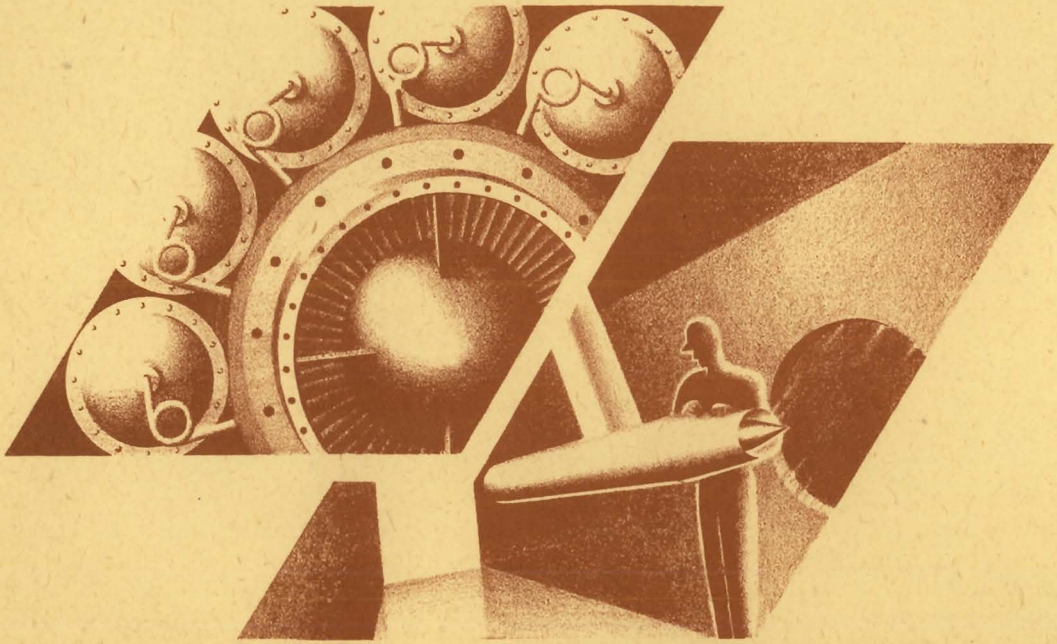
1951 INSPECTION

LEWIS FLIGHT PROPULSION LABORATORY

NACA

CLEVELAND, OHIO



welcome.....

The National Advisory Committee for Aeronautics welcomes you to the 1951 Biennial Inspection of the Lewis Flight Propulsion Laboratory. The discussions and demonstrations of this year's Inspection are representative segments of an integrated and comprehensive program of propulsion research. New tools and techniques devised to carry forward this research will be shown.

Ten years ago, the first of the Laboratory's facilities was still under construction. Since then, the introduction of many new engine types for aircraft and missile use has increased enormously the scope of propulsion research. It has become apparent that in addition to searching for immediate answers to urgent questions, we must gain also a better understanding of the fundamental properties of the metals we use and the fuels we burn. To insure that the limited research effort possible be expended most wisely, it has become necessary to analyze, almost continuously, the problems the goals, and the directions our investigations should take.

We enjoy greatly this opportunity to greet again old friends and to become acquainted with those who visit us for the first time. We hope your visit and inspection of our facilities will prove worthwhile.

J C Hunsaker

Chairman
National Advisory Committee for Aeronautics

Propulsion research requires integrated group effort

On January twenty-third of this year, the staff of the Lewis Flight Propulsion Laboratory paused briefly to note the tenth anniversary of the breaking of ground on the site of the NACA's new engine research center. The anniversary was an occasion for a brief look backward; it was also a time for consideration of present requirements and, most important, for charting of future research goals.

In 10 years the Lewis laboratory has grown from an engineering staff of 125 and an appropriation of $8,000,000 for research facilities to a complex but smoothly operating organization of 2700 trained research and technical personnel, with facilities now in use and under construction valued at more than $100,000,000. In this same period America has made great progress in the design and construction of aircraft engines; today our power plants are as powerful as any in the world.

If our engines are as good as the best, why should we continue to spend more money and more effort at the Lewis laboratory to broaden still further our understanding of the fundamental principles of propulsion? The answer is twofold. One part is to be found in the skies over Korea. From what can be learned there it is obvious we cannot rest upon past accomplishments. Second, although we have learned how to design and manufacture immensely powerful engines - turbojets, ram jets, turbine propellers, and rockets - we have yet to learn how to make them really economical in their use of fuel, and how to make them entirely of the materials plentiful on our continent. We have yet to learn how to exploit fully the potential of jet propulsion, and how to make best use of it.

In the attainment of these goals we must make use not only of the experience and accomplishments of the past, but also of a specialized and somewhat artificial type of experience known as scientific research. Cultivated and controlled types of experience which we call theoretical and experimental research must be

employed to supply the additional elements which make progress possible. There must be present also the catalyst, vision, which can transform a mass of scientific and technical facts into usable knowledge.

