FORTY-THIRD ANNUAL REPORT

OF THE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1957

ADMINISTRATIVE REPORT
INCLUDING TECHNICAL REPORTS
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Letter of Transmittal

To the Congress of the United States:

In compliance with the provisions of the act of March 3, 1915, as amended, establishing the National Advisory Committee for Aeronautics, I transmit herewith the Forty-third Annual Report of the Committee covering the fiscal year 1957.

DWIGHT D. EISENHOWER.

THE WHITE HOUSE,
JANUARY 27, 1958

Letter of Submittal

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON, D. C., *October 10, 1957.*

DEAR MR. PRESIDENT:

In compliance with the act of Congress approved March 3, 1915, as amended (U. S. C. title 50, sec. 151), I submit herewith the Forty-third Annual Report of the National Advisory Committee for Aeronautics for 1957.

Fifteen years ago this month the Bell P–59, powered by General Electric I–16 engines, made America's first jet-propelled flight. Ten years ago this month, the X–1, piloted by Capt. Charles E. Yeager made the world's first supersonic flight. Since then, research airplanes have exceeded three times the speed of sound, and tactical military aircraft have flown at twice sonic velocity. The strides we have made in perfecting ballistic missiles capable of spanning intercontinental distances have been no less significant.

Now, our leadership is being challenged. Within recent days the Russians have demonstrated once again a very high degree of technical competence in aeronautics. They have shown they are determined to achieve world leadership in this area.

Our national security requires that we rather than Russia be first to find answers to the formidable questions that now limit the performance of aircraft and missiles. We can succeed in this objective only if we are prepared to make the necessary investments of money in research facilities and scientific talent. Early acceleration of our research programs to the extent necessary is earnestly recommended.

Respectfully submitted.

JAMES H. DOOLITTLE,
Chairman.

THE PRESIDENT,
The White House, Washington, D. C.

National Advisory Committee for Aeronautics

Headquarters, 1512 H Street NW., Washington 25, D. C.

Created by Act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight (U. S. Code, title 50, sec. 151). Its membership was increased from 12 to 15 by act approved March 2, 1929, and to 17 by act approved May 25, 1948. The members are appointed by the President and serve as such without compensation.

FORTY-THIRD ANNUAL REPORT

OF THE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Washington, D. C., *October 1, 1957.*

To the Congress of the United States:

In accordance with Act of Congress, approved March 3, 1915, as amended (U. S. C., title 50, sec. 151), which established the National Advisory Committee for Aeronautics, the Committee submits its Forty-third Annual Report for the fiscal year 1957.

Since World War II the Committee in its annual reports to the Congress has emphasized the urgency and value of its aeronautical research programs. They represent a sound investment in national security.

The most powerful military weapon of today, the nuclear bomb, is largely dependent for its effectiveness upon airplanes and missiles capable of delivering it to the target in the face of intelligent opposition. Only new, basic research knowledge, when coupled to adequate applied research and engineering development, will make possible the greater speed, higher altitude, and longer range required in our air weapons.

In time of peace research is the first line of defense. Wars are fought with weapons based on fundamental principles discovered during years of peace. Research requires time. Money invested in research buys not only new knowledge but also that priceless commodity—time. In a decade of uneasy peace there has been a relentless build-up of international pressures that make critically important a continuingly increasing aeronautical scientific competence.

Limitations on military expenditures mean that utmost care must be exercised by the military services in deciding which new airplane and missile designs shall be developed. It is necessary that the National Advisory Committee for Aeronautics be able to provide the new basic information needed by the military and industry to insure success of the new airplane and missile designs that are selected for procurement. Only an adequately manned and financed NACA can do this.

Qualitative superiority in the performance of American aircraft and missiles is an essential objective. Significant advances are being made, but with each increase in speed, altitude, and range, new and more complex problems arise. New facilities for their scientific investigation are being provided by the Congress, but our overall research effort is still not adequate to keep pace with growing needs. Progress could be achieved at a faster rate were scientific research kept in advance of development efforts of the military and industry. Progress then would be more certain and much less costly, and America's relative position in the international field would be improved.

A factor that is becoming increasingly serious is the spiraling cost of everything connected with national defense. Part of this is the decline in the purchasing power of the dollar. Even more serious is the sharp advance in the real cost of designing and producing the very complex modern air weaponry which has performance requirements hitherto unattainable.

Modest increases in appropriations for research have been largely offset by rising costs, so that the amount of research accomplished relative to that required has been diminishing when it should be increasing. In addition, the current pay structure, fixed by law, makes it more and more difficult to retain irreplaceable top rank research scientists and engineers, and to recruit a fair share of talented young research-minded graduates. The Committee believes that this handicap should be removed by authorization of a reasonably competitive pay structure.

During the past year, the research centers of NACA were engaged in accelerated programs to provide assistance to several companies in competition for the design and production of a new, high-performance bomber. Similarly, the facilities and staff of NACA have been marshaled to provide solutions for many difficult problems that surround development of intermediate and long-range ballistic missiles. These are only two examples of numerous comprehensive programs of applied research NACA is conducting.

At the same time, NACA is concentrating on basic problems that can be solved only after years of intensive effort. In rare instances a breakthrough is achieved, such as the discovery and development at the NACA Ames Aeronautical Laboratory of the blunt-nose theory to minimize the missile re-entry heating problem, which is described in more detail on page 4 of this report. More often, the value of long-range research lies in the systematic accumulation of new information. In this latter category is the work begun in 1945 at the NACA Lewis Flight Propulsion Laboratory on high-energy or "exotic" fuels. This research program in which both industry and other governmental agencies are participating, is described on page 2.

Over the years, the Congress has appropriated funds for construction of highly specialized laboratory facilities needed by NACA for the study of new problems associated with supersonic and hypersonic flight. The cost of these facilities has been repaid many times in performance gains of American aircraft and missiles. Now, as we continue to advance into new aeronautical frontiers, additional funds will be needed for the complex new research equipment required for the scientific investigation of the new problems.

SUMMARY

The pressure for governmental economy, coupled with the effect of rising costs, has resulted in the general level of NACA research effort compared to that of the Soviets being lessened when it should be increasing. Thus, America's relative position in aeronautical science has been deteriorating. There is an urgent need at this time for a genuine increase in the level of research effort.

Respectfully submitted.

James H. Doolittle,
Chairman.

Part I—TECHNICAL ACTIVITIES

THE NACA—WHAT IT IS AND HOW IT OPERATES

During the 42 years since the Congress founded it as an independent Federal agency, the National Advisory Committee for Aeronautics has sought to assess the current stage of development of aircraft, both civil and military; to anticipate the research needs of aeronautics; to build the scientific staff and unique research facilities required for these research needs; and to acquire the needed new knowledge as rapidly as the national interest requires.

By discharging its primary responsibility—scientific laboratory research in aeronautics—the NACA serves the needs of all departments of the Government. The President appoints the 17 unpaid members of the Committee, who report directly to him. They establish policy and plan the research to be carried out by the 7,900 scientists, engineers, and other persons who make up the staff of the agency.

The NACA research programs have both the all-inclusive, long-range objective of acquiring new scientific knowledge essential to assure United States leadership in aeronautics and the immediate goal of solving, as quickly as possible, the most pressing problems. In this way, they effectively support the Nation's current aircraft and missile construction program.

Most of the problems to be studied are assigned to the NACA's research centers. The Langley Aeronautical Laboratory in Virginia works on structural, general aerodynamic, and hydrodynamic problems. The Ames Aeronautical Laboratory in California concentrates on high-speed aerodynamics. The Lewis Flight Propulsion Laboratory in Ohio is a center for powerplant studies. At the High-Speed Flight Station in California special fully instrumented research aircraft probe transonic and supersonic problems in flight. The Pilotless Aircraft Research Station at Wallops Island, Virginia, is a branch of the Langley Laboratory where rocket-powered free-flight models are used to attack aerodynamic problems in the transonic, supersonic, and hypersonic speed ranges.

A major task of the NACA since its beginning in 1915 has been coordinating aeronautical research in the U. S. Through the members of the Committee and its 28 technical subcommittees, the NACA links the military and civil government agencies concerned with flight. The aviation industry, allied industries, and scientific institutions are also represented.

Assisting the Committee in determining and coordinating research programs are 4 major and 24 subordinate technical committees with a total membership of nearly 500. Members are chosen because of technical ability, experience, and recognized leadership in a special field. They also serve without pay, in a personal and professional capacity. They furnish valuable assistance in considering problems related to their technological fields, review research in progress at NACA laboratories and in other establishments, recommend new research to be undertaken, and assist in coordinating research programs.

Members of the technical committees and subcommittees and of the Industry Consulting Committee are listed in Part II of this report, beginning on page 71.

Research coordination is also accomplished through frequent discussions by NACA scientists with the staffs of research organizations of the aircraft industry, educational and scientific institutions, and other aeronautical agencies. Through a west coast office the NACA maintains close liaison with aeronautical research and engineering staffs in that important aviation area.

The first report of aeronautical research published by the NACA covered a study conducted at the Massachusetts Institute of Technology under a research contract. Throughout its existence, NACA has utilized this means of obtaining the benefits of the special talents, unique facilities, and fresh points-of-view of scientists outside its own laboratories. The resulting independent thought and novel attacks upon research problems are a continuing stimulus to NACA scientists. They produce valuable data and theoretical analyses to complement internal NACA research. Thirty-six reports of sponsored research were published during the fiscal year 1957. During this year the following institutions participated in the program:

University of Alabama
Battelle Memorial Institute
Polytechnic Institute of Brooklyn
Brown University
California Institute of Technology
University of California
Carnegie Institute of Technology
Case Institute of Technology
University of Cincinnati
Cornell University

Forest Products Laboratory
Franklin Institute
Georgia Institute of Technology
University of Illinois
Iowa State College
Johns Hopkins University
University of Kentucky
Lightning & Transients Research Institute
University of Maryland
Massachusetts Institute of Technology
University of Michigan
University of Minnesota
National Bureau of Standards
New York University
University of North Carolina
Purdue University
Rensselaer Polytechnic Institute
Southwest Research Institute
Stanford Research Institute
Stanford University
Stevens Institute of Technology
Syracuse University
Virginia Polytechnic Institute
University of Washington
University of Wisconsin
Yale University

Proposals from such institutions are carefully weighed to assure best use of the limited funds available to the NACA for sponsoring research outside its own facilities. Published research reports of the useful results of this part of the NACA program are distributed as widely as other NACA publications.

Most of NACA's research information is distributed by means of its publications. Technical Notes and Reports are not classified for military security reasons and are available to the public in general. Translations of important foreign research reports appear as Technical Memorandums. The NACA also prepares research reports containing classified information. For reasons of national security, these receive carefully controlled circulation. When such information can be declassified, the research reports may be given wider distribution. Current NACA publications are announced in the NACA Research Abstracts.

Every year the NACA holds a number of technical conferences with representatives of the aviation industry, the universities, and the military services present. Attendance at these conferences is restricted because classified material is presented and the subject matter discussed at each conference is focused on a specific field of interest.

HIGH ENERGY FUELS RESEARCH

Announcement was made in 1957 that multi-million-dollar installations are being built under military sponsorship to produce relatively large quantities of chemical fuels for aviation use. This public disclosure focused attention on one aspect of an intensive, long-range effort that previously had been carefully shrouded for reasons of national security—the search was succeeding, to find or develop new fuels with substantially greater energy content per unit volume and weight than provided by the commonly used petroleum products, JP–4, etc.

The search for high-energy fuels began in the United States at the end of World War II. It was a consequence of the propulsion revolution that had resulted in production of powerful turbojet, ram jet, and rocket engines. Very high speeds now could be attained by airplanes and missiles, but the high rates of fuel consumption of these new engines kept range below maximum military requirements. What obviously was needed was a fuel that would, as it were, give more miles to the gallon—at even faster speeds and higher operating altitudes.

Many characteristics of a substance have to be considered before it can be determined whether its advantages over conventional hydrocarbon fuels of the gasoline and kerosene type are sufficient to justify its use. These include its properties when burned, such as heating value, density, air specific impulse, and fuel-weight specific impulse. Other questions also have to be answered. Is the substance, or the raw material from which it is made, generally available? Can we learn how to make it in large quantity, and at reasonable cost? What about toxicity of the substance and its products of combustion?

Since late 1945, at least 11 organizations in this country, with increasingly strong encouragement from the Military Services, have conducted experimental investigations of one or more of the many suggested substances to determine their suitability as a high-energy aviation fuel. The NACA's work in this area has been conducted at the Lewis Flight Propulsion Laboratory and is being vigorously continued at the present writing.

The approaches to the problem have been many sided. Work has included investigation of light metals as fuels, although here, the gains would be in higher thrust instead of greater range. This is because such metals as aluminum and magnesium burn to higher temperatures and at higher overall fuel-air ratios than hydrocarbons, but do not contain as much heat per pound. Studies were made of the burning characteristics of the light metals as solids, and also as finely suspended particles in hydrocarbon slurries.

Beginning in 1946, the NACA studied the combustion of powdered metals to determine their suitability as ram jet fuels. Ready availability, together with the belief that the resulting combustion problems would be typical of other metals, led to selection of aluminum for the first of these studies. They also included use of metal wire, metal-impregnated plastic wire and metal-hydrocarbon pastes as the researchers at the Lewis laboratory sought a practical, high-energy-fuel feed system.

Still another approach to the possibility of using aluminum, one that appeared to present fewer combustion problems, was to use a slurry, i. e., suspending finely powdered metal in a fluid such as kerosene or JP–4. Thus, it was hoped, a high-energy fuel might quickly be brought to a stage of usefulness. The fact that a slurry fuel could be used in tanks and fuel-feed systems similar to those existing made the idea attractive.

Slurries containing aluminum, magnesium, and boron were studied most intensively. It was known that there were other metals thermodynamically competitive with these three, but for one reason or another they were eliminated from the NACA's investigation of slurry-type fuels. Aluminum was quickly dropped from the program because of the serious deposit problem in the combustor caused by the large quantities of sticky, molten aluminum oxide produced during combustion.

Magnesium as a fuel also offered considerably more thrust per pound of air than is possible with the maximum obtained from conventional jet fuel. One analysis, using a hypothetical bomber, heavily loaded, serves to illustrate the importance of the gains possible from use of a magnesium slurry. The "paper" bomber was incapable of a takeoff, without thrust augmentation, even after using many thousands of feet of runway. When JP–4 was used in the afterburner, 43-percent thrust augmentation was obtained, permitting takeoff over a 10-foot obstacle in 13,500 feet. When a 60-percent magnesium slurry was used in the afterburner, thrust augmentation rose to 67-percent and the distance to takeoff was shortened to 10,600 feet. When the 60-percent magnesium slurry was used with water injection, 100-percent thrust augmentation was achieved and takeoff was possible in about 8,000 feet.

In slurry preparation, the objectives have been to achieve a high concentration of the desired metal in stable suspension that remains sufficiently fluid to be flowed, pumped, and sprayed. Unless proper additives are employed, only a muddy mass of metal powder results when large quantities of finely powdered metal are shaken up in a carrier fluid such as JP–3 or –4. Although much work remains to be done in this field, a reasonably satisfactory working knowledge of the properties of slurries has been gained, based on the shaping and sizing of the metal particles, the composition of the fluid, and the concentration of the additives used. Satisfactory storage-life exceeding 45 days has been accomplished.

Because, speaking generally, the finer the suspended particles the more stable the slurry and the better it burns, preparation of the metal can be extremely important. Attempts to mill or grind magnesium to acceptably small size, using ball or hammer mills, results mainly in flattening the particles without reducing them appreciably in size. One laboratory technique, in which magnesium vapor is shock-chilled, brought good results; of the small quantities of magnesium prepared in this fashion, 50 percent of the particles measured less than about 1.5 micron in size (a human hair is about 50 microns in diameter). Unfortunately, very large and difficult technical problems arise if such processes are to be used on quantity production of slurry materials.

Boron, in addition to high-temperature burning, has a high heating value per unit weight of fuel, and consequently is attractive as a means of extending range as well as increasing thrust. When JP–4 hydrocarbon fuel was given a range index of 1, in a paper study of a ram-jet missile flying at an initial altitude of 60,000 feet and at a speed of 2,100 m. p. h., it was calculated that use of boron would extend range by 40 percent. Range extensions resulting from the uses of pentaborane and a 60-percent boron slurry were also calculated, and were 35 and 25 percent, respectively.

Combustion studies using boron slurries were made in apparatus ranging from burners with a 2-inch-outside-diameter tube to a large-scale 16-inch-diameter engine resembling closely the design layout of a typical ram jet. Early in 1955, the NACA reported that the complete story of how to design a flame holder had not yet been learned. The high temperature required for high combustion efficiency destroyed engine parts. At lower combustor temperatures, deposition of boric oxide, a product of combustion, poses problems not the least of which is low combustion efficiency.

In the 1955 report, only recently declassified, it was concluded that, respecting slurries:

"Combustion of boron is not at all satisfactory at present. There are still a few research leads to be tried, however.

"Combustion of magnesium shows excellent promise. Not only has the high thrust been realized, but also, magnesium provided a bonus in that it burns well under (very high altitude) circumstances where hydrocarbons burn only with great difficulty.

"The art of burning metals as fuels for aircraft engines is now emerging from small-scale research to research in combustors and engines of practical size. Continuing problems are production, storing, handling, fuel systems, combustor design, and cooling. Plans for future effort should consider the status of development of other fuels that conceivably might replace either boron, or magnesium, or even both."

Research on boron metals in slurry form has been terminated at the Lewis laboratory, and interest now is centered on investigating the high-energy potentials of liquid boron compounds. Three reasons led to this shift in research emphasis: (1) There are higher heats of combustion available in liquid boron compounds than in metallic slurries; (2) the liquid boron compounds are more conveniently handled in aircraft tanks and systems; and (3) liquid boron compounds have been shown to burn rapidly and with high efficiency, in marked contrast to the burning characteristics of boron metal slurries.

In all such high-energy fuel studies, consideration of the availability of a material is inescapable. Beryllium, for example, ranks at the top of a chart showing the relative ranges for a ram-jet missile flying at a Mach number of 3 at an altitude of 70,000 feet. And yet beryllium is seldom given more than briefest consideration because of lack of availability. In a recent, single year, hardly more than 5,000 metric tons of beryl ore, imported mostly from Brazil, India, and Argentina, were used in the United States. Moreover, beryllium is highly toxic. Thus, beryllium or its compounds, however attractive they may be, based on performance, is not being considered as a possible aviation fuel.

The availability of boron and boron-compound fuels, is substantially better. While only a very small tonnage of boron is now produced annually, there are extensive deposits of boron-containing salts, notably in California, but also in Chile, Tibet, Peru, and Canada. These salts are sodium borates (e. g., borax) and calcium borate (e. g., colemanite). Consumption of boron minerals in the United States has averaged about 500,000 tons a year, being used principally in soap and glass manufacture, and for water softening.

In 1951, the NACA noted the current market price for amorphous boron was $12 a pound, and observed that "although fairly large sources of supply for boron exist, it appears to be a very expensive fuel. Improved technology in boron or boron carbide production to lower the price of the fuel is needed."

In addition to such problems and those related to combustion, there are a number of practical considerations respecting use of high-energy fuels that must be solved or circumvented before service use can be realized. The whole field is so new and attention has been so concentrated on the combustion problems that only a small amount of work has yet been done to solve some of the related problems. In addition to learning how to establish suitable storage and handling methods for new fuels being considered, it is often necessary to develop pumps, valves, and related hardware that can handle the high-energy materials.

Up to 1951, only the briefest of experimental combustion research with boron hydrides (boranes) in liquid form had been accomplished. Some of the problems of use, such as the large production of boric oxide during burning, had been defined, but hardly more. Because of the elaborate and difficult chemical processes in their manufacture, diborane, pentaborane and other boron compounds were priced in the hundreds of dollars per pound, and were manufactured only in very small, pilot-plant batches.

"There are fuels other than hydrocarbons that offer performance improvement for ram jets that can be obtained in no other way," the NACA noted in 1951 in a report on research on ram jet engine fuels. "Much cheaper boron and boron-derived fuel is needed," it said, describing existing costs as being "fabulously expensive."

The attractiveness of the boron compounds, "so very superior for long-range ram-jet propulsion," caused the Navy in 1952 to provide the extensive support that enabled the NACA and other organizations to intensify study of problems ranging from the devising of boron-compound materials that would be more suitable for aviation-fuel use, to learning how to produce the new materials, if not commercially, at least less expensively than before.

For its part, the NACA in the past 5 years has concentrated on studying the combustion characteristics of the boron-compound fuels. Because of earlier experience in the field and the specialized laboratory facilities there, scientists at the NACA's Lewis research center were called upon to burn by far the largest part of the boron fuels compounded through 1957.

When a borane fuel is burned in a conventional turbojet engine, sticky, liquid boric oxide accumulates in the primary combustor and on the turbine blades. Faced with this problem, the researcher seeks ways and means that will enable the engine to tolerate boric oxide.

It is, of course, one thing to accomplish satisfactory use of a radically new fuel type under the precisely controlled conditions of the laboratory, and something perhaps entirely different and much more difficult, to achieve similarly happy results in actual flight use. That the latter step has been taken, successfully, can be disclosed. Speeds greater than a Mach number of 3 were recorded by an experimental full-scale ram-jet test missile burning a boron-compound fuel.

THE RE-ENTRY PROBLEM

Development of ballistic missiles capable of crossing intercontinental distances is a matter of great national urgency, supported by billions of dollars. Without understating the difficulty or complexity of scientific and engineering problems of guidance, structures, and propulsion for missiles, it may be said with confidence that solutions for these problems are being found as a result of the great research and development effort being made. Far different are the problems posed by aerodynamic heating.

The long-range ballistic missile, moving many thousands of miles per hour as it enters the earth's atmosphere, encounters aerodynamic heating of great magnitude. So serious and so large are these problems of heating that success or failure of the whole long-range ballistic missile program hinges on their practical solution.

Many NACA facilities have been brought to bear on the problems. Aerodynamic studies at the Ames Laboratory; powerplant investigations at the Lewis Laboratory; structural and aerodynamic research at the Langley Laboratory and at the latter's Wallops Island Pilotless Aircraft Research Station—all have contributed to the growing fund of missile technology.

Two considerable difficulties held up rapid progress: The need for a simplified analytical understanding of the important fundamentals, and the equally vital requirement to learn ways to duplicate in the laboratory the true temperatures, speeds and gas dynamics of atmospheric entry. It was foreseen that useful answers to both requirements would accelerate missile development and point the way to manned penetration beyond the earth's atmosphere.

In 1957 the NACA publicly reported two significant steps taken at its Ames Aeronautical Laboratory toward eventual solution of the heat problem for missiles. One was a new concept of shaping the missile nose cone, postulated by H. Julian Allen. The second was the design by Dr. A. J. Eggers, Jr., of a relatively simple laboratory tool to simulate with useful accuracy the aerodynamic heating and resulting thermal stresses experienced by a missile entering the atmosphere.

Allen's concept, essentially completed in 1952, resulted from an analysis of the fundamental forces acting upon missiles entering the earth's atmosphere at high supersonic speeds. The study sought ways by which a missile designer could minimize aerodynamic heating. It emphasized the convective heating problem including the total heat transfer, and the maximum average and local rates of heat transfer per unit of missile area. At the outset, Allen determined that the heat quantities to be dealt with depended on the ratio of pressure drag to viscous or friction drag. This concept asserted that the most promising variable which a designer could alter in his favor was pressure drag. By shaping the nose cone to achieve high pressure drag, it is possible to deliver large quantities of the total heat generated into the surrounding air, leaving smaller amounts to be accepted by the missile shell.

Thus employed, blunting has particular application to the relatively light missiles of sizes, weights, and speeds currently of interest. The blunt shapes found most favorable generate a strong bow shock wave in front of and detached from the missle nose. Creation and maintenance of this heavy shock absorbs a large share of the ICBM's kinetic energy which is being transformed into heat during the atmospheric entry process. The missile body can be designed to absorb the remainder without exceeding tolerable limits.

For a different class of missiles, for which the reentering body is much larger and heavier than those of current interest, analysis points to long, slender shapes, which nevertheless retain as much nose roundness as possible to obtain the lowest possible local rate of heat transfer and hence impose the least thermal stress.

Even so, the potential for excessive heating remains the inescapable price to be paid for the hypersonic speed at which the ICBM plunges into the earth's atmosphere. Temperatures may climb more than 100° F. per second during the critical phase of flight and temperatures of thousands of degrees may occur in the thin boundary layer air next to the missile surface.

Destruction of the missile is the penalty for excessive heating. To avoid this penalty designers require detailed knowledge of the several ways in which failure may take place. Perhaps the most serious are the high thermal stresses which develop in the missile structure, stresses of much greater magnitude than those produced by aerodynamic forces, in themselves not small. High temperatures may also raise the structural material to its weakening point, again producing failure. And finally, aerodynamic heating may be so intense that the missile may be consumed as if it were a flaming meteor.

Eggers in his work posed the question: Could a practical method be devised for simulating on the ground the aerodynamic heating and resulting thermal stresses in a ballistic missile during atmospheric entry? His affirmative answer was followed in 1955 by the preliminary design of equipment which could simulate missile velocities, missile shapes and the density variation found in the lower portions of the earth's atmosphere.

Among the required conditions for useful simulation of the aerodynamic heating and resulting thermal stresses in a ballistic missile are these: The test model and missile must be similarly shaped and made of the same material; model and missile must have the same flight speeds and Reynolds numbers (scale effect), based on local conditions outside the boundary layer, at corresponding points in their trajectories. To assure these conditions and thus obtain equal heating of the model and missile, the simulator test chamber must contain air with density variations along the model flight path equal to those in the actual atmosphere through which the missile would descend. In the simulation the time scale of flight is greatly foreshortened.

Means for attaining the necessary model flight speeds were already at hand. The Ames Laboratory for years had been refining the techniques of gun-launching aerodynamic models and studying their reactions in actual flight. As early as 1955, gun-launched models had been driven to speeds of 10,500 mph in the laboratory, a velocity 60 percent of satellite speed and about that reached by a ballistic missile with 2,000-mile range. Development effort had produced several types of launchers capable of providing the full-scale velocities required for useful simulation, and the progress attained strongly suggested that one or more of these guns could be improved to yield the substantially higher speeds also of interest.

To provide a flight-test chamber that realistically simulates part of the earth's atmosphere below 200,000 feet, Eggers proposed using a supersonic nozzle of special trumpet-shaped design. He determined that he could obtain a variation in air density between the nozzle exit and the settling chamber of the apparatus matching the density variation in a range of 100,000 feet in altitude where the greater part of the heating of a ballistic missile takes place.

The model would be launched from a high velocity gun at the speed of a ballistic missile as it begins entering the earth's atmosphere, and while flying the 20-foot distance through the special nozzle to the upstream settling chamber would pass into ever-denser air to duplicate the flight history of the full-scale missile. He calculated he could simulate the aerodynamic heating experienced by a 4,000-mile range 3-foot diameter missile weighing 5,000 pounds by a model only 0.36 inches in diameter weighing 0.005 pound.

It was recognized fully that the simulator could never be used to duplicate *all* of the complex mechanism of aerodynamic heating present during atmospheric entry at very high speeds. Nevertheless the most important conditions of extreme heat transfer and thermal stress could be created in the simulator. Further, the device offered a relatively direct means of observing the effects of aerodynamic heating on a flight model, at a cost negligible in comparison with full-scale flight tests. In September 1955, Eggers wrote, "In the simplest test, the simulator could provide with one photograph of a model rather substantial evidence as to whether or not the corresponding missile would remain essentially intact while traversing the atmosphere." Since that date a working pilot model of an atmospheric entry simulator embodying this concept has been built and is operating at the Ames Laboratory, yielding useful data in the missile design field. A larger version of this new research tool is nearing completion and initial use early in 1958.

Included among the aerodynamic problems which must be understood to guarantee that a particular intercontinental ballistic missile will remain essentially intact during atmospheric entry are the same characteristics of force, moment and stability that are of concern for any aerodynamic shape. For the ICBM warhead or nose they are particularly critical because of the special shape it requires to withstand aerodynamic heating, and because of the necessity for precise control of the vehicle's trajectory throughout the wide range of flight conditions it will traverse. Extreme temperatures generated during atmospheric entry change the physical properties of the air through which the missile is moving and we must know the mechanisms of change in greater detail so that proper allowances may be made.

The strategy of research has been to study these problems separately insofar as possible. Fortunately, at both the Ames and Langley Laboratories existing facilities have lent themselves to intensive, systematic study of many phases of the complex problem. New facilities, only now becoming available, will permit broadening the areas under scrutiny.

For example, at Langley forces and pressure distributions have been measured on a series of 14 models with various degrees of nose bluntness and varying angles of the flared skirt on the afterbody at subsonic and low supersonic speeds. Supersonic wind tunnels have provided force measurements and pressure distributions at Mach numbers up to 3.5, and an 11-inch hypersonic wind tunnel is being used similarly at Mach numbers of 6.8 and 9.6 (6,336 m. p. h.). Several ballistic-type facilities are in use at the Ames Laboratory, yielding time histories and shadowgraph flow pictures of scale models fired through instrumented ranges.

Valuable correlations from actual flight are obtained from the Pilotless Aircraft Research Station at Wallops Island, Va. Here rocket-powered research models telemeter heating data obtained on flights through the atmosphere. Four-stage rockets have been flown from the Wallops Station at 10 times the speed of sound; five-stage vehicles have reached even higher velocities. To achieve closer duplication of the entry conditions an ICBM will actually encounter, the technique of firing multistage rockets on "over-the-top" trajectories has been performed by NACA scientists. The first two or three stages drive the test model through its climbing phase; the remaining stages push it to even higher speeds as it enters denser air on the returning portion of its trajectory. In one important flight, a Wallops Island test model warned designers that then-current estimates of the areas of laminar flow over a missile were too optimistic.

The amount of heat which enters the shell and structure of an ICBM depends importantly upon where airflow in the boundary layer near the surface of the missile changes from laminar, or smooth, to turbulent. Flow at the nose of a body usually is laminar, continuing rearward until disturbances grow and the flow becomes turbulent. Inasmuch as heat transfer is less in the region of laminar flow, methods of delaying as far as possible the onset of turbulence are important research objectives. Detailed understanding of the very complex mechanisms which trip a laminar airflow into turbulence has long been a research goal. Surface roughness, pressure distribution over a body and relative temperatures of the missile and the surrounding air are some of the factors which determine the point of transition. At the Langley Laboratory supersonic wind tunnels, supersonic jets, and a hypersonic wind tunnel are being used in studies relating to flow transition in the Mach number range from 2 to 9.6. At the Ames Laboratory, several supersonic wind tunnels and a number of ballistic facilities are probing related phases of the transition problem.

In the Langley Laboratory heat transfer investigations described above, the temperature range is such that the physical properties of the air are not greatly different from those at ordinary temperatures. At the higher maximum temperatures the ICBM will actually experience, air may be expected to dissociate and become ionized. The oxygen molecule will break into two separate oxygen atoms, some of which may lose an electron and thus acquire a positive charge. Temperatures at which these processes of dissociation and ionization occur cannot be duplicated in conventional wind tunnels because available structural materials would be destroyed. Consequently it has been necessary to employ in studying these phenomena a shock tube in which flow at very high temperatures is accomplished. In this device the rates at which air molecules dissociate and recombine in a realistic temperature environment are being measured. Other studies have sought to establish that simulation in the shock tube is a valid duplication of the conditions in actual missile flight.

