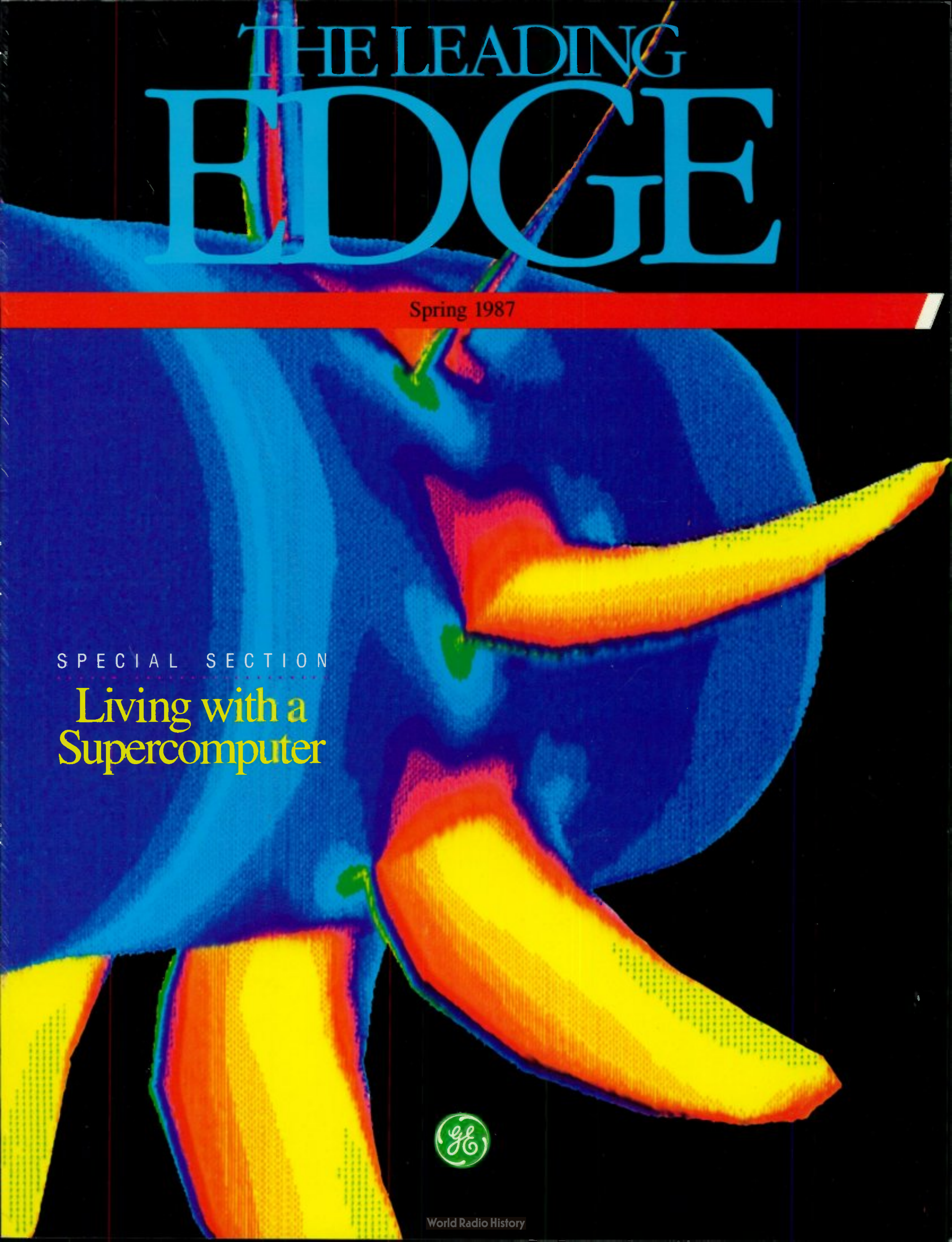
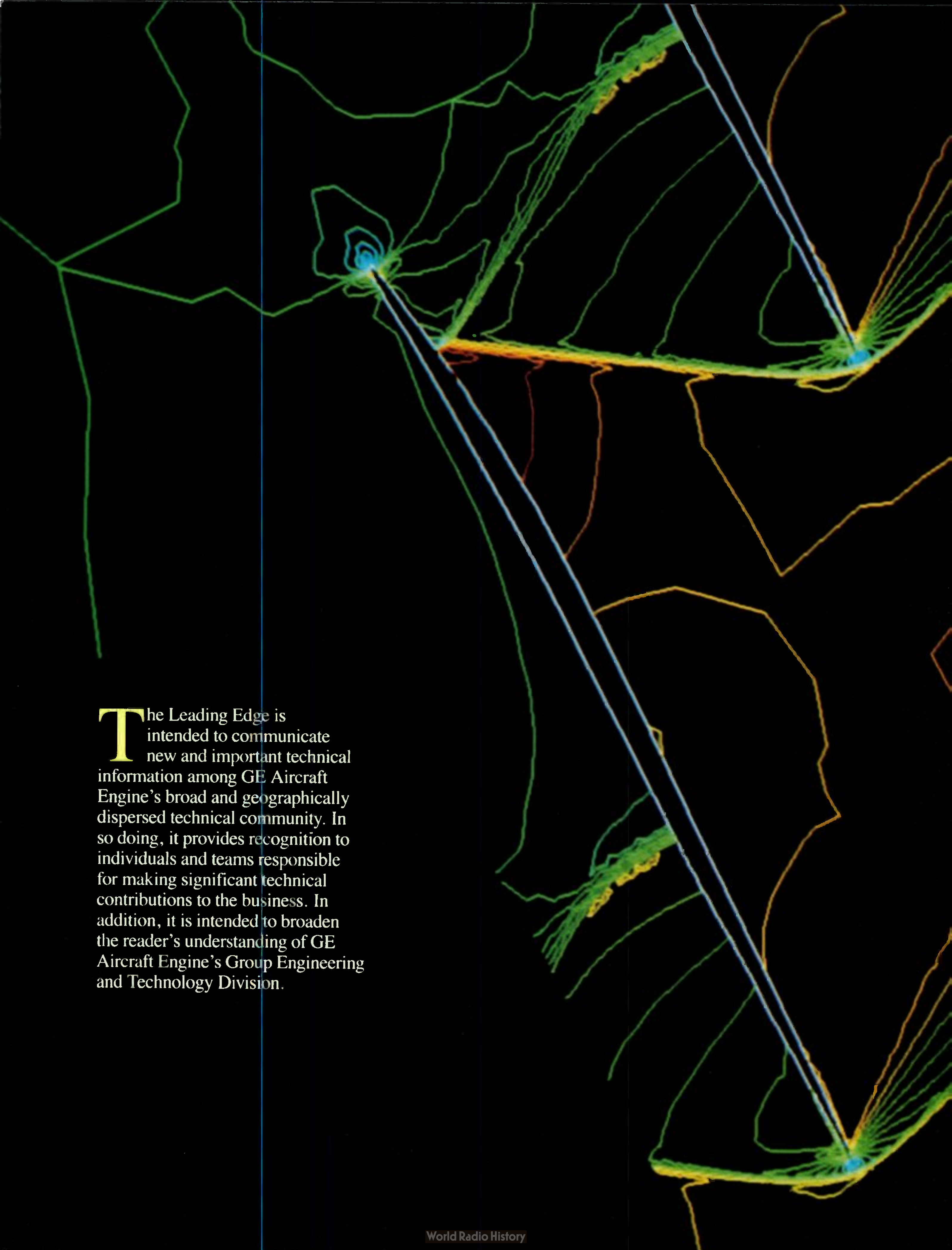
THE LEADING EDGE

Spring 1987

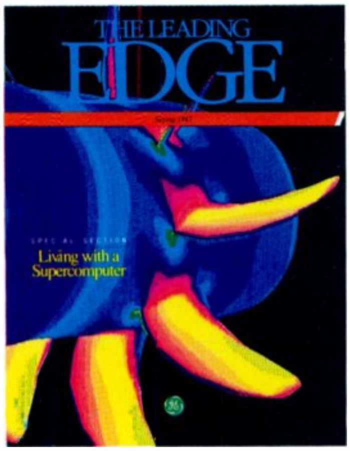


SPECIAL SECTION

Living with a Supercomputer



The Leading Edge is intended to communicate new and important technical information among GE Aircraft Engine'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 GE Aircraft Engine's Group Engineering and Technology Division.



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Contents

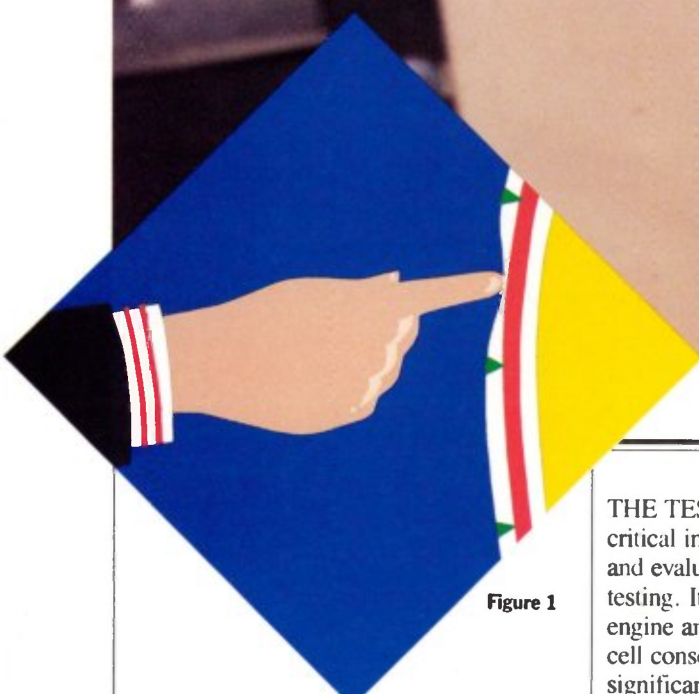


Figure 1

Touch-Screen Test Cell Controllers

By
Daniel J. Schlueter

THE TEST CELL console system is the critical interface for both the test operator and evaluation engineer during engine testing. It lets the operator control both the engine and the test facility. Engine test cell console systems have gone through significant changes over the past decades, from hard-wired, cumbersome controllers to today's touch-screen electronic system. This article surveys the development of test cell controllers and comments in some detail on the advantages of the touch-screen system being put in place today.

A variety of display devices is used to monitor critical engine and facility events and communicate them to the operator. In the pre-computer era the console systems consisted of a myriad of gauges, dials and meters. Each parameter, such as temperature, pressure or speed, required an individual display device. Space requirements for the devices sharply limited the instrumentation being monitored. This meant that not all the important parameters could be tracked. The test operators had to have a quick eye and be alert at all times in the event there were any problems demanding immediate action. Events which occurred faster than humanly possible to observe were missed. During the course of a test all data had to be manually recorded, a process which was time consuming and prone to errors.

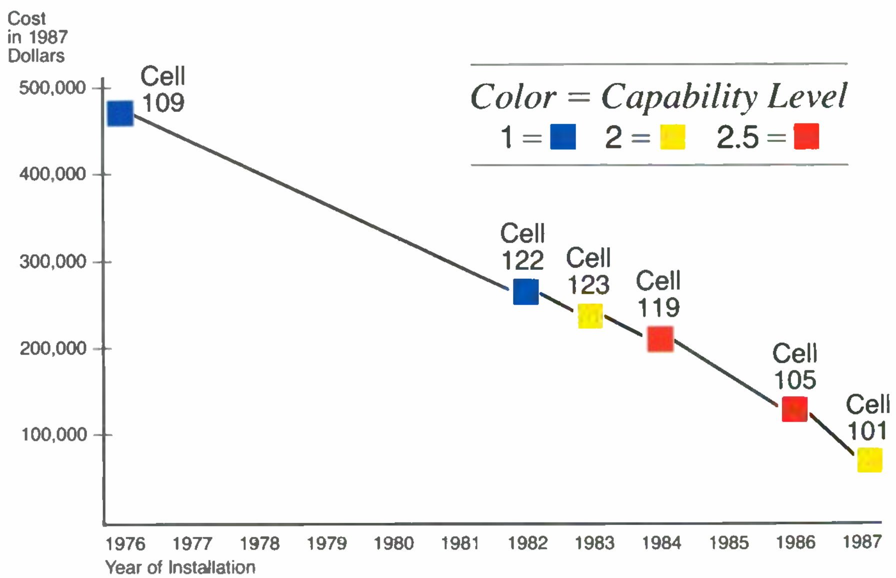
D.J. SCHLUETER

As computer technology advanced it became evident that computerizing the test cell console systems would overcome many of the limitations of the early consoles. In 1973, E. Wayne Holt of the

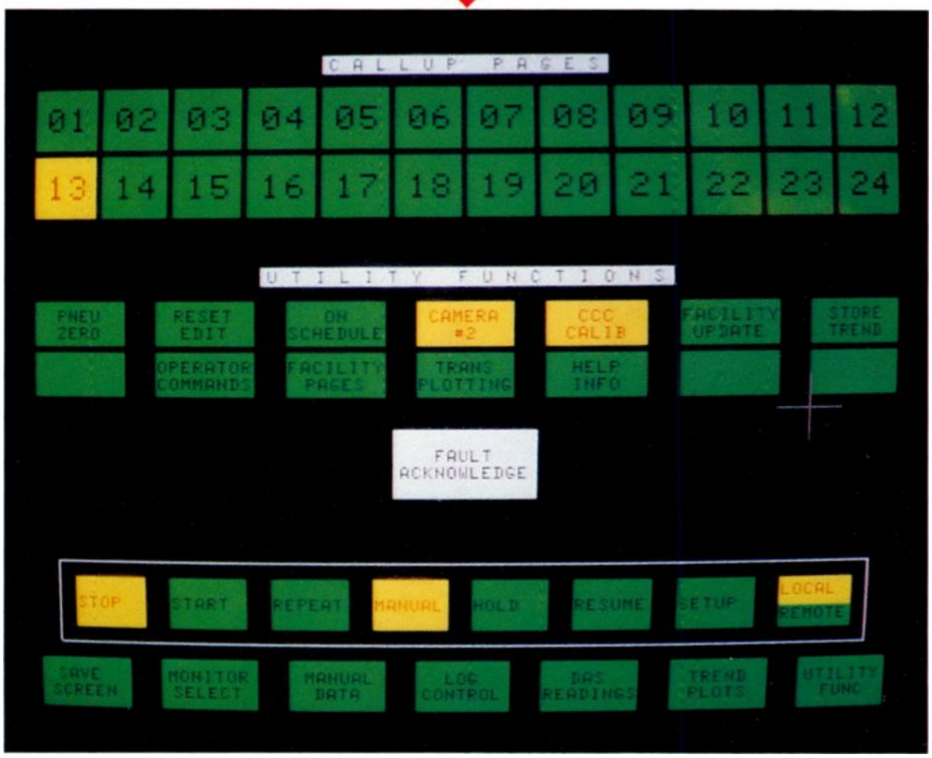
Aircraft Engine Business Group in Evendale, Ohio, developed a specification for a computerized console system. The specification called for a computer system which would perform the console functions in real-time. (Real-time is the actual time of a physical process. For a computer to process in real-time means it has the speed to perform operations as close to the actual time as possible.)

The Holt system was re-specified in 1976 and was built by Systems Research Labs, Inc. This system was able to acquire data from 195 channels of instrumentation on the engines. Data were acquired in the form of voltage readings and needed to be converted to an engineering unit such as degrees or RPM's. The data were then checked to insure that they were within specified limits. This conversion and limit checking was done at rates of once, 3.5 and 5 times a second. Most channels were

Figure 2 Decreasing Costs of Cell Computer Systems 1976-1987



All functions became centrally located



Menus make function selection quick and easy

processed at the one and 2.5 rates because the computer could not process all data at the faster rates.

After processing, the data were then displayed on three video screens twice a second. The system also had the capabilities to perform calculations on data once per second, keep a running log of critical data accumulated over the last ten minutes, enter manual data such as the serial number of the engine, spot trends during engine testing and generate a hardcopy log of all data upon request. The system could keep track of a total of 280 parameters (channels of data, calculations, manual data, etc.).

Tester interface to the console system was accomplished through a variety of panels. The engine and facility control modules (ECM/FCM) provided the control of the engine and facility operations. Functions such as ignition, rollover and anti-icing were located on an engine control module. The facility control module controlled such functions as power, lights and fuel valve control.

Two additional panels, a console data panel (CD-10) and a manual data panel (MD-10), provided the necessary interfacing for such functions as the taking of logs, camera control, display page selection and entering manual data. Additional input was required through a keyboard terminal for such commands as clearing logs, restarting the video display system and selecting different predefined test setups.

This initial computerized console system was used in Lynn (cells 109, 115 and 121) until 1982 when the Test Facilities group at Lynn designed and developed its own console system for cell 122 for CT7 turboprop testing.

Although the initial consoles provided the needed automation for test cell consoles, the computer system still had limitations. Temperature and speed changes can take place in less than a quarter or a fifth of a second, too fast for the Holt system to track. Faster data acquisition rates were needed. Lynn upgraded the processor and the acquisition equipment being used and increased the rate at which data was converted, limit checked and displayed to 5 times a second. Calculations were increased to a rate of twice a second and limit checking was extended to all 280 parameters, not just the 195 scanned channels of data.

Even with the increased processing power available with the new system, a keyboard was still required for certain functions and was awkward and error-prone. The CD-10/MD-10 panel interfaces for console functions had no room to move some of the functions from the keyboard. Even if there was room, modification of the panels was costly and time consuming. In 1983 cell 123 was constructed for F404 production engine testing. In order to overcome the interfacing problems and reduce the keyboard requirement, the first touch-screen system was introduced to the console design.

Early Flaws

Touch-screen technology was in its infancy, so there was some risk involved. The first system installed had flaws. It used a capacitance technology and touching the screen changed the local capacitance of the screen, thus identifying where the touch was made. It was discovered that the screen was susceptible to low blood pressure and calloused fingers!

A second design was quickly identified which used a two-layered screen, illustrated in Figure 1. The outer screen is physically pushed to make contact with the inner screen, creating a resistance change. This technique proved extremely reliable and was integrated into the console system. All of the console functions on the CD-10/MD-10 panels and all operator commands

previously executed on the keyboard were moved to the touch-screen. Initial concerns over reliability and operator acceptance were soon overcome as the users gained experience with the system.

Touch-screen technology provided several benefits. Panel changes were no longer required. To change a switch or option meant simply changing a software program which was quick and easy. Installation was easy—no complex wire schemes—and the costs of installation were half those of the older setup. But the key benefit was the ease of use. All functions became centrally located and were accomplished through touching—far faster and less error-prone than typing.

In 1984 the success of the initial touch-screen system led the Test Facilities group at Lynn to replace the ASE designed ECM/FCM in the design of the console for the cell 119 environmental test facility. The ECM/FCM were also a part of the initial computerized console system. Like the older console panels, these too were expensive and changes were costly and time consuming and a unique engine control module had been required for each engine line because of the differences in the engines.

A GE Series 6 Programmable Logic Controller (PLC) was chosen as the basis of the new ECM/FCM. The Series 6 uses a simple programming language to accomplish what used to be done with very complex wiring schemes. An IBM PC with a touch-screen mounted on the display was used as the interface.

Protective Measures

The risks of unintentional touches, emergency situations and the critical nature of the functions being implemented on the new ECM/FCM touch system prompted caution. At first, the touch-screen was used only for a restricted number of functions. However, a second installation of the system for the cell 105 F404 testing program added a special protection function to the system to eliminate the incidental touch problem. The continued success of the touch technology resulted in all ECM/FCM functions' being implemented with touch. A single emergency switch was provided in the event of problems requiring a quick override from the tester.

Using touch screens like this one in cell 105 is faster and less error-prone than typing

In addition to significant cost savings to implement the ECM/FCM touch system ($200K vs $40K), the system provided a further consolidation of functions and reduced the space requirements for the console. Changing the ECM/FCM from one engine to another is now accomplished through a simple switch selection on the touch-screen which changes the software on the IBM PC. By establishing a communication link between the ECM/FCM touch system and the main console computer, critical information such as the status of switches or information for controlling throttle movements on the engine can be passed back and forth.

