributions, or shapes that are difficult to incorporate into the computer model. In these cases, photoelastic testing may be the sole source of data.

Figure 1. *Model of the stage 1 low pressure turbine wheel from the F118.*

For example, the F118 stage 1 low pressure turbine wheel assembly model[5] shown in Figure 1 includes the disk and blades, forward blade retainer, spacer seal flange (for the stage 2 attachment), and aft shaft. Stress data were obtained for the disk at the bore, dovetail slots (with back-to-back comparisons of old and new designs), rim bolt holes, rim fillet regions, cross arm fillet regions, aft flange bolt holes, air holes and flange scallops. Stress data were also obtained for other components at the air holes and bolt holes, rabbet fillets and flange scallop regions. Figure 2 shows photoelastic fringe patterns for the blade retainer ring together with engine part stress data shown for bolt hole and air hole locations.

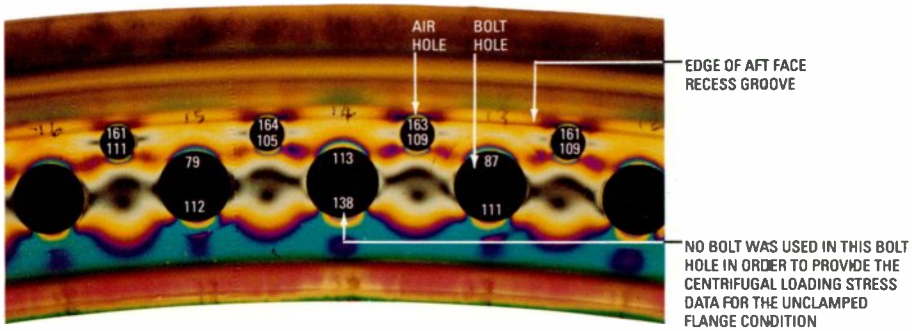


Figure 2. *Overall frozen-stress photoelastic isochromatic fringe patterns in low pressure turbine stage 1 blade retainer ring from the F118.*

The aft face of the blade retainer has a recess groove configuration that intersects the outboard edge of the air holes. This intersection presents an acute corner at the breakout zone between the air hole and the recess groove. Photoelastic analysis provides accurate stress data for this complex shape. Such data would be very difficult to obtain from general finite element analysis.

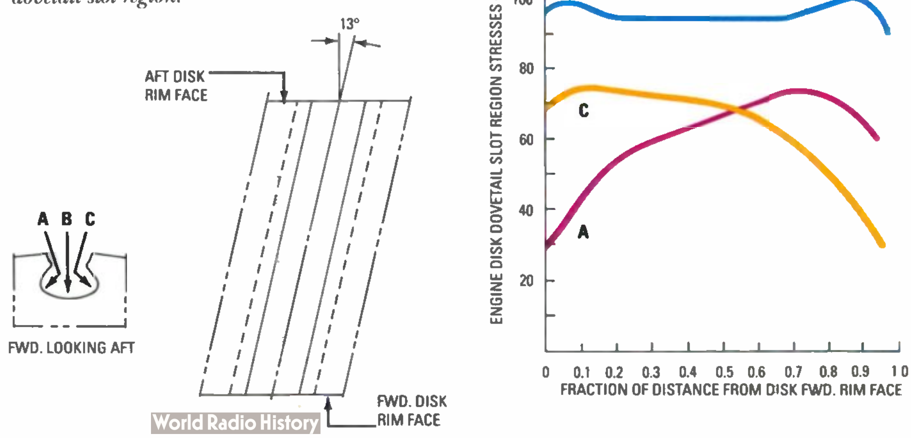
Figure 3. *Using photoelastic techniques, stress magnitudes and distributions were obtained for all three stages and the rear shaft of this three-stage fan rotor assembly model of the F110.*

As another example, in the F110 three-stage fan rotor assembly model[4] shown in Figure 3, stress magnitudes and distributions were obtained for all three disk stages and the rear shaft. These include the canted dovetail slots, flanges with scallops and bolt holes, oil drain holes of different sizes and shapes, and the disk bore and web regions. Figure 4 shows a typical plot of some of the stage 1 disk dovetail stresses.

Cooperation between the photoelastician and the designer/analyst is essential throughout the test program. As with any experimental procedure, the photoelastic analogy can not precisely simulate real engine hardware in service. Tests are generally limited to elastic, steady-state, isothermal, isotropic conditions. Further, rotating tests are generally designed to impose only rotational stresses. It is also difficult to simulate blading air loads and non-linearities, correct Poisson's ratio, and different densities and elastic moduli (in tests involving multiple parts). These limitations can be better managed with a cooperative effort to develop supplementary analytical techniques.

For example, after finite-element analysis has been completed for a real engine component, the analysis is run again for the photoelastic test

Figure 4. *Plot of surface stresses determined through photoelastic analysis of the F110 stage 1 fan disk dovetail slot region.*



conditions; i.e., with material properties, loads, and shape identical to the test. This procedure verifies the basic stress-field analysis methods. It also enables the photoelastic stress-ratios or concentrations to be applied to the basic stress fields for all real part design conditions.

Information from the finite-element analyses helps us determine the rotational speed of the photoelastic model, through the laws of similarity. The goal is to impose model stresses that are high enough to give adequate fringe orders for accurate optical readings without risking model failure.

At times, depending on shape, test results may be improved by mathematically correcting for the effect of Poisson's ratio on the stress concentration, which is different in photoelastic materials than in metals. Corrections also may be made for the distribution of the stress concentration, such as across the thickness of a member.[6]

Rotating Parts Modeling

Suitable methods and materials for casting photoelastic models from prototype engine hardware have been well known for some time. However, a number of developments have improved geometric simulation, fit-up, and general accuracy of the stress analysis. These include machining critical areas, modeling internal cavity features, properly stressing fasteners, and preventing shroud "shingling."

In some cases, cast models are machined to obtain precision in assembly, or to incorporate some design variations. Cast models are fabricated to a locally increased size by adding sheet waxes or putty material to the prototype part, or by cutting a little material from the mold. If the metal engine part is not available to use as the mold pattern, an aluminum prototype will be machined from the engineering drawings. For smaller parts a plastic prototype is made using computer-programmed stereolithography.

Figure 5. *Photoelastic models of parts with internal cavities – such as this CF6-50 cast hollow turbine blade – can now be made using waxes or low-melt alloy techniques that parallel manufacturing methods.*

Models of parts with internal cavities can now be made in either of two ways. In one method, pieces are glued together using glue made of the same material as the models. Though the joints can be glued with virtually no disturbance to the fringe patterns, the joints are usually located so that they do not pass directly through critical areas of the analysis. The second method is to cast parts, such as the blade shown in Figure 5, in one piece, using waxes or low-melt alloy techniques that parallel manufacturing methods used for hollow metal blades.

Special methods also have been developed to obtain realistic bolted flanges and to avoid shroud "shingling" or overlapping during test.

Instrumentation and Fixturing

Balance is maintained for rotating models by adding weights or by shifting blades prior to stress-freezing. However, the dynamic balance of the model assembly can degrade during the heating cycle. Degradation occurs when the thermal expansion of the plastic causes the model components to grow by a greater degree than the metal rotating shaft and related support structure.

For single-wheel models, rotational centering was formerly maintained using lightly spring-loaded conical disks positioned at the forward and aft sides of the wheel bore during the stress-freezing cycle. However, the spring-loaded cones often caused small stresses. To counteract this effect — and to freeze more complicated multi-stage assemblies without asymmetric distortions — we now use spring-loaded epoxy plastic plugs with local tapered sections within the disk bores. These plugs are designed to move axially into place with some small clearance at a predetermined rpm without placing extraneous stress into the model. An example is shown for an F110 two-stage low-pressure turbine (LPT) rotor assembly in Figure 6.