High temperature jets have found a place among the research tools useful to scientists probing the fundamentals of high velocity missile flight. At the Langley Laboratory an acid-ammonia rocket jet provides a stream of gas at a stagnation temperature (the temperature a gas particle would reach if suddenly brought to missile speed) of 4,100° F. and a velocity of 7,000 feet per second. Also an ethylene-air combustion products jet 12 inches in diameter will yield stagnation temperatures of 3,500° F. and velocities up to 5,000 feet per second. The pebble-bed heater, using an air stream brought to very high temperatures by being passed through an incandescent bed of ceramic spheres, permits studies at high speeds and temperatures with the added advantage of air as the testing medium.

At the NACA's Langley and Lewis Laboratories valuable knowledge is being obtained with arc-powered air jets. These devices are relative newcomers in aeronautical research, capable of developing temperatures of 12,000° Fahrenheit and heating rates as high as 2,200 B. t. u. per square foot per second for testing times of many seconds. These are the heating rates and temperatures which will occur during an actual ICBM penetration into the earth's atmosphere, and no research tool previously at hand could reproduce exactly these conditions. In the equipment now being used, a high intensity electric arc imparts energy to compressed air to raise the air pressure and temperatures. Hot high pressure air is then discharged through a nozzle to produce a supersonic jet.

The arc-jet is particularly useful in finding out how materials react to the extreme conditions of atmospheric entry. It can provide information on such matters as the time lapse between the presence of heat and the beginning of melting; the rate of ablation or loss of surface material; chemical interaction between the metal and the hot air jet; spalling due to thermal shock and other phenomena which must be understood in detail.

Increasing knowledge of the temperatures to be encountered has made more firm the requirements for materials able to survive the conditions of hypersonic flight. One approach to the materials question has been to use thick metal skins for missile nose cones; skins so thick they have large capacity to absorb heat and to store it. In this way, it is possible to insulate the interior portions of a missile during the critical period of atmospheric entry. But more efficient solutions are desirable, bringing with them advantages in structural design and reductions of overall missile weight. Metals such as tungsten and columbium have very high melting points and other favorable properties at elevated temperatures. They have, however, a serious drawback; they are subject to rapid oxidation when heated in air. For this reason, studies are being energetically pursued to develop useful protective coatings which, it is hoped, may make it possible to employ such materials. If this can be done, the full potential of the metal may be used in absorbing heat, thereby effectively reducing the convective heat input and raising the rate of radiation away from the missile skin by permitting a much higher operating temperature at the outer surface.

Cooling methods also command attention. Studies at the Ames and Langley Laboratories have demonstrated usefulness in a method of transpiration cooling in which a coolant is forced through a porous outer surface of a missile. Another technique employs a film of liquid or gas which can be spread over the missile surface in such a way as to absorb heat and at the same time shield the metal skin from the intense heating.

Finally, NACA scientists have worked closely with the military organizations and industry groups engaged in developing Intercontinental and Intermediate Range Ballistic Missiles. Every effort has been made to assure that newly won laboratory knowledge passes rapidly into the industry. NACA staff members frequently furnish consulting services, and in one recent instance, proposed a redesigned missile shape, superior in heating resistance, aerodynamic stability and ease of packaging. This and other contributions have made NACA a key organization in this major national undertaking.

AERODYNAMIC RESEARCH

One of the prerequisites to either manned or unmanned flight through and beyond the earth's atmosphere and at speeds up to satellite velocities is a greater knowledge and a fuller understanding of the fundamental problems of fluid mechanics of hypersonic flows. During the past year the NACA has increased its emphasis on this area of research. Much thought and ingenuity has gone into the development of suitable facilities and techniques for laboratory studies of high-speed gas flows at very high temperatures. In a number of cases, experimental results have been obtained which constitute a valuable complement to earlier theoretical work.

The continuing need for more detailed research information for design of newer and faster supersonic airplanes and missiles has required that this area of aerodynamic research also continue to receive a great deal of attention. The goals here continue to be higher performance, greater efficiency, and improved stability and controllability over an ever-widening range of speeds and altitudes. The more advanced supersonic airplane configurations have in turn made the problems of flying and handling qualities more difficult at low speeds for takeoff and landing. In summary, then, the range of speeds and altitudes of interest in aerodynamic research has continued to expand as in other years, but at a greater pace than before.

More detailed information on NACA research in aerodynamics will be found in the pages that follow. In a report such as this, however, it is impossible to include all of the information that may be of interest. From the variety of programs undertaken we have selected some of those which seem to be representative.

FLUID MECHANICS

We are witnessing a very rapid advance in the speed of flight of aircraft and missiles. This spurt in performance began several years ago and has continued at an ever-increasing pace. Under the pressure of military need our greatly expanded performance goals have of necessity led to the construction of hardware on the frontiers of technical knowledge.

In order to secure the required knowledge, the NACA has in recent years increased significantly its research effort in the field of fluid mechanics which deals with the fundamental aspects of gas flows and which is basic to a major part of the overall aeronautical picture.

One of the most difficult and pressing problems that appears as a consequence of high-speed flight is that of aerodynamic heating, and the NACA's research effort in fluid mechanics, although diversified and extensive, has during the past few years experienced a shift in emphasis toward this and related problems. The discussion in the paragraphs following reflects this shift in emphasis and reports progress on a few selected problems related largely to the high-speed heating question.

Boundary-Layer Transition

The problem of the transition of boundary layers from the laminar to the turbulent state is of basic importance in the heating of aircraft surfaces and in the friction drag, because rates of heat transfer and skin friction may be many times larger for a turbulent boundary layer than for a laminar layer. The problem of boundary-layer transition is extremely complicated and has not been solved even for the low-speed case; the transition process at high speeds is dependent on a large number of factors such as Mach number, Reynolds number, heat transfer rate, surface roughness, body shape, airstream turbulence, noise, and other items. Nevertheless, because of the increased importance of the transition question for very-high-speed aircraft and missiles, a considerable effort is being made to obtain a better understanding of the phenomena involved.

From wind-tunnel experiments there have been several significant new findings. One of these is that for the case of basically slender aerodynamic shapes, a slight blunting of sharp leading edges promotes a substantial favorable effect on the Reynolds number at which transition from laminar to turbulent flow takes place. Another finding which appears to be of potential importance but which probably must be regarded as preliminary until additional experiments are in hand has to do with a phenomenon of "transition reversal due to overcooling." It has been shown previously on theoretical grounds and demonstrated experimentally that heat flow from a hot boundary layer into a cooler body (representing the usual case of practical high-speed flight) stabilizes a laminar boundary layer and makes it more resistant to certain kinds of disturbances. Recent supersonic wind-tunnel experiments on bodies of revolution cooled to low temperatures with liquid nitrogen, however, produced unexpected results. It was found that at the lowest body temperatures, the variation of transition Reynolds number with temperature was opposite to that observed in the same and other experiments with more modest cooling. This reversal in the expected trend of transition Reynolds number with body cooling at low body temperatures is not predicted by existing theory, and the cause is not known. Additional experiments are being made, including free-flight tests, to shed further light on the problem.

Research has been conducted during the past year in wind tunnels and in free flight, and at low speeds and high speeds, to study the role of roughness in the transition question. The low-speed work, performed with roughness in the form of distributed carborundum grains on an airfoil, demonstrated a distinctly different behavior of the transition process in the presence of distributed three-dimensional roughness over that previously found for two-dimensional roughness elements. The work also produced criteria regarding the critical roughness height. The research on roughness effects at high speeds showed the predominant part played by even very small amounts of roughness on boundary-layer transition.

Because of extraneous disturbances usually present in wind tunnels (such as airstream turbulence and the existence of wall-generated pressure disturbances) and because of limitations on obtainable Reynolds numbers and in the simulation of air and body temperatures, it is necessary to conduct certain critical experiments in free flight in which the extraneous influences can be eliminated. An extensive program of free-flight experiments using rocket-powered models has been in progress, in which a number of special models representing both blunt-missile and slender-airplane shapes have been flown at hypersonic speeds and under realistic conditions of Reynolds number and temperature. New, large-scale, high-Mach-number data have thus been obtained on a number of questions such as the effect of roughness, nose shape, and body surface temperature on heat transfer, skin friction, and boundary-layer transition.

Blunt Body Solution of Missile Heating

During the past year the results of some earlier research were announced dealing with the motion and heating of long-range ballistic missiles on re-entering the earth's atmosphere. Prior to the time that these research results were available, the work dealing with warhead shapes for ballistic missiles considered primarily slender aerodynamic configurations inherited from earlier research findings which were concerned mainly with efficient supersonic flight. The study in question showed that the slender body suffered greatly from aerodynamic heating and that, inasmuch as flight efficiency was not the problem of the ballistic missile but rather survival under conditions of intense heating, the blunt high-drag body had great superiority as an ICBM warhead shape. The principal investigator, H. J. Allen of the Ames Aeronautical Laboratory, received the Committee's highest honorary award for his contribution.

Research on the problems associated with the use of blunt ICBM warheads has progressed during the past year. Experimental research, both flight and wind tunnel, has been conducted with the objective of refining these blunt shapes to reduce the heating further. Studies have been made of the boundary-layer transition problem for the special case of extremely blunt bodies.

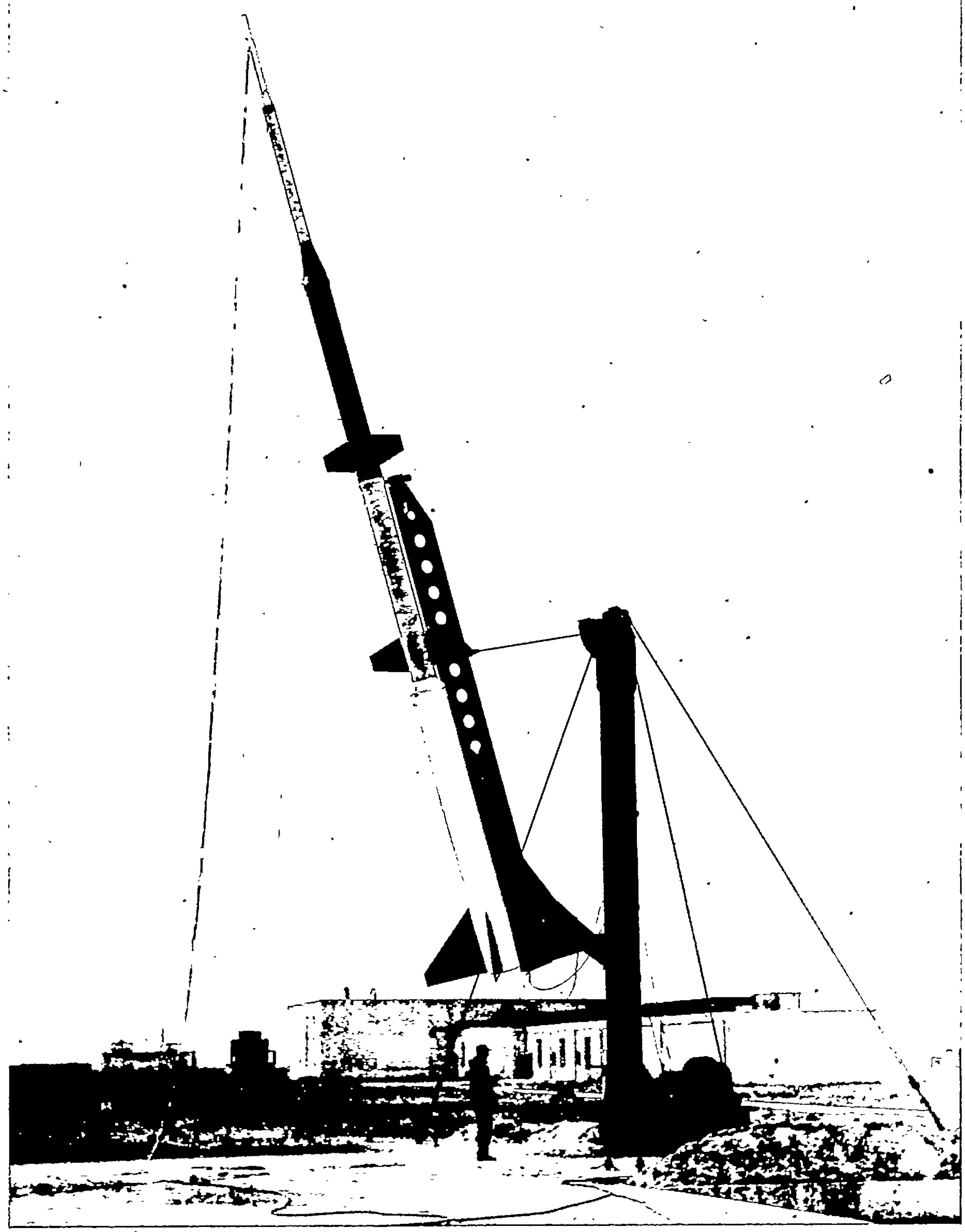
One problem that has occupied the attention of a number of investigators is that of calculating the flow field between the body surface and the detached shock wave standing ahead of the body nose. One contribution to this problem has been a report in which two new methods of calculating body surface pressures are presented and compared.

High-Temperature Gas Dynamics

Many of the studies of the kind discussed in the preceding paragraphs are of necessity conducted under conditions for which the air flow is that of a thermodynamically perfect gas. In the case of theoretical work the assumption is usually made of an ideal gas; in the case of experiments the temperatures are often in the range where the air behaves as a perfect gas. In reality, however, for hypersonic flight the air affected by the passage of the bow wave from the body and the air within the boundary layer is heated to very high temperatures, under which conditions the collisions among the air molecules are energetic enough to initiate ionization, dissociation, and chemical reactions. These effects cause large changes to take place in the fundamental properties of the air, such as the heat capacity, molecular weight, etc., which cause important deviations in air temperature and flow fields. These are known as "real-gas" effects. A number of investigations have been made during the past year of several aspects of this problem, ranging from studies of the properties of high-temperature air and the rates at which the several physical and chemical processes proceed, to studies of the effects of the changing properties on the flow fields around bodies. Some results of these studies deal with the formulation of a theoretical method for the calculation of dissociation effects in a flow not in chemical equilibrium and with the formulation of flow equations across oblique shocks in hypersonic flow in chemical equilibrium.

Heat Transfer

If the state of the boundary layer is known, that is, whether it is laminar or turbulent, and if the temperature is not so high as to cause the properties of the air to change appreciably, it is possible, as a result of work



Five-stage hypersonic research rocket.

done in previous years and continued into the past year, to calculate or to estimate with engineering accuracy the heat transfer for a number of simple shapes and flow configurations. Some such cases, for example, are cones, ogives (or bulletlike nose sections), hemispherical noses, flat plates, etc., mostly at zero or near-zero angles of attack. The problems now lie in determining the heat transfer under more complex flow conditions which include separated flow, interfering flow fields, flow around bodies and low-aspect-ratio wings at high angles of attack, and conditions of very high flight speed for which the air is dissociated and ionized. Research on several problems in this category progressed during the past year. Some examples are experimental measurements on the heat transfer at supersonic speeds to bodies of revolution at angle of attack and a theoretical analysis of heat transfer in separated flows.

The improvement in transition Reynolds number found to result from modest blunting of leading edges was mentioned in a preceding paragraph. Such blunting for slender airplane shapes has also been found to be effective in reducing generally the extremely high heat transfer rates encountered at the leading edges of wings and noses of bodies, and in fact, is found to be necessary to prevent the destruction of these critical heating areas under conditions of hypersonic flight.

Another related finding has been announced which is of particular importance to airplane and winged-missile applications, and that is the large favorable effect of wing leading-edge sweepback on aerodynamic heating. Large amounts of sweepback were found to have the dual advantage of providing a direct reduction in the heat input and of reducing the drag of blunted leading edges which, as mentioned, are necessary to resist the heating.

Hypersonic Research Techniques

An extremely difficult and persistent problem has been that of devising techniques for experimental research on the problems of hypersonic flight. It is difficult because of the extremely high temperatures involved and persistent because no completely satisfactory solution is yet in sight. Nevertheless, progress was made during the past year on several different approaches. Heavy reliance has had to be placed on the rocket-propelled-model method, since with this technique simulation of flight conditions is correct, testing times are relatively long, and models are large enough to be properly instrumented for the simultaneous measurement of various important factors. Aside from difficult problems of mechanical design and instrumentation, one of the principal problems has been that of finding means to provide the needed increases in flight speed rapidly and at a minimum cost. This has been accomplished through developments in multiple staging of various solid-propellant rocket motors. Progress has been gratifying.

A considerable effort has been put on the study of a number of laboratory techniques for hypersonic research. One of these, the ballistic technique, is somewhat similar in its problems to the rocket-model method, except that models are fired from high-velocity guns and are necessarily much smaller. One of the major problems has been in the development of the launching guns themselves and progress has been such that model launching speeds in excess of 10,000 miles per hour have been achieved. A new scheme of interest for studying certain problems in connection with the entry of ICBM warhead bodies into the atmosphere is called an "atmospheric re-entry simulator." The technique involves the firing of a high-velocity model upstream into a long hypersonic tunnel in which there is a variation in air density similar to that encountered by a full-scale warhead entering the atmosphere. As of the time this report is written, preliminary experiments are being made in a small-scale simulator and the construction of a larger device is in progress.

The familiar wind-tunnel method in which the air is blown past a stationary model is still an extremely useful research tool for speeds up to about a Mach number of 10. When attempts are made, however, to apply it to speeds appreciably higher than this, if air is used as the test medium and if testing times are to be reasonably long, the method is beset with great difficulties. The problem is basically that of generating, containing, and directing a steady and continuous flow of high-pressure air heated to a temperature of many thousands of degrees. Various approaches are being studied and progress has been made along several lines.

One promising new development makes use of a special ceramic heat exchanger. In this scheme the wind tunnel settling chamber is a ceramic-lined steel tank filled with a mass of ceramic pebbles. In operation, after the pebbles have been preheated, compressed air is brought into the tank, passed through the pebble bed and heated, and then exhausted through a water-cooled supersonic nozzle to provide the test flow. The first experimental equipment built on this principle was a small-scale apparatus operating at 150 pounds per square inch stagnation pressure to produce a Mach number 2 flow with stagnation temperatures up to about 4,000 degrees Fahrenheit. Within the past few months a second, larger piece of apparatus has been completed capable of operation in the same temperature range, with greater flow rates and with a stagnation pressure of about 1,500 pounds per square inch, permitting increases in test section size and test Mach number.

Prevention of the destruction of the nozzle throat, where heat transfer rates are critically high, has posed an important problem with the high-temperature hypersonic wind tunnel. For the present, water-jacketed stainless steel nozzles have provided a workable solution. As design pressures and temperatures continue to rise, however, new and more effective methods of nozzle cooling will be required. One such method is the injection of a thin insulating layer or film of cold helium gas between the hot airstream and the nozzle wall. Experiments on helium film cooling have been carried out during the past year which have provided information on effectiveness and also experience with design and handling problems.

In the continuing search for means of providing still higher air temperatures for research purposes, investigations have been underway on the heating of air by electric arcs, and several small laboratory devices have been built which produce extremely hot supersonic air streams with temperatures in the neighborhood of 15,000° F. Such air streams suffer from contamination from vaporized electrode material and their chemical and physical states are not yet accurately known. They are nevertheless of immediate usefulness for certain kinds of research and the general method of electric arc heating is promising enough to warrant continuing study.

Other methods which involve short testing times have also been under investigation and development. These make use of heating of air by rapid compression, either by means of a piston or by means of shock waves (i. e., the shock tube device).

Certain aspects of the problems of flow at hypersonic speeds can be studied in wind tunnels which use helium as the working fluid instead of air. Small wind tunnels have been built to operate to Mach numbers in the neighborhood of 20 using helium as the working fluid. Some considerations on the use of helium as a test gas have been investigated and reported.

Magneto-Gasdynamics

Under conditions of extreme temperature encountered at higher hypersonic speeds, electrons are knocked out of the atoms of the gases of which air is composed, with the result that the air becomes ionized and electrically conducting. This circumstance means that there exists the possibility of exerting powerful forces on the air by the application of electric and magnetic fields. Thus a new field for research is opened dealing with the flow of electrically conducting fluids in the presence of electric and magnetic fields, which has been variously called magneto-gasdynamics, magneto-aerodynamics, and magneto-hydrodynamics. Research on this subject directed toward aeronautical applications is just beginning but new developments are to be expected. One study reported during the past year involved a theoretical analysis of the effect of a magnetic field on the heat transfer and skin friction in the boundary layer of a conducting fluid on a flat plate. One of the findings was that a magnetic field transverse to the flow and fixed with respect to the plate caused a reduction in both heat transfer and skin friction but caused an increase in the total drag force on the plate.

HIGH-SPEED PERFORMANCE

High speed is a relative term which a few years ago embraced the speed range near the speed of sound. However, great strides have been made in the last few years in improving the speed, range, and operational capabilities of military and commercial aircraft. Some military aircraft now operate supersonically at more than one and a half times the speed of sound at altitude, and missiles are flying at several times the speed of man-carrying aircraft. Design studies are being made to attain even higher speeds and altitudes and a research airplane is being constructed to explore the problems of manned flight at very high speeds and altitudes.

Recent achievements in advancing aircraft performance have been brought about by a major research effort in which the NACA has played a leading role. It is not possible to describe in detail the problems of supersonic flight or the attacks on these problems in this report but the following paragraphs describe in a general way some of the work that has been accomplished in the past year by the NACA in its continuing effort to increase aircraft and missile performance and flight efficiency at supersonic speeds.

When air flowing around one part of an airplane or missile disturbs another part the phenomenon is called aerodynamic interference. The aerodynamic key to high performance and flight efficiency at supersonic speeds is the proper orientation and shaping of aircraft components to minimize the drag or resistance resulting from unfavorable interference effects. A clear understanding of the nature of the supersonic flow fields around airplanes and missiles is required, therefore, if aircraft are to be efficient and have good flying qualities.

In addition to affecting airplane and missile performance, aerodynamic interference also affects the air loads or pressures the structure must sustain, and the stability and control of the vehicle. The latter two items are discussed in other parts of this report. Performance as treated here is concerned mainly with lift and drag.

The drag of an airplane or missile can be broken down into three major parts, namely the form drag, friction drag, and drag-due-to-lift. The form drag, as the name implies, is caused by the form, or shape, of the aircraft. Drag-due-to-lift is an additional drag force that is caused when lift is developed on the wings and body. The total drag of the configuration which must be overcome by the thrust of an engine is the sum of the friction drag, the form drag, and the drag-due-to-lift.

At speeds near the speed of sound, the form drag suddenly increases to as much as five or more times its value at subsonic speeds. This large increase in form drag may be greatly reduced by applying the transonic area rule, and as a result more efficient aircraft have been designed to fly at low supersonic speeds.

The transonic area rule subsequently led to a supersonic area rule.

Wing-Body Combinations

Through the use of the supersonic area rule and detailed studies of aircraft in supersonic wind tunnels at the Langley Laboratory, improved lift-to-drag efficiency has been obtained in the supersonic speed range up to about twice the speed of sound.

Extensive theoretical and experimental research has led to reduction in drag-due-to-lift by adjustment of the wing planform and improvement of the loading distribution through effective use of wing camber and twist. A wind-tunnel investigation of the effects of camber and twist has shown rather good agreement between theoretically predicted and experimentally measured span loadings at low angles of attack.

At the Ames Laboratory a unified design method has been developed for predicting wing-body and wing-body-tail interference at supersonic speeds. This design method was developed through theoretical studies and the use of experimental wind-tunnel results.

A study of the problem of drag-due-to-lift has led to the development of a "conical" cambered wing, so named because of the conical shape of the wing leading edge to which it is applied. Conical camber has been studied on triangular and sweptback wings of various aspect ratios, taper ratios, leading-edge sweeps, design lift coefficients, and with varying extent of the cambered area, to delineate the limits to which the lift-drag efficiency is improved. Test results have shown, in general, that the maximum lift-drag ratios of triangular and sweptback wings can be increased at high subsonic and low supersonic speeds.

Complete Aircraft Configurations

In addition to the wing, fuselage, and tail, a complete aircraft consists of engines with engine-air inlets and jet exits, cockpit and canopy, and the external stores (bombs, rocket missiles, auxiliary fuel tanks, etc.) that airplanes are required to carry. The effects of all these components are a very important consideration from an interference drag viewpoint.

The most difficult problem is that of efficient inlet-engine installation. Conventional design methods result in propulsion system installation drags of the same order as the drag of the wing and body alone. To reduce this drag, engine installations must be carefully integrated into the airframes. Theoretical research results in this field are encouraging and investigations are being conducted to determine the extent to which anticipated gains can be incorporated in practical configurations.

The first results of a program at the Ames Laboratory have shown desirable engine locations for airplanes with wings of short span, and modifications of the airframe are being considered now to provide greater lift-to-drag efficiencies through closer integration with the power plant.

In addition to interference from the physical components of the airplane, the streams of hot exhaust gases from turbojet engines can cause serious interference effects. For example, it is possible that a jet exhaust which caused no harmful interference at an altitude of 20,000 feet could produce at 60,000 feet a flow pattern giving serious interference. Techniques for accurately simulating jet exhausts in wind-tunnel models have been developed and experimental and analytical study of jet-exhaust interference problems has provided design guides for avoiding or alleviating the adverse interference effects of jet exhausts.

At the Langley Laboratory an experimental investigation of cockpit canopy shapes at supersonic speeds has indicated the drag reductions possible with proper design of the windshield shape and location of the canopy on the fuselage. Also at Langley, an extensive wind-tunnel investigation of aerodynamic interference between aircraft and external stores has been conducted. This program has provided experimental information indicating the proper locations for carriage of external stores for the least performance losses.

Launching of missiles and bombs from supersonic aircraft is an important and difficult problem. Lack of knowledge of the flow phenomenon involved has resulted in large deviations of the launched weapon from its intended flight path, and in loss of the launching aircraft in some cases. Wind-tunnel measurements of the aerodynamic forces on missiles immediately after being launched from an aircraft have provided information to aid in the prediction of the flight path of missiles launched from aircraft at supersonic speeds.

Advance Design Concepts

At high supersonic speeds (two to five times the speed of sound) theoretical studies indicate a possibility of combining some aircraft components in such a way as to produce favorable interference effects on other components. However, the complex flows involved in complete configurations can be determined accurately only by experiments using large models in large supersonic wind tunnels. Not only lift-drag efficiency, but also stability and control characteristics and performance of the engine air inlets must be investigated at these speeds. Also, at these speeds aerodynamic heating becomes a major problem leading to use of current high-temperature materials such as the stainless steels. Care must be taken in detail design to avoid the adverse effects of interference flows on aerodynamic heating which can produce local "hot spots."

In general, it can be said that the interference problems of modern supersonic airplane and missile designs are so complex that much wind-tunnel testing and analytical investigation is required to effect satisfactory solutions.

In the very-high-speed range, the past few years have seen preliminary studies of vehicles for flight at velocities approaching satellite speeds. Some of this work has been concerned with the boost-glide system, so named because of its mode of operation which consists of rocket boost to cruising speed and altitude and a powerless glide to its destination. Boost-glide vehicles should have high lift-drag ratios and aerodynamic heating problems must be solved. Analytical studies have indicated approaches to higher lift-drag ratios, but experimental research in all phases of aerodynamics must be extended to much higher speeds to provide the required information.

INTERNAL FLOW

The performance capability of an airplane or missile with an air-breathing engine becomes increasingly dependent on the efficiency of the internal flow system as the Mach number is increased above the speed of sound.

As the design Mach number is increased, the ratio of the inlet frontal area to the engine compression face area must also be increased if the inlet is to supply the amount of air required by the engine. Accordingly, a hypothetical turbojet engine designed for a maximum Mach number of 4.0 would require an inlet with a frontal area over three times as large at maximum Mach number as that required when flying at transonic speed. Conversely, if the frontal area is maintained constant at a value compatible with Mach number 4.0 operation and the internal geometry of the inlet is varied to maintain the proper engine airflow characteristics over the Mach number range, then the inlet frontal area will be too large at transonic speeds and over half of the inlet airflow must be diverted. This considerable airflow variation with Mach number has necessitated the use of more complex inlets having variable geometry components to realize high levels of net thrust.

Since the thrust produced by an air-breathing engine is a function of the pressure at the engine compressor face, research is being conducted to reduce the pressure loss of inlets designed for Mach numbers in excess of 2.0 while simultaneously reducing the drag created by the inlet to a satisfactory level. Because high-pressure recovery at the design speed is insufficient to guarantee satisfactory performance throughout the flight range, research is also being directed toward the establishment of inlet flow characteristics and operational limits at Mach numbers other than maximum.

In integrating the power plant into the airframe, it is also necessary to minimize the external drag of the installation. Toward this end, extensive tests have been conducted to determine optimum nacelle afterbody shape, particularly in the high subsonic cruise condition where adverse effects are most severe.

Inlet Performance

As the speed of aircraft and missiles ultilizing air-breathing engines is increased, the need for highly efficient inlet designs becomes of paramount importance. The wide range of conditions encountered with high Mach number designs necessitates the use of variable geometry inlets and removal of the low energy boundary layer air adjacent to the inlet walls. External compression inlets have been used extensively for speeds up to twice that of sound, but as the Mach number is increased further, the cowl drag tends to increase rapidly. One method for overcoming this cowl drag is to decelerate all or part of the supersonic airflow within the inlet ducting. This method is attractive because it can provide high pressure recovery and very low drag; its disadvantage is a discontinuous flow characteristic that requires special control if near optimum performance is to be obtained.

At the Lewis Laboratory, experimental investigations on all-external compression inlets designed for Mach numbers in excess of 2.0 have indicated that the external drag can be appreciably reduced below previous concepts by providing adequate boundary-layer removal. Similar tests on a shorter inlet utilizing mixed external-internal compression have yielded relatively high pressure recovery with relatively low drag coefficient. An all-internal contraction inlet has also yielded very promising pressure recoveries.

At the Ames Laboratory, work on inlets has been mainly concerned with improving the performance of internal-contraction inlets for flight at Mach numbers greater than 2.

Small-scale models have been used to study the effect on total pressure recovery and flow distortion of such items as the internal shape of the annulus and centerbody and boundary-layer bleed. These studies during the past year have indicated that the pressure recovery of a carefully designed internal-compression inlet is comparable to the better external compression inlets. Significant principles concerning design requirements of internal-compression inlets with translating centerbody to provide satisfactory off-design characteristics have also been determined and experimentally verified.

The results of these small-scale studies have been incorporated in the design of larger scale, more complex models with more complete instrumentation.

Typical problems investigated concern methods of improving the pressure recovery at high angles of attack, the steadiness of the internal flow, the external drag, and the interference effects of surfaces contiguous to the inlet, such as a fuselage or wing on the inlet characteristics. Results to date have shown a method by which the pressure recovery can be improved at high angles of attack and that the inlet design is satisfactory from the standpoint of flow steadiness and low external drag.

As the design flight Mach number increases, the range of stable off-design inlet operation becomes increasingly small and the occurrence of extremely violent shock wave fluctuations, known as buzz, becomes an increased operating hazard. The accompanying adverse pressure fluctuations have a strong detrimental effect on engine performance and can cause the destruction of inlet componets. Methods have been devised and investigated that are capable of delaying the occurrence of buzz, thereby extending the useful inlet operating range. Mechnical buzz suppressors have been successfully applied to specific designs, but because of their high losses can be considered satisfactory only for emergency use where pressure recovery is of secondary importance.

