1954 NACA INSPECTION

LEWIS FLIGHT PROPULSION LABORATORY
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WELCOME . . . .

The National Advisory Committee for Aeronautics welcomes you to its 1954 inspection at the Lewis Flight Propulsion Laboratory.

The researches of the Lewis laboratory are concentrated upon problems requiring solution in order to provide the more powerful, more efficient engines needed for tomorrow's airplanes and missiles of superior performance. Its work is integrated with the investigations of aerodynamic and structural problems in progress at the other NACA laboratories and, in a larger sense, with the national aeronautical effort in which the Military Services, the aircraft industry, and the NACA are joined as partners.

We value this opportunity to discuss trends and new techniques in aeronautical research. We enjoy greeting again old friends and meeting with those who visit us for the first time. We hope your brief stay at the Lewis laboratory will be both profitable and enjoyable.

J C Hunsaker

Chairman
National Advisory Committee for Aeronautics

New ideas in aeronautics await exploitation

Since the end of World War II, great advances have been made in aeronautics. Our research airplanes, once supersonic flight was attained, have gone on to Mach numbers of 2 and 2.5. The first of our tactical faster-than-sound fighters have taken to the air. We have so accelerated the development of guided missiles that several are currently in service use. Yet there is no sign we are nearing the end of spectacular accomplishment.

Never in the history of aeronautics have there been so many fruitful ideas to be explored by research and never has there been a greater need for exploitation of those ideas. Urgency is a consideration which, increasingly, must affect the thinking and actions of our aeronautical team.

Because of the very large amounts of thrust required to reach higher supersonic flight speeds and provide greater range, the need for greatly improved power plants has become critical. Somehow, the Military Services, the manufacturers, and the NACA -- working as partners -- must find ways to accelerate the process of transforming ideas into the useful developments upon which our country's aeronautical progress depends.

For its part, the Lewis Laboratory has been investigating problems relating to aircraft propulsion, with greatest effort being focused on the jet engine. As a result of this effort, break-throughs have appeared at several points. New and powerful means have been uncovered for increasing greatly the performance of military aircraft. Some of these improvements represent steps forward in the progress of supersonic aircraft propulsion that are revolutionary rather than evolutionary.

In considering the current state of the aeronautical art and where we must seek to project it, it may be helpful to redefine the basic problem of supersonic propulsion. In simplest terms, it is to produce a tremendous amount of power in a small, lightweight engine, with efficiency high enough, or fuel consumption low enough, to provide the desired range capabilities.

Three engine types, the rocket, the ram jet, and the turbojet, are of special interest in efforts to meet the supersonic propulsion requirements of fighters, bombers, and both short- and long-range missiles. To a varying degree, each engine type satisfies certain supersonic propulsion requirements. Each can be improved beyond its present state of development.

In the case of the turbojet, for example, considerable gains in thrust can be realized by increasing airflow through the engine, and by increasing turbine-inlet gas temperature. Recent researches have shown how to accomplish both objectives. Improved turbojet compressors have been built and tested which not only have greater air capacity and are lighter, but in addition develop higher pressure ratio and have higher efficiency.

Experimental combustors have been developed which operate at high efficiency at the higher air flows. Work with cooled turbines is providing information necessary to permit

Scientist analyzes material by electron diffraction

engine operation at increased inlet temperatures.

Incorporation of such improvements in a turbojet engine will provide the increased power output, with less weight, to propel tomorrow's supersonic aircraft at faster speeds. But what about long-range requirements for our faster-than-sound aircraft? Range, too, may be extended by the improvement of engine efficiency. It may be necessary also to seek the means of obtaining more energy from a pound of fuel.

Space prevents discussion here of research on ram-jet or rocket problems, but it may be said that in these areas, also, good progress is being made. Especially as power plants for supersonic missiles, these engine types offer much promise.

The task ahead, of developing the engines required for tomorrow's high supersonic flight speed, is very difficult. It can be accomplished only by strenuous effort on the part of talented workers in many fields. But difficult though it may be to reach, the goal appears in clear sight.

Beyond all this lies the possibility that we, or another nation, can successfully apply nuclear energy to supersonic aircraft propulsion. If and when that becomes possible, range will be extended to the point where it is limited only by human desire and human endurance. Our national security requires that the research and development of nuclear power plants for aircraft be carried forward with unceasing effort.

Nuclear energy for aircraft

The power required to propel an airplane at supersonic speeds is very large, as much as five times the amount needed to sustain the same airplane at subsonic speeds. It has become increasingly apparent that if supersonic aircraft are to possess the long-range capabilities required, a way must be found to breach the fundamental limits inherent in engines using chemical fuels.

One obvious way to extend the range of supersonic aircraft would be to utilize nuclear energy for propulsion. Fission of a single pound of uranium will produce as much heat as burning 2,000,000 pounds of gasoline. Stated another way, the total energy which can be obtained from the "burn-up" of a single pound of uranium equals the energy in 3,500,000 pounds of coal, yet the uranium would be a one and one half inch cube against 32 railroad cars of coal.

