World Radio History

THE LEADING EDGE

WINTER 1986/1987

LV100

Turboshaft Power for Tomorrow's Tanks

The Leading Edge is intended to communicate new and important technical information among AEBG's broad and geographically dispersed technical community. In so doing, it provides recognition to individuals and teams responsible for making significant technical contributions to the business. In addition, it is intended to broaden the reader's understanding of AEBG's Group Engineering and Technology Division as a part of the General Electric Aircraft Engine Business Group.

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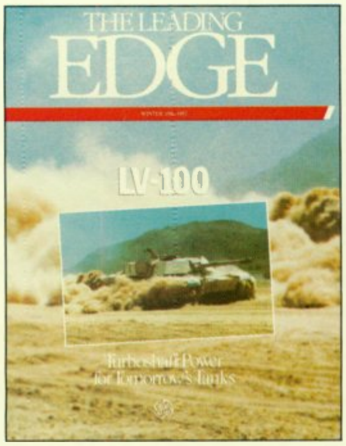

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Computer Modeling to Improve Forging Design

By
Shesh K. Srivatsa

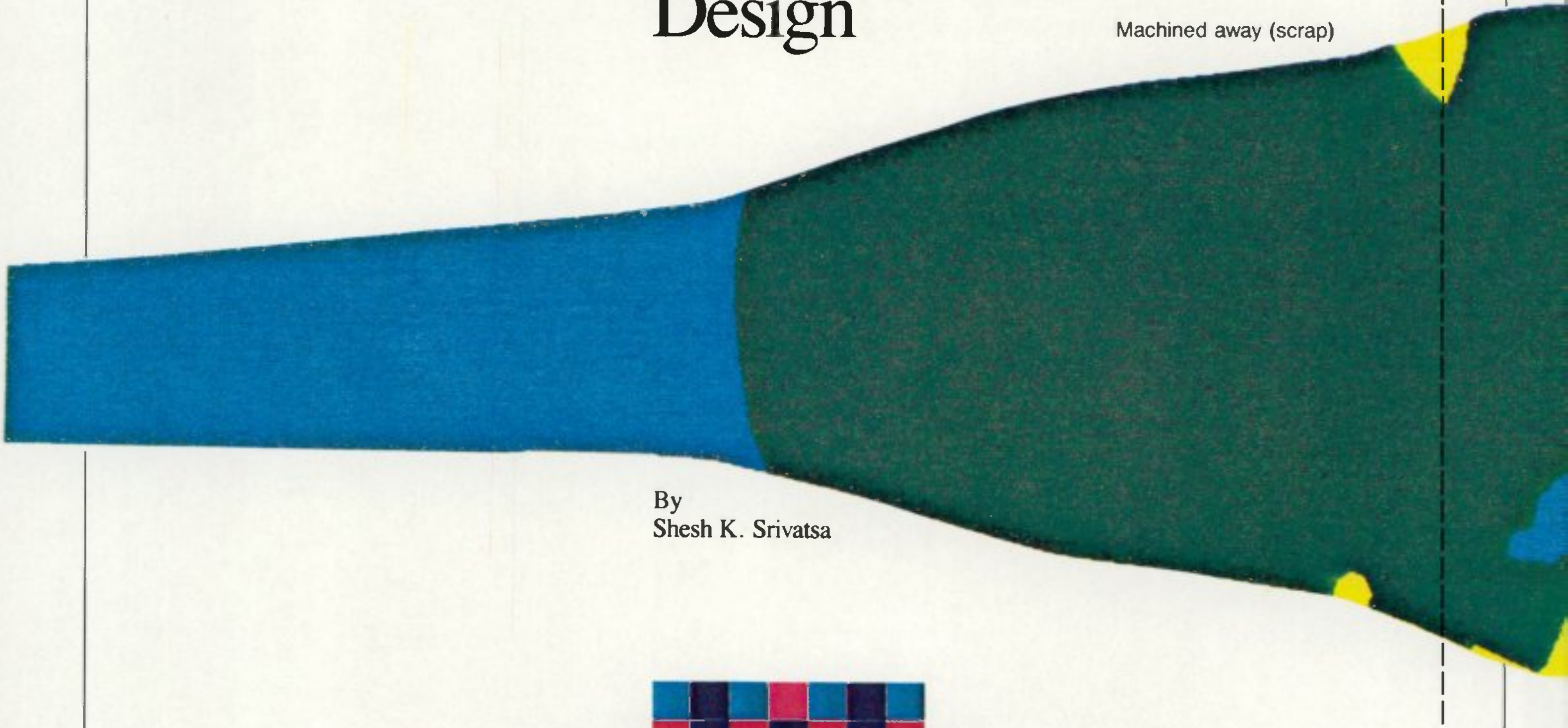

Figure 1

Figure 2
Ladish Stage One
Compressor Disk—Pancake

Business pressures today are forcing major changes in every step of the product development cycle, from conception through design and production. The trend is towards making the product "right" the first time and adopting the "just-in-time" production philosophy to reduce inventory costs and scheduling backlogs. The emphasis is on developing lower cost, higher quality new products in smaller volumes and in less time.

Forging, the process which produces many of our component parts, is a good place to look for cost and time improvements. Many of the high temperature titanium and nickel-base superalloys used in aircraft engines are shaped by hot forging processes, especially highly-stressed critical parts in fans, compressors and turbines. Such parts

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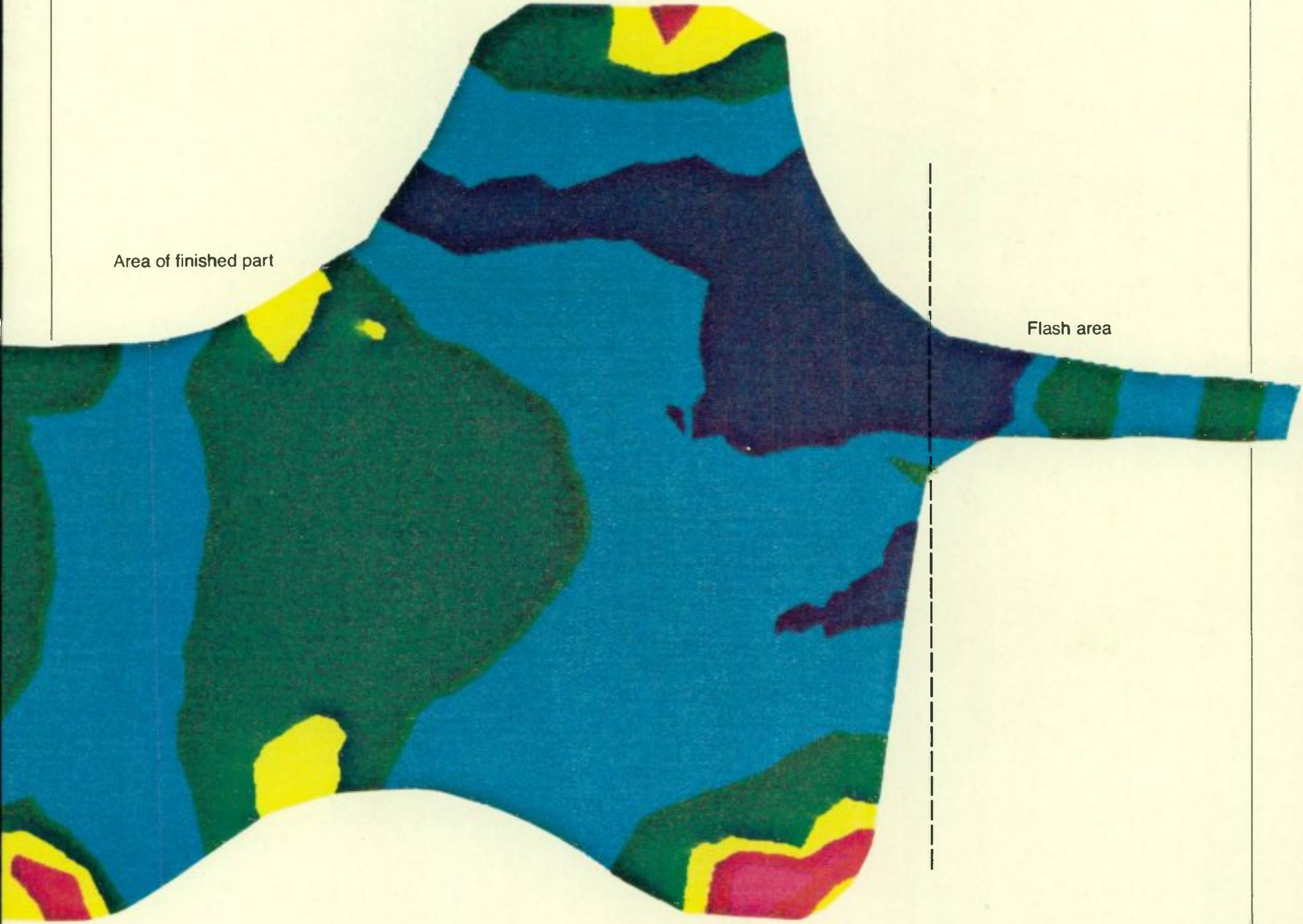

include spools, disks, shafts, seals, blades and vanes. As parts become more sophisticated, both in shape and in metallurgical reactions needed to attain certain properties, they become increasingly difficult to form; however, costs are sharply reduced if parts can be forged to near their final shapes (near-net-shape forgings).

The design of a forging die starts with the finished part, then works backwards, searching for tooling and processes which can produce the shape in question with the desired metallurgical properties from a raw billet like that shown in Figure 1. The design has traditionally depended on experience, empirical rules and trial-and-error methods. It is not uncommon in the forging industry to make two or three modifications to the die geometry before an acceptable part can be produced. Such methods require long processing and lead times, may use less than optimal processes, and waste energy and material. The result: low productivity and high manufacturing, inspection and testing costs.

The key to improving the forging design process—and hence to meeting the business challenges of lower cost and higher productivity—is in understanding exactly what happens in a given forging process. Computer models are providing the necessary information.

AEBG's Engineering Materials and Technology Laboratories (EMTL) has been actively involved in developing better models and making sure they are available to our forging vendors. GE and three of our vendors (Wyman-Gordon Co., Cameron Iron Works, and Ladish Co., Inc.) are jointly paying for the development; GE is coordinating the effort. These initiatives have received a considerable boost from Air Force-sponsored programs like Blueprint for Tomorrow, Factory of the Future, Forecast II, ManTech, TechMod, and other technology transfer programs.


S.K. SRIVATSA

To do the most good, computer aided engineering (CAE) must be conducted early to influence the design decisions as they are being made. Early computer simulations enable the process designer to modify dies and preform geometry and other processing parameters on the

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Figure 3
Ladish Stage One Compressor Disk

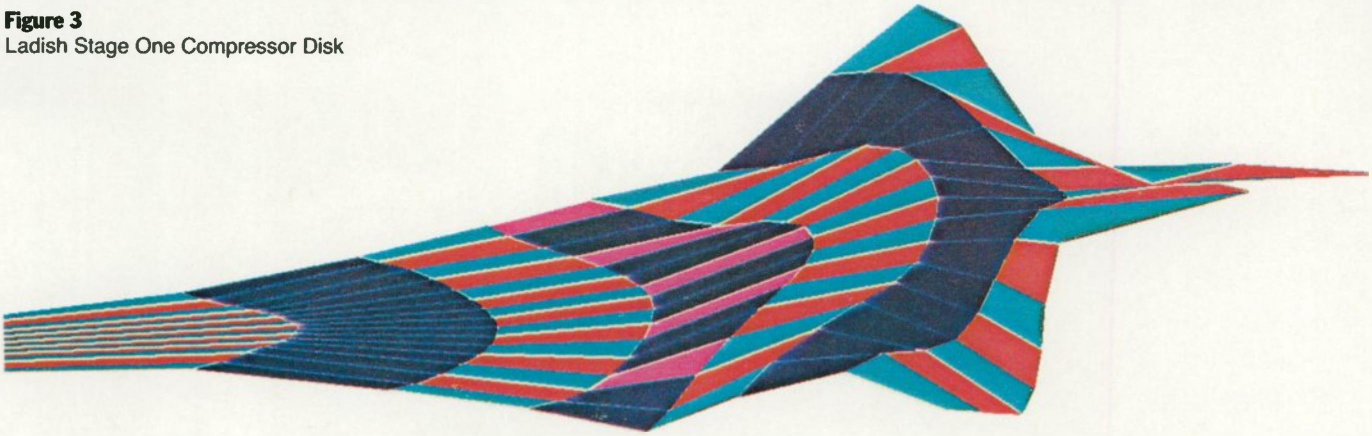
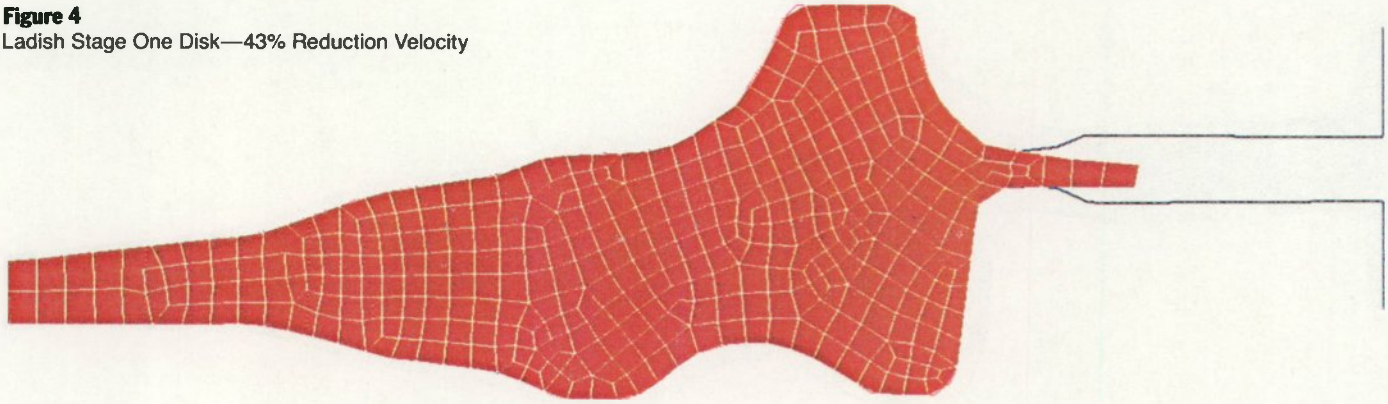


Figure 4
Ladish Stage One Disk—43% Reduction Velocity



computer, before having to expend money and time making actual dies and preforms. Both GE and the Air Force now encourage vendors to run simulations first. Trial-and-error development can be greatly reduced by early use of models.

Two Forging Process Models

The Finite Element Analysis Method (FEM) is the basic modeling tool for forgings. It is most useful where prototype testing is difficult, expensive, or impossible, as is often the case. FEM mathematically breaks down a part's geometry into simple sided elements like triangles or rectangles like those in Figure 2. Each element is analyzed separately, and the results are combined using carefully defined boundary rules to give a total analysis of the complete component.

The use of finite-element methods involves a large volume of data. Interactive pre-and post-processing coupled with computer graphics manage all the data. Computer graphics like those accompanying this article allow the engineer to obtain rapid comprehension through color displays. These displays can verify models, speed up input preparation and reduce input data errors.

Two major FEMs are now in use. One analyzes plastic deformation (metal flow during forgings), and the other examines the heat treatment process.

ALPID, which stands for Analysis of Large Plastic Incremental Deformation, is a program which examines two-dimensional geometries of visco-plastic materials. The program provides information on metal flow, forming load, stress, strain, strain rate and temperature distributions in the workpiece during forging. Enhancements of the ALPID program have been underway since 1984 at Structural Dynamics Research Corporation (SDRC) in Milford, Ohio, under the sponsorship of GE and its forging vendors. These enhancements have improved the program's user-friendliness. They have introduced automatic re-meshing, defect tracking throughout the forging process, thermal capability for non-isothermal forgings and a relational data base for storing descriptions of material properties.

ALPID makes it possible to evaluate die stresses and deflections using standard elastic or elastic-plastic stress analysis programs.

