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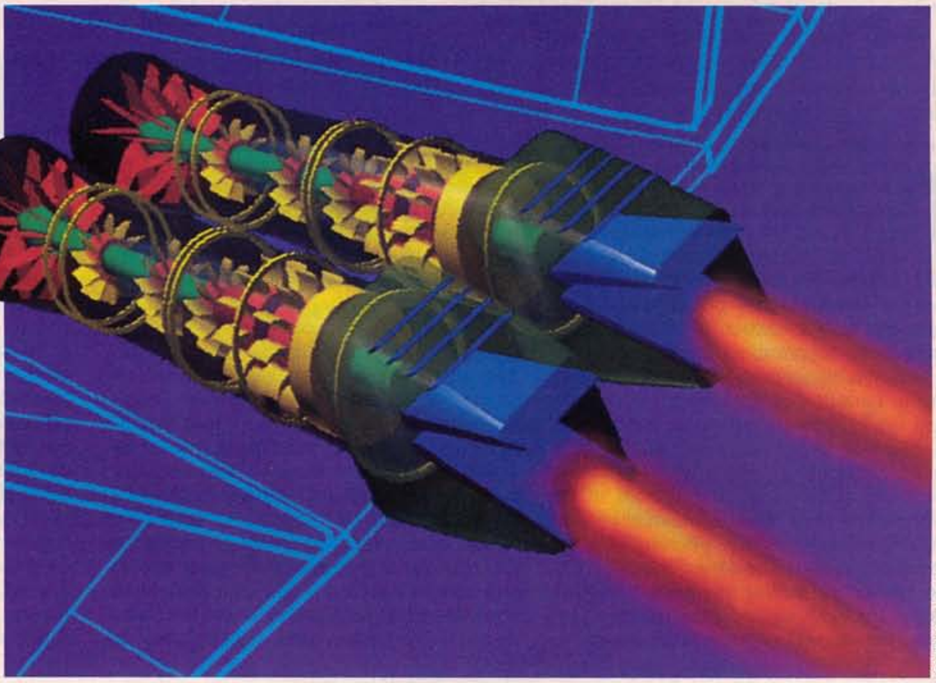
21st CENTURY HOT JET ENGINES



JONATHAN HERBERT

A bold research program aims to double the thrust of jet aircraft engines by the early 21st century.

By STUART F. BROWN

"For years we were busting our tails to get another one hundred degrees [F] out of a superalloy—now we're talking about breakthroughs that will take temperatures up 1,000 degrees in one leap," exults Dr. John P. Henderson of the Wright Research and Development Center in Ohio. Henderson is the recently retired chief of the metals behavior branch of the center's Materials Laboratory, where scientists pursue the exotic high-temperature substances from which jet engines are made.

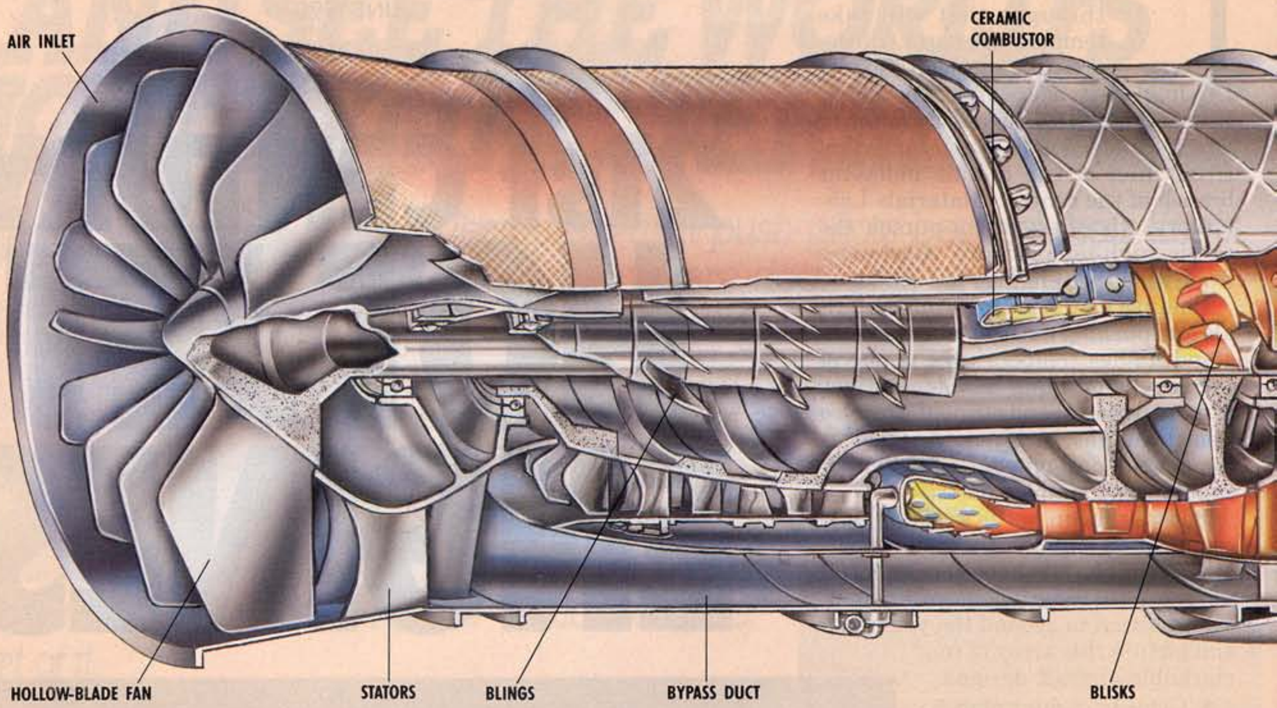
Finding new heat-tolerant materials and pushing existing ones to withstand higher temperatures is one of the keys to building new generations of more powerful and efficient jets, also known as gas turbines. Another is component design—building lighter, smaller, and simpler parts.