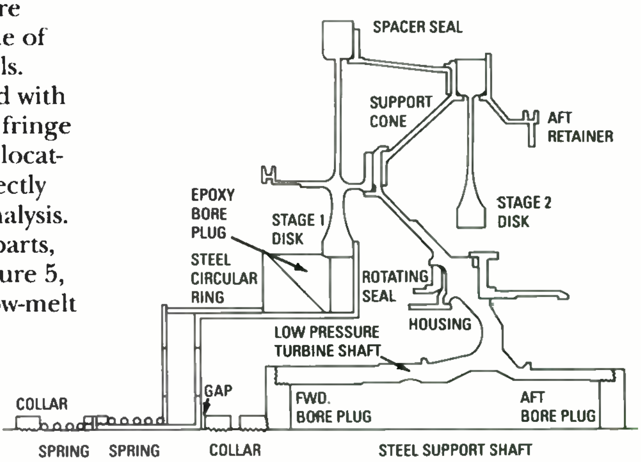


Figure 6. *Centering support arrangement for rotating photoelastic model using a spring-loaded epoxy plug at the stage 1 disk bore region of the F110.*

In this assembly, the stage 1 and 2 turbine disks are structurally supported by the LPT shaft conical shell structure which transfers the turbine torque to the engine fan assembly. For the photoelastic model stress-freezing test additional support was needed for the turbine disks. This support provided a safety net in case the assembly encountered balance problems during the elevated temperature rotation of the model when the plastic material has relatively low strength.

A movable bore plug was used at the bore of the stage 1 disk. The plug moved axially into place when the model rpm reached a predetermined level, slightly below the intended stress-freezing rpm. At this point, the sum of the disk's expansion due to temperature and centrifugal stress loading just exceeds the bore plug outside diameter. The plug remains inside the stage 1 disk bore during the test with close enough clearance to maintain the disk's concentric rotation without applying axial load or significant radial load.

Three-dimensional rotating stress-freezing tests often contain "optimized" features in fillets, rabbet shapes, hole patterns, slot bottoms, etc. The shapes are determined by preliminary two-dimensional optimization procedures. The optimized contour is then incorporated into the three-dimensional model and its precise effect verified after the model is stress-frozen and sliced for detailed photoelastic analysis.

Figure 7A. *Photoelastic model showing F118 slip ring assembly with embedded thick/thin location thermocouples.*

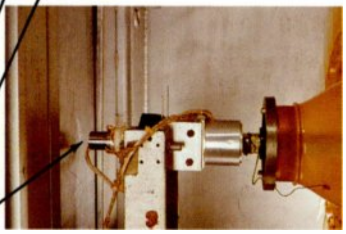


Figure 7B. *Close-up view of slip ring assembly.*

The stress-freezing oven facility simultaneously imposes and controls temperature, vacuum, and rotational speed. Thermocouples provide temperature control and prevent thermal stress by monitoring temperatures at several locations in the chamber and at "thick" and "thin" locations in a non-rotating dummy plastic part, mounted beside the rotating model. We've also recently added a slip ring assembly for large complex models (Figure 7). Mounted to the shaft, the slip ring monitors temperatures at several limiting points within the model assembly itself (for example, embedded in thick wheel hubs and on thin shell surfaces). This set-up is similar to those used in factory engine tests, except that the temperature level and the difference between thick and thin areas are controlled far more precisely in order to avoid induced residual thermal stresses. Since the test is conducted in a vacuum with primarily radiant heat transfer, the cooling cycle occurs more slowly than the heating cycle.

The laboratory has also acquired an electronic, automatic contour tracing machine that maps the precise shape of the slice being analyzed to a greatly expanded scale. This precise equipment improves analysis of parts that have an external corner with two intersecting surfaces, one or both of which may be curved. An example is the break-edge radius of a skewed blade dovetail corner. For such locations, fringe orders are read in a slice analysis polariscope (with at least 10x magnification) at several measured locations from the corner inward, with thicknesses at each reading point taken from the contour tracing. Results are accurately extrapolated to the corner, with the reading closest to the corner taken at a thickness as small as 0.1 millimeter.

Splines

A shaft spline is one rotating part that can be tested without rotation. A static rig (Figure 8) uses four dead weights to apply the torque loading to the spline components in the stress-freezing oven. The spline's design makes it difficult to extract the complete state of stress, i.e., shaft torsional stress in combination with the tooth bending stress (from the tooth loading), in the extremely small tooth root fillet regions. The laboratory now has a slice analysis polariscope that offers 50x magnification to view and analyze parts containing very small design features. Recently developed methods use very thin slices and an oblique incidence photoelastic analysis technique to more accurately determine the extremely variable stress distributions along the full spline length (Figure 9).

Figure 8. *Loading rig for torsional stress-freezing static test of fan shaft spline coupling.*

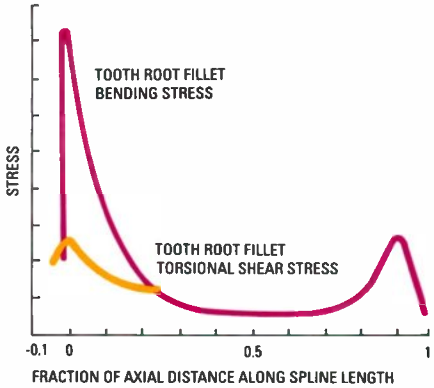


Figure 9. *Stresses in spline of fan drive shaft. New techniques provide more accurate determination of variable stress distributions.*

This analysis has shown that the ends of the spline can have extremely high stresses. As a result, design modifications have been incorporated to reduce stress at the ends of the spline and to place more of the load in the middle of the spline.

New Developments/Outlook

Since accurate and efficient determination of stresses is critical to jet engine design, we are always seeking new, faster-curing, low-residual-stress materials, as well as additional ways to make our product more accurate and efficient. New controls will soon be installed on the current rotating stress-freezing oven. We've also designed a new facility that may be purchased in the future to accommodate larger-sized rotating stress-freezing tests. We have made some use of computer programmed stereolithography equipment to rapidly provide small patterns for mold preparation, and are investigating the use of this method to produce complex birefringent models directly without casting or machining.

Summary

Photoelastic analysis either increases confidence that the stresses in designed parts provide the required design life or indicates the need for redesign if stresses are too high. Properly designed tests permit us to select which of several design alternatives provide the lowest stress at minimum weight, optimizing the design based on stress levels. ≡

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__Jerry Macke__ is previously Manager, Photoelastic Laboratory, and currently Consultant, GEAE

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Stress-Optic Theory and Photoelastic Analysis

Photoelastic analysis makes use of certain physical properties of some transparent materials when subjected to stress and viewed in polarized light. As the polarized light beam passes through the stressed material and then through another polarizing filter in a system called a polariscope, the photoelastic effect is produced because the beam is split into two components. This double-refraction optical effect (also called birefringence) of the light components (whereby the velocity of one component is retarded relative to the other) is associated with two principal stresses in the material in the plane perpendicular to the light beam. With white light consisting of all wavelengths in the visible spectrum, brilliantly colored bands called isochromatic fringe patterns appear throughout the stressed material. The double-refraction optical effect must be analyzed in order to determine the stresses. The polariscope provides the necessary polarized beam of light and the optical measurements. The fringe patterns appear because the degree of optical interference varies due to the variation in the state of stress at different locations throughout the photoelastic model. By measuring the fringe order, the stress can be accurately calculated from the stress-optical equation of photoelasticity that relates color to stress. In some transparent plastics, stresses can be "frozen-in" by heating. This makes it possible to lock in the stresses and photoelastic color patterns (due to rotation of the model, for example), so that analysis can be done later on slices cut from the model.