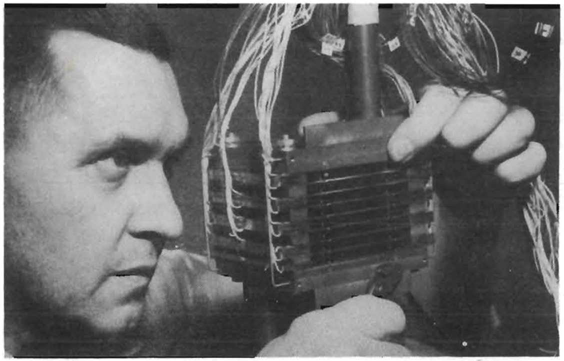
There are many ways in which the heat generated in a nuclear reactor can be converted into power or thrust. One of the simplest is to use the reactor to do the air-heating job in a turbojet engine in place of the usual combustion chambers where chemical fuel is burned.

Unfortunately, the rate of heat-transfer

Scientist adjusts high-temperature corrosion furnace

to air is relatively low, and the amount of power required for supersonic flight forces use of larger and heavier reactors. Shielding problems for a small reactor in an airplane in themselves are serious; they ar greatly intensified by the need to utilize a larger reactor.

Shields must be constructed from several materials to protect against the different



Heat exchanger is instrumented for reactor studies

kinds of radiation. For example, water or paraffin may be used to stop fast neutrons. Cadmium or boron can be used to absorb slow neutrons, and lead can be employed to stop gamma rays. The weight of the resultant shield is presently extremely heavy; in fact, so heavy as to make it most difficult to design a nuclear-powered airplane with the desired performance. Much study on the best combination of shielding materials, as well as the relationship with respect to the reactor and the crew, will be necessary to obtain the necessary weight reductions.

Another approach is to obtain sufficient heat release from a smaller reactor by cooling it with a liquid which then transfers the heat to the air in the engine using a second heat exchanger. Reactor parts such as fuel-element parts and heat exchangers must have high strength at high temperatures, satisfactory corrosion resistance, and ability to withstand the effects of intense radiation.

Any material in a reactor absorbs neutrons; materials with a tendency to absorb neutrons readily are said to have a high capture cross section, and are unsuitable because such high absorption would deplete the neutron supply and interfere with the fission process. Aluminum is low on the capture-cross-section scale but lacks high-temperature strength; iron is higher on the scale but by careful design it is possible to use iron-based alloys which have high-temperature strength.

At the high temperatures involved, some coolants react with and corrode the material over and through which they flow; material dissolved from the reactor heat exchanger may be deposited on the cooler surfaces of the air heat exchanger, weakening the structure and plugging the flow passages.

Because of the high flux of radiation present in the reactor, the characteristics of materials used may be altered. Molecular structure may be broken down; there may be changes in brittleness, hardness, strength, and dimensional stability. The radiation stability of materials considered for nuclear power plant construction is a factor of great importance.

Both experimental and analytical investigations of the many problems of nuclear aircraft engines are necessary. Often problems are so complex as to require development of novel facilities which can be used to split them into their several parts for piecemeal study and solution.

The performance capabilities to be realized from harnessing nuclear energy for aircraft propulsion would be nonstop supersonic flight to any point on the face of the earth, and return. With so large a gain the goal, industry, the Atomic Energy Commission, the Military Services, and the NACA are participating in vigorous, sustained attacks on the formidable technical problems that must be solved.

Full-scale research is vital

Experimental full-scale engine research, as conducted at the Lewis Laboratory, performs two functions which are important in the over-all effort of learning how to make aircraft and missile engines more efficient and powerful. Most of this work is carried on in facilities which provide the means of simulating on the ground the conditions which would exist in actual flight.

Components of an aircraft engine not only must have good individual characteristics, but their operation must be in harmony with that of all related parts. For example, in a jet engine, the compressor must operate efficiently under the flow conditions imposed by the air inlet. The combustor must operate under the varying pressures and velocities delivered by the compressor, and in turn must perform according to a prescribed velocity and temperature pattern for satisfactory turbine performance. The turbine must deliver the proper amount of power to the compressor and maintain a desired speed. Full-scale experimentation is vital in achieving satisfactory integration of component characteristics.

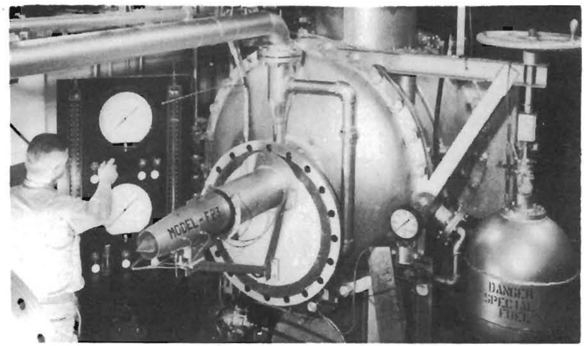
A second important function is study of new components or concepts in the environment of a complete engine. During this work, new problems are often observed, defined, and solved. Discovery of such unforeseen difficulties prior to flight testing reduces the amount of flight testing necessary and minimizes hazards to pilot personnel.