The computerized console systems have gone through some significant changes. The changes have provided not only more processing power but have integrated some new technology which has allowed the design to become more compact.

Not only has the size of the system been reduced but so has the cost, as shown in Figure 2. These two factors were key to the decision to utilize a console system for the LV100 testing which is to be done in Lynn cell 101. The cost of the computerized console system for this cell will be less than $60,000! The computerized console systems are helping to provide the safest and most cost-effective testing available.

Daniel J. Schlueter is Manager, Mini Computer Systems Operations.

An Interview with Russ Larson

Test

AT CERTAIN TIMES of the year the wind blowing across the Mojave Desert carries a pervasive smell of sage. The wind blows hard most of the time: doorways into hangars and offices are baffled against the blowing dust and grit. Mountains, mostly bare upthrusts of ochre and umber rock, jolt their way out of the desert floor: the San Andreas fault runs just a few miles from the Mojave airport where GE operates a flight test facility.

At the airport, old hangars are interspersed with new steel structures. The Voyager aircraft draws a steady stream of tourists to one out-of-the way hangar. A row of derelict jets sits in the middle of the airport, polished by the blowing dust. Inside one of the GE buildings, the MD-80 aircraft is being readied for the next phase of UDF™ flight testing.

Mojave is where the Leading Edge found Russell Larson, GE's chief pilot. Russ Larson has been flying since 1949, joining GE as an engineering test pilot in 1956. Beyond his flying duties, he is responsible for organizing and managing the flight operations at Mojave, including training aircrews, maintaining Quality Systems to meet both FAA and DOD requirements, and procuring FAA certificates and approvals for flight testing.

Russ, you're the Chief Pilot and Manager of Flight Operations. Why do we do flight tests?

A big contribution of the flight test program is giving the project some evaluation of how you think the engine really looks in an airplane. Most of the people at GE run engines in test cells, and that's really different than running them in an airplane.

Do you have a "for instance"?

Generally it has to do with operability, things like acceleration times, the ease with which you can set power and response to aircraft dynamics. How does the engine behave, is it kind of user-friendly, and so forth. It's different for ground-based personnel to have a good feel for that. We just went through it with the CFM56-5. There were a number of engine schedules which were changed because of findings by myself and some other pilots that weren't really very satisfactory. I don't think that would have happened without the pilot input into it.

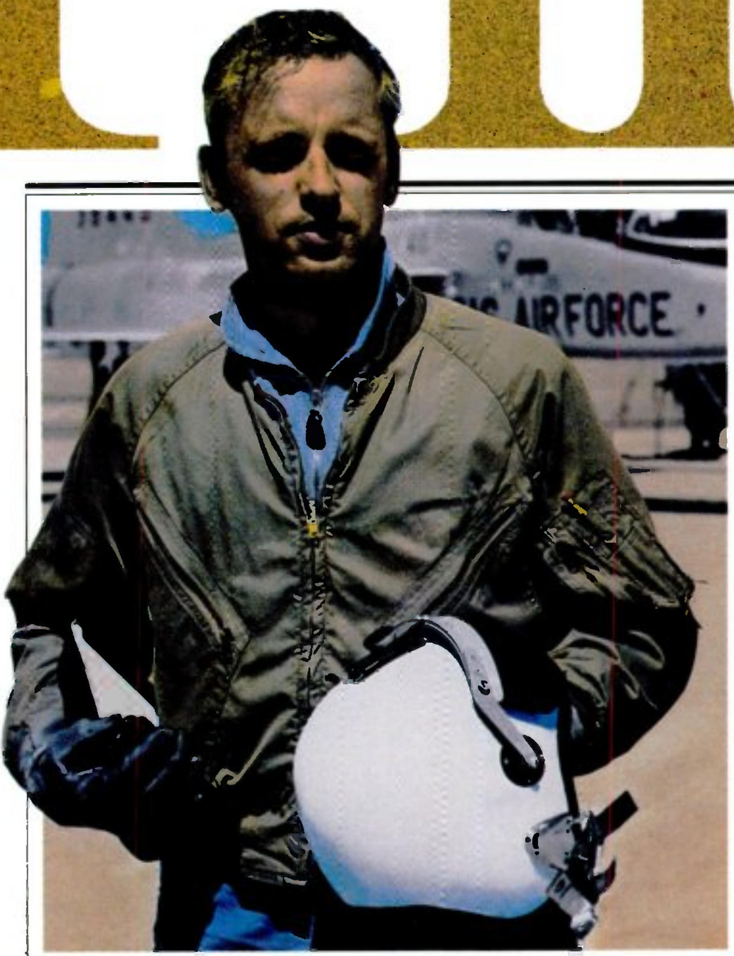
It sounds like one of the important things about your job is putting the human element back into the engine, and by doing that you can really make a difference.

That's it. We're not into flight test because we think it's a great idea, but because our customers think it's a great idea. They want engines proven in flight, not just in test cells. You may learn 90% of what you need in a test cell, but that last 10% is sometimes kind of painful. The GE36 airflow was a good example. It turned out to be very different on the aircraft than in ground test. We had no way to know that without a flight test program. All the dynamics of real airplanes, you just can't get in a test cell.

How did you get into flight testing for GE?

Well, you know a lot of things in your life happen by accident instead of the grand design. After the Air Force I went back to finish school. I was in the library one day and I read this ad in

Pilot



LARSON WITH THE F-5E, EDWARDS BASE, 1970

Aviation Week—"major company needs test pilot." It didn't even tell who it was. I just tore out a piece of paper and scribbled a note and sent it off and forgot all about it. About the day I graduated I got a call from the General Electric Company, and was I interested in going to work for them?

That was in Schenectady. They were the original flight test organization for GE. In fact they did all the original engine tests—the engines were sometimes carried around underneath other airplanes, B-29s, B-50's, and B-45's, that sort of aircraft. Later, as the flight test business gravitated to Edwards, I moved west with it.

I understand that shortly after you came out here, flight test got kind of sleepy. Yet you chose to stick around during what can't have been a very rewarding period. How did you come to decide that?

I came out to Edwards and we were quite busy for close to 10 years. Then the Air Force decided it wanted to do its own testing. At about the same time, many at GE weren't sure we needed to be in the flight test business. We periodically go through that kind of evaluation. I stuck around hoping things would get better, and eventually they did. It took a while: maybe I should have done something else. But as it turned out, the past five years have been the most interesting part of my career with GE.

Flight test must really be your thing, to go through a long dry spell like that. Why flight test? Why is that something that you, Russ Larson, want to be in?

Test Pilot

Because it's not routine, that's one reason. There's always something new going on as opposed to just flying from point A to point B in an airplane. Also, I had a technical background and interest in aircraft and engines. So test flying turned out to be kind of natural. I think the bottom line in being a test pilot is, where else could you get a job you would enjoy so much and somebody would pay you for it?

Did you always want to be a pilot?
I grew up on a farm in the midwest, and I suppose I might be a farmer today, except for one thing... I had to milk the cows when I was a kid. I thought, "Lord, get me out of here. No way am I ever going to do that!" So I got out and looked around for a couple of years. I saw a recruiting poster with a pilot heading off into the wild blue yonder, and I thought, "That looks better than what I'm doing now. I oughtta try that." So I signed up. That was in 1949.

The impression that I've gotten about test operations in GE is that you guys labor way out here in isolation, nobody knows you're here unless something goes awfully wrong.
Well, there's some of that. One of the reasons we survive in the business is we get all the panics out somehow. We are hard working, 7 days a week, 24 hours a day when that's required. They don't do that every place.

Between the UDF™ and Voyager, this place has had a lot of publicity. All of a sudden you've got cameras out here, the international press corps, airframers and foreign dignitaries. What does that do to the way you run your shop?
It really hasn't changed a lot. We're kind of an independent little operation here. We try to take things in our stride.

I know that flying is a big part of your job. But isn't the engineering management part of your job just as important?
Now I manage the flight operations and the quality operations both here at [Mojave] and in Edwards. So I am responsible for flight planning, for certifying airframes and training for air crews. I've got the quality functions plus the engineering, and flight safety—that's part of my concerns, to make sure we run a safe operation. No matter how good you are, you have to run a safe operation. Some people think flight testing is a pretty wild bunch, but in actuality it is a pretty conservative operation. We can't afford to do anything else.

What makes a good test pilot? What are the characteristics?
Today you have to be technically competent. You also need good powers of observation and analysis. Most of the glamour is gone from flying, so it generally comes down to long hours and hard work like many other jobs. You have to be willing to do that. Of course, it takes some kind of feel for airplanes. Some people have a feel for airplanes, and some people don't, even though they are pilots. You can do a lot of things in a mechanical sort of way, but some things you have to have a feeling for. You have to have some...or you really couldn't do it very long.

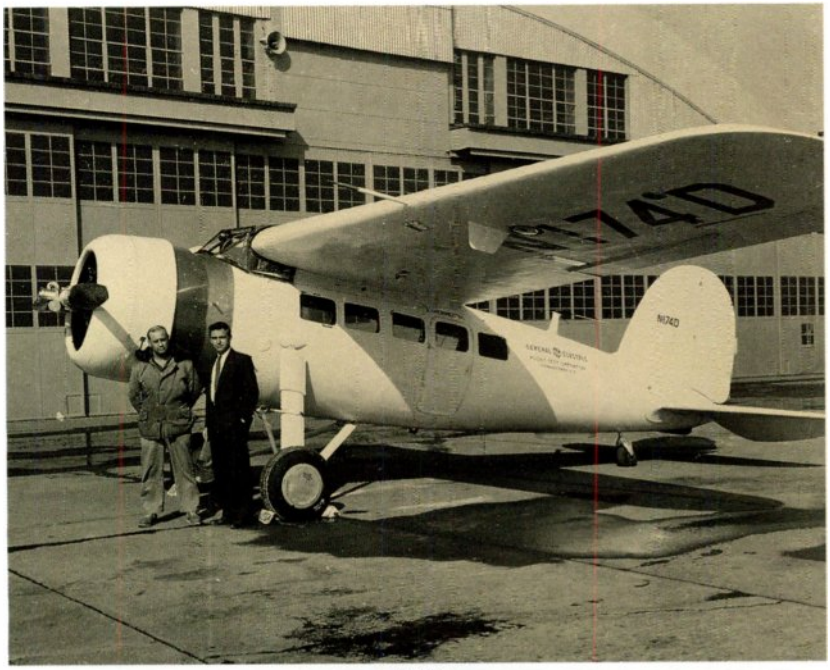
Who's the best pilot you know?
I guess I don't recognize a best pilot. There are lots of good pilots, and most of them you never heard of. It's a hard question to answer. We're kind of specialized these days, like everybody else. Everybody works in a fairly small niche, and you get people who do an excellent job in this little place and others who do a good job somewhere else.

What is your niche?
Well, I do a lot of different things. I suspect that compared to a typical test pilot that I have done a wider range of testing than most. I've done a lot of different things on a lot of different airplanes. Fighters, sail planes, widebodies, big airplanes, bombers...

Out of them all, do you have any standouts? A sort of personal best and worst?
The worst would have to be the Lockheed Vega we flew when I was in Schenectady. When we first got that Vega it had mechanical brakes on it as opposed to hydraulic brakes, and you had no control over the tail wheel at all, so it was really a bear on the ground. The brakes were like bent over water pipes coming up out of the floor and the rudders were similar pipes. The problem was that they weren't connected together. You'd land and the thing got squirrelly, so you pushed the rudder in and hoped it made an impression. If that didn't work, you were in big trouble, because now your foot was up there and the brake was way back here and there was no way to reach the brakes. It also had very poor visibility from the cockpit.

> "There's always something new going on, as opposed to just flying from point A to point B in an airplane."

What were you testing that airplane for?
We got the airplane because it had very little radar reflectivity,



LARSON, RIGHT, WITH THE LOCKHEED VEGA, CA. 1956: "It's about the coldest I've ever been in an aircraft...it also had very poor visibility from the cockpit."

except for the big engine. The plane had wooden sides, and we radiated out a lot of energy through the wood. One of the problems was that we started out doing this in summer time, but come winter they wanted to fly the aircraft at 20,000 feet. It turned out we couldn't fly in the daytime because it interfered with TV channels or something. We'd start after midnight and stay till the sun came up, cramped and cold. It's about the coldest I've ever been in an aircraft. A remarkable airplane in its day.

How about the best?
The F-4 was a good airplane. It was a fun airplane, an airplane that performed many missions well. It had great performance. It had the J79 engine, which turned out to be one of the great fighter engines, partly because it had extensive in-flight testing.

Let me tell you another story. One day somebody issued a test request to fly the F-4 to maximum altitude. I took that fairly seriously. I did considerable research, trying to figure out what the best way to do it was. The idea was to get all the kinetic energy you could by going flat out in level flight at an altitude which would give you the best airspeed. Going downwind would add maybe another 100 knots. When you have maximum airspeed rotate to about a 45° climb angle. By doing that, I went up to 93,000 feet.

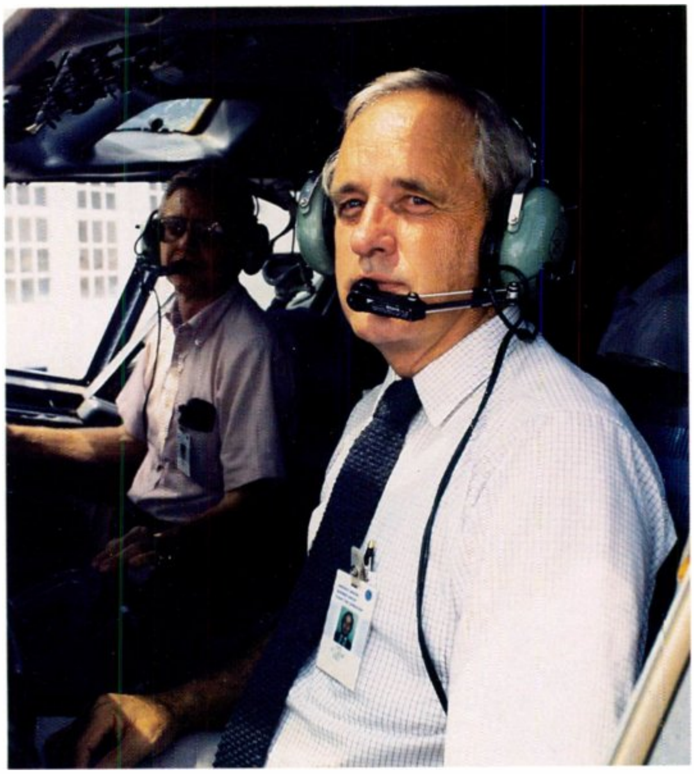
Of course, I shut the engines off—they can't run up there, there's not enough oxygen and just the minimum fuel flow pushes the temperature way up. But in the pressure suit it was kind of hard to move quick enough, I guess. Anyhow, when I got back down, one of the engines had some overtemperature damage. It didn't have a lot of life left in it. They asked me, "why did you go that high?" Nowadays our flight plans are spelled out a little more carefully.

You have an Engineering degree, don't you?
I have a mechanical engineering degree and I have a master's degree in engineering management. I took computer courses at UCLA for a while. I enjoy going to school, even if it's not something that's directly applicable to your job. I even signed up for a course in yacht design once.

A lot of engineers are really strongly goal-oriented. Yet increasingly GE management is stressing process, the quality of our working life, as well as the tasks we accomplish. If process and goal are on the ends of a line, where do you fit along the line between them?
I guess I'm still primarily goal oriented, but I may have a lot more control over process—my own process, at least—than a typical engineer does. I have a pretty unique job at GE. I don't have too many people coming around telling me how to do my job. I think I'm very lucky in that respect.

Test flying is a very measured business, flying under set conditions to test specified parameters. Yet you seem to get kind of impatient with too many rules. Care to comment?
Yeah, well, I keep thinking we ought to have a rule that you can't pass a new law unless you eliminate an old one.

One last question. Here's your chance to stand on a soap box. What would you want to leave our readers with?
I've worked at GE for a long time, and I think GE has been very good to me, given me a lot of opportunities. If I had chosen to do something else, there were enough opportunities at GE to go on to something different. I'm happy with the way my career turned out. I've had a unique job and an interesting job. Most of the interesting things that happen sort of happen on the spur of the moment...you just wake up in the morning and see what the day will bring. ■



PILOTING THE UDF™/BOEING 727 TEST AIRCRAFT, FEBRUARY 1987

Artificial Intelligence–

A new productive design tool

by
Carol J. Russo


C.J. RUSSO

"Artificial Intelligence" (AI) conjures up visions of JOSHUA in "War Games" or HAL in "2001," computers running out of control. Such images are profitable for Hollywood, but what about the real world of engineering design? Could AI be useful today in designing components for such complex systems as jet engines?

This was the question that a small group of engineers and computer programmers in Aircraft Engines/Lynn and Corporate Research & Development (CR&D) in Schenectady set out to answer. We already knew about some AI programs, such as massive "expert" systems like XCON, which Digital Equipment Corporation uses to configure its VAX and PDP-11 computers to a customer's needs, and the GE-developed system called CATS which diagnoses operating problems for diesel locomotives. These AI "expert" systems were composed of massive lists of logical statements (rules) that told the program how to "think" through a given problem such as 'If the car won't start and you are not out of gas, then check the battery voltage.'

Such systems are called "expert" because they capture in their lists the experience and knowledge of highly trained persons. Expert systems were highly successful but required many man-years and millions of dollars to develop. They also required significant work to update the massive rule bases that tell the computer how to solve the chosen technical problem.

The expert system approach was clearly not attractive for designing complex jet engine components for Aircraft Engine's diverse applications. Our engines range from very advanced turbofans like the UDF™ to new application areas like vehicular turboshaft engines for tanks. There is no such thing as a "garden variety" jet engine whose design rules can be neatly listed.

If it was impractical to give the computer all of the rules used to design a jet engine, one might still supply a small set of basic design rules for a specific component and tell the computer to use them to run design analysis codes. This approach would mimic the experienced design engineer's repetitive iterations of the analysis codes—tedious but necessary steps in studying trade-offs to reach an optimum design. At the same time, the user could have maximum control over this process by building in direct and easy access to the design rule base, to the set of parameter constraints that guided the iterations, and to the results of the iteration process itself.

Our idea was to build a generic shell that could be applied to many different analysis codes without major reprogramming while avoiding a "black-box" program. In this way, the experienced design engineer could apply the judgment necessary to balance performance against development risk—judgment which is the key to a successful design. The potential productivity benefits appeared enormous if the resulting tool were properly focused on the key engineering tasks and if the design rules and AI programming techniques chosen could drive the iteration process efficiently.

Project Parameters

The next step was to choose for our project an engine component and set of analysis codes that were simple enough to be driven by a relatively small set of rules, yet complex enough to require the resolution of conflicting multi-disciplinary goals such as aerodynamic performance and mechanical stress and life goals.

The preliminary design of a centrifugal compressor offered the right scope. In practice, designing a centrifugal compressor requires several hours to explore a range of potential aerodynamic centrifugal stage designs, followed by several days of mechanical analysis to determine if the impeller disk will have acceptable stresses and life.

We fed the computer a small, fast-running set of preliminary design aerodynamic codes with a limited set of driving design parameters. The primary mechanical analysis code was ANSYS which, although relatively large, was a mature code with an automatic meshing feature (shown in Figure 1) which enables a rapid analysis of the disk geometry.

Still needed was a program that would look at the aerodynamic design and specify a reasonable impeller disk geometry for analysis by ANSYS. This program would also have to allow rapid modification of the disk geometry keyed to the geometric parameters driving the mechanical stresses. An added benefit to developing this program would be an immediate and significant reduction in the time required to identify a good preliminary design for a centrifugal compressor even before the AI shell becomes available.

A pilot project was launched in late 1985. A close collaborative effort evolved between software engineers at CR&D lead by Dr. Siu Tong and preliminary design engineers at Aircraft Engines/Lynn. The results were surprisingly good, and the project has opened a whole new field in computer-aided design.