ALPID characterizes the intrinsic workability of the workpiece material so that deformation rates and temperatures are readily identified. Under these specific conditions, called a "processing window," materials can be fabricated to obtain the fewest defects and best dispersion characteristics possible for the material. The analysis produces material maps which can be used to define the process control algorithm.

The second program, called NIKE/TOPAZ, predicts transient temperatures and resulting thermal stresses, and distortions. It also predicts sag of the workpiece in the heat treating furnace and the potential for cracking of workpieces during furnace

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Figure 5
Ladish Stage One Disk—Finisher

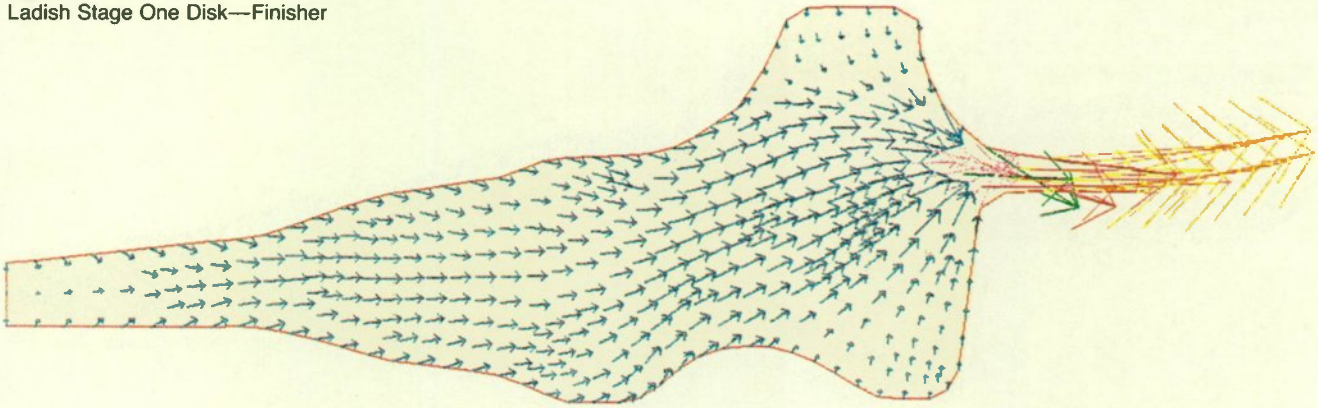
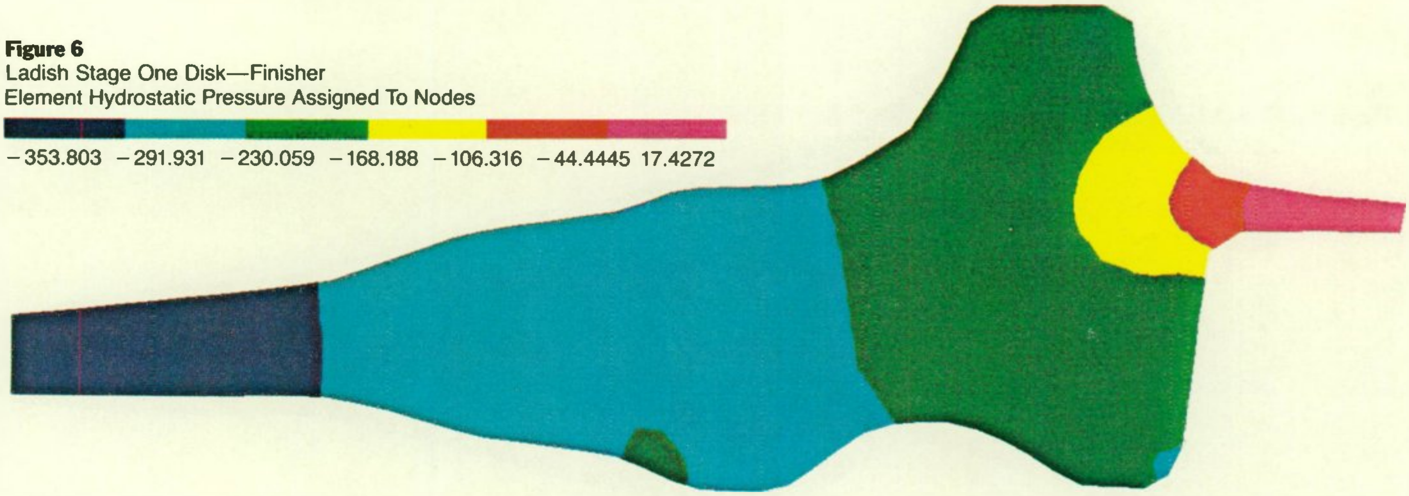


Figure 6
Ladish Stage One Disk—Finisher
Element Hydrostatic Pressure Assigned To Nodes



heat-up and subsequent quenching. The ability to predict such events is needed to address the increasing difficulties encountered in heat treating near-net shapes and new materials, such as titanium aluminide and some varieties of Rene 95, which are prone to quench-cracking. NIKE/TOPAZ is based on the public domain programs NIKE and TOPAZ from the Lawrence Livermore Laboratories. Like ALPID, NIKE/TOPAZ has been further developed by SDRC under the sponsorship of GE and its forging vendors.

ALPID and NIKE/TOPAZ at work

Several parts have now been modeled to obtain predictions of metal flow and die filling patterns, the influence of different preform shapes, the strain (or total work) distributions in the finished forging, and die loads for die stress analysis. The simulations have shown areas of potential defects or forging problems, and the flow patterns have revealed the design of better preform shapes.

Some of the parts that have been analyzed using ALPID and NIKE/TOPAZ are:

- CFM56 High Pressure Turbine Disk
- CF6-80C Stage 6-9 Compressor Spool
- Four Integrally Bladed Rotor (IBR) Disks
- F404 Stage 2 Low Pressure Compressor Disk
- F101/CFM56 Stage 1 Compressor Disk

The results of modeling the F101/CFM56 Stage 1 Compressor Disk, manufactured by Ladish Co., Inc., provide a good example of the ways modeling can improve the die-making process.

The purpose of the modeling study of the Stage 1 Compressor Disk was to improve understanding of defect distribution and detection by sonic measurement, leading to the elimination of component failures caused by "hard alpha" defects. Hard alpha defects are inclusions which serve as the starting points for failures in the material. The model predicts the ways these defects will align in the material, and so leads to proper alignment of ultrasonic testing equipment to detect them if they are present. Concern for this problem surfaced when a billet with seeded defects displayed an unexpectedly low level of sonic indications after forging.

Figure 2 shows a mesh of alternating colors representing the original billet seen in Figure 1. Since the billet is symmetrical, only one half is shown here. The deformation of the original mesh to the final forged shape is shown in Figure 3. The finite element mesh had to be regenerated several times during the forging analysis, as the workpiece shape was continually deformed. Figure 4 shows the mesh in the final forged shape. The arrows in Figure 5 depict the predicted direction of metal flow. The flow lines indicate most likely orientations of defects, providing information which helps optimize the ultrasonic inspection plan for the finished part.

In addition to flow pattern and defect movement, the finite element model provided complete information on the

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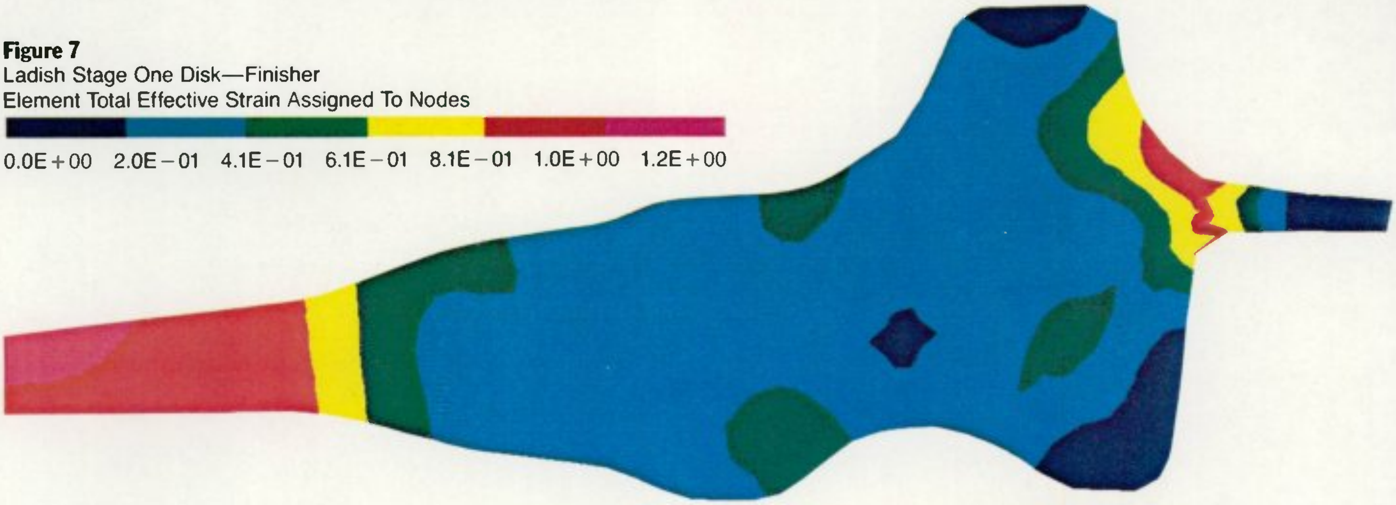

Figure 7
Ladish Stage One Disk—Finisher
Element Total Effective Strain Assigned To Nodes

Figure 8
Ladish Stage One Disk—Finisher
Uon Mises Stress

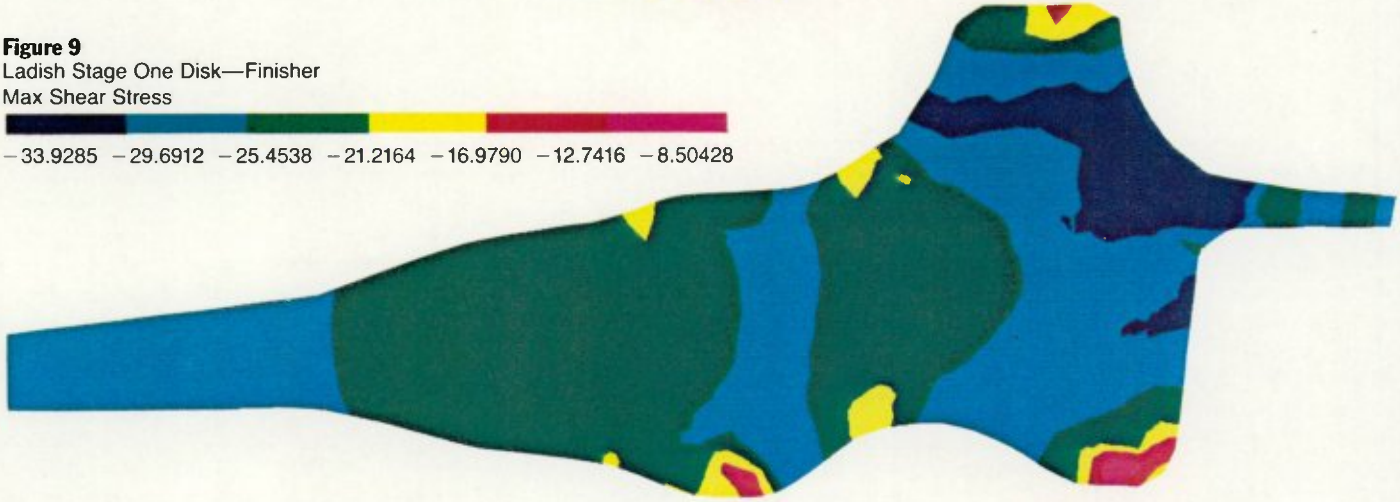

Figure 9
Ladish Stage One Disk—Finisher
Max Shear Stress

distributions of other quantities of interest. Figures 6, 7, 8 and 9 show respectively the distributions of hydrostatic pressure, total effective strain, the effective stress, and the maximum shear stress in the finished forging. It is desirable to have a compressive hydrostatic pressure to prevent cracking, and the model showed the needed pressure everywhere except at the flash area, which is discarded in any event. The strain distribution indicates the amount of working the different regions of the forging undergo, and in this model strain is within specifications for the Stage 1 Compressor Disk.

The benefits of such simulations include less time and money spent on the shop floor. The early work results in fewer problems with expensive and long-lead tooling. Critical strain, strain rate, and temperature windows for the material can be met accurately, reducing waste and producing better quality parts. As models such as ALPID and NIKE/TOPAZ come more widely into use, productivity will rise while costs of developing ever more sophisticated forgings will drop. ❐

Shesh K. Srivatsa is an Engineer working in Computer Assisted Engineering.

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The finished CFM56 Stage One Compressor Disk.

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An Interview with Martin Hemsworth

Hems

Marty Hemsworth's deep bass voice has echoed around GE for some 45 years. Starting in 1940 as a test engineer, he quickly became involved in designing test facilities in Lynn. When GE acquired the Evendale plant in 1948, Marty was made assistant to the plant manager with the challenge of designing and managing the operation of all the test facilities in the new plant. In 1951 he began a series of engineering management assignments, including the GE1/6 high bypass demonstrators, TF39 and CF6-6 and -50 engines and the E^3 (Energy Efficient Engine). In 1971 he was named the first Chief Engineer. In 1975 he became Manager of the Evendale Design Technology Operation, and in 1980 he once again became Chief Engineer, a position he held until 1985 when he took on his current role as Chief Consultant for Engine Design.

Over the years many honors have come to Marty Hemsworth, among them the Steinmetz Award and the Ralph J. Cordiner Award for excellence in engineering. He has won the SAE's Franklin W. Kolk Air Transportation Progress Award. He holds 12 patents. He is a member of the National Academy of Engineering and an Associate Fellow of the American Institute of Aeronautics and Astronautics. He is a Fellow of the American Society of Mechanical Engineers and the Society of Automotive Engineers. He is also a member of Tau Beta Pi and Pi Tau Sigma, honorary engineering fraternities.

Marty, you were AEBG's first Chief Engineer. What was the job and why was it established?

The Chief Engineer's Office was created to provide a way of controlling the quality of our engineering practices and a way of passing our engineering lore down from one generation to the next. We've had design practices for many, many years; I think the first major effort to get a complete structure of design practices was probably made in the early '50's, and a major effort was made by Don Berkey in the 1960's to bring them up to date. When I became the Chief Engineer in 1970, they needed an overhaul. So we set up Design Boards with the most experienced engineers we could find in all the disciplines. The idea was, and it still is, for the Design Boards to be a mechanism for exchanging technical experience, addressing specific problems and bringing to bear all of our accumulated knowledge and experience to serve common ends. They can bring a degree of objectivity to bear that individuals buried in a problem maybe don't have.

I guess the answer to your question is, the Chief Engineer's office was set up to manage Design Boards and through the Design Boards we would oversee the design practices.

Your job as Chief Engineer was partly to encourage the Design Boards to do that?

Very much. It takes a lot of work to write design practices and there are many, many design practices that are required. It takes many engineering man-weeks to write any one practice. So, it is a case of encouragement, of working with managers of the people involved to have them also encourage the design board members because it's a voluntary activity; it involves work that is above and beyond the individual's day-to-day work.

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worth

What are the characteristics needed in a Chief Engineer?

First and foremost he has to be an exceedingly good engineer. He has to have a good feel for a broad spectrum of engineering discipline, not simply mechanical design or aerodynamics, and he needs a very good sense of what's right in a broad spectrum. He has to have a good appreciation of what sound design is. He's got to have very high standards of technical excellence and a strong personality; he can work with both the designers and the management to make things happen. He has to have a good vision of the importance and necessity of design practices, to guide a large and complex operation such as ours to do things in a logical and consistent fashion.

Everybody is motivated differently, everybody has different things that are really important to them in their professional careers. For some people it's a spotless record of on-time performance, for others it might be really making sure every i is dotted and every T is crossed. What would it be for you?