Research information is also obtained during performance evaluation and work on development problems of new engines. These programs are carried on in close cooperation with the Military Services and the manufacturers. The Lewis Unitary Plan Wind Tunnel, with a 10- by 10-foot test section and operating speeds ranging from Mach 2 to Mach 3.5, is being built to permit extension of the development testing work. The total electrical power consumption of the new wind tunnel will be about 300,000 kilowatts.

Ram-jet speeds increase

Conditions encountered in flight which cannot be readily simulated in ground test facilities include very high acceleration, with rapid changes in altitude and speed. As a consequence, the Lewis Laboratory's research with ram-jet engines has included considerable flight work with pilotless models being used. Information about engine operation is obtained by use of telemetering equipment in the models that radios data to ground receivers, and by radar-tracking of the flight path followed.

The ram-jet engine has no moving air compressor - it has been called a flying stovepipe. It depends on forward velocity to compress, or ram, air into the engine. Heat is added to the compressed air by burning fuel in a combustion chamber, and the heated air discharges from the exit nozzle in a steady, high velocity stream, giving thrust. It is necessary, therefore, for the ram jet to be traveling at high speed to produce useful thrust. Some models tested are ground-launched, using booster rockets to attain speed; others are launched from an airplane at high altitudes. Sometimes, the two techniques are combined by air-launching models carrying booster



Ground test of flight ram-jet engine

rockets. The booster accelerates the model to about Mach 2.2 after which it drops off and the ram jets take over. Both gasoline and experimental ram-jet fuels have been used.

The speed range of ram-jet engines being studied under flight conditions has been extended from subsonic in 1946 to a Mach number of about 3.5 (2310 mph) at the present time. Should it prove desirable to operate ram jets at substantially higher speeds, the problems of aerodynamic heating, discussed elsewhere in this brochure, will become important. Study of the aerodynamic heating problem has included work with rocket-propelled models which have reached Mach 5, a speed of about 1 mile per second.

Shock controls boost performance

Continuing research on supersonic ram-jet and turbojet engines has pointed to the desirability of employing shock-control devices located in the path of air flowing through the engine to obtain more efficient operation. In the case of both engine types, the performance gains from such a step appear attractive.

In the ram jet, compression of the supersonic stream of air entering the engine is accomplished mostly by shock waves. At the inlet an oblique shock wave forms. As the air passes through the shock wave, it is slowed down and its pressure increased. Inside the engine there is another wave, called a normal shock, at right angles to the air stream. Passage of air through the normal shock produces most of the remaining compression. The ideal location of the normal shock is far forward, as close to the inlet entrance as is possible without disturbing the oblique shock. If the normal shock moves too far forward, air flow becomes unstable. This buzzing can become so violent as to affect engine operation or even cause structural damage.

One means of controlling the position of the normal shock, and thus assuring most efficient operation, has been to locate a pressure-sensing device near the inlet. When the normal shock is behind the sensor, fuel flow is increased, and the higher rate of combustion pushes the shock forward. As the shock moves past the sensor, fuel flow is decreased, and the shock retreats. Tests of experimental control systems have been conducted in the 8- by 6-foot supersonic tunnel. Results indicate that shock-control systems can be successful over broad ranges of speed, altitude, and angle of attack.

In contrast to the ram jet, which is essentially an engine designed to operate at fixed speed, a turbojet intended for supersonic flight must operate efficiently over a large range of speed. One requirement for efficient operation is the same sort of position control of the oblique inlet shock and the normal shock as outlined above for the ram jet.

Ram jet missile that will "fly" at 1300 mph

Because of the range of flight speeds of the supersonic turbojet, it becomes necessary to vary the inlet opening so that the desired shock positions may be maintained. One way to accomplish this is by use of a conical spike in the center of the inlet, which moves forward to cut down flow, and retracts to increase flow. It may be necessary also to provide a bypass door which can be opened to dump excess air, and thus avoid buzzing. Inlet controls for turbojets serve only to meter the required amount of air into the engine; conventional controls are, of course, also necessary.

Crash-fire research extended —

The Lewis Laboratory's long-range studies of crash fires have been extended to include aircraft powered by turbojet engines. Much of the information gained during earlier work with reciprocating-engine aircraft -- which led to development of a successful, experimental fire-inerting system -- has been found to be applicable to the jet-engine crash fire problem. In this category is an understanding of how fuel spills during a crash and how spilled fuel moves to ignition sources.

The program followed included detail studies on the test stand. In addition, full-scale research was carried on, using service-weary aircraft on which, after the piston engines had been removed, turbojet engines were pylon mounted under the wing.

The turbojet, it became quickly apparent, poses additional problems. After a crash, its compressor and turbine continue to rotate for some time, drawing large quantities of air into the inlet. Because extensive areas of the engine remain hot, crash-spilled fuel, oil, and hydraulic fluid are likely to be ignited if they come into contact with the engine outer surfaces or are sucked into the inlet.

Extended crash-fire research produces useful information about jet installations

It was found that parts were rapidly cooled by the continuing flow of air through the engine. There was, however, a critical period of several seconds after the crash, during which all of the engine parts aft of the compressor remained hot enough to start a fire. The turbine wheel itself stayed hot enough to cause ignition for many minutes after the crash.