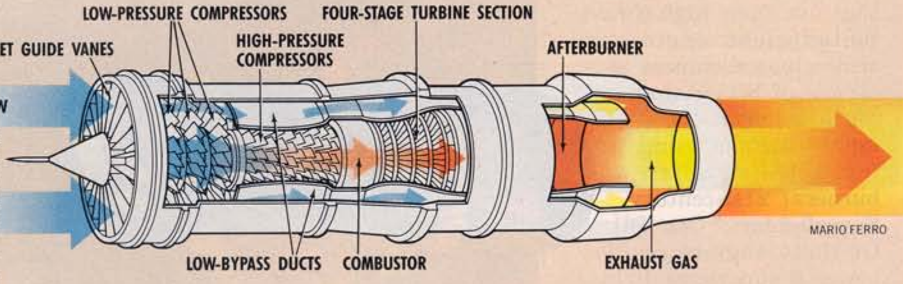
Put to work in hotter running, less complicated engines, these new heat-tolerant materials have the potential to transform aviation as we know it. Think ahead to around the year 2010 and picture this array of remarkable aircraft designs:

- Compact fighter planes that use their high-thrust, fuel-efficient engines to cruise long distances at speeds of better than Mach 3 (about 2,100 mph)—without using fuel-gobbling afterburners ["21st-century Superfighters," Oct. '86]. Or these engines could power a supersonic fighter with Harrier-like, short takeoff and vertical landing (STOVL) capability, plus two-thirds more range than that notoriously fuel-thirsty airplane.
- Heavy-lift helicopters with either twice the payload or twice the range of today's choppers.
- Airliners that are built to go twice as far or carry twice as many passengers, while matching the fuel consumption of current fan-jet-powered transports.
- Cruise missiles no larger than existing ones with two to three times their range at both subsonic and supersonic speeds.

Scientists and engineers at labs across the country are exploring these ideas and others in a coordinated government-and-industry multi-billion-dollar 16-year research project. Government entities involved in the Integrated High-Performance Turbine

ADVANCED AND CONVENTIONAL TURBINE ENGINE





MARIO FERRO

The advanced engine concept shown above incorporates many of the most promising structural and materials technologies now being explored in industrial and government research labs. It would generate more than twice the thrust of today's most powerful engines with only a fraction of the number of components—a mere six rotating compressor and turbine stages would replace the 17 used in current designs (see the schematic of an F-16 fighter-jet engine at right).

In the F-16 engine, actually a Pratt & Whitney F100 series, air entering the spokelike fixed inlet guide vanes at the front of the power plant is raised to a temperature of about 300 degrees F by the compressing effect of the aircraft's inlet. The vanes' function is to turn the airflow so that it strikes efficiently against the first of the three rotating fans—also known as low-pressure compressors. By contrast, the new engine would have only one large fan with swept hollow blades.

The F100's three fans pull the air through the core of the engine, forcing it through bladed, non-rotating stator rings located between them, which slow down the airflow and cause its pressure and temperature to rise to about 600 degrees F. The air is further and further compressed as it passes through the increasingly angled blades of each successive compressor stage. The diameters of the compressor stages grow smaller as the air becomes more compressed. By the time the airflow exits the 10-stage high-pressure compressor section, it has been progressively compressed to more than 25 times atmospheric pressure and has risen to a temperature of over 1,000 degrees F. The concept engine would reduce the compressor stages to three, using high-efficiency "blings" (see text) with short, squat blades.

Next the air enters the F100's donut-shaped combustor, where a ring of continuously operating injection nozzles adds fuel to the heated air, causing it to burn at as much as 3,800 degrees F. More air is then added to