H E S

interview

Some might call him a quality zealot, but that's okay with Jeff Heslop. In fact, he agrees with the description. As Total Quality Advisor for Evendale Product Engineering Operation, Heslop coaches and helps managers with the Continuous Improvement efforts of three departments. Prior to that, he was a designer and later unit manager in bearings, seals, and supporting structures.

Although Continuous Improvement encompasses many complex theories and analyses, Heslop says the driving philosophy is to improve quality through four principles — 1. application of statistical thinking; 2. viewing work as a process; 3. focusing on the needs of the customer; and 4. demonstrating respect and dignity for others. He struggles daily to help managers keep GEAE's culture moving in the direction of this philosophy. While there's still much work ahead, Heslop firmly believes that Continuous Improvement provides the best means to ensure our competitive survival.

L O P

H E S

You started your career with GE here in Evendale. What first brought you to GE?
When I graduated from college at Kansas State my older brother, Jon, worked for General Motors in Dayton. He and I were very close, and I came to Dayton and started working at GM. A while after that I was laid off and went to a recruiting agency that told me about Aircraft Engines. As far as I was concerned, for a mechanical designer, GE was a paradise. I was anxious to come down.

What do you mean by paradise?
GE has mechanical designers in just about anything you could think of. You could get involved in fluid systems, heat transfer, structures... all these things that I trained for in college.

What job did you start out in?
I went right into ground equipment design. That involved mechanical design of equipment that helps you assemble an engine or maintain an engine. I designed tools that would lift a turbine rotor, or remove spanner nuts off of a turbine shaft, things like that. We also designed simple tools that would just act as protective devices when assembling things. Everything was unique.

But my ambitions were to work more on engine components, so I began applying for jobs in component design areas. After a little less than three years, I moved into bearings, seals, and supporting structures and got into actual engine design.

I have been in that area up until this present job.

What engines did you work on?
I worked on the 80A engine. This was maybe a year before that engine was certified. We then did similar work on the 80C. Before delayering, I was a unit manager on the UDF® engine — the GE36. I had about five people who worked on the sumps, bearings, seals, and the secondary systems that would cool the various areas of the turbine. That was a very fascinating program.

What made it fascinating?
The UDF® engine had these rotating fans on the back end — where the thrust came from — which made everything about the design different. We had never designed seals anywhere near that size in diameter. We had never designed bearings like that before. There were about six main shaft bearings just in the fan section. And I couldn't even begin to count all the bearings that were involved in the system to change the pitch of the fan blades. That was a remarkable fan. We were just on new ground all the time. The further we went, the less we found out we knew. It was very educational.

You mentioned that you were delayered. What happened there?
I was on the GE36 as a unit manager and I was really proud of that. I enjoyed the people I was working with. When delayering began I became a senior staff engineer. My manager, Ed Beck, put me full

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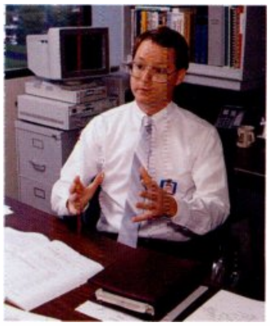

time working on Continuous Improvement. This was back in 1988 before we had anything going as far as the Group Staff's leadership or our consultant, Joiner Associates. But Ed had gone to the Deming four day seminar and it totally changed him. I was the right guy because I had developed a keen interest through my brother, who was already very much into the quality movement.

Weren't you one of only a handful of people in the company working on Continuous Improvement at that time?
Yes. I found out later that several people were already working with the Group Staff, but nothing was centralized. All we knew was that when we saw what Deming taught and looked at the way we managed, it was just embarrassing. My gosh, we were so far away.

What was different between the Deming principles and the way that we manage here?
I can only speak for our section. One of the fundamentals that Dr. Deming taught the Japanese back in 1950 was to view work as a process. In other words, you have a supplier, you process a product in some way, and then you provide that product to a customer. So, Dr. Deming taught the Japanese statistical ways to improve this process.

I realized just how far we were from this kind of thinking after a conversation I had with my brother. He said if we were going to be involved in Dr. Deming's philoso-

phies, we had to address some basic questions. Who is our customer? Who is our supplier? What's our process? Do you know what your customer wants? How can you improve your process? Now, these seemed like very basic questions. But when Paul Bisset, who was another manager in Ed's area, and I really thought about it, we couldn't answer a single one. We just didn't know. But that was a tremendous breakthrough, because then we were willing to do something about it.

What did you do?
I had a guy working for me, Ravi Kurumety, who was going to design a spanner nut, which is a big bolt that holds components on a shaft. I got to thinking about how we actually design a spanner nut. It's the most simple design you could imagine, but we didn't have any idea what our process was. So the first flowchart I ever made was for the spanner nut. I did it by hand on an old dirty piece of paper and I gave it to Ravi to work with. It was a mess. I mean, I had erased it, it was full of fingerprints, but it was a flowchart. And it was a tremendous improvement, believe it or not. Eventually Ravi and his team improved that chart and you ought to see it today; it's a real piece of art.

What happened next?
Well, that was in early 1988. I realized that I really didn't know much about this whole process, so I started studying. And, of course, I loved it

because I enjoy studying. The amount of knowledge that you need to learn is so challenging. It's humbling, too. I was overawed by my ignorance in how far I had to go to really learn these things. But it's turned into the most exciting time of my career.

Then Paul Bisset started to form some teams. Now we didn't know what we were doing, but those people were willing to try and they wanted to work on improvement and they were motivated. I know a lot of them got perturbed because we didn't know how to help them. But they stayed with it. Eventually I started going to all of their meetings to try to help them in what they were doing, explaining some simple principles about the need to understand a process. We discussed the need to reduce variation in the design process and things like that. And they understood it. They picked it up immediately, they started changing.

After that we got the <u>Team Handbook</u>, which was a real breakthrough. As far as I'm concerned, this is the outstanding book on getting teams together. What we found out right away is that we don't know how to work together. We just absolutely don't know how to do it.

What do you mean?
We just haven't done it. Competition is killing us.

Internal competition?
Internal competition. It's an unwritten philosophy that American com-

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panies have held for years. It's the belief that by putting people in competition with one another, you'll bring out the best in them. We would get in these meetings and everyone was only interested in their own needs. And I'm the same way. The environment encourages it. To get ahead you have to be more assertive, more aggressive, than the other guy. And it just totally devastates any ability to cooperate to get a job done. When we started we were having yelling matches... all kinds of problems. Then we got the Team Handbook and it told us how to work together. And it worked, we changed.

What improvements did the team make?

To me, one of the most important improvements they made you can't even measure. Their attitude changed. They were being allowed to work on the processes they had control over and improve them. They were able to get barriers out of their way. And you don't have to motivate people to do that. People want to do that.

They started flowcharting processes that they had control over and started working better. And they started thinking in terms of a customer; that they had a customer and that they provided a product to that customer. They began to see their job was to provide the highest quality

product they could to their customer. It changed the way they think. How can you put a price on that?

Can you give an example of what happened as a result of that?

We had a tremendous problem with rotor thrust loads on a production engine. We began using statistical analysis to better understand thrust load. It was an absolute breakthrough. We were able to quantify the variation in bearing thrust load and demonstrate what components have what effect upon variation.