Once theoretical concepts have been established, they must be proven by actual test. This is applied research, which may be of a very specific nature directed to limited objectives, or of a very general nature directed to broad objectives. Once it has been learned that the "bits and pieces" will work individually, it is still necessary to determine that the "grand design" can stand the test of use.

In the performance of its work the Lewis laboratory must be more than a loosely knit confederation of experts, each working on problems in his particular field of accomplishment. Today, even in the matter of conception, group effort is necessary. The problems now faced are individually so difficult, so complex, and so intermingled with other equally difficult and complex problems that an entirely new order of team activity is required. The laboratory staff must be composed of teams of specialists with knowledge of more and more scientific fields. These teams in turn must be welded into a single-purposed organization exploring deliberately and intelligently the aircraft propulsion problem.

In this way alone can the Lewis laboratory make its most effective contribution to the nation. In other places scientists are studying aircraft fuels, and doing good work. Elsewhere other scientists are seeking to solve the critical materials problems, and making progress. Elsewhere scientists are working on other problems, and profitably. At the Lewis laboratory all the problems must be considered as parts of a single problem, and attacked as such.

On the following pages there are presented brief discussions of some of the problems under intensive study at the Lewis laboratory. Consider them as parts of the single problem, the solution of which demands group effort, group thinking, and group cooperation from the Lewis laboratory staff.

Compressors for specific tasks

The increasing use of gas turbines in a variety of applications, from very long-range bombers and supersonic fighters to expendable missiles, leads to a broad range of desirable compressor performance characteristics. Long-range bombers require the highest possible efficiency; fighters will tolerate a slightly lower efficiency provided a lighter-weight engine can be obtained. For transonic airplanes, the frontal area of the engine must be held to a minimum, imposing on the compressor the requirement of large air-handling capacities per unit of frontal area.

Desirable compressor characteristics are high efficiency, high pressure ratio, light weight, and small frontal area, but no compressor type can best meet all these requirements. Consequently, research must be carried on with several types of compressor, with the engine application dictating the final choice of the compressor of any particular power plant.

The centrifugal compressor, the first type having widespread application in aircraft gas turbines, has the advantages of good reliability, light weight, and ease of manufacture. It is, however, less efficient than some of the axial-flow types and has a low mass flow for the engine frontal area. Its applications are mainly in high-speed subsonic aircraft designed for submerged engine installations, where the much lighter weight offsets the lower efficiency. Improvement already has been made both in efficiency and in mass flow capacity. Still further performance improvement may be expected through the use of mixed-flow impellers.

Conventional types of axial-flow compressor are designed for subsonic velocities relative to the rotor and stator blades, with blading design following the usual subsonic airfoil or propeller shapes. This compressor type has the advantages of high efficiency and a relatively high mass flow for its frontal area. However, the restriction to subsonic relative velocities limits the wheel speed of the rotor, resulting in a relatively low pressure ratio per

compression stage. Consequently, many stages are needed to obtain a high over-all pressure ratio, and this requires as many as 4000 blades. Not only that, but the blading differs from one row to the next, requiring many different kinds of blade in a single compressor. Research is being conducted to find ways of increasing the amount of work done by each stage in the axial compressor, and one approach is to increase the camber, or curvature, of the blades. Experimentally, it has been determined that boundary-layer removal from the suction surface of the stator blades enables appreciably higher turning angles, before encountering flow separation from the blade surface, than now is possible with standard blading.

A second type axial-flow compressor, one which is comparatively new, is called transonic, because the speed of the air striking the rotor blades ranges from high subsonic at the roots to low supersonic at the tips. With removal of the air-speed limitation within the compressor, it is possible for the designer to use high inlet velocities with greater mass flow and increased total engine thrust. Blading for this type of compressor has the sharp-leading-edge and thin-cross-section characteristics of supersonic airfoils, with a substantial increase in curvature from tip to root.

Such a compressor could have immediate and profitable application in existing axial-flow engines and would enable substantial thrust-output increase without the long delay of designing and putting into production an entirely new power plant.

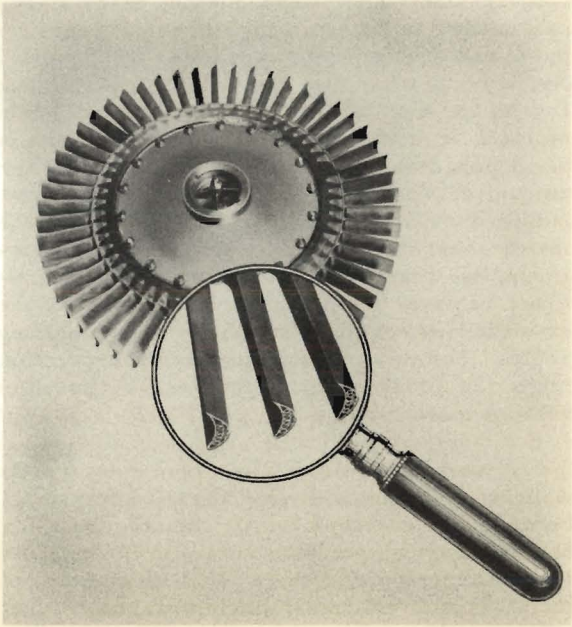
Supersonic compressors are those in which the velocities of the air relative to the rotor are entirely supersonic. With use of rotor tip speeds as high as 1600 feet per second, pressure ratios from 2.0 to 6.0 in a single stage may be attained depending on the rotor design. Two methods of utilizing the supersonic velocity in the rotor are being investigated. One of these has blading which decelerates the incoming velocity through compression waves caused by changes in direction of the blade surface. The other has blading designed for a large amount

of supersonic turning. This may be efficiently accomplished provided strong shocks in the rotor passage are avoided.