Getting Started

The first task was to define the list of design rules for the beginning analysis code in a typical design sequence (CENTCAL in this case). The design rules had to reflect the basic physical laws governing the aerodynamic performance of centrifugal compressors modelled in CENTCAL in order to apply to most applications. A total of 46 rules such as "to increase efficiency, first try to increase backsweep" were listed in order of priority.

These rules were used together with a set of maximum and minimum constraint values such as "maximum backsweep angle is 55 degrees" for each important parameter in the aerodynamic analysis code. The user could easily change the values of these constraints to reflect specific application requirements or could choose between sets of "canned" values typical of production or advanced technology designs.

> Dennis Nicklaus at the GE Corporate Research & Development facility christened the AI program ENGINEOUS

The next step was to develop a set of strategies the AI program could use to search for a design meeting a user-specified goal such as "maximize efficiency" while staying within the specified set of constraints. These search strategies had to enable the AI program to:

- explore variable changes where dependencies were not given in the knowledge base
- combine rules to change more than one variable at a time
- sort proposed variable changes in order of "most likely to improve the design"
- backtrack around input values that cause the analysis program to "bomb"
- when an optimum design was found, to continue searching for a better design for some limited range of input values in case the design found is only a local optimum.

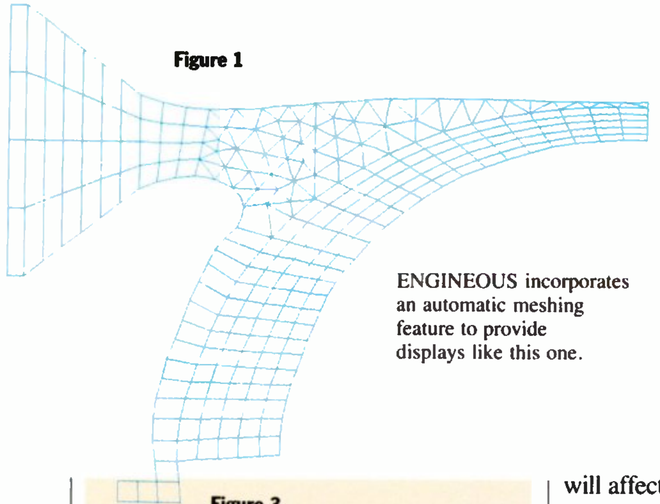
The search strategies were developed by Dennis Nicklaus at the GE Corporate Research & Development facility in Schenectady as part of his second assignment in the GE Software Technology Program (see references 1 & 3).

From the outset, the team was concerned that ENGINEOUS, as Dennis christened the AI program, be straightforward to use and be able to work with other analysis codes. To make ENGINEOUS effective, a sophisticated user interface was designed in from the beginning.

ENGINEOUS operates in three menu-driven modes. Users make choices, and ENGINEOUS handles the internal manipulations, providing the results in the form of graphs of key variables and their constraints.

The three modes ENGINEOUS uses are:

Figure 1



ENGINEOUS incorporates an automatic meshing feature to provide displays like this one.

MODE A
• Bring design within default or user-selected constraints
MODE B
• Optimize design with user-specified variables and goals
MODE C
• Perform a single or multiple parameter study with or without optimization at each step.

Mode C is particularly important because it allows the user to see quickly where in the design space the optimum design lies and to see how trade-offs in key parameters will affect the desired goal. This insight is critical because the final design must be balanced for both performance and development risk—a solution which is often less than the mathematically optimum design.

Initial Results

Several months of work went into writing and de-bugging ENGINEOUS using a sample centrifugal design case. Finally, the day arrived when the program was ready to test. In March, 1986, two new on-the-spot test cases were brought to CR&D. These

Figure 2

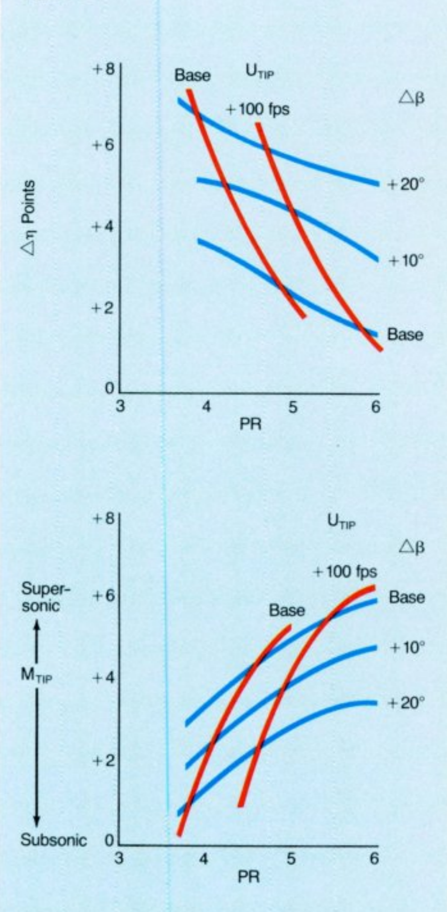


Figure 3

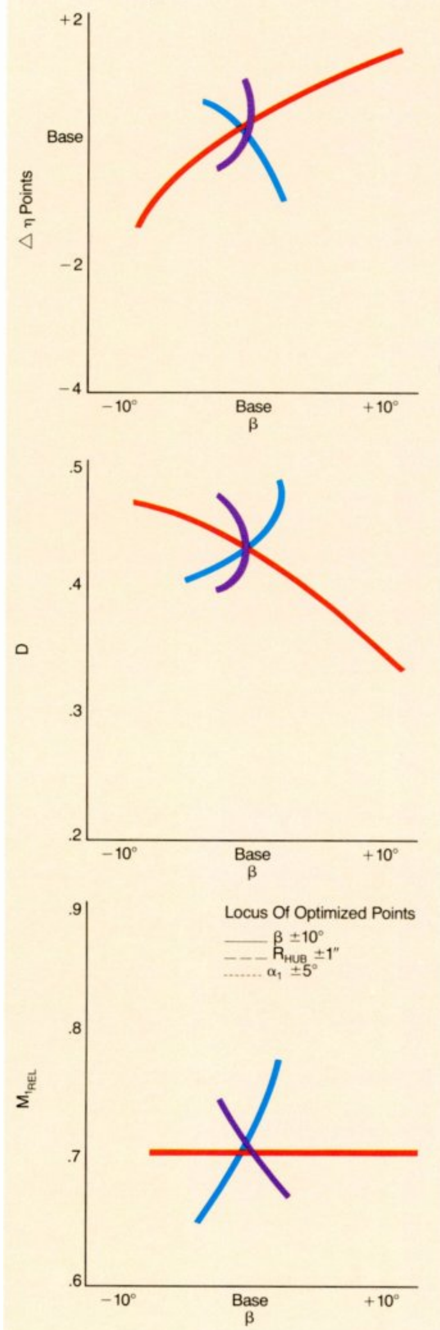
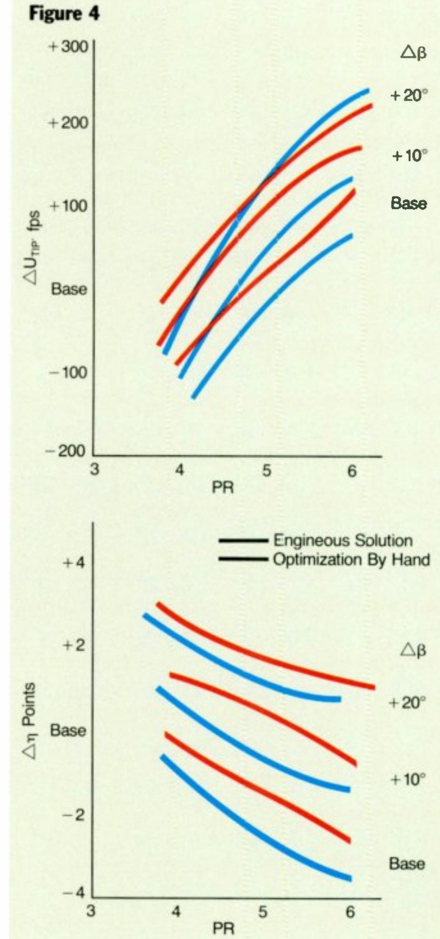


Figure 4



Figures 2, 3, 4: Results obtained by ENGINEOUS. See text for detailed explanation.

cases had been iterated by hand by an experienced centrifugal compressor designer but were new to the CR&D staff. We hoped that ENGINEOUS would optimize the efficiency and arrive at the same final design as the experienced engineer.

ENGINEOUS did much more. It found two designs that were equal or slightly higher in efficiency than the experienced engineer's design, but which were significantly lower in impeller diffusion factor—a prime aerodynamic risk parameter. The experienced engineer had stopped iterating at a higher diffusion level, believing that some compromise was necessary for the higher pressure ratios of these two compressors. ENGINEOUS went right on iterating, varying the same parameters as the engineer, and in 20-30 runs had uncovered two better design choices.

This initial result was very encouraging. The program was easy to set up and run, but much more testing was necessary before any general statements about ENGINEOUS could be made with confidence. Therefore, a systematic matrix of over 100 test cases was laid out.

Findings

The results of the initial cases run with ENGINEOUS iterating on only one analysis code (CENTCAL) are discussed in some detail in (2). Some key findings are:

• ENGINEOUS will iterate to the same optimized solution from widely different initial starting points.

• ENGINEOUS often iterates to non-obvious solutions even for simple goals like "maximize efficiency."

• The parameter study option turned out to be a very powerful tool which could rapidly produce graphs like those in Figures 2 and 3. It could significantly improve on optimization-by-hand studies as shown in Figure 4.

• As the number of goals and variables is increased, the number of iterations ENGINEOUS requires remains reasonably small and varies linearly with the number of variables as shown in Figure 5.

Some of the test cases had multiple, conflicting goals such as "maximize efficiency and minimize tip speed" to simulate the addition of mechanical goals such as minimizing impeller disk weight. The test matrix was extensive enough to draw some general conclusions about some advantages of using AI search techniques to design turbomachinery components.

Advantages

AI offers a number of advantages for designing turbomachinery components. These include:

• A flexible and powerful user interface relieves the user from any need to know symbolic programming languages such as LISP.

• The solution path and key quantitative parameter relationships are visible both during and after the optimization, allowing the user to gain confidence in the solution and to apply more qualitative judgments such as development risk.

ENGINEOUS can improve on designs iterated by an experienced designer, particularly for unfamiliar applications

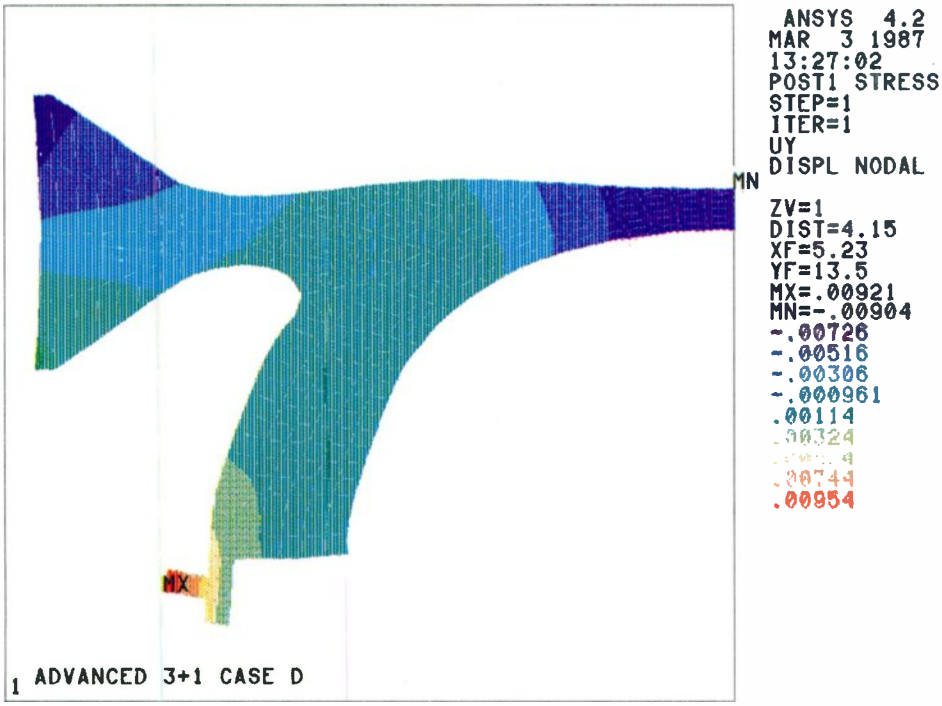
• Many more design options and parameter trade-offs can be explored in a given period of time.

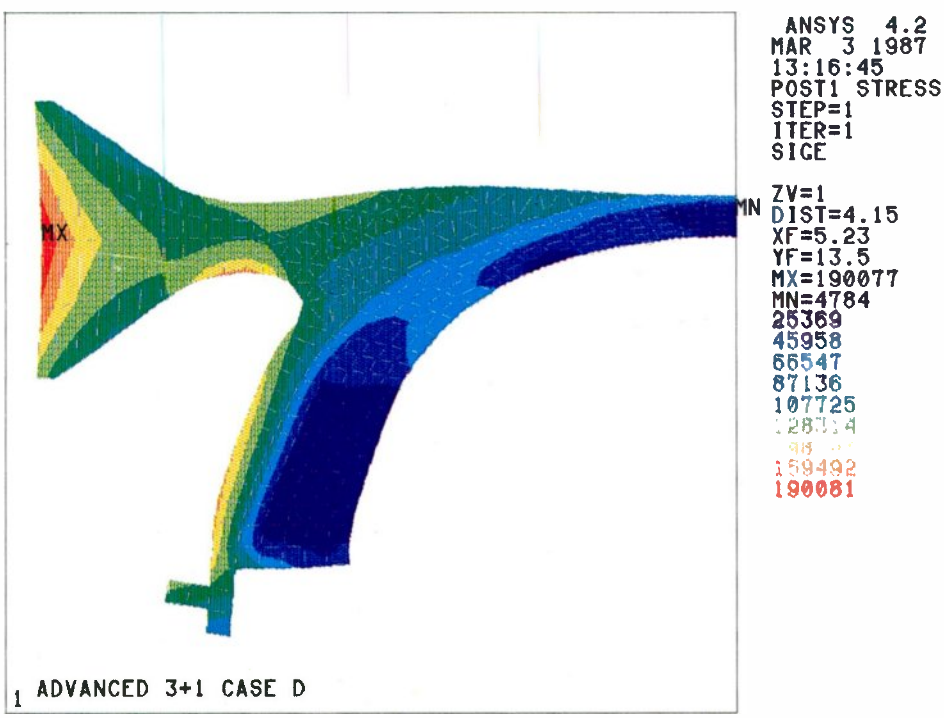
• An inexperienced designer can quickly gain an understanding of the parameters driving a particular design without lengthy trial-and-error runs.

• ENGINEOUS can improve on designs iterated by an experienced designer, particularly for unfamiliar applications.

• Design rules for specific applications can easily be added without reprogramming.

• The shell can couple design codes from multiple disciplines such as aerodynamics





and mechanical design to effectively balance inter-related and often conflicting goals.

• ENGINEOUS can easily recover from a run that "bombs" the analysis code and can avoid local optima.

• The AI search and optimization techniques are efficient for 1-D analysis codes with the number of iterations varying linearly with the number of variables.

Potential Problems

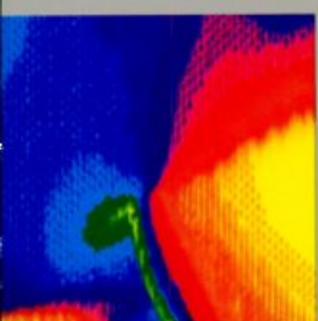
For all of AI's virtues, there are some potential problems worth noting. First, there needs to be on-going teamwork among software and design engineers before and during the development of an AI design program. Close cooperation is essential in order to use the AI techniques to the greatest advantage and to build in the needed flexibility and functionality. The user interface is a major source of the productivity gain AI techniques can provide.

Numerical optimization techniques offer mathematical assurance that at least a local optimum has been found, but AI techniques lack this assurance. Care needs to be taken to ensure that the AI search techniques do not stop prematurely because not enough logic has been included to explore the design space adequately. A good matrix of test cases should highlight any premature AI optimization problems.

Continued on Page 29

Top: Regions of constant effective stress are color contoured with red the maximum stress at the bore center. Areas where geometry needs to be modified are immediately obvious to the design engineer. In the ANSYS version of ENGINEOUS, rules on allowable stress will be used to modify the disk geometry for adequate life and minimum weight.

Bottom: Regions of constant cold-to-hot displacement are color coded with red the maximum displacement. Of critical importance is the displacement of the blade surface immediately under the fixed shroud to maintain tight clearances and the displacement of the impeller exit for proper alignment with the following diffuser. Acceptably small and well-distributed displacements are key to an efficient design.



C

LIVING WITH A SUPER-COMPUTER

Photo by Bill Strode

The Cray X-MP/28

The Arrival of the CRAY

IN 1985, A GE TASK FORCE DETERMINED that the resources of a supercomputer were vital to continued leadership in many of the Company's advanced-technology businesses. At the same time, many engineers in GE Aircraft Engines were beginning to push the limits of the available computers; computer analyses were running days or even weeks on existing systems, and there were requirements—notably in hypersonics and in designing the UDF™—for even more advanced analyses. Anything less powerful than a supercomputer simply could not do the job.

In early 1986, to meet the growing need for advanced, high-speed computing capabilities, Aircraft Engines ordered a CRAY X-MP/28 supercomputer from Cray Research, Inc. Delivery was scheduled for the third quarter.

In the interim, Aircraft Engines forged an agreement with Boeing Computer Services (BCS) which enabled engineers and scientists to buy CRAY time from BCS at very favorable rates. The relationship with BCS not only satisfied the immediate need for supercomputing, but also facilitated education, training and program conversion and optimization. This preliminary experience proved to be very beneficial, and when the GE CRAY became fully operational on October 6, 1986, there was an existing base of experienced CRAY users.

GE's supercomputer is located at the Governor's Hill complex, about 12 miles northeast of the Evendale plant. The CRAY is installed in a steel-encased, radio-frequency-(RF) shielded computer room approved for secure processing.

The GE CRAY is a two-processor system with 8,000,000 words of main memory and 32,000,000 words of solid-state storage. The system is configured with 20 high-capacity disk drives having a total on-line storage capacity of 24 million bytes. Eight IBM cartridge tape drives handle data. Users access the system through IBM, Honeywell, VAX or Apollo front-end systems, which are connected to the CRAY with very-high-speed data channels. (For details of this network and access system, see Mike Tomsho and Robert Healey's article next in this section—Ed.)

The CRAY has tremendous speed and capacity. It can perform an instruction every 0.5 nanoseconds, yielding performance over two times that of the original CRAY 1 supercomputer. While actual performance depends on the type of application being run, typical single-processor performance comparisons range from 200 to 400 times faster than a VAX 11/780, the standard engineering computer used in Aircraft Engines before the arrival of the CRAY. The CRAY not only performs existing computational analysis in a fraction of the time, but it also enables the analysis of larger and more complex designs that could not be run on conventional computers. (For examples, see "Designing with the CRAY," later in this special section—Ed.)

By allowing us to use more sophisticated computational design and analysis tools, the CRAY will significantly contribute to Aircraft Engines' ability to compete in the commercial and military markets. In addition, the CRAY serves as a resource to other GE businesses, including the Corporate Research & Development establishment in Schenectady. In the nine months since the CRAY was installed, the turbomachinery aerodynamic design and structural analysis groups have achieved impressive productivity improvements in engine design techniques. Similar advances are expected from other GE users.

BY JEAN A. BUCKLIN

CRAY ACCESS

WITHIN MOMENTS AFTER THE OFFICIAL opening of the CRAY on October 6, 1986, engineers at Aircraft Engines' Lynn, Massachusetts plant were sending jobs to it.

Lynn began preparing for the CRAY in the early spring of 1986, when the decision to buy the supercomputer became firm. By mid-year, Computer Aided Engineering (CAE) in Lynn began performing benchmark testing over low-speed (9600 bits per second, or bps) communications links through Evendale's Gateway VAX to Boeing Computer Service's CRAY in Seattle.