Because ignition occurred in the engine in only those relatively limited areas where the gas flowing through was moving at low velocity, it was found to be feasible to provide cooling by direct application of water. The steam so generated protected against ignition while the cooling was in progress. It was also determined that the outer surface of the tailpipe required cooling, and that a stainless steel screen wrapped around the tailpipe would keep water in contact with the hot surface to promote cooling.

An experimental inerting system has been successfully used in full-scale crash-fire tests of turbojet-powered aircraft. It uses water stored under pressure. Crash sensitive switches release this water. In four crashes, the barriers were positioned to cause different kinds of damage. For example, in one, the airplane ground looped; in another, the engine was torn from the wing and tumbled through the cloud of fuel spray behind the airplane. Fire did not occur in any of the crashes in which the inerting system was used.

The crash-fire studies are being continued, with ignition hazards being considered covering a variety of aircraft gas turbine engines, including ones with high compression ratio. Such factors as mechanical condition and cleanliness of the engine also are being studied.

Crash-survival chances studied

Aeromedical research has established that man can withstand very high impact loads providing their duration is short. Analysis of non-fire, crash-landing airplane accidents showed the lowest percentage of severe and fatal injuries among personnel who remain seated. This information suggested the possibility of learning how to reduce the frequency and severity of injuries in this type of accident.

By installing special instrumentation in the aircraft used in the crash-fire program, discussed elsewhere in this brochure, detailed information was gained about the forces transmitted through the airplane structure to that part of the fuselage where passengers would be. In one test it was found that loads exceeding 12g's were imposed. Under these conditions a 200-pound passenger would exert a force of more than 2400 pounds on his seat belt. Such loads might tear the passenger from his seat or the seat from the airplane structure. In either event the passenger would be likely to suffer serious injury as he was hurled about the cabin.

Other tests were conducted with light airplanes, using dummies supplied by the Military Services. The dummies possess bone stiffness, joint action, and tissue texture similar to man's. In these tests, slow-motion picture records of the dummy's reactions were obtained, as well as information about the loads imposed during a crash.

The research findings led to formulation of design requirements for an aircraft passenger seat which could absorb safely the loads imposed during a crash landing. Among the seat specifications were the following: (1) It should be strong enough to hold the passenger in place; (2) It should be capable of enough elastic deformation to absorb the shock of peak loads, but with considerable frictional damping to prevent elastic rebound; (3) It should be able to withstand shocks from any direction, since a crash-landed airplane may swing around and hit objects while moving sideways or rearward; and (4) It should be constructed of such materials that if breakage occurs, no sharp or pointed objects will endanger the passenger.

To determine whether such requirements could be met within the space and weight limitations present in aircraft construction, an experimental seat was built for study under crash conditions. Unsuited for commercial production, the seat incorporates construction features necessary for research, that interfere with passenger comfort.

The seat back, side arms, and seat-pan are air-inflated members free from structural metal parts. A body or head striking these parts would be well cushioned. Rubber linkages between the structural members afford necessary elasticity and ability to support a blow from any direction, while friction surfaces prevent elastic rebound.

Preliminary tests of the experimental seat have been encouraging. Final evaluation of this approach to seat design, however, will involve performance of the seat in a full-scale crash of one of the airplanes used in the fire-research program.

Jet reversal slows planes

Stopping a high-speed turbojet airplane, during landing, within the runway limits of today's airports has become a problem of increasing concern as the size and landing speed of such aircraft have continued to grow. Providing wheel brakes of sufficient size to do the job alone imposes too great a weight penalty. Other devices, such as 'chute brakes, have been used, but high cost and other disadvantages have served to spur the search for a better way of obtaining the rate of deceleration desired.

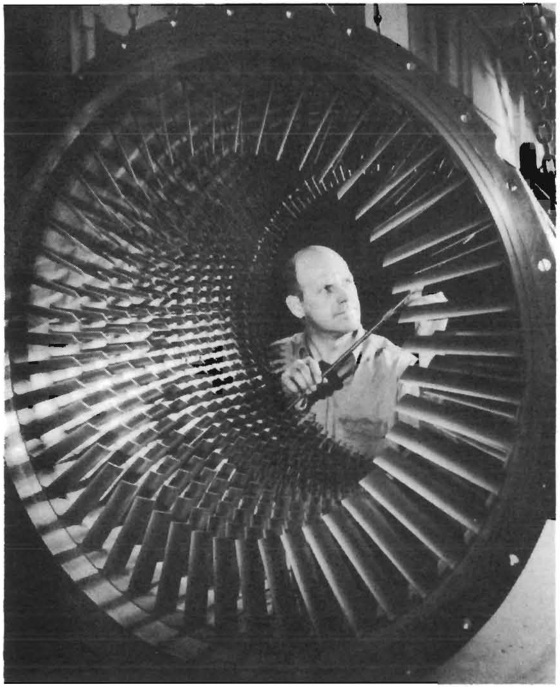
Both in this country and in Europe the idea of obtaining the necessary braking power by turning the rearward turbojet blast to a forward direction has been explored. Much work has been done on the problem, and several ways of obtaining satisfactory thrust reversal have been studied.

Basic requirements for a practicable thrust-reversal device, in addition to effectiveness and reliability, include light weight and minimum penalty on flight performance. Also, the jet stream must be reversed in such fashion that it will not strike parts of the airplane which would be damaged by intense heat.