Cooling for turbine blades

Of all the complex and expensive rotating parts that go into a jet engine, the turbine blades and wheel are subjected to the most severe combination of high centrifugal force, hot corrosion, and extreme operating temperatures. Each turbine blade on the wheel must withstand the hot blast of driving gases discharged by the combustion chambers.

At the same time, the root section of the blade must support continuously a centrifugal load of about 5 tons over an area less than the size of a postage stamp. In present production engines, large quantities of the finest high-temperature alloys are necessary to achieve a practical operating blade life under these conditions. Supplies of these alloys have been adequate up to this time, but future expansion of jet engine production must be accomplished in the



Air-cooled blades installed on test turbine wheel

face of inadequate supplies and reserves of vital alloy metals, such as cobalt, chromium, and nickel.

An obvious solution to this problem is the use of cooling, both for the turbine blades and the turbine wheel, which also is made of alloys compounded of scarce materials. In addition to easing the critical materials shortage, such a solution would provide greater power output for an engine of given size fabricated with high-temperature alloys, because higher operating temperatures would be permissible.

Air cooling of gas turbines appears to be the most practicable method for turbojet engines at this time. In present practice, more than half the air that passes from the engine compressor through the combustion chambers is not burned. Instead, it is used to dilute the burning gases to reduce their temperature to the limits imposed by the structural members of the engine, especially in the turbine. A logical solution is to use a small part of this excess air to cool the turbine parts, which in turn will allow more of the air in the combustion chambers to be burned, increasing both gas temperatures and power output.

At the end of World War II, the best available air-cooled blade design was a simple hollow shell cooled by air bled from the main engine compressor, through the turbine wheel, but the air flow required was prohibitive. Fundamental heat-transfer studies pointed to the need for increasing the surface area within the blades to be cooled, and the most practicable means for accomplishing this seems to be packing the coolant cavity with small tubes.

The result is a blade relatively easy to fabricate and with satisfactory cooling. Other possibilities suitable for quantity production now are being explored. If the stator blades are twisted, it is aerodynamically satisfactory for the turbine blades to be straight, which also eases the production problem.

Investigations have shown that as the quantity of cooling air provided for the blades

and wheel is increased, there is additional cooling, but this gain is progressively smaller. Fortunately, the amount of air required for economical cooling with the tube-filled blades is relatively small, less than 5 percent of the total air flow.

From temperature reductions already obtained by air cooling, it now appears possible to build turbine wheels and blades of steels more plentiful and cheaper than the high-temperature alloys now used. In time of emergency, this would be of utmost importance in production of engines in the numbers which are required by the military services.

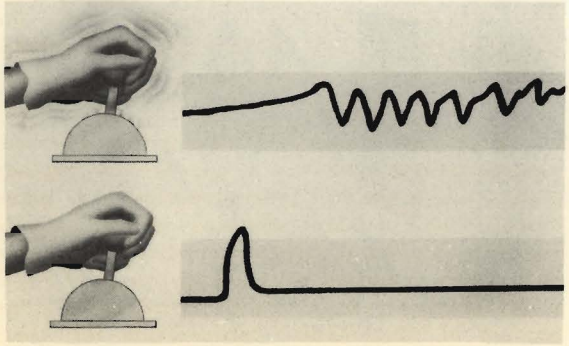
Replacing manual engine control

In order to obtain maximum thrust from a gas-turbine engine, it must be operated close to its limits of strength and endurance throughout the entire altitude range of flight. Even relatively slight variations from this near-limit operation can result in damage to the engine by excessive temperature or operating speeds. Complete failure of thrust may also occur if combustion blow-out or compressor surge takes place.

To avoid these difficulties by manual operation, it would be necessary for the airplane pilot to monitor constantly a multitude of instruments and manipulate simultaneously several control levers. At the high operating speeds of current military aircraft, to say nothing of the even higher speeds to be expected soon, the time available is too short for the pilot to observe and correct possible control difficulties in this fashion.

Automatic control systems that will permit safe near-limit operation of gas-turbine engines from a single control lever are virtually mandatory. Such control systems, providing safe engine operation at optimum conditions of thrust output and economy over a wide range of flight conditions, are extremely complex, and a large amount of fundamental information for their design is needed.

The research attack on this problem has required extensive use of the Lewis altitude wind tunnel, where full-scale engines can be studied under conditions matching those under which the power plants would operate in actual flight. In the determination of a most suitable control-systems solution a great amount of mathematical calculation is also required, and this work is speeded greatly by use of electronic computers.