Concerns Identified

The computer performed well, but it was immediately obvious that file transmission times and methods for accessing the CRAY were going to be a concern. The analysis time saved by the computational speed of the CRAY was being offset by slow transmission of large data files. As a further deterrent, it appeared that engineers in Lynn would have to master complex methods of job submission over a network of intervening processors. The key to Lynn's successful utilization of this powerful new computing resource required improvements in transmission time and ease of access.

Improving Communications Speed

Lynn's engineering network was already well established when it was announced that the CRAY was coming. CAE's engineering network consisted of a wide range of processors and communications links to other GE sites throughout the continental United States. A high-speed, fiber optic ETHERNET link between CAE's twin VAX 11/785 computers in Lynn's building 2-40 and the Lynn Computer Center's Gateway VAX in building 59 was providing access to the IBM, IBM/FPS array processor and Honeywell mainframe via the computer center's Multi Computer System (MCS). Engineers had been routinely

FROM LYNN

BY
MICHAEL E. TOMSHO
AND
ROBERT V. HEALEY

performing file transfers and remote job submissions on these systems since early 1985. Starting in June, 1986, we began adapting them to handle the CRAY.

By early July, Aircraft Engines/Lynn had established dedicated 19,600 bps communications telephone links between the Gateway VAX in Lynn and the Gateway VAX systems in Cincinnati. The Gateway systems in Cincinnati act as "front ends" for staging jobs and data being submitted to and brought back from the CRAY. In early 1987 the speed of the Lynn-Cincinnati link was increased to 56,000 bps. The network is shown graphically in Figure 1.

Plans are under consideration for upgrading the Lynn-Evendale link to a very high speed, on the order of 1,400,000 bits/second.

Supercomputing made EASY

Overcoming the second hurdle, accessing applications on the CRAY, meant providing a straightforward, easy-to-use method for submitting jobs and getting the results back. The process of transferring files to Evendale, getting them into the CRAY, submitting a batch job to the CRAY, and getting files all the way back to the Lynn CAE VAX could easily become a nightmare of undecipherable computer commands, special hardware, uncertain job status, and long delays in the mind of the engineer who is trying to meet design deadlines. After investing hundreds of hours in mastering VAX, IBM, APOLLO, and Honeywell command languages, the prospect of having to learn yet another operating system's command language was certain to meet with less than enthusiastic acceptance.

Lynn CAE recognized this problem in early 1985 and began developing the EASY system (**E**ngineering **A**ccess **SY**stem). This system was specifically designed to free engineers from having to become computer and network experts in order to transfer files or run programs on our multiply interconnected systems. The amount of knowledge required to run an ANSYS solution on a wide selection of operating systems on the IBM, the IBM/FPS array processor or any VAX system in the network is about the same. Using a menu-driven interface, engineers need only enter the names of input and output files, authorization data such as user ID's and charge numbers, run control data in the form of maximum run times, print and plot options, etc, then enter the command to continue. From there EASY performs all the computer-to-computer tasks invisibly and swiftly: the engineer is immediately free to do other tasks.

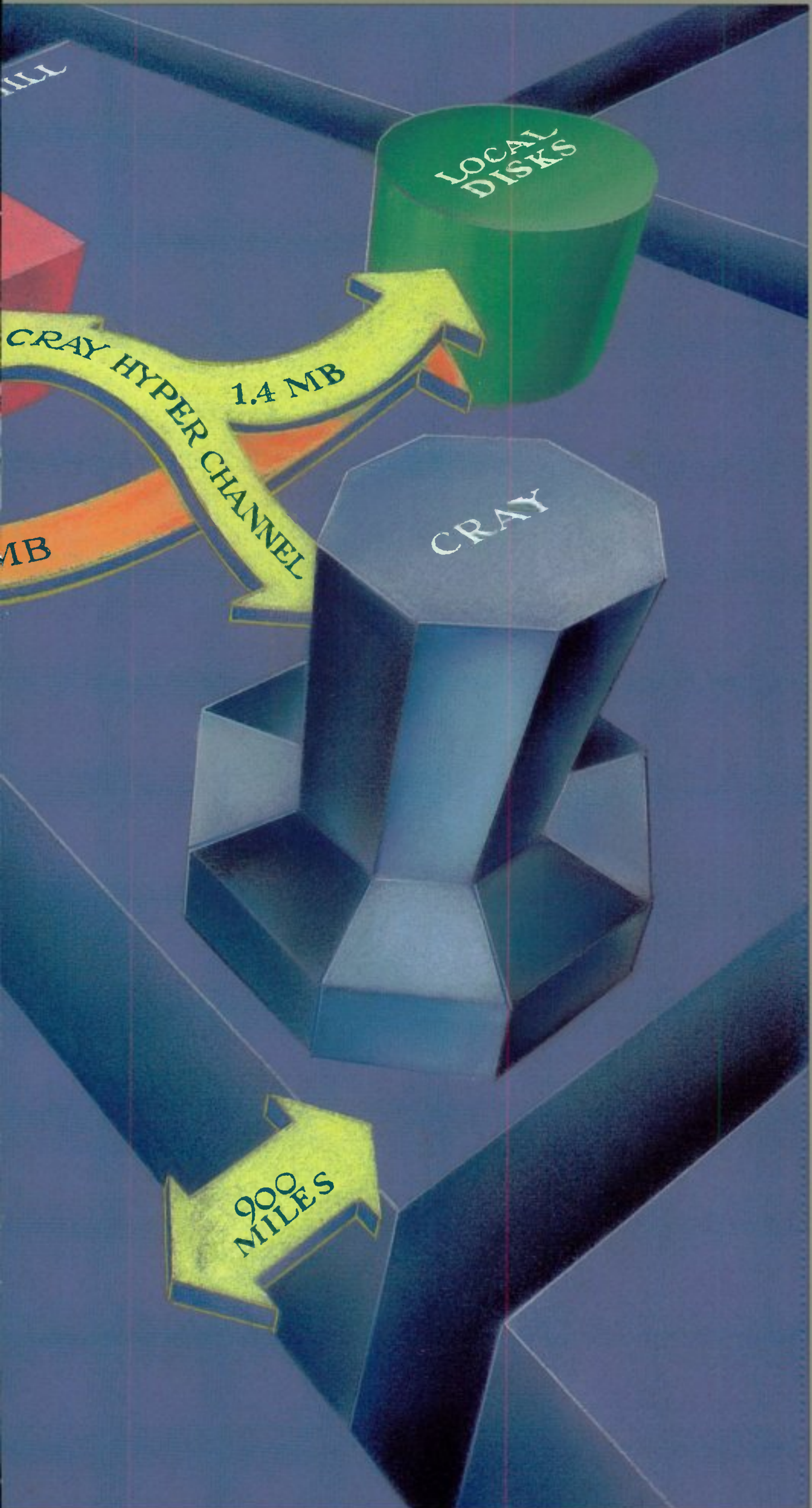
Since the EASY system was already in place and working well, it was only natural to extend its capability to include the CRAY. Within a few months, the menu-interface and all background system procedures necessary to provide access to the ANSYS and EULER3D codes on the CRAY were developed and put in place. New applications can be added quickly using template command procedures developed for ANSYS and EULER3D. Integrating TRIAD2D access on the CRAY required less than a day's effort.

Desk Top Access

Each EASY application interface is intentionally simple to use. Engineers can type in answers to easily understood queries. These are presented in a series of menus which are accessible from the engineer's own desk-top terminal.

EASY automatically stores the user's input data each time, so that once entered, it can be recalled from data bases when the user performs the next run. For security reasons, passwords required to run on each of the different systems are not stored and must be reentered each time. All remaining input information is retained so that a series of submissions (parametric studies, for example) can be made with a minimum of retyping. EASY also has an extensive structured HELP


LYNN COMPUTER CENTER
FPS
IBM
HONEYWELL
HYPER CHANNEL
MASS NET
GATEWAY VAX
5.6 KB COMM LINK
EVENDALE - GOVERNOR'S
GATEWAY VAX
FUTURE COMM LINK 1.4
HIGH SPEED FIBER OPTICS
LYNN CAC VAX CLUSTER
VAX 11/785
VAX 11/785
LOCAL DISKS



facility for on-line documentation describing both the EASY system itself, and each application program such as ANSYS or EULER3D. For example, typing a ? at a menu prompt provides a brief one-line description of the option in question. Typing ?? for the menu option displays a detailed, full-length description of the option. Often the single "?" HELP level is enough to remind the user what the menu option means. In addition to the HELP utility, EASY has its own NEWS library to keep engineers apprised of application-related information, network news and operations schedules.

Recovery from System Failure

A recurring nightmare for any engineer is to run an immensely complicated and important analysis requiring hours of computing time, only to have the system fail somewhere along the line. Failures can occur in any one of the steps along the way: file transmissions may be interrupted due to system or network failures. Often the engineer sees these catastrophes as long waits with no news, followed by a painful decision to resubmit the job.

EASY allows users to recover from such failures without starting over again from the beginning. In fact, every step of the process is tracked and recorded. The engineer can query the system for an up-to-the-minute status report at any time. For instance, the status report might say that the input files arrived safely in Evendale, and that the CRAY completed the run successfully, but that the network failed while the output files were being transmitted back. Ordinarily, this would leave perfectly good (and expensive) analysis output data stranded on the Gateway VAX in Evendale. However, EASY allows the engineer to restart the job exactly where it failed, with no loss of valuable analysis.

Thanks to careful pre-planning and the EASY access system, engineers at Lynn have a supercomputer at their fingertips. Nonetheless, continuing improvements are planned as we learn how to make full use of the CRAY.

Figure 1

DESIGNING WITH THE CRAY

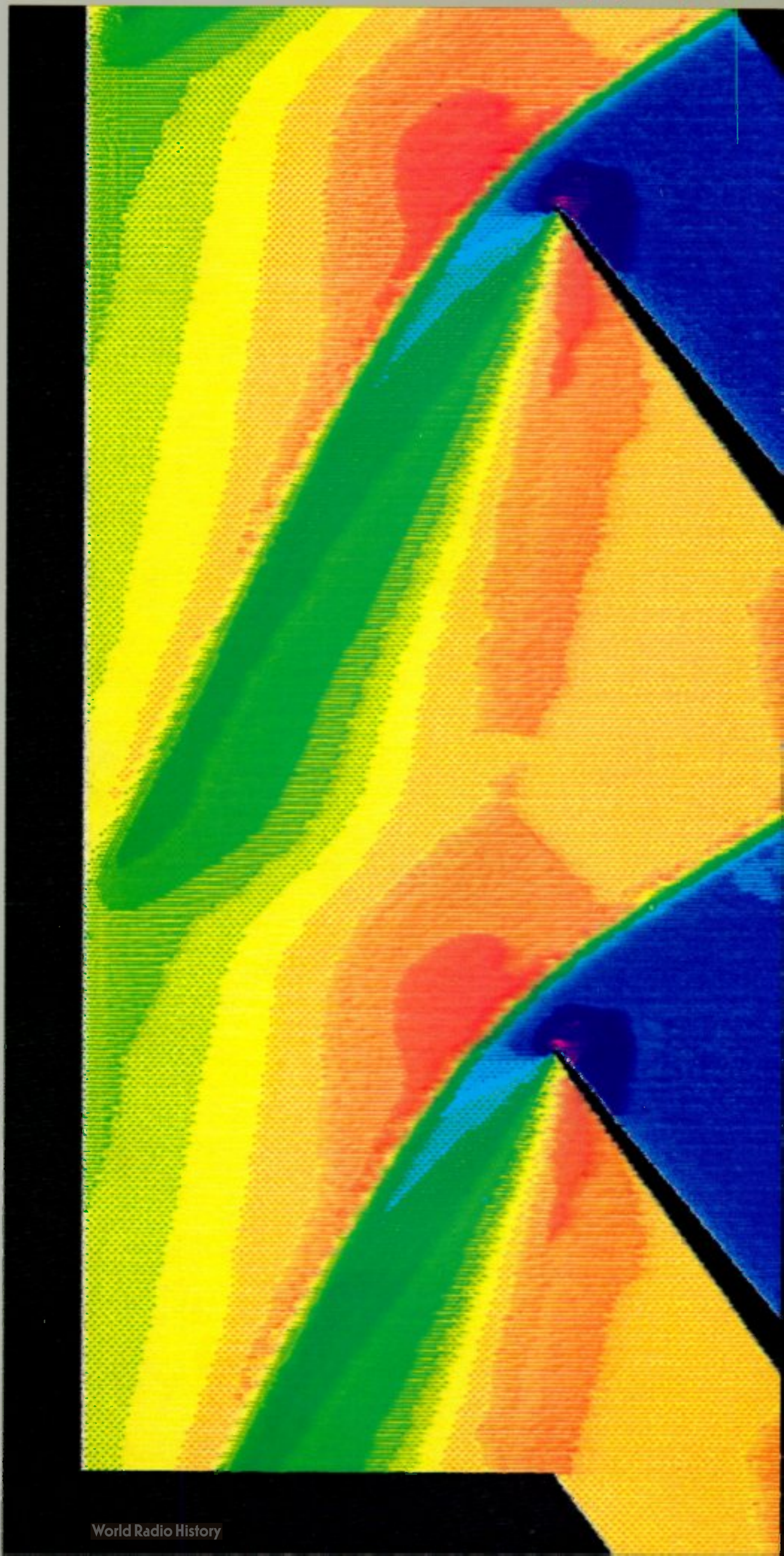
WITH THE ARRIVAL OF THE CRAY X-MP/28 at Aircraft Engines, the way aerodynamic design takes place is changing. By reducing the computing time required by applications programs, the CRAY has had two major effects: it has made it possible to run computational flow models that could not have been seriously addressed until now, and it has made more routine calculations almost interactive. Typical results can be obtained from the CRAY up to 300 times faster than from a VAX 11/780, a standard engineering design computer.

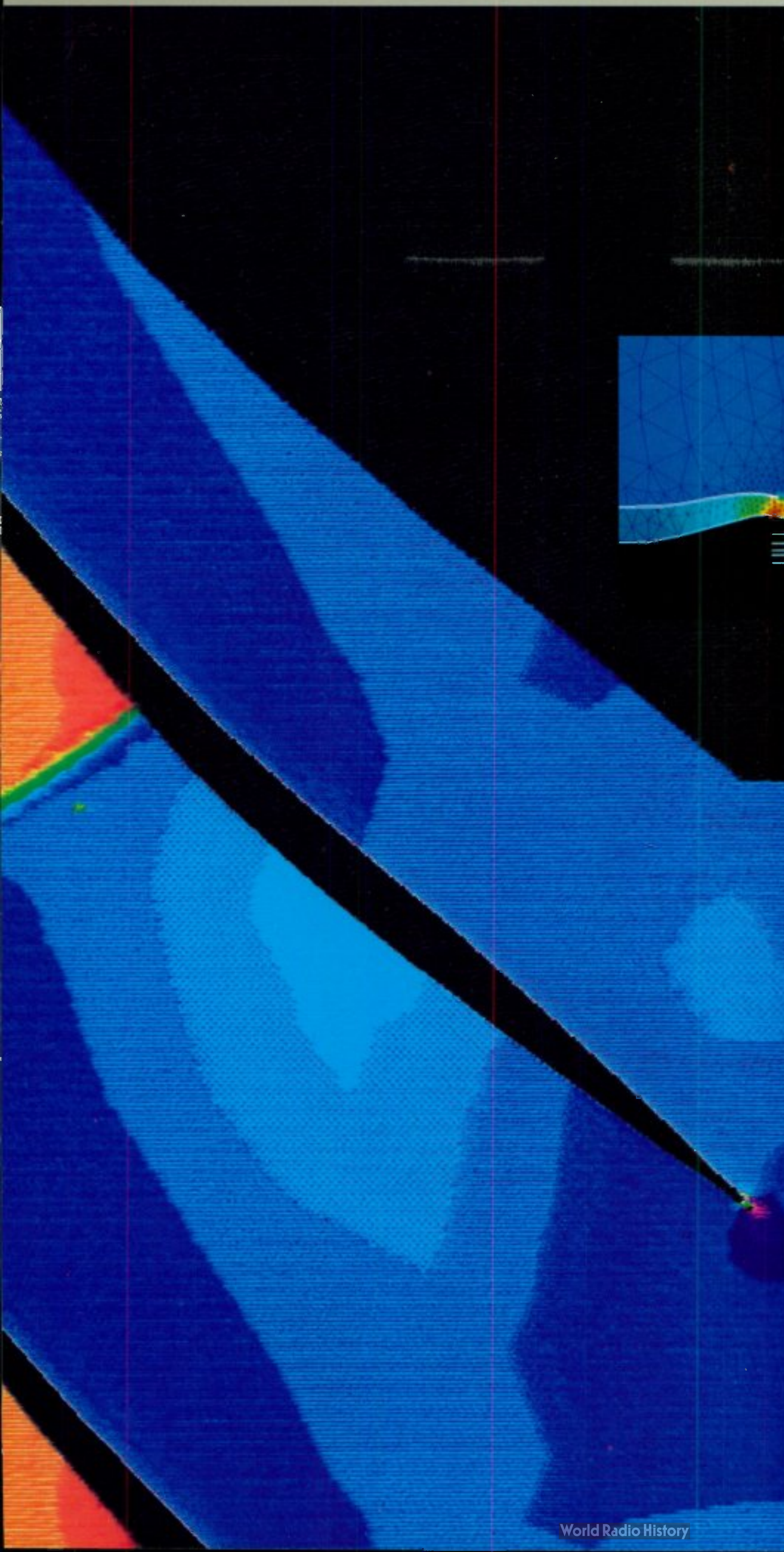
The aerodynamic codes currently used on the CRAY work in two or three spatial dimensions and can accommodate both inviscid approximations and viscous solutions. In general, as more dimensions or viscous terms are added, the codes become more complex and therefore more expensive to run. The TRIAD2D code provides an example. TRIAD2D models flow in two dimensions without allowing for viscosity. It is based on a triangular grid which adapts to the flow features by adding new triangles as the solution emerges. While TRIAD2D is intended for the blade-to-blade analysis problem shown in Figure 1, the use of triangles provides a very flexible geometry base, and the program is easily adapted to solve problems ranging from hypersonic inlet flows to exhaust flow-field studies as illustrated in Figure 2.

TRIAD2D could be run overnight on a VAX, but on the CRAY it is fast enough to be treated as interactive, requiring only a few minutes of processor time. The code's flexibility in handling various flowfields and geometries, coupled with fast execution time—made possible by the CRAY—have made it a popular tool with designers.

The ability to compute viscous flows adds extra complexity to analytic programs. Such programs were prohibitively complex before

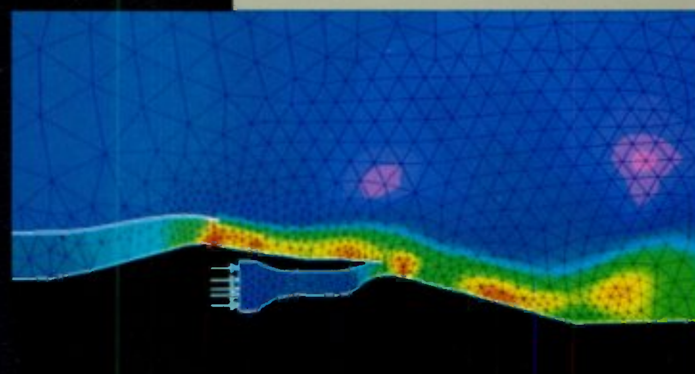
BY IAN K. JENNIONS





Left, **Figure 1**
Detached shock from compressor blade leading edge, shown in black.

Below, **Figure 2**
Free stream study shows triangular mesh.