So that was a tremendous step forward right there, but that was just the beginning. Once we did some of that it became obvious that we needed to begin thinking about reduction of variation and centering distributions on target. You can't even think about the quality of a system, or of a component, unless you can quantify its functional variation. That's the measure of quality. It's a total transformation of thinking. We started applying the Quality Loss Function to allow us to reduce variation.

What's the Quality Loss Function?

The Quality Loss Function is a different theory for looking at variation of a process. Today, the theory is that as long as a component, or quality characteristic of a component, falls within specification limits, it doesn't matter if one is on the low end and

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another component is on the high end, they are of equal quality. The Quality Loss Function lets you quantify the penalty you pay for deviating from a best value. Any time a component deviates from its best value, there's an economic price to pay for that.

Let's talk a little bit about your role as a Total Quality Advisor. Tell me specifically what areas you work with and what it is you do.
I was hired by Jim Tucker who had Evendale Product Engineering Operations at the time. That's composed of three departments: Evendale Product Engineering, Design Engineering, and Product Development Engineering. Those are the three departments that I'm trying to coach, you might say. I have to get people to see how exciting this can be. Of course I sometimes turn people off.

How do you do that?
I often make people angry by telling them how much there is to improve. We have lots of people who still believe everything is okay. They're not in a panic. I'm in a panic. We're in a new economic age. I feel a great sense of urgency to make tremendous changes. I mean fundamental changes to these systems and the way we think. We can't do it fast enough. But you can't just talk to people and convince them to change. You have

to try things out on a small scale and demonstrate actual applications.

There's been a lot of discussion regarding the differences between Work Out and Continuous Improvement. Can they co-exist?
There's no question that they can. Work Out is very effective when you can identify a large process with all the people involved in the process. You get them together and agree on things that don't need to be done, that don't add value. That's exactly what you try to do in Continuous Improvement. There's no conflict there at all.

Work Out is often the first step in making improvements, but there is more that's needed. Continuous Improvement can be following a Work Out exercise to focus on statistical thinking and scientific method, for example. So, Work Out is an important part of improving quality, but it's often just a first step followed by Continuous Improvement.

Do you use the principles of Continuous Improvement outside of work?
I've used the techniques for preparation of Sunday School lessons. I use fishbone diagrams to get my thoughts collected for exams. I was doing that in preparing a lesson one evening at home and my oldest girl — she's seven — came in and asked me what I was doing. I taught her how to make a fishbone

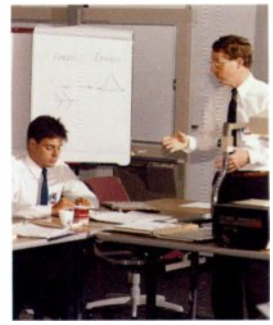

diagram and she used it to diagram how she got to school on the bus.

Where do you see GE ten years from now in terms of Continuous Improvement?
Well, ten years from now, provided we stay with the transformation, we'll still be in business. Statistical thinking will absolutely be a habit as it is in Japan now. Key processes will be understood by all involved in them. Processes will have been improved over and over again ten years from now. We will have elaborate, thorough, systematic, logical systems for identifying what the customer needs. We will treat each other with a dignity and respect you can't even imagine today.

We will have a mentality that says we can't please the customer if we don't please our internal customers first. Everything will run so much smoother. People won't be frustrated with all the barriers anymore, people will be encouraged to improve their lives.

Eventually, we'll go outside of Aircraft Engines. We'll think about optimizing society as a whole. As Dr. Deming teaches, we'll even begin thinking in terms of the world as a system that we do not want to suboptimize. That's probably too ambitious for just ten years from now. But if we are serious about this, that's the kind of thinking that would take place. ≡

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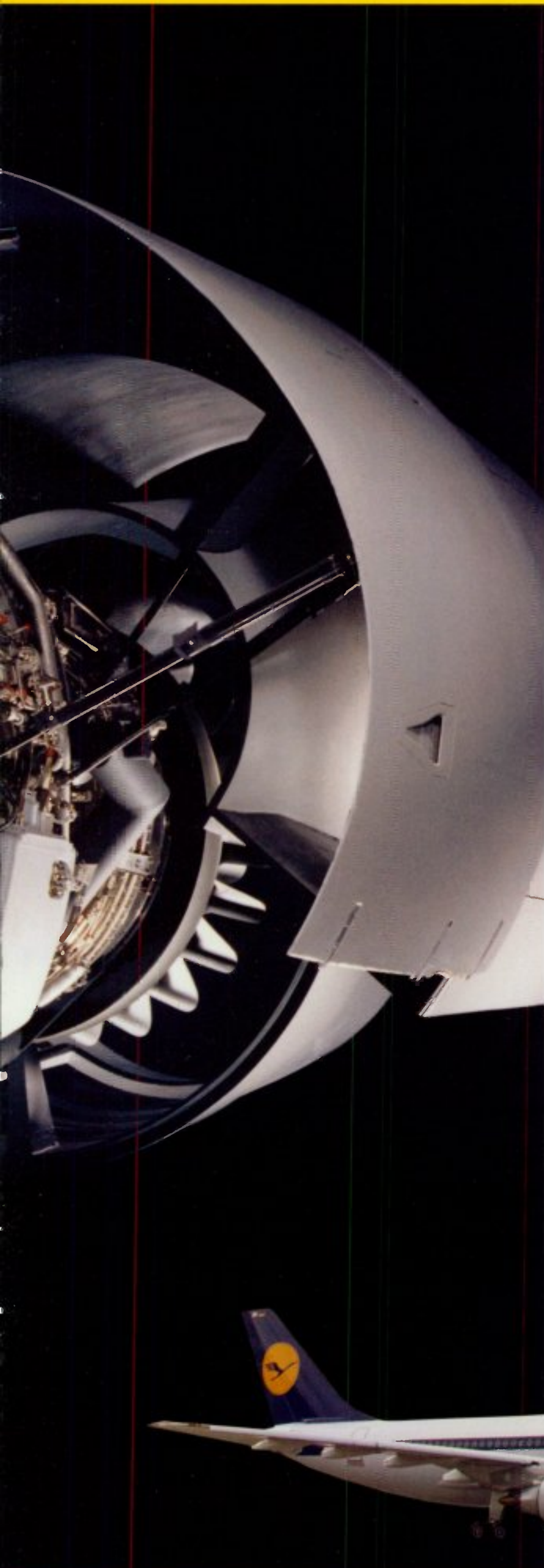
GEAE Integrated Propulsion Systems

By Donald F. Keck,
John A. Gill, Al Lingen,
Mike J. Sepela

GEAE builds more than engines. In some cases we build entire propulsion systems, which include both the engine and a nacelle system. Prior to 1979, when GE first designed an integrated propulsion system for the CF6-80A3 engine on the A310 aircraft (Figure 1), the airframer designed the nacelle.



Left. *CFM56-5C propulsion system.*

Figure 1. *(Below) GEAE designed propulsion system for the A310 aircraft.*

GEAE became involved in propulsion systems at the request of airline and airframe customers who wanted the engine manufacturer to assume responsibility for the complete underwing engine and nacelle system. This arrangement provides the customer with a central source for resolving all propulsion system requirements for installed performance, weight, and system reliability and maintainability.

GEAE also stood to benefit from this arrangement. With control over the numerous interfaces to the aircraft we can better match the engine and nacelle configuration to improve performance, exceed customer requirements, and improve our competitive position. Our entry in this market also provides a new, high-value product that can be sold with every engine.

Since entering the market for nacelle product design, GE has developed many new technologies to meet competitive weight, performance, and cost goals. This article provides an overview of current total propulsion systems and reviews several key technology developments.