Perhaps in a fundamental way, I welcome the challenge of designing anything to do its job and to do it right and fully the first time, whether that product is a C-clamp or an engine. It's just the challenge of anticipating the requirements, of knowing what the laws of engineering and physics are and creating a design that pulls all the requirements together in a balanced sort of way. By balanced, I mean it meets the requirements, it has a reasonable cost and high reliability. In a circumstance where weight is important, as it is in engines, it obviously has to have a proper weight. Bringing the laws of nature and engineering and physics together to create a

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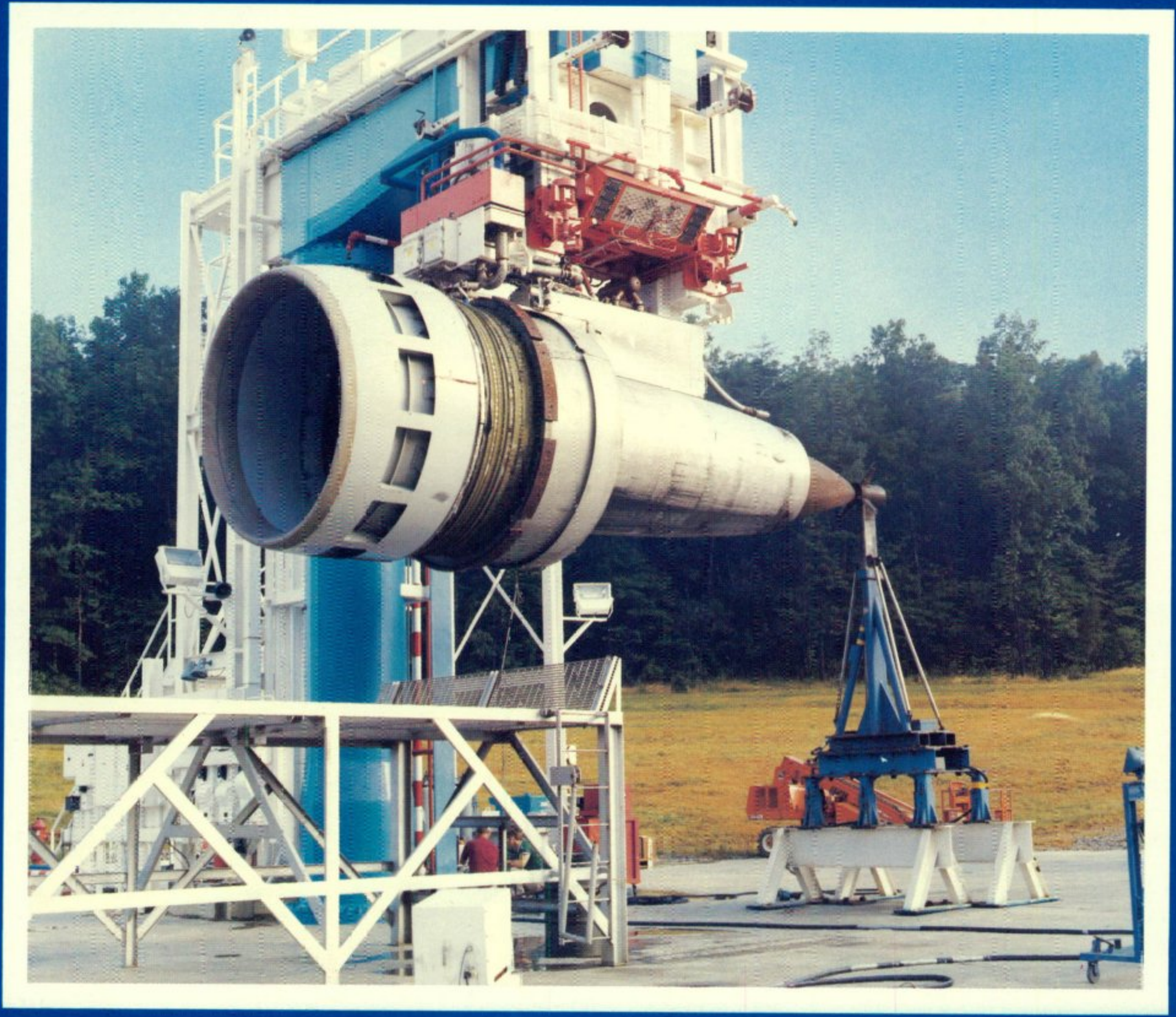
“I think a lot about working”



TF39 on Test at Peebles, Oh.

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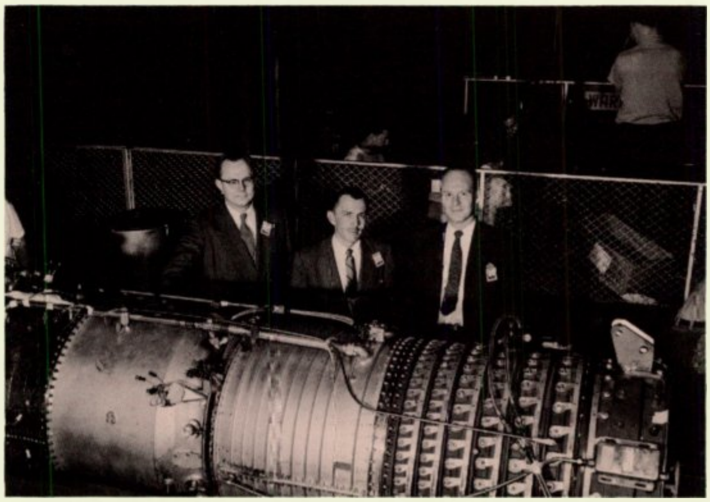

Marty Hemsworth, Neil Burgess, and Perry Egbert inspect J79 engine that was shipped to GE Flight Test Center for first flight in XF4D. Flown by Roy Pryor.

design that meets the requirements and does it well—that's a major driver for me.

What would you say are the biggest technical obstacles that AEBG is facing in the next 10 years?

I really don't think of technical obstacles. There are technical challenges, and I'm not just playing with words there. Our job is to surmount obstacles—you could say, to solve problems. I don't think of problems as obstacles. In order for something to be an honest-to-goodness obstacle it would have to be something that impeded our progress but did not impede the progress of our competition; our failure to grasp something fundamental that's necessary to building good engines. Anyway, I think the necessity for us is to use all the experience we have, anything we gain anywhere, for the benefit of every other program. We really cannot afford to re-discover ways to solve problems. We need to develop a General Electric way of dealing with design problems and making designs, which is not to say we don't need and welcome progress in design. We'll never solve the problems of the next generation of successful engines if we don't innovate in many areas. But the elements of the design need to be done in ways that are known to be satisfactory. I always think of this in terms of how to design, let's say, dovetail forms. What we need in any given situation is a very good dovetail form. We don't need three or four different very good dovetail forms.

Then you would be a strong supporter of the "derivative engine" concept?

Yes, even in a brand-new, very advanced engine like the GE37. There are many elements in that which should be built directly on the experience we've already demonstrated and come to understand and which can be used with no penalty. I'm sure that's being done, I know the kinds of engineers who're working on it. Often problems that do crop up, however, are traceable to unwise innovation, sometimes unknowing innovation.

Do you have an immediate example?

A common one is for us to overlook or use unproven heat transfer data. We often don't use the correct assumptions on steady-state or transient temperatures and temperature gradients and that sometimes leads to our underestimating thermal stresses.

Why don't we?

Sometimes it's a matter of judgment. Sometimes it is the result of using the output of computer programs without testing the soundness of the result or the input data. Sometimes we try to calculate things which are incalculable—we *need* experimental data.

Let's change subjects again. What does Marty Hemsworth do when he's not working?

Well, I think a lot about working!

I enjoy reading when I'm at home. I also enjoy sketching and calculating. I keep a calculator beside the chair and I spend a fair amount of time thinking about ways to do some aspect of engine design. When I'm *really* not working, my wife and I like to travel. I am interested in photography. I have a workshop that's got quite a full complement of metal and woodworking tools and welding equipment, and I very much enjoy working there. I enjoy increasing my capacity and ability to make things in the workshop. I also have an electrical bench and I like to work with that, just fool around with elementary circuits. I'm a real babe in the woods when it comes to electronics, but I enjoy experimenting.

Let's go back 45 years. When and why did you join GE?

I went to school in Nebraska, and over the years, GE used to take one and sometimes two very good engineers every year from

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Opening the Evendale plant in 1949. Marty Hemsworth is third from the left.

Nebraska. I had a vision of GE being all a technical company could ever be. To me it was the best. When I got the offer from GE, that was the end of my job search. I was just tickled to death and I have been ever since. It's not to say there hasn't been an up or a down from time to time, but you don't expect things to be perfect.

As it happened, I took one test assignment and went to work for the Supercharger department, designing test equipment under Joe Alford. I've been in the Gas Turbine business ever since. Maybe I wouldn't have, but I had the very good luck to spend eight years working for Gene Stoeckly and also with Joe Alford, two of the finest engineers I've ever met.

Have you ever been tempted to join a competitor?

Not for a second. I can't even imagine working for a competitor.

What would you say was your single biggest accomplishment?

I suppose managing the design and development of the TF39. It was the biggest job. It was all new, a big stretch in every design parameter. I've been very pleased and satisfied with a number of other things like the E^3 engine. That was great as far as I was concerned; that was an ideal assignment.

What made it ideal?

It was technically important, important to the business. It was technically challenging, and it was pretty much a "clean-sheet-of-paper" engine. A very good preliminary design of the engine had been done by the guys in Lynn, Bob Neitzel and his team. That was the starting point, and we ended up with an engine that looked a lot like the engine that Bob had designed. But it's one thing to draw a picture and it's another to decide exactly how you're going to make this thing. We had to make some changes. It was a great job because we had an opportunity and a requirement to work with a lot of our advanced technology people because everything in the engine was new, and most especially it was new aerodynamically. The engine worked, and it was a couple of percent better than we said it was going to be. Performance was the whole name of the game. We said we'd be 12% better than the -50C and we were actually around 13½% better. It was just a very satisfying experience.

What are some of the technological innovations from that engine that we have since put into our product line, that we found ways to use?

They were mostly in aerodynamic aspects of the engine. The aerodynamicists did a superb job on the whole E^3 engine from fan to turbine. The low-pressure turbine was more highly loaded than earlier turbines, and it turned out to be very efficient. That turbine was very much the prototype, from an aero design standpoint, for the turbines in the CF6-80A and -80C. You can say pretty much the same for the high-pressure turbines as well.

The core compressor was a remarkable thing. What was novel about it was that it did 23:1 pressure ratio in 10 stages, which in itself is much higher loading and much higher output per stage than had been done before. The second thing was that the 23:1 pressure ratio in a single spool was a lot higher than had been done before, and we were very concerned about whether the engine would start

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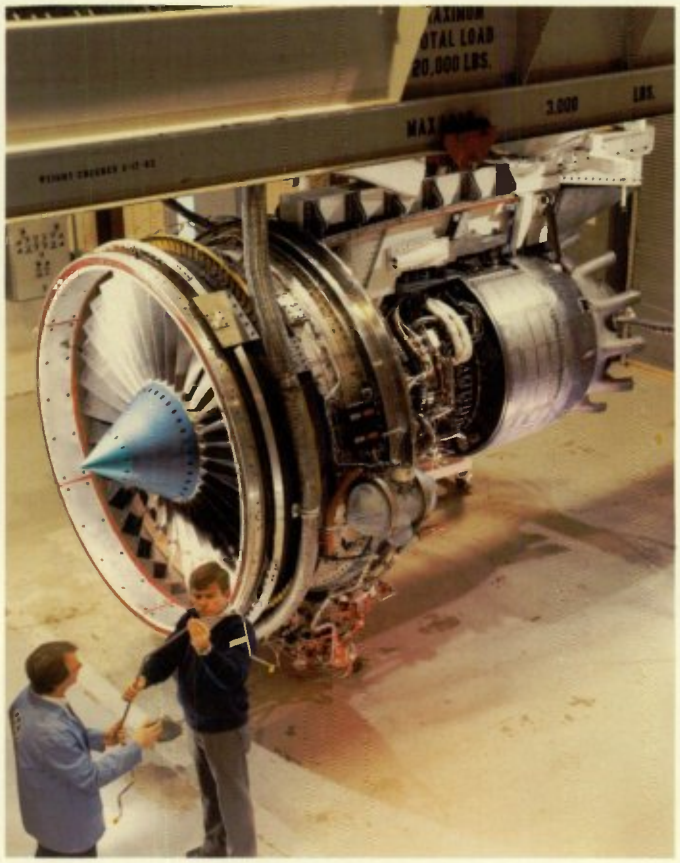
Chief Engineers, present and past: Mel Bobo (L) and Marty Hemsworth at a patent award ceremony, ca. 1958.



E^3 Engine

Marty Hemsworth putting the monogram on GE 1/6, December 1964

reasonably well. So, we built the thing with additional variable geometry stages to help the starting, and we provided bleed capability in case that was necessary. It turned out we didn't need either of those things. That compressor has been very, very successful. And, it has sort of driven a stake in the ground, that 23:1 in a single spool is something manageable.

Looking back, if you had something that you would change or do differently over your career what would it be?

Oh, gosh, I don't know. I guess I would probably try and devote more attention and effort to doing a good job of managing. I guess if I were going to drive the road again, I'd try to do better. I don't really feel that I'd try harder to be a vice president. I don't think I was built to be a vice president.

One last question. Is there anything you'd like to tell Leading Edge readers that you think that they'd want to hear, or you think they should hear from you?

Not a whole lot. I've spent my life telling Leading Edge readers what I think they ought to know. I certainly hope they derive the same stimulus and satisfaction and challenge out of their work that I have for all these years. I certainly don't see anything to indicate that the exciting times are behind us. I think the future is going to be just as stimulating and require as much in the way of creativity. There's so much opportunity for growth, I envy these guys starting their 40 years down the road. ❑

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Space Claim

Performance (Acceleration, speed on grade, power degradation, cooling, braking, starting, etc.)

Fuel Economy

Reliability and Durability

LV100—Turboshaft Power for Tomorrow's Tank

By Larry Kutz

The LV100 is General Electric's entry in the Advanced Integrated Propulsion System (AIPS) technology demonstrator competition. Sponsored by the U.S. Army Tank Automotive Command (TACOM), the competition is to design, build and demonstrate advanced technology propulsion systems for tomorrow's battle tanks and other heavy tracked vehicles. The competition includes both advanced diesels and gas turbines, and the winner may emerge with a new business producing about 10,000 engines in ten years—a prize worth very serious effort by the contestants.

At first glance, tanks and turboshaft aircraft seem to have little in common. Yet the LV100 relies on technologies and disciplines we have used successfully for years. Table I lists the LV100's unique characteristics and those it shares with aircraft turboshafts. There are more similarities than differences—GE has been building powerful, fuel efficient, reliable engines with wide stall margins and fast throttle response all along. Nonetheless, the differences are significant. This article addresses the Army's design criteria and discusses the LV100's approach to meeting them.

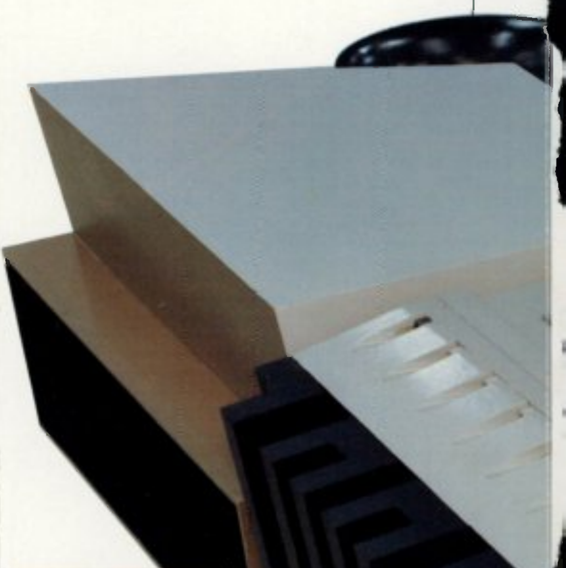
Gas turbines offer advantages for tracked combat vehicles. First, turbines offer high specific power (output power relative to size or total system airflow); accordingly, they can fit in compact spaces. Second, compared to currently-fielded diesels, the gas turbine offers significant improvements in engine volume and weight. Third, the gas turbine's excellent low-speed torque output enhances system performance. Figure 1 compares a typical turbine engine's output torque with both conventional and turbocharged diesels. Because the diesel engine's crankshaft speed is the same as the output speed, diesel engine airflow falls off rapidly as output speed drops, thus reducing available power/torque. Even though turbocharging helps this condition to some extent by increasing airflow, the air consumption characteristics of pistons soon pull down the possible output. Fourth, gas turbines are ordinarily very reliable engines, starting and running well even in extreme temperatures.