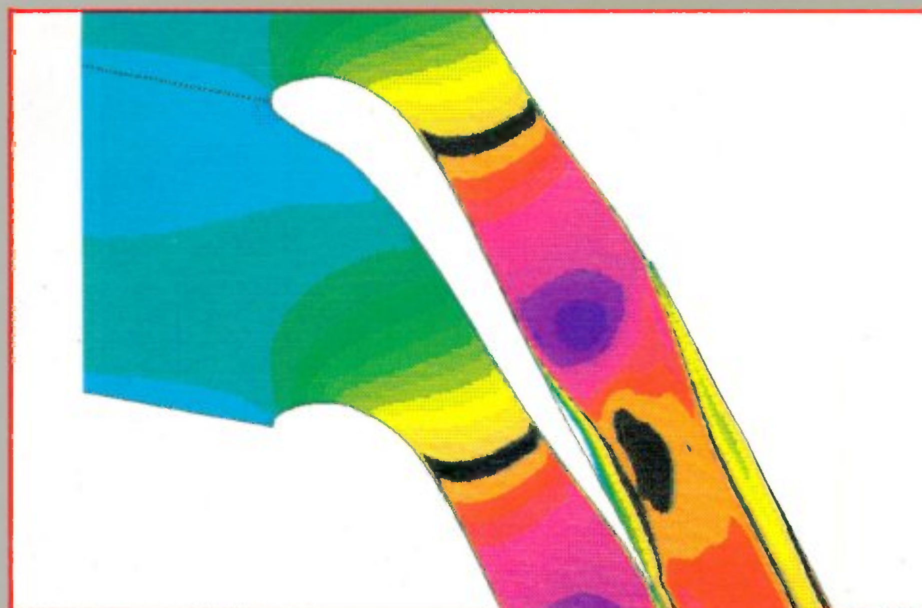
the advent of the CRAY; today, such programs are still experimental, but they are promising design tools. When viscous effects are added and we solve the full Navier-Stokes equations, features such as shock/boundary-layer interaction, wake formation and overall loss can be predicted.

BTOB is a two-dimensional code which can predict such features; a recent study of a high exit Mach number is presented in Figures 3 and 4 as an example. The design flow is shown in Figure 3, while the off-design flow illustrated in Figure 4 is obtained by increasing the back pressure (decreasing the exit Mach number). In this off-design condition the flow is forced to produce a shock wave in order to meet its new exit conditions. This shock impinges on the suction surface of the blade and rips the boundary layer off the surface as seen in Figure 4. While this illustration is qualitatively correct, truly accurate models of this complex flow feature remain in the future.

EULER3D is a program which places still more reliance on the CRAY's speed. During the course of the UDF™ design, EULER3D was used extensively. It computes the full three-dimensional flow through the counter-rotating blades of the UDF™ with the simplification that the fluid is assumed to have no viscosity.

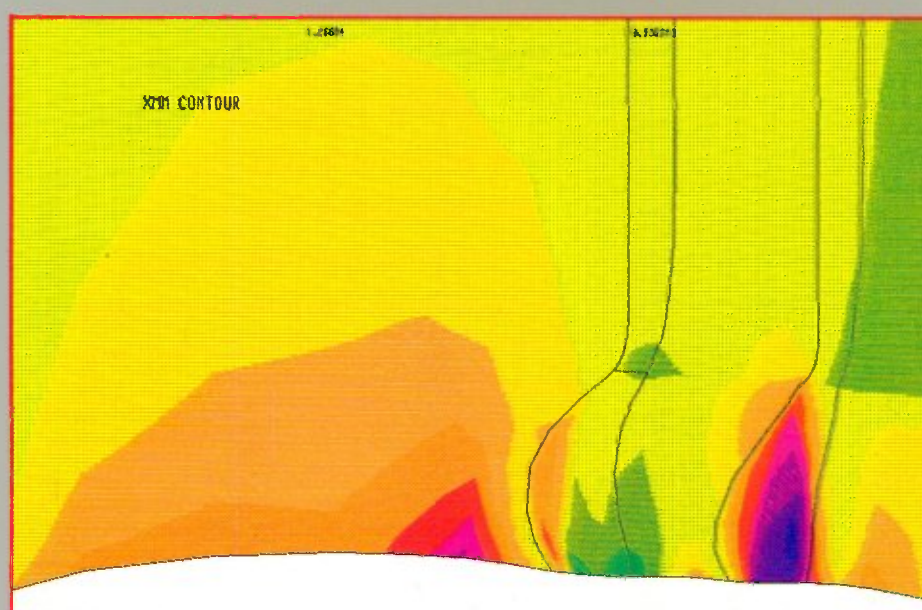
The design approach for the UDF was essentially the same as that used for ducted turbomachines. The complete flow is built up by superimposing two or more basically two-dimensional flowfields. The first and principle solution is a through-flow analysis (Figure 5) which treats the circumferential average flow; mathematically, the solution is axisymmetric and out of it come axisymmetric streamsurfaces.

Above, **Figure 3** Controlled Expansion Supersonic Airfoil (CESA). Turbine Nozzle Mach number is at design point.



Right, **Figure 4** Off-design M-exit = 1.2 showing reverse flow suction surface.

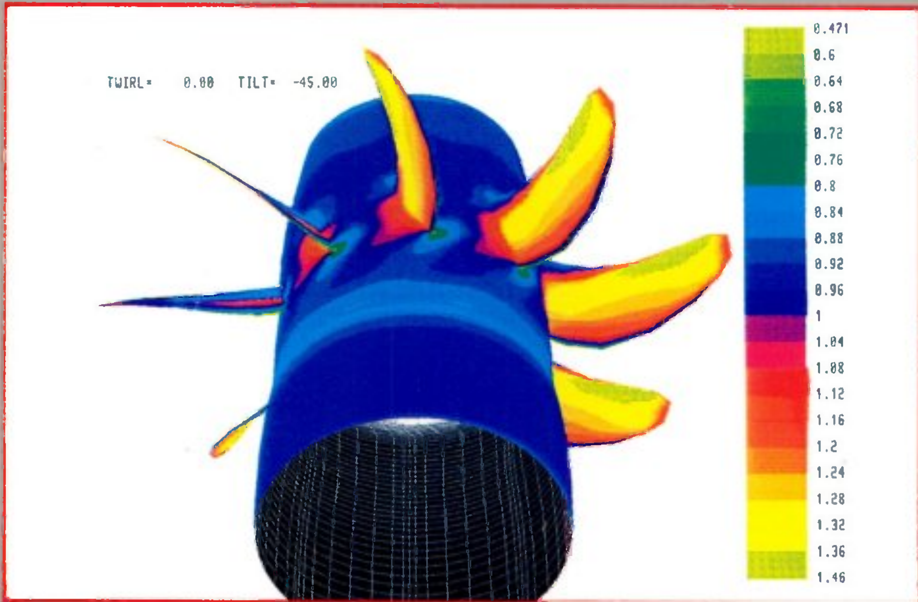
The airfoils being studied are designed on these streamsurfaces using blade-to-blade analyses like that shown in Figure 1 or cascade concepts. Recognizing three-dimensional secondary flow effects which deviate from the flow calculated by the quasi-three dimensional method, the design process stacks individual airfoils to generate the blade shape. The final check on the design is done by running EULER3D for each blade row; the blade shapes are altered if necessary to achieve desirable surface loadings.



Right, **Figure 5** UDF Through-Flow (Side) View. We see transonic flow in 2nd rotor.

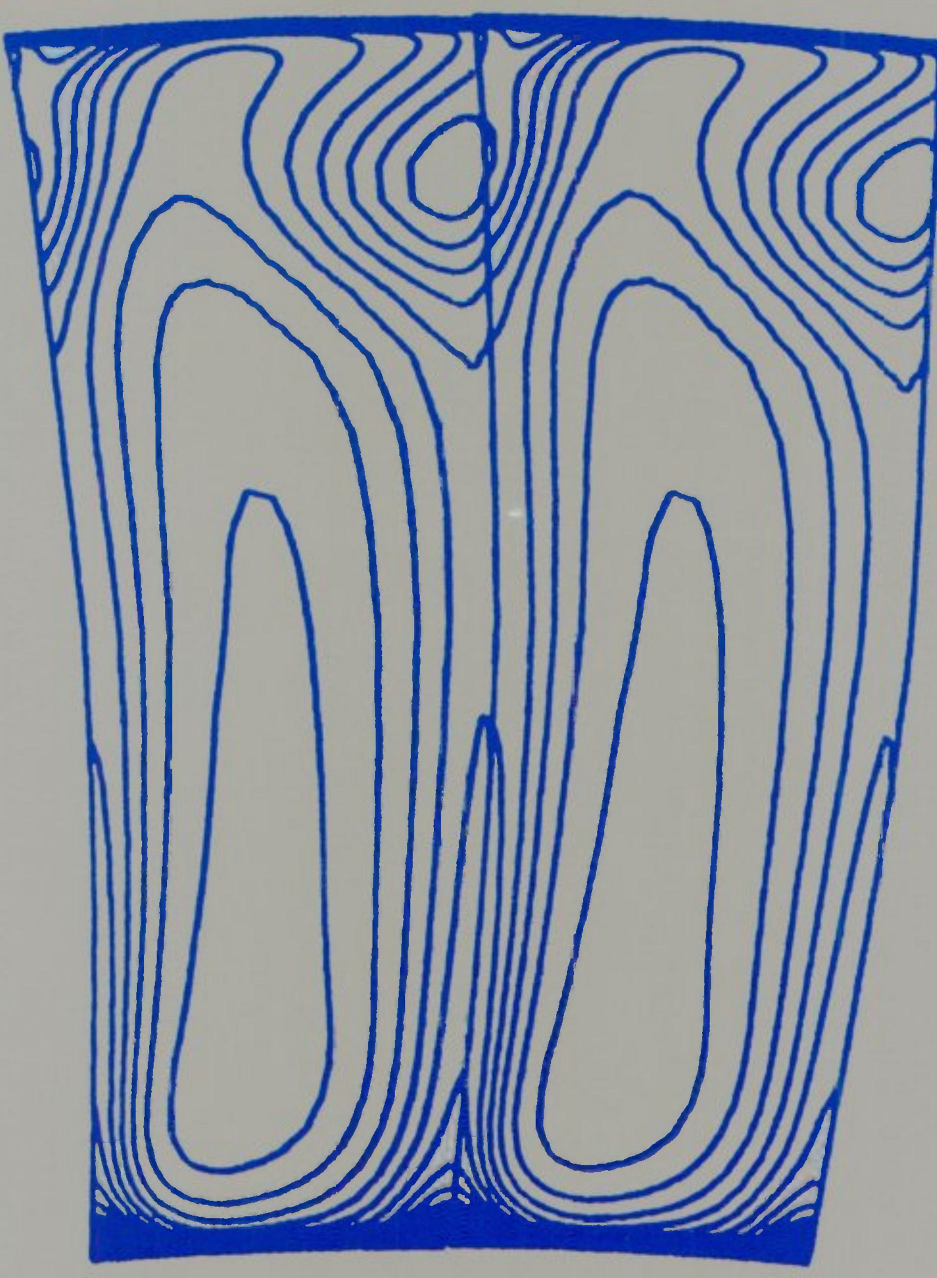
In the case of the UDF, the full three-dimensional flow is solved for each rotor by representing the other rotor on a circumferential-average basis, thus getting around the problem of the flow's being variable over time. A solution for the aft rotor with the forward rotor treated in this manner is shown in Figure 6.

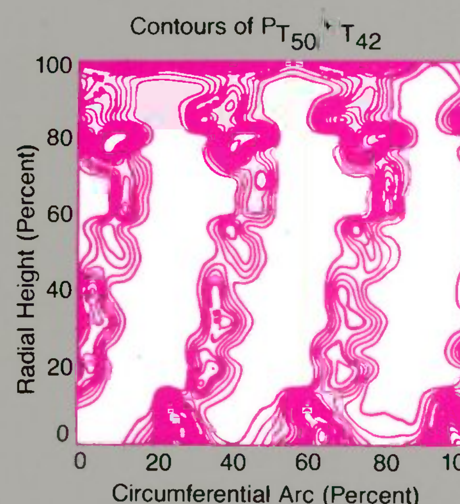
EULER3D could not readily be run without a CRAY since a fine-grid UDF solution using 140,000 grid points would use 40 minutes of CRAY processor time—or about 200 hours



Left, **Figure 6** EULER3D solution for aft rotor with forward rotor removed (treated as axisymmetric)

Figure 7 Measured (right) and computed (left) contours of total pressure in crossflow plane at downstream measurement site show good correlation.





on a VAX. EULER3D presents an inviscid solution; it can be seen that viscous solutions, some incorporating turbulence equations, are really possible only on a CRAY.

The HAH code is such a three-dimensional, viscous flow model incorporating a two-equation turbulence model. It uses two hours of CRAY time for a 64,000 grid-point solution, compared to 80 hours on an IBM 3081, no desk-top toy itself.

HAH is still being readied for use; pre- and post-processor codes are now nearing completion, at which time this code will be released to the design community for initial check out runs. Some preliminary case studies have been done on a turbine nozzle guide vane. Figure 7 shows a comparison of experimental and predicted data using HAH.

We are still learning how to live with a supercomputer. It is already clear, however, that both the productivity of the individual design engineer and the quality of the new designs coming along will be greatly enhanced by the order-of-magnitude improvement in running times offered by the Cray.

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Designing with the Cray

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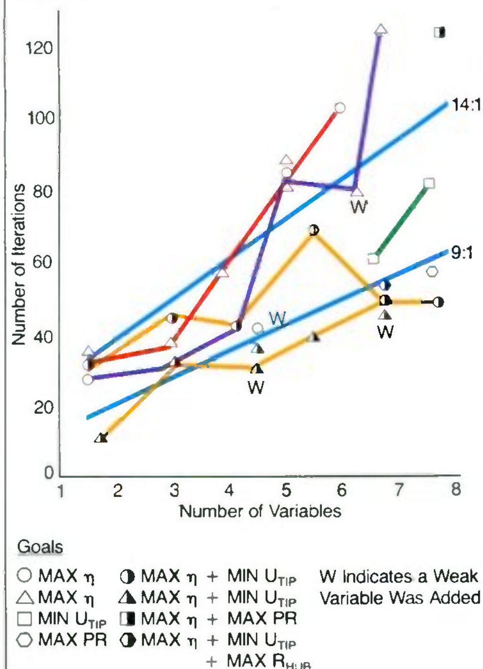
Continued from Page 16

AI

Figure 5



Applying the AI shell to iterate analysis codes with long computational times such as 3-D viscous programs is, at present, probably less efficient than direct input manipulation by a design expert. Sophisticated rules for searching patterns and deducing the required blade or flowpath shape changes are needed before AI search techniques can be effectively applied to such complex codes.

Effectively using the AI shell requires powerful workstations and new software licenses. It is not yet clear which hardware should be acquired to support extensive use of AI programs written in LISP coupled with analysis codes written in FORTRAN. ENGINEOUS was developed on a Symbolics work station which efficiently handles programs written in LISP but is slow to execute programs written in FORTRAN. Hardware which can handle AI needs to be included as soon as possible in the continuing upgrade of our computer facilities and capabilities.

Finally, considerable care must be exercised in deciding where AI programming should be applied. A clear and continuing dialogue among software and design engineers needs to be established and development plans cooperatively evolved to ensure that AI is applied where it will be most productive and practical. Otherwise, the expectations of engineers and management will not be realized and AI will be viewed as yet another expensive tool that doesn't deliver.

It appears certain that AI will play an ever-increasing role in airframe and engine design. The challenge will be to use AI to support the engineer in making key design decisions and to create flexible programs whose inner workings are visible to the user. The designer can then spend less time cranking out numbers and more time thinking creatively about the factors driving a particular design. It appears that AI can make designing jet engine components a lot more fun.

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AI Update

A user-interactive version of ENGINEOUS is now available on a Symbolics workstation. A design engineer without LISP programming knowledge can couple ENGINEOUS to a FORTRAN program, enter rules and parameters, and create an interactive AI program which will bring a design within constraints, optimize the design, and do parameter studies.

In addition, with mechanical design input from Tim Higgins in Lynn, the mechanical program DISKSHPE has been coupled to ENGINEOUS as a pre-processor to ANSYS and is being tested over a wide range of cases. The FORTRAN program linking ANSYS to DISKSHPE and to the centrifugal compressor aerodynamic programs has been written and is now being incorporated into ENGINEOUS.

In other AI work, ENGINEOUS has been extended by CR&D and Brent Gregory in Evendale to iterate the turbine aerodynamic analysis code TP3. A comprehensive shell called GEN-X has been developed for diagnostic analysis and troubleshooting. Other AI programs for manufacturing and engineering are also under development.

An AI Users Group has been in existence for over a year to disseminate new AI program experiences within GE/Aircraft Engines. The group is coordinated by Dan Shih and Danny Cornett in Evendale. Readers interested in AI are invited to contact them, or Carol Russo in Lynn, for further information. Dr. Russo's dial com number is 8263-1442.

MEASURING

Test rig for tracer gas experiments. Inset shows detail of manifolds.

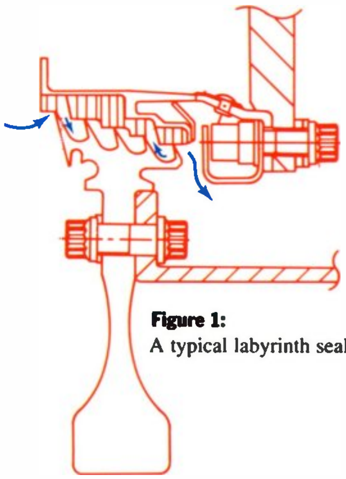

Figure 1:
A typical labyrinth seal

SEAL LEAKAGE

Labyrinth Seal Flow Measurement by Tracer Gas Injection

by William F. McGreehan, Fred G. Haaser, and Laurence T. Sherwood

Air losses in modern jet engines are a costly business. Even small leakage flow rates seriously hurt efficiencies. Consequently, it is worth substantial effort to improve the seals in any given engine. Because actual contact between rapidly rotating parts causes wear, non-contacting labyrinth seals, like the typical example shown in Figure 1, are commonly used in aircraft gas turbine engines. Labyrinth seals work by gradually reducing the pressure through a series of narrow openings; reducing the area of the restriction of any one step reduces the volumetric flow through the opening. Labyrinth seals are ideally suited to control leakage when large thermal and centrifugal growths exist between rotor and stator.

However, all seals leak, and it is both difficult and necessary to find out how efficient a particular design may be. This article describes an experimental method of measuring actual flow leakage in a labyrinth seal, as opposed to the theoretical or calculated value used heretofore: Seal flow characteristics have been studied extensively[1], but until now the difficulty of accurately determining running clearance has made performance evaluation of labyrinth seals an uncertain science.

Although in principle[2] leakage flow can be measured by standard pressure differential flow measurement techniques, this is an impractical method in high-speed, high-temperature gas turbine seals. The other traditional method, calculating leakage rates based on seal flow characteristics, has too much uncertainty; one is unsure of the actual seal clearance due to the large relative thermal and centrifugal growth of rotor and stator components. Often the growth of rotor and stator far exceeds the cold clearance, resulting in a great measure of uncertainty in the calculated operating clearance. In our experience, a calculated clearance range of 9 to 12 one-thousandths of an inch for the seal illustrated in Figure 1 is not unusual. This amounts to a 30% uncertainty in clearance and the associated flow.

To address the need for accurate seal flow data a new tracer gas injection technique is under development for on-line seal leakage measurement. When developed, such a system would eliminate the difficulties of measuring seal clearance. Initial testing of such a system suggests that plus-or-minus 10 percent accuracy is possible, compared to 30% uncertainty in calculated methods.