Thrust-reversal devices which have been investigated most thoroughly fall into three broad types. Perhaps most intensively developed to date has been the so-called target type, which obtains flow reversal by positioning a cup or dish squarely across the path of the rearward jet. When not in use, the cup elements are retracted into the engine nacelle or other airplane structure. The cup must be large enough to cause sufficient flow reversal; it cannot on the other hand be so large as to impose an excessive weight or drag penalty when not in use. It must be located close enough to the tailpipe to obtain good thrust reversal, but not so close as to reduce jet flow.

A second type employs a series of thin metal rings which, when not in use, are retracted into the engine tailpipe. To obtain thrust reversal, the jet stream is deflected against the rings by an upstream air blast piped from the compressor, or by action of the jet stream on adjustable swirl vanes attached to the tailcone. As the amount of the air blast or the angular setting of the vanes is increased, more of the jet stream moves outward against the rings, which are so curved in cross section as to cause flow reversal. In this type, "cost" must be measured in terms of thrust losses during flight, caused by presence of the swirl vanes or of the blast tube in the jet stream.

In a third type, now under study by the NACA, a double set of blades located inside the tailpipe causes thrust reversal. When not in use, the blades are closed in such



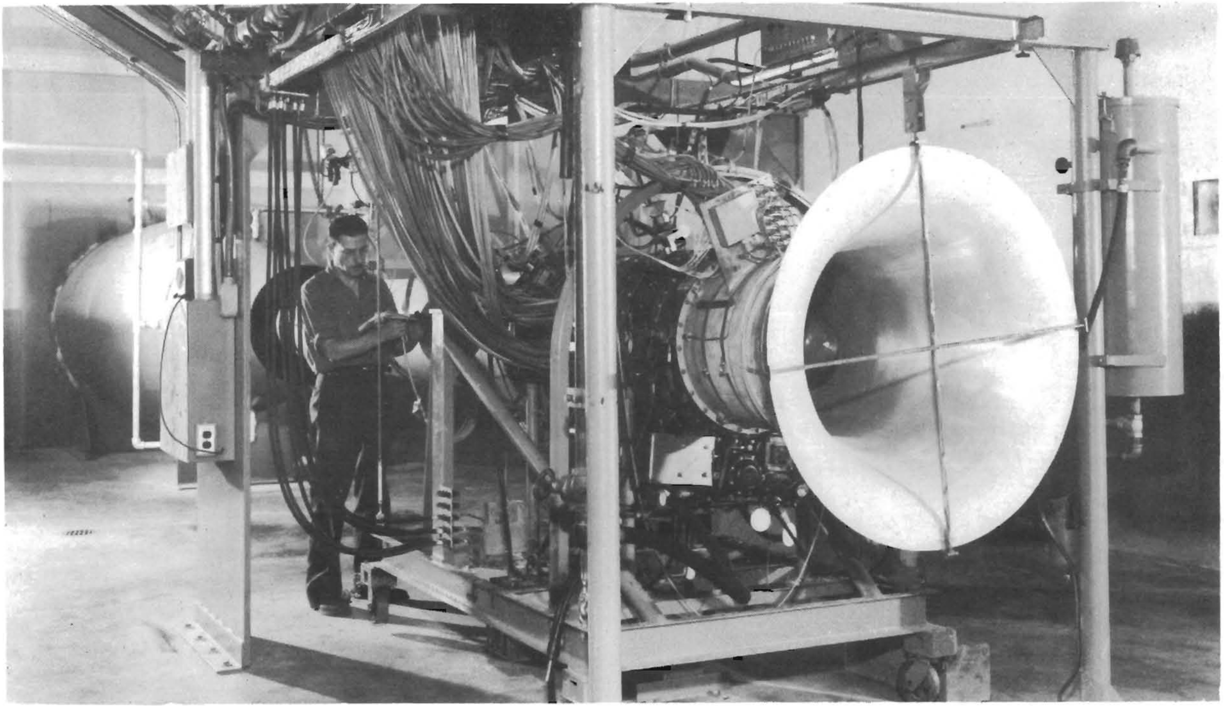
Technician checks compressor for test operation

fashion as to impose minimum drag. Although these blades impose some thrust loss during flight, this type is of interest because of its relative simplicity and also because it is possible to direct the reversed jet flow so as to avoid hitting airplane parts.

More air means more thrust

One of the most direct ways of reducing turbojet engine weight while increasing thrust output is to improve compressor design. In the research to attain such gains, it becomes necessary to solve difficult aerodynamic problems and also to gain a better understanding of the structural problems involved in the higher blade and air speeds required.