Diesels typically offer better specific fuel consumption (sfc) than turbines. However, sfc has to be considered in light of fuel storage requirements, range, and performance requirements. The unique design of the LV100, using variable area turbine nozzles and a heat recuperation cycle, makes its sfc competitive with diesels in all but extreme low-speed operations.

Table 1 Engine Design Criteria

	Similar	Unique
Metric Design		●
High Specific Power	●	
Low sfc	●	
Stall Margin	●	
Throttle Response	●	
Thermal Cycle Life	●	●
Shock/vibration	●	●
Weight		●
Output Speed		●
Engine Volume		●
Environmental	●	●
Maintainability	●	
IR	●	
ILS	●	
Noise	●	

IR = Infra Red ILS = Integrated Logistic Support



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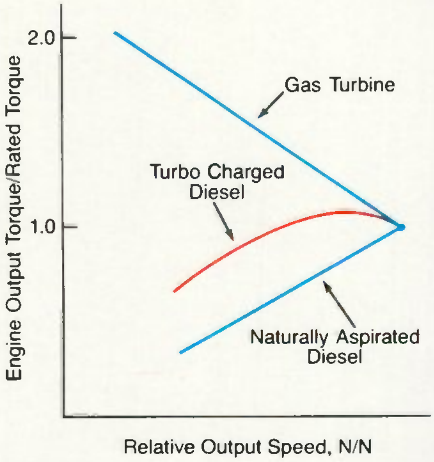

Figure 1

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Fuel Tolerance

Maintainability, Diagnostics, Human Factors, Safety

Weight

Signature Reduction and Survivability

Larry Kutz is Manager, LV-100 Systems Design Integration.

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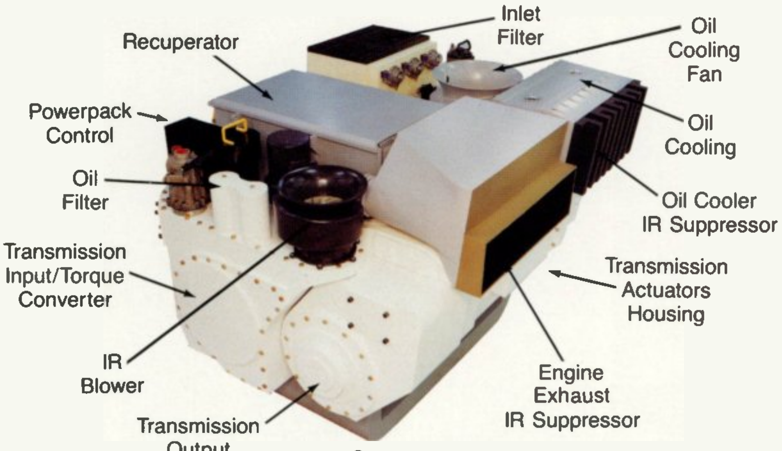

Figure 2 LV100 Powerpack

The LV100 is more than an advanced gas turbine; it is an entire propulsion system. It will come complete with transmission, oil cooling system, air filtration system and exhaust heat recuperation system, as illustrated in Figure 2, all set in a compact package to fit in the limited space available. The LV100 is comparable to the entire system needed to create and deliver power to the wheels of your automobile—if your car weighs 60 tons and travels cross country with 1500 horsepower pushing it.

From the Army's point of view, the tank engine is purely a means to the end of transporting a gun and its support system. The Army's design priorities listed in Table 2, are determined by the job the tank must do and by the conditions in which it must operate. Lurking behind trees, it must be able to jump out, fire, and change its position quickly enough to avoid return fire; that means very flexible performance and rapid acceleration. Churning through the muddy fields of March or spewing the dust of August, the tank has to keep going: it has to be reliable. It must operate far from fuel sources and travel substantial distances: the engine must have low sfc.

Table 2 Power pack Technical Priorities

The technical requirements for the AIPS in priority order are as follows:

(1) Space Claim
(2) Performance (Acceleration, speed on grade, power degradation, cooling, braking, starting, etc.)
(3) Fuel economy
(4) Reliability & Durability
(5) Fuel Tolerance
(6) Maintainability, Diagnostics, Human Factors, Safety
(7) Weight
(8) Signature Reduction and Survivability

Before the tank can perform any mission, it must be transported to the operational area. For this reason tanks are sized to fit the cargo space of aircraft. In turn that dictates a compact powerplant if there is still to be adequate room for ammunition, electronics and crew. In fact, size is the Army's first criterion. The LV100 meets this criterion. The actual power pack uses a heat recuperator to reduce sfc; the space lost to the recuperator is more than regained by reduced fuel tank size.

After compact space requirements, the Army needs performance and fuel economy. The vehicle will weigh about 60 tons, yet it must be able to accelerate from 0 to 20 mph in less than seven seconds. It must be able to move its own length from a standstill very quickly, requiring engine acceleration times from idle to maximum power in 2-3 seconds; by comparison, traditional turboshaft aircraft engines spool up in 7-9 seconds. In addition, the tank faces continually changing power requirements to allow it to roar down open roads or clamber over rubble. And all the while it must have excellent fuel economy.

The GE approach to the problem of excellent fuel economy over a wide range of power requirements is three-fold: a recuperative cycle, a variable area turbine nozzle (VATN) to improve thermal efficiency, and an automatic transmission with fixed gear ratios to transfer power to the tracks.

The LV100 recuperator reduces sfc at all power levels by transferring residual heat in the engine exhaust to the compressor discharge air. This action raises the compressed air's temperature before it enters the combustor; accordingly, less fuel must be burned to achieve a fixed level of turbine inlet temperature, as shown in Figure 3. The combustor itself uses an extremely efficient heat transfer design, yet will meet durability goals for the engine.

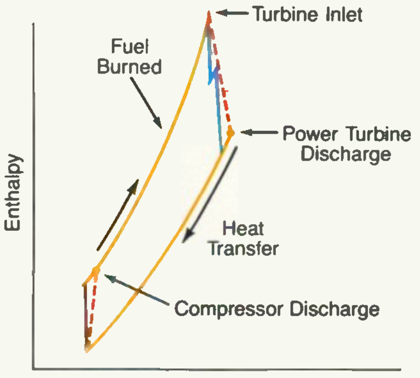

Figure 3

The recuperator results in sharply reduced sfc at lower pressure ratios with correspondingly lower compressor exit temperatures—conditions which are of great benefit to tank engine design requirements. Figure 4 compares recuperative and non-recuperative cycles, showing that the optimum cycle pressure ratio of the recuperated cycle is well below that of non-recuperative cycles.

The LV100 combines the heat recuperation system with a VATN. This results in excellent sfc down to about 35% of maximum power, below which sfc rises as it does in all turbine engines. The VATN is used to alter the core engine speed and temperature characteristics so that the high turbine inlet temperatures used at maximum power can be maintained into the lower range of output power. See Figure 5. In other words, the VATN improves the thermal efficiency of the engine at low speeds. The effect is limited by physical and geometrical constraints on the VATN. When the limit of effectiveness is reached, the engine's sfc will rise, as does the traditional turboshaft engine. The rise in sfc can be reduced by using the variable compressor geometry to maintain efficiency and stall margin to very low compressor operating speeds, down to about 3% of maximum power.

The VATN helps the engine meet the savage throttle demands of combat use, as does the automatic transmission. Tanks must operate over very rough terrain, maintaining mobility up hills, down grades and around corners. Their manner of operation results in virtually constant and significant throttle movements. To accommodate these movements, the

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Figure 6

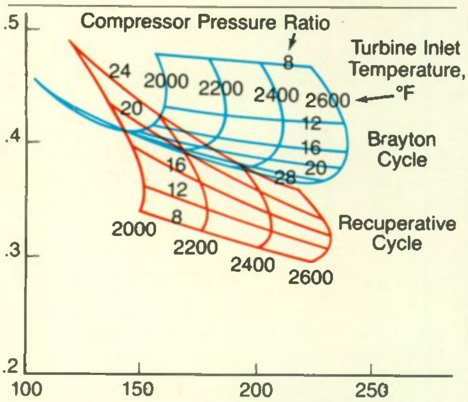

Figure 4 Parametric Turboshaft Cycle Analysis Impact of Recuperation

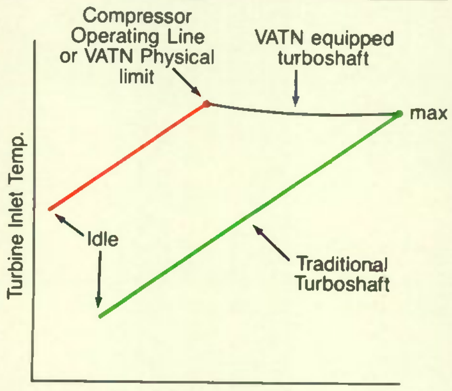

Figure 5

automatic transmission permits engine output speed to vary anywhere between 30% and 110% of design speed.

After the engine itself, the automatic transmission is the greatest single contributor to performance, for it must efficiently transmit power for propulsion, steering and braking. These functions are separate in the typical automobile but are combined in tracked vehicles.

The way a tank turns explains why the transmission must do so many jobs. In order to turn, the track on the outside of the turn radius must travel at a faster speed than the inner track. In fact, when track slip is neglected, the inner track velocity is less than the vehicle centerline. Because the power required to turn a 60-ton vehicle is very high, it is helpful to transfer the energy given up by the inner track to the outer one, thus reducing engine power requirements. This technique is called regenerative steering, and it takes a complicated transmission to do it. Detroit Diesel Allison is developing the LV100 transmission as a conservative evolution of a field-proven design; it should work well in the LV100 propulsion system.

One drawback to the automatic transmission is waste heat. Typical turboshaft engines reject about 30,000 btu of waste heat per hour by heating the engine oil, the power equivalent of about 8 horsepower. In the LV100, the wasted heat from engine and transmission is equivalent to about 150 horsepower. The oil cooler visible in Figure 2 deals with this waste heat. The cooler uses an air-oil heat exchanger with an operating principle similar to that used in a car but with more sophisticated cooling fin structure and a significantly larger size. Cooling air flow is provided by a dedicated cooling fan with a flow rate approximately equal to the gas turbine itself. The LV100 design provides adequate cooling while keeping the power pack profile low enough to fit the specified space.

Other Army priorities have affected the LV100 design. For example, reliability and durability are high on the list. In particular, the engine must withstand mud, dust, and debris—see Figure 6. Note the dirt pattern; the rearward power pack location exposes the engine air intake to extremely high concentrations of dirt. Helicopters also generate heavy dust clouds, but when the aircraft rises past 50 feet or so, the dirt disappears. Not so with tanks; they must live with dirt all the time. The LV100 power pack includes a self-cleaning air filter to protect the engine. This unit must be compact in size, yet provide positive barrier filtration while passing appropriate amounts of clean air to the compressor.

The Army has set other technical criteria for the AIPS competition. For instance, the engine must be able to tolerate varying fuel quality and types including gasoline and diesel. Since different fuels have differing lubrication values as well as differing combustion characteristics, heat values and viscosity, engine design must be extremely rugged, and control modes must accommodate such wide differences.

The engine must be easily fixed when it does break, with minimum tooling and facilities required. It should weigh as little as possible, and it should have low infrared and noise signatures. It should also be able to survive and run when damaged by enemy fire.

The LV100 program is well under way. Power pack demonstration is scheduled for completion in 1990. High pressure turbine aerodynamic testing and combustor testing have already been accomplished, and the axial compressor began testing in December, 1986. Combustor testing has shown that the profile and pattern factors are acceptable for an initial engine build, and the first core engine test will occur this spring, followed by the addition of the power turbine. Finally, the recuperator will be added and the complete engine system tested by the end of 1987.

Two more test engines are planned. The second engine will begin testing in March, 1988. Afterwards, this engine will be shipped to Indianapolis for the first union of the LV100 and its transmission. A year later, all subsystems will be joined for the first time as a complete propulsion system.

The ideal tank engine would fit in a suitcase, produce the power of a locomotive and get 100 miles per gallon on whatever could be fed into it. It would weigh 20 pounds and need service once every hundred years with a Phillips head screwdriver and two wrenches. The LV100 won't match that ideal. It will be an efficient, rugged, flexible power pack that will meet the Army's mission and design requirements for a long time to come. ❐

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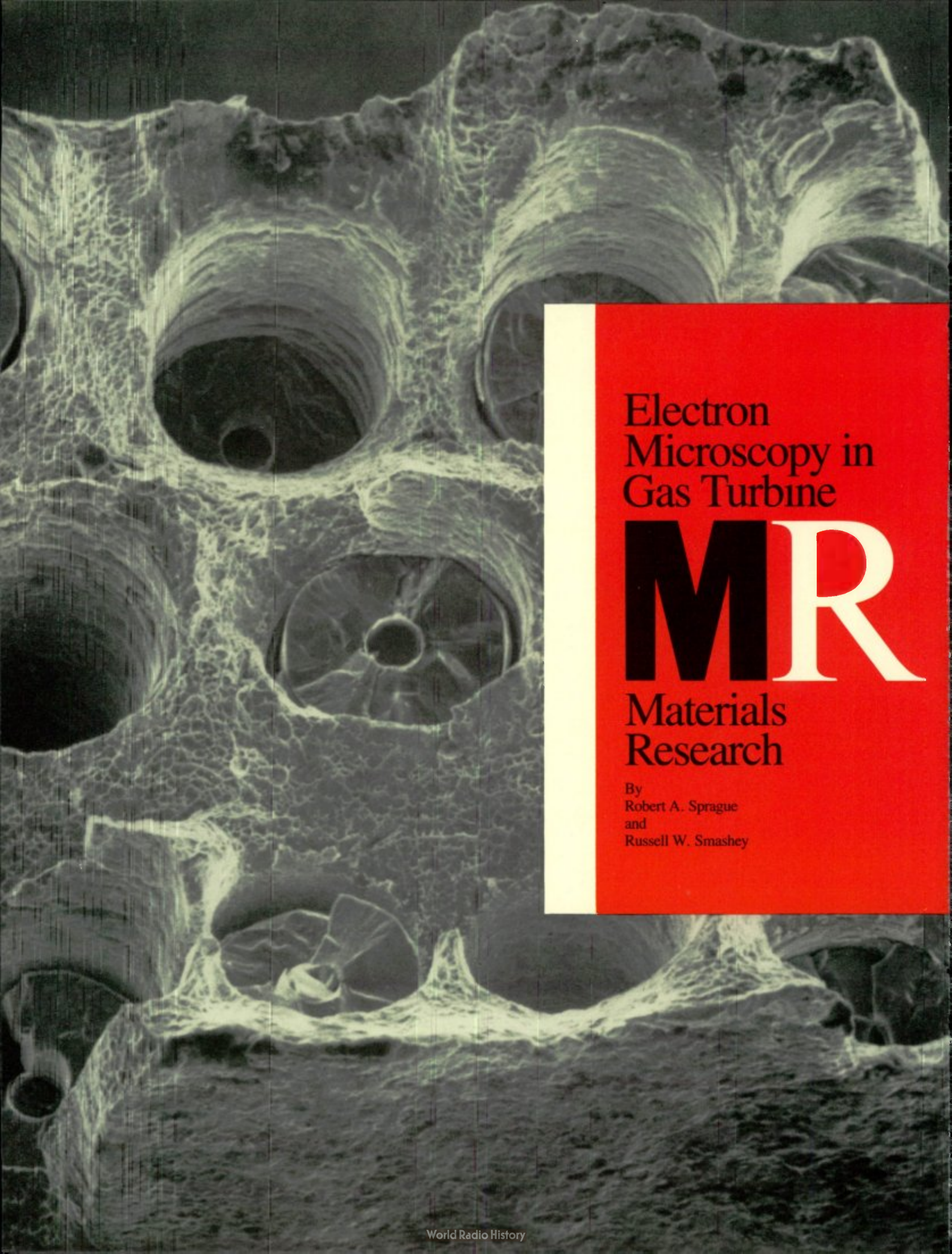

Electron Microscopy in Gas Turbine

MR

Materials Research

By
Robert A. Sprague
and
Russell W. Smashey

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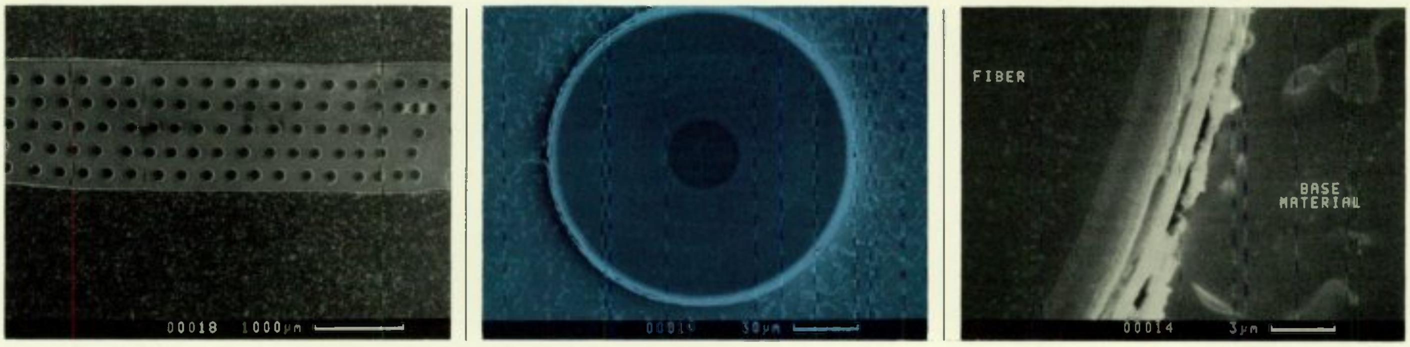

Figure 1, top: Left hand picture shows fibers set in a composite matrix; middle picture shows a single fiber set in the matrix. Right picture shows areas of poor bonding between fiber and matrix.