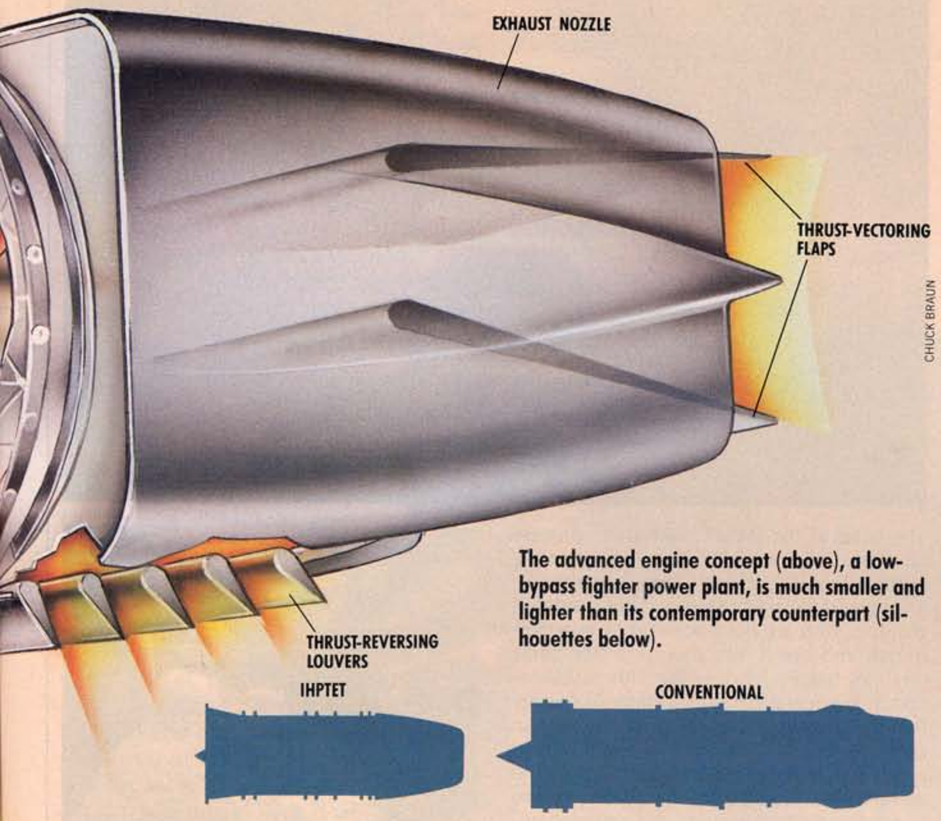
Engine Technology effort (IHPTET is the inevitable acronym, pronounced ip-tet) are the Air Force, Army, Navy, NASA, and the Defense Advanced Research Projects Agency (DARPA). Picking up about one-third to one-half of the program's cost, however, and building most of the prototype hardware are seven U.S. turbine manufacturers: General Motors' Allison Gas Turbine Division, Garrett, General Electric, Pratt & Whitney, Teledyne CAE, Textron-Lycoming, and Williams International.

Even though the types of engines specifically intended to benefit from the program are used in military aircraft, civil airliners should share in the advancing technology as well.

"Historically, most successful civil engines have had military cores," notes Dr. Donald M. Dix, staff specialist for propulsion at the Pentagon. "The CFM-56 used in the Airbus and other airliners is an example. They basically take the core from the GE F101 engine that powers the B-1B bomber and put a big fan on the front. Right now, it's the best-selling engine in the world."

The unprecedented IHPTET program has ambitious goals. One hope is to increase engine thrust-to-weight ratios from a 10:1 baseline to 13:1 in 1991, 16:1 in 1997, and 20:1 in 2003—a doubling of performance. Even the baseline for these anticipated gains is lofty: It roughly describes the performance level of the highly classified Air Force Advanced Tactical Fighter and Navy Advanced Tactical Aircraft engines, which themselves eclipse the 8:1

HOW THEY WORK



CHUCK BRAUN

The advanced engine concept (above), a low-bypass fighter power plant, is much smaller and lighter than its contemporary counterpart (silhouettes below).

the combustion gas to reduce its temperature to a level that the turbine can withstand. The resulting stream of rapidly expanding hot gas rushes out of the combustor and passes through the engine's four-stage turbine section, subjecting the first stage to temperatures as high as 2,600 degrees F. The first and second turbine stages drive a sleevelike shaft connected to the high-pressure compressor section, while the third and fourth turbines drive a central shaft coaxial to the first one, which drives the fan section at the front of the engine. The turbine section of the concept engine consists of only two stages, single high- and low-pressure "blisk" turbines that counterrotate against each other, increasing efficiency and canceling the twisting torque reaction found in co-rotating engine designs.

Arrayed between the F100's turbine and the exhaust nozzle is a second ring of fuel injectors that can add more fuel to the out-rushing hot gas, causing a secondary combustion. This afterburner, or augmentor, greatly increases engine thrust, but can only be used for short periods of time due to the massive amounts of fuel it requires. Because of its high gas temperature, the concept engine would not need an afterburner.

The blue areas surrounding both engine's turbine cores are the bypass ducts. The large first-stage fan pushes air both through the core and around it, where it contributes to the engine's thrust. A fan pumping bypass air around the core of an engine is no different in its action than a ducted propeller. Most of the bypass air joins the engine's core flow just downstream of the last turbine stage, while a small remaining amount is used to cool the double-walled exhaust nozzle.—*S. F. B.*

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thrust-to-weight ratio of today's hottest production fighter engines, according to Dr. James S. Petty, acting deputy for technology at the Wright Research and Development Center and manager of the project for the Air Force. Similarly lofty goals exist for reduced fuel consumption and for higher performance in all classes of engines.

The program isn't expected to start building advanced jets according to some set of formal specifications that will emerge from the effort, however. Rather, the goal is to develop and demonstrate those technologies that will enable advanced engines to be built.