Turbojet engines need automatic control systems

Actually, the Lewis laboratory's automatic-control-systems investigations follow a three-step pattern. First, the condition to be remedied for a specific engine is studied in the altitude wind tunnel. An example might be analysis of one of the most serious difficulties that must be overcome by proper design information, the oscillation of engine thrust which may occur in some cases at high altitudes. This particular oscillation may be so violent as to make effective combat impossible and result in rapid destruction of the engine. Such thrust oscillation would be found and measured on the specific engine, when it is operated with afterburning at high-altitude conditions in the tunnel.

The second step would be to chart a solution, utilizing information obtained in the altitude wind tunnel and by use of electronic computers. Once final calculations have been made, a control system would be constructed incorporating the data. The final step would be operation of the engine, equipped with the new

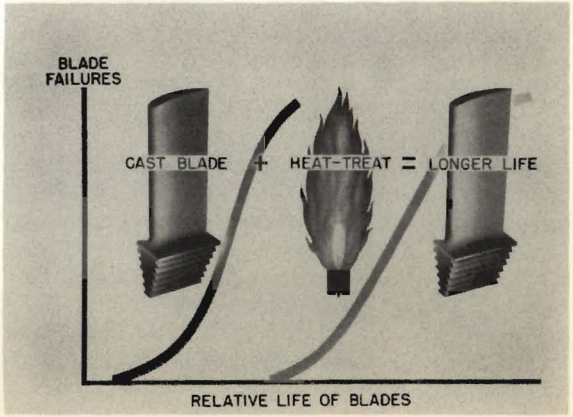
automatic control system, under the same conditions which previously had resulted in the destructive thrust oscillation.

Results obtained to date have been both encouraging and gratifying. It may also be said that the control problem will be lessened in the days ahead.

Progress made with ceramals

The present requirements for engine production are staggering when compared with the amount of presently used high-temperature alloy material available. In the event of full-scale war, the material shortage problem could be crippling. At the Lewis laboratory major effort is being directed at strategic material conservation, especially in the turbine wheels and blades which operate under the severest conditions of temperature and stress, and contain the largest amount of critically short materials.

Several approaches to the problem have been taken. One of these, discussed elsewhere in this booklet, is to use materials of reduced strategic element content, by reducing blade temperatures by cooling. Another approach is by the use of newly developed alloys of lower strategic content, increasing the strength where



Heat-treating improves reliability of cast turbine blades

necessary by suitable heat-treatment and improved fabrication processes.

A typical cast turbine blade alloy, which is composed of smaller amounts of strategic elements than forged blades, has in the past been unsuitable because of poor reliability and short life. However, use of such an alloy would be desirable because production facilities could be expanded rapidly and at relatively low cost, in addition to the greater supply of material content. Research has shown that large improvements in both reliability and life can be obtained if the processing variables can be controlled to optimum values. Significant gains in blade life have been possible with heat-treatment of the blades after casting, and additional improvement may be possible through further casting-technique research.

A third is by use of materials containing ceramics. Although ceramics possess excellent strength at high temperatures, in their pure form they lack thermal shock resistance and shatter under sudden temperature changes. Consequently, in this form, they cannot be readily used in turbine blades because of the severe thermal shocks which are experienced.

It was reasoned, however, that if blades could be made of a mixture of a ceramic and a metal, it might be possible to combine the good qualities, the strength of the ceramic at high temperatures with the thermal shock resistance of the metal. After preliminary investigations had indicated that such ceramals, combinations of ceramic and metals, might have adequate thermal shock resistance for turbine blade application, intensive work has begun to find means of actually fabricating and using such ceramal blades.

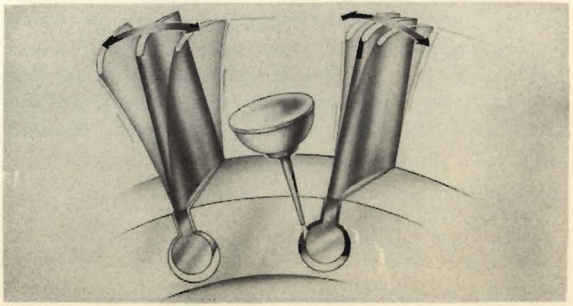
A powder-metallurgy technique, sintering, is used to fuse the ceramic and metallic materials into the complex turbine blade shapes desired. Good results have been achieved, but further study of the fundamentals of sintering continues.

Blades made in this manner were tested in a turbojet engine under full operating conditions and brought out a new problem. The ceramal blades had the conventional fir-tree type of fastening at the root, but it was found that the high stress concentrations set up in the sharp corners of the fastening caused failures. By redesigning the root to reduce the stress concentration, it was possible to produce experimental ceramal blades capable of use in an engine operating at full rated speed, temperature, and power output.

The ceramals give promise of even longer life than high-temperature alloy blades at current operating temperatures. The potential superiority of ceramals over alloys would be even more pronounced if gas temperatures were increased. Before the possible advantages of ceramal blades can be fully exploited, however, further research is required on problems associated with their design, fabrication, and use.

