Cleveland, Ohio.
September 19, 1949.

MEMORANDUM For Group Leaders

Subject: Suggested Introductions for Speakers - 1949 Inspection

1. 8- x 6-ft. SWT: Supersonic Propulsion

Here, in the Control and Observation Rooms of the newly completed 8- x 6-ft. Supersonic Wind Tunnel, Mr. Wyatt will lead the discussion on the general problems of propulsion for sustained supersonic flight. Mr. Wyatt.

2. Alt. Wind Tunnel Shop: Turbojet Altitude Operational Problems

We are now in the Altitude Wind Tunnel building where turbine propeller engines and jet engines of all types are operated under high speed high altitude flight conditions in the 20-foot diameter test section high above us. Here Mr. Fleming will lead the discussion of certain problems encountered in the operation of turbojet engines at high altitude. Mr. Fleming.

3. Rocket Laboratory: Rocket Research

You are now in the new Component and Accessory Test Building in in the heart of the Rocket Laboratory. Here Mr. Sloop will begin the presentation of the Committee's study of liquid-fuel rocket engines. Mr. Sloop.

4. W-6 C&T Wing: Compressor & Turbine Aerodynamics

The rapid progress made by turbojets in becoming dependable and efficient propulsion engines depends to a large extent on the intensive study of compressors and turbines, the various aspects of which will be described here in this large compressor laboratory by Mr. English and other speakers. Mr. English

5. W-2 C&T Wing: Turbine Cooling

The significance of turbine cooling has already been mentioned by Mr. English in the preceding discussion. Here Mr. Arne will demonstrate turbine cooling and begin the discussion of our research. Mr. Arne.

6. CW-5 ERB: Heat Transfer and Turbojet Fuels

The economical design and development of jet engines and their extensive use in an emergency requires exact knowledge of the fuel that will be available to run them and the nature of the heat transfer involved in cooling the engine. Here in one of the combustion laboratories we have brought these two problems together for you. Mr. Lowdermilk will first describe an important phase of our heat transfer research. Mr. Lowdermilk.

7. CE-6 ERB: Materials, Stress and Vibrations

The materials and the stress and vibration to which they are subjected in an aircraft power plant have much to do in limiting the maximum output and the safe life of the engine. Here Mr. Deutsch will start the discussion of recent research by the Committee in the field of high-temperature materials. Mr. Deutsch.

Edward R. Sharp

Edward R. Sharp,
Director.

WHH:mlm

NACA - Lewis

Cleveland, Ohio.
September 19, 1949.

MEMORANDUM For Those Concerned

Subject: Speakers for Inspection, September 20-22, 1949

1. The following men are speakers and alternate speakers at the locations indicated and are listed in the order of their presentations at each location:

Location	Speakers	Alternates
8- x 6-ft. SWT	Wyatt*	Pinkel*
	Cortright	Perchonok
	Carlton	Luidens
	Godman	Schueller
8- x 6-ft SWT Drive Bldg.	Hausmann*	Hausmann*
8- x 6-ft SWT Test Chamber	Slomski*	Slomski*
W-6 C&T Wing	English*	Graham*
	Costello	Cummings
	Hauser	Plohr
	Montgomery	Medeiros
	Finger	Lieblein
W-2 C&T Wing	Arne*	Jackson*
	Rossbach	Hubbartt
CW-5	Lowdermilk*	Grele*
	Barnett	Jonash
CE-6	Deutsch*	Ault*
	Manson	Brown
AWT Shop	Fleming*	Dr. Gibbons*
	Childs	Beitwieser
	Koenig	Gold
	Wilsted	Vincent
Rocket Lab	Sloop*	Kinney*
	Ordin	Morrell

2. The lead-off speakers, indicated by asterisks, are to be introduced by the group leaders. Group leaders should check which lead-off speaker will make presentation before he starts his introduction.

Edward R. Sharp

Edward R. Sharp,
Director.

WHH:mlm

J. Hall

A70829

Cleveland, Ohio,
September 8, 1948.

MEMORANDUM For Mr. Jesse H. Hall.

Subject: Talk for the Second Annual Inspection, FPRL, September, 1948.

1. Transmitted herewith is the talk to be presented by Dr. Walter T. Olson at the Second Annual Inspection, during the month of September, 1948.

Walter T. Olson, Chief,
Combustion Branch.

WTO:yet
BP

cc: Hall
B.Pinkel
Olson
Childs

J. Hall

COMBUSTION RESEARCH

Proposed Talk for 2nd Annual Inspection, FPRL, September 1948.