Propulsion systems pose several design challenges which applied to our first system as well as to those under development today:

- Developing nacelle composite structures and designs that would achieve the lightest weight propulsion systems in the marketplace for a given thrust size.
- Developing nacelle aerodynamic and acoustic criteria for achieving the best installed internal/external performance for the propulsion system.
- Integrating the design of the engine, nacelle, and aircraft systems to achieve a competitive overall-propulsion system applicable on different aircraft to achieve maximum commonality.

The nacelle part of the system is an aero-mechanical enclosure that effectively captures engine airflow through an inlet cowl and discharges the engine air through an exhaust nozzle system. The two basic nacelle configurations shown in Figure 2 are the separate-flow, short-duct, and the mixed- flow, long-duct designs. The external aerodynamic contours are shaped in wind tunnel tests to provide a low drag installation when mounted on the aircraft.

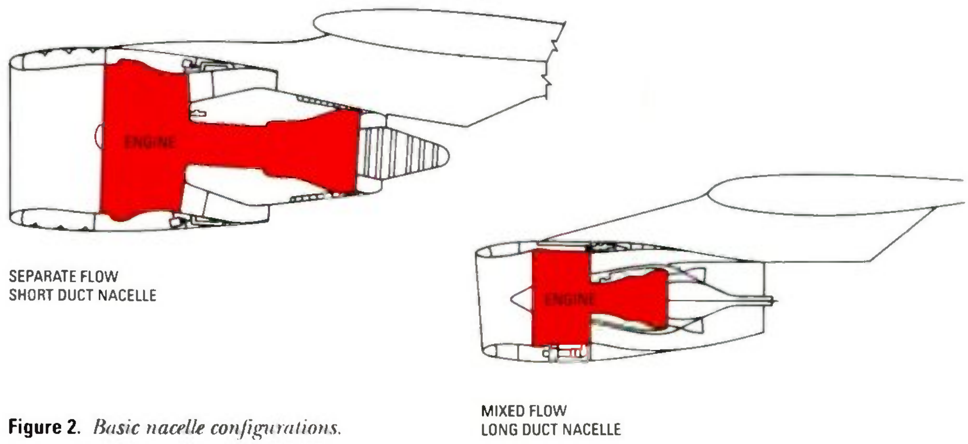


Figure 2. *Basic nacelle configurations.*

A typical separate-flow nacelle consists of the major components shown in Figure 3 and is assembled with the engine prior to delivery to the airframe. The inlet and primary nozzle are attached to the engine front and aft flanges, respectively. The fan and core cowling and reverser are hinged to the pylon and interface with the inlet, engine, and nozzle upon closing. Aircraft and engine systems (Engine Build-Up or EBU) such as hydraulic and electrical power, fire detection, fuel supply, pneumatic system, mounts, and electrical control harnesses are installed under the cowling and connect the engine and gearbox to pylon interface points for the aircraft systems.

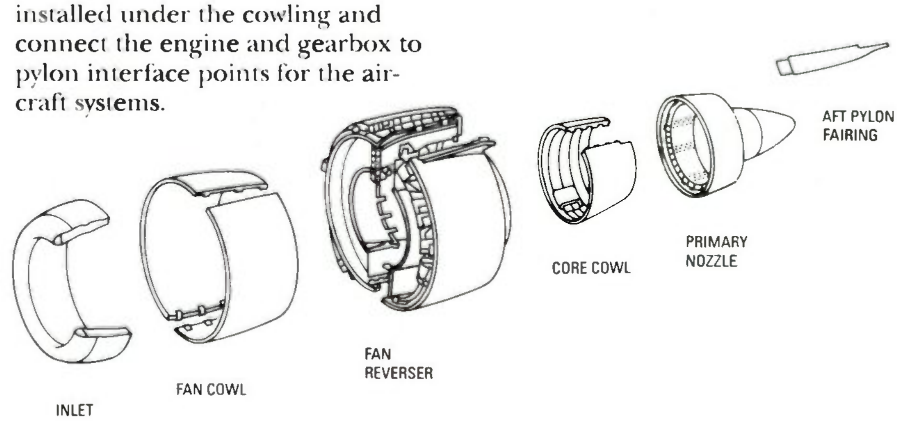


Figure 3. *Nacelle and exhaust system products.*

CF6-80A3

The CF6-80A3 propulsion system (separate flow configuration) was based on an extension of technologies gained on the CF6-6 and -50 engines and exhaust systems. Even though the system was certified in 1983, GEAE had been designing and building commercial exhaust systems (including thrust reversers) since the 1960s for the CJ805 (J79 derivative) engines. For the CF6 propulsion system, we developed graphite composite structures on the reverser and established criteria for aerodynamic nacelle lines.

These technologies were further improved when the higher thrust (62,500 lbs) CF6-80C2 propulsion system (Figure 4) was developed in the 1980s. The use of light weight graphite composites and structures was extended into the nacelle cowling and additional reverser components such as blocker doors and cascades. Replacing aluminum structures with graphite composite structures reduced component weight by 20 to 25%. Also, improved aerodynamic and acoustic systems were developed for a common set of nacelle lines to satisfy requirements for the A300, A310, 767, 747 and MD11 aircraft.

With the advent of electronic controls on the CF6-80C2, new, modulated-undercowl cooling approaches were incorporated to minimize cooling flow at cruise. The CF6-80C2 nacelle aerodynamic design was developed to suit a wide variety of aircraft requirements. The target was a single set of inlet and exhaust lines to suit five different widebodied aircraft. The nacelle being replaced on each of these aircraft was produced by a different source. The key requirements are summarized in Table 1.

The diverse requirements were met by designing for the most demanding application, i.e., the B747. The greatest challenge to achieve a "common nacelle" for all airframers was to convince Boeing aerodynamics designers that the GE technology could meet their extreme inlet angle of attack requirements.

AIRCRAFT	PRIOR ENGINE	PRIOR NACELLE DESIGN	DESIGN CRUISE MACH NO.	INLET ANGLE OF ATTACK REQUIREMENT
A300-600	CF6-50C	DOUGLAS	.79	17°
A310	CF6-80A3	GE	.79	17°
B767	CF6-80A	BOEING	.80	20°
B747	CF6-50E	BOEING	.85	25°
MD11	CF6-50C	DOUGLAS	.82	17°

Table 1.

Boeing's main concerns were low speed angle of attack capability and critical Mach number (wave drag). GE and Boeing models were developed for competitive testing at the Boeing slow speed wind tunnel. When GE proved to have a better design, the two companies began working together to minimize the inlet wave drag at the high speed cruise Mach of 0.86. This effort resulted in minor recontouring of the top, or crown line, which had no effect on the other low speed inlet characteristics. Boeing B747 aerodynamics people then accepted the GE design and are using the common inlet in the other aircraft without change.

The CF6-80C2 nacelle was successfully flown on four airplanes and certified. Nacelles for the MD11 will be certified in 1990. There have been no aerodynamic problems in the many flight hours accumulated by the CF6-80C2 fleet in airline service.