As one means of increasing engine thrust efforts have been made to increase the air-handling capacity of compressors. Reduction in compressor weight is also desirable; one means of accomplishing this is use of fewer blade rows to produce the desired com-



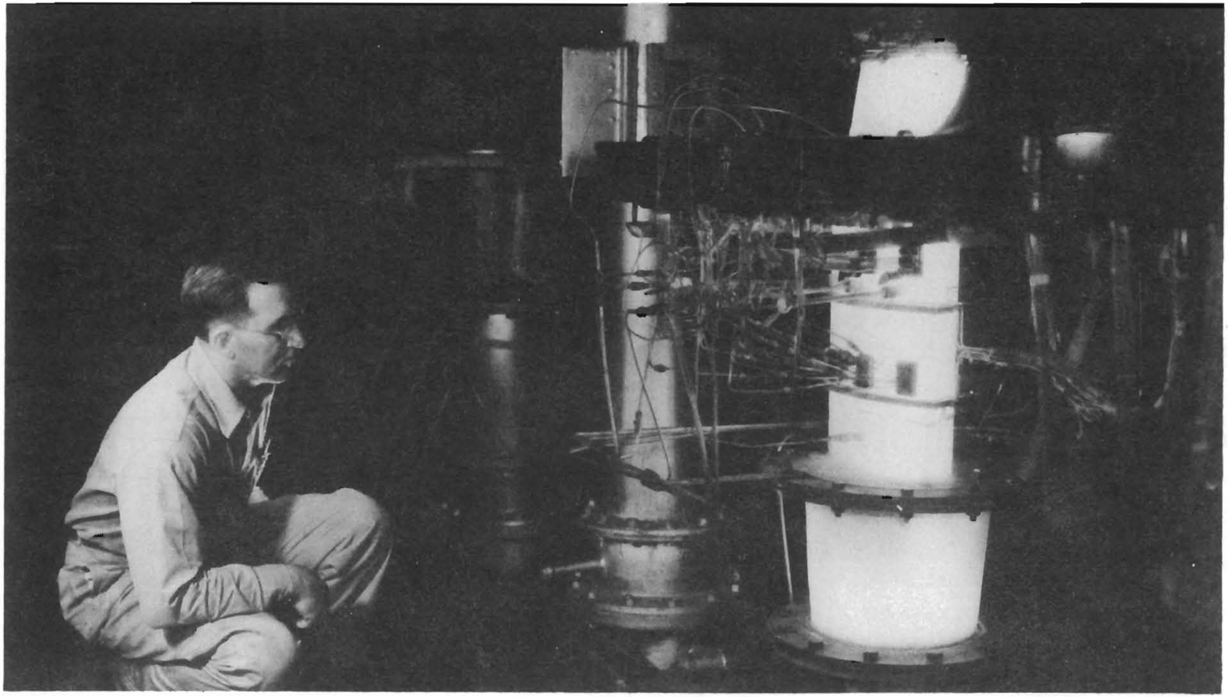
Elaborate instrumentation permits scientists to study airflow inside the compressor pression. This requires that each remaining blade row provide more compression. These objectives can be accomplished by increasing wheel speed, by removing the inlet guide vanes to increase air speed, and by reducing the hub diameters of the compressor rotor. Thus the length of individual compressor blades is increased.

These changes introduce aerodynamic problems. When the air stream passing through the compressor rises above a certain speed (about Mach 0.7 for compressors with conventionally-shaped blades) efficiency drops rapidly. The fuel required for the engine to do its job then has to be increased, thus cancelling out any reductions in engine weight. These losses in efficiency are the result of compressibility shocks and thick boundary layers. Increases in efficiency require that the compressor blades be redesigned for operation at higher speeds.

When a single blade row does more work and passes more air flow the structural stresses imposed on it are also larger. Unpredictable blade vibrational stresses encountered when the engine is operated away from its design point now require heavy construction of blades and rotors. The aerodynamic causes of these vibrations have been found to be rotating stall conditions.

Combustors must be efficient

The goal of obtaining greater thrust from a turbojet engine by increasing the velocity and thus the volume of air passing through the engine affects the performance of parts other than the compressor. If the compressor delivers more air, all other parts of the engine through which the air passes must be made capable of handling the increase. For example, research has been focused on combustors, in which fuel is burned, and more particularly, on combustion liners, which shield the combustion space from the blast of air coming from the compressor.



Experimental jet engine combustor glows red hot

In order to achieve efficient burning of the amounts of air expected to pass through tomorrow's turbojet engines. it will be necessary to maintain combustion while the air passes through the combustion liners at velocities substantially higher than those which now can be tolerated. Combustion efficiency is measured in terms of the ratio of the heat output of the combustor to the heat input of the fuel. Current combustors operate at high combustion efficiency, but today's high velocities must go still higher to handle the needed volume of air.

If other parts of the turbojet engine were improved to enable air to pass through the engine faster, and the combustors were left unchanged, combustion efficiency would drop, and there would be pressure losses sufficient to cause excessive engine thrust losses. As velocity was increased, air would pass through the combustion chamber so rapidly as to cause the flame to blow out.

In the research on combustion liners, considerable attention has been given to the size and arrangement of the air holes. Effort also has been applied to making the liners slimmer, thus reducing combustion space. As a result of the work done, combustors have been built capable of maintaining high combustion efficiency while handling air at velocities higher than that originally set as a goal. Some increase in pressure loss occurred, but it remained well within the allowable operating range.

Screech can wreck an engine

A most vexing problem, requiring intensive research for a solution, is the unsteady operating condition which may develop in turbojet afterburners and ramjets as the pressures and temperatures approach the very high values necessary to provide the desired amount of thrust. One form of instability has been called screeching combustion - it is characterized by a high pitched, intense note.