INTRODUCTION

It is intended here to tell you the scope and nature of the combustion research at NACA and to indicate the status of results in this field.

The major problem of combustion in all jet and gas turbine engines is to release efficiently tremendous quantities of heat energy from the fuel in a small volume and in a short space of time. Just for example, present-day gas turbine combustors such as these (point to display), release about twice the amount of heat that a large steam locomotive does. There are, of course, important attendant problems, such as a low loss of engine cycle pressure in the combustion system; light weight and durable combustion equipment; flexibility of operation, especially at "off-design" points; and, when a turbine is employed, proper distribution of temperature across the combustor outlet area to avoid subjecting the turbine blading to harmful hot zones. As is so frequently the case in engineering, compromises are required in the satisfactory solution of all of these problems, some of which are conflicting. We shall discuss some of these problems to illustrate the sort of work that we are doing currently.

RAM JET COMBUSTION

Consider first, for example, combustion in a ram-jet engine. As you know, the ram-jet is that celebrated "flying stovepipe". (Fig. 1). The forward motion of the ram-jet is used to gather air and this air is compressed by being slowed down from supersonic through the speed of sound to subsonic velocity in a diffuser, a section of duct that is first contracting and then expanding. Fuel burned in this compressed air imparts high velocity, and the resulting momentum of the exhaust jet drives the engine forward. Simple. No moving parts.

Fuel must be burned efficiently in an air stream flowing at as much as 300 feet per second, or more, and in mixtures near stoichiometric where the highest possible temperature is obtained. Because it has no mechanical compression, but depends only on ram, the ram-jet cannot tolerate much loss of its hard-won cycle pressure in the combustion process.

But you must do more than spray fuel into an air stream and light it to have a ram-jet combustor. Here is an air-duct with a window, a fuel spray, and a spark-gap for ignition. Note how easily the flame is blown out of the duct and at low air velocities. (Demonstrate by increasing velocity to blow-out). Introduction of a flame holder, such as this one (show), by creating turbulence and stagnant regions permits flame to be held to much higher air velocities. The gases are hot enough to melt this metal rod. (Demonstrate). Blow-out is possible, but at high air velocity. (Demonstrate by increasing velocity to blow-out.) For any given inlet conditions, a limited range of fuel-air ratios where operation is possible exists. (Demonstrate by decreasing fuel-air ratio to blow-out).

Right here is the problem: To maintain efficient combustion at velocities of as much as several hundred feet per second, principally so that high thrust can be obtained and over a range of fuel-air ratios so that operation over a range of thrusts and speeds is possible. This chart for a typical ram-jet combustor amplifies the situation (Fig. 2). Here is plotted, for a simulated flight Mach No. of 1, the velocity of the air at the combustor inlet at which combustion can be maintained for different fuel-air ratios. This curve is at sea level. In this area, combustion can be maintained, in this area, blow-out occurs. This curve represents the same phenomenon, but at 10,000 feet, instead of sea level. Note how much narrower the operable region is at altitude. By utilizing variable pressure and variable temperature air supplies and low pressure exhaust systems such as exist here at Cleveland ram-jet combustion can be studied over the entire speed-altitude spectrum of interest. The problem is to widen the operational limits for the ram-jet combustor, and especially to keep them from shrinking at altitude, by discovering and then applying appropriate design rules.

High combustion efficiency is also desired so that range will not be shortened by wasted fuel. This chart shows combustion efficiency plotted against fuel-air ratio at sea level and at 10,000 feet. Combustion efficiency decreases as altitude increases and as the air for combustion gets thinner and colder. Again the problem is that of learning design criterions for flame holders and fuel injectors that will result in high combustion efficiency. Here are some examples of the types of combustor that have been investigated. These are not necessarily the best. (Display).

One further ram-jet problem is created by the fact that enormous quantities of air are required for research and development of full scale combustors. Although this laboratory has sufficient air-handling capacity now to do research on full-scale ram-jets, industry does not have such facilities. Consequently, it is important to know whether design principles that work in small units will be applicable in large units. Scale and simulated are being investigated in 4, 8, 12, and 20-inch diameter combustors.