A theoretical phase of the Ames program has been concerned with the calculation of the external pressures on inlet cowls. A knowledge of these cowl pressures is necessary for the determination of cowl drag. Experimental work has verified the accuracy of the method for computing external pressures on inlet cowls so that it is now possible to compute accurately and quickly the external wave drag of inlet cowls of arbitrary shape.

Several inlet problems for specific airplane and missile configurations were also investigated during the year. The direct application of these results has led to excellent performance gains in the Mach number 2 range.

Flow Distortion

An air-breathing propulsive system requires nearly uniform air flow at the engine face if maximum thrust is to be attained. Uneven flow distribution and pressure pulsation can cause inefficient engine operation with the inherent danger of flow separation from the compressor blades and the attendant possibility of engine flame-out. Unfavorable regions of low energy air in the inlet duct can be caused by separation of the low velocity boundary layer air adjacent to the inlet walls as the air flow progresses through a shock wave or negotiates a rapid change in direction.

Experimental studies at Ames have been made in the wind tunnel, and bench tests have been performed with various throat and duct arrangements at near-sonic velocity to demonstrate the significance of secondary flows in an air-induction system and emphasize the necessity of maintaining flow uniformity from the free stream to the engine face. Another phase of this investigation was to study in detail the flow in the transonic region of a duct. It has been shown that not only must such a flow be uniform, but it also must be steady, and several ideas which contribute to these requirements have been developed.

Considerable research has also been conducted at the Langley and Lewis Laboratories on methods for obtaining more uniform flows at the engine face. Various types of flow control devices have been investigated in detail, and design criteria have been established.

The use of screens in the subsonic diffuser offers a powerful means of reducing distortion but does so at the expense of reduced pressure recovery. Investigations at Langley have determined the extent to which the flow may be improved by the use of screens as well as the magnitude of the associated losses. It has been found that the losses which accompany the use of screens can be largely avoided by the use of a free-wheeling inlet rotor which draws its energy from high velocity regions to reenergize low pressure areas with consequent improvement in the velocity distribution.

Ducts and Diffusers

The air passing from the inlet to the engine must be decelerated and must often negotiate some degree of duct turning prior to induction into the engine. To obtain maximum thrust from the propulsion system, the losses inherent to ducts and diffusers must be minimized.

At Langley, research in subsonic ducted flows during the year has resulted in the development of analytical methods of predicting the pressure distribution in a 90° bend of arbitrary contour and of calculating the wall contours necessary to obtain a specific pressure distrbiution. Applicability of these methods to the design of vaned turns appears assured. Losses resulting from shock boundary-layer interaction in ducted flows have been satisfactorily predicted in low-angle diffusers; the addition of a constant diameter section between the inlet and shock sharply reduced losses in short diffusers.

Jet Exits

Aircraft operating at high Mach numbers require an exit nozzle area considerably in excess of that required for the transonic speed range. The variable geometry aspects of exhaust nozzles can result in low drag afterbody configurations at the maximum flight Mach number and high drag at the high subsonic cruise condition. Any decrease in the high afterbody drag at cruise will result in increased range.

Transonic wind tunnel tests conducted at Langley on afterbody models without jets have provided detailed pressure distributions for representative afterbody shapes, and optimum angles for basic designs have been determined. Systematic studies of the effects of the primary jet on the drag of conical afterbodies have also been completed and reported; areas of favorable and unfavorable jet interference are defined.

A jet exhaust gas generator utilizing the catalytic decomposition of hydrogen peroxide has been constructed at the Langley Laboratory which is capable of producing a hot jet that closely simulates the exhaust of a turbojet engine. With this jet simulator, some of the performance gains possible through proper selection of afterbody geometry have been determined for boattailed nacelles with a primary jet and with secondary air supplied through ejector action of the primary jet.

Transonic flight tests of both single and twin jet configurations also showed a favorable jet effect on drag under simulated jet operating conditions. The effects of boattail asymmetry and aerodynamic interferences from adjacent tail surfaces are being studied with available results indicating marked changes in drag from those of isolated bodies. Analyses of these and other data are in progress to develop empirical criteria for evaluating jet effects on bodies of arbitrary shape.

At the Lewis Laboratory, jet exit research has been predominantly concerned with the off-design performance of primary engine nozzles. General research on various nozzle and ejector designs has shown that the external flow greatly alters nozzle performance at off-design conditions from the results predicated from quiescent-air tests.

AERODYNAMIC STABILITY AND CONTROL

Airplane Stability

The sometimes radical geometric design changes in airplanes (such as longer bodies and smaller wings) required to reduce drag and obtain increases in performance have, unfortunately, increased the difficulty of providing adequate stability and control. The problem of providing adequate directional, or "weathercock", stability for advanced airplane configurations for example, continues to tax the ingenuity of designers. Influences on directional stability of the complex flow fields generated by the wings and bodies are inherently difficult to predict, and even when they can be determined, a challenge is presented in devising effective means for avoiding their adverse effects. For example, an investigation at Langley of the effects of fuselage nose length on the low-speed static-stability characteristics of a complete high-performance airplane model with a 45° sweptback wing shows that an increase in nose length caused large decreases in the directional stability of the model at moderate and high angles of attack. An exposed canopy also reduced the directional stability of the model over almost the entire angle-of-attack range for all nose lengths investigated. An Ames Laboratory study of the effect of body and wing interference on stability characteristics shows that the interference of the body is especially important in causing directional instability at supersonic speeds. In spite of these difficulties, however, it has been possible through detailed investigation in some cases to satisfy the directional stability requirements on specific airplane designs by use of increased or redistributed tail area, through the addition of various arrangements of vertical fins located beneath the fuselage ("ventrals"). or by means of forward located flow control devices.

Langley has conducted an investigation to determine to what extent the fuselage is involved in the large differences in directional-stability characteristics observed between unswept and sweptback wing-fuselage configurations at high angles of attack. Two wing configurations were studied; one wing with an unswept half-chord line, and another with 45° sweepback of the quarter-chord line. The results indicate that both the favorable decrease in the wing-fuselage directional instability of the straight wing and the unfavorable increase in instability associated with the sweptback wing were due to forces, induced by the wings, on the fuselage afterbody.

Static wind-tunnel investigations at Langley and Ames of general-research airplane models have also revealed important effects of the fuselage forebody shape on stability characteristics and indicate possible advantages that careful selection of the fuselage shape may provide.

Other recent studies indicate that special types of wing-body-tail arrangements may be specified that will avoid or use to advantage the complex interference fields to alleviate the directional-stability problem.

Although a somewhat analogous situation has existed concerning the occurrence of pitch-up—a violent longitudinal instability prevalent at some speeds and angles of attack with advanced airplane configurations—extensive research has provided a better understanding of the basic design parameters that influence this instability. Thus, while the prediction of the interfering flow fields is a difficult task that requires detailed experimental evaluation, a greater choice of effective methods for alleviating the problem is now within the designer's grasp. Quantitative research information for use in the choice of such primary design variables as wing height, tail height, and wing dihedral have, during the past year, been provided at Mach numbers ranging from subsonic, through transonic, and into fairly high supersonic speeds. Sometimes a completely satisfactory aerodynamic cure of pitch-up cannot be effected. In such cases some means of insuring that the airplane does not enter the flight region where pitch-up occurs must be provided. Several NACA studies were made recently of automatic control devices designed to provide this capability.

Although the pitch-up problem now appears fairly well understood, another longitudinal stability and control problem is becoming of concern. Conventional, tail-rearward, airplanes usually become more stable, or less maneuverable, as the flight speed increases to supersonic. This excessive stability means that larger control deflections are required to maneuver the airplane. To aid in the solution of this problem, several unconventional airplane arrangements have been subjected to analytical and wind-tunnel investigations. The tail-forward arrangement appears to be fairly adaptable to high supersonic-speed requirements. Calculations indicate that tail-first configurations can be designed to have attractive stability and control characteristics and may have a lower trim drag than a configuration trimmed by aft controls. Preliminary programs in various subsonic and supersonic wind tunnels at the Ames and Langley Laboratories have also been conducted on generalized tail-first airplane configurations over a broad speed range to provide experimental results.

Continued theoretical and experimental studies have provided the designer with more complete information on the influence of basic design parameters on the dynamic stability of airplanes and missiles. One dynamic stability problem of recent concern is the adverse effect of inertia forces introduced when a high-speed aircraft rolls about an axis not alined with its longitudinal axis. These forces tend to swing the aircraft out of line with its flight path, sometimes leading to such extreme and rapidly developed angles of attack and sideslip that structural failure results. The importance of foreseeing the occurrence and magnitude of this inertia coupling has led to the recent development at the Langley and Ames Laboratories of more comprehensive but simplified methods for predicting the response of an aircraft in a steady roll. Recent studies have shown that redistribution of some of the mass of the airplane along the wings can have important advantages in controlling adverse inertia cross-coupling effects. Other NACA investigations have studied the stability-augmentation devices (such as pitch or yaw dampers) required to alleviate the inertia-coupling problem.

The introduction of various concepts of vertical and short takeoff and landing airplanes has increased the scope of stability and control problems facing designers. Research conducted thus far has established the feasibility of such operation by both propeller and jet-powered aircraft and provided a wide range of information for such designs. Vigorous attacks have been made on VTOL and STOL stability problems during the last year—especially on the transition of VTOL airplanes from normal forward flight to hovering flight—in several conventional and specialized facilities and by means of free-flying dynamic models.

Aircraft designed to penetrate beyond the effective atmosphere, will have a multiplicity of additional problems of space stability and control, particularly since the vanishing air density will make ineffective conventional aerodynamic methods of providing control and oscillatory damping. Because such aircraft present modes of operation far beyond current experience with manned aircraft, pilot-controlled flight simulators play a vital part in assessing some of the problems that will be encountered and in providing important design criteria. Preliminary NACA analytical studies and exploratory experiments in the last year have mainly served to expose some of the severe and radically new stability and control problems that will be encountered.

Missile Stability

As the speed of missiles has advanced far into the supersonic regime, the general design tendency has been toward wings having low aspect ratio (small span). Configurations with such wings have been found to have satisfactory aerodynamic characteristics at high speeds and also avoid most of the aeroelastic problems associated with the use of wings having larger spans. For airplanes armed with internally stored air-to-air type missiles, the smaller span missile is additionally attractive since more of them can be carried in a given volume. Because of these reasons, extensive NACA studies were made on this type of configuration last year. One Langley wind-tunnel study recently reported was concerned with the supersonic characteristics of a series of low-aspect-ratio wing missile models in which the effects on stability of wing shape, body size, and forebody and afterbody length and shape were investigated.

One of the problems of concern to designers of externally-mounted, air-to-air missiles is the large forces acting on the missile caused by the effect of the nonuniform flow field generated by the airplane. These forces can result in deflection of the missile's flight path during the launching phase endangering the airplane and also affecting the accuracy of the missile. The Langley Laboratory has recently reported on several investigations made to provide additional high subsonic speed information on this problem. In these studies, the forces acting on missiles during simulated launching from unswept-, sweptback-, and triangular-wing airplane models were determined. The effects of mounting position of the missile on the airplane wing were also determined.

The NACA experimental and theoretical program to determine the stability characteristics of the long-range ballistic missile has been expanded in the last year. Particular emphasis has been placed on the very-high altitude type of ballistic missile and the evaluation of its aerodynamic stability characteristics during the atmosphere reentry stage. Results of recently reported studies at the Ames and Langley Laboratories of a wide range of missile reentry shapes permit selection of configurations having the desired static and dynamic stability without compromising the requirements for high performance and minimum aerodynamic heating. The characteristics of a short range ballistic missile, whose trajectory is entirely within the atmosphere, have also been studied. The adequacy of the supersonic static-stability characteristics of a typical ballistic missile configuration of this type having a fin-stabilized body of revolution was determined in a Langley investigation utilizing the rocket-powered model technique.

Control

Continuing emphasis has been placed on the challenging problem of providing adequate control systems for the wide range of airplane and missile configurations which are of current and future interest.

A comprehensive Langley program to provide needed additional information on the transonic and supersonic characteristics of conventional wing flap and spoiler controls continues. During the last year reports on portions of this program to determine the transonic effectiveness of several flaps and plain spoilers on sweptback wings; the supersonic hinge-moment characteristics (directly related to the forces required to operate the controls) of a series of flaps on triangular wings; and the supersonic effectiveness characteristics of plain spoilers located in various locations on an unswept wing were published.

Conventional flap controls, primarily developed for use at subsonic speeds, generally lose effectiveness because of aeroelastic effects and also require larger forces for deflection at higher speeds. Plain spoilers, the most common substitute for a wing flap, usually have good effectiveness and relatively low operating forces through the transonic speed range but have a tendency to lose effectiveness at high angles of attack; previous studies have shown that a slot behind the spoiler and a wing lower surface deflector improve greatly the effectiveness at angles of attack in the subsonic range. In order to determine the supersonic characteristics of the spoiler-slot-deflector control over a range of angle of attack, a wind-tunnel study was conducted on a representative sweptback high-speed airplane wing.

Another device that has been suggested for providing improved roll control in high-speed flight is an all-movable differentially deflected aft horizontal tail. Such a control avoids the wing aeroelasticity problem and also many of the structural problems associated with use of more conventional controls on the thin wings typical of high-speed airplane designs. A wind-tunnel study was made at Langley to provide supersonic information on the effectiveness of a control of this type on two sweptback wing airplane models. In addition, the effects of this use of the horizontal tail on the longitudinal characteristics were determined.

Exploratory and evaluation studies were also made on other promising new airplane control arrangements involving all-movable forward tails for pitch control, body-mounted spoilers and flaps, and wing jet spoilers.

Additional studies were made to provide control information on low aspect-ratio wing, slender-body missile configurations, mentioned previously as having certain advantages. Some of this information was obtained from a recent Langley free-flight, rocket-propelled model study of a series of roll-control arrangements on a cruciform, highly swept, low-aspect-ratio missile configuration. The effectiveness of wing flaps, all-movable forward tails, all-movable wings, wing spoilers and jet devices was determined over a range of subsonic, transonic, and supersonic speeds.

Supersonic-speed wind-tunnel studies of the effectiveness of various controls, including the all-movable wing and forward tail, on other low-aspect ratio wing missiles were made at the Ames Laboratory.

In another Langley study of wingless missile models having bodies of square and round cross section, the supersonic effectiveness of rearward mounted body spoilers was determined.

For airplane or missile flight at very high velocity and altitudes where aerodynamic controls will be ineffective because of the thin atmosphere, reaction-type devices utilizing deflection of the main thrust jet or auxiliary control jets which furnish control independent of the surrounding atmosphere appear most feasible. Some of the results of research studies of these controls in various Langley, Lewis, and High-Speed Flight-Station facilities have been reported recently.

In one Langley study the high-speed effectiveness of three types of reaction controls—an immersed jet vane, a jet flap, and a jet spoiler—all of which acted on the main rocket jet of a slender missile configuration, was determined, using the rocket propelled model technique.

The High-Speed Flight Station study was concerned with the simulation of a jet-control system suitable for an airplane flying at extreme altitudes. This preliminary study has provided valuable information for the design of the control system to be used in high-altitude flight tests of a research airplane.

Flying Qualities

Research investigations to study several phases of airplane handling qualities have been made in the last year. For example analytical studies have been conducted to develop simplified and improved methods for calculating the characteristics of the sometimes unstable or insufficiently damped "Dutch-roll," a combined yawing and rolling motion of an airplane. In addition, methods have been developed for calculating the lateral response of an airplane to random atmospheric turbulence, a type of motion which previously could not be predicted accurately.

In order to determine the factors that limit the minimum landing speed of high-performance airplanes, flight programs have been conducted at the Langley and Ames Laboratories. These studies were undertaken because of the uncertainty of the causes for the tendency toward high landing speeds prevalent for most current airplanes. Consideration was given in the studies to the effects of stall warning, engine thrust, engine response, altitude and speed control, lateral control effectiveness, static longitudinal stability, and pilot visibility.

Spinning

During the past year, research on airplane spinning problems has continued primarily through investigation in the free-spinning tunnel of specific airplane designs for the military services. Analysis of the results of these studies has emphasized the importance of mass distribution, fuselage nose length, and proper control manipulation for recovery for a given design. For some future designs, wind tunnel and flight studies have shown it may be essential to prevent the fully developed spin by proper control technique during the incipient phase of the motion. In order to study this incipient spin, not possible in the spin tunnel, a new technique has been developed involving the launching of dynamic radio-controlled models from a helicopter. This facility can also be used to study the fully developed spin and therefore as a check for spin tunnel tests, if desired.

AUTOMATIC CONTROL

Missiles

The unmanned aircraft, or missile, depends upon self-contained control devices to provide it with stability and to control its direction of flight. These control systems, because of the growing need to fly higher and at great speeds, are very complex and expensive. The NACA's automatic control research in the missile field has concerned itself with simplification of stabilization and guidance systems, and with improved means of analyzing and optimizing complex controlling networks under realistic flight conditions such as turbulence in the atmosphere and electronic interference in radar guidance information.

Studies at the Langley Laboratory to establish simple stabilization and control systems for missiles have led to the consideration of on-off or flicker controls which are momentarily deflected and returned to neutral to correct for errors in a missile's course. Control system theory for nonlinear control techniques of this nature show that flicker controls can maintain a desired missile flight path with minimum use of the controls and with minimum deviations from the desired path. This is accomplished by a particular control switching sequence. An analytical method for determining such a switching criteria, and mathematical techniques for analyzing such discontinuous control systems have been developed.

In another Langley Laboratory study, concerned with simplification of missile control and guidance systems, advantage was taken of certain nonlinear aerodynamic characteristics as a means of providing an on-off control system for adjusting a missile's flight path.

Results of studies of the above type have been encouraging enough to justify a missile trajectory study of the final phase of target interception with simplified schemes of missile guidance and control. It has been shown that simplified control techniques can provide accurate flight path control and in addition both the power required and the size of the power unit to actuate the controls may be less than that for other more conventional control techniques.

When missiles are required to operate over broad ranges of speed and altitude, correction of flight path errors require different control deflections for various flight conditions. The required flight path is usually maintained by a complex gearing system to vary the control surface deflections as a function of flight speed and altitude. Studies of ways and means of simplifying this gearing problem have been made at the Langley Laboratory. The analytical and model flight programs conducted show that if the aerodynamic control surface is deflected by an actuator that provides a given force for a given guidance-error signal, the control system can be simplified and at the same time produce fairly uniform missile response to command signals for a large range of flight conditions.

At the Ames Laboratory, studies were undertaken to develop an analytical method for the design of control systems for two types of guidance that would provide a missile with the best probability of hitting the target. It was shown that exact analytical solutions may not be feasible; however, approximate solutions can be obtained for an optimized control system by means of a combination of analytical and electronic computer studies. The guidance systems considered were beam rider and homing. In the first system the movements of the target airplane are followed by the electronic beam of a radar device much as the target might be followed by a beam of a searchlight. The missile attempts to fly along this beam to the target. In the homing system, the missile contains its own guidance. Information on target position with respect to the missile is obtained through a tracking radar carried in the missile. A computer in the missile uses the target information and missile flight information to provide signals to the controls to fly the missile toward the target. In these studies, missile aerodynamic characteristics, target evasive maneuvers, and electronic interference signals associated with radar tracking of targets are considered.

Recently, because of their application both to missile guidance systems and to airplane armament firing control systems, considerable attention has been given to optimization techniques for systems subjected to disturbances having statistical characteristics, such as radar noise (electronic interference) and air turbulence. A mathematical technique has been developed at the Ames Laboratory for optimizing control systems subjected to random (statistical) disturbances. The method can be used to study cases where the statistical characteristic of the disturbance is either stationary, which is to say, does not vary with time, or nonstationary, that is, varies with time.

Airplanes

Use of airplane configurations selected primarily from performance considerations has accelerated the need for automatic systems for alleviation of stability and control deficiencies. Increased performance has also emphasized the limited control capabilities of the human pilot and pointed to the need for automatic controls to assist him in the performance of special functions such as target tracking.

One problem encountered by high-performance airplanes has been extreme inadvertent divergence from the desired flight path during rolling maneuvers. Recent research has provided a better understanding of the phenomena and has resulted in the construction and testing of several promising automatic systems at the Langley and Ames Laboratories and at the High-Speed Flight Station, to control flight path divergence where practical airplane modifications were not adequate or could not be employed.

A parallel problem for high-performance airplanes has been that of inadvertent pitching motions in longitudinal maneuvers. Analytical studies have indicated several methods for alleviating these undesirable characteristics by automatic means. In one Langley Laboratory program a pitch-up limiter which effectively modifies the aerodynamic pitching moment of an airplane appears to be a promising control device. In another study, an automatic braking device on the elevator, actuated by a combination of normal acceleration, pitching-velocity, and pitching-acceleration signals successfully limits normal acceleration to desired values.

In modern airplanes the pilot is no longer linked directly to the aerodynamic control surface through a cable and pulley or push-pull rod mechanism. Most high-performance airplane control systems contain hydraulic actuators although some use is being made of electric actuators. With hydraulic systems the pilot, through the control stick, is linked to a valve which controls the flow of hydraulic fluid to the actuator which in turn deflects the aerodynamic control surface. Since the pilot is not directly connected to the aerodynamic control surface, he is not immediately aware of the aerodynamic force imposed on the control surface. Artificial feel systems have been shown to be necessary and are incorporated in powered control systems.

Studies of control deficiencies of modern airplanes show that the pilot is not necessarily provided with the best cues to enable him to maneuver the airplane with precision. Some exploratory ground simulator and flight research at the Langley Laboratory has shown that when control system feel characteristics are functions of normal acceleration, pitching velocity, pitching acceleration, or combinations of these functions, the pilot can improve his precision of control.

It has been learned that factors such as the force required to start the powered control system moving, time lags between control stick movement and control surface movement, and associated airplane response characteristics to control surface movement can affect greatly the pilot's opinion of the airplane and its control system and more importantly his ability to control the airplane precisely. Studies have been made at the Langley and Ames Laboratories to determine desirable values of the important control system variables as associated with control stick deflection and force.

Automatic pilots are being used extensively for such tasks as pilot relief for cruising flight control, bombing navigation, and target tracking. In the usual case the automatic pilot is added to the existing control system. The extensive use of automatic pilots has raised questions as to the need for duplication of control system elements. If the human pilot flew the airplane through the automatic pilot, it should be possible to simplify the airplane control system. In this area the Langley Laboratory has conducted a number of flight and ground simulation studies of two autopilot control systems that provide control of airplane attitude and airplane acceleration respectively. Thus the human pilot by movement of the control stick does not move the aerodynamic control surface directly but commands the control surface, through the automatic pilot, to move in such a manner that the airplane develops the desired attitude or acceleration (depending on type of autopilot) commanded without further manipulation of the control stick by the human pilot. These systems inherently provide such features as stability augmentation and uniform airplane response over broad ranges of airplane operation. Pilots that have flown these command control systems believe them to be an important advance in control system design.

The use of powered controls and autopilot control systems makes it possible to use small control sticks mounted on the side of the cockpit. Side-mounted control sticks are of interest because they clear the central area of the cockpit for use of radar fire-control equipment, and enable the pilot to minimize inadvertent movement of the control stick during rapid maneuvering. One side-located stick has been tested at the Langley Laboratory in conjunction with angular rate and normal acceleration automatic pilot control systems and with a conventional power control system. In general the pilots found this side-located controller to be comfortable and natural to use, and could fly the airplane with good precision.

Experience shows that the human pilot of a high-speed interceptor must be assisted in the target tracking phase of an attack of another high-speed aircraft if the mission is to have a reasonable chance of success. In the past this assistance has taken the form of optical and radar sights which compute the desired aiming point for particular types of attacks. Recently automatic tracking systems have been used which completely relieve the pilot of the tracking control task. This latter system has received the bulk of attention this past year.

Automatic tracking systems rely on radar to give the position of the target relative to the interceptor. Target location information is passed through a computer which provides signals to the airplane controls such that the airplane performs the necessary attack maneuvers. The performance of existing and proposed automatic control systems has been evaluated at the Ames and Langley Laboratories to establish comparative performance and to define problems. In particular, programs have been carried out to determine ways to improve accuracy of tracking or maneuvering targets; ways to optimize airplane response to commands to roll and pitch; means of optimizing the command computer; and studies of the effects of airplane aerodynamic characteristics on the performance of the automatic attack system. An interesting byproduct of one flight investigation concerns human pilot tolerance to airplane motions when the airplane is tracking automatically. It was demonstrated that automatic tracking systems must be designed to insure that the pilot is not exposed to motions that unduly reduce his capability to monitor the attack.

LOW-SPEED AERODYNAMICS

The design of airplanes to operate at higher speeds generally involves compromises resulting in higher takeoff and landing speeds. The longer runways necessitated have been of increasing concern and expense especially to the military services. There are many situations where it is especially advantageous to have aircraft that are capable of taking-off and landing vertically or in extremely short distances (commonly referred to as VTOL or STOL aircraft) in relatively rough terrain, and that have significantly greater speed and range capabilities than helicopters or convertiplanes. Research on airplane configurations capable of accomplishing vertical or short takeoff and landings as well as research on the low-speed characteristics of high-speed configurations is receiving much attention by the NACA.

High-Lift Devices and Boundary-Layer Control

Various devices including wing leading-edge modifications—such as slats, nose droop or flaps, and changes in nose radius—in combination with wing trailing-edge flaps have been tested in wind tunnels and in flight as means of increasing lift. Higher lift is achieved with such arrangements by either an increase in camber or, in some cases, by delaying the separation of the low energy air adjacent to the wing surface. Ultimately as lift is increased, however, the energy of this boundary layer air decreases to the point where it separates from the upper surface of the wing and its high-lift devices thereby causing stalling and loss in lift. It is possible to delay this boundary layer separation to higher lift by removing the low energy boundary layer air artificially by suction through slots or a porous area on the wing or flap surface or by reenergizing the boundary layer air through blowing. The development of simple and effective pumping means in recent years with the advent of the turbojet engine has revived strong interest in boundary-layer control and the NACA has accomplished extensive wind-tunnel and flight research on boundary-layer control methods.

The direction of the present NACA flight research on landing and takeoff is toward a general study of the factors influencing the pilot's choice of landing speeds and piloting techniques. The maximum reductions in landing speeds available through the use of boundary-layer control have often not been realized in flight because of factors other than stalling. Items such as airplane stability, control response, visibility, and engine response have limited the minimum speed at which pilots will make landing approaches. Attempts are being made to evaluate these factors as they relate to the minimum speed chosen by the pilot in the landing approach maneuver. The use of boundary-layer control to increase the lift of a wing normally results in reductions in landing approach speeds to such an extent that the airplane operates in a low-speed high-drag range where more thrust is required as speed is reduced. This is an unstable condition in which pilots do not like to operate for other than very short periods. The establishment of piloting techniques in this low-speed high-drag range should be of great benefit for landing operations of future supersonic aircraft as well as for VTOL and STOL aircraft since these latter types will require similar piloting techniques. So far, this type of flight experience has been with fighter-type aircraft. In order to check the validity of the results as they apply to transport type aircraft, it is planned to perform similar investigations with multiengined aircraft when suitable ones become available.

Jet Flaps

Research aimed at reducing takeoff and landing speeds and distances has also included several studies of various types of jet flaps. The jet flap may be defined as a high momentum sheet of air blown in the vicinity of a wing in such a manner as to produce a forced circulation of air around the wing, and hence, additional lift. The jet flap concept differs from the conventional boundary-layer control concept primarily in that much more power is employed to induce the circulation than is required merely to maintain attached flow to a surface. In fact some arrangements involve discharging the entire jet engine exhaust through suitable nozzles.

A new type of jet flap arrangement was conceived during NACA investigations which might be applied to jet bombers and transports having pod-mounted engines. In this arrangement, called the external-flow jet-augmented flap, the exhaust of the engine is directed upward by a vane or swiveling tailpipe through the slot of a trailing-edge slotted flap. Results indicated that this arrangement was somewhat less efficient as a lift producer than the type of jet flap in which the exhaust is internally ducted through the wing from fuselage mounted engines or engines buried in the wing. The external arrangement does, however, allow the internal areas of the wing to be used for fuel and may allow a lighter weight installation since very little ducting is required. Preliminary estimates which do not take into account any weight increases resulting from the external jet flap installation indicate that significant reductions in takeoff and landing speeds and distances may be realized through the use of this jet flap principle. Before the jet flap can be used safely, however, a considerable amount of research remains to be done particularly in regard to the effects of heat and noise-induced vibration on the wing adjacent structure. In addition, the safety aspects of an airplane equipped with jet flaps need to be investigated in the event of an engine failure in critical flight conditions.

VTOL and STOL Aircraft Operation

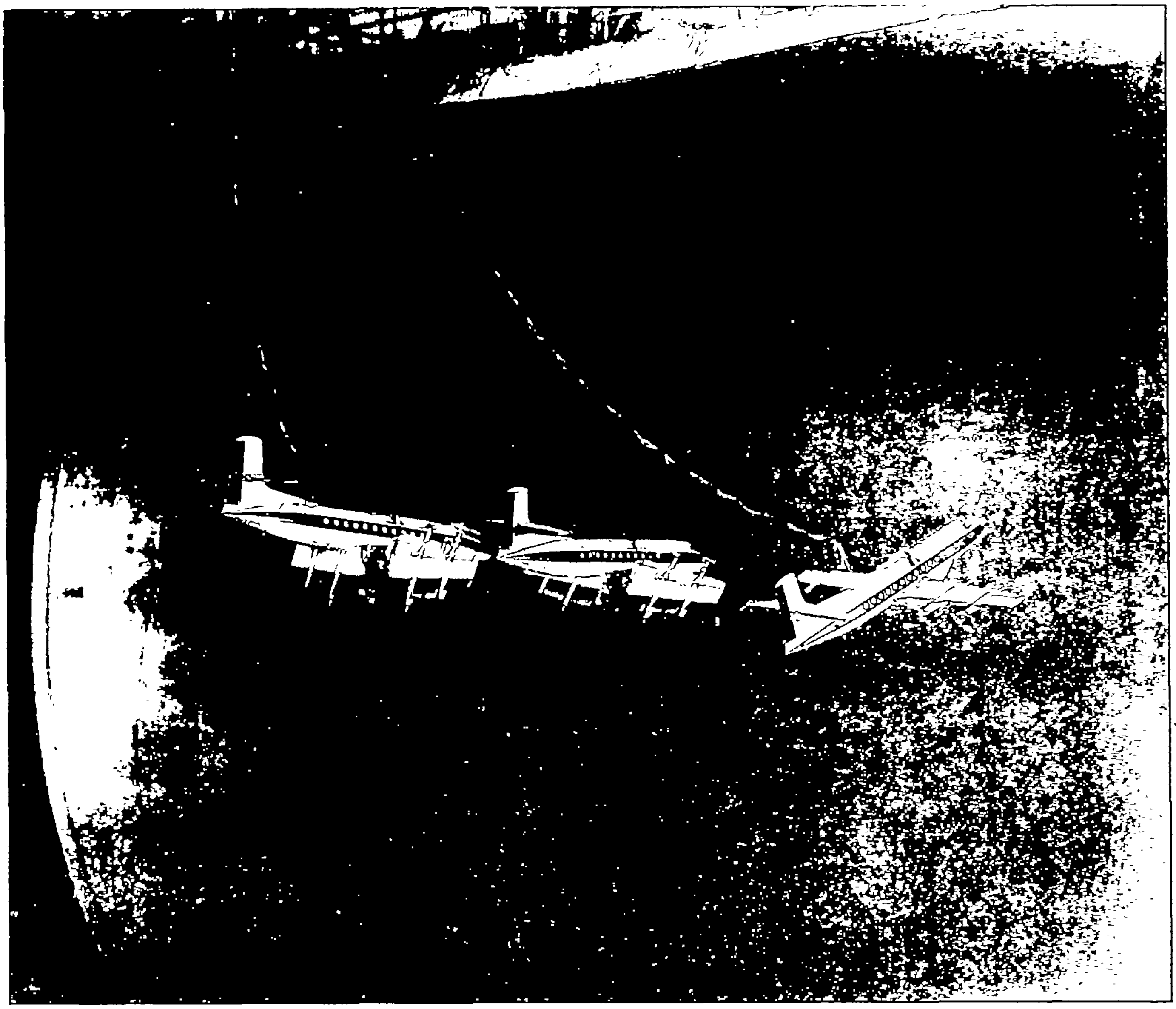
In recent years pioneering NACA free-flight and wind-tunnel research has led the way in the development of several airplanes which hold promise of spanning the operational gap between helicopters and conventional aircraft. Several jet-powered VTOL aircraft and propeller-driven VTOL and STOL aircraft have been flight demonstrated by contractors to the military services or are to be demonstrated in the near future. A wide variety of configurations can be employed for aircraft of these types, although all depend to a large extent or entirely on the use of power to generate lift. Consequently, a new series of performance and stability and control problems has arisen. Most of the VTOL configurations flown to date may be described as tail sitters and require that the fuselage rotate from a vertical attitude at takeoff to a horizontal attitude in forward flight. For transport aircraft rotation of the fuselage is impractical and lift must be generated in takeoff and landing by such means as directing the propeller slipstream or jet exhaust downward while the fuselage remains essentially horizontal.