The frequency, or pitch, of the screech in a burner has been studied to determine the effects of changes in fuel flow and air velocity. The pressure variations within the burner have also been measured. Combustion screech may affect combustion efficiency.

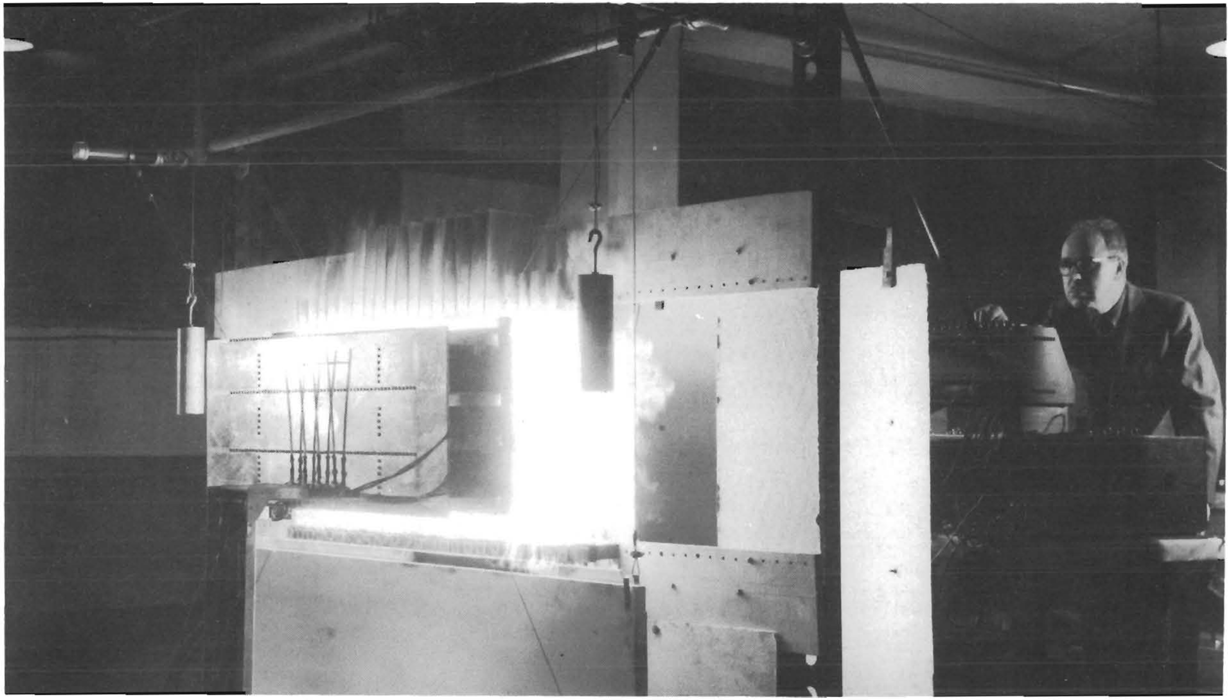
All too frequently screech is accompanied by fatigue failures of the metal burner shell, the combustion liners, or the flameholders. The scrubbing action of the combustion gases as they move back and forth against the metal, combined with the high flame temperatures, may cause the metal to weaken and fail.

Special instrumentation has been developed to enable study of the how and the why of the screech phenomenon. Tiny, water-cooled probe microphones are used to determine the sound characteristics within the burner. Ionization gap probes, which make use of the low electrical resistance of a flame, are used to study the location of the flame front and its movement. Photocell probes are employed to learn more about how the rate of heat release varies with time and location.

As a better understanding of screech is gained, it is hoped ways of controlling it may be found. They may include changes in combustor construction, and also changes of the flow conditions or the type of fuel used. Investigations of screech difficulties in several afterburners have provided the basis for new design techniques for elimination of screech.

Speeds high enough to melt metals

Continuing research is bringing a realization that, at even the relatively low supersonic speeds contemplated for tomorrow's airplanes, the effects of aerodynamic heating will profoundly aggravate already difficult design problems. The high temperatures



Radiant heat simulates aerodynamic heating reached by the airplane parts reduce their strength and stiffness. The rapidity with which the temperature rises is perhaps as important as the temperature level; thermal stresses may develop which can cause structural difficulties, like buckling, or aero-elastic troubles, like flutter, of great severity.

At the extremely high speeds considered for some long-range missiles (above Mach 10, or 6600 mph), the temperatures reached would be enough to melt any presently-known materials. A missile of this type would follow a ballistic trajectory, climbing rapidly above the earth's atmosphere. Aerodynamic heating would not be too troublesome during the climb or level flight. But when it made its descending re-entry into the atmosphere, heat would be poured into the missile at an extremely high rate, with temperatures being reached sufficient to vaporize diamonds.

Preliminary studies have already been conducted at the Langley Laboratory with small models made of low-melting-point metal. By this means it has been possible to observe the probable behavior of full-scale missiles at high supersonic speeds. The model tests showed clearly that the structural material of the model will melt unless means are employed to prevent this from occurring. Various expedients to preserve the structure from disintegrating have been suggested, such as the use of high-melting-point ceramic and metallic materials, water cooling, and insulation.