In conversations with numerous researchers involved in the program, I was struck by how enthralled they appear to be with the bounty of promising turbine-related discoveries that have occurred in several interrelated fields within a relatively short period of time. Here is a close-up look at several types of advanced materials and research methods being used in the quest for tomorrow's hot jets.

There has been remarkable progress in the quest for heat tolerance. Hotter is better in a turbine because at elevated temperatures more of the oxygen entering the engine combines with the fuel (turbines burn kerosene), releasing more energy in the form of expanding hot gas.

Unlike previous generations of researchers accustomed to struggling to achieve incremental improvements in the performance of metal alloys, today's "hot materials" scientists are making rapid progress on so many fronts that they can't help radiating an aura of excitement. "It's a materials revolution," Henderson proclaims. "We're starting to realize whole families of new kinds of engineered materials that have a very high payoff."

One result of the ferment in materials development is the advance of metallics. Ingenious manipulations of the crystalline structures existing superalloys have increased their strength and temperature tolerance. One unique alloying method uses extremely rapid cooling to entice normally incompatible kinds of metals to coexist in dozens of new alloys with properties that can be tailored to the job they will perform. Metallurgists have even figured out how to embed reinforcing fibers in solid metal parts to increase their strength.

Metal-foundry specialists go to great lengths to control the crystal formation that occurs during casting of superalloy turbine blades as the molten metal cools and solidifies in the mold. Why this preoccupation with the microstructure of the metal? Because the borders, or grain boundaries, between crystals are where small amounts of the contaminants present in any alloy congregate during cooling, forming weak points. Under the tremendous thermal and mechanical stresses in a jet engine, tiny cracks can begin to form along these boundary lines. Unchecked, these fissures can eventually lead to catastrophic component failures like the disintegrated disc that caused the DC-10 airliner accident in Iowa last year.

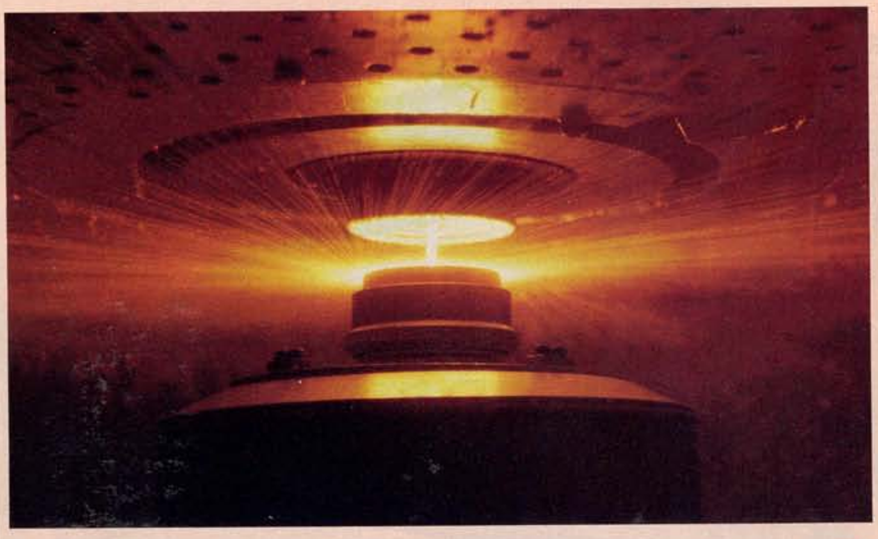
Guided by these observations, researchers began to focus on finding ways to cast alloys with crystals as large as possible. Pratt & Whitney developed a method using an insulation pack surrounding the fresh-cast blade, and a water-cooled metal "chill plate" mounted on its root—the end where the blade attaches to the turbine disc. By slowly extracting the blade from the casting furnace and chilling the root end at the same time, the technique exploits the rules of crystal formation: "Any grain that starts to form at the chilled plate will continue growing until it hits the mold walls, or another grain boundary," Pratt & Whitney's Frederick C. Polhemus Jr. says. "The result is that a fairly small number of roughly parallel, columnlike crystals will work their way toward the tip. We call this directional solidification. It yields a much stronger part than we used to be able to make."

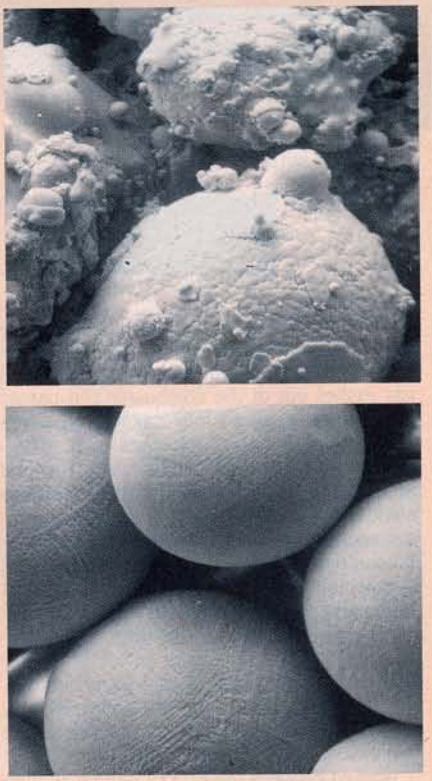
The success of directional-solidification technology sparked an assault on the next step in tweaking the microstructure of cast superalloys: "Growing" entire parts composed of a single crystal of alloy material.