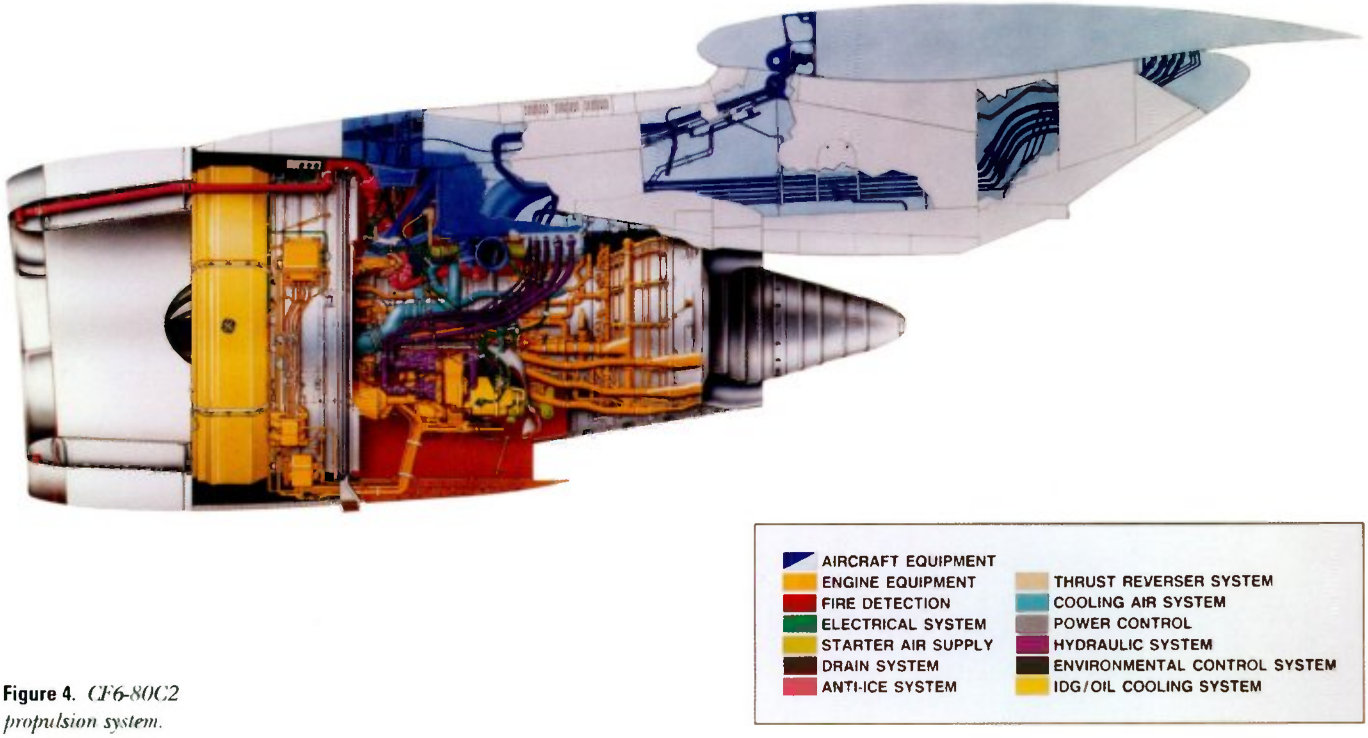


Figure 4. *CF6-80C2 propulsion system.*

Propulsion system developments

Three additional propulsion systems (Figure 5) are being developed by GEAE for service starting in the mid-1990s:

- CFM56-5C for the A340 Airbus aircraft,
- CF6-80E1 for the A330 Airbus aircraft, and
- GE90 for the B777 Boeing aircraft.

The propulsion system for the high thrust (72,000 lbs) CF6-80E uses nacelle technology developed on the CF6-80C2. Improvements in external installed performance (lower drag) are being investigated with scarfed inlets and laminar flow designs.

CFM56-5C

The CFM56-5C propulsion system (long-duct, mixed flow configuration) has a thrust up to 34,000 lbs. This configuration was selected as the most fuel-efficient system for the long-range A340 aircraft mission (Figure 6). The system provides an increase in climb thrust for a longer time at the cruise altitude at which the aircraft has the best performance.

The inlet, fan cowl, thrust reverser, and nozzle are made primarily of structural graphite composites similar to the CF6-80. This design reduces weight and provides advanced acoustic treatment in the inlet and thrust reverser. The thrust reverser is a new four-door type, consistent with reverser thrust and weight requirements. The mixer and centerbody are IN625 fabrications, selectively chem-milled for weight. A new manufacturing process is being developed by Rohr Industries to use titanium.

Originally, high bypass turbofan engines had separate exhaust flowpaths for the fan and core flow in order to minimize nacelle weight. Very high efficiency flowpaths were developed which had minimum loss and drag when installed on the aircraft, in spite of the exposed high speed flow of the fan exhaust. As composites were introduced to drive the nacelle weight down, the use of a common exhaust and "daisy" mixer became more practical.

Thermodynamically, the mixed exhaust provides virtually no fuel consumption payoff at takeoff. Fuel consumption benefit increases with flight speed to a value of 3 or 4% at the high speed cruise. Climb thrust of the engine also is enhanced by the mixed flow arrangement by 3 or 4%. The penalties are weight, drag of the additional external nacelle, and increased risk of installation drag penalties. These penalties, when expressed in terms of the fuel consumption benefit, erode 1½ to 2% of the payoff without consideration of installation drag increase.

When the separate flow and long duct installation penalties are equal, then long duct nacelles may be selected for use, as in the case of the A340/CFM56-5C2 application. The A340's long-range mission makes it well suited to this system, which has the largest benefit at cruise.

Figure 5. *(Left) GEAE propulsion systems.*

Figure 6. *(Right) CFM56-5C propulsion system.*

Light weight technology

Light weight Graphite Nacelle Structures — Early nacelle inlet cowlings for the CF6-50 were made solely with metallic materials (Figure 7). Advances in graphite/epoxy composites led to greater use of graphite fabric beginning in early 1980. For example, nacelle structures on the CF6-80A3/C2 used epoxy graphite designs coupled with metallic structures (Figure 8A). The 1990 family of nacelle designs for the CFM56-5C and the CF6-80E uses structures solely manufactured from graphite epoxy materials (Figure 8B).

Compared to similar metallic structures, graphite/epoxy composite materials reduce weight 20% and ensure adequate operational load carrying capability while providing equivalent structural stiffness. Figures 7 and 8 compare the metallic and composite inlet inner and outer barrel structures. The composite materials offer many challenges in manufacturing and in providing protection against direct lightning strikes.

Composite Graphite Cascades are currently being developed for cascade type fan reversers, i.e., CF6-80C, CF6-80E and GE90. The new cascades are in the process of being tested and FAA-certified on the CF6-80C2 fan reversers.

The fan reverser cascades (Figure 9) are a series of airfoils that direct the fan flow forward as the diverted flow exits from the fan discharge. The graphite epoxy composite cascades replace aluminum cascades and reduce the weight of the CF6-80C2 fan reverser by about 70 lbs.