Advanced engine designs assume dramatic improvements in engine thrust-to-weight ratio, specific fuel consumption, higher component operating temperatures, increased component life, enhanced reliability and reduced cost. At the same time, the real temperature limits of the superalloys are now being reached. New materials and processes are needed to meet these demanding—and conflicting—goals.

AEBG materials researchers are now working with high temperature resin, metal, carbon/carbon, ceramic composites, single crystal alloys, intermetallic compounds (particularly titanium and aluminum based), refractory metals, coatings for performance retention, no-coat alloys and isotropic alloys with homogenous microstructures and higher temperature capabilities. Such exotic materials require extraordinary fine-tuning to control their properties, and the difference between success and failure can be hard to detect and control.

R.A. SPRAGUE

R.W. SMASHEY

Fortunately, the need for increasingly sophisticated materials and processes has also helped produce the tools needed to do the job. Electron microscopy is one such tool; developed to include sophisticated analytical abilities and a wide range of enhancement technology, it has become more useful than anyone would have guessed even ten years ago. Over the last decade significant improvements in equipment and analytical software have led to electron microscopes (and their variants) which can analyze the surface structures of a material, the boundaries and interactions among the components (phases) of a material and establish relationships between microstructural features and the behavior of a material. These are critical tools for developing the materials for tomorrow's high-performance engines. This article will survey some of the ways the electron microscope and its descendants are used in materials research at AEBG.

The underlying principle behind electron microscopy is that electrons' wavelengths can be much shorter than those of visible light. It follows that an image produced by bouncing electrons off or transmitting them through the target sample will have much finer resolution than images produced by visible light. The electron-generated image is then viewed on a screen for analysis.

The growth of the electron microscope as a practical tool has been unspectacular but crucial. Equipment and procedures which began as tools for basic research have in the past 10 years become indispensable engineering tools.

The scanning electron microscope (SEM) has become the basic member of the electron microscope family. It is a versatile instrument, suitable for identifying rudimentary phases in experimental alloys, determining the origins of failures in actual engine components or test samples, or determining the probable behavior of test samples.

The great depth of field, stereographic imaging capability, magnification range and resolution of the SEM make it the ideal tool to examine a composite materials structure before mechanical testing. Figure 1 (top) provides an example. Examination of the interface region shows that the fiber and matrix have only partially bonded together; two large microvoids are clearly visible as is an ongoing discontinuity around the fiber/matrix interface. A structure like this can be expected to have degraded mechanical properties because the fibers tend to pull out of the surrounding matrix.

Figure 1 (bottom), shows the same material after tensile testing. The material has suffered the expected failure. Using the SEM to examine composites for defects is faster and less costly than machining and mechanically testing samples.

X-rays Characterize Materials

Energy Dispersive X-ray analysis (EDS)

Figure 1, bottom: Left: After tensile testing, the material has failed as predicted. Right, the SEM used to carry out the composite study discussed here.

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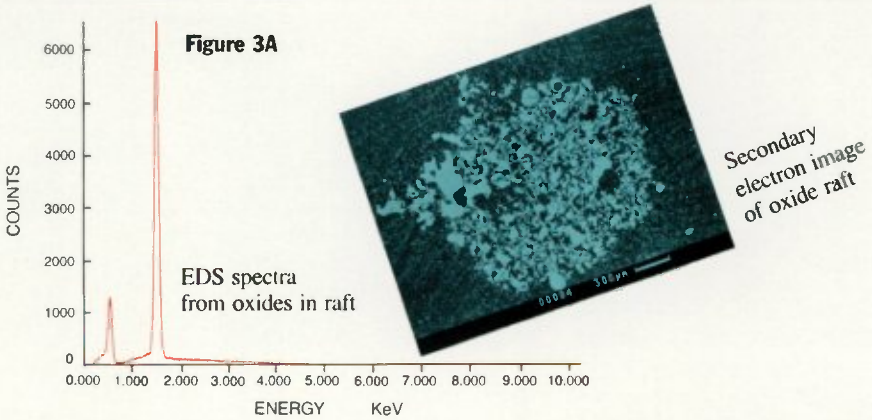


Figure 3A

EDS spectra from oxides in raft

Secondary electron image of oxide raft

is a powerful adjunct to the SEM. EDS measures the energy of X-rays emitted when a sample is bombarded with electrons. Different elements have different X-ray emission characteristics which function as signatures; the energy of the X-rays identifies which element is present, and X-ray energy maps tells where that element is located in the sample under study.

EDS provides a powerful tool for studying the structures of high temperature materials. The nickel-base superalloys provide a case in point. In these alloys performance depends on minute quantities of constituents that cannot be visually resolved and whose chemistry can reflect characteristics of any of the fifteen to twenty-five elements that must be precisely controlled in forming them.

Here is an example. Say that a cast blade is made from a nickel-base alloy whose primary constitutents (other than nickel) are chromium, molybdenum, tungsten, tantalum, titanium, hafnium, columbium, zirconium, aluminum, cobalt and rhenium. In addition, to achieve the right properties, the material must have tight control of a raft of residual or deliberately added other elements such as yttrium, carbon, boron, silicon, sulfur, iron, magnesium, vanadium, columbium, manganese, copper, nitrogen and oxygen.

To achieve the right balance of high temperature properties, the allowable amount of each element has to be carefully controlled. Yttrium, for instance, is added to improve resistance to oxidation. If it is added in excess of the solid solubility limit, the formation of low melting intermetallics will compromise properties. How to tell if the amount is correct? The ease with which the yttrium-rich phases are pitted-out by electrolytic or chemical etching procedures, as well as the minute amounts of the phase, makes mechanical or chemical testing techniques ineffective. Scanning electron microscopy, backed up by dispersive analysis, easily allows the unequivocal definition of yttrium solubility in our latest generation alloys.

The properties of airfoils made from superalloy castings are also very sensitive to trace impurities as well as to deliberate additions. One such impurity is silicon, commonly introduced through liquid metal reaction with refractory mold materials. Here again the SEM can use EDS to detect and identify silicide contamination in airfoils.

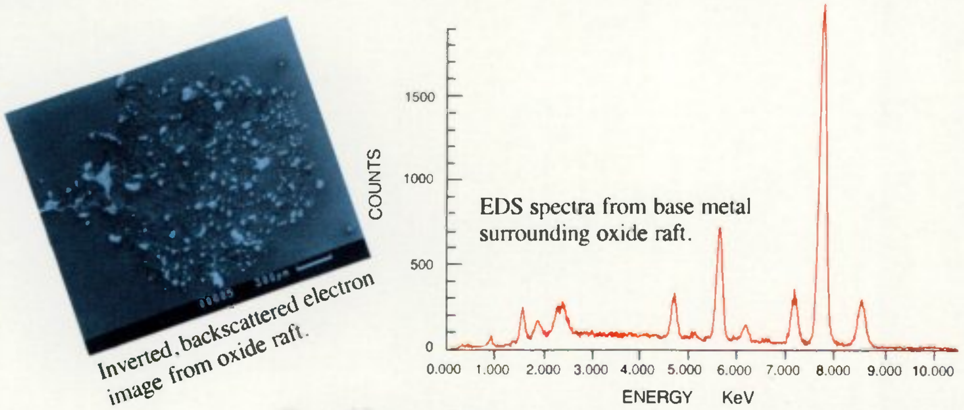
When dealing with complicated alloys, characteristic X-ray energy maps produced using EDS are very effective in revealing the location and distribution of the various elements within the microstructure. More specific information is available through the use of X-ray spot analysis. This technique uses a tightly-focused electron beam only one or two microns wide to give a detailed picture of the area under the beam.

The SEM uses three imaging techniques in addition to EDS to enhance understanding of the microstructure of new alloys. The first, false-color imaging, assigns arbitrary colors to the various energy levels of X-rays emitted by the sample; in effect, each element gets its own color, and the locations of the colors form a "map" showing how the elements are distributed in the sample. The second technique is called "secondary electron imaging." It uses electrons emitted by the sample itself in response to electron bombardment to study the topography of the sample. The third technique, backscatter imaging, uses "bounced" electrons returned from the sample to establish local densities of phases or regions in a sample.

With these three techniques it is possible to study how elements in an alloy are diffused and segregated. The combination approach also helps us analyze how the various elements interact when they occur in different phases. For instance, many topographically close-packed (TCP) phases look the same but actually have radically different compositions. Frequently, these differences may be associated with specific microstructural locations such as the grain boundaries and ultimately with mechanical behavior. X-ray imaging using secondary and backscatter images can differentiate these visually identical phases.

Image Analysis Techniques

A combination of SEM and Image Analysis (IA) techniques can determine



Inverted, backscattered electron image from oxide raft.

EDS spectra from base metal surrounding oxide raft.

Figure 3B Image Analysis study of oxide rafts on surface of EB melted button sample.

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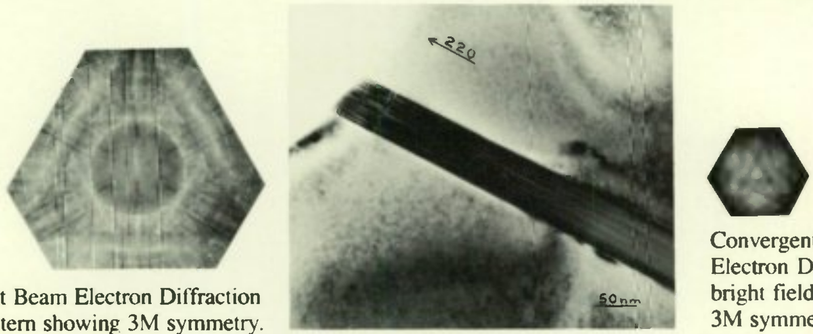

Convergent Beam Electron Diffraction whole pattern showing 3M symmetry.

TEM image of acicular Mu precipitate

Convergent Beam Electron Diffraction bright field image showing 3M symmetry.

Figure 4 Thin foil analysis study of Mu Phase in an advanced nickel-base superalloy.

Figure 2 EB melted superalloy button ready for analysis.

the volume percentage and size of microstructural features. Image magnifications in the 5,000 to 10,000X range are needed to obtain sufficient detail for separation of microstructural features; by analogy, this is like enlarging a very fine grain of sand to the size of a beach ball.

The key to image analysis is turning the image into digital data, then analyzing the data using powerful computers. Until very recently, only a few researchers with access to off-line computer systems could perform IA. Today, thanks to the advent of high speed, large storage capacity microcomputer systems, the ability to process electron microscopy images is now within the reach of many labs. Moreover, the new computers allow microanalysis, image processing and image analysis in a single, on-line interactive system.

A problem in powder metallurgy illustrates the usefulness of such an integrated system of microanalysis. Oxides and other inclusions had hurt the low cycle fatigue life(1,2) of disk components made using powder metallurgy; cleaner processing was essential in order to put powder metallurgy to work and realize its cost savings potential. The key was developing a new means of evaluating superalloy cleanliness to a higher standard than had ever been achieved before. A new cleanliness rating system was developed using a SEM/EDS/IA system to quantify the size distribution and the total oxide content in specially prepared buttons of nickel-base superalloy(3). In practice, a button melted by an electron beam was positioned on the stage of a SEM, Figure 2. Cathodoluminescence located the oxides on the button surface and a suitable magnification was selected. A LeMont IA system found and sized the particles, Figure 3, and collected X-ray information from each of them. The collected information was quantified and used to determine the oxide content of the sample.

This particular application demonstrated that Electro-Slag Remelt and Electron Beam Cold Hearth Remelt were "cleaner" than Vacuum Induction Melt/Vacuum Arc Remelt for improved metal cleanliness(4). The evaluation technique is being refined as a standard tool for evaluating new batches (heats) of metal(5). Its development represented a significant improvement in our ability to measure the quality of powder-metallurgical products. It was critical to the success of the powder metallurgy turbine/disk program.

Electron Microprobe Analysis

Like SEM, Electron Microprobe Analysis (EMA) has found a variety of applications in the study of jet engine materials. The electron microprobe focuses a small (<0.3 μm) electron beam on a sample surface and characterizes the X-ray spectrum generated at that point by using a variety of diffraction spectrometers. The X-radiation's wavelength is used to identify the element from which it was emitted, and the quantity of the element is calculated by comparing the X-ray count from the sample with the count rate of the same X-ray from a standard of known composition. Elemental X-ray distribution maps can be produced by rapidly deflecting the electron beam over the sample and displaying specific elemental X-ray intensities on a cathode-ray tube.

Geometry-sensitive X-ray spectrometers make quantitative EMA data generally more accurate than that produced by SEM/EDS systems, and EMA imaging quality is now about the same as SEM's. Used to generate vast quantities of quantitative and point analysis information, EMA's are

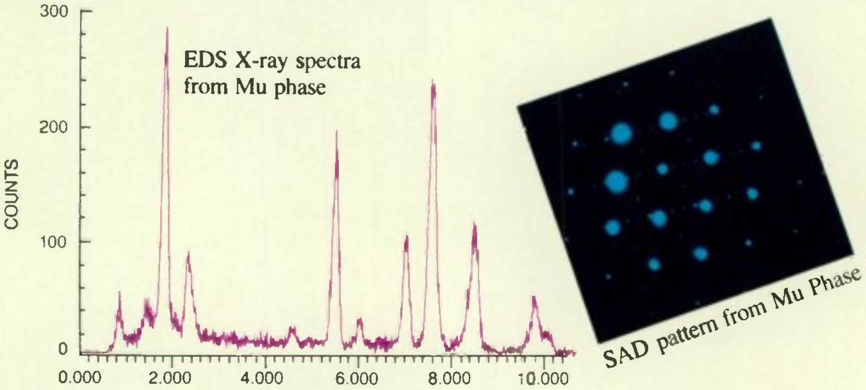

Figure 5 Electron diffraction and X-ray energy analysis study of Mu Phase in an advanced nickel-base superalloy.

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typically heavily automated. Some, such as EMTL's machine, can operate unattended for several days, continuously producing useful data. Common applications of EMA in EMTL include the study of structural composition for experimental coating systems and elemental segregation in cast, brazed and welded components.