NACA research with free-flying models has resulted in a fairly complete evaluation of the stability and control characteristics throughout the flight range for three variations of a basic VTOL transport model. The model was of the tilting wing and propeller type and had both flap-type controls on the wing and jet-reaction controls mounted at the rear of the fuselage. The accompanying photograph shows the model being flown in a wind tunnel. The results indicate that in forward flight a high-wing configuration was more stable longitudinally throughout a larger center-of-gravity range than a low-wing configuration and that the reaction-type pitch and yaw controls were more effective than flaps operating in the propeller slipstream. All of the configurations could be flown easily in hovering flight despite the fact that the rolling and pitching motions had unstable oscillations.

Research on the principle of deflecting the propeller slipstream for obtaining higher lift at low speeds has also continued in conjunction with the use of blowing boundary-layer control. Various flap configurations have been tested in efforts to obtain higher lifting efficiency and less airplane nose-down pitching moment caused by the concentration of lift near the wing trailing edge. The results show that the boundary-layer control system produced increased lift and slipstream turning; however, it was also brought out that the economies of an overall aircraft system would depend on the particular system employed and, for a particular installation, would have to be determined from a detailed analysis.

Facilities for VTOL/STOL Free-Flight Studies

Initial free-flight tests of VTOL models conducted in the Langley full-scale tunnel simulated slow, constant altitude transitions from hovering to high speed forward flight. It became apparent early in these studies that there existed a need for a study of the handling qualities of these types of aircraft during rapid accelerating and decelerating transitions to forward flight and back to hovering flight. The rapid changes in airspeed necessary for such studies could not be obtained in wind tunnels, and consequently a new test facility was developed in which the speed of the transition depends only on the amount of model power available. This new facility consists, essentially, of a small rotatable crane and is similar in operation to the control-line technique used by model airplane enthusiasts wherein the model is tethered by wires and flies in a circle. The results of the first investigation of a propeller-driven, delta-wing, tail-sitter VTOL model



Multiple exposure showing tilt-wing model in various stages of flight.

using this facility indicated that decelerating transitions from level flight to hovering were more difficult to perform than accelerating ones because of the closer coordination required between the thrust and pitch controls to maintain constant altitude. The facility has also been used to advantage as a testing ground for jet powered models using hydrogen peroxide rocket motors. To date models of a tail-sitter and a horizontal fuselage VTOL airplane powered with hydrogen peroxide units have been tested.

Propellers

The use of propellers in new aircraft is currently limited to those in which range rather than speed is a primary design criterion, and to most of the VTOL and STOL flying test bed aircraft. The NACA has, however, continued a transonic propeller test program utilizing the XF–88B propeller research airplane. It was determined several years ago that a propeller must have thin airfoil sections and operate at high tip speeds to obtain efficient transonic performance. Propellers with airfoil sections as thin as two percent have been investigated in flight from a structural as well as performance standpoint. These propellers create considerable noise. The performance penalties associated with compromise propellers designed to operate at lower tip speeds are presently being studied.

The primary problem associated with propellers for VTOL and STOL aircraft applications is to achieve high values of thrust at static and low-speed conditions without unduly compromising the higher speed performance. Consideration is being given to means of accomplishing this while at the same time keeping propeller weight to a minimum. Some interest has been evidenced in the shrouded propeller or ducted fan for VTOL and STOL aircraft as such devices can develop

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higher values of static thrust for a given diameter than conventional propellers. Offsetting the advantage of higher static thrust, however, is the added weight of the shroud, its drag at cruise conditions, and possible structural problems imposed on the propeller or fan blades. Some preliminary research on shrouded propellers has led to the development of improved shroud shapes, and further work on actual shroud-propeller performance is under way.

SEAPLANES

Recent NACA research in exploring and applying advanced aerodynamic and hydrodynamic concepts has opened the way for achieving markedly higher-speeds with new seaplane designs not having the performance compromises presently associated with water-based aircraft. Following the trend of high performance land-based aircraft, however, these advanced seaplane types would have higher takeoff and landing speeds than present day seaplanes. For instance some of the configurations may have takeoff speeds as high as 200 knots. Consequently, a major part of the NACA's hydrodynamic research during the past year has been directed at studying hydrodynamic surfaces and seaplane configurations at higher speeds than before in order to investigate not only hydodynamic performance but also other important factors such as spray and water flow characteristics, airplane stability and control on the water, and water loads on the seaplanes operating in various wave conditions. These latter characteristics are often difficult or impossible to predict based on present experience, as the new advanced configurations are in many respects considerably different from present day seaplanes. It is encouraging that in the NACA hydrodynamic tests some types of hull forms and hydroski and hydrofoil gears have shown real promise for coping with the severe water loads at the high landing and takeoff speeds, although a large amount of additional research is needed to assess and solve the loads problems.

High-Speed Hydrodynamic Facilities

A new hydrodynamic tank facility (see accompanying photo) has been placed in operation at Langley this year and has a speed capability of 170 feet per second and a planned future capability of 200 feet per second. In the first investigation in the facility it was determined that the lift coefficient of a flat bottom planing surface at various operating conditions was essentially constant throughout the speed range from 80 to 170 feet per second. The experimental results agreed well with those obtained in the larger Langley tanks having lower speed capabilities' as well as those obtained in a small high-speed water jet. A better understanding has also been achieved of the proper jet boundary corrections to apply to data obtained in the latter facility.

Planing Surface Theory

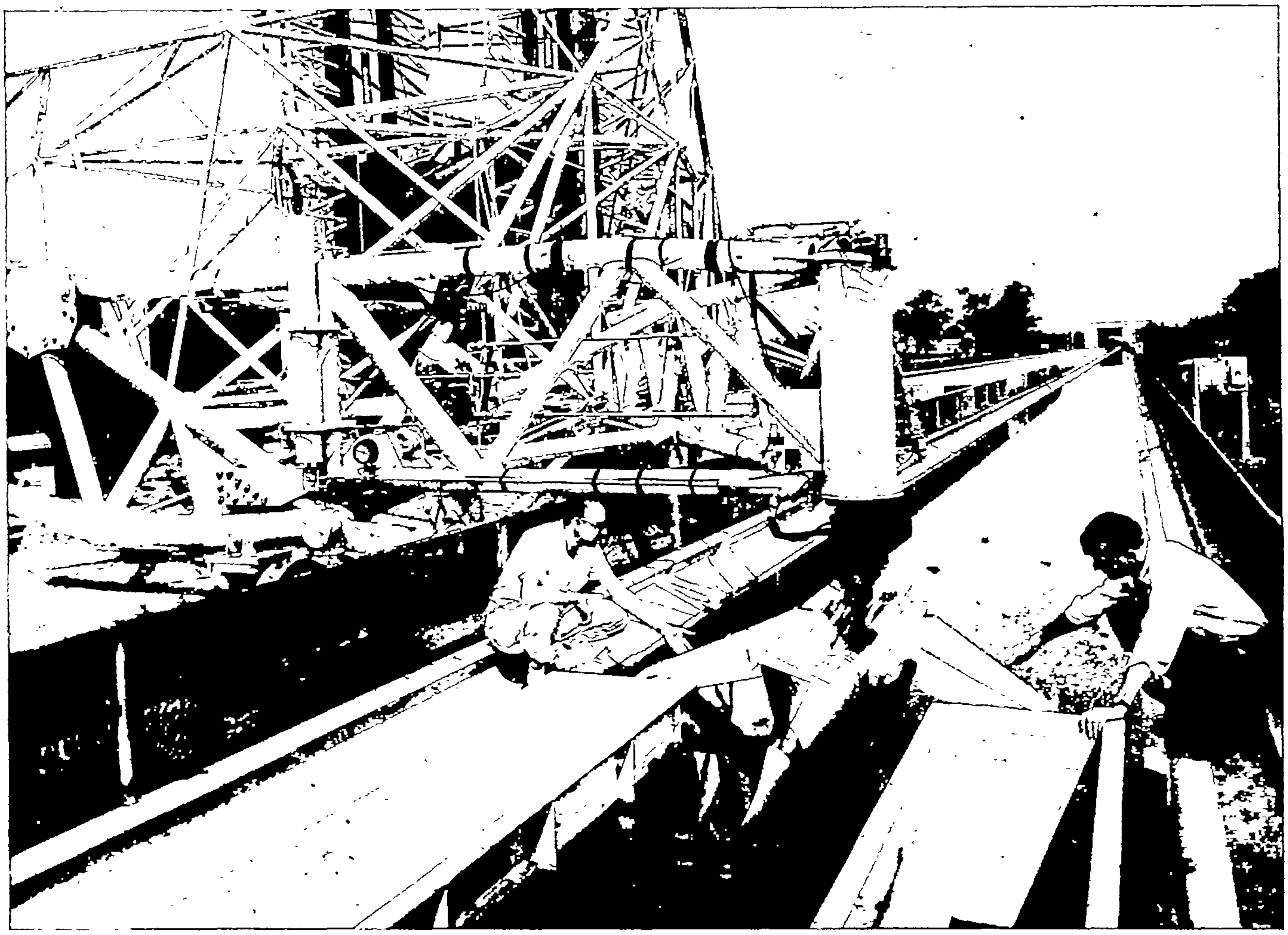
Better theories have been needed to correlate the vast amount of experimental data on lift of submerged and planing hydrodynamic surfaces and to provide better tools for guiding future research and seaplane design. Advances have been made in this regard during the past year and work has progressed on several fundamental programs dealing with basic hydrodynamic lifting elements such as hull bottoms, hydroskis and hydrofoils. In one example a general nonlinear theory was established for calculating the forces and moments on planing surfaces of various shapes and planforms. Previous theory considered only the linear component of the suction lift and was limited mainly to rectangular surfaces. Special experiments have been conducted in the Langley tank No. 2 to verify the new theory.

Hydroski and Hydrofoil Landing Gears

The ability of hydroskis and hydrofoils to alleviate the motions and loads of seaplanes operating on rough water has spurred additional research on such devices for landing gears. There are still many unknowns concerning optimum shapes and planforms for hydroskis and attention has been given during the past year to effects of bottom and upper-surface curvature on the ski characteristics during operation at various submerged and planing conditions. Also in multiski arrangements the interference effects of multiple wakes have been explored. Some shapes with particular structural and retraction advantages have been incorporated in the program. Skis often produce violent spray at emergence and one experiment has been aimed at investigating the effect of ski nose shape on spray. Submerged lifting surfaces at certain operating conditions near the water surface incur air ventilation on their upper surfaces with large losses in lift and lift/drag efficiency. Experimental investigations have provided a better understanding of the nature of these flow changes, the effect of model size on the phenomenon, and the operating conditions at which the ventilizated flow can be expected to occur.

Supercavitating Hydrofoils

Normal hydrofoils intended for efficient operation at low speeds develop cavitated flow at moderate water speeds with attendant serious losses in lift and lift/drag efficiency. By designing hydrofoils purposely to operate in cavitated flow, however, good lift and drag properties can be achieved at the higher water speeds. These so-called "supercavitating" hydrofoils offer considerable promise for high-speed seaplanes not only in providing efficient landing gears from a lift and drag standpoint but also in alleviating the severe seaplane motions and overall loads at high speeds in rough water. In the past year refinements have been made in the theory for designing the shapes of such hydro-



New Langley high-speed hydrodynamic test facility.

foils. Several supercavitating hydrofoil configurations have been tested in the Langley Tank No. 2 and the tests will be extended to speeds up to 200 feet per second in the new high-speed hydrodynamic facility.

ROTARY WING AIRCRAFT

Vibration

One of the major operational problems associated with current helicopters is the high vibration level. In addition to seriously limiting the life of some major and expensive components, the vibration induces severe pilot fatigue after only a short period of flying time. In order to study this problem of vibration considerable effort has been applied to determine the sources of the aerodynamic loads which excite them. Various flight and wind-tunnel tests have been conducted in which rotor-blade vibratory stresses and fuselage vibrations in a number of steady and maneuvering flight conditions have been measured. The results show that the coupling effect between the fuselage and rotors, which is often neglected or else treated by unproven theoretical methods, can produce an important shift in resonant frequency. The method developed during the flight investigation should prove a satisfactory means for "flight-test checking" of helicopter prototypes for coupled frequency effects on vibration. In addition, the measurements are being used to establish more satisfactory theoretical treatments which should help designers to alleviate the vibrations at the sources.

A better understanding of the basic aerodynamics of the rotor airflow is a prerequisite to the development of more efficient helicopters. Since the characteristics of the flow field change with each flight condition, theoretical treatments of helicopter characteristics are very difficult and time consuming. Using previously obtained rotor flowfield measurements as a guide, analytical work has been continued in an effort to provide methods for more accurately predicting the induced flow. These studies have included the effect of tip-speed ratio and the use of nonuniform blade loadings which were not included in previous work. Automatic computers have been used to compute rotor blade motion, rotor blade airloads, rotor thrust and power, longitudinal and side forces, and certain stability derivatives. The computational setup is general and the equations can be used for blades of any airfoil section, mass distribution, twist, planform taper, root cutout, flapping-hinge offset, and can account for the effects of pitching and rolling velocities. Stall and compressibility effects can be predicted, as well as the effects of the reversed flow occurring over part of the retreating blade. The use of high-speed computing equipment has enabled the rapid solution of very detailed equations in which no simplifying small-angle limitations need be made regarding inflow angles, angles of attack, or flapping angles.

Experimental work has supplied information relating to the aerodynamic interference between the rotor and other components, a problem that has become more important in view of the trend toward increased rotor blade loadings and convertiplane arrangements involving airplane-type lifting surfaces. An investigation of the effects of a rotor slipstream on a panel representing a wing mounted below a hovering rotor has indicated that the vertical drag; that is, the loss in thrust due to blockage of the rotor slipstream, can be calculated with good accuracy. Various span panels were located at varying distances below the rotor and both steady and pulsing pressures on the panels were measured.

Performance

Current helicopters are limited in top speed by the compressibility drag rise on the advancing blade which causes large increases in the power required for flight at high speeds. In addition to analytical work on the problem of reducing the effects of compressibility, the problem has also been attacked experimentally. Using rotors varying in thickness from 6 to 15 percent of the blade chord, investigations have indicated that significant gains in high-speed performance can be achieved with little loss in efficiency. One important objective of this continuing project is to accumulate a sufficiently wide range of airfoil section data at suitably matched angles of attack and Mach numbers for design information related to high tip speed rotors.

Stability and Control

Full utilization of the helicopter requires a true blind-flying capability, which in turn has been reflected in continued effort toward a fuller understanding of the factors influencing helicopter stability and control characteristics and flying and handling qualities. Research conducted by means of flight tests has been concentrated on the important problem areas of low-speed flight, steep approaches, and vertical landings, in order to determine the effect of changes in various stability parameters on pilot proficiency. Specialized piloting tasks such as hovering over a fixed spot or executing a low-speed instrument approach have been included. Being considered also is the relative importance of improved instrumentation for the pilot in conjunction with improved helicopter stability for instrument flight. Low airspeed flights, including efforts to hover over a ground reference, are being conducted under simulated instrument conditions with an HO3S–1 helicopter equipped with electronic autopilot-type components which permit alteration of the apparent (to the pilot) stability and control characteristics of the helicopter. By means of these components, systematic variations in such parameters as control power, damping in roll, yaw, and pitch, and stabilization about each axis can be evaluated. In order to insure adequate coverage in the present investigations a current production helicopter with stability augmentation equipment (HSS–1) has been flown and appropriate data published. The first results show that significant improvements in flying qualities can be obtained with automatic stabilization equipment, particularly with yaw stabilization.

Propulsion

Various design studies by the military services and industry have indicated that propulsion devices mounted on the rotor blade tip would be suitable for very large, short range helicopters. Such systems employing pulse-jet and pressure-jet propulsion devices have been tested on the Langley helicopter tower. Pressure-jets may be either cold cycle; in which the working fluid, usually air, is ducted through the blade and no burning of fuel occurs at the rotor blade tips; or hot cycle, in which burning does occur at the tip. The results of a preliminary experimental program on a pressure-jet rotor using both cold and hot cycles have been published, as well as a set of design charts derived to facilitate rapid analysis of compressible flow properties in a whirling duct. In general, the hot cycle system showed about double the ratio of rotor propulsive horsepower to equivalent compressed-air horsepower of the cold cycle but resulted in a significant increase in specific fuel consumption. The analysis of the flow in a whirling duct presents in chart form the internal aerodynamics of a pressure-jet rotor blade. Also in conjunction with this project, an analytical study of the hovering performance of various helicopter propulsion systems has been completed and the results presented in the form of charts for estimating hovering over endurance.

POWER PLANTS FOR AIRCRAFT

Much progress has been made in increasing the performance of the turbojet engine since its introduction in the United States in 1942. A comparison of the performance of the early production engines with the latest models is of interest. Overall efficiency has been at least doubled, weight for a given thrust output has been cut in half, altitude operating limits have been more than doubled, and finally, flight speed has been approximately tripled. Further substantial improvements can be made. However, the bulk of the research that is necessary for further improvements on the engine proper has been completed. Future research to be done involves inlet diffuser and exhaust nozzle, the interactions between these components and the engine itself, and the alterations in the engine to reach flight speeds of four times the speed of sound.

The NACA has made many contributions to turbojet and turboprop progress. From its altitude facilities has come a steady flow of performance data on specific engines, which would otherwise not have been available. This data has been generalized and the results of component research incorporated, with the result that the designers of each successive family of engines has had an increasingly firm basis on which to design new engines. Certain specific components such as the afterburner and the transonic compressor have been based primarily on NACA research results. The progress of the turbojet has been the result of a joint effort on the part of the industry, the Department of Defense, and the NACA.

NACA research on the ram jet has been parallel to research in the turbojet. The ramjet is capable of use to speeds of at least seven times that of sound and for special applications can be used for even higher speeds. The rocket engine is now coming into extensive use. The NACA is increasing its emphasis on research problems peculiar to this engine. Studies of new high energy propellants, fluid flow studies aimed at providing information on which to base the design of fuel pumps, control system and heat transfer studies are among the more important investigations. The ever-present high temperature materials problem is intensified by the rocket engine. Also underway are studies of new propulsion systems such as the ion rocket and the application of nuclear energy to both chemical and electrical rocket systems.

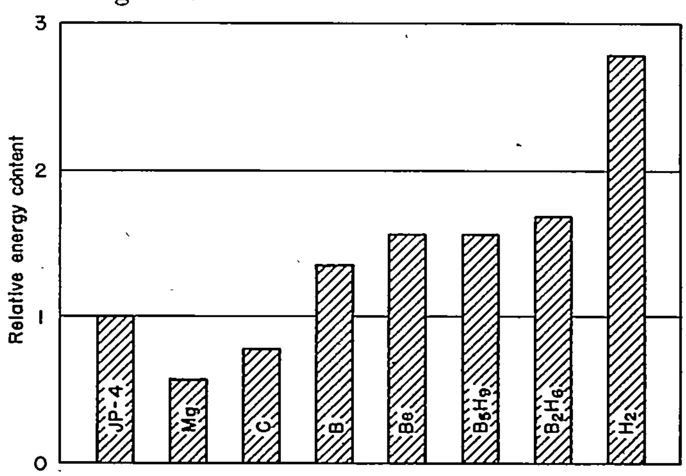
A description of some of the Committee's recent unclassified research in the field of aircraft propulsion is given on the following pages.

AIRCRAFT FUELS

Energy must be expended to move any object. More energy is needed in a smaller package than is now available if aircraft are to fly much farther at high speed. Theoretical studies show that the desired ranges can be approached with some of the proposed high energy fuels.

The rate at which energy is expended will determine the velocity of an object and the duration of the expenditure will determine the range of the object. The energy available in burning 1 pound of jet fuel with air, for example, is sufficient to provide 1 pound of thrust for 2,750 miles. In an aircraft system, however, the greater part of this energy is lost because the efficiency of the engines is less than 50 percent. At supersonic speeds the efficiency of the engine is increased but this increase is more than offset by the increase in airplane drag. For example, the range of a jet bomber at supersonic speeds could be less than half of the range of the same bomber at subsonic speeds because of the drag factor. The range of an aircraft may be increased by increasing the efficiency of the engine, by decreasing the drag, or by increasing the amount of energy in the system.

Much has been done and is being done to increase engine efficiency and to decrease airplane drag. Considerable increase in range has been effected by increasing the amount of fuel in the system (over 50 percent of the takeoff weight of a manned aircraft). Theoretical studies show that considerable gains can be obtained in the amount of energy in the system from the use of lighter weight elements in the fuels or from compounds containing these elements. The relative amount of energy per pound (compared with conventional jet fuels) from some of these is illustrated in the following sketch:



It is obvious from the figure that hydrogen contains much more energy per pound than any other examples shown. However, hydrogen, even as a liquid, has a density about one-tenth of JP-4 and would therefore require much larger tanks for the same energy content. Beryllium, the next highest element, is quite scarce and is extremely poisonous. Boron, however, is available in large quantities.

NACA has studied the use of boron, in the form of powders mixed with conventional jet fuel. The results indicated that such fuels can be utilized. However, boron has the further advantage of forming compounds with hydrogen and carbon. In this way the higher energy available from hydrogen as well as boron can be used. Many of these boron compounds are liquid and can be used in systems quite similar to conventional systems.

Since the boron hydrides do not occur in nature, they must be manufactured and are quite expensive. However, for certain applications, the potential increase in range warrants the additional cost.

For the past seven years, the Lewis Laboratory of the NACA has been studying the application of the boron fuels to aircraft power plants. The work has included chemical laboratory studies, theoretical studies to determine the most suitable types of engines and operating conditions, and experimental studies in actual engines.

The rocket fuels program has the same goal as the air-breathing engine program—obtaining more energy and higher performance from each pound or gallon of propellant. The theoretical performance of several fuel and oxidant combinations has been calculated. These calculations are used to design experimental engines and then to evaluate the results of tests in those engines.

Until recently, the theoretical calculations for specific combinations required considerable time and effort. Now, however, the use of an IBM 650 computer will permit the calculation of theoretical rocket performance for any chemical system containing as many as ten elements. The lower atomic weight elements (such as carbon, oxygen, fluorine, hydrogen, nitrogen, and boron) are of interest in rocket propellants as well as in fuels for air-breathing engines.

Research on rocket fuels is discussed in more detail under "Rocket Engines."

COMBUSTION

One of the serious problems encountered in the operation of turbojet aircraft is the decrease in combustion efficiency that occurs at high-altitude flight conditions. Experimental investigations with turbojet combustors show that combustion efficiency is adversely affected by the high airflow velocities at which these combustors are required to operate and by the low air-pressures and low air-temperatures encountered at high altitude. Combustion efficiency is the proficiency with which the chemical energy of the fuel and air is converted into kinetic energy of the propulsive air-stream. There is a need, therefore, for a means to explain these deleterious effects, and to indicate design approaches that are useful in alleviating these adverse effects.

A theoretical treatment of the turbojet combustion process is difficult because several different processes are involved. The fuel must be vaporized, mixed with air, ignited, and oxidized to the final products of combustion. The combustion process may be visualized as a competition between these conversion processes and the quenching that occurs when the reacting mixture is cooled by dilution air and when the reacting mixture contacts the relatively cool walls of the combustor liner. Because of the complicated nature of the overall process, no simple yet exact theoretical treatment is currently possible.

By making certain simplifying assumptions regarding the turbojet combustion process, it is possible to arrive at equations to describe the process. The NACA treatment assumes that one step in the overall chain of processes which constitute turbojet combustion is sufficiently slow to be the rate-controlling step. The analysis is essentially semiempirical, since the theoretical equations are based on assumptions which are somewhat flexible, and are selected to agree with observed experimental trends. The relation,

$$N_b=\varphi\left[\frac{(P_t\ T_t)}{V_r}, f, \alpha\right] \tag{1}$$

was derived from the assumption that chemical reaction kinetics control the combustion efficiency. P_t is the combustor-inlet pressure; T_t is the combustor inlet temperature, V_r is the combustor-inlet gas reference velocity based on P_t, T_t, and the maximum combustor cross-sectional area; f is the overall fuel-air ratio; and α is the oxygen concentration.

A similar relation,

$$N_b=\varphi\left[\frac{(P_t^{1/3}T_t^{1.1})}{V_r}, f, \alpha\right] \tag{2}$$

was derived from the assumption that the rate of flame spreading controls combustion efficiency.

Experimental combustion data were obtained in tests of several turbojet combustors. The experiments were conducted to provide an evaluation of the theory and included tests with a turbojet combustor in which (1) the oxygen concentration in the inlet mixture was varied, and (2) the pressure and mass flow rate were independently varied through wide ranges.

A comparison between the experimental data and the predictions of theory show that the parameter

$$\frac{P_tT_t}{V_r}$$

correlates the combustion efficiency data for several turbojet combustors. The parameter

$$\frac{P_t^{1/3}T_t^{1.1}}{V_r}$$

was found, however, to give a better correlation of the data for certain ranges of conditions.

The experimental data indicate that a shift from one rate-controlling step to another occurs as combustor pressure is increased, and the reaction kinetics parameter,

$$\frac{P_tT_t}{V_r},$$

therefore best correlates the data at low pressures. The flame spreading parameter

$$\frac{P_t^{1/3}T_t^{1.1}}{V_r}$$

is better at high pressures. No single correlating parameter can, therefore, be expected to be adequate for all combustors and for the entire range of operating conditions.

LUBRICATION AND WEAR

Bearing Research

One of the important problems included in the general field of lubrication and wear has been the failure of bearings. While the quality and thus the average life of bearings has been improved considerably in recent years, there is a lack of knowledge of why some bearings fail after being operated for very short times.

Until recently, much of the testing was done on full scale assembled bearings. However, there are so many variables involved in a test of this kind, that the fundamental causes of failure cannot be determined. Research on the failure of various parts of a bearing was started at NACA in 1953 to reduce the number of variables involved, and the progress on the improvement of bearing cages and cage materials was reported in the NACA Annual Report for 1954. Also in 1954, NACA started development of a method for testing individual balls from bearings to try to find the basic causes of ball failure—the cause of about 35 percent of bearing failures in turbojet engines. Preliminary results indicate that, while the causes of failure are quite complex, most of the failures are caused by some discontinuity in the structure of the metal. This indicates that improvements can be made by changing the process of manufacturing balls as well as races.

Fundamentals of Friction and Wear

Research to solve current and anticipated problems in obtaining satisfactory lubricants and seals for high temperatures, for low temperatures, and for operation in nuclear radiation has continued.

Liquid lubricants can be developed for temperatures up to about 700° F., but their use at higher temperatures is doubtful. The NACA has done considerable basic research on the use of solid lubricants for application to temperatures above 1000° F.

Fluid flow systems of missiles require pumps having seals and bearings that operate at extremely low temperatures—a temperature of −300° F. for liquid oxygen, for example. Very little is known about the behaviour of materials at these temperatures. The NACA has begun a program to obtain fundamental lubrication and wear data at these low temperatures.

COMPRESSORS AND TURBINES

Compressor Research

Research efforts by the NACA in recent months have resulted in greater knowledge of the compressor stall and surge phenomena, and a clarification of the armament firing problem.

At any particular rotating speed, a compressor can impart a maximum increase in pressure to the airflow it delivers, and beyond this point compressor stall and surge occurs. Stall is characterized by a sudden decrease in airflow and results in dangerously high combustion temperatures. Surge is characterized by violent oscillations in airflow and results in excessively high stress and temperature fluctuations. Operation at these conditions is eliminated by the engine control system which maintains operation below experimentally determined stall and surge limits.

With the advent of increased rocket armament firepower and air-launched guided missiles, it was found that the engines swallowed large amounts of rocket exhaust gases. Simultaneously the engines would stall or surge, despite the action of the engine control system. It was determined, however, that the stall and surge points did not agree with anticipated stall and surge points predicted from previous engine calibrations. This situation not only had its immediate and practical significance, but also gave rise to a question as to the fundamental validity of those parameters used to predict the occurrence of stall and surge.

NACA research efforts have led to a major clarification of the armament firing problem and a more realistic approach toward the delineation of compressor stall and surge limits. It was determined that under the conditions of the sudden ingestion of rocket exhaust gases, the multistage compressor no longer could be considered as an integral unit. Instead, the compressor must be accepted as a series of individual compressor stages, each one operating under different airflow, pressure, and temperature conditions, and similar only in that all stages rotate at the same speed. Prediction of stall and surge based on this more sophisticated concept of a multistage compressor was found to correlate accurately with hiterto unexplained experimental data, and the basic parameters used to delineate stall and surge were verified. It is therefore now possible to seek a solution to the armament firing problem with a firm understanding of the fundamentals involved.

Additional compressor research completed during the year indicates that the translation of compressor performance from one gas to another is a cumbersome procedure unless only approximate results are required. This study is important when it is desired to apply knowledge of air compressors to compression of a different gas, or to extend the useful range of a test facility to higher power or speed ranges by using a special gas medium for test purposes.

In the fundamental work of determination and prediction of losses across axial flow blade rows it was determined that major mixing losses resulting from the wake downstream of the blade occur within ¼ to ½ chord length behind the blade trailing edge. These results are indicative of the important part played by mixing losses in the development of overall compressor losses and point out suitable measuring stations for comparisons of different blade configurations.

Jet airplane firing rockets.

A rapid approximate method for the design of centrifugal compressors of given blade shape has been developed.