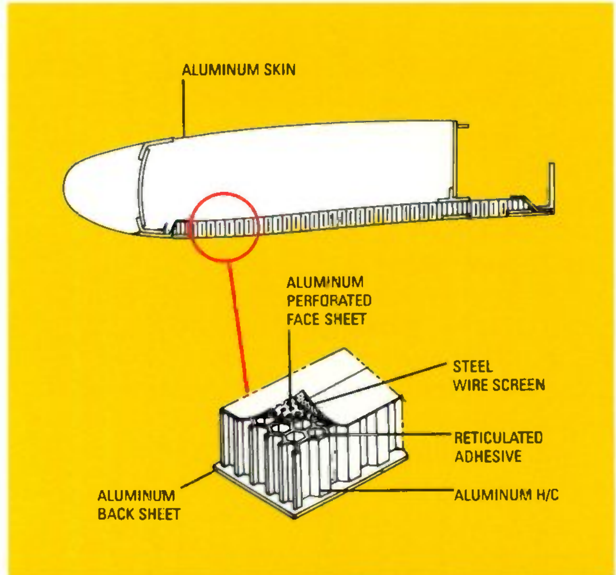


Figure 7. *CF6-50 inlet cowling produced from metallic materials.*

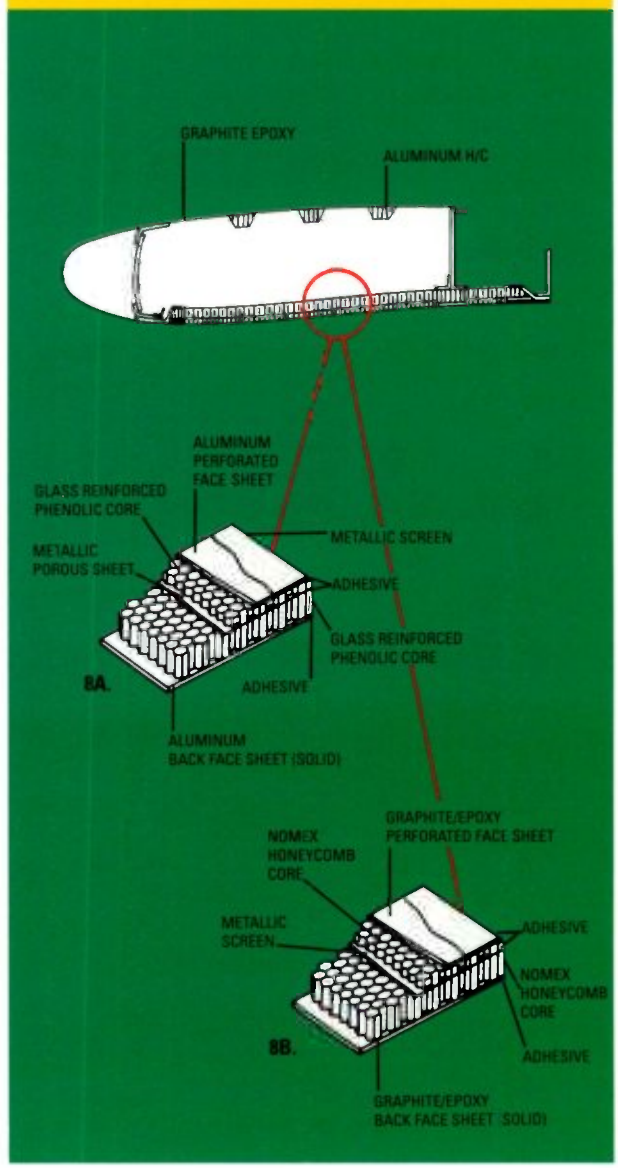


Figure 8A. *CF6-80A3/C2 nacelle structure coupling epoxy graphite designs with metallic structures.*

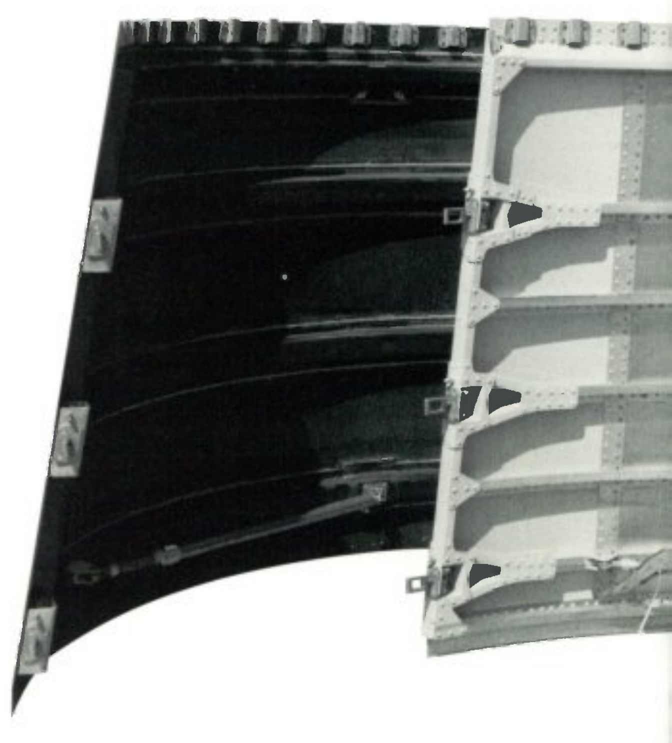
Figure 8B. *CF6-80E nacelle design using structures solely manufactured from graphite epoxy materials.*

Because the CF6-80C2 fan reverser cascades are structural members of the reverser, they must carry large hoop loads. While this design eliminates redundant frame structures and reduces reverser weight, new composite layup techniques were needed to carry the combined loading. Developing the layup was a critical step, since the composites were designed to be interchangeable with the cast airfoil aluminum cascades. Designers were further challenged by the small size and tight spacing of the cascades, which makes it more difficult to work with composites.

Figure 9. *(Left) Composite graphite fan reverser cascades.*

Figure 10. *(Below) Test set of PMR-15 composite core cowl (left) and aluminum core cowls currently in use.*

PMR-15 Composite Core Cowl — GEAE advances in composite technology have been applied to nacelle components such as core cowls that operate at a moderately high temperature of 550°F. The current product core cowls are made of aluminum, as shown in Figure 10. A test set of composite core cowls made from graphite/polymide PMR-15 (also shown in Figure 10) is 30% lighter than current metal core cowls. The composite cowl set is being service-evaluated by GE and Lufthansa German Airlines on the A310-200 aircraft, and has successfully accumulated 750 hours of service. The service evaluation will



accumulate a total of 3000 flight cycles and study the thermal effects on the composite materials.

Nacelle aerodynamic technology developments

Inlets with Unusual Face Planes — The inlet, face, or highlight plane is ordinarily designed to be normal (perpendicular) to the inlet axis as in Figure 11A. Past NASA studies included face planes which were scarfed (angled) upward (Figure 11B) in an attempt to reduce forward radiated noise, since the noise radiation axis tends to be normal to the inlet face plane. These studies found that low speed inlet performance did not deteriorate, but rather improved with the scarfing of the face plane.

Recent GE studies have quantified the enhanced low speed performance for 10 and 20 degree scarf angles. Low speed angle capability increased by an inlet angle roughly equal to half the scarf angle. Hence, scarfed inlets have the potential of using much lower contraction ratios than conventional designs, thereby effecting weight and cruise drag gains.

Laminar Flow Nacelles — GE, Rohr, and NASA are jointly studying practical boundary layer bleed systems which allow the prevention of transition over large runs of the lifting surfaces. The technology is targeted at nacelle structures, with a plan to demonstrate the amount of bleed flow required to maintain a laminar boundary layer over the inlet (Figure 12). The studies will quantify the amount of bleed flow required and evaluate perforated skin structure weight and attendant manifolding required to collect the bleed flow.