Blade vibration can be lessened

An important cause of failure of rotating blades, especially in the axial-flow compressor of a turbojet engine is vibration. This has been a problem demanding immediate solution in order that remedial action could be taken to give engines in production longer service life. One of the most important sources of vibration is stalling flutter, a condition in which the compressor blades vibrate as reeds in a strong wind.



Blade vibration minimized by use of dry lubricant

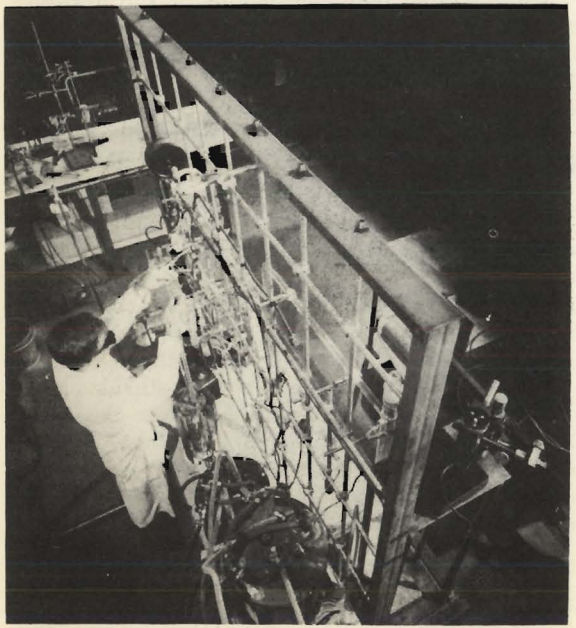
Compressor blades normally operate at very high angles of attack, near the point of aerodynamic breakdown, or stalling. Investigation of one engine showed that the critical velocity which starts this stalling was actually being encountered, with a resulting high rate of blade failures. Reduction of the angle of attack made the appearance of stalling flutter less likely. This was accomplished merely by twisting the guide vanes in front of the compressor stage where the blades were failing. No loss in efficiency of the compressor occurred as a result of the change in guide vane angle.

A second remedy has been introduction of enough damping action in the blade mount to overcome the aerodynamic excitation of the wind stream. In the conventional method of blade mounting, when the engine is operating, the centrifugal pull on a blade is so great that it is effectively locked in the mount and it is difficult to introduce damping. If a thin film of dry lubricant is introduced between the blade and the mount, then the locking action is minimized and damping can be effectively achieved. Use of this technique, when applied to compressor blades, reduced the stress amplitude to about one-third its former magnitude.

What causes materials to fail ?

In continuing the search to discover ways of building even greater strength and endurance into aircraft power plants, it is becoming increasingly urgent that more be learned about the fundamental properties of engine materials, thus to achieve increased strength or longer life at high stresses and temperatures. Specifically, it is hoped to find the basic causes of failure, to predict the effects of thermal and mechanical treatments on properties, and to supply information for use in the design of materials possessing specified properties.

Such fundamental research is long range; it may be years before benefits resulting from it can be incorporated into engine design. But it is vital work, a part of the integrated, planned



Scientist studies materials behavior at 5000° F

program of materials research at the Lewis laboratory just as much as are projects like the study of blade vibration, which is producing information of immediate value, or of other studies, such as work with ceramals, which promise to be useful in designing tomorrow's engines.

Materials used in aircraft engines are never in a fully annealed state. Such properties as tensile strength and creep resistance are made higher than in the annealed state by such treatment as forging or heat treating. In use, however, these desirable properties disappear and failure results because of the high temperature and stress. To enable choice of proper original treatment for the material and to prevent, or delay, deterioration of its properties in use, it is essential that a better understanding be gained of the basic factors changed by metallurgical treatment, and also the connection between these basic factors and the strength properties of the material. This fundamental

problem is being attacked both experimentally and theoretically.

Measurements of the energy released when the temperature of a swaged or twisted piece of metal is slowly raised are being made. If two pieces of metal, identical except that one has been drastically cold-worked, are placed in an insulated enclosure and heated at the same rate, the temperature of the cold-worked specimen will be higher than that of the annealed specimen in certain portions of the run. This is due to an evolution of heat. From the amount of heat evolved, in conjunction with the theory of crystals, it is possible to deduce details of the basic differences in atomic arrangement between the cold-worked and the annealed samples.

If a bar of metal is set in vibration by an impulse, such as striking, the duration of the vibration will be longer if the metal is annealed than if it is cold-worked. Using samples similar to those described above, measurement is made of the internal damping of annealed and of cold-worked bars. The results of this type of measurement can be interpreted theoretically in terms of the motion of dislocations and the trapping of dislocations at centers of disturbance, and therefore additional information as to their distribution can be obtained.

Wanted: test blades made quickly

Every advance in compressor research is based upon the acquisition of new understanding of the laws governing internal aerodynamics. This process involves use of complicated theories of compressible fluid mechanics, and as each new concept is formed, it becomes mandatory to secure experimental proof of its soundness before a further step in the reasoning process can be confidently taken. This transformation of mathematical equations into pieces of metal must be rapid and inexpensive; above all, it must be accomplished with utmost accuracy.