Turbine Research

In the field of turbine research, NACA has demonstrated the possibility of reducing the weight and simplifying the production methods for turbines. The weight reduction is not limited only to the turbine itself. It is reflected also in the reduction of the weight of the engine frame and aircraft frame because of the lighter turbine. Manufacturers estimate that between 5 and 10 pounds of airplane weight can be saved for each pound of turbine weight. Three basic advantages are gained by weight reduction: (1) Increase either range or load capacity of aircraft; (2) decrease the rotational inertia which results in more rapid engine acceleration and less gyroscopic effect, and (3) conserve strategic materials.

Turbine research efforts have led to the development of a light weight turbine particularly applicable to use in short-life expendable uncooled engines. A turbine with the advantages of light weight, simplicity of fabrication, and low strategic alloy content was designed and tested under full-scale engine operating conditions. The research turbine represented a weight saving of almost 50 percent over a standard turbine of approximately 200 pounds, yet it operated satisfactorily for longer than the period of time required for the completion of an expendable missile mission.

Considerable research effort has been devoted to fundamental turbine problems. This effort has involved highly technical aerodynamic analysis. It aims to resolve the basic losses due to boundary layer flow separation and secondary flow. Work completed during the year includes similarity solutions for three dimensional incompressible laminar boundary layers; an analytical and experimental investigation of secondary flows in ducts; and analysis of particle motions in three dimensional incompressible laminar boundary layers.

A tabulation of mass flow parameters for use in design of turbomachine blade rows has been published. These tables permit a quick and accurate determination of the integrated mass flow and various locations throughout a blade passage.

Turbine Cooling

The application of turbine cooling to gas-turbine-type engines permits increases in turbine inlet temperature to the point where engine power can be increased greatly. Some applications can serve to improve the specific fuel consumption. Furthermore, cooling will permit increased allowable stress levels. As a result, it is possible to increase the mass-flow rate through the turbine and, in all probability, the turbine can be made more reliable.

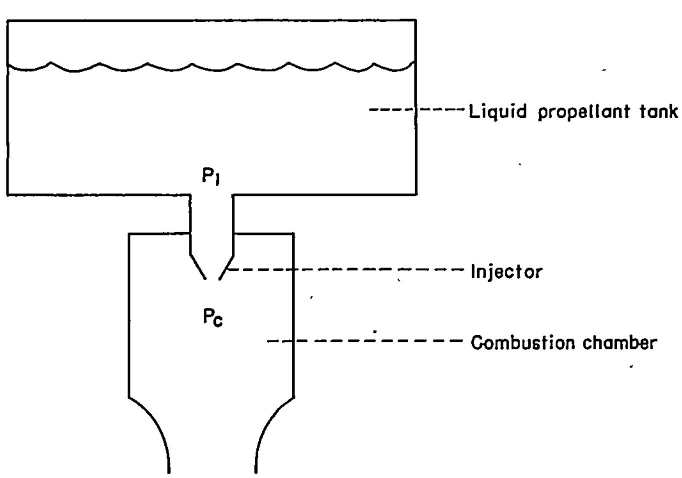
Application of the various methods of air cooling to the specific design of turbine blades has been studied. The use of plain hollow blades is impractical for cooled turbines because the coolant-flow requirements are exorbitant. On the other extreme, the transpiration cooled turbine blade ideally requires only very small amounts of coolant, even for large increases in turbine-inlet temperature. Generally, it is desirable to use blades requiring the smallest coolant flow, but other factors such as fabrication problems, cooling-air pressure required, clogging, blade weight, and durability must be considered. Recent research has shown that considerable savings in coolant flow are made possible by utilizing a smaller number of large chord blades rather than a larger number of small chord blades.

Additional contributions to the field of turbine cooling include a method for rapid determination of core dimensions of cross-flow gas-to-gas heat exchangers, and an analysis of laminar incompressible flow in semi-porous channels.

CONTROLS

Liquid propellant rocket motors have been characterized by long development and "de-bugging" programs. Much of the costly and time consuming procedure is devoted to the redesign of previously satisfactory hardware in order to eliminate unanticipated "chugging" or rocket motor instability. NACA research in the field of rocket dynamics and controls has indicated that paper designs can be translated directly into successful rocket motors if effects of rocket motor component dynamics are properly considered.

The phenomenon of "chugging" is one of the most serious problems associated with liquid propellant rockets. Chugging is characterized by severe oscillations in combustion, in the range of 75–300 cycles per second; these oscillations can result in rocket motor failure, missile structural failure or guidance inadequacy.



A basis for understanding the nature of the instability may be achieved by examination of a simple rocket system consisting of a thrust chamber fed from a large pressurized tank, and having a very short line from the tank to the injector, (see sketch). In this hypothetical case the pressure, P_1, ahead of the injector can be considered constant, but the combustion chamber pressure, P_c, and therefore the pressure drop across the injector can fluctuate rapidly with changes in combustion. Thus, a disturbance in combustion chamber pressure causes a change in the pressure drop across the injector and a corresponding change in propellant flow; the change in propellant flow in turn causes another change in combustion pressure. Consequently, any fluctuations in the combustion chamber pressure are amplified and the system can be unstable. For any specific rocket motor it has been found that increasing the propellant pressure at a fixed combustion chamber pressure, can stabilize the system and eliminate chugging. However, the stability has been achieved at the expense of an increase in weight resulting from the heavier pumps and lines that must be used. Furthermore, the same propellant pressure does not necessarily result in stability for a larger or smaller version of the same basic rocket motor.

In an NACA controls research project, a basic rocket system, consisting of a propellant tank, pipe lines, pump, injector and combustion chamber, was simulated on an electronic analog computer. It was shown that the dynamic behaviour of each component has an effect upon the propellant pressure required for stability. The reason for unsuccessful scaling of rockets to either smaller or larger sizes becomes apparent, as it is shown that component dynamic characteristics do not vary proportionately with size. Proper attention to selection of components can eliminate resonances that lead to instability, and increased propellant flow velocities can substantially reduce the propellant pressure (and therefore the rocket weight) required for stability. In addition, the requirements that must be met by a control system in order to maintain rocket motor stability over a range of thrust levels, are shown. Analog computer simulation of the rocket system prior to assembly of the physical components can greatly reduce development time and cost.

In turbojet engine controls research, experimental programs on speed control and temperature control were completed. Previously derived analytical optimization techniques were corroborated and gains in controlled engine performance were evaluated.

Instrumentation research has resulted in new automatic data recorders and data reduction techniques, a new mass-rate flowmeter for rocket propellants, a lithium fluoride scintillating dosimeter for measurement of ionizing radiation, and advanced thermocouple techniques. The feasibility of measuring temperatures in the range from 3,000° to 4,000° F. by use of a cylindrical tube cooled by interior liquid circulation (cooled-tube pyrometer probe) was established.

POWER PLANT MATERIALS

High Temperature Alloys

It has been recognized for a number of years that small variations in chemical composition can result in large variations in the strength properties of alloys. These effects have been well explored for the major alloying constituents such as chromium, nickel, cobalt, and iron. The effects of minor alloying additions such as boron, zirconium, hydrogen and nitrogen, have been recognized where the effects have been drastic, such as the hydrogen embrittlement of titanium and steel. However, there is insufficient generalized information available on the extent of these effects, and the nature of the mechanism by which quantities on the order of 50–100 parts per million can be so influential.

A recent study directed toward obtaining a better understanding of the problem made use of vacuum melting since this process offered the best chance of controlling alloy chemical composition precisely. Crucibles made from three materials, aluminum oxide, stabilized zirconium oxide, and magnesium oxide were used to contain the melts.

It soon became apparent that alloys melted under these conditions were quite variable in their strength properties. Further, the variability did not seem to be consistent. Chemical analyses of the alloys showed no variations in the major constituents. Analyses for the minor constituents, zirconium and boron quickly revealed significant differences, although neither of these elements had been deliberately added. Several questions were raised by these results. First, where was the boron and zirconium coming from? Second, could the effects be related specifically to the variations in boron and zirconium. And last, what was the mechanism?

The source of boron and zirconium was traced to the crucibles, specifically the zirconia and magnesia. Small amounts of boron and zirconium are present in crucibles made from these materials, and during the melting process are dissolved by the molten metal. Alloys melted in alumina crucibles containing no zirconium or boron, did not show any zirconium and boron pickup. Further, studies of alloys with controlled additions of zirconium and boron yielded the desired relationship between strength and chemical composition.

The investigation has shown that both zirconium and boron must be present to obtain the maximum effect and this occurs at 100 p. p. m. of zirconium and 88 p. p. m. of boron in the Udimet 500 alloy studied. These levels of zirconium and boron result in a stress rupture life of 640 hours as compared with 50 hours for a composition containing less than 100 p. p. m. of zirconium and 2 p. p. m. of boron.

The results serve to clarify many puzzling and seemingly contradictory variations in strength properties for both experimental and commercial heats. In particular, variable boron pickup from the usual magnesia refractories used in commercial vacuum melting could explain many of the variations. Unrecognized introduction of boron or zirconium with the melting stock could be another source of variability. In addition, the relationship between zirconium and boron is probably a further source of variation when such elements have been purposedly added to an alloy.

Physics of Solids

Ceramics have long offered promise as practical high temperature materials. Their strength properties, oxidation resistance, and stability upon exposure to high temperatures are all good, but their brittleness or lack of ductility leads to poor resistance to thermal and mechanical shock. These latter characteristics have so far prevented their use in applications such as turbine engine parts.

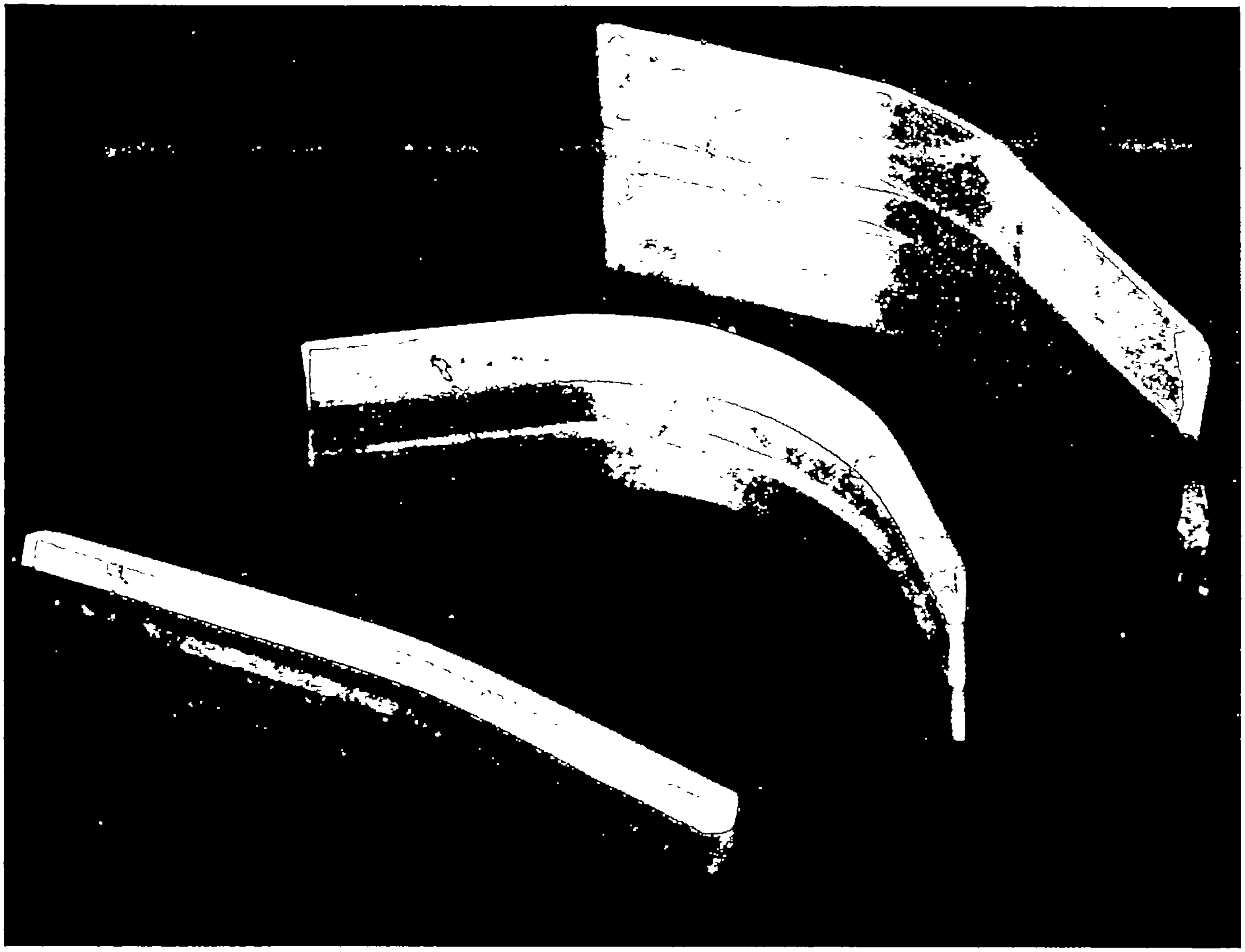
The reasons for their lack of ductility are not understood. It is possible that some of the brittleness may be due to surface imperfections on an atomic scale. This possibility has been studied for a number of years and is based on experiments with rock salt single crystals.

These studies show that a freshly polished salt crystal surface will develop microscropic cracks if allowed to stand in air for a few hours. Electron microscope studies reveal that these cracks tend to aline themselves along planes that have the highest atom density. Repolishing by dissolving the surface in water will produce a surface free from cracks until it is again exposed to air.

Concurrent strength studies of the rock salt crystals showed that the strength of the crystals was drastically altered by the polishing process. Further experiments indicated that a polished crystal could be easily bent without cracking, while an unpolished specimen would break like a piece of glass if bent in a similar fashion.

While the above experiments did not furnish conclusive proof that surface cracks are the fundamental cause of brittleness, the results were of sufficient interest to warrant similar studies of a material of more practical nature, such as magnesium oxide. This ceramic has a very high melting point, is resistant to oxidation, and has a useful strength at elevated temperatures.

Single crystal specimens were fabricated and the surfaces treated to remove imperfections and cracks. The specimens were then bent at room temperature in much the same manner as the rock salt crystals. The



Ductility of magnesium oxide crystals.

results were similar. The crystals were bent easily and showed no evidence of cracking.

The above results are preliminary and at best are applicable only to single crystals. Since practical engineering materials are usually polycrystalline, it is too early to determine whether ceramics may be made ductile for engineering applications. Much additional research is needed before ceramics can be considered for use in aircraft and missiles engines.

ROCKET ENGINES

Propellants

The rocket engine is unique among the various heat engines in that it can operate beyond the earth's atmosphere. Unlike airbreathing engines, it carries with it all of the fuel and oxidizer that it needs. In one sense, this is a disadvantage, since the payload of a rocket powered vehicle must be reduced to make room for the oxidizer. The effective energy content, or specific impulse, of the fuel and oxidizer is, therefore, a combination of great importance. The higher the propellant specific impulse, the greater is the potential performance of the vehicle that may be designed to use the propellant.

Research on fuel and oxidizer combinations or propellants is directed toward obtaining materials yielding higher specific impulse. Commonly used propellants include modified jet engine fuel and liquid oxygen, red fuming nitric acid and dimethylhydrazine. Propellants having substantially higher specific impulses include combinations of fluorine with ammonia, hydrogen, and hydrazine.

Studies of fluorine indicate that in many ways it is one of the most desirable oxidizers. Unfortunately many of its desirable characteristics pose difficult problems. It is so reactive that it will combine violently with many of the common pipe, tank, and gasket materials. It combines with fuels to produce very high temperatures, thus complicating an already difficult cooling problem in rocket nozzles and combustion chambers.

A portion of NACA's propellant research is directed toward learning how to use fluorine in practical engines. Analytical procedures have been developed to permit the prediction of fluorine fuel combinations for various conditions. These procedures resulted from a more comprehensive study to determine the performance of chemical rockets using propellants containing carbon, oxygen, fluorine, hydrogen, nitrogen, and boron.

A number of investigations on the compatibility of gaseous fluoride with a number of seal materials, thread lubricants, valve packings, etc., have been completed. Studies of materials compatible for use with fluorine in practical rocket propulsion systems are continuing.

AIRCRAFT CONSTRUCTION

Research at high temperatures and for high-speed aircraft and missiles is holding the center of the stage in the aircraft construction field. Problems are multiplying at so fast a rate that it requires not only ingenuity to pursue them but a keen perception to focus attention on the most important items. Particularly in the case of research at high temperatures the need to reproduce the environments in which structures must operate calls for new testing techniques on which significant effort is being spent.

As in previous years, dissemination of important research results on aircraft construction through a special NACA conference was found to be effective. The conference, attended by representatives of the military services and a large number of their contractors was concerned with many of the problems reported herein.

A summary of some of the Committee's recent unclassified research in the field of aircraft construction is given in the following pages and is divided into four sections: Aircraft Structures, Aircraft Loads, Vibration and Flutter, and Aircraft Structural Materials.

AIRCRAFT STRUCTURES

The burning up and disintegration of a meteor as it enters the earth's atmosphere is a graphic illustration of one of the most important problems ever to face aircraft structural designers. This problem is aerodynamic heating. Any object such as a meteor moving at high speed through the atmosphere compresses the air ahead of and around it and this compression heats the air. The higher the speed, the greater the heating. For an airplane or missile traveling at 2,000 miles per hour the air may be heated to 600° F. and at 13,000 miles per hour the temperature is nearly 20,000° F. The problems associated with the design of aircraft structures to withstand such heating are staggering. Solutions must be found if such flight speeds which are otherwise possible are to be realized.

Solution of thermal structures problems requires a knowledge of the temperature distribution expected in flight. Heat flow and temperature distributions within typical aircraft structures have been determined analytically as well as through the use of an Electrical Thermal Analogue Computer. Recent investigations have utilized aerodynamic and radiant heating facilities to provide test data on the effects of joint thermal conductivity and internal radiation on structural temperature distribution. The heat transferred by thermal radiation has been found to have an important effect on temperature distributions.

Not only must an aircraft withstand heating, it must at the same time possess sufficient strength and stiffness to withstand the loads to be encountered in flight. The nonuniform temperature distributions experienced by aircraft structures at high speeds induces thermal stresses in the structures with resulting reductions in strength and stiffness. Radiant heating facilities have been utilized to obtain test data on the effect of thermal stresses on the buckling and ultimate strengths of wings and fuselages. The combinations of compressive stresses and thermal stresses which result in permanent buckling of structural components has also been investigated experimentally and a simple method for predicting the onset of permanent buckling has been developed. Structures loaded under high temperatures for long periods may gradually deform and finally fail by creep. Recent contributions on the creep problem have included data on the creep behavior of structural elements and the correlation of test results with basic materials data. In addition, a new analytical method has been developed for the creep analysis of structures.

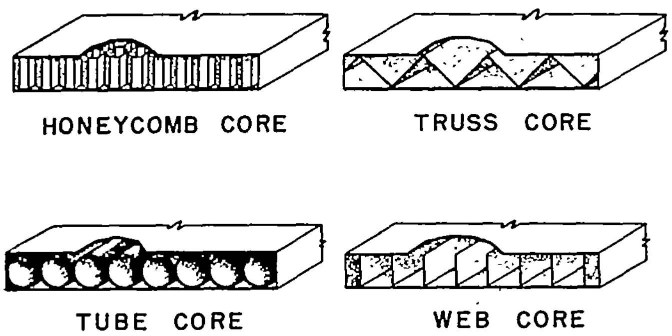
Structures capable of carrying a given load once or twice may fail if subjected to that load a sufficient number of times. Such failure is termed fatigue and constitutes a serious problem. One possible approach to the problem is to design the structure so that it will not experience a catastrophic failure when partially damaged by fatigue or rupture. Methods for estimating the length of a fatigue crack required to precipitate a sudden failure, for determining the static strength of structures containing fatigue cracks, and for proper proportioning of pressurized fuselages to prevent catastrophic failure have been investigated. Constant-amplitude fatigue tests of full-scale transport wings have been completed and a program of spectrum loading of similar wings is nearing completion.

Aircraft are designed as much from a stiffness standpoint as from a strength standpoint. One means of predicting the stiffness or deflection of structures has been shown to be through the use of inexpensive plastic models. Analytical methods have also been developed for calculating the static deflections as well as the vibration modes and frequencies for various types of wing structures.

Not only must aircraft structures withstand the heating and loading encountered in flight without failing or suffering excessive deformations or loss in stiffness, they must also be light in weight. An extra pound of structure starts a chain reaction in the growth of aircraft weight. It takes more fuel to carry the extra structure; heavier engines to carry the additional fuel; more structure to carry the heavier engines and on and on until that single pound of structure has been responsible for as many as 10 to 30 pounds of additional aircraft weight. The return for dollars spent on research which increases structural efficiency thereby eliminating these weight penalties is indeed high from the standpoint of both aircraft cost and aircraft capabilities. The problem of structural efficiency has been the subject of a continuing program of theoretical and experimental research. Various methods of fuselage and wing construction have been explored and information has been obtained on the more efficient use of structural materials.

Sandwich Construction

Sandwich construction is an excellent example of the results of man's attempts to use structural materials efficiently. It is this same idea which is used so extensively in the fabrication of cardboard for boxes and packaging. In this case the sandwich consists of two sheets separated by a corrugated core. There are many types of sandwich which have been successfully used in the construction of aircraft but their use has generally been limited to lightly loaded, secondary parts of the structure. Increases in flight speeds and temperatures and in the need for reducing structural weight, as well as recent developments associated with the fabrication of sandwiches now make this type of construction even more promising for airplanes and missiles. Research aimed at a better understanding of the structural characteristics of sandwiches has been conducted and is continuing in order that their many advantages over other types of construction can be reflected in future aircraft.



Four types of sandwich construction considered for aircraft and missile structures.

Probably the most important attribute of a sandwich lies in its high bending strength and stiffness per unit weight. Studies have been conducted of airframe components made of various materials to assess the relative structural efficiencies of those made from sandwiches with those employing other means of construction. In almost every case sandwich construction proved to be the most efficient.

Another advantage of sandwich construction is its resistance to acoustic vibration. Intense sound waves can vibrate aircraft skins just as they do the diaphragm of a microphone. Engine and aerodynamic induced sound waves increase with engine power and flight speeds respectively. Tests have shown that an aircraft skin, unless properly supported, can be completely destroyed by such acoustic vibration. The advantage of sandwich construction over conventional construction is that it affords more favorable support and, therefore, can endure more severe acoustic environments.

The most severe structural problems arising from aerodynamic heating are those associated with thermal stresses caused by uneven heating. The results of thermal stresses are well known to anyone who has broken a glass container by dunking it into hot water. Aircraft structures which are heated unevenly also develop thermal stresses and may fail. Structures, particularly sandwich structures, can be designed in such a way that thermal stresses and the effects of such stresses are minimized. This thermal stress-releaving characteristic of sandwiches will play an important role in permitting aircraft to fly under conditions where severe thermal gradients exist in the structure.

The high insulating capacity of sandwiches makes their use particularly promising for high speed aircraft where the structure is heated aerodynamically. The natural insulating qualities of sandwiches can be supplemented by the addition of insulating materials placed within the cavities or on the interior surface of the sandwich panel. Sandwich panels of various designs have been tested in laboratory heating facilities and wind tunnels to determine their insulating capacity. These panels, even without insulating material, were found to be effective in retarding heat flow.

Insulation can at best merely retard the flow of heat. It cannot stop it. Certain flight environments are such that the temperature within the interior of an aircraft cannot be kept below an acceptable limit by insulation alone. For such environments it is necessary to provide cooling systems. Sandwiches with their cavities lend themselves to such systems by providing passages for the flow of coolant.

Another advantage of sandwich construction is that materials of thinner gages can be used. Elevated temperatures resulting from aerodynamic heating during high speed flight require the use of high temperature materials such as steel, titanium, and nickel base alloys. These materials are heavier than aluminum and, therefore, must be used in thinner gages if structural weight is to be minimized. Although these thin skins would buckle if the usual methods of construction were employed, they are afforded adequate support in sandwiches. Only recently such thin skins could be fabricated into sandwiches. Progress in welding, and other methods of attachment, have now made such fabrication possible. The results obtained from current studies indicate that sandwich type plates provide an effective means of efficiently utilizing high-density, heat-resistant materials.

Unfortunately, there is not a single sandwich configuration which will provide optimum values of all of the above properties. In spite of the progress to date, additional structures research is needed to guide the aircraft designer in selecting the sandwich types and proportions most suitable for his particular application.

AIRCRAFT LOADS

A few years ago the payload was a large percentage of the total airplane weight, but this ratio, which has been decreasing gradually, is being drastically reduced for future airplanes; in fact, for missiles the payload approaches zero. It therefore has been necessary to determine more closely the environmental conditions under which airplanes operate in order to obtain the lightest possible structure adequate for the job. Thus items such as operational statistics on aircraft usage, blast effects of weapons on aircraft, and better definitions of turbulence environment have assumed increased importance; furthermore, knowledge of the detailed distribution of load over wings, fuselages and tails, has become increasingly critical for efficient structural design.

As part of the general program for improving structural design, statistics of airplane utilization in routine operations are required. The military services have contributed to the available statistics on maneuver loads by fairly wide coverage of flight operations of specific airplane types by means of relatively simple three-component VGH (velocity, acceleration, altitude) instrumentation and by more detailed eight-component studies on selected operational aircraft. The NACA has contributed by collecting data from one completely instrumented airplane of each of several types. As a result of these measurements there now exists a better understanding of how airplanes are used; for instance, enough information on control motions and airplane response has been analyzed for the various classes of airplanes that it is apparent pilots do not use all of the "built-in" capabilities of airplanes. These studies also provide an understanding of the instrumentation required and the procedures to be followed in evaluating a large sample of data. It is, for example, apparent that careful control of sampling technique must be established if exorbitantly large computing facilities for analysis of the data are to be avoided.

Gusts induced by high energy explosions such as from atomic weapons, which envelop the whole airplane, are becoming increasingly important; consequently, experimental studies are being conducted with specially instrumented models to investigate factors such as varying the direction from which the blast wave intercepts the model. Blast intensity is controlled by testing at various distances from the explosion center and by varying the size of the explosive charge.

Collection of gust loads data from airplane in normal commercial operation is continuing and the methods of analysis are being improved. Because of the increased importance of gusts that affect the vertical tail loads and the reduction of directional stability characteristics at high speed, special emphasis is being given to studies of horizontal gust components on aircraft loads as well as motions in flying through turbulent air. In these studies airplanes and rocket-powered test models are being used. The results obtained during the past year have contributed to the general knowledge as well as furnished improved methods of accounting for effects of structural elasticity on the results. Procedures have been developed for calculating the lateral and longitudinal response of a rigid airplane to continuous turbulence and a method has been developed for converting flight test data to any equivalent wing stiffness for comparison with wind tunnel data or for converting to the rigid wing condition. Recent results obtained from commercial transports equipped with airborne radar show a reduction of the larger gust velocities by about 25 percent. The radar, however, seemed to have no appreciable effect on frequency of encountering the smaller repeated gust loads which affect the fatigue life of the airplane structure.

Research on ground loads has been directed toward more accurate determination of the characteristics of the input forces by accumulating data on runway roughness, by obtaining statistics on the landing contact conditions of airplanes, and by undertaking tests in which loads were measured in the landing strut while taxiing over obstacles of various shapes. The experimental work has been supplemented by analytical studies of effects of shock strut friction, metering pin design, and orifice coefficients on the landing gear responses.

The coefficient of friction of tires as affected by forward speed, condition of yaw, tire pressure, and prerotation continues to be of interest particularly because this information is needed in analytical computations of loads on landing gears during landing as well as in ground handling. A number of tests of various tires at slow speeds and various angles of yaw have been completed and show that for yawed rolling in a straight line the tendency for the tire to "go around a corner" increased with yaw angle, but the tendency for the tire to turn into a straight path decreased as the yaw angle increased.

The distribution of loads over wings and tails under various flight conditions continues to be particularly important for stubby (low-aspect-ratio) wings, at transonic speeds. Under these conditions existing theories are least accurate and the tendency for the fuselage to blanket the wing, or vice versa, is relatively large. Pressure distribution tests of thin triangular planform and other stubby swept wings are being conducted to obtain basic information on the division of load among aircraft components. Effects of warping the wing surfaces by twist or camber are of particular interest. Such data will be useful in providing the information needed for development of analytical methods encompassing the high subsonic and sonic speed ranges. Experimental investigation of the loads over various types of unique control devices, such as wing spoilers or deflected tips, have been undertaken to supply a deficiency in the data that exist for control loads at transonic speeds.

Although much has been accomplished toward developing rational methods for estimating vertical tail loads, designers are plagued with tail loads that occur when rolling at high angular velocities, when the airplane is flown near conditions where instability occurs, or when disturbed flow from the fuselage intersects the tail. Consequently, tests of specific airplane models for a range of configurations in sweep, tail height, etc., have been undertaken to measure loads. The combined tests cover a range of speeds, angles of attack, and yaw angles such as would occur in flight. The information obtained will assist in accounting for these effects on the tail loads.

Loads over models of specific airplanes and missiles have also been measured for the purpose of supplying structural design information. While such tests have not been part of a planned research program, the data obtained generally yields information which can either fill in existing gaps or indicate areas where more work is needed. Flight investigations of flexible aircraft where many of the variables cannot be controlled have indicated the need for more accurate methods of data reduction and data correction so that wind-tunnel and flight results can be compared on some common basis.

Landing Loads Problems

Typical of many problems confronting the airplane designer is that of providing landing gear of sufficient utility with regard to ground handling procedures, of adequate strength to withstand the initial landing impact and other ground loads, and yet of sufficiently light weight so as not to penalize the operational efficiency. In addition the designer must avoid problems that are associated with oscillatory landing gear behavior.

Perhaps the best known of these oscillatory phenomenon is shimmy—an oscillation involving rotation of the gear about a vertical axis so that the track of the wheel on the ground forms a wavy rather than a straight line. More recently airplanes have also been subjected to phenomena that have been designated as "brake chatter" and "walking" both of which involve a fore and aft oscillation of the wheel and strut. Brake chatter occurs because of the undesirable friction characteristic of some brake-lining material when subjected to high braking forces; in effect the brakes do not hold uniformly but instead periodically "release" the wheel and permit it to roll, and thus induce periodic drag loads that cause the landing gear to shake in a fore and aft direction. Although the "walking" phenomenon has the same wheel motion as that of brake chatter it is quite different and can perhaps be best illustrated by grasping a lead pencil by the sharpened end and then trying to push the eraser smoothly along a table top. The frequency of the oscillation in this case is primarily a function of the combined flexibility of the landing gear and the structure to which it is attached.

Having noted some of the general problems faced in designing a landing gear, we can look in more detail to the specific problems of providing data which the designer needs. For convenience of discussion, the overall design problem can be divided into smaller units such as: The initial condition at contact with the ground, the ground reaction during landing, the loads encountered during ground maneuvering, problems encountered because of special use of airplanes, designing for fatigue, and effects of component behavior.

In order to improve design criteria it has been necessary to devise methods of collecting more accurate statistical data on descent velocity, airplane altitude, and rotational and sidedrift velocities. Because these data are concerned with the approach condition during landing, and are governed largely by unpredictable factors such as piloting technique, visibility, air gustiness, etc., the problem of collecting these data is fundamentally of a statistical nature.