The answer to the riddle of growing single-crystal parts turned out to be simple—once somebody hit upon the idea of the "pigtail" mold sprue. A sprue is normally a cone-shaped plug of metal formed at the top end of a cast part by the funnel-like opening in the mold through which the molten metal is poured. After casting, the sprue is removed from the part.

A pigtail sprue acts as a metallurgical sieve, or filter, that one by one snuffs the growth of the directionally solidified crystals originating from the chill plate. As the crystals proceed through the sprue's corkscrew-shaped obstacle course, more and more of them run up against its edges and stop growing. Finally, a solitary crystal emerges from the end of the pigtail and fills the mold with homogeneous metal completely free of grain boundaries. Determining the proper twist, length, and diameter of the pigtail is the key to making sure only one crystal comes out the sprue's other end.

RAPIDLY SOLIDIFIED ALLOYS





The heart of the rapid-solidification process developed by Pratt & Whitney is the rotating water-chilled disc shown above. As molten alloy ingredients are poured onto the center of the disc, they are flung outward as in a centrifuge and break into countless tiny particles that harden into powder. This solidification of the metal particles occurs so quickly that the alloying ingredients have no time to segregate themselves, and therefore remain evenly distributed throughout the material. The powder is next passed through a sieve, heated to a moderate temperature, and extruded under high pressure into billets suitable for machining into components.

Scanning-electron microscope photos (right) show powder-metal alloys produced by conventional (top) and rapid-solidification processes (bottom). The crusty surface and globular eruptions of the conventional particles indicate segregation of their constituent ingredients, which will hurt the material's performance. By contrast, the rapidly solidified alloy forms smooth-surfaced egg-shaped particles with homogeneous microstructures. Rapid solidification results in alloys called dispersion-strengthened materials composed of intermetallic compounds. Because of their uniform microstructures, the intermetallic compounds exhibit high strength and temperature performance. Both of the samples are magnified 2,000 times.— *S. F. B.*

To observe another fascinating metallurgical process, I followed Polhemus up a walkway at Pratt & Whitney's Palm Beach, Fla., facility to the top of an unusual two-story-tall furnace invented for the production of rapidly solidified metal powders. The alloying process occurring inside was one that mates metals that would normally be strange bedfellows.

"Before rapid solidification was developed, the performance of all alloys was limited by their solubility content—the amount of an alloying ingredient you could add and still get good results," Polhemus explains. "For instance, with structural aluminum we want to improve hardness by adding iron and molybdenum, but with traditional alloying methods the addition of only about 0.1 percent of alloying ingredient will cause the iron to begin forming large agglomerations, which act as weak spots in the alloy. Using rapid-solidification technology we cool the material so quickly that the agglomerations never have a chance to form, and we can add eight percent iron and two percent molybdenum to the aluminum."

Pratt & Whitney has also developed an intriguing rapidly solidified material called Alloy Y that has "self-healing" properties. Used as a coating for single-crystal parts, it contains nickel to match the coefficient of expansion of the underlying nickel-based component, chromium and aluminum as oxide-formers, and yttrium as a rare-earth stabilizer. "Using a rapid solidification process, we can put an overabundance of these materials in the alloy to create a corrosion-resistant material that forms its own oxide protective coating—and if you scratch it, it forms a new one," Polhemus boasts. "This is good for the pilot because if he flies through a debris cloud in combat, any nicks that might occur in his engine's hot section will immediately be coated over to prevent failures."

The latest scheme for Alloy Y—using it to make entire turbine blades—calls for a microstructure-manipulating strategy worthy of a metallurgical Houdini. "You see," Polhemus says, "I can't cast this material, because if I do, I lose all of the supersaturation of the alloying elements. They would clump up and ruin my alloy. So a blank made of the alloy has to be forged. Then we can take this multi-crystalline piece, heat it just above its recrystallization temperature, and seed it with a preferential crystal, which we grow out into the rest of the material. The large single-crystal piece that results can be machined into a forged blade." Polhemus figures it's all worth the effort: Blade life could be tripled or quadrupled.

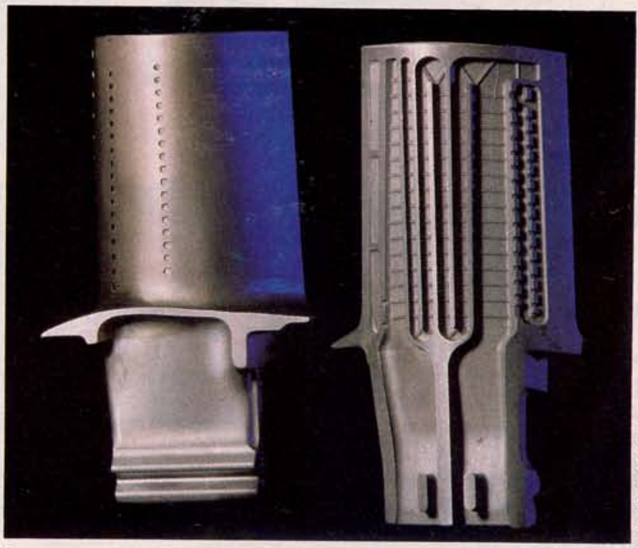
Another class of metallic materials called intermetallic compounds—specifically titanium aluminide—is receiving lots of attention from turbine designers too. Stephen J. Balsone, a materials engineer at Wright, explains their appeal: "An intermetallic is a chemical compound with ordered bonds between the atoms, rather than a random orientation as in a conventional metal. Titanium aluminide is a stack-up of titanium and aluminum atoms in a specific ratio and orientation that gives you attractive properties for making a high-temperature material. But it also exhibits problems such as the tendency to brittleness at room temperature. So we may end up adding continuous fiber reinforcements to improve impact resistance."