Uses of Analytical Electron Microscopy

Analytical Electron Microscopy (AEM) has become essential for alloy development. For instance, during a study to determine the feasibility of using an advanced alloy for HPT blades, a Mu phase was observed. Mu phase is a topographically closely packed phase occurring in nickel-base superalloys. It can cause grain boundary embrittlement and other problems. In this case, the electron diffraction capability of the AEM was used to obtain Convergent Beam Electron Diffraction patterns from the precipitate, shown in Figure 4. These patterns were consistent with the presence of a Mu phase. A Selected Area Diffraction (SAD), Figure 5, and EDS results obtained from the same particle while in the AEM confirmed the presence of Mu phase.

The advent of Rapid Solidification Technology (see *The Leading Edge* for Spring, 1986) has produced a spectrum of alloys having unique microstructures

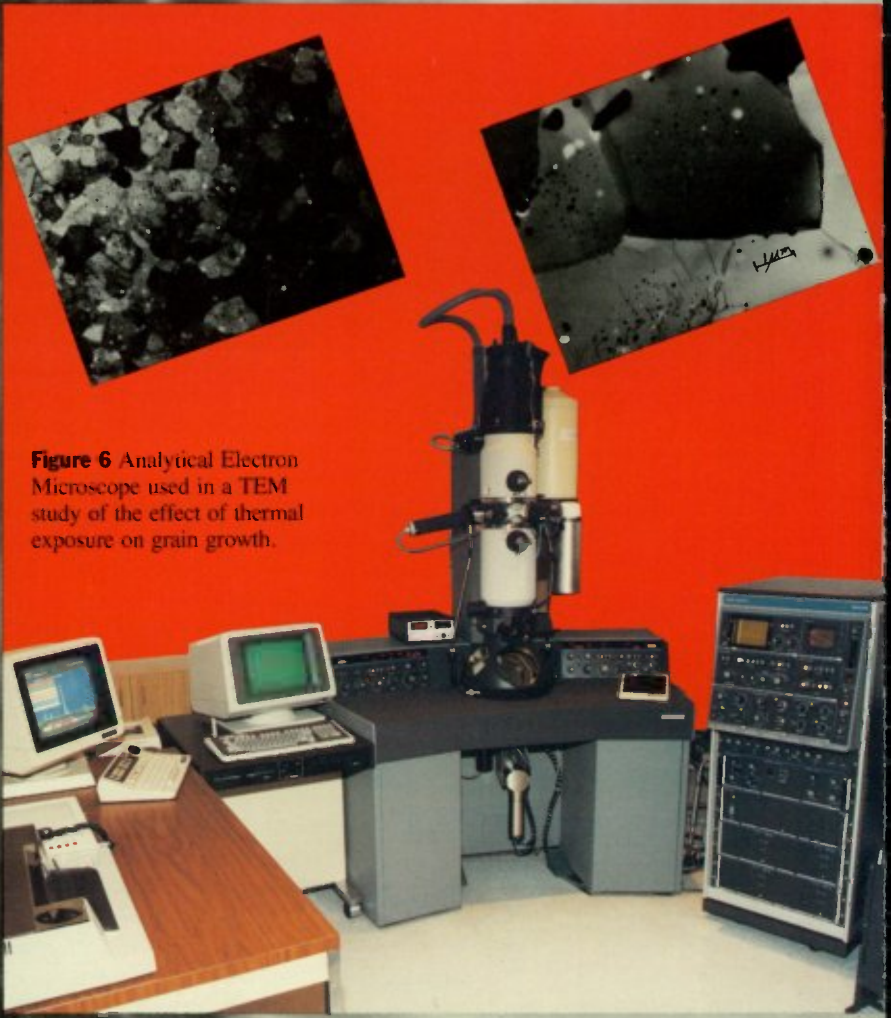

Figure 6 Analytical Electron Microscope used in a TEM study of the effect of thermal exposure on grain growth.

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which feature ultra-fine arrays of a dispersoid phase. Because of its high resolution and ability to image, analyze and identify the internal microstructural features (see Figure 6), the AEM is becoming increasingly important in observing the microstructural evolution of RST materials. It is the most convenient instrument available which can monitor internal microstructural changes from the as-solidified condition through to the fully consolidated and heat treated product with sufficient sensitivity for us to be confident that the material will retain its properties.

One technique that is being used to enhance the properties of alloys is the dispersion/precipitation of rare-earth oxides using RS techniques. A large number of fine (50-200 Ångstrom) precipitates can strengthen the material, while fewer micron-sized oxides can lead to slip redistribution and increases in ductility. AEM is used to measure the size distributions of these phases.

In developing these alloys it is important to identify the optimum consolidation techniques for the RST product. AEM is the only way to determine when the phases precipitate, when they coarsen, how they effect dislocation motion and grain and most important of all, how stable phases are at the service temperature. See Figure 7.

Future Directions in Electron Microscopy

During the last 20 years, truly remarkable progress has been made in the ability to perform localized submicron elemental analysis, including light element analysis (C, N, O, B) and in ultrahigh-resolution, scanning transmission electron microscopy. With the movement toward increased use of composite materials like carbon/carbon, intermetallic compounds and ceramics, developments are needed in the high spatial resolution identification of compounds. This is particularly true for the study of organics. Despite the ability of electron beam microdiffraction to identify compounds from areas smaller than 50Å, this is of little practical value because the electron beams tend to damage organic samples. Also, many organics are in noncrystalline form, for which conventional electron microscopy is inadequate.

Two additional techniques hold promise for the future. Secondary Ion Mass Spectrometry analyzes surfaces by using a rastered ion beam to "sputter" positive and negative ions and neutrals from a surface, enabling operators to measure mass/charge ratios in a tiny area of the sample surface. Scanning Auger Electron Spectroscopy analyzes elements within the top ten atomic layers of a sample. It is a promising way to analyze light elements by measuring the energy of an "Auger" electron emitted as a result of ejection of a core-level electron from the sample. Techniques like these, which are essentially nondestructive, would be useful to characterize dissimilar material interfaces on an atomic scale. ▱

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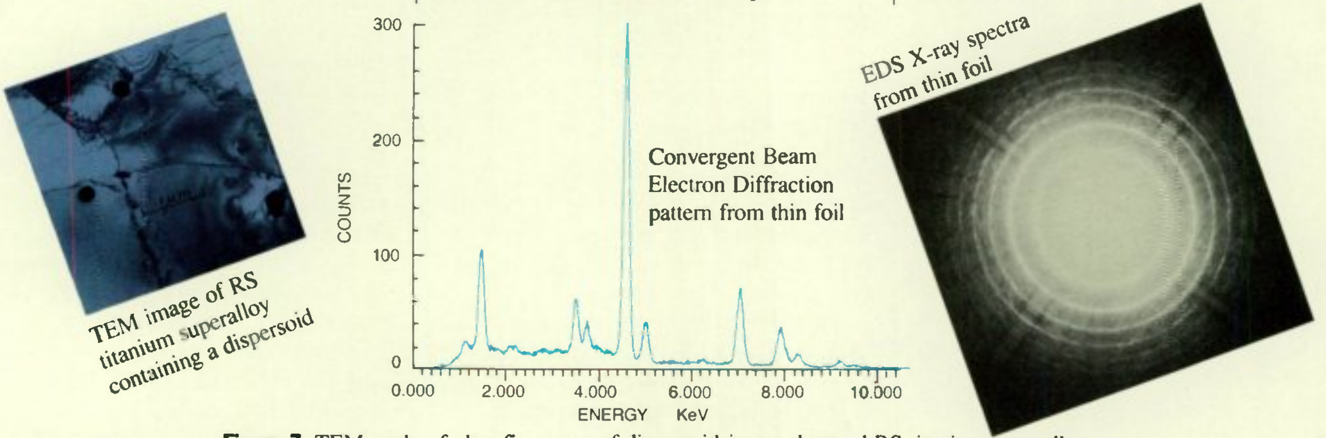
TEM image of RS titanium superalloy containing a dispersoid

Convergent Beam Electron Diffraction pattern from thin foil

EDS X-ray spectra from thin foil

Figure 7 TEM study of ultra-fine array of dispersoid in an advanced RS titanium superalloy.

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GEM

Engine Monitoring Comes of Age

By Richard J.E. Dyson
and John E. Paas

Economic pressures of differing sorts are leading both commercial and military operators to insist that their engines be equipped with the best monitoring systems available. The stringent competition arising from airline deregulation is forcing commercial operators to shave costs. For the military, the Gramm-Rudman-Hollings Act has also increased cost awareness. Engine monitoring offers both groups ways to keep expensive equipment operating efficiently. Other factors also encourage engine monitoring. Over the years, concerns over fuel costs, improved performance, availability, maintainability, safety of flight and overhaul have stimulated the development of effective monitoring systems.


R.J.E. DYSON


J.E. PAAS

Military and commercial operators have traditionally taken different approaches to engine monitoring. The airlines have historically been interested in performance monitoring. They ask, "Is the engine performance trend changing, and if so, what maintenance will we need to schedule?" The military, on the other hand, has been more interested in Line Replaceable Units, fault isolation and engine go/no-go decision-making using existing indication and control parameters. They ask, "Is the engine available and will it complete a mission; if not, what do we have to do to fix it?"

Table 1 Ground-Based Engine Monitoring System Analysis Functions

Function	Purpose
On-Wing Temper*	Analyze cruise gas path data to determine overall engine and module health
Test Cell Temper*	Analyze acceptance test gas path data to determine overall engine and module health
Takeoff Margin Assessment	Analyze takeoff data to determine the EGT margin of the engine
Control Schedule Analysis	Compare measured control variables to nominal schedules and limits
Vibration Trend Analysis	Compare measured vibrations to limits to identify potential imbalances
Fan Rotor Imbalances	Use measured fan vibration amplitude and phase angle to determine balance weights to correct fan imbalance
Fleet Average	Compute fleet statistics for engine family and identify low performing engines

*For Turbine Engine Module Performance Estimation Routine

Today's monitoring systems have improved to the point where both groups are finding them cost-efficient and effective. As with many good things, success does not come without a major contribution from the users themselves. Today our customers know what they want and why they want it. They are prepared to dedicate personnel who will understand, maintain, and utilize the system.

Commercial Systems

The heart of today's commercial engine monitoring programs is a system called GEM, for Ground-based Engine Monitoring. Data are recorded and stored on board the aircraft. On the ground, the data are fed into computers for analysis.


Figure 1

GEM combines all of the functions shown in Table I into a single, very flexible program capable of handling a wide range of engine thermodynamic and mechanical measurements. The GEM program monitors and analyzes modular performance, take-off margin, control schedules, vibration trends and fan rotor imbalance. In addition, it incorporates the Turbine Engine Module Performance Estimation Routine (TEMPER), a program originally intended to diagnose engine modular performance in airline test cells. GEM extends the TEMPER program to the analysis of installed cruise performance.

The TEMPER analysis function requires accurate data from expanded instrumentation. An engine-mounted Propulsion Multiplexer (PMUX) was developed to handle the increased data. See Figure 1. The PMUX supplies highly reliable digital data from the engine sensors to the airborne system for CF6-80A3 and CF6-80C2 engines.

As part of GEM, measurements taken during the aircraft takeoff are also analyzed to project the exhaust gas temperature (EGT) margin of the engines. Once the

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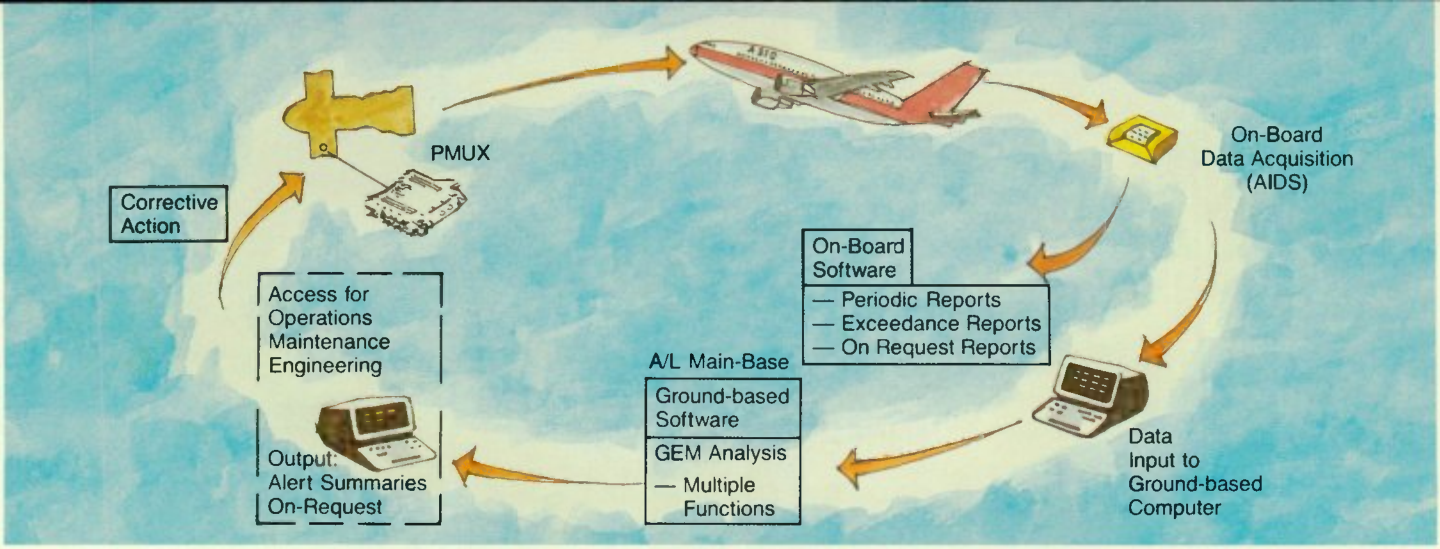


Figure 4 Schematic of Engine Monitoring Information Flow

aircraft has reached cruising speed, vibration levels and trends of control parameters are compared to limits. Later the data will guide airline personnel in line maintenance needs and the possibilities for fine-tuning the engine.

The GEM system started as a General Electric/airline team effort for the CF6-80A3 engine on the Airbus A310-200 aircraft. AEBG, KLM, Lufthansa and SAS, along with Airbus Industrie, have been working together to define, develop, implement and refine this extensive monitoring system. General Electric's participation has included the development of the GEM nucleus of analytical functions, within a mutually agreed software structure, to manage the data flow. GE also developed the special monitoring instrumentation. On the airline side, each user has developed individual software to process and present the engine data in a manner compatible with their own operation. Further, they have contributed to the overall design and implementation of the system.