When airplanes were small and landing speeds were low it was sufficient to design a landing gear and its supporting structure to sustain merely the vertical impact loads. As airplanes became larger and landing speed increased, it became necessary to consider the large drag force that results when the wheel scrubs on the runway before coming up to the required rotational speed. This drag force is now commonly referred to as the "spin up and spring back load" because the strut will deflect backward as the wheel first contacts the runway and then spring forward as the force required to spin the wheel diminishes. Because of the flexible wing structure to which gears are attached it has now become necessary to know in detail how these impact forces are applied to the landing gear. The two major uncertainties regarding landing gear drag loads are: (1) The magnitude and variation of loads applied to the landing gear, (2) the dynamic response of the gear, its adjacent attachment structure, and remote structure such as engine nacelles that are excited by the loads transmitted through the landing gear. Information is needed not only on the maximum values of load but also on the time history of the applied drag load, because the shape and duration of the time history can significantly affect the dynamic loads in the gear or other parts of the airplane structure. Effective progress has been made toward an understanding of the wheel spin up and spring back process both by analytical techniques and by experimental studies wherein single wheel impacts have been made under controlled forward and descent velocities.

The problems encountered due to ground maneuvering have also been magnified by faster landing runs and taxi speeds. Small bumps in the runway can impose large loads when heavy airplanes roll rapidly over the bumps. Particularly difficult situations arise when the wing is heavily loaded by engine pods, fuel tanks, or externally mounted missiles, because the runway roughness may cause the wing to vibrate through large amplitudes at its natural frequency. To assist in solving the problems encountered in ground handling, the contour of typical rough and smooth runways have been measured. Other factors affecting ground handling loads are side loads generated in turns, loads due to unsymmetrical braking and pivoting or porpoising bined tests cover a range of speeds, angles of attack, and yaw angles such as would occur in flight. The information obtained will assist in accounting for these effects on the tail loads.

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Perhaps the best known of these oscillatory phenomenon is shimmy—an oscillation involving rotation of the gear about a vertical axis so that the track of the wheel on the ground forms a wavy rather than a straight under rolling conditions. Progress has been made toward solving these problems and the Landing Loads Track is contributing significant results that are obtained under conditions of forward speed.

Landing Loads Track

To assist in providing basic data needed to improve landing gear design the NACA has recently put into operation a unique facility, the Landing Loads Track. The Langley facility consists of a hydraulic jet catapult, a carriage that rolls on a track, an arresting gear for stopping the carriage, and suitable housing for the test equipment, carriage, and control room. The track upon which the carriage rolls is 2,200 feet long with a 30-foot tread and is built to a very close tolerance, deviating not more than 0.003 inch from level nor more than 0.015 inch in rail spacing. The carriage and test equipment weighing approximately 50 tons are accelerated by a hydraulic jet impinging on a specially shaped "bucket" at the rear of the carriage so as to exact a thrust of 200 tons on the carriage. Water is ejected through a 7-inch diameter nozzle by air under 3,260 pounds per square inch pressure to form the jet which travels a maximum of 400 feet while accelerating the carriage to 150 miles per hour. It is interesting that although the energy involved is sufficient to accelerate a B-29 class airplane to takeoff [illegible] ing for fatigue, and effects of component behavior.

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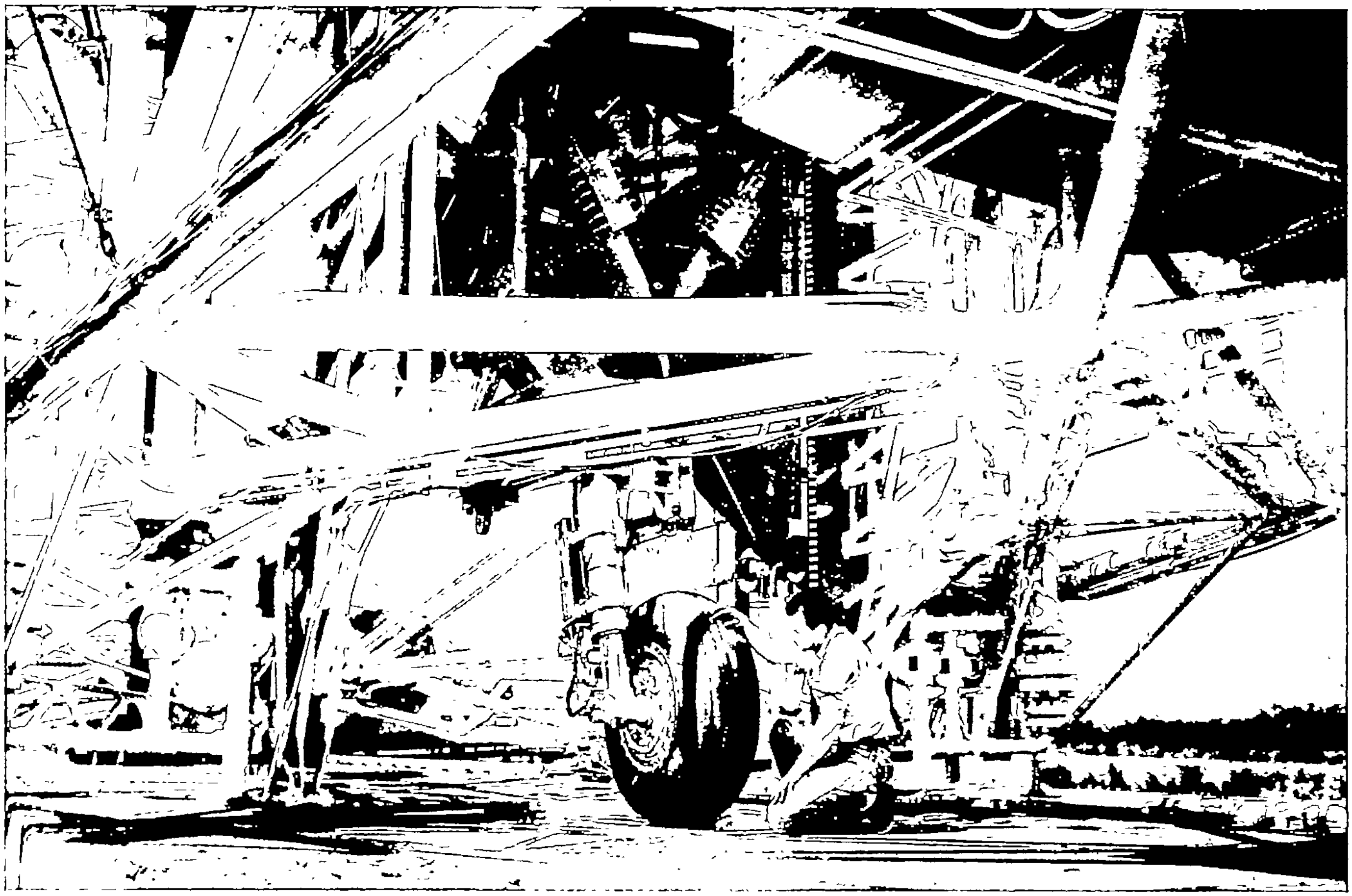


Landing gear mounted on carriage of Landing Loads Track.

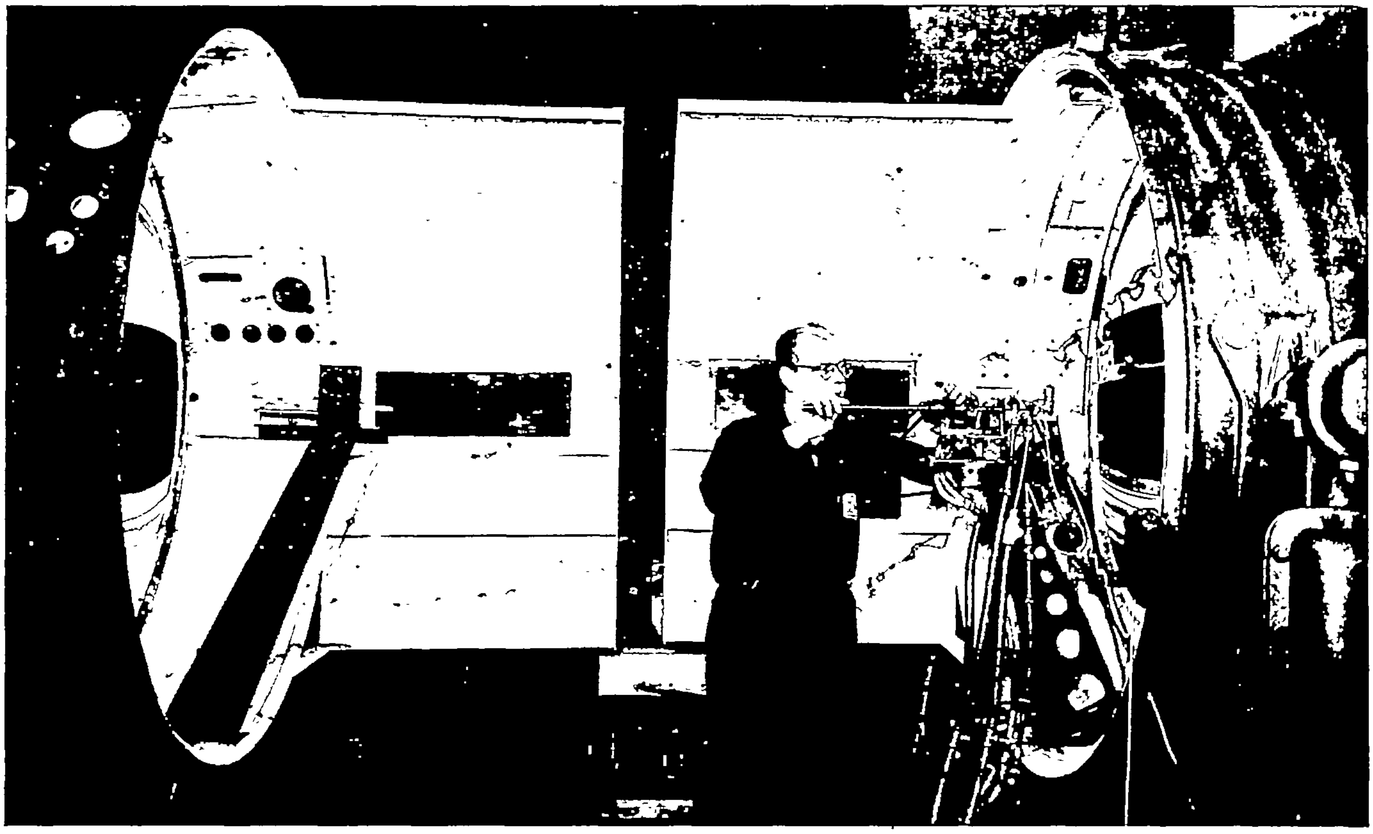
the operating limits of the aircraft. Maintaining this margin between operating speed and flutter speed is increasingly difficult in view of the trends toward thinner wings and more slender fuselages which not only provide the aerodynamic improvements leading to increased performance but the trends themselves complicate the flutter problem. Thus for supersonic fighter and bomber airplanes and to a lesser degree the jet transport, the providing of adequate structural stiffness to forestall flutter is becoming more critical than providing enough strength to sustain the aerodynamic loads.

Flutter

Because flutter is a complicated phenomena involving the air forces on a vibrating wing and the elastic and inertial structural properties which determine its vibration characteristics, the flutter analyst cannot intuitively judge the relative importance of the various parameters. Furthermore, he cannot rely entirely upon his calculations because of the simplifications and idealizations inherent in present theoretical approaches. Accordingly, there exists a need for an experimental knowledge of the flutter characteristics of wings representative of those being considered by designers.

A major part of flutter research consists of determining the susceptibility to flutter of wind tunnel models which are scaled down versions of full scale aircraft components. Thus, for example, by testing a series of wings which constitute a systematic variation of some parameter such as planform, its effect and importance is furnished. Several such studies have been carried out for limited ranges of certain parameters. Examples of recent studies of this type were the flutter tests made of a series of wings of varied planform whose spans were shorter than their chords, a series of wings with external stores mounted in various locations, and a series of wings with control surfaces. The results of such research furnish the designer with engineering information on configurations which approximate his design and suggest ways in which the design can be improved.

In addition to these studies of generalized models numerous studies were made of the flutter characteristics of models which were accurately scaled to represent particular military aircraft. Such studies provide a more accurate estimate of the flutter characteristics of the full scale airplane than does the theoretical analysis, an important consideration in view of the narrow margins between maximum speed and flutter speed re-



View of arc image furnace.

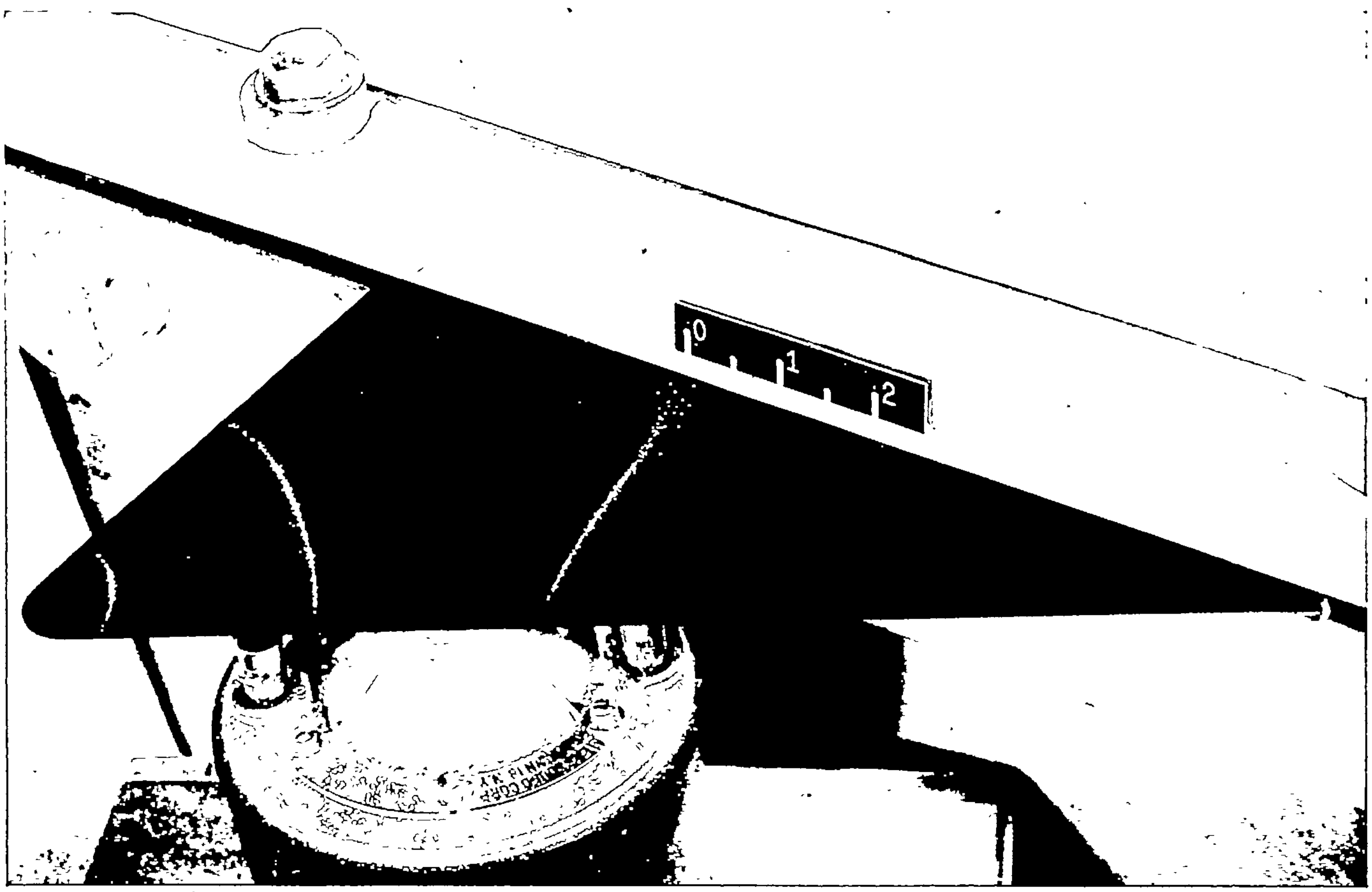
quested of the flutter analyst. These studies have provided designers with information as to the distribution of the structural weight, stiffness, effectiveness of dampers, effect of mass and store locations and control surface parameters for his particular design so that flutter can be avoided. In the last 5 years the number of these projects relating to specific designs has increased from 2 to 12 annually which is convincing evidence of the increased importance which flutter considerations are playing in aircraft design.

Aerodynamic Aspects of Flutter

The aerodynamic forces on a wing during flutter are, of course, an important part of the flutter problem. During the 1930's, mathematical methods of calculating these oscillatory forces and methods for using them in the flutter equations were developed. In obtaining these aerodynamic derivatives it was assumed that the wing was of infinite span, of zero thickness and that compressibility effects were nonexistent. Subsequent modifications of these methods furnished reasonable estimates of the aerodynamic forces until airplanes attained transonic and supersonic speeds and wings and stabilizers of short span came into use. The increasing critical nature of flutter and the need for narrower margins have made the inaccuracy in these methods unacceptable. One particular line of research toward improved methods has to do with application of the kernel function method which will be described in more detail later.

These earlier theories based on flat plate or zero thickness considerations indicated the encouraging prospect that susceptibility to flutter might actually decrease with increasing speed in the supersonic speed regime. Recent investigations made at a Mach Number of 7 shattered this hope when it was found that flat plate airfoil theory did not agree even approximately with experiment. When the theory was modified to include some of the aerodynamic effects of airfoil thickness it was found that the susceptibility of an airfoil may not decrease with speed. As a consequence an increased attention is being given to flutter research at high supersonic speeds.

Experimental studies are also being carried out on the fundamental aerodynamic forces and moments relating to flutter. In these studies a model is forced to vibrate in a wind tunnel and the aerodynamic forces resulting from this vibratory motion are measured. In the past, these measurements have been limited to so-called rigid vibratory modes, i. e., pitching and translatory motions of a two-dimensional wing. More recent studies have included measurements of the oscillatory pressures over the surface of rigid wings of fi-



Photograph showing vibration mode of wing. Sand has been sprinkled on a vibrating wing. The sand concentrates where no vibrational motion exists, thus defining the node lines.

nite span oscillating in pitch and translation and of similar wings with an oscillating control surface. It is hoped to extend these studies to the cases of wings vibrating in realistic elastic modes. These measurements afford a direct evaluation of the various theoretical methods of calculating air forces. Such measurements, especially at high speeds and high vibration frequencies, represent an extremely difficult task and successful attainment represents the culmination of many years effort in developing the unique instrumentation and experimental techniques required.

Structural Aspects of Flutter

A knowledge of the vibratory characteristics of the aircraft structure, that is, the modes of vibration and their frequencies, is an essential part of the flutter problem. The factors important to structural vibration are the elastic properties of the structure, the distribution of weights supported by the structure and the weight of the structure itself.

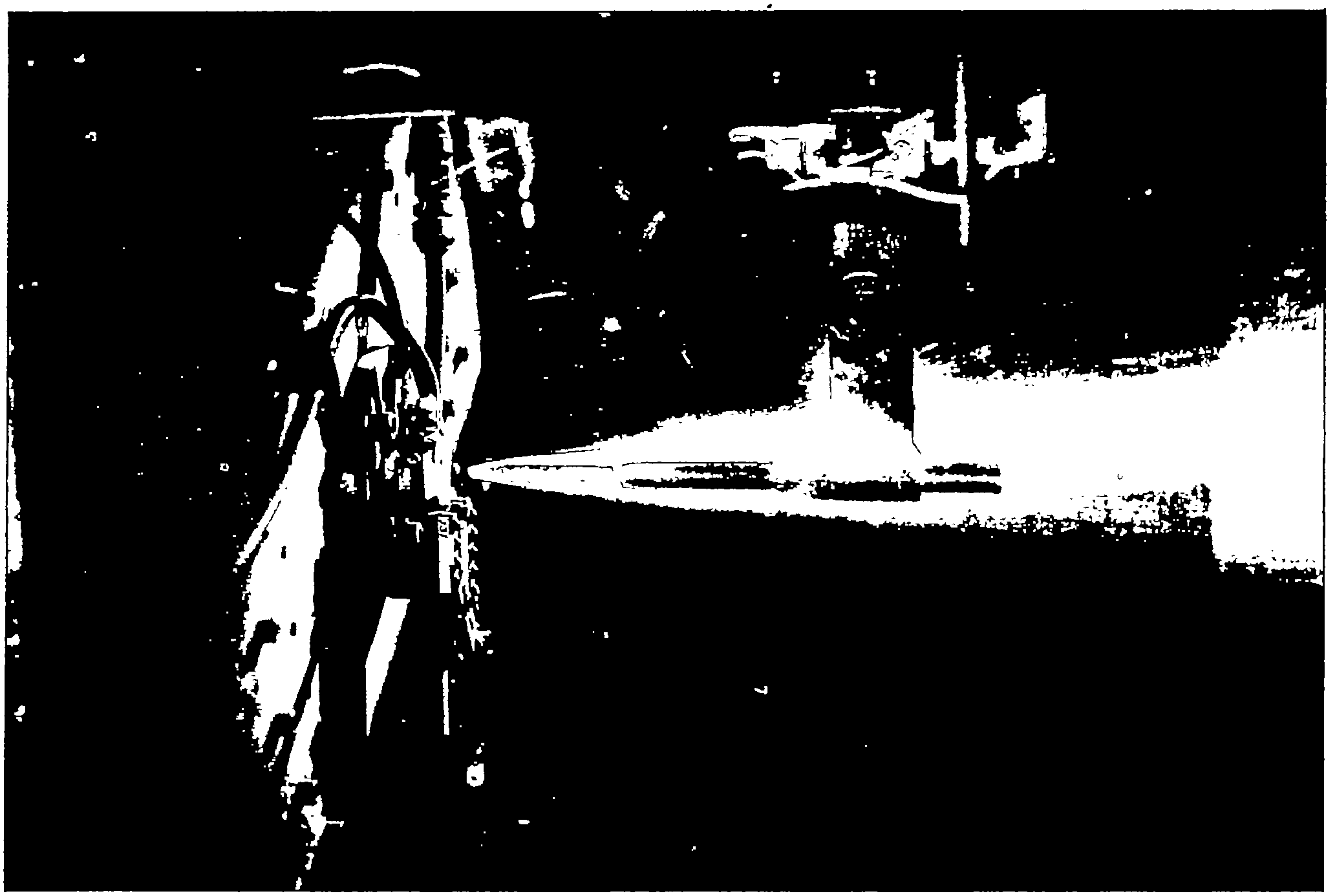
The short-span, thin wings coming into use present a different problem than that for the long span wings which could be treated analytically as beams subjected to bending and twisting. These short-span wings behave more like thin plates and exhibit complex vibration characteristics. Delta shaped wings having a structure representative of actual airplanes have been constructed and their elastic and vibration characteristics determined experimentally. Using these experimental results as the basis for comparison, it was found that even the most sophisticated existing theoretical methods had deficiencies. The manner in which these deficiencies can be reduced by further refinements in the theory was demonstrated.

While improvements in analytical techniques are being gained through current research, much reliance must still be placed on the experimental measurement of vibratory modes and frequencies of airplanes and models. Such experimental work has been aided by the recent development of the "accelerometer" technique for determining vibration modes, and the development of a device using an air jet which will apply a vibratory force for a wide range of frequencies.

The aerodynamic heating which accompanies supersonic flight adds further complication to the flutter problem. Exploratory studies have shown that aerodynamic heating can produce a reduction in structural stiffness and thus greatly increase the liability to flutter.

Kernel Function

The accuracy with which flutter can be predicted depends largely upon the accuracy of the calculated aerodynamics. The need for improved accuracy in



Test model in high temperature air jet.

flutter engineering thus resolves into a need for more accurate methods of calculating the aerodynamic forces. As reported in previous Annual Reports it has been found possible to mathematically express the relationship of the oscillatory pressure at any point on an airfoil due to the motion of any other point of the airfoil. This complicated and highly technical mathematical relationship is usually referred to as the kernel function. The computing necessary to apply this kernel function solution to obtain the aerodynamic derivatives at subsonic and sonic speeds corresponding to a particular vibratory motion of a wing represents an extremely large computing task but one which is within the capabilities of some modern electronic computers.

The advantage of the kernel function approach is that it affords a calculation of the detailed pressures over a vibrating wing having any arbitrary planform. It applies to wings of short span whose vibration modes are representative of thin plates and it takes into account the effects of compressibility.

In a cooperative project, the Air Force has sponsored the computation of the mathematical functions relating to the kernel function utilizing the large Mark IV computer operated by Harvard University. This tabulation is virtually complete and the voluminous tables resulting from this computation will be published.

The acquisition by the NACA and many of the aircraft manufacturers of IBM 704 computers has made practical elaborate flutter analyses using the kernel function method to obtain the aerodynamic forces. On this type of problem this computer will, in less than 15 minutes, furnish a solution which would require several years by an operator with a desk calculator. A considerable effort has been expended on the development of a computer programing and coding procedure necessary to such a flutter analysis. For a large and involved computing task such as this, this programing and coding constitutes an integral and important part of the analytical solution. The results of this development work are being supplied to interested aircraft manufacturers possessing suitable computers.

While the techniques which have been evolved to date furnish reasonably accurate answers which constitute a major advance over previous flutter analysis methods, efforts are being applied to further improvements.

STRUCTURAL MATERIALS

The foremost problem of aircraft structural materials is the development of materials that can withstand the high temperatures that come with hypersonic flight and aerodynamic heating. Before the advent of hypersonic flight, the aircraft designer could get by with conventional materials, available from suppliers and adequately characterized in handbooks. These structural materials were not developed with high temperatures in mind so it is not surprising that their utility in hypersonic aircraft is something less than optimum.

The structure of future aircraft will run a temperature gamut from a few hundred degrees for some supersonic airplanes to the stagnation temperature of the ICBM, which will be high enough to vaporize any known material. It obviously would be a rare case where optimum material for one type aircraft would be optimum for another. In the future, many more different types of materials will be required than has been the case in the past.

At atmospheric temperatures, nearly all of our structural materials can be considered to be stable, i. e., their characteristics will vary only slightly with time. Consequently, stability of structural materials with time has been of relatively little importance. But at the high temperatures to be encountered by future aircraft, this stability is lost, and the properties of materials change with time. This fact has to be taken into account in the development and selection of materials, and the effects of time on the properties of materials has to be known.

Materials properties, such as emissivity, specific heat, thermal expansion, and thermal conductivity, are of little or no importance to aircraft operating at atmospheric temperatures. At high temperatures, however, they become very important for they influence such things as equilibrium temperature, thermal stress, and suitability of a material for use as a heat sink; therefore, these properties that could be ignored in the past now must be known and considered in design.

For certain new designs there is the possibility that our present "on the shelf" materials will be satisfactory or at least usable on an interim basis. Their worth cannot be fully appraised, however, until we know more about them. The NACA is gathering some of the needed data. In addition to conventional tests for physical properties, short time tests at high temperatures, in which a material is stressed and then heated at various rates, are being conducted on the more promising of the available materials. These tests will provide data that can be applied immediately in the design of aircraft.

The emissivity of a material is a very important property in hypersonic aircraft. This is so because it has a strong influence on the amount of heat lost at high temperatures by radiation. At low temperatures, radiant energy is insignificant, but at high temperatures radiation becomes important, since it varies as a fourth power of the temperature. In NACA laboratories and under contract research, apparatus has been developed to measure emissivity. Emissivity data on materials such as stainless steel, nickel based alloys, titanium alloys, experimental ceramics and many others have already been obtained.

High-Temperature Facilities

During reentry into the earth's atmosphere, the heat input and stagnation temperature of the ICBM nose cone will be so high that there has been no test facility capable of producing even an approximation of the conditions. The NACA has developed several kinds of test facilities for research in this range of temperatures. High temperature air jets in which air is heated by passing it through a mass of ceramic materials at very high temperature have recently been constructed. Temperatures to 4,000° F., speeds to Mach 4, and stagnation pressures to 1,600 p. s. i. are possible. To date, about 400 tests of materials have been made. Efforts are being made to increase the temperature, the air speed, and the sizes of the models that can be tested in these facilities. For tests at still higher temperatures the NACA has developed an air jet, powered and heated by an electric arc. This facility can produce a supersonic air jet of 12,000° F. with an ability to produce a heat input to model as high as 2,200 B. t. u.'s per square foot per second. The arc-image furnace is still another facility for research on materials at very high temperatures that has been developed by the NACA. In this facility an arc located at the focal point of one parabolic mirror is imaged by another parabolic mirror, and the energy can be focused at a point, entirely free of extraneous chemical, electric, or magnetic effects. A material can be exposed to extreme rates of heat flux at either high or low pressures in any desired atmosphere.

Research work on structural materials for supersonic aircraft has been greatly hampered by the lack of test facilities. This need is fast being satisfied by the use of facilities such as those mentioned above. In the future an ever-accelerating rate of progress in research on structural materials can be expected from these facilities.

OPERATING PROBLEMS

The NACA has conducted research to study those areas and problems concerning aircraft operations that exist and those that may have future importance in the around-the-clock operation of civil and military aircraft. Solutions to some of these problems have been sought for many years while some, due to the rapid advancement in airplane design and performance, have been given new emphasis. Several aspects of the Aircraft Noise problem have been receiving intensive research; noise as it affects personnel and noise as it affects the aircraft. Another area that involves continual research is that of Aeronautical Meteorology. Aircraft flying at high altitudes, high speeds, and the desire to operate in all weather conditions has emphasized the need for more extensive knowledge of weather phenomena and for more accurate predictions of its variable characteristics wherever aircraft are operated. Upper regions of the atmosphere must also be probed to determine its effects on missile operations. Methods of coping with special meteorological problems, such as Aircraft Icing, have also been studied by the NACA for many years. This research has resulted in the accomplishment of satisfactory methods for minimizing the hazardous effects of icing on aircraft operations. With the attainment of satisfactory solutions to the principal icing problems, research in this field has been deemphasized and only special problems are being studied. Aircraft safety is an area of NACA research which covers many aspects of aircraft operations. Problems associated with the techniques of aircraft control for all phases of operation, measurement of airspeed and altitude which the pilot needs for safe operation, alleviation of atmospheric effects that may endanger normal flight, devices to insure successful pilot escape during emergencies, appraisal of equipment reliability, prevention of fires following aircraft crashes, and the loads associated with human survival and crash-load design criteria are some that have received research attention by the NACA during the past year.

To assist the NACA in formulating activities on those operational problems requiring research, the following technical committees, which are made up of members from all phases of the aircraft industry, help to outline the research required to solve problems pertinent to military and civil aircraft operations: Committee on Operating Problems, Subcommittee on Flight Safety, Subcommittee on Aircraft Noise, Subcommittee on Icing Problems and Subcommittee on Meteorological Problems.