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F.G. HAASER

L.T. SHERWOOD

Background

Tracers have been used for many years to determine the existence of leakage in enclosed systems, to follow the course of flow streams, and to measure flows in pipes and ducts[3,4]. To be useful in aircraft engine

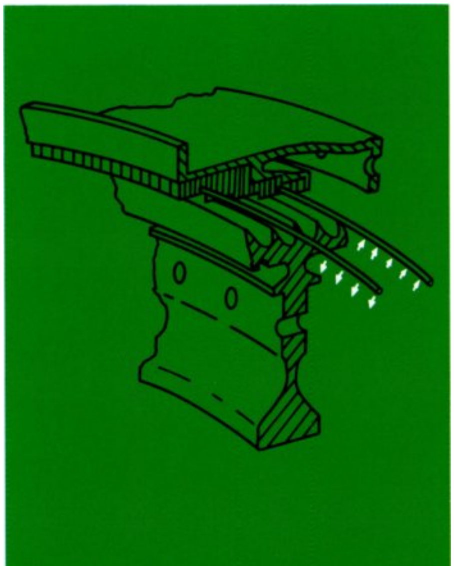

Figure 2: Test rig showing manifold installation

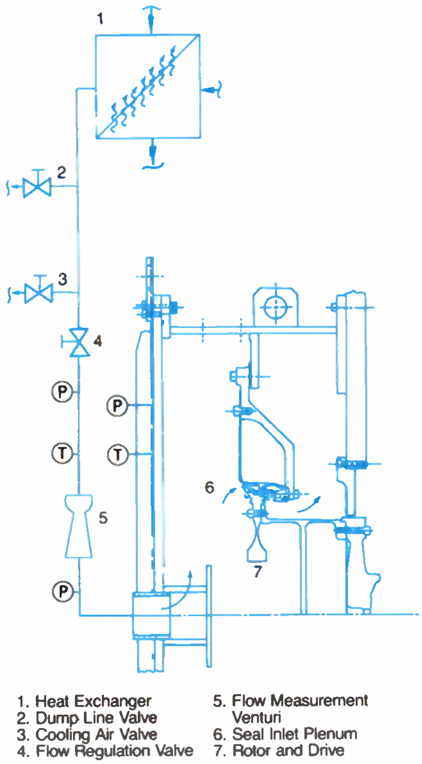

Figure 3: Gas injection system schematic

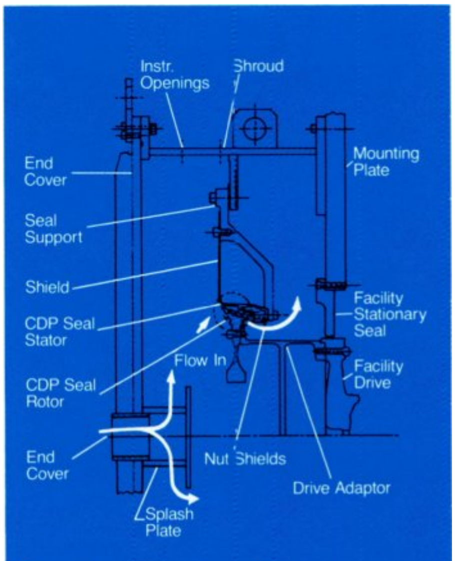

Figure 4: Test Rig Assembly

testing, leakage determination by tracer injection must be accurate and reliable while requiring no major modifications to engine hardware. Moore and Perkins[5] used a tracer injection technique to measure leakage through a labyrinth seal, but found the inferred flow to be inaccurate due to inadequate mixing of the tracer with the seal leakage flow. It was clear that for our experiments to succeed, complete mixing would be essential.

Measurement Method

The basic set-up we devised is shown in Figures 1 and 2; its operation is illustrated schematically in Figure 3. High pressure air, applied to the upstream face of the seal, leaked through the seal at approximately 0.25 pounds per second. Leakage flow rate was measured by a critical-flow venturi located upstream of the seal inlet plenum. A known flow rate of tracer was continuously injected into the first seal tooth pocket, and the mixture of air and tracer was sampled at the downstream tooth pocket. The leakage flow rate was calculated from the dilution of the tracer as it passed from the upstream to the downstream tooth pockets. The accuracy of the calculated value of leakage flow rate was evaluated at various speeds and operating pressure ratios.

Tracer Selection

To avoid a fire hazard, we chose carbon dioxide and helium instead of the more common ethylene, even though they mix less well. Although not the same density as air, they are non-hazardous, relatively inexpensive, and can be measured accurately. The amount of turbulence inside the seal, coupled with the injection manifold's design, provided adequate mixing.

Accuracy of Method

Accurate determination of leakage flow rate by the tracer injection technique requires: 1) accurate measurement of the mass flow of the injected tracer; 2) complete mixing of the tracer with the leakage flow; and 3) accurate measurement of the concentration of the tracer in the extracted sample. If the tracer is a constituent of the seal leakage flow (as is the case for CO_2), the mole fraction of the tracer in the leakage flow also must be known. The measured concentration of CO_2 in the leakage air with no tracer injected was approximately 350 parts per million (ppm) by volume.

The concentration C by volume of the tracer in the extracted sample is related to the mass flow rate X of the injected tracer and the mass flow rate Y of the seal leakage by the following equation:

$$C = \frac{X + YJ}{X + \frac{M_1}{M_2} Y}$$

where J is the fraction by weight of the tracer in the flow stream before any tracer is injected, and M_1 and M_2 are the molecular weights of the tracer and leakage flow without tracer, respectively. Since X is measured by the flowmeter, and C is measured by the gas analyzer, the leakage rate Y can be calculated from this equation.

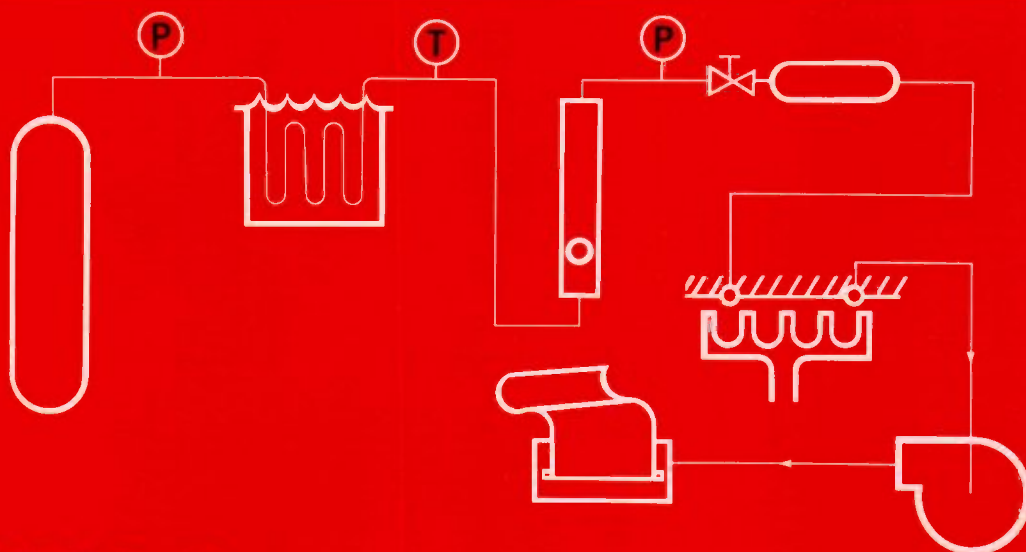

Figure 5: Regulating Tracer Gas Flow and Temperature

Apparatus and Instrumentation

The rig test assembly is shown in Figure 4. Air temperatures in the range of ambient to 600° F and pressures from 3 to 21 psig were used for the test. The variable speed rig drive was operated in the range of 0 to 15000 rpm.

Design of the tracer gas injection and sampling system is shown schematically in Figure 5. Tracer gas stored at high pressure was regulated to the desired pressure before passing through a room temperature bath. An accumulator downstream of the needle valve isolated the flow meter from fluctuating pressures in the seal. Flow was manually controlled by a needle valve downstream of the flowmeter to maintain a concentration of tracer between 0.5 and 1.0% by volume in the extracted sample in order to minimize disturbance to the leakage flow. This range of tracer level was sufficient to permit accurate measurement of concentration in the sample.

The sampling and detection system consisted of a sampling manifold and 15 feet of 0.125 inch o.d. tubing, a diaphragm pump, and a gas analyzer. Needle valves throttled the pump discharge to insure constant flow to the gas analyzers.

Gas Injection and Sampling Manifolds

Complete mixing is essential for accurate results. The injection manifold was designed to mix efficiently. Tracer was injected through numerous orifices located around the seal's circumference, and flow through the various orifices was equalized.

Figure 2 shows how the .060 inch manifold tube was installed. Tracer entered the seal through the upstream end of the manifold tube to feed the .010 inch diameter injection orifices.

Initial testing was performed with 18 and 12 orifices in the injection and sampling manifolds respectively. To determine if accuracy would be improved by adding more injection points, the number of orifices was increased to 24 and 18 in the two manifolds, but the 24-hole version showed too much pressure drop in the manifold. Eighteen orifices appeared to be a practical limit if uniform flow was sought.

Future tests will use a slightly larger tube with a limited number of orifices fed from both ends of the manifold. These changes should enhance uniformity of flow.

The sampling manifold, which was wrapped around the last seal tooth pocket, was similar to the injection manifold, but the number of holes was reduced to prevent "phasing." Phasing produces distorted concentrations of tracer due to incomplete mixing; to prevent phasing, the air in the seal must be retained for a longer time than it takes the seal to rotate. Reducing the number of holes in the sampling manifold to about 75% of those in the injector increased the dwell time somewhat, though tested dwell time was always smaller than optimum. The maximum dwell time tested was 0.0003 sec. versus a minimum rotational period of 0.004 sec. This implies that without multiple injection points the seal would not be able to generate sufficient mixing. Seal designs with more teeth,

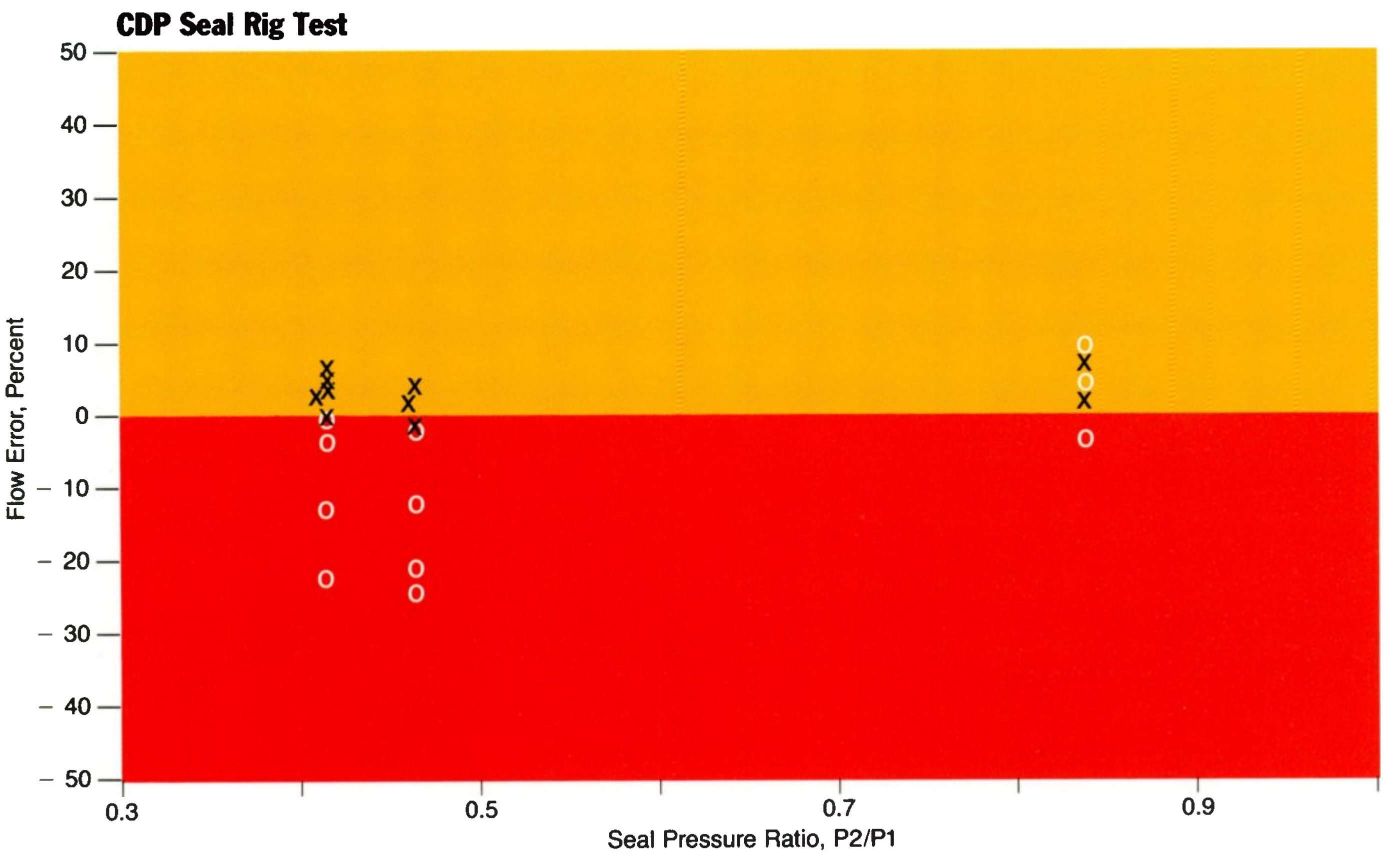

Figure 6: Gas injected into the plenum (x's) mixed better than gas injected into first seal tooth pocket.

longer length, lower pressure ratio, or higher face speed could show improved mixing.

The Tests and Their Results

Three different types of tracer gas injection tests were performed using the rig shown in Figure 3. A threshold test determined the threshold accuracy of the tracer gas flow measurement technique. Two other tests varied seal rotor speed and seal pressure ratio in order to test the effects these two variables had on the accuracy of the tracer gas calculated flow rate. The actual flow was measured by a critical flow venturi upstream of the seal.

Threshold Test

For threshold testing, tracer gas was injected into the facility flow pipe upstream of the seal inlet plenum to assure complete mixing of the tracer gas with the facility's air. A second run checked the results from injection straight into the first tooth pocket. Figure 6 illustrates the results. The x's show gas injected into the plenum; the o's show the results of injection in the first tooth pocket. The figure shows that, as expected, mixing and therefore accuracy are improved for upstream injection. Error from injecting upstream is less than +6%, compared to +22% for injecting into the tooth pocket.

Seal Rotor Speed Variation Test

Rotor speed was varied between 0-15000 rpm to determine the effect of rotational period on flow measurement error. The error is higher (up to +40%) for zero seal rotation. This result is due to the lack of mixing as discussed earlier. Some rotation appears to benefit accuracy, by improving mixing, but there is no increasing improvement as the speed increases.

Inlet Pressure Variation Test

During this testing the supply pressure to the seal inlet plenum was varied over the pressure ratio range 0.3-0.8 to assess the effect of tracer/leakage flow dwell time on mixing. The results are plotted in Figure 7. Pressure ratios closer to 1 would be expected to result in lower error and better mixing due to longer dwell time of the air within the seal. However, results did not always confirm this expectation, as in Figure 7.

Summary

Our experiments have shown that leakage flows can be measured using a tracer gas

'Testing is continuing… for use on a full scale engine test.'

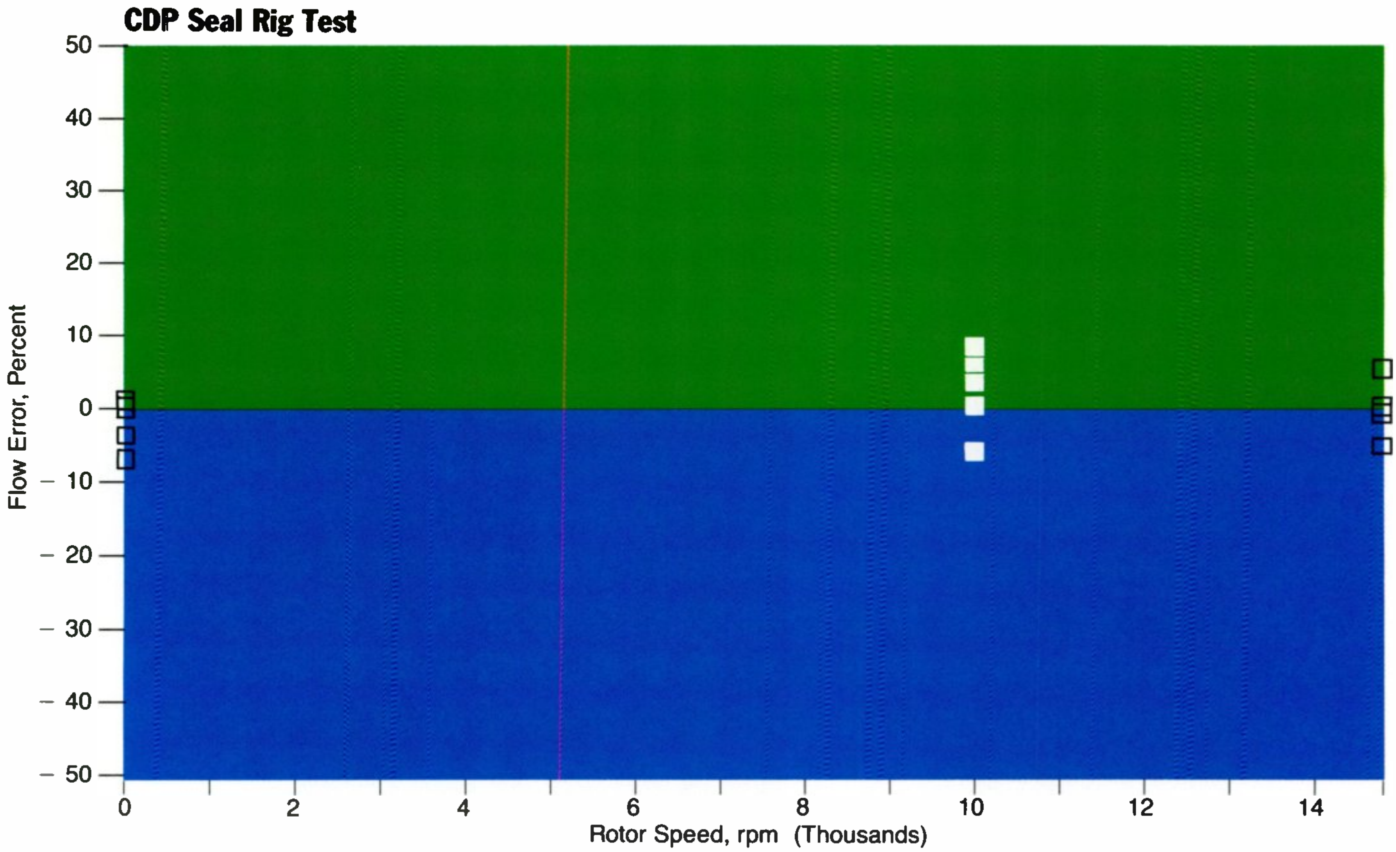

Figure 7: Extending dwell time did not necessarily improve mixing.

injection and sampling technique. The resultant error (rotating points only) was always within +16%. The ratio of dwell time to rotational period was found to be significant in terms of the influence on error. Optimum mixing takes place at short rotational periods with high dwell time (a function of seal pressure ratio). Mixing was often poor when the seal did not rotate.

Testing is continuing with the system adapted to use on a full scale engine test. The tracer supply system must be capable of operating at the high pressures necessary to inject into a region where the pressure is 350-400 psia. Injection and sample gases must pass through the distribution orifices at a temperature of about 1100° F as opposed to a supply at ambient temperature for bench tests.

Inside the engine the supply and sample tubes must be small enough to route through the support structure and connect to the seal fittings. Within the seal stator the mounting of the manifold tubes requires secure attachment to prevent dislocation in the proximity of the seal rotor.