The materials fall into three groups: The Alpha 2 and Gamma titanium aluminides can tolerate temperatures up to 1,400 and 1,800 degrees F, respectively; and the so-called "advanced intermetallic" materials, such as nickel aluminides and niobium-based refractory alloys, are candidates for temperatures approaching 2,800 degrees F, Wright's Henderson says.

Still another metallic advancement involves so-called "metal-matrix" composites—fiber-reinforced metals—which are strong and much lighter than other materials in their temperature range. Titanium-aluminide-and-fiber composites, for example, may perform in applications where temperatures reach up to 1,800 degrees F with only half the weight of the superalloys they replace.

"Everyone figured out before World War II how neat it was to take some very strong fibers and support them in a matrix of plastic—this was fiberglass," Mike Hudson, general director of engineering at Allison recalls. "Now we've developed the concept of reinforced plastics to a fare-thee-well. Then someone got the bright idea of putting fibers in metal—but you can't make metal composites the same way you make plastic composites."

As a result, engine builders have had to dream up their own ways of getting fibers into metal. They have found that chopped-up fibers can be added to some types of aluminum, and the resulting material can still be poured in somewhat the same way as plastic. To use high-strength metals like titanium, superalloys, and intermetallics, however, closely guarded methods are being developed for coaxing chopped or continuous fibers into composites of the three substances. In some cases, continuous fibers are wrapped up with metallic foils, which are then bonded together into a solid material. Another technique involves placing metal powders around the fibers and pressing the combination into a solid composite.


GREGORY W. ROBERTS

Serpentine passages inside this cutaway turbine blade route cooling air to rows of escape holes. The horizontal ribs are "trip strips" that induce turbulence in the airflow, increasing heat transfer.

Metal-matrix composites arose out of a whole new approach to designing. "As we move toward composites," Polhemus says, "we can actually design materials to fit particular applications. The process is called concurrent engineering, and it involves the component designer, the material specialist, as well as the manufacturing expert."

The trend in concurrent engineering is toward designing fewer parts that work harder to deliver higher performance. Two new turbine component designs, amusingly named "blisks" (for bladed discs) and "blings" (for bladed rings), were conceived to satisfy these goals. Metal-matrix composites were developed with the new turbine components in mind.

Blisks are one-piece disc-and-blade components that weigh about 20 percent less than conventional turbine wheels because they don't require the heavy machined keyways that lock the individual blades onto a conventional disc. Because effective repair methods for the costly blisks remain to be developed, they are contemplated for use far back in the engine where damage due to ingested debris is less likely to occur.

Blings, essentially hoops with blades bonded onto them, promise large weight savings because they have no massive disc at their centers. Hudson foresees that blings will be essential in the compressor section of his company's engine of the year 2000. "Blings look like the only way to build twice the thrust-to-weight of what we have today," he says. "We've tested fiber-reinforced metal-matrix rings used as spacers in engines and reduced their weight from thirty-four pounds to under two."

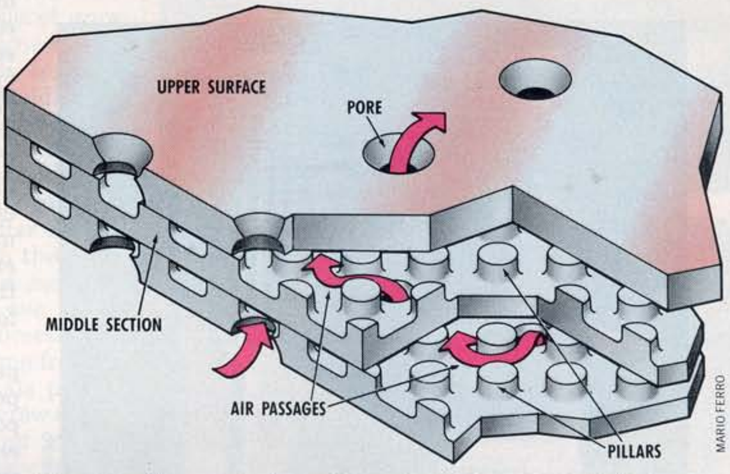
Temperature control, especially for metallic components, is critically important. In today's fighter engines, about 25 percent of the air flowing through the turbine core is used for cooling critical parts. Of this amount, roughly half ends up contributing to the engine's thrust, while the other half represents lost energy.