One area of work where new concepts are being projected most vigorously is compressor blading. In this fundamental research, use is

made of single-stage compressor test rigs to study the effect on performance of various design variables such as blade twist. In the investigation of more complicated problems such as multistage effects, it may be necessary to work with several stages or even with complete compressors. A compressor designed for high over-all pressure ratios may have as many as 4000 blades. Although the quantity of any single design may be small, the total number of experimental blades required is large indeed.

To provide such quantities of experimental blades, development of special equipment has been necessary. This is in addition to use of commercially available machine-shop equipment. By striving always to minimize the amount of tooling necessary to reproduce a new blade shape, it has been possible to speed the production processes whereas costs of individual blades have been reduced.

During the past year considerable improvement has been made in the method of reproducing an airfoil section. Working directly from a greatly magnified drawing of such a section, the specially developed machine quickly reproduces the desired section in thin metal. As soon as the several sections making up a blade have been machined in this manner, they are stacked in order and become the master template for the entire blade.

A further advance in the techniques eliminates the need for making templates. In a new device that enables this production shortcut, mathematical information concerning the design of the blade desired is fed into an "electronic brain" which then transmits impulses into machining equipment that cuts the blade shape out of metal. Only recently put into operation, this new development already has been used to cut a number of airfoil sections.

New instrumentation required

In the conduct of intensive, integrated, aircraft-propulsion research an urgent problem has been that of developing new adequate instrumentation. Accurate, simultaneous measurement must be made of temperature and

pressure at hundreds of locations in a test engine during operation. New devices must be developed to provide information about, for example, temperatures 1000° F higher than the melting point of instrumentation originally used. Finally, means must be found to permit rapid reduction to useful form of the tremendous quantities of data recorded.

The most widely used heat-measuring device has been the thermocouple, which has the advantages of being inexpensive, easily reproducible, and compact. A conventional thermocouple is unsuitable for measurement of the rapidly fluctuating temperatures inside a power plant because of a lag in the response to temperature change and also because it is not mechanically strong enough. To make it more rugged alone would have increased the response lag; however, by introduction of an electrical lag-compensator, it becomes possible to make the thermocouple sturdy enough and still capable of providing accurate, fast response measurements.

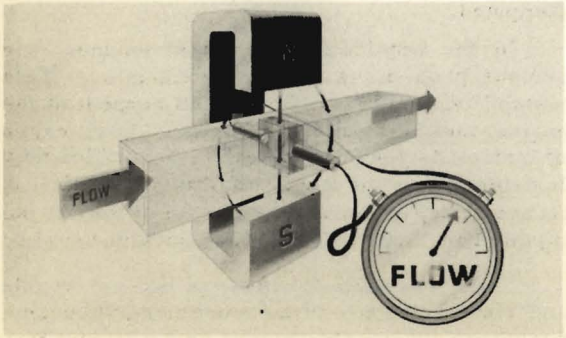
Especially in the investigation of afterburning problems, the research scientist needs to measure temperatures far beyond the upper limit of standard industrial thermocouples. The solution here involves careful measurement of the amount of cooling, provided through tiny tubes leading to the base of the thermocouple, required to maintain it at a constant temperature well below its melting point. From this information, the desired information about temperature within the operating engine can be computed.

In the application of rocket engines, one serious problem is unsteady combustion. This instability may bring about rapid burnout of the engine; fuel lines may be broken. In all cases of instability, there is a great loss in efficiency. In determining the cause of this instability, it is necessary to measure the rate of flow of the liquid propellants while the engine is under test.

Since available flowmeters did not enable sufficient accuracy of measurement, it became necessary to develop a new instrument which utilizes electromagnetic principles. The new

flowmeter responds rapidly to variations of flow rate and has the advantage of not requiring insertions of moving parts in the flow passage. At present, with this device flow of such liquids as water, acids, alcohol, and acetone can be measured. With further development it is believed that flow rates of hydrocarbon fuels can also be measured.

The conventional method of recording pressures from as many as 300 pickup points in



Electromagnetic meter gives accurate flow rate

an operating turbojet engine has been to connect the pressure probes to a manometer board, of which photographs were taken at frequent intervals. Then it was necessary for a computing staff to read the films with magnifying glasses, record the data, and perform necessary calculations to reduce it to useful form. This process is long and tedious; it is also costly. Because of manpower shortages, there have been long delays between taking of recordings and analysis by the research staff. As many as 5000 pressure readings would be taken in this manner during a single test run of an engine. To process such material gathered throughout the laboratory in an average day, 100 man hours of effort are now required.

When test facilities now under construction are completed, the accumulation of data will be tripled. A first step to streamline the recording and reduction of measurements has been the use of punch card machines to calculate the data, but the bottleneck of this method is getting the data onto the cards.