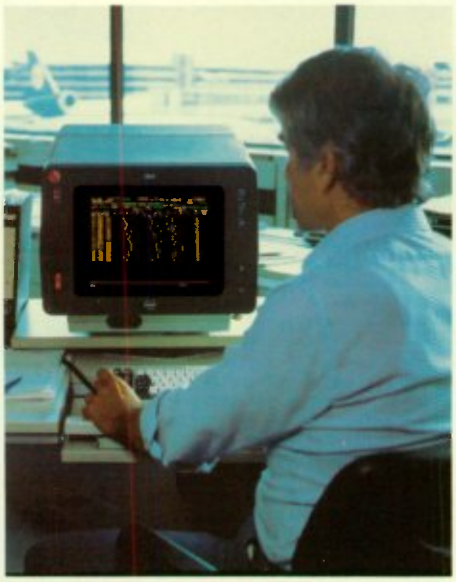
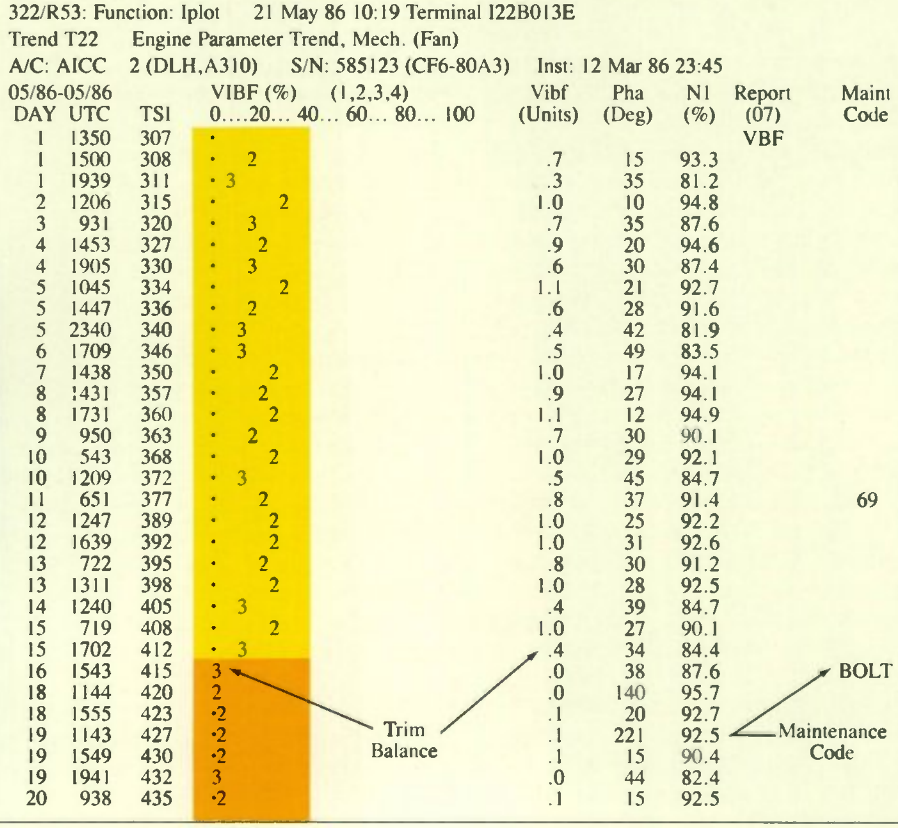


Figure 2

One of GEM's important features is the "Alert Report" for potential engine problems. As engine limits are approached or trends change significantly for an individual engine, an alert is automatically provided to the airline analyst. This contrasts with the more typical situation where the analyst must examine performance data for each individual engine, one at a time. The GEM alert feature promises better recognition of trend changes, monitoring more parameters with less labor.

Both KLM and Lufthansa rely on alert summary reports to monitor the engine trends for their CF6-80A3 fleets. Further, KLM uses a mini-GEM version to monitor its CF6-50 engine trends instead of daily examination of trend charts. The engine trend analyst at each airline interrogates the alert summaries at a computer terminal like that shown in Figure 2. The analyst can obtain supplemental information using a menu of available plots in order to investigate any particular alert. Generally, previous trends for the engine are retrieved from the airline's history files, which might include codes indicating maintenance performed on the engine. Based on this examination, the analyst will recommend appropriate actions. Efforts continue to fine-tune the trend recognition routine in

Figure 3 The trim balance performed on Day 16 shows lowered vibration levels on subsequent flights.



```
322/R53: Function: Iplot     21 May 86 10:19 Terminal I22B013E
Trend T22      Engine Parameter Trend, Mech. (Fan)
A/C: AICC    2 (DLH,A310)     S/N: 585123 (CF6-80A3)    Inst: 12 Mar 86 23:45
05/86-05/86             VIBF (%)      (1,2,3,4)              Vibf      Pha      N1    Report        Maint
 DAY  UTC      TSI      0....20... 40... 60... 80... 100    (Units)   (Deg)    (%)    (07)          Code
   1  1350     307      ·                                                             VBF
   1  1500     308      ·    2                                  .7      15    93.3
   1  1939     311      · 3                                     .3      35    81.2
   2  1206     315      ·        2                             1.0      10    94.8
   3   931     320      ·    3                                  .7      35    87.6
   4  1453     327      ·     2                                 .9      20    94.6
   4  1905     330      ·    3                                  .6      30    87.4
   5  1045     334      ·        2                             1.1      21    92.7
   5  1447     336      ·    2                                  .6      28    91.6
   5  2340     340      ·  3                                    .4      42    81.9
   6  1709     346      ·  3                                    .5      49    83.5
   7  1438     350      ·       2                              1.0      17    94.1
   8  1431     357      ·     2                                 .9      27    94.1
   8  1731     360      ·       2                              1.1      12    94.9
   9   950     363      ·   2                                   .7      30    90.1
  10   543     368      ·       2                              1.0      29    92.1
  10  1209     372      ·  3                                    .5      45    84.7
  11   651     377      ·     2                                 .8      37    91.4                 69
  12  1247     389      ·       2                              1.0      25    92.2
  12  1639     392      ·       2                              1.0      31    92.6
  13   722     395      ·     2                                 .8      30    91.2
  13  1311     398      ·       2                              1.0      28    92.5
  14  1240     405      ·  3                                    .4      39    84.7
  15   719     408      ·       2                              1.0      27    90.1
  15  1702     412      ·  3                                    .4      34    84.4
  16  1543     415      3                                       .0      38    87.6
  18  1144     420      2                                       .0     140    95.7
  18  1555     423      ·2                                      .1      20    92.7
  19  1143     427      ·2                                      .1     221    92.5
  19  1549     430      ·2                                      .1      15    90.4
  19  1941     432      3                                       .0      44    82.4
  20   938     435      ·2                                      .1      15    92.5
```

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order to reduce some of the unnecessary alerts.

Another significant advance is the use of cruise data to perform fan trim balances without expensive ground runs. Lufthansa has successfully used this procedure to balance their CF6-80A3 fans to keep fan vibrations well below limits. The benefit to Lufthansa should be extended life for accessories and parts (such as brackets) which can be affected by high vibration. In this system, both fan vibration amplitude and phase angle are acquired during cruise. Back on the ground, these data are used to project appropriate weight changes; these are done by changing the configuration of the balance bolts. When fan vibration trends increase, the airline can make corrections based on cruise data alone, without extensive (and expensive) ground operation. Figure 3 shows just such a fan vibration trend plot; the resulting trim balance produced very low vibration levels for the subsequent flights.

Similarly, engine control parameters—Variable Stator Vane (VSV) setting, Variable Bypass Valve (VBV) position, and torque motor current—are monitored to promote maximum fuel efficiency. Should adjustment of the VSV or VBV be needed, such as after a main engine control change, this can be accomplished based on cruise data without a ground run-up.

Both KLM and Lufthansa have added a number of features to integrate the GEM condition monitoring system with their own operations. These include features to process, store and present GEM data automatically. KLM retrieves data from their on-board system using cassette tapes containing data sampled throughout the flight. Lufthansa, on the other hand, uses optical scanners to read data from its on-board system's printed reports; these are then loaded into the main computer via the reservation system. Lufthansa has further developed a virtually real-time system in which GEM results are available to their analyst within a few hours of the airplane's landing. These GEM results are also available to GE via a direct data link, provided by Lufthansa, between the GE Product Support Center in Cincinnati and Frankfurt, Germany. The entire Lufthansa system is shown schematically in Figure 4.

Future Gains

In the future, analysis of on-wing modular performance promises information to better manage engine maintenance. Shop refurbishment workscopes can be largely defined prior to engine removal based on the assessment of modular performance changes. This will be far more efficient than the "once-we-get-it-apart-we'll-know-what-we-have-to-do" method of engine analysis.

The success of the A310/CF6-80A3 GEM system has led to expansion of the monitoring capabilities to other applications. This system, called Universal GEM, includes monitoring capabilities for the CF6-80C2, CF6-50 and CFM56-3 in addition to the CF6-80A3. It provides a single monitoring system to use with all the CF6 and CFMI engine models in the KLM and Lufthansa fleets, as well as in the Air France and SAS fleets in 1987. In addition, the system will be used to detect trends for Thai International's CF6-80C2 engines and will be available for our A320/CFM56-5 customers when that engine goes into service.

Military Monitoring

Military monitoring systems emphasize go/no-go decision making, more than long-term engine performance trends. AEBG is developing military monitoring systems which include instrumentation of the engine, airborne diagnostic algorithms, and ground software/hardware combinations. GE is developing the total system for the F-16 aircraft with the F110-GE-100 engine, and similar ground systems are being developed for the F110-GE-400 (Navy) and F101-GE-102 (Air Force/SAC).

The engine monitoring system (EMS) for the F-16 acquires relevant engine and aircraft data during flight, communicates with the aircraft data bus, processes the data and provides a concise output at the flightline to define recommended maintenance actions. The system also transfers stored data from the aircraft into the USAF ground computer system for additional processing and output.

F110-GE-100 EMS

Early in 1983, General Electric received a contract from the USAF for the full scale development of the F110-GE-100 engine, complete with EMS. The system was required to incorporate the following features:

(a) Determination of engine limit exceedances.

(b) Isolation of the source of these limit exceedances to the appropriate level.

(c) Acquisition of data to support identification of long term engine performance trends.

(d) Acquisition of data to enable the tracking of life-limited engine components.

(e) Indication of flightline go/no-go to reflect the engine status as determined by EMS.

(f) Ground support software to process EMS data and interface with other USAF data systems.

The EMS configuration which interfaces with the Augmenter Fan Temperature Control consists of three hardware components: an engine mounted EMS Processor, an airframe mounted EMS Computer and a Data Display and Transfer Unit—flightline equipment. The processor digitizes the data and clocks the use of life-limited parts. The computer continually monitors the engine and records data whenever appropriate. The Data Display and Transfer Unit displays faults and transfers data to the ground processing computer. Figure 5 shows a diagram of the entire system.

This system has been flying successfully at Edwards Air Force Base on the F-16C3 flight test since mid-1985 and is now operational. The level of real event detection is high. Nonetheless, as engine and aircraft characteristics are revealed, software will continue to be modified and released to enhance the diagnostic logic capabilities and to avoid erroneous event detection; false alarms are always a difficult challenge for monitoring system design.

There is confidence that this system design is providing the basis for future systems in which hardware is integrated with the engine control or software is integrated with the aircraft avionics.

Conclusions

Engine monitoring systems are coming of age. Recent advances have included:

- Development of miniaturized electronics

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which can exist in a harsh environment e.g. engine mounted PMUX and EMSP, aircraft mounted EMSC.

- Introduction of digital controls on an increasing number of engines: CFM56-5, GE37, F110 IPE, and CF6-80C2. Digital controls reduce the need for unique monitoring instrumentation, provide highly accurate, reliable digital data and isolate faults better.
- Development of software analysis techniques and availability of computer facilities to guide troubleshooting, maintenance, logistic support and planning.

Military and commercial philosophies will come together in advanced engines like the GE37 and the UDF which will incorporate performance monitoring, modular health analysis, Line Replaceable Unit fault isolation, vibration monitoring, fan trim balance and control analysis programs. Such systems will reduce ground support, make the engine easier to support, track warranty provisions, and control the cost of ownership for both military and commercial users alike. ◪

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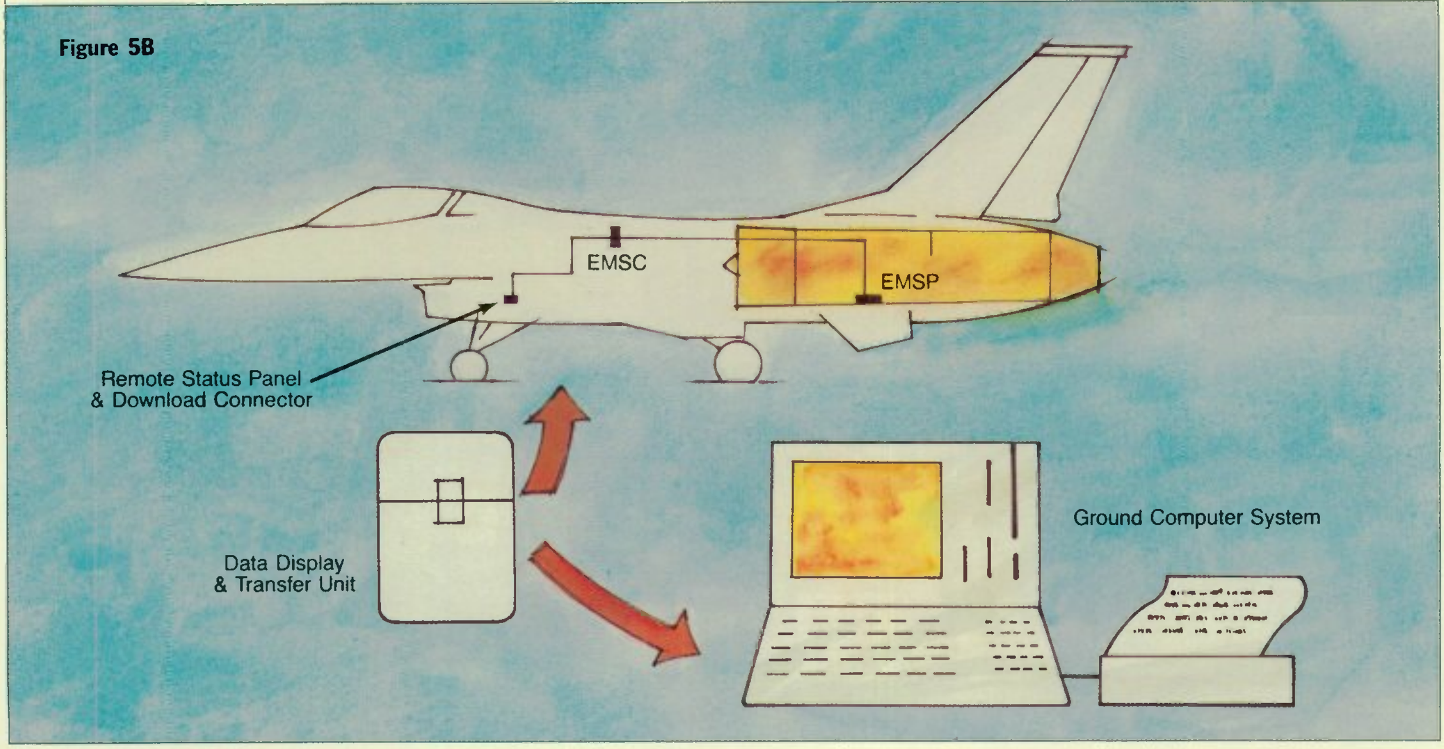
John E. Paas is Senior Project Engineer for Condition Monitoring Programs.

Figure 5A F110 Engine Monitoring System

Figure 5B



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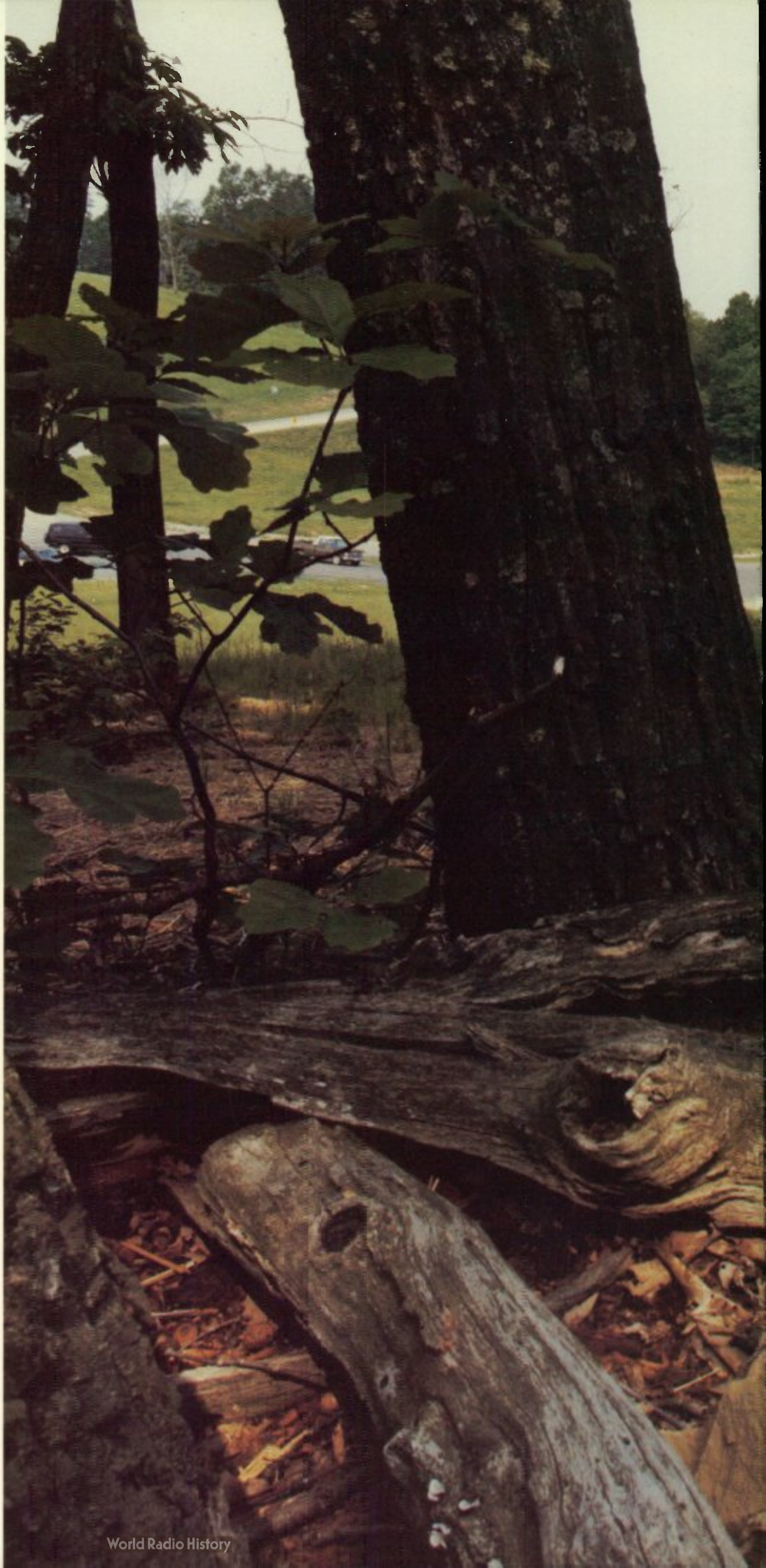
Peebles Test Operation: A High-Tech Pastorale

In the 1950's GE anticipated the need for a rocket engine test facility. For noise, safety and security an isolated site was sought. A rural hillside in southwestern Ohio near the village of Peebles provided ideal conditions. Though the anticipated rocket tests never came to pass, the Peebles site provided excellent cold-weather test conditions, plus the ability to test for noise in an outdoor environment.