Propulsion system challenges of the future

The GE90 and CFM56 family of engines will require further integration of aircraft and propulsion system designs to meet performance, reliability, and weight requirements for efficient airline operations. We're currently working on the design of engine and EBU systems that facilitate maintenance and increase the reliability of interconnecting engine/aircraft systems. ≡

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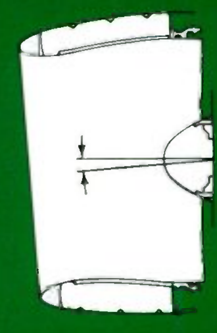
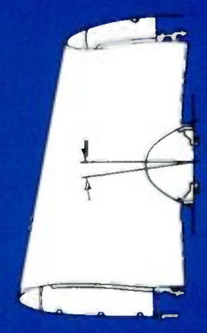
John Gill *is Manager, CFM56/CF6-80E1 Propulsion Systems*

Al Lingen *is Manager, Nacelle Aero/Acoustic and Installed Performance Design*

Mike Sepela *is Staff Engineer, Nacelle Structures*





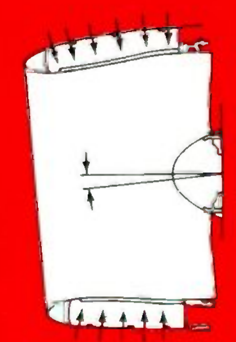


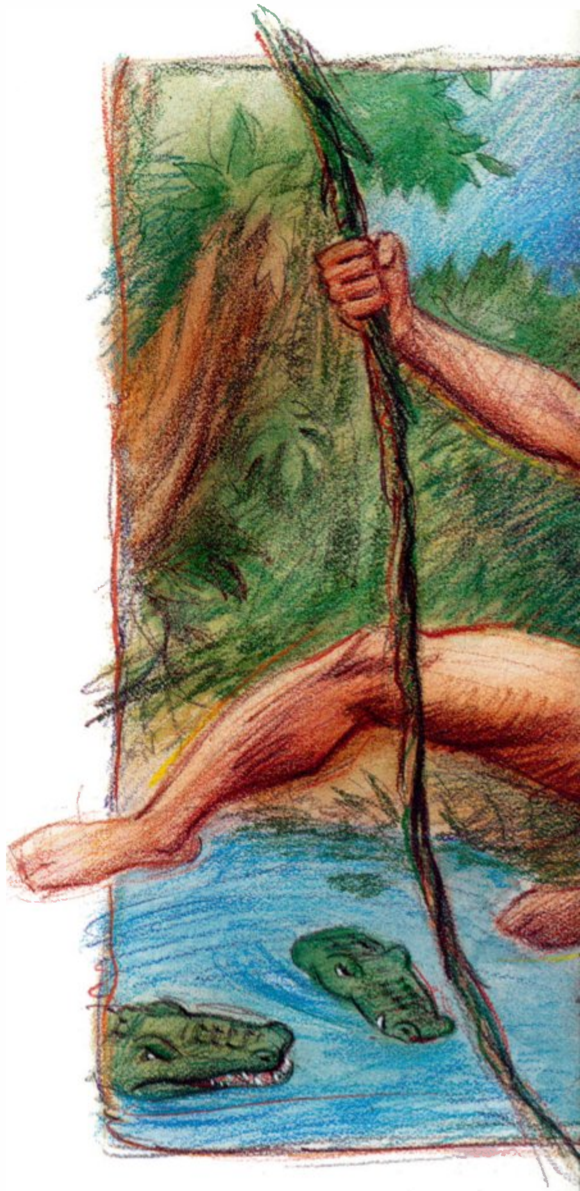
Figure 11A. *(Top) Conventional inlet plane.*

Figure 11B. *(Middle) Scarfed inlet plane.*

Figure 12. *(Bottom) Laminar flow inlet.*

OPINION

Up the Bureaucracy



One of Brian Rowe's five desired outcomes for 1995 is to identify and reduce bureaucratic roadblocks. In an organization steeped in control and bent upon specific financial targets, that is no mean task. Such a goal means nothing less than totally restructuring the values of the organization.

It is no wonder that, faced with such a revolutionary vision, players by the old rules might view such a change not as emancipation but as a descent into chaos. One can almost hear Emily Latilla on Saturday Night Live. "What's all this I hear about overthrowing democracy?"

Instead of running off in all directions pursuing misconceptions, it would be the wiser course to ask, "What are we really talking about?" In terms of statistical thinking, this means forming an operational, measurable definition of bureaucracy. That way we all aim at the same target and have some way of telling if we hit it.

Mister Webster's wonderful dictionary gives us several ways to understand bureaucracy. (There are other ways to form operational definitions, but this is a start.) Three definitions apply:

1. The administrative, policy-making group in any large organization.
2. Systematic administration characterized by specialization of function, objective qualification for office, action according to fixed rules and a hierarchy of authority.
3. A system of administration marked by constant striving for increased functions and power, by lack of initiative and flexibility, by indifference to human needs or public opinion and by a tendency to defer decisions to superiors or impede actions with red tape. (Red tape, by the way, is bureaucratic procedures especially as marked by delay or inaction.)

While these definitions might be linked, their relationship, like close encounters, is additive. It seems fairly clear that Brian Rowe's target is bureaucracy of the third kind.

The appropriate weapon for attacking that kind of bureaucracy is the Jack Welch-inspired system of Work-Out. The essence of Work-Out is to ask the question, "Does this activity add value in the eyes of my customer?" If the answer is anything other than yes, Work-Out demands that one look more deeply at that activity for possible elimination.

Bureaucracy of the second kind is a different organizational condition. This kind of bureaucracy arises out of a realistic need to survive in a highly structured, potentially threatening environment, such as dealing with the bureaucratic customers. Until now, bureaucracy of the second kind has been a successful survival tool. The difficulty, however, is that it creates a rigidity — a hardening of the categories — that screens out any conflicting (and often useful) viewpoints. (Or, as Homer Simpson might put it, "Never say anything unless you're sure everyone feels exactly the same way.")

To compete in the future we see unfolding before us, such rigidity is no longer an asset. It is, in fact, a liability. But to free ourselves of that liability is no easy task. To move forward, we must, like Tarzan swinging

through the jungle, release the vine of rigid control and grasp the vine of flexible collaboration. If we try to hold both, we stop. (Over the crocodile pit, probably.) If we do not grab for the next vine, we swing backward.

The rigid boundaries of bureaucracy of the second kind must be dealt with by changing the culture of the organization and the values of its managers. Unlike acceptance of the more demonstrable problem-solving aspects of Work-Out and Continuous Improvement, embracing culture change requires an act of faith. Technique alone is not enough. Work-Out and Continuous Improvement can not be truly effective unless that leap of faith is made. Engineers, perhaps more than others, may find it stressful to take anything on faith.

The leap can not be delegated. It must be made by leaders at all levels. While an informed cadre of change agents may be necessary to facilitate and guide this change, only the leaders can make it happen.

Is there a likelihood of regression to bureaucratic rigidity when business pressures rear their heads and threaten to bite us? Yes, there is. Then can't we just perfect the bureaucracy? No, we can't.

There is reason to argue for determining what is important to us and focusing specifically on those things. Where there appears to be too much to do, it makes some sense to limit the areas of activity. That's one way of getting work out. Bureaucracies are good at that: "That's not our job. We only do turbine buckets. Dovetails are over there..." Unfortunately, this fixation on specialization leads to a hypnotic trance where practically everything that does not fit in a preconceived pattern or "solution" is concerned.

Bureaucracies are good at rejecting work — but they're good at making work, too. Bureaucracies, like other organisms, are prone to proliferation and defense. As long as boundaries — even logical boundaries — exist around problems, people will use their energy to defend and extend them.

Some would contend that today's unbearable workloads make the additional effort of culture change impossible. They argue for keeping the bureaucracy until we "catch up." These "unbearable workloads" are almost surely driven by the bureaucracy spending energy keeping itself afloat. To expect the bureaucracy to relieve them seems less than logical.

Defending present ineffective methods by citing past successes using those methods is defending your limitations. And, as author Richard Bach warns, if you argue long enough and strong enough for your limitations, you will find that, sure enough, they're yours. ≡

– MAD

GE Aircraft Engines

The Leading Edge
One Neumann Way, Cincinnati, Ohio 45215 U.S.A.
Fall 1990