The answer has been development of auto-

matic equipment which records both pressures and temperatures on tape and then transmits this information to punch cards. Further work to improve existing equipment continues, but already it is possible to compute from a turbojet engine test such information as air flow in the engine, thrust, specific fuel consumption, and compressor efficiency, and to accomplish this task within 15 minutes from the end of the run.

Keeping the fire lit at altitude

The first turbojet engines developed and built in this country were suitable only for low-altitude flying at moderate speeds. With the use of the unique test facilities at the Lewis laboratory, it became quickly apparent that these early engines would blow out, under certain operating conditions, at altitudes as low as 10,000 feet and that fuel economy was poor largely because of low combustion efficiencies. In order to increase the flight speed, altitude ceiling, and economy of operation of jet aircraft, an intensive research program was begun to improve combustor performance. So that the United States could ultimately assume leadership in the jet engine field, this program included both fundamental and applied research on the turbojet, ram-jet, and rocket engines.

A major part of the long-range research program was a study of the basic combustion processes of combustible-mixture preparation, ignition, and flame propagation. These processes which, in jet engines, occur in sequence in a total time of less than 0.01 second had to be developed to meet the demands for increased flight speed and higher altitude ceilings.

Studies of the mechanism of spray atomization, high-speed motion-picture observation of the mixing of fuel and air in the combustor, and research on the effect of fuel properties on combustor performance enabled the designer to obtain higher power outputs from smaller combustors along with greater economy due to more efficient utilization of the fuel.

These improved engines operating under the more severe conditions of high altitudes and low temperature created the need for better

ignition systems. The combustor could operate under conditions at which ignition could not be accomplished if the flame should blow out during maneuvers. Fundamental research on the proper ratios of fuel and air required in the vicinity of the igniter, as well as the amount of energy necessary to initiate flame in such mixtures, enabled the designer to raise the ignition ceiling to correspond to the operations ceiling.

At the same time the high-speed combustion process of the ram jet and rocket were being developed and new fuels capable of releasing large quantities of energy per pound and per cubic foot of fuel were found as well as fuel capable of burning at two to three times the velocity of conventional fuels.

These advances in the different engines required not only extensive theoretical study and basic experimentation on combustion processes, but also the study of actual combustors under conditions simulating the most severe flight problems, and, finally, the testing of full-scale engines under these same conditions. Since the ultimate test of the research progress on the combustor is the behavior of the entire engine, the Lewis laboratory facilities must keep in step with the greater air demands and higher altitude ceilings of the improved engines in order to determine their operating limits.

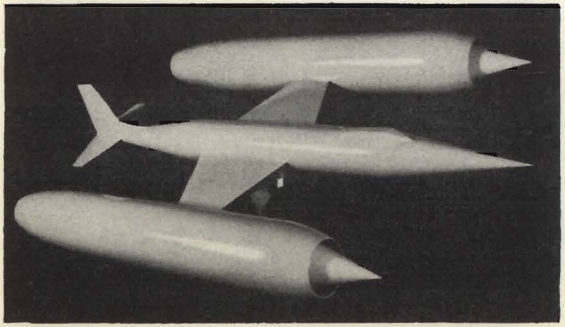
The combined research on fundamental processes, engine components, and full-scale engines has more than doubled the flight speed of jet aircraft and increased the altitude ceiling more than four fold in recent years. Current research promises even greater future gains. Close work with engine designers and manufacturers has made it possible to contribute greatly to the technical excellence of our country's aircraft.

Twice as much with "reheat"

One of the most spectacular accomplishments in the field of aircraft propulsion research in recent years has been the work which resulted in development of the afterburner for the turbojet engine. Fundamental research at the Lewis laboratory on the prob-

lems involved began more than 5 years ago and progress has been made to the point where it can now be said this "reheat" device enables the pilot to more than double the useful thrust of his engine at supersonic speeds with only a slight increase in weight and size of the engine.

Basically, the afterburner is a ram-jet engine installed in the tail pipe of the turbojet engine. It is an auxiliary power plant characterized by the simplicity of its concept and application. Fuel burned in the exhaust pipe of the turbojet engine increases the temperature of the gases flowing through the engine, and results in an increase in jet velocity, which produces the greater engine thrust output desired.



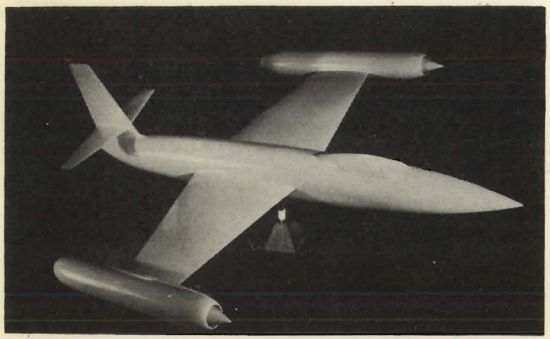
This hypothetical 1350 mph airplane lacks afterburners

Elsewhere in this booklet are pictures of two model airplanes which illustrate graphically the importance of afterburning. Each of the models is of a hypothetical airplane designed to fly at 1350 miles per hour. One model represents the design which would be possible using turbojet engines equipped with afterburners. The other model, a design so unrealistic and impractical as to be worthless, is equipped with the huge nacelles which would be required to house turbojet engines, not equipped with afterburners, sufficiently powerful to attain the desired speed.