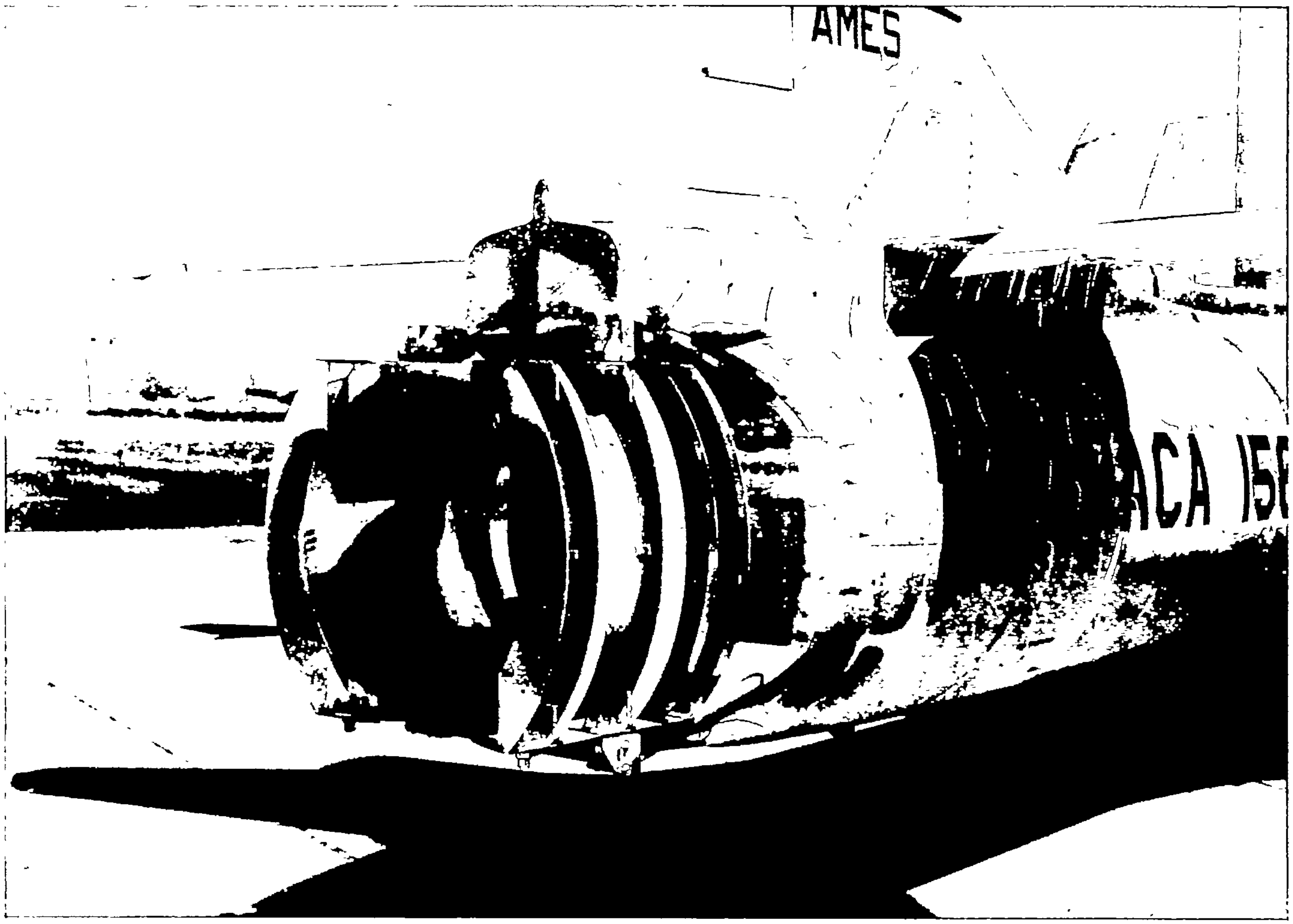
FLIGHT SAFETY

Approach and Landing Operations

Accident statistics indicate that two-thirds of the major accidents occur during landing and takeoff operations. High landing approach speeds may result in overshooting the runway, while subminimum approach speeds may result in undershooting the runway, both of which can and do result in major aircraft damage, injuries, and fatalities. As part of the NACA research program, a comprehensive study has been conducted on 42 fighter-type aircraft to determine those factors which influence the pilot's choice of approach speed. Flight and simulator studies were conducted utilizing lift-drag characteristics, longitudinal stability characteristics, and engine response characteristics. Important factors influencing the choice of approach speed were isolated and examined in detail. Simple criteria for predicting approach speeds within a given tolerance are presented in the published report on this study. Other data obtained from this study afford a basis for a description of the factors that influence the pilot's determination of approach speed as well as flight measurements of engine responses to throttle movement.

The comprehensive studies just described point to the importance of precise glide-path control during the landing approach. For propeller driven aircraft, precise glide-path control is usually accomplished by pilot adjustment of the throttle. However, for jet aircraft, airplane response to throttle manipulation is not nearly as rapid as in the case of the propeller driven airplane. The NACA, therefore, initiated a study to apply the principles of jet thrust reversal as a means of modulating the thrust during the landing approach. It is felt that the successful application of this principle will provide the pilot with a positive means of controlling the aircraft during the landing approach such that a precise glide path will be more readily attained. A thrust modulator has been constructed and installed on a fighter-type aircraft. Ground and flight test evaluations to date have indicated no serious problems. Comprehensive flight tests are being conducted to explore the usefulness of this device during the landing phase of flight.

Once an aircraft has touched down on the runway during a landing, airplane handling technique and braking effectiveness become of major importance, particularly on runway surfaces covered with ice, snow, or water. An analytical study has recently been conducted to determine the effect of different airplane attitudes on the distance along the runway required to come to a stop. Comparisons were made between the techniques of keeping the nose-wheel off the runway and the technique of keeping the nose-wheel on the runway for several types of jet fighter airplanes and a transport-type airplane. Effects of factors such as speed, braking effectiveness, residual thrust, and instantaneous flap retraction are discussed in the published report on this study.



Three-quarter rear view of experimental thrust reverser.

Braking effectiveness has been mentioned as most important during the landing roll, and although characteristics of the mechanical brakes are well documented, the prediction of stopping ability depends largely on the knowledge of the friction created between the airplane tire and the runway surface. On this particular point, reliable information with respect to braking friction generated during aircraft landings has been almost nonexistent for various reasons; namely, the large variability of the runway surface smoothness, the many different types of runway surfaces, the modification of surface conditions due to inclement weather, the differences in tire design, and the difficulty in providing instrumentation to measure tire to surface friction values. A flight and ground investigation is being conducted by the NACA to obtain information on the breaking coefficients available on various runway surfaces for use in determining the landing operation limitations of airplanes. The investigation includes development of a towed vehicle suitable for the measurement of runway braking coefficient characteristics for the advice of incoming traffic. To date, a towed vehicle called the NACA friction cart has been developed, and braking coefficient measurements on a variety of runway surfaces under various conditions have been made with both the friction cart and an airplane in an effort to correlate the cart and airplane measurements. The tests included both concrete and macadam runways in the dry and wet condition and also snow and ice surfaces. Braking coefficient values have been evaluated from some of the tests. With the airplane, mean braking coefficients varying from 0.2 to 0.6, depending on the amount of rain, were found to exist on wet surfaces; a mean value about 0.4 on snow; and a mean value about 0.2 on ice. Values obtained with the friction cart were in general agreement with the airplane results. Further tests are being planned with the NACA friction cart to study the effects of water depth, forward speed, and tire pressure on the braking coefficient available on wet surfaces.

Another method used in stopping aircraft in addition to wheel brakes is that of aerodynamic brakes. For jet airplanes, this is accomplished by reversing the direction of the jet at the tail of the engine such that the thrust normally used to push the airplane forward is used to slow the aircraft down. The NACA has investigated the characteristics of two types of full-scale thrust reversers on airplanes during both static and taxi tests. The magnitudes of the problems of the heating of the airplane structure in the vicinity of the reversed jet and the reingestion of the exhaust gases in the engine inlet are discussed in the published report on this subject.

Takeoff Operations

The ability of the pilot to recognize quickly any appreciable deficiency in airplane acceleration during takeoff is becoming increasingly important as performance during takeoff becomes more critical. The use of high wing loadings and wings with lower maximum-lift capabilities, particularly on the newer jet airplanes, has resulted in smaller takeoff performance margins on existing runways. Crashes have occurred during takeoff because of the pilot's apparent inability to recognize the fact that the airplane performance was less than that predicted by the use of available meteorological data and takeoff charts. Losses in airplane takeoff performance can occur from a loss in thrust, an increase in rolling or aerodynamic resistance, or meteorological conditions different from those used in the takeoff calculations. An instrument to aid the pilot in detecting malfunction of the airplane during takeoff has been proposed by the NACA. An evaluation has been made of a prototype instrument designed to give an immediate indication of loss in airplane acceleration at any time during takeoff when the pilot still has a choice of continuing or stopping. Flight tests of this instrument have revealed that some undesirable, but satisfactory, frequency oscillation in the instrument indicator needle existed due to airplane response to runway roughness. However, the indication remained essentially constant throughout the takeoff. Response of the indication to simulated partial power loss was immediate and the indication was consistent for given power settings in different takeoffs. Complete details of the instrument principles and operation have been published.

Airspeed and Altitude Measurements

Continual need has existed for an accurate method of measuring altitude and airspeed. These two quantities are essential to accurate flight navigation as well as terrain clearance and aircraft separation required to reduce the hazard of aircraft collision. One of the most widely used methods for measurement of airspeed and altitude involves a measurement of two types of pressure known as total head pressure and static pressure.

In the measurement of altitude by the pressure method, numerous types of errors exist. Many of these errors are relatively small and are associated with the instrument itself, but one of the most important errors is concerned with the location of the static orifice on the aircraft which senses the static pressure. In an effort to summarize the errors involved in the measurement of static pressure, the NACA has summarized the errors associated with various design features of static pressure tubes. Errors due to the position of the static pressure tube are also given for various locations on and around the airplane. An appraisal of the more satisfactory locations is given for various aircraft configurations, attitudes and speeds and of the methods of calibrating static pressure installations in flight.

A study has also been conducted to determine the effects of high-speed dives or climbs, particularly at supersonic speeds where shock and expansion waves can affect the measurement of static pressure since air flows out of or into the static pressure orifices under these conditions. Tests made at supersonic speeds and over a range of airplane attitudes have indicated that errors in static pressure would be enough to result in a Mach number error that is not insignificant.

The errors in the measurement of altitude increase with both airplane speed and altitude. However, this does not mean that high-speed, high-altitude flight is the most critical aspect of the altitude measuring problem, since the measurement of altitude during the landing approach can also present a difficult problem. Errors which can be tolerated near the ground are much smaller than those that can be tolerated at high altitudes. Many agencies and organizations have studied the problem of measuring pressure altitude of aircraft. In an effort to gather all available information on this subject, a study has been made which summarizes the errors involved in pressure altimeter systems that arise from the design of the measuring system itself, from the operation of the system, and from the variations in atmospheric pressure. Available information on the magnitude of the errors in each of these categories is given as well as an indication of the means by which some of the errors can be reduced. Calculations are also presented of the overall accuracy of pressure altitude as measured in a single aircraft and the overall errors of two aircraft in an effort to show the minimum vertical separation which can be tolerated with present instrumentation and operating practices.

Pilot Escape

During aircraft operations it is sometimes necessary in emergencies for the pilot and crew to leave the aircraft in flight. At low speeds this is readily accomplished by the pilot merely climbing out of the cockpit and throwing himself clear of the airplane prior to using the parachute. In high-speed flight, however, the wind forces are so great that the pilot must be mechanically ejected from the aircraft. Usually this is accomplished through the use of an explosive charge to insure that he does not strike any part of the aircraft structure during his egress. Exiting systems of pilot ejection in present day aircraft have not been entirely satisfactory because of the air forces and the resultant tumbling that is a direct result of placing an irregularly shaped configuration such as a pilot-seat combination into a high-speed airstream. As an interim solution to this ejection problem, the NACA has been conducting wind tunnel tests at high speed in an effort to determine modifications which, if applied to existing ejection seats, would reduce the deceleration forces as well as provide stability and thus prevent tumbling. In this manner, adverse effects on the pilot may be reduced so that he can be successfully separated from the seat and descend to the ground without incident. General modifications have been investigated for two types of ejection systems. These consist of airstream deflectors which have been found to afford satisfactory stability during an ejection and reduce wind blast pressure on the pilot.

Crash Fire Research

The fire that often follows an airplane crash has been shown to be an important factor in the survival of the aircraft occupants. This is particularly true in types of crashes such as during landing and takeoff operations when the crash forces are relatively low and there is a good chance of survival if fire does not occur. The NACA has previously reported on its initial full-scale aircraft crash investigations aimed at determining the mechanism of the initiation of crash fires. The results of this study which have provided a means for inerting power plants, thereby reducing the likelihood of fire following a crash. The study also included the magnitudes and time histories of crash loads that occur during the deceleration of the crashed airplane.

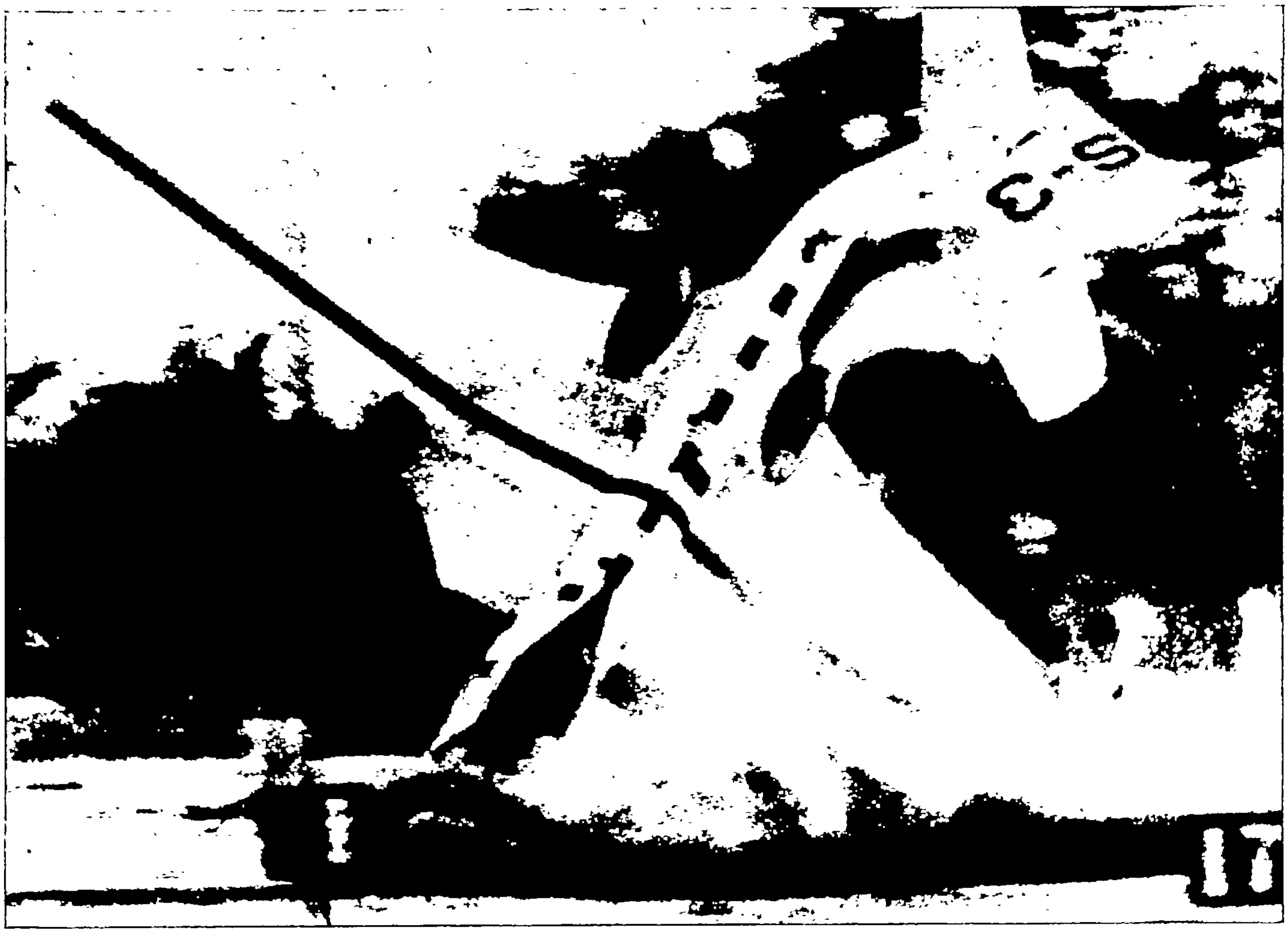
The previously reported results on the crash-fire inerting system for both reciprocating and jet engine aircraft have been extended to more powerful turbojet and turbine-propeller type engines which are currently being used in military operations and which soon will be used in civil transport operations. The purpose of these current studies is to determine if there are any significant obstacles in the application of the successfully demonstrated crash-fire inerting principles to more powerful engines. Some effort is also being given to combining the crash-fire inerting system and the flight-fire inerting system so that a common extinguishing agent can be used for combating both of these hazards.

During this general crash fire program knowledge was gained as to the many ignition sources around a crashed airplane that are available to ignite spilled combustibles. One of the ignition sources which is not suppressed by the crash fire inerting system is that of friction sparks which may be generated during the scraping of aircraft metal along a runway or stony surface during an airplane crash. The friction spark ignition hazard was investigated by dragging samples of aircraft metals that are commonly used in aircraft construction along both concrete and asphalt runways. Steel, aluminum, titanium, and magnesium samples were tested under varying conditions of dragging speeds and bearing pressures in the presence of a combustible mixture to determine if ignition could occur. Although no ignition was obtained with aluminum, ignition did occur with all the other metals. Titanium proved to be the most hazardous metal while magnesium was the next most hazardous and steel the least hazardous of those metals that caused ignition. It has been concluded that such metals should not be used in aircraft construction in areas where they are likely to scrape along a runway surface during a crash or belly landing.

Another aspect of fighting crash and flight fires is that of providing the most effective agents that can be produced to quickly put out any fire that may start. In the past few years, halogenated fire-fighting agents which act through a chemical reaction process have proven to be fairly effective in fighting fires. These agents, however, have normally been used in liquid form and therefore are rather readily dispersed under conditions of airflow which normally exist in aircraft. A study was therefore sponsored at Syracuse University by the NACA to determine if some of the promising halogenated agents could be adsorbed by powder particles such that when these particles were dispensed in powder form in the area of a fire they would, in the presence of heat, desorb or release their fire-fighting chemical properties. This basic research study has provided results as to the adsorption and desorption rates of various fine powders containing halogenated methanes. Some limited data has been obtained with respect to the fire-fighting characteristics of these halogenated powders.

Crash Survival Research

As previously noted the NACA full-scale crash fire program afforded an opportunity to measure the deceleration forces that existed on the seat and seat occupants during typical crashes with both transport and military fighter-type aircraft. The analyses of the time histories and magnitudes of these decelerations have afforded a basis for determining whether the human tolerance to deceleration in the horizontal, vertical, and lateral directions are exceeded for the types of crashes and airplanes studied. It was found that, except for the more severe impact type of accident, the human tolerances to deceleration may be within survivable limits. These data also provided a basis for proposed design criteria and methods for absorbing crash impact deceleration such that the forces felt by the occupant were reduced below those which would normally be experienced. A method is presented for determining the seat strength, spring stiffness and deformation beyond the elastic limit to accomplish this reduction in impact forces felt by the occupant. These data are expected to be of interest to designers seeking means of providing aircraft seats



Crash impact of military aircraft.

that can be expected to retain their strength characteristics without failure during aircraft crash circumstances.

Aircraft Ditching

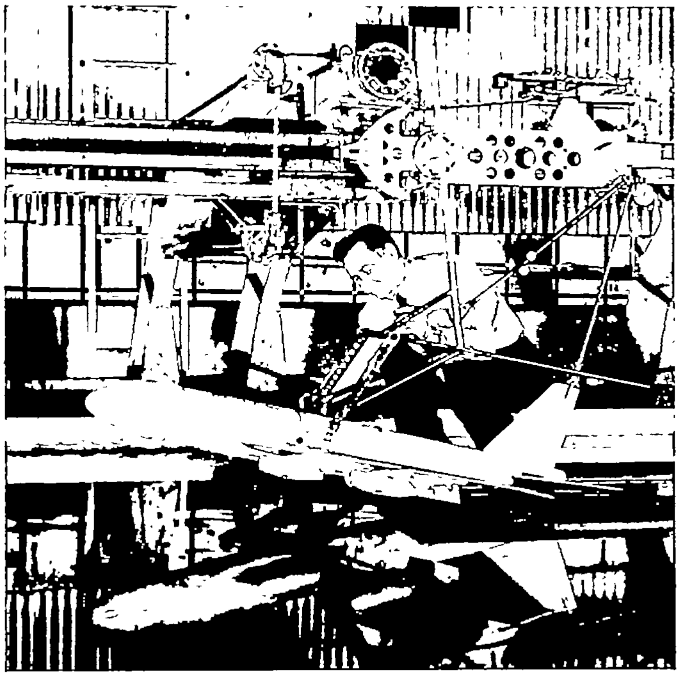
The day to day operation of aircraft is sometimes interrupted by an emergency which may cause an unscheduled landing on water, referred to as a ditching action. For many years the NACA has conducted ditching investigations using dynamic scale models of conventional aircraft which are launched from a monorail carriage into a tank of water. Information was obtained to help not only aircraft designers but also operations personnel concerned with training crews for over-water flight.

In anticipation of the introduction of turbojet swept-wing transport aircraft with different engine installations, more recent investigations have been undertaken to determine the best ditching procedure and the probable ditching behavior in calm and rough water. Various conditions of fuselage damage, landing attitude and speed have been studied and data obtained from visual observations, instrument records and motion pictures, which have been analyzed to determine results applicable to full-scale aircraft. The use of a ditching aid, such as a hydroski attached to the fuselage bottom, has been investigated to determine its effect on the model's ditching characteristics.

The results of some of the NACA tests indicate that a low-wing turbojet transport should be ditched at a nose-high attitude with the landing flaps down, and that the various engine installations made no great difference in the overall ditching performance. In some cases, depending upon the configuration, engine nacelles would probably be torn away and the fuselage bottom damaged enough to cause rapid flooding by the water.

In tests with one hydroski attached, very little or no damage was sustained by the fuselage bottom when the ditching was accomplished under the proper installation and approach conditions. The maximum normal acceleration without hydroski was about twice as great as with hydroski installed.

At the request of the military services, several investigations have been undertaken to determine the ditching characteristics of fighter-type aircraft of various configurations. In such tests, information was also obtained wherein the ditching behavior was noted for the conditions of landing gear extended and retracted.



Ditching tests of jet transport model. Tank No. 2 monorail.

Gust Alleviation

Aircraft operations in severe or even moderate turbulence for long periods of time require that the pilot devote constant attention to maintaining level flight. This can cause the pilot to become fatigued. The possibility of pilot error is more prevalent if a pilot is fatigued. Atmospheric turbulence, in addition, demands that design requirements be such that the airplane can cope with the loads imposed on the structure under such conditions. In civil aircraft operations the rough air also sets up undesirable aircraft motions and adversely affects passenger comfort. For these and other reasons, the NACA has been for some years studying turbulence in the atmosphere and relating these data not only to aircraft structural design criteria but also to the aircraft response characteristics so that the pilot's job of flying in rough air can be eased and passenger comfort improved. The NACA has not been satisfied to learn of the nature of these atmospheric effects on aircraft operations but has felt it desirable to find ways and means of alleviating the aircraft motions caused by turbulence in the atmosphere as well as additional motions that may be inadvertently applied by the pilot in controlling the airplane when flying in turbulent air. One of the various means that is being studied by the NACA to alleviate undesirable airplane motions imposed by rough air has been an experimental and analytical investigation to determine the effects of auto-pilot control, rather than human pilot control. This study will provide information on the longitudinal response of the airplane for various settings of the automatic pilot. The objective of this program is to determine whether the motions experienced by the airplane by use of the automatic pilot can be reduced below those normally experienced.

Another system designed to alleviate the normal accelerations due to rough air and thus improve the smoothness of flight in rough air is undergoing flight tests in a small transport-type airplane. In this system, the rough air is sensed by an instrument mounted on a boom ahead of the nose of the airplane and/or by a sensing instrument at the airplane's center of gravity. This sensing signal operates wing flaps such that they cause the airplane to have less response or motion resulting from the rough air. A portion of the elevator is also automatically operated in order to reduce the effects of flap deflection. Flight tests are being conducted to determine the optimum settings for the alleviation control. Initial results from flight tests indicate that approximately 50 percent alleviation is achieved. Structural loads are reduced in wing bending but wing shear and tail bending and shear loads are somewhat increased. More recent results indicate improved alleviation through the use of a small-span inboard flap. In addition to the results that have been obtained and published, additional information is being gained from flight tests which are being made to determine the airplane response to acceleration control and the alleviator gearings required to reduce structural loads.

Another means of providing gust alleviation that has been studied by the NACA is that afforded by the use of deflectors and spoilers to modify the lift characteristics such that the airplane will have smaller response and thus smoother flight in rough air. Published results of investigations made of this device indicate that spoiler-deflector types of controls can be designed to provide considerable gust alleviation for a swept-wing airplane. These aerodynamic controls also will aid in slowing down airplanes in rough air. One disadvantage, however, is that these controls tend to magnify the longitudinal stability problems encountered by swept-wing aircraft.

Engine Reliability

The desirability of having operating engines that have a long life without failure has importance to the safety of flight. Engines that must be prematurely removed from service have serious effects on the operational capability of both military and civil aircraft. In addition this results in requiring manpower and money to put the airplane back in service. Perhaps of even greater importance is the failure that occurs in flight which may result in a costly airplane accident. The NACA is studying jet engine reliability in order to obtain an insight into the effects of operational procedure, manufacture and assembly methods and overhaul practices on service life. One of the important factors affecting jet engine reliability is compressor blade failure due to vibration. Methods are being studied to reduce these vibrations so that blade failures can be reduced and the frequency of removal of engines for repair reduced. The service life of engines can also be seriously affected by damage due to foreign objects that are sucked into the engine inlet. An investigation has been undertaken by the NACA to determine when blades have been damaged seriously enough to cause premature failure. As a result of this study, a method has been devised to predict the life of a compressor blade which has been nicked by a foreign object. This method shows promise on the basis of the results that have been obtained to date.

AERONAUTICAL METEOROLOGY

In the design and operation of aircraft and missiles, the primary weather problem is to the variability of such meteorological elements as gusts, wind, temperature, humidity, pressure and all types of precipitation including ice. Generally, the manufacturer desires data on average and extreme values of weather conditions; whereas the aircraft operator is concerned with timely observations and with accurate short and long period forecasts; both are of course concerned with the effects of weather on the flight vehicle. With the newer, high performance aircraft, the requirement for more accurate weather information is complicated by both the shorter time available for decision and by the scarcity of basic meteorological information in many areas.

For many years, the NACA has studied several phases of two aeronautical meteorological problems, namely, turbulence and icing; other problems of the atmosphere have been investigated on a smaller scale. Such research information has been sought to help achieve the ideal of safe and efficient all-weather flight.

Atmospheric Turbulence

When aircraft fly in regions of rough or bumpy air, the usual practice is to reduce flight speed or change course in order to lessen the gust loads on the structure and thus increase passenger comfort. In extreme cases, such as thunderstorms, the safety of the aircraft may be seriously threatened by strong drafts or gusts.

For many years the NACA has been investigating the gust problem from both the experimental and analytical approaches. Specially instrumented airplanes have been flown into turbulent areas to measure the response of the structure to the gusts. From the data the velocity of the gusts can be calculated. To obtain data on the extent, frequency, and severity of gusts over wide areas, a recording instrument was developed for use on commerical aircraft during their routine flights.

Theoretical calculations to determine the reactions of an airplane to a single gust or a series of gusts have also been made in order that a comparison might be made with experimental data. During the design stages of airplane construction a theoretical solution to the gust problem which would accurately portray the aircraft's response in actual turbulence would be most valuable.

Of particular interest has been the investigation of the effect of using airline weather radar in the amount of turbulence encountered during scheduled airline operations. The results to date indicate that the magnitudes of the largest gust velocities and gust acceleration for a given number of flight miles during operations with airline radar were approximately 25 percent less than those experienced before the radar equipment was installed.

High-Altitude Turbulence

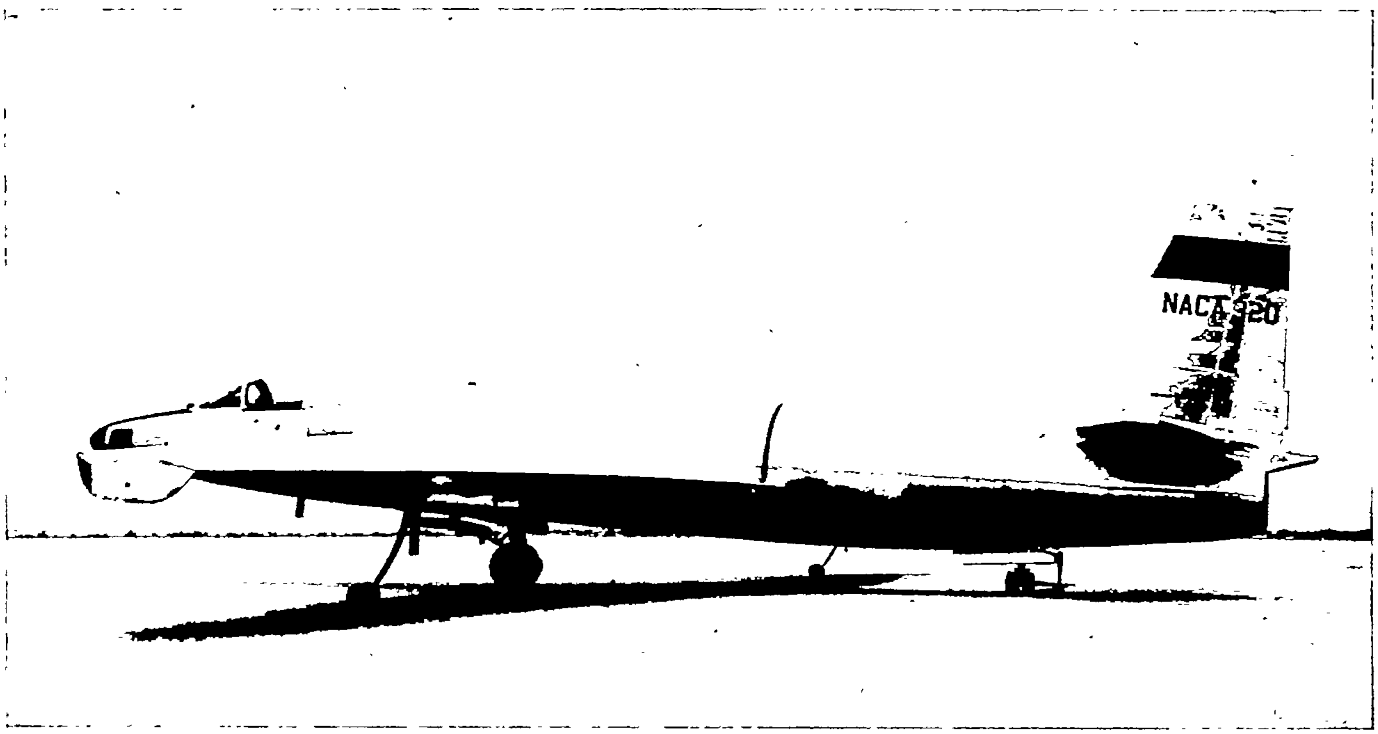
With the cooperation of the Air Weather Service, an investigation has been undertaken to determine the intensity and amount of atmospheric turbulence at an altitude of approximately 50,000 feet for various geographical locations and in various seasons of the year. Using specially developed aircraft (see photo), data have been obtained over England and Western Europe and the western part of the United States. Data collection has recently been initiated to cover two additional areas, namely, Japan and Turkey. The importance of such high-altitude turbulence information will be in the determination of design gust loads for missiles and aircraft which must operate through or at the higher altitudes.