"By using a combination of new materials and more-sophisticated cooling strategies, we'd like to use less than half the current amount of air to cool a turbine that runs more than 1,000 degrees hotter," says Wright's Petty.

One way to increase cooling efficiency is to create intricate mazelike passageways inside hollow blades through which the air must pass before it escapes through rows of small holes on the airfoil's surface. The complicated air-passage layouts are developed using large transparent plastic models through which tinted water is circulated. "Dead spots," where flow is poor, are located this way, and passage shapes are refined to eliminate them. Both GE and Pratt & Whitney have developed one-piece, single-crystal turbine blades with serpentine internal cooling passages (see photo).

Another way is to make a sandwich. During my visit to his lab, Petty let me scrutinize a fascinating part that the developer, Allison, never let me get a second look at—not even in a photograph. It was a turbine blade made with what Allison calls its Lamilloy cooling technology. The two-piece blade consisted of an airfoil with extremely complex (and beautiful) raised patterns in its shiny surface, and an appropriately curved sheet of metal peppered with tiny holes that formed a mating cover. Joined together, the two layers formed a sandwich inside of which cooling air would pass through a dense maze of pillarlike shapes and then out through the array of surface holes.

"Lamilloy is a rather broad term that we use to describe transpiration-cooled laminated structures," Allison's Hudson explains. "Transpiration cooling is a process in which we actually make metal 'perspire' air. The air forms a film around the alloy that protects it from the high-temperature gases that envelop the airfoil or the afterburner liner or whatever. Remember, we're talking about gas temperatures on the order of 3,500 to 4,000 degrees [F]. The exact temperatures are classified, but if you get out your handbook of superalloys, you'll find that most melt at about 2,200 or 2,300 degrees.



Allison's Lamilloy transpiration-cooling method: Pillars cast or etched into sheet material give this triple-layer sandwich a large area over which air must pass before it exits the surface "pores."

MARIO FERRO

"We have developed a sophisticated system of electrochemical milling so that we can photo-etch complex shapes, much as circuits are etched in the electronics business," Hudson continues. "We are also able to cast patterned sheets and structural members. Both types have a large internal metal surface area for efficient transfer of heat to the cooling air. We think that we can cut the amount of cooling air needed in half with transpiration cooling."

Allison's cooling method has its share of admirers. Says the Pentagon's Dix: "It's the most efficient cooling scheme anyone's come up with because it has the most surface area that the cooling air contacts on its way from the inside of a blade to the outside. Whether it can be made to work satisfactorily is still a question."

As some researchers struggle to develop complex cooling strategies, others keep the hope alive for using heat-resistant materials like ceramics. For ceramics researchers, however, the past two decades have been a long road strewn with shattered expectations, while among technology watchers an attitude of chronic weariness has developed toward reports promising a wave of new ceramic applications soon.

Despite the technological uncertainties surrounding ceramics, they are too appealing a class of materials for the curious investigator to walk away from. "They actually get stronger as they heat up," marvels Pratt & Whitney's Polhemus. "Although they have the brittleness problem at engine startup temperatures, once they are hot you can hit them, and they will bend. It's like trying to rip a sheet of pliable plastic compared with ripping paper. If you shoot a BB at a piece of ceramic at room temperature, the ceramic will shatter. But if you heat the ceramic up to about 1,800 to 2,000 degrees, the BB will just bounce off, or at worst go right through and leave a little round hole."

There is new-found cause for optimism in the results of experiments being conducted with ceramic matrix, or fiber-reinforced ceramic, composites. These materials appear to be able to resist some of the brittleness-related failures that have dogged the monolithic, or non-reinforced, ceramics. Says Wright's Henderson: "When you put a coupon [test strip] of ceramic-matrix composite in a tensile-strength test to see what happens when you pull it apart, it sort of elongates as if it were yielding. Next you start to get microcracks in the matrix, but then you gradually get fiber pull-out instead of the thing snapping in two.

"These demonstrations get a lot of attention and generate a lot of enthusiasm," Henderson observes, "and we'd love to build air-cooled rotating parts out of ceramic-matrix composites that would run at up to 3,000 degrees. But the real problem is what happens when you design a jet engine with this stuff that gets hot, and rotates, and gets cold. First you've got to understand and codify the behavior of the material in this environment before you can even think about using it in a flying component. Is the interface between the fibers and the matrix stable? Will it cause problems after a long period at high temperatures? How's the thermal conductivity? When we try to cool it will it crack owing to uneven expansion in different areas of the part? We're still a long way from knowing the answers to all these things."

On still another ceramic front, Pratt & Whitney is testing a ceramic-ceramic composite process called Solgel, which consists of a woven belt of aluminum-oxide fiber into which a fine aluminum-oxide powder is baked. "It's an engineered, tailored material. You can take a hammer and drive a nail right through it, and it won't shatter," Pratt & Whitney's Polhemus says.

The Solgel process may be used to make blade outer-air seals, adjustable bands of material that can change slightly in circumference to minimize the amount of wasted air sneaking between the blade tips and the inner wall of the engine casing. During acceleration, engine heat causes the bands to expand away from the rotating blade tips slightly to prevent their being damaged by rubbing the seals. "Then when the aircraft gets up to cruise conditions," Polhemus explains, "cooler air is bled in around the outside of the seal, which shrinks it down thermally without any actuators. We call it active clearance control. The pilots will tell you it feels like shifting into overdrive."