Operation of afterburners is accompanied by several problems, including combustion efficiency, altitude operating limits, ignition, and combustion stability. Research on all these problems continues, utilizing all the major

altitude and sea-level facilities of the Lewis laboratory.

With great emphasis presently focused on airplanes capable of flight at supersonic speeds, new problems are introduced in the design of afterburners. There is urgent need for maximum thrust augmentation resulting in extremely high gas temperatures - 1500° F above the melting point of the best high-temperature alloys now used in tail-pipe construction. Obviously, some means of cooling the burner shell must be found which will not penalize airplane performance unduly. Another major problem imposed by supersonic flight is the increased velocities through the afterburner and the consequent difficulty of maintaining combustion within the burners.



This hypothetical 1350 mph airplane has afterburners

This work of transforming simple research concepts into practical engine components that can be used in flight is being accelerated. Much yet remains to be accomplished under the impetus of providing the military services with airplanes of ever increasing speed and range and of meeting the requirements of flying at higher and higher altitudes. In this task, those engaged in research and production are working intimately and effectively.

Maneuvers affect engine output

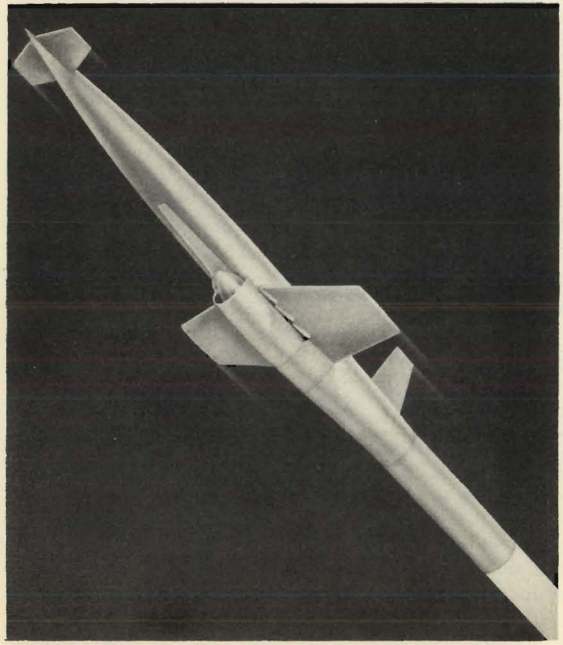
With missiles flying faster than twice the speed of sound and tactical supersonic airplanes a certainty, it is necessary to give

immediate research attention to the problem of how to eliminate or lessen the serious effects upon power-plant output imposed by flight maneuvers. At the same time study must be continued on problems of further improvement of engines for such high-speed flight, and on the additional problems created by the mating of the power plant with other components of a supersonic airplane or missile. One of the most valuable research tools available for such work is the Lewis 8- by 6-foot supersonic tunnel.

Among factors influencing the thrust of supersonic air-breathing engines, the most important from an engine installation viewpoint is the total pressure "felt" by the engine inlet; a 25-percent pressure loss, for example, between the free-stream and the combustion-chamber inlet will result in a 35-percent thrust reduction. Although pressure losses are not wholly avoidable, the inlet problem has been explored and data assembled to enable design of inlets giving good engine thrust at twice the speed of sound, at zero angle of attack. However, the problem remains that if the angle of attack is increased to 20°, as might be essential during climb of a missile, pressure losses would be so large as to reduce engine thrust to 70 percent of the output at zero angle of attack.

To provide a missile with certain control advantages, it is desirable to locate the horizontal stabilizing fin as a bow plane at the front instead of at the rear. This breaks up the uniform supersonic flow field ahead of the missile and the resulting disturbances, which trail rearward, may seriously affect engine performance. Besides being a region of disturbed flow, this is also a general area of reduced pressure. A combination of these losses would result in a considerable reduction in engine thrust at a time during the start of a maneuver where maximum power is required.

Because such pressure-reduction effects are not a steady operating condition, there is no easy solution to this sort of power-plant installation problem. Instead of an isolated problem demanding solution, the research scientist is faced with a complex assortment of questions



Supersonic missile model with buried ram jet

requiring complete evaluation through the whole range of anticipated flight conditions for several possible power-plant locations. The installation position finally chosen undoubtedly will represent a compromise which permits the missile to perform its intended mission, in all particulars, most capably.

With respect to installations where the engine is submerged in the fuselage instead of in nacelles, it is important, to avoid undue thrust losses, to remove adequately the boundary layer, or low-energy friction layer, that forms along the fuselage surfaces ahead of the engine inlet. When it is impossible to position the submerged engine so as to avoid the boundary-layer problem, it becomes necessary to incorporate a boundary-layer removal system.

The problem is complicated by the variable influence of the bow plane on the boundary-layer distribution. Research is underway to determine the best compromise for a fixed removal system and the possible advantages of an adjustable system.

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