In other cooperative efforts with the military services, NACA gust instrumentation has been placed in aircraft which are flying in areas associated with the jet stream, a narrow band of strong winds usually at altitudes of 35,000 to 40,000 feet during the winter in the United States. Analysis of the limited data so far obtained indicates that atmospheric turbulence may be found in certain regions near the jet stream. The gust information is useful to meteorological researchers attempting to formulate improved methods of forecasting.

In connection with the National Hurricane Project, NACA gust instruments are being flown in Navy and Weather Bureau aircraft to obtain data on the intensity, and frequency of occurrence of gusts within hurricanes. Some data have been obtained which show that gust velocities of less than 30 feet per second were encountered four times as frequently as in routine long-haul commercial aircraft operations.

The Icing Cloud

To provide the most effective icing protection systems for aircraft, detailed and statistical information



U–2 airplane used by NACA for gust-meteorological studies at high altitude.

is required on the characteristics of icing clouds. Such information can only be obtained by basic measurements and observations. In this connection, the NACA has conducted investigations to develop more accurate instrumentation to measure liquid-water content and water-droplet sizes of supercooled clouds both in flight and in icing tunnels. At the same time, routine data on icing encounters by military and commercial aircraft equipped with special NACA icing meters have been collected for analysis.

In order to determine whether differences in liquid-water content values measured by different instruments were real or due to instrumental errors, a flight evaluation was conducted in icing conditions. The instruments were mounted in close proximity to each other to minimize airplane and cloud effects on the data recorded. The results of a partial analysis of the data show good agreement was obtained between the liquid-water-content measurements obtained with a multicylinder instrument and a pressure-type icing-rate meter. Water-content measurements were also obtained with a new droplet-collecting instrument which gave values averaging slightly higher than those for the other two instruments. Droplet size measurements obtained with multicylinders and the newly developed instrument agreed reasonably well.

In a recent Navy flight test program to evaluate the capability of an airship to remain on station during freezing rain, snow or icing conditions, NACA cooperated to the extent of furnishing advice and icing instrumentation. A preliminary study of the airship icing problem indicated that accumulations of ice or snow on the large top surface area of the bag could produce a serious weight problem extending beyond the lifting capacity of the airship. The primary problem of ice loads created from conditions of freezing rain was analyzed on the basis of droplet paths, heating calculations, and temperatures and rainfall rates typical of freezing rain conditions.

Extensive icing-cloud data on the extent, frequency, and severity of icing conditions experienced during scheduled flights over worldwide air routes have been obtained using NACA recording instrumentation installed in transport, bomber, and fighter-type aircraft through the cooperation of several major airlines and the United States Air Force. In one program, data were received over a 5-year period from 3,100 icing encounters experienced by several types of aircraft while flying over air routes in the United States and the Atlantic and Pacific areas at altitudes under 20,000 feet. About 90 percent of the icing conditions were less than 120 miles in horizontal extent and less than 4,500 feet in vertical thickness. Liquid-water contents of the icing clouds exceeded 1.0 gram per cubic meter only 7 minutes of every 100 minutes of flight in the icing conditions.

In another program, a statistical study was made of thousands of inflight observations reported from weather reconnaissance aircraft flown by the United States Air Force over areas of the Atlantic, Pacific, and Arctic Oceans. The probabilities of icing their relation to the frequencies of flight in clouds and were derived for the several ocean areas at altitude levels of 10,000 and 18,000 feet. The relative frequency of icing varied widely throughout the year from near zero in cold Arctic areas in winter up to 7 percent in areas of greater cloudiness and warm temperatures. The data revealed a general tendency for colder cloud temperatures to reduce the probability of icing in equally cloudy conditions.

AIRCRAFT ICING

Aircraft and missiles entering clouds having temperatures at or below freezing can expect to encounter icing conditions which are potentially dangerous, especially at the lower flight speeds associated with takeoff, landing or holding. Ice accumulation on airframe surfaces and powerplant components may lead to performance deterioration, control inefficiency or engine failure unless some icing-protection equipment is provided. The design of such equipment requires a knowledge of how fast and where the supercool water droplets strike the aircraft and of the heating characteristics of the components requiring protection.

For current aircraft configurations and operations, the ice-protection systems based upon past research and development investigations are adequate. However, for new aircraft shapes and engines, further experimental and analytical icing research is indicated in some cases. Accordingly, laboratory studies during the past year have been concerned primarily with icing-protection requirements for bodies of revolution which approximate nose radomes, external fuel tanks and spinners for turboprop engines, aerodynamic penalties (lift, drag and pitching moment changes) associated with icing of a thin airfoil section and evaluation of several other aircraft components.

Water Droplet Impingement and Icing Protection

The development of an experimental technique to indicate the areas exposed to the cloud droplets and a method of determining water droplet-size distribution have made it possible to determine more readily the droplet impingement characteristics of arbitrary bodies. Several two-dimensional airfoils were studied over a typical range of flight and meteorological conditions in the Lewis Flight Propulsion Laboratory icing tunnel using this technique (see photograph). The results generally showed good agreement between the theoretical and the experimental impingement data and thus pointed out the regions where icing protection is required. An egg-shaped body and a coned body were also investigated both in dry air and in tunnel icing conditions as part of the general study. Heating data, droplet impingement characteristics and icing protection requirements were determined for several attitudes both with and without rotation of the body.

In evaluating the mission capability of a high-speed, high-altitude jet aircraft which is to be flown in all types of weather, its performance in icing conditions must be determined. Since it is difficult to build an airplane and then attempt flight tests in actual icing conditions to find which aircraft parts need protection, tunnel tests become very useful in gathering such information during aircraft design and construction stages. Accordingly, a full-scale unheated, supersonic nose inlet of a jet engine was tested in the Lewis Laboratory icing tunnel to determine the effects of ice accumulations on the flow of air through a portion of the engine. Data on the rate and area of water-droplet impingement on parts of the engine housing were obtained to show where some protection might be needed to prevent or remove ice formations.

Auxiliary inlets or air scoops mounted on an airplane are susceptible to blockage by ice and snow with consequent losses in performance and possible malfunction. To study one phase of this problem, a full-scale air-inlet in a section of a vertical tail-fin was subjected to tunnel icing conditions. The internal walls of this inlet were electrically heated to provide protection. Analysis of the data taken over a range of icing conditions indicated that, except for the extremely severe conditions which actually occur very rarely in nature, the inlet operated satisfactorily without the application of heat. The inlet lips, however, did require heat in cases where the ice formations tended to block the inlet opening.

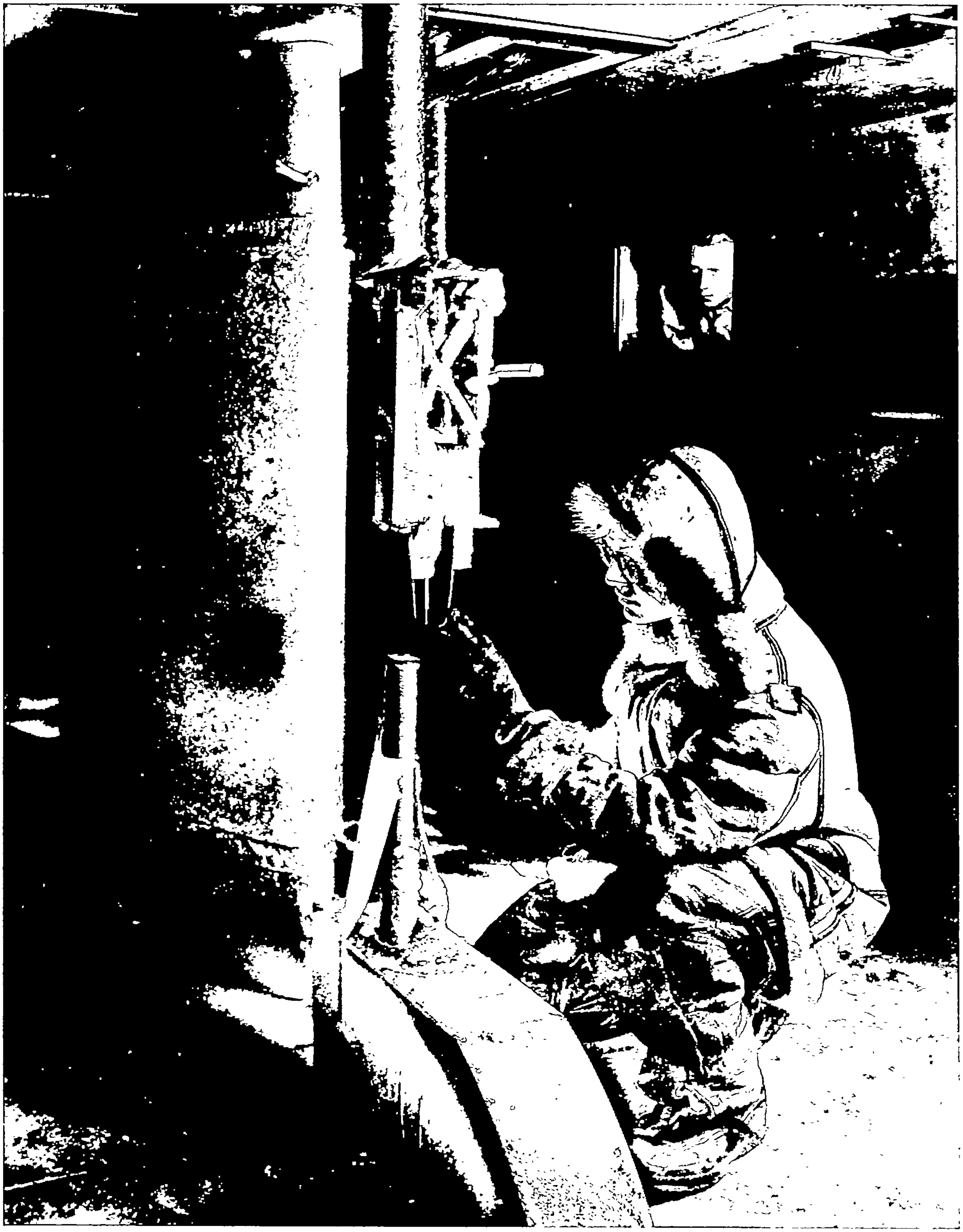
Penalties Due to Icing

On higher-speed aircraft, increasing use has been made of thin airfoil sections for more efficient flight. A recent icing tunnel study was thus undertaken to determine the effects of ice formations on a thin airfoil with and without operation of an electric cyclic de-icing system. The results show that in some conditions ice formations increase the drag and reduce lift and diving moment thus hindering airplane performance; in other cases these aerodynamic characteristics may be either increased or decreased depending upon the shape of the ice formation. Data from the heating tests indicated very good de-icing performance and efficiencies at the higher power densities employed in the tests.

AIRCRAFT NOISE

The noises produced by aircraft and missile powerplants have reached such high levels that the orderly development of aviation is being impeded. The noise is objectionable to those living near airports, can be physically damaging to personnel near the noise source, and, as noise is a fluctuating pressure wave, can damage the structure, equipment, and control systems of the engine and the vehicle.

As the power produced by jet and rocket engines increases, we know that the noise levels will also increase unless methods are discovered with which to control the noise. The NACA has underway a three-way research program aimed at alleviating aircraft noise



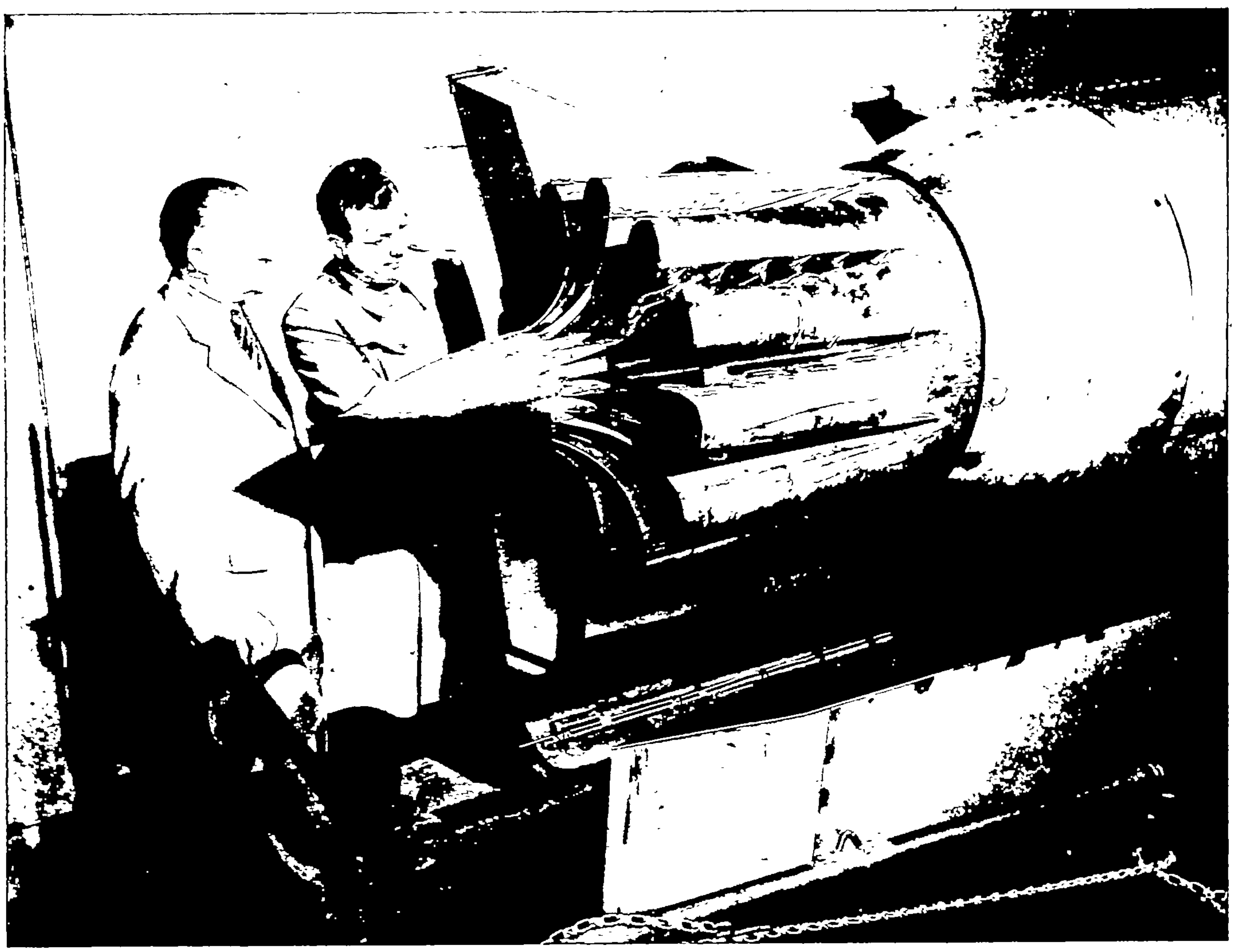
Model mounted in tunnel for icing studies.

problems. One part is a basic study of the amount of noise and the ways in which it is produced by aircraft and missiles and their powerplants. Another part is aimed at reducing the amount of noise being produced, and the third part concerns research on aircraft structures and equipment able to withstand the noise pressure.

Jet and rocket engines operating on the ground and during takeoff produce about the loudest nonexplosive noises known to man. Research has demonstrated that this noise is caused by the mixing of the high speed exhaust gas with the surrounding air, and that the amount of noise can be related to the area of the jet and the velocity of the jet. The noise fields around various operating turbojet and rocket engines have been mapped at distances from a few feet to several hundred feet from the engines.

The NACA is continuing its basic research on the manner in which this noise is produced, since an understanding of the mechanisms of noise production is required in order to properly estimate the noise fields for new jets, as well as to show the way toward reducing the noise at its source. Correlations have been obtained between the turbulence in the jet exhaust for nozzles of various shapes and the noise field, and a method has been devised to estimate noise from the turbulence pattern in a flow.

In order to reduce the noise produced by the mixing of the jet with air outside the tailpipe exit, the NACA has been investigating methods of altering this mixing process so as to reduce the noise. A large number of tailpipes of various shapes such as shown in the photograph have been tested, as well as such other shapes as long narrow slots such as might be used with a jet flap. These suppressors have been tested on full-size jet engines under stationary conditions in an open field and those showing best noise suppression characteristics have been tested in wind tunnels where flight operations were simulated, and the aerodynamic performance of the nozzles determined. While considerable success has been achieved with various suppressor devices for ground operation, work is still progressing



Experimental jet engine noise suppressor.

toward developing suppressors for flight operations that have satisfactory noise characteristics without imposing excessive penalties on the performance of the aircraft. Similar work is being done with model jets with a view toward correlating model and full-scale data so that as much future research as possible can be done on small model jets.

The strong shock waves encountered in supersonic flows such as those of a rocket exhaust produce extremely loud sound waves at certain frequencies, and other nozzles are being developed which reduce these shocks and their noise.

The air flowing over an aircraft flying at high speeds is another source which produces a considerable amount of noise. The magnitude and nature of this aerodynamic noise is being studied in subsonic and supersonic flight tests with aircraft such as the F–94, B–47, and research airplanes, as well as in wind tunnel tests by the NACA and by the California Institute of Technology under an NACA research contract. The effects of a sonic boom produced by an aircraft flying at supersonic speeds near another aircraft has been investigated.

The effect of propeller blade shape on the noise field produced by subsonic propellers has been investigated with a view toward determining the best shape for minimum noise. A theoretical method has been established for estimating the noise field around a propeller in subsonic flight for various blade loading conditions. Experiments have been conducted on the noise characteristics of supersonic propellers. The shock fields created by these propellers produce very loud noises which are a major handicap to the use of such propellers for high-speed aircraft. However, static tests have been made of supersonic type propellers in which the operating conditions of the blade have been varied so that while maintaining its efficiency, the tip speed is subsonic and the noise level is about the same as conventional propellers.

Noise levels around aircraft and missiles have increased to such intensity that parts of the structures and equipment are being destroyed or damaged so as to impair the proper operation of the vehicle. The third area of NACA noise research concerns how the noise is transmitted to and through the structure and thereby the equipment, and how to most efficiently design the structure so as to withstand the noise loads. Various types of aircraft structures are being tested to destruction by the noise pressure from such sources as jet and rocket engines, air jets, and laboratory sirens, and the information obtained is being used to devise methods for designing better structures.

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RESEARCH PUBLICATIONS

AERODYNAMICS

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3825. Comparison of Mechanical Properties of Flat Sheets, Molded Shapes, and Post-Formed Shapes of Cotton-Fabric Phenolic Laminates. By F. W. Reinhart, C. L. Good, P. S. Turner, and I. Wolock.

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1292. Intensity, Scale, and Spectra of Turbulence in Mixing Region of Free Subsonic Jet. By James C. Laurence.

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3576. Further Measurements of Intensity, Scale, and Spectra of Turbulence in a Subsonic Jet. By James C. Laurence and Truman M. Stickney.

3710. Preliminary Investigation of the Effects of External Wing Fuel Tanks on Ditching Behavior of a Sweptback-Wing Airplane. By Ellis E. McBride.

3763. Near Noise Field of a Jet-Engine Exhaust. I—Sound Pressures. By Walton L. Howes and Harold R. Mull.

3764. Near Noise Field of a Jet-Engine Exhaust. II—Cross Correlation of Sound Pressures. By Edmund E. Callaghan, Walton L. Howes, and Willard D. Coles.

3770. Impingement of Droplets in 60° Elbows With Potential Flow. By Paul T. Hacker, Paul G. Saper, and Charles F. Kadow.

3775. Crash Injury. By Gerard J. Pesman and A. Martin Eiband.

3777. Seat Design for Crash Worthiness. By I. Irving Pinkel and Edmund G. Rosenberg.

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3953. A Limited Correlation of Atmospheric Sounding Data and Turbulence Experienced by Rocket-Powered Models. By Homer P. Mason and William N. Gardner.

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PART II.—COMMITTEE ORGANIZATION AND MEMBERSHIP

The National Advisory Committee for Aeronautics was established by Act of Congress approved March 3, 1915 (U. S. Code, title 50, sec. 151). The Committee is composed of seventeen members appointed by the President, and includes two representatives each of the Department of the Air Force, the Department of the Navy, and the Civil Aeronautics Authority; one representative each of the Smithsonian Institution, the United States Weather Bureau, and the National Bureau of Standards; and "one Department of Defense representative who is acquainted with the needs of aeronautical research and development." In addition seven members are appointed for five-year terms from persons "acquainted with the needs of aeronautical science, either civil or military, or skilled in aeronautical engineering or its allied sciences." The representatives of the Government organizations serve for indefinite periods, and all members serve as such without compensation.

The following changes in membership have taken place during the past year:

On January 14, 1957, President Eisenhower appointed Mr. Charles J. McCarthy, Chairman of the Board of Chance Vought Aircraft, Inc., a member of the NACA to succeed Dr. Arthur E. Raymond, Vice President, Engineering, Douglas Aircraft Company, whose term of membership expired December 1, 1956.

As a result of his resignation on February 15, 1957, as Assistant Secretary of Defense (Research and Development), the membership of Honorable Clifford C. Furnas on NACA was automatically terminated, since he was serving as the Department of Defense representative authorized in the NACA enabling legislation as revised. Dr. Furnas' successor on the Committe has not yet been appointed.

Honorable James T. Pyle, Administrator of Civil Aeronautics, was appointed a member of the Committee on March 1, 1957, as one of the representatives of the Civil Aeronautics Authority. He succeeded Honorable Joseph P. Adams, Vice Chairman of the Civil Aeronautics Board, whose membership on the NACA was terminated December 31, 1956, with the expiration of his service as a member of the Board.

On July 18, 1957, Rear Admiral Wellington T. Hines, USN, Assistant Chief for Procurement, Bureau of Aeronautics, Department of the Navy, was appointed a member of the NACA to succeed Rear Admiral Carl J. Pfingstag, USN, who had recently been detached as Assistant Chief for Field Activities, Bureau of Aeronautics.

Following the promotion of General Nathan F. Twining, USAF, to be Chairman of the Joint Chiefs of Staff, the President on August 26, 1957, appointed General Thomas D. White, USAF, a member of the NACA vice General Twining. General White had just succeeded General Twining as Chief of Staff of the Air Force.

In accordance with the regulations of the Committee as approved by the President, the chairman and vice chairman and the chairman and vice chairman of the Executive Committee are elected annually.

At the annual meeting of the Committee on October 10, 1957, Dr. James H. Doolittle was reelected Chairman of the NACA and Chairman of the Executive Committee. Dr. Leonard Carmichael was reelected Vice Chairman of the NACA and Dr. Detlev W. Bronk Vice Chairman of the Executive Committee.

The present members of the Committee are as follows:

James H. Doolittle, Sc. D., Vice President, Shell Oil Company, Chairman.
Leonard Carmichael, Ph. D., Secretary, Smithsonian Institution, Vice Chairman.
Allen V. Astin, Ph. D., Director, National Bureau of Standards.
Preston R. Bassett, D. Sc.
Detlev W. Bronk, Ph. D., President, Rockefeller Institute for Medical Research.
Frederick C. Crawford, Sc. D., Chairman of the Board, Thompson Products, Inc.
William V. Davis, Jr., Vice Admiral, United States Navy, Deputy Chief of Naval Operations (Air).
Wellington T. Hines, Rear Admiral, United States Navy, Assistant Chief for Procurement, Bureau of Aeronautics.
Jerome C. Hunsaker, Sc. D., Massachusetts Institute of Technology.
Charles J. McCarthy, S. B., Chairman of the Board, Chance Vought Aircraft, Inc.
Donald L. Putt, Lieutenant General, United States Air Force, Deputy Chief of Staff, Development.
James T. Pyle, A. B., Administrator of Civil Aeronautics.
Francis W. Reichelderfer, Sc. D., Chief, United States Weather Bureau.
Edward V. Rickenbacker, Sc. D., Chairman of the Board, Eastern Air Lines, Inc.
Louis S. Rothschild, Ph. B., Under Secretary of Commerce for Transportation.
Thomas D. White, General, United States Air Force, Chief of Staff.

Assisting the Committee in its coordination of aeronautical research and the formulation of its research programs are four main technical committees: Aerodynamics, Power Plants for Aircraft, Aircraft Construction, and Operating Problems. Each of these committees is assisted by from four to eight subcommittees, totaling 24 in all. Effective January 1, 1957, a new Subcommittee on Low-Speed Aerodynamics was established under the Committee on Aerodynamics in place of the Subcommittee on Propellers for Aircraft, to study, in addition to the problems of propeller operation, problems in areas not covered in the previous NACA subcommittee structure, principally in relation to the improvement of the landing and takeoff characteristics of high-speed aircraft, and the low-speed operation of vertical- and short-takeoff-and-landing (VTOL and STOL) aircraft.

The Committee is advised on matters of policy affecting the aircraft industry by an Industry Consulting Committee.

The membership of the committees and their subcommittees is as follows:

COMMITTEE ON AERODYNAMICS

Mr. Preston R. Bassett, Chairman.

Dr. Theodore P. Wright, Vice President for Research, Cornell University, Vice Chairman.

Maj. Gen. Ralph P. Swofford, Jr., USAF, Director of Research and Development, U. S. Air Force.

Col. James O. Cobb, USAF, Chief, Aircraft Laboratory, Wright Air Development Center.

Rear Adm. L. D. Coates, USN, Assistant Chief of the Bureau of Aeronautics for Research and Development, Department of the Navy.

Mr. Abraham Hyatt, Bureau of Aeronautics, Department of the Navy.

Capt. Robert L. Townsend, USN, Assistant Director, Research and Development Division, Bureau of Ordnance, Department of the Navy.

Maj. Gen. August Schomburg, USA, Assistant Chief of Ordnance for Research and Development, Department of the Army.

Col. George P. Seneff, Jr., USA, Office of the Chief of Research and Development, Department of the Army.

Mr. Harold D. Hoekstra, Civil Aeronautics Administration.

Dr. Hugh L. Dryden (ex officio).

Mr. Floyd L. Thompson, NACA Langley Aeronautical Laboratory.

Mr. Russell G. Robinson, NACA Ames Aeronautical Laboratory.

Capt. W. S. Diehl, USN (Ret.).

Mr. L. L. Douglas, Vice President, Engineering, Vertol Aircraft Corp.

Rear Adm. R. S. Hatcher, USN (Ret.), Aerojet-General Corp.

Mr. Clarence L. Johnson, Vice President, Research and Development, Lockheed Aircraft Corp.

Dr. A. Kartveli, Vice President, Research and Development, Republic Aviation Corp.

Mr. Schuyler Kleinhans, Assistant Chief Engineer, Santa Monica Division, Douglas Aircraft Company, Inc.

Mr. F. A. Louden.

Dr. Clark B. Millikan, Director, Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology.

Dr. William J. O'Donnell, Assistant Chief Engineer, Development and Experimental, Republic Aviation Corp.

Mr. Kendall Perkins, Vice President, Engineering, McDonnell Aircraft Corp.

Mr. George S. Schairer, Director of Research, Boeing Airplane Company.

Mr. R. C. Sebold, Vice President, Engineering, Convair, Division of General Dynamics Corp.

Mr. H. A. Storms, Jr., Chief Engineer, Los Angeles Division, North American Aviation, Inc.

Mr. Charles Tilgner, Jr., Chief Aeronautical Engineer (Staff), Grumman Aircraft Engineering Corp.

Mr. George S. Trimble, Jr., Vice President—Chief Engineer, The Martin Company.

Mr. Milton B. Ames, Jr., Secretary

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Mr. E. Haynes, Air Force Office of Scientific Research.

Dr. Frederick S. Sherman, Office of Naval Research, Department of the Navy.

Mr. John D. Nicolaides, Bureau of Ordnance, Department of the Navy.

Dr. Joseph Sternberg, Ballistic Research Laboratories, Aberdeen Proving Ground.

Dr. G. B. Schubauer, Chief, Fluid Mechanics Section, National Bureau of Standards.

Dr. Adolf Busemann, NACA Langley Aeronautical Laboratory.

Mr. Clinton E. Brown, NACA Langley Aeronautical Laboratory.

Dr. D. R. Chapman, NACA Ames Aeronautical Laboratory.

Mr. Robert T. Jones, NACA Ames Aeronautical Laboratory.

Dr. John C. Evvard, NACA Lewis Flight Propulsion Laboratory.

Prof. Walker Bleakney, Princeton University.

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Prof. Wallace D. Hayes, Princeton University.

Prof. Lester Lees, California Institute of Technology.

Prof. Hans W. Liepmann, California Institute of Technology.

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Mr. Newell D. Sanders, NACA Lewis Flight Propulsion Laboratory.
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Mr. Albert W. Cobb, Aerojet-General Corp.
Mr. Allen W. Dallas, Director, Engineering Division, Air Transport Association of America.
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Part III.—FINANCIAL REPORT

Funds appropriated for the Committee for the fiscal years 1957 and 1958 and obligations against the fiscal year 1957 appropritions are as follows:

	Fiscal year 1957		Fiscal year 1958
	Allotments	Obligations	Allotments
SALARIES AND EXPENSES APPROPRIATION			
NACA Headquarters	$1, 643, 360	$1, 623, 981	$1, 840, 000
Langley Aeronautical Laboratory	24, 171, 100	24, 113, 694	27, 050, 000
Ames Aeronautical Laboratory	12, 687, 200	12, 668, 978	14, 035, 000
Lewis Flight Propulsion Laboratory	21, 574, 758	21, 555, 462	24, 010, 000
High-Speed Flight Station	2, 125, 740	2, 117, 607	2, 415, 000
Pilotless Aircraft Station	1, 017, 335	1, 001, 005	1, 095, 000
Western Coordination Office	24, 405	23, 940	37, 000
Wright-Patterson Liaison Office	16, 602	16, 421	18, 000
Research contracts with educational institutions	727, 500	727, 311	410, 000
Research contracts with Government agencies	188, 500	188, 500	90, 000
Unobligated balance		139, 601	
Total	[1] 64, 176, 500	64, 176, 500	[2] 71, 000, 000
CONSTRUCTION AND EQUIPMENT APPROPRIATION			
Langley Aeronautical Laboratory	7, 696, 000	3, 682, 576	5, 679, 000
Ames Aeronautical Laboratory	906, 000	598, 372	11, 355, 000
Lewis Flight Propulsion Laboratory	5, 712, 000	4, 107, 118	16, 406, 000
Pilotless Aircraft Station			1, 560, 000
Reserve transferred from prior years	−314, 000	−262, 986	
Unobligated balance		[3] 5, 874, 920	
Total	[1] 14, 000, 000	14, 000, 000	[2] 35, 000, 000

[1] Appropriated in the Independent Offices Appropriation Act, 1957, approved June 27, 1956, and the First Supplemental Appropriation Act, 1957, approved July 27, 1956. Includes $1,500,000 reappropriation of fiscal year 1956 funds.

[2] Appropriated in the Independent Offices Appropriation Act, 1958, approved June 29, 1957.

[3] This balance remains available until expended.