The Bell X-1-A research airplane has reached Mach 2.5. Because this speed was held for only a matter of seconds, aerodynamic heating did not become serious. If, however, the speed had been maintained even for a few minutes, surface temperature of the airplane would have been close to 400° F. If a fighter cruising in the stratosphere at high subsonic speed were to accelerate to Mach 3, heat would be developed at a rate sufficient to melt a ton of ice per minute. Sustained speed of Mach 4 would increase the temperature to 1000° F.

Analytical comparisons have been made of materials available for use in the skins of aircraft structures designed to operate in various speed ranges. They show that aluminum is superior as a plate material up to about Mach 2, that titanium is best between Mach 2 and Mach 3, while steel is best for still higher speeds.

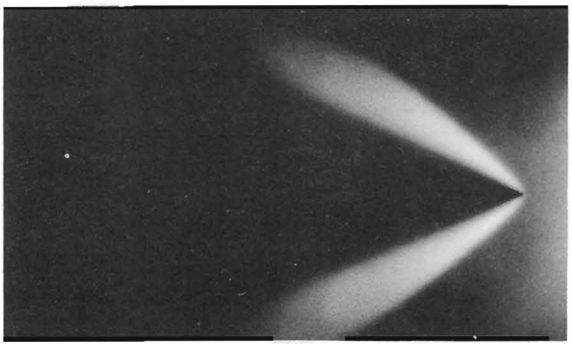
In experimental studies of heating rates, it has been necessary to employ radiant-heat sources, which can provide large quantities of heat very quickly. At the Langley Laboratory, temperatures above 4000° F have been reached within seconds. In addition to such means of simulating aerodynamic heat, supersonic jets are used to produce actual aerodynamic heating comparable to that which would be experienced in flight.

Looking at air flow

As speeds continue to rise, it has become increasingly important to obtain a more direct understanding of the air flow around and through various parts of an airplane or missile. Such understanding, of course, is the goal of all aerodynamic research. The fact that air flow is invisible has made necessary considerable effort to devise techniques which would make satisfactory flow observation possible.

For example, behind the wings of an airplane in flight there trail at least one pair of vortices - miniature tornadoes - which must be paid for in drag. The trailing vortex systems from the wings can also twist and distort flow over the tail. Among the simplest and earliest techniques used in air-flow studies were the attachment of tufts to the surface of the model under test, and the introduction of smoke filaments in the wind tunnel.

The trend of airplane and missile design has been to slender fuselages with short wing-spans. Aerodynamically, this has meant additional interference problems affecting the tail. Techniques for studying such interference have included use of a tuft grid located in a wind tunnel downstream from a wing-body model, and study of models,



Nitrogen afterglow observed at Mach 3

their wings dusted with aluminum powder, which are lowered into a tank of water. The powder stays on the surface of the water, tracing the wake of the wing.

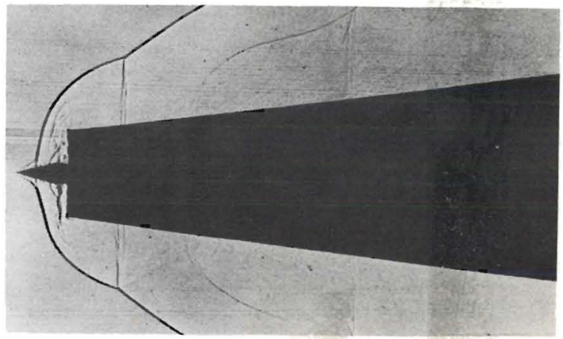
Long, slender missiles sometimes behave erratically because of body-tail interference. In studying such problems a vapor-screen technique has been found useful. By strongly lighting a thin slit of the fog in a wind tunnel, visualization of the flow disturbances is possible.

At transonic and supersonic speeds, variations in air density throughout the flow field are large enough to bend light rays in much the same manner as glass, thus permitting adaptation of optical techniques for flow visualization. The simplest of these is the shadow method, in which parallel rays of light pass through the wind tunnel test section to a photographic plate. It is sensitive only to abrupt changes in air density, but is useful in studies of transition from laminar to turbulent flow in the boundary layer. Greater detail can be visualized by the schlieren system, which is sensitive to the rate of change of air density. This method, in effect, adds a mirror and knife edge to the shadow device. Not only are shock waves pictured, but indication of their strength is shown.

The schlieren technique was first used to study steady-flow characteristics, but when it became necessary to investigate fluctuating flow, the system had to be modified by adding a stroboscopic light source. Sometimes flow fluctuations do not pulse at a regular rate, and then it becomes necessary to use a light system, developed at the Ames Laboratory, which is automatically controlled by the flow fluctuation being observed.

Recently, it has become possible to take schlieren pictures in which the changes in air density are recorded in color. First developed in England, the color-schlieren technique is especially useful where it is necessary to study shock strengths with greater care.

There are numerous other flow visualization techniques. Among these methods are the nitrogen after-glow used to study shock waves and density variations in low-density flows, and the luminous lacquer and china-clay techniques for studying boundary layer.



Stroboscopic camera pictures pulsing shock

NACA-Lewis-Cleveland, Ohio

NACA

CLEVELAND, O I .