GAS-TURBINE COMBUSTION

Consider next combustion in a gas turbine - a turbojet, or a turboprop. The problems encountered are not all the same as for the ram-jet. True one must burn fuel efficiently in a fast-flowing air stream with low pressure loss. But in addition to this, combustor outlet temperatures in the turbine engine must not exceed value harmful to the turbine blades. This is achieved by rapidly mixing dilution air with the combustion gases. The combustor must be shorter than for the ram-jet to permit use of a short shaft to avoid torsional vibration. Fortunately, because compression is performed mechanically, more pressure loss is acceptable in a turbine engine combustor than in a ram-jet combustor. This pressure drop can be used to create turbulence which increases flame speed and shortens the flame. In general, all gas turbine combustors operate on the same principle. (Illustrate with Fig. 4). Some sort of liner or flame-tube is used to separate primary air that will burn the fuel from secondary air that will mix with the flames and cool it to temperatures tolerated by the turbine. Holes in the liner or can send the air stream where needed. This results in pressure loss, but is compensated for by resulting short combustors.

Here is a liner or flame tube similar to that of a turbojet combustor. It fits onto our fuel nozzle in the air duct, thus. Now note that stable combustion can be maintained to fairly high velocities. The outlet temperature only makes the metal rod glow dull red. (More demonstration here).

Initial research at this laboratory on gas turbine combustors was aimed at the finding the causes and cures for low-altitude operational limits and low combustion efficiency. This first phase of gas turbine combustor research has been successful to a large degree. Some of you will recall our summary of this work at last years inspection. However, another problem was aggravated in the process. That is the problem of maintaining a preferred temperature profile across the combustor outlet. A consideration of the stress along a turbine blade as a result of centrifugal force and the strength of the blade material at different temperatures leads to a preferred temperature distribution from the blade root to tip of this sort (Illustrate with figure 5(a). A temperature distribution of this sort frequently leads to blade failure. (Figure 5(b). This incorrect distribution of temperature is easily encountered. With incorrect distribution of temperature into the turbine, either the life of the engine is shortened, or its thrust will be lowered and its fuel consumption increased as a result of the engine being operated at lower temperatures to avoid turbine failure. Currently, effort is going toward finding design criterions that when applied will help to produce this correct distribution of temperature. This research comprises finding ways and means of admitting air through the wall of the flame tube or liner so that the air will mix well and produce the desired temperature pattern.

Also active at present is an investigation of fuel sprays and the role of fuel atomization in turbojet combustor performance. This chart illustrates and points up one of the problems. (Fig. 6). The chart is for a turbojet combustor operating at high altitudes, a severe condition for good combustion as is noted by the generally low values of combustion efficiency shown. Combustion efficiency is plotted against temperature rise through the combustor. High temperature rise is required for high rotor speeds. It is seen that a different fuel nozzle is required at each temperature rise if maximum efficiency is to be achieved. Note that at low temperature rise, highest efficiency is obtained with a small nozzle, whereas high temperature rise cannot even be obtained unless a larger fuel nozzle is used. This is only one of several significant findings to come from this study so far, but it is illustrative of the work.

TAIL-PIPE BURNING

Although we have discussed the primary combustion processes for ram-jets and for turbine engines, auxiliary combustion is of interest for special applications. For example, by burning fuel aft of the turbine of a conventional turbojet engine it is possible to obtain higher gas temperatures in the exhaust jet than can be withstood by the turbine. This increases the momentum of the exhaust jet and the thrust of the engine. Thrust augmentation by tail-pipe burning, as it is called, is useful for take-off, emergency bursts of power, and supersonic flight.

The combustion problem in tail-pipe burning is similar to that of the ram-jet - retention of flame in a high velocity gas stream. The problem differs from that of the ram-jet in that combustion occurs in an air stream that is hot, about 1200° F, and that has been altered in composition by partial consumption with fuel in the primary combustion process. The problem also differs in that any pressure loss in the tail-pipe due to combustion equipment becomes an appreciable loss in fuel economy for the turbojet engine when it is operating at cruising conditions without tail-pipe burning.

Operational characteristics and design factors of tail-pipe combustion systems are being studied in full scale engines operated in the altitude tanks of the laboratory. Again, by means of the variable pressure and temperature air supply and the exhaust system, a speed altitude spectrum can be covered in this research. This chart illustrates one of the problems encountered: blow-out at altitude. Blow-out limits are shown on a plot of altitude versus flight speed for one of the tail-pipe burners investigated. (Fig. 7). At altitudes and flight speeds above this line, the tail-pipe burner would blow-out; below the curve combustion was maintained. We are currently engaged in the project of increasing this altitude operational limit without causing any appreciable obstruction to the flow in the tail-pipe.

ROCKET COMBUSTION

The rocket engine (show model) operates on fuel and oxidant that are carried in tanks and thus requires no outside air. The fuel and oxidant are expected to react so vigorously upon mixing in the combustion space that no flame retaining devices are required, even for flow rates in a unit