Another new heat-resistant material with a likely future in turbines is carbon-carbon. Made by mechanically knitting closely intertwined strands of carbon fiber (also known as graphite) bonded into a carbon matrix, carbon-carbon is shaped into "preforms"—cylinders, sleeves, or rings—from which a component is later machined.

"Carbon-carbon is fascinating because it maintains its strength as you go to high temperatures where every other material drops off," Petty explains. "But the big problem is that at temperatures above 700 degrees [F] it

FIBERS TO PREVENT FAILURE

The photo at left captures the fleeting instant of catastrophic failure of a ceramic turbine rotor running at 111,000 rpm in an overspeed spin rig at GM's Allison Gas Turbine Division. A specially developed high-speed photo technique uses a strobe, triggered when the first fragment breaks a loop of fine electric wire encircling the rotor, to expose the film. The burst occurs within microseconds. The radial streaks of light are considered to be caused by the physical release of stored energy from the rotor fragments. Fiber-reinforced ceramic composites could prevent such failure. The specimen in the scanning-electron microscope photo below was loaded to near ultimate stress (the point of complete failure)—and then unloaded—in an instrumented tensile-test rig. Fibers can be seen bridging the matrix cracks, permitting the composite to carry high loads despite localized damage. —*S. F. B.*

DR. TAI-IL MAH

oxidizes rapidly, or burns—in the industry it is known as designer coal—so it needs a ceramic coating on it to keep out the oxygen."

"What's needed," Polhemus states, "is a coating that will keep the free carbon bound to the fibers in the material. The molecular chain of the coating might be modified to build in an element that will react with the oxygen and tie it up, rather than letting it attack the carbon." When asked what elements look promising for the task, Polhemus smiles and answers "Yes," his reply to queries about topics that aren't up for public discussion.

Petty showed me a silicon-carbide-coated carbon-carbon turbine nozzle that was run on a test rig by Williams International. The coating had failed in some places, and the underlying material had been eaten away, leaving hollow, undercut areas. "These are the headaches with carbon-carbon," he lamented. "If you get a little pinhole in the coating, after a while there's nothing left underneath—and it still looks fine. Until you tap on it and find out that it's empty and has no strength at all."

Polhemus cites another unresolved problem with the material: "If I take a carbon-carbon component today—unless it's been properly treated, which they are just beginning to figure out how to do—it will absorb a certain amount of moisture while it's sitting on the ground. When I start the engine, the water vapor that's entrained inside the piece is going to flash to steam and blow it into a million little bits."

On the positive side, in addition to its high strength in scorching environments, carbon-carbon is light in weight and has excellent thermal conductivity. This latter property gives component designers the option to expose one end of a part to high temperatures and to extract the heat from the other end where it may be more convenient from a structural or aerodynamic point of view.

In contemplating new types of aircraft that will carry the lighter, more powerful engines that will result from IHPTET research, designers must consider a baffling web of interconnected changes for the better that become feasible when weight is removed from the power plant.

"The engine and the fuel represent forty to sixty percent of the takeoff gross weight of an airplane," says Petty, "and in a fighter, one additional pound of engine weight typically means seven pounds of airframe weight. So if you take a pound out of the engine, you can take seven pounds out of the airframe. Then you don't have to carry as much fuel... and the whole thing snowballs. The result is that the aircraft shrinks dramatically in size and weight while remaining capable of performing the same mission. Or we could make the aircraft the same size and improve its capability, such as increasing mission radius by sixty-five percent."

According to the Pentagon's Dix, the equation for reducing the life-cycle operating costs of aircraft calls for doing whatever it takes to achieve higher thrust to weight or lower fuel consumption.

"We're trying to double the thrust of the engine or reduce the specific fuel consumption by fifty percent," he observes. "Some people wonder why we're not trying to reduce the cost by fifty percent or increase the life by fifty percent. The fundamental point is that the path to an economic airplane is with a high-performance engine, not a cheap engine. This is simply because getting weight out of the propulsion system—engines plus fuel, which account for such a large chunk of the airplane's gross weight—has a very big impact on economics."

And now, perhaps more than ever, the emphasis on economics is vital. With the remarkable events occurring in the USSR and Eastern Europe, talk in Congress and in Washington D.C.'s political circles centers evermore on the expected peace dividend from a declining defense budget. No one is certain at this juncture how the pieces of the shrinking defense-budget pie will be divvied up. While the IHPTET program is likely to face the prospect of funding cutbacks, it could also emerge relatively unscathed. In view of its potentially large civil impact—as defense projects go—arguments will probably be made that money invested in jet-engine development is well spent. Jets are, after all, one of a dwindling number of technologies in which the United States remains preeminent—a lead that could quickly be lost to emerging competitors in Europe, the Soviet Union, or Japan.

From his vantage point as Air Force manager of the project, Petty confesses: "My basic problem is I'm like a kid in a candy shop. There's so much good stuff out there, and we won't be able to afford to do it all. That's tough for people who love technology."