Conclusions

These factors make the flow measurement process much more difficult than that traditionally required using pressure differential devices. Yet the tracer injection technique is presently the only one which offers the needed accuracy compared to flows based on predicted seal clearance. The additional cost and complexity are justified where there is a need to accurately determine the flow rate. ❑

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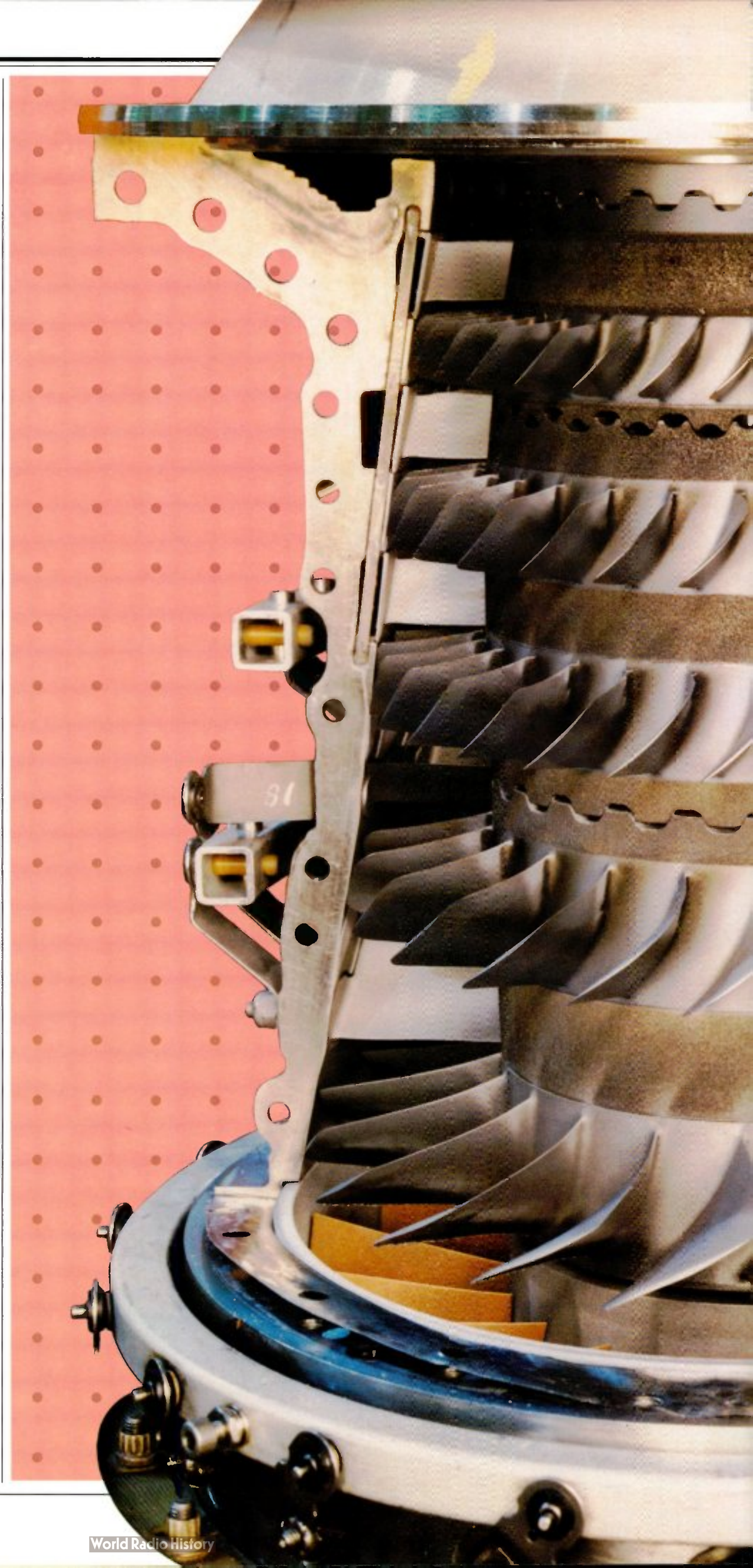
Coatings for Performance Retention

By
Robert V. Hillery



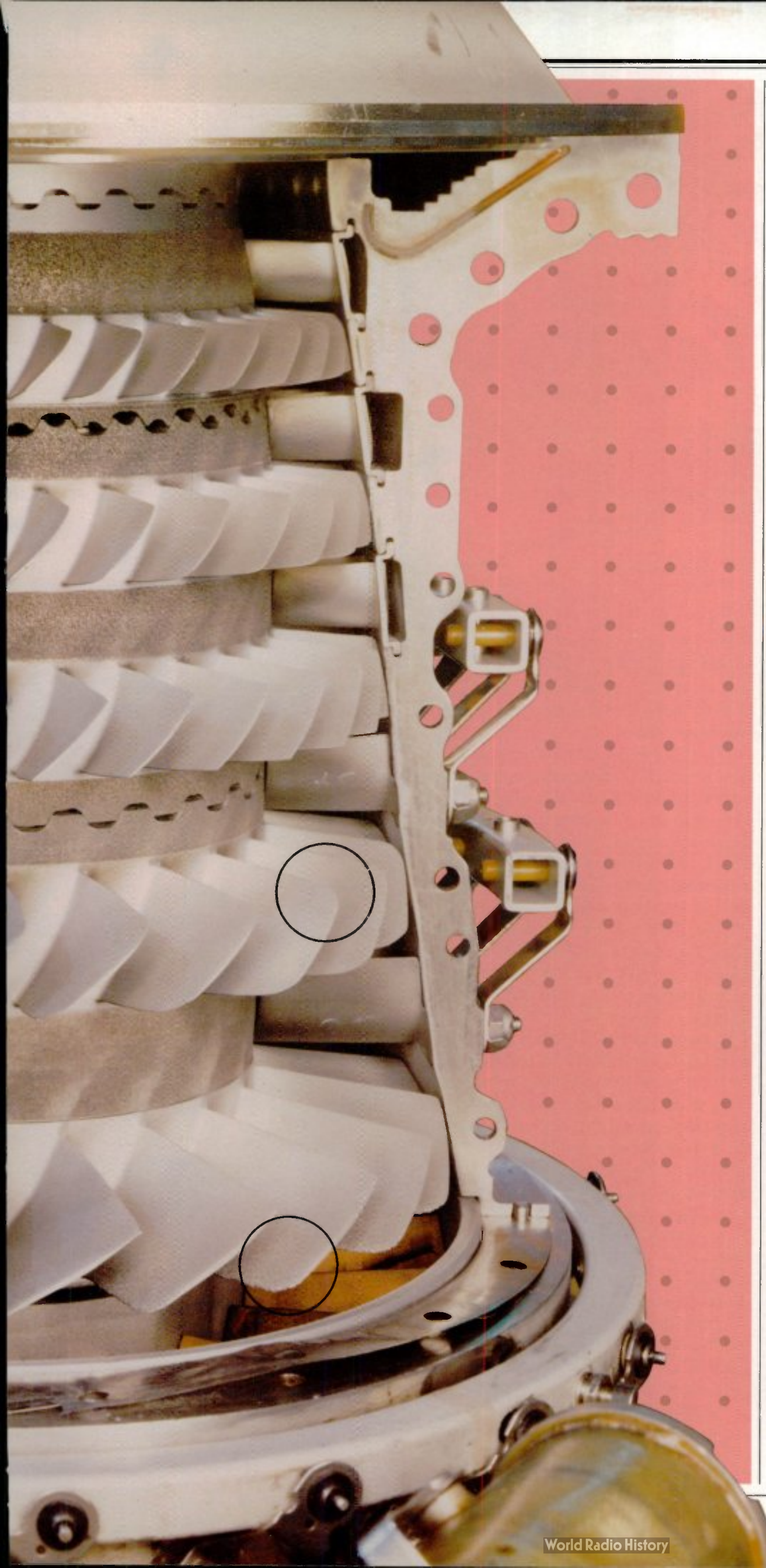
The badly worn-away compressor blades in the lower portion of Figure 1 show the damage that erosion can do to the workings of a modern jet engine. Wear—a natural consequence of repeated contact between parts in an engine, or of erosion resulting from particle ingestion and combustion by-products—limits engine life and can cause significant efficiency losses in modern engines. Premature wear and efficiency losses can cost GE and its customers many thousands of dollars; finding ways to reduce wear is an ongoing focus of materials and process research at GE Aircraft Engines.

This article reviews both progress and challenges in three areas: wear-resistant coatings, erosion-resistant coatings and coatings for seal systems. For many years, wear-resistant coatings have been used in fans and compressors to minimize wear from impact, fretting, or galling. Airfoil and blade tip coatings have been used to combat erosion problems in the fan and compressor as well as erosion problems resulting from combustor deterioration, but considerable room for improvement remains. In the area of seal systems also, while significant improvements have been made in materials for compressors, labyrinth seals, and turbine gas path seals, there remains much to be done.

Wear at Mating Surfaces

Wear can occur when a surface is rubbed, when a pair of sliding surfaces come in contact, or when two components impact directly upon one another. Wear of mating surfaces can and does occur throughout the aircraft engine but is most significant in the fan and compressor where titanium alloys are

R.V. HILLERY



widely used; fatigue related problems are among the potentially serious consequences of this interfacial wear.

A wide variety of wear-resistant coatings is used today to combat wear at mating surfaces. The various coatings have differing properties which make them appropriate for use in different situations and in different temperature regimes.

Table 1 Commonly Used Wear Coatings

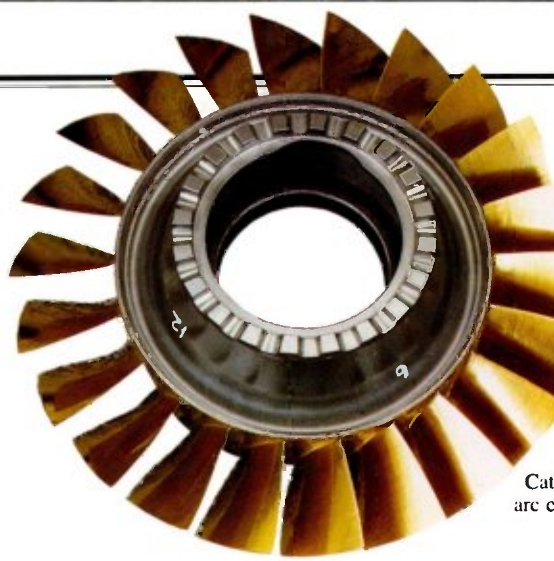
	Application temperature range		
	RT–430°C	430°C–650°C	650°C–870°C
Carbides	WC/Co (W, Ti) C		CR_3C_2/NiCr
Metals	Al bronze Cu-Ni, CuNi In Tribaloy 400 Hard chrome plate Electroless nickels		Cast metals Tribaloy 800
Others	Titanium nitride Aluminum oxide Chrome oxide		
Solid film lubricants	Epoxy resin -MoS_2	Aluminum phosphate -graphite Silicate-graphite	

Table I lists some of the more commonly used wear coatings and their useful temperature ranges.

Hard carbide materials are the most common industrial wear-resistant coatings. In the fan of a modern aircraft engine, for example, the mid-span shroud of the blade is very often coated with a tungsten carbide coating or a brazed-on carbide pad to minimize the impact damage as the shrouds touch one another during service.

The proprietary Tribaloy coating materials, (Cobalt or [Nickel], Molybdenum, Chromium, Silicon compounds) are thermally sprayed coatings in which a hard, wear-resistant phase is precipitated within the coating matrix. Typical aircraft engine applications are rotating shafts, blade interlocks and vane ledges, where rubbing wear can take place. Two forms of this coating system have been developed—Tribaloy 400 for use up to about 1,000°F, and Tribaloy 800, which

Figure 1: An uncoated T700 compressor shows severe erosion damage in sand ingestion test



Cathodic arc coating

is used to temperatures of approximately 1,500°F.

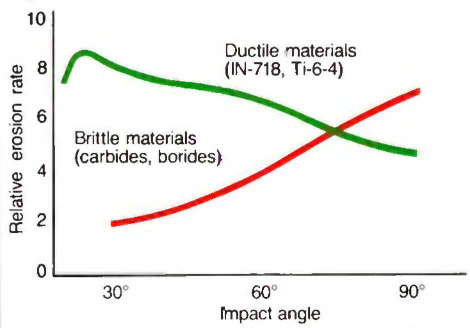
Thermally sprayed oxide coatings (aluminum oxide and chromium oxide) have been used to provide wear resistance and some cutting capability in seal teeth applications. More recently, titanium nitride, widely used in the cutting tool and drilling industries, has been evaluated as a wear-resistant coating for aircraft engine applications, although the application techniques (chemical or physical vapor deposition) are relatively new and expensive.

Hard coatings work well to minimize impact damage, while softer materials are often used to resist fretting and galling wear. In fan and compressor blade dovetails and disk slots, for instance, fretting and galling can take place as the rotating components are centrifuged in the disk slot under the rotational G-loads experienced in service. In this case, a relatively soft coating has been used which provides a cushion between the two titanium alloy components. The most widely used such coating is a copper-nickel-indium plasma sprayed coating which is applied to the disk slot and/or the blade dovetail, usually in conjunction with a solid film lubricant such as molybdenum disulfide (MoS_2).

Erosion Resistant Coatings

Erosion can occur throughout the engine and indeed can be severe in both compressor and turbine; however, the majority of erosion problems occur in fan and compressor sections where relatively large ingested particles tend to hit the very high-speed first stage fan or compressor blades at angles close to 90°, thus eroding and deforming the thin leading edge along its entire length. Further downstream in the compressor, where the particles tend to be somewhat smaller and are centrifuged towards the periphery of the rotor, the particles hit at a lower angle and typically erode the airfoil on the pressure surface

Figure 2



from the mid-chord region to the tip and even at the trailing edge.

Ductile materials exhibit their maximum erosion rates at impingement angles between 15 and 30 degrees and are more difficult to erode at higher impingement angles[1]. Conversely, brittle materials exhibit an erosion rate which increases continuously with impingement angle, with the maximum rate usually occurring at 90°. For these reasons, materials are often characterized as responding in either a ductile or a brittle mode. The two types of behavior are shown schematically in Figure 2.

Compressor blade materials such as Titanium-6-4 and INCO-718 exhibit a ductile response and withstand erosion better at the higher impact angles. On the other hand, typical coatings materials (carbides or borides), which may be 5-10 times better than the substrate alloy at lower impact angles, may provide little or no added protection at the higher impingement angles because they are brittle. This phenomenon often means that a design change to a component—adding material thickness to the leading edge of a fan blade, for example—may be a better solution to a high impingement angle problem than adding that same thickness as a coating.

Nonetheless, as more and more graphite/epoxy and polyamide materials (which erode easily) are used in the front end of the engines, the need for metallic or intermetallic erosion-resistant coatings becomes increasingly apparent.

The application process and the texture of the finish have a strong bearing on a coating's performance. For instance, in compressor materials and applications, the choice of coating processes available is often restricted by the processing temperature and by the need for aerodynamically smooth surfaces.

Although a consensus exists for the *type* of materials to be used for low angle erosion (carbides/borides), there is less agreement on the application process. Several of the competing coating processes which have been employed for the various coating systems are:

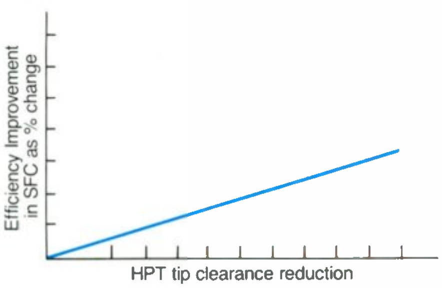
- Pack diffusion process (CrB)
- Other diffusion process (MoB)
- Chemical vapor deposition (TiB_2, Tikote C)
- Thermal spray/D-gun/Gatorgard Plasma (Ni/Co-WC)
- Physical vapor deposition (MoB, B_4C, TiB_2)
- Electroless entrapment plating ($NiTiB_2$, Nibron®)
- Sputtering ($NiCr_3C_2$, TiB_2 $NiTiB_2$)

The first three of these are chemical deposition processes in which the coating interacts with the substrate: the latter four are physical deposition processes in which there is no such interaction. Which process one chooses is a function of the alloy, the application, and the manufacturing economics of the particular use in question.

Sprayed carbides (fourth in the list above) are the choice of many operators, and for some purposes they work well. Recently, during initial operation of a CFM56 re-engining an older type of aircraft, the low clearance caused the engine to ingest an excessive amount of dust from the runway. This resulted in rather severe erosion of the compressor airfoils, particularly in the middle stages of the compressor. We solved the problem by applying a commercially available sprayed carbide coating which was readily applied and has performed well in service.

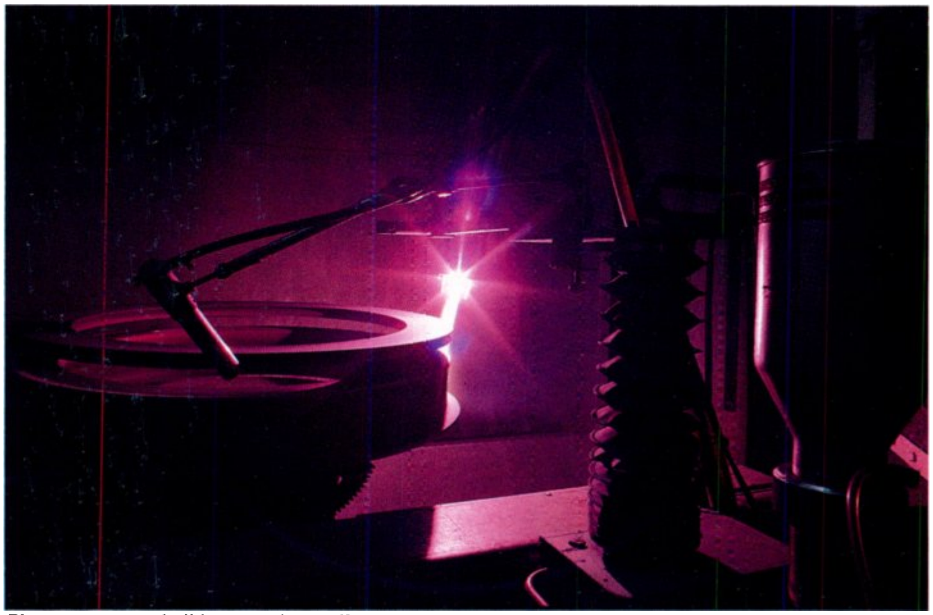
While this solution worked well, sprayed carbide coatings have drawbacks such as rough texture and a deleterious effect on high cycle fatigue. For the future, a physical-vapor-deposited coating system, applied by sputtering, cathodic arc deposition or similar process, will perhaps provide an alternative to plasma spraying, one in which the need for significant

Figure 3



surface finishing will be dramatically reduced. Many materials applied by these methods have at least as good erosion resistance as the sprayed coating, and their development is actively being pursued. They hold much promise for the future.

Better coatings—and better coating methods—would be easier to find if erosion mechanisms were better understood. Work is being conducted to gain fundamental and significant understanding of the erosion mechanisms that can and do occur as a result of different impact impingement angles. Detailed scanning-electron-microscope studies have shown the micro-mechanisms occurring as particles impact on different materials, revealing how the coating material degrades until it is penetrated. From this work[2] it is apparent that defects or flaws in the coating play a significant role in the overall degradation mechanism. As with most coating systems, the preparation and application methods are vital, and we need to concentrate on



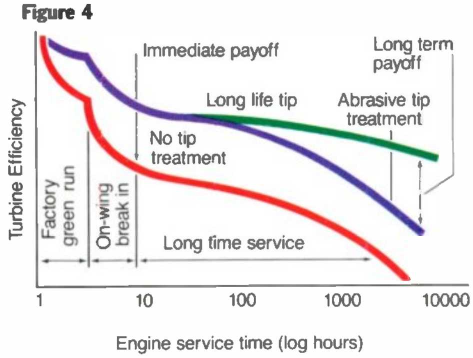
Plasma spray can build up metal as well as apply coatings

process development just as much as we do on materials selection.

Seal Systems

In addition to wear that occurs as a result of interfacial or impingement contact, wear results from incursion of a rotating member into a static component. In labyrinth seals and in compressor and turbine gas-path seals, the incursion of a vane or blade tip into the seal can wear either or both of the components. Wear on these components results in lost efficiency as compressor and turbine clearances open up in service.

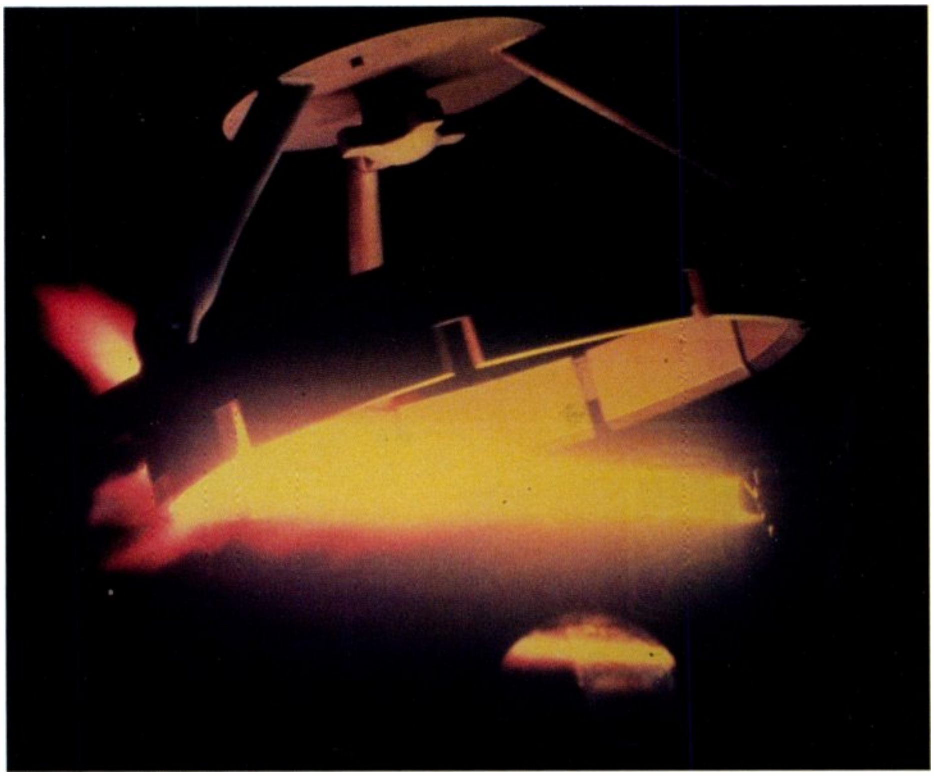
Figure 4



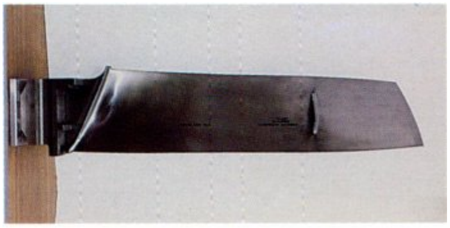
Such loss can be significant. Figure 3 compares the change in specific fuel consumption (SFC) occurring as a result of reductions in blade-tip-to-seal clearances. For a large engine turbine (lower line), loss of tight clearances will result in a corresponding loss of turbine efficiency. For small engines, the effect on efficiency of losing tight clearances is even more dramatic.

This same effect on efficiency is seen in both turbine and compressor. For engines with high temperatures and rotational speed, turbine blade tips will contact the shroud, particularly during fast transients in RPM. The incursion of the blade tip into the shroud can result in blade tip loss, shroud loss, or both. Ideally, the blade tip should experience no wear during the incursion, with the entire result of the incursion being taken by the shroud. In this ideal case, the blade tends to seat itself within the seal.

This is the ideal; but with today's materials, more often it is the blade tips which wear, because the shroud oxidizes in service, thus becoming harder than



Plasma spraying ceramic shrouds



Carbide coating on mid-span shroud of CF6 blade

the blade tip. This wear tends to open clearances quite significantly, up to as much as 20 thousandths of an inch. Even worse, if blade tip material is transferred to the shroud, as is likely, the resulting "scab" will wear *all* the blades in the rotor and reduce performance even further.

The deterioration resulting from this type of interference is greatest in the first few hours of operation, when the blade is seating in the seal and the "out-of-roundness" is being "machined" out of the stator. After the initial break-in, a long period of much slower deterioration occurs. This longer period is generally a result of tip recession due to environmental effects (oxidation and hot corrosion), although further blade-shroud incursions can occur with resulting loss of clearance. This series of events is shown schematically as the bottom line in Figure 4.

The answer to the environmental blade tip problems can be found in design changes (increasing the cooling and reducing the oxidation rate, for example), in a material change, or in both. Material changes may be by means of an alloy change—and significant improvements have been made in turbine alloy environmental properties—or by applying an environmentally resistant tip. Several techniques—plasma spraying, bonding preforms, welding, etc.—are available to apply such tips.

The answer to the blade/shroud clearance problem is being provided by applying to the blades abrasive tips that will cut a path in the seal and minimize recession of the blade tip. The benefit of enabling the blade tip to cut into the shroud, rather than vice-versa, is shown as the abrasive tip treatment line in Figure 4. There is a real benefit even if the abrasive lasts only a few hours. A long life abrasive tip would provide far greater benefits.

GE has had a great deal of success with the use of Borazon™ (Cubic Boron Nitride) applied tips which have been very effective in maintaining turbine efficiency and maintaining tight clearances throughout the first few hours of operation of the engine[3]. Unfortunately, Borazon is not thermally stable at turbine operating temperatures, and we have been searching for a long-life blade tip (Upper line in Figure 4). This tip would incorporate long-term abrasive ability and environmental resistance in a single-tip system.

We have looked at a number of approaches. Clearly, a bonded tip in which an abrasive is entrapped in a matrix could provide a long-life tip. Similarly, a plasma-sprayed tip in which the abrasive is entrapped could also provide the desired material properties. Both ideas have some merit, but both also have some limitations, particularly in stress capability at the turbine operating temperatures and stress levels that exist in modern single stage turbines.

Abrasive tips are one route to retaining efficiency; so are improvements to the gas path seal. Many materials have been used as turbine gas path seals, and attempts have been made via processing modification to make such seals abradable, yet resistant to erosion. Also, as turbine temperatures increase, the seal needs enhanced environmental resistance. As a result, the most common seal system in engines today is a metallic (a nickel-cobalt

The challenge is for the equipment and process developers to come up with economical uses of today's sophisticated techniques while finding new routes for reducing wear in tomorrow's engines

alloy containing chromium, aluminum and yttrium for enhanced oxidation resistance) vacuum plasma sprayed coating. This technique has found widespread use for the past several years. Other materials for solid shrouds, which may not require an added coating, are also being evaluated.

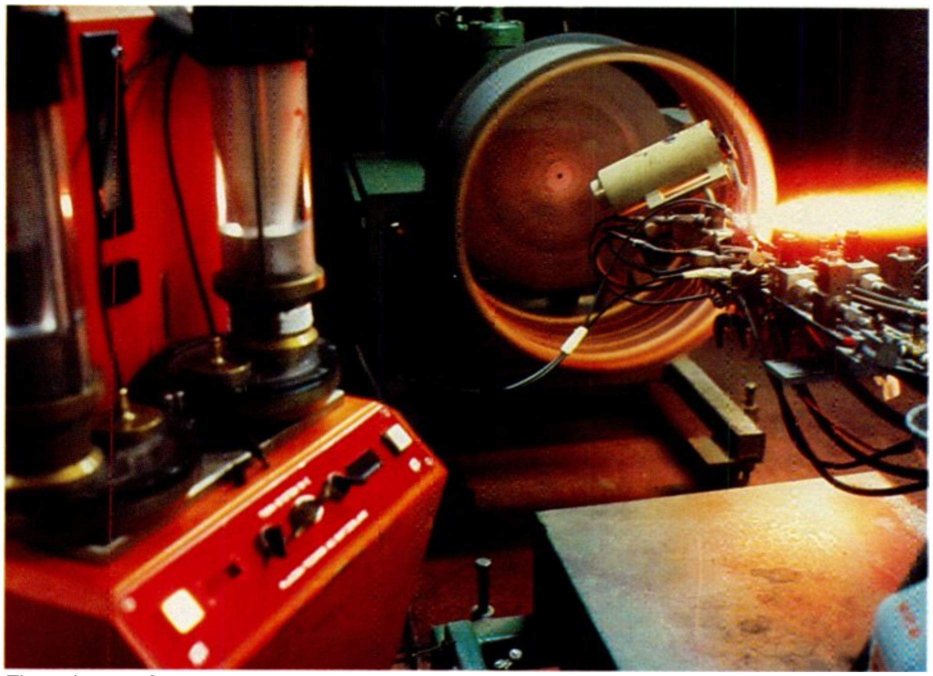
We are looking beyond metallic materials toward ceramic gas-path seals. A ceramic seal, made for instance from zirconia, which is common in thermal barrier coatings, will withstand higher temperatures than any metallic coating system. However, zirconia suffers from the known problems with ceramics: poor ductility, limited strain tolerance as a result of stresses induced by thermal expansion mismatch, and poor erosion resistance.

Several development programs to overcome these drawbacks are in place throughout the industry, and it seems likely that these systems will find widespread use in the future. Again, plasma spraying seems to be the most likely technique to be used for such systems, although some of the more sophisticated techniques for physical vapor-deposition may prove effective here.

Table 2 Application temperature ranges

RT–200°C	200°C–650°C
Silicone rubber	Sintered NiCr powders
Teflon	Sintered metal fibers
Aluminum honeycomb	Hasteloy x honeycomb
	Nickel graphics
	Aluminum, Al-Si
	Nickel aluminides
	NiCr/BN
	Aluminum oxides
	Hasteloy x honeycomb

The systems approach of treating the rotating and stationary elements together is useful in both the high pressure turbine and the compressor. In the past, attempts have been made to combat the problem of compressor clearance control through the use of an abradable seal material. That is, the inner wall of the casing has been coated with a material that can easily be rubbed by the blade tip under all



Thermal spray of compressor

conditions of incursion and rotational speed, thus providing a good seal. Table II is a partial listing of such coatings.

The combination of properties required in the rub surface—ability to be abraded, erosion resistance, resistance to high temperatures, the absence of any deleterious downstream debris—makes the materials problem quite challenging. For the past several years the emphasis has been on treating the blade tip/seal combination as a system in which both components require some specific properties and treatment. Hence, in addition to an abradable coating, which also has inherent erosion resistance, the compressor blade tip may have a wear-resistant or abrasive component to cut the shroud and form a tight and continuing seal.

In the compressor the temperature requirements are not as severe as in the turbine, but a number of other constraints make the job equally challenging. For example, the tip of a compressor blade is much smaller than its turbine counterpart, and add-on systems are increasingly difficult to apply. The challenge is for the equipment and process developers to come up with economical uses of today's sophisticated techniques while finding new routes for reducing wear in tomorrow's engines. ❐

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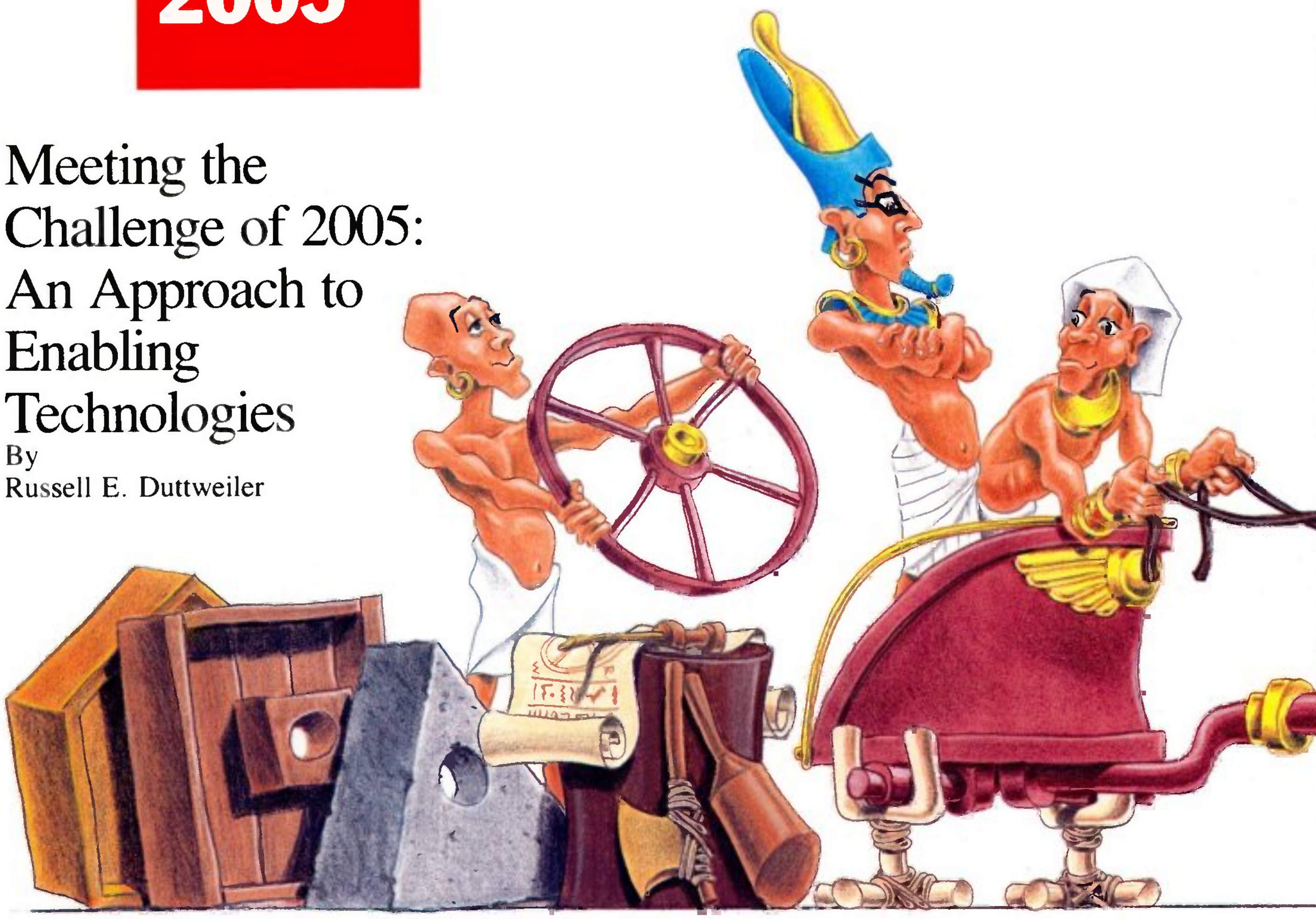
TOWARDS

2005

Meeting the Challenge of 2005: An Approach to Enabling Technologies

By
Russell E. Duttweiler



James Burke contends in *Connections* that new technologies emerge in unpredicted fashion from the coincidental merging of fortuitous contacts, economic interests and the novel application of a seemingly unrelated technology—a happy mix of serendipity, greed, and intellect. The process Burke describes operates in every technology-dependent business, and ours is no exception. The problem is that with the imperative needs of our next generation of engines clearly in view, we can't afford to sit around and wait for the next coincidence to occur. We have to spur Burke's mechanism along, steering it down as focused a path as we possibly can.

The UDF™ shows how the *Connections* mechanism operates in Aircraft Engines. The UDF™ propulsor, one of our major innovations, would be prohibitively heavy and slow without the strength/weight properties of carbon-fiber/epoxy composite epoxy composite materials, materials which were pioneered for use in spacecraft, not aircraft engines. The UDF's emergence at this time results from the serendipitous coming together of an unrelated technology, a market need for much better specific fuel consumption, and an intellectually innovative concept.

By developing an understanding of the basic scientific principles underlying most of our material and process technologies, we can, at least to some extent, modify Burke's mechanism for technological change, making it more deliberate—and thus alter and positively influence the course of technological development.

Living productively with Burke's mechanism requires awareness of and openness to new ideas, in order to make the most of opportunities when they occur. That's primarily a matter of attitude. But we can actively identify and develop the enabling technologies required before break-through engine designs can become realities; that's a matter of discipline and direction. Guiding technology requires better understanding of the scientific principles underlying the selected technological possibilities.

It is this process we have been actively pursuing for the past ten years. Increasingly during that time, our empirical data bases have been replaced by scientific understanding and methodical data acquisition. In our Engineering Materials Technology Laboratories (EMTL), we have evolved a coherent body of cross-disciplinary principles by which we operate. In particular, we have begun to build a materials-and-process research community whose efforts are *need-driven*—those needs being the identification and development of key enabling technologies.

What are enabling technologies?

Enabling technologies are the processes and materials you have to have if a project is to succeed. They are go/no-go points

R.E. DUTTWEILER

along a given path of development.

Enabling technologies can make or break an engine design. Much as "the kingdom was lost, all for the want of a nail," there have been several instances where a hastily developed plan for an effort produced a less than satisfactory result because the leader of the effort failed to envision all of the enabling technological elements required for success.

Enabling technologies have always been gateways to development. Edison's incandescent lamp needed the carbonized bamboo filament and a good vacuum inside the bulb to be successful. As Edison said, "nothing that's good works by itself, just to please you; you've got to *make* the damn thing work." In the eighteenth century, before a ship's captain could accurately calculate his longitude, he needed an accurate time piece. The precise manufacture of chronometer gears was a key enabling technology to the British fleet's domination of the sea-lanes.

Today, more than ever, enabling technologies hold the keys to our future. We know we need quantum jumps in material properties to meet our customers' future needs. We even think we know where such jumps can be made. EMTL's near-term efforts are focused on some rather specific objectives:

- Large structural castings to simplify components
- Polymeric composites for light weight and strength
- Directionally solidified airfoils—especially mono-crystal—for temperature resistance
- Super clean materials produced through electron beam and plasma melting to prolong the life of components
- Coatings and surface treatments, also for long life

Early in 1986, EMTL evolved a strategic plan detailing the path for Aircraft Engines' future material and process development efforts. Entitled VISION 2005, it is our attempt to look at what's out there, outside our own narrow corridors, and it sets in motion prioritized and very focused initiatives for Aircraft Engines' material and process developments. VISION 2005 relies on a process we have evolved and modified over the past twenty years, a process by which we can be fairly sure of developing the enabling technologies we need—and meeting our needs while living with Mr. Burke. This process has identified polymeric composites, metallic and ceramic matrix composites, and light-weight, intermetallic compounds as key enabling technologies.

Our experience with polymeric composites shows how the process of guiding technological growth can work. In learning to work with polymeric composites like those used in the UDF™ blades, we learned that the component design team (mechanical designer, materials engineer, and manufacturing engineer) had to be willing to venture into designing composites using anisotropic material properties—i.e., the materials behaved differently along one axis than along another. Looking hard at existing composites has given us new analytic tools which help us tell the feasible from the possible. For instance, using new techniques which focus on the unique properties of composite materials, we constructed models of carbon fibers, polymeric matrices, and fiber/matrix interface behaviors. Analysis of these models permitted us to anticipate potential barrier problems and thus identify unique material, process and design solutions. These solutions led in turn to more effective selection of materials for the intended applications.

Next, the entire process for manufacture of composite tapes and the processes used to consolidate them and form them also had to evolve. Techniques for joining, fastening, and finishing were developed; wear and environmental coatings were needed in some cases.

The point is that very little of this technology developed randomly. Instead, we formulated a basic understanding of the properties of materials, foresaw the difficulties, and deliberately set about finding ways to overcome them. We were able to do so because the depth of our scientific and theoretical knowledge, as opposed to simply empirical engineering, was adequate to the purpose.

We can use this same process in the future. Properly armed with our science-based vision for these new materials, we're ready to attack and develop the enabling technologies. We must evolve prescriptive methodologies that allow us to model the designs, the materials, the processes and the products of tomorrow.

To be most effective, product design and process definition should occur in harmony; process planning, integration, and closed-loop-control must be a *single* function. In the process I'm describing, ambiguities and conflicts among design, manufacturing, material, and process must be satisfactorily arbitrated at the start, not down-stream when it's too late.

In EMTL, the intellectual base is already beginning to shift direction and to expand. We are experiencing the excitement and stimulation brought on by the challenge of these innovative concepts. Serendipity is welcome—it will only add to the more deliberate process that will let us master the challenge of the enabling technologies behind VISION 2005. We must remain open to the achievements of others and avoid the trap of Not Invented Here. Yet if we are to realize the full potential of our VISION 2005 material systems, and do it in a reasonable time frame—at a cost something less than the national debt—then our science-based approach to technology must guide us into the future.

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The Leading Edge
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