Over the past 30 years Peebles has developed from a crude landing strip and a tobacco-barn hanger to a sophisticated test facility with the latest in electronic data gathering and transmission equipment. FAA certification testing, including bird strike, containment, water ingestion, icing and cross-wind tests are conducted, as are a range of other tests.

Despite its technical function and advanced testing technology, Peebles has retained its pastoral character. The intersection of technology and nature is what we've tried to capture in this issue's Photo Essay.



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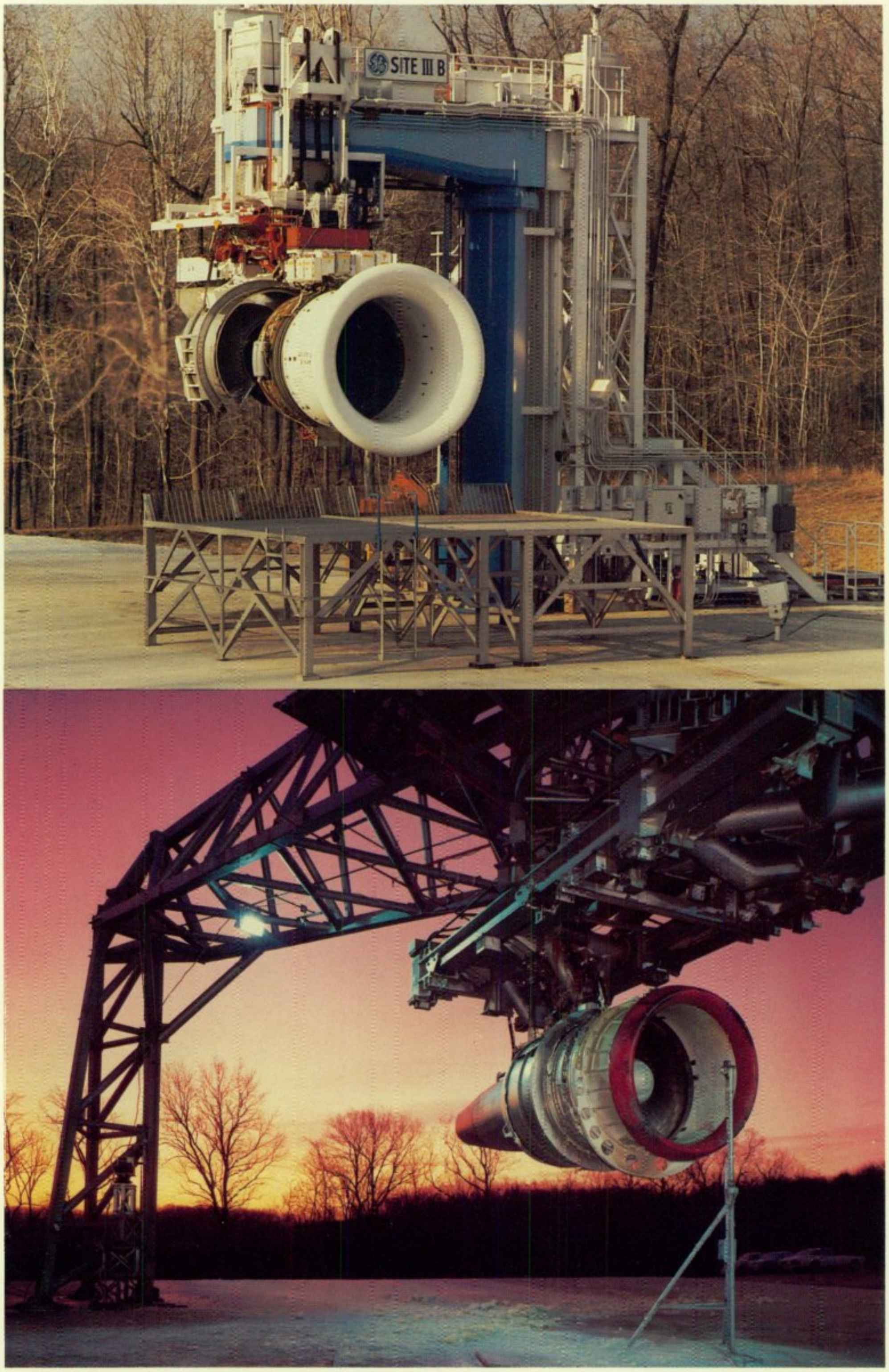

A High-Tech Pastorale

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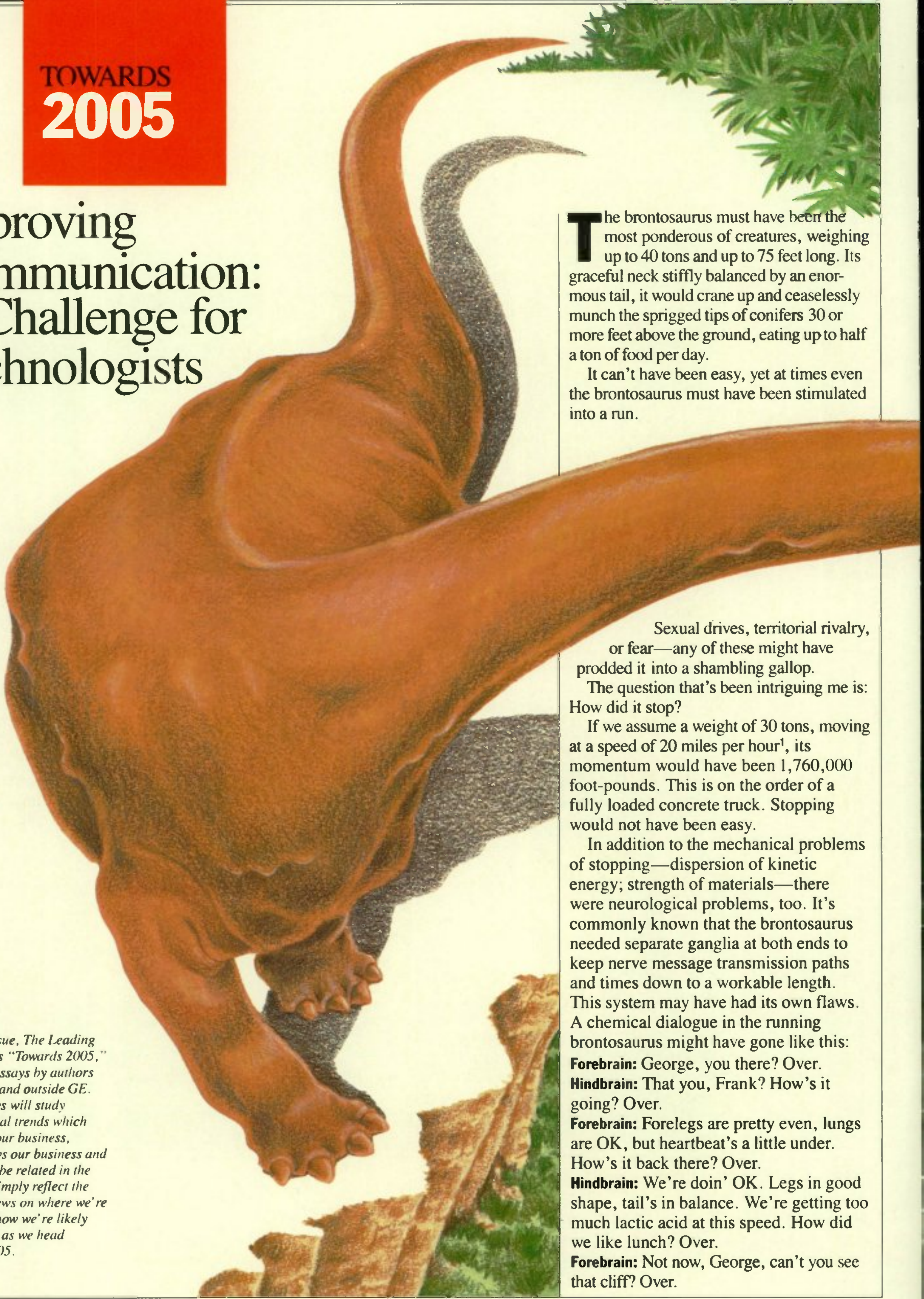
TOWARDS
2005

Improving Communication: A Challenge for Technologists

With this issue, The Leading Edge begins "Towards 2005," a series of essays by authors both inside and outside GE. These essays will study technological trends which may affect our business, suggest ways our business and others may be related in the future, or simply reflect the authors' views on where we're going and how we're likely to get there as we head towards 2005.



The brontosaurus must have been the most ponderous of creatures, weighing up to 40 tons and up to 75 feet long. Its graceful neck stiffly balanced by an enormous tail, it would crane up and ceaselessly munch the sprigged tips of conifers 30 or more feet above the ground, eating up to half a ton of food per day.

It can't have been easy, yet at times even the brontosaurus must have been stimulated into a run. Sexual drives, territorial rivalry, or fear—any of these might have prodded it into a shambling gallop.

The question that's been intriguing me is: How did it stop?

If we assume a weight of 30 tons, moving at a speed of 20 miles per hour[1], its momentum would have been 1,760,000 foot-pounds. This is on the order of a fully loaded concrete truck. Stopping would not have been easy.

In addition to the mechanical problems of stopping—dispersion of kinetic energy; strength of materials—there were neurological problems, too. It's commonly known that the brontosaurus needed separate ganglia at both ends to keep nerve message transmission paths and times down to a workable length. This system may have had its own flaws. A chemical dialogue in the running brontosaurus might have gone like this:

Forebrain: George, you there? Over.

Hindbrain: That you, Frank? How's it going? Over.

Forebrain: Forelegs are pretty even, lungs are OK, but heartbeat's a little under. How's it back there? Over.

Hindbrain: We're doin' OK. Legs in good shape, tail's in balance. We're getting too much lactic acid at this speed. How did we like lunch? Over.

Forebrain: Not now, George, can't you see that cliff? Over.

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Hindbrain: I can't see anything. The eyes are your department, not mine. Over.
Forebrain: George, we've got to stop RIGHT NOW! Whoa! Hold it. Over.
Hindbrain: Gee, I dunno Frankie, feels like we're movin' pretty good back here. Are you sure you wanna... (dialogue terminated by sudden arrival at base of cliff)

Many large organizations suffer similar communications problems. If there's just one big central brain, it can take too long to send messages to the extremities and have them received, interpreted, and acted upon. If there are several brains, they may not coordinate well or cooperate even when it's important.

Being smarter than the brontosaurus, most large corporations are well aware of these fundamental problems, and as many solutions have been devised as there are companies. None works perfectly. Some have tried deliberately limiting the size of the organization, keeping it small enough to function well and adapt easily to changing conditions (one commonly cited explanation for why the mammals outlived the dinosaurs). Other companies work at improving the effectiveness of communications, so essential messages arrive quickly and get prompt response. Certain others have tried using complete decentralization and a matrix structure to improve integration, thus avoiding the need for either central control or local control. Still others have relied on new technology to improve communications.

Thanks to the technological revolution in word processing, copying, and data transmission we can connect the head and tail far faster than ever before. But technology is far from a panacea and in fact can make communications worse.

As an organization grows, the amount of paper consumed increases exponentially. It increases much faster than staff does. Given that most people can only read between 120 and 300 words per minute (average is around 180), reading the floods of paper pouring out of ink jet printers and supercopiers takes more and more time—the one commodity most of us don't have.

Technology has improved the speed of communication and the volume of information communicated. But communication is not necessarily improved by transmitting more data, and technology which encourages volume without substance is actually counter-productive. It costs significant time and money to print, collate, distribute and read all that paper. Simply shoving more information at more people does not increase their knowledge, their degree of understanding, or their ability to take informed action.

Increasing transmission speed also looked like a technological panacea when electronic mail first became a practical reality in the early '80's. But it too can make things worse. We can now transmit reams of information from coast to coast in minutes. In making certain kinds of decisions or documenting flight test events, this ability is genuinely useful, even essential. But all too often the lightning speed of transmission has once again resulted in piles of unread paper.

Good communication has something worthwhile to say and says it concisely and clearly. Good communication is readable and interesting. Of late, technology has played no great role in meeting these criteria. More important are skill and judgment and empathy in the writer or speaker.

This isn't to say that there can't be technology which genuinely aids communications. Electronic spelling checkers and thesauri improve clarity by reducing spelling errors and improving word choice, and they work in a fraction of the time their hand-held predecessors required. But what about new technology like the long-heralded voicewriter? Freely available by 2005, will it encourage long-windedness, or will it shock its users into editing themselves more carefully? It's possible that new technology like the voicewriter will improve the human communicator's performance, just as the ruthless fidelity of compact disks has forced singers to breathe more quietly and phrase more articulately. But it's equally possible that new communications technology will intimidate, bury, or stupefy its users without actually benefitting them at all. Coming up with technology which actually improves the quality and clarity of communication will be a challenge for technologists well beyond 2005.

At AEBG, we are generally eager to try the latest technology as soon as it's available. Luckily, we haven't relied solely on technology to improve our communications. That is why we have boss talks, dialogue meetings, skip-level meetings, exempt employee surveys, HEADLINES, FFO's, and THE LEADING EDGE. Less formally, it's why we have so many IOI's, telephone calls, conferences, seminars, and meetings ranging in length from 15 seconds to several days.

The nature of a corporation's personality, its behaviors and attitudes, ultimately controls the nature of its communication. Even in companies like GE, which genuinely understand the need for, and support, improved communication, changing these attitudes is a long-term job. Once it got up to speed, no brontosaurus was ever going to stop quickly, no matter how hard it tried.

For all our size, AEBG is smarter and more flexible than the brontosaurus. Unlike the great dinosaurs, we are rapidly evolving. It is the nature of our cultural evolution, more than any emerging technology, which will dictate whether or not we'll have the communication skills we'll need to survive in 2005. Then or now, communicating is an essentially human endeavor which machines can aid or hinder but never supplant. The challenge to technologists will be to remember they are human, and that the responsibility for improved communication rests with them as individuals more than with the machinery they invent. ❐

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[1] These are conservative figures provided by Dr. Robert Bakker, leading authority on locomotive morphology in vertebrate paleontology. They assume the brontosaurus was warm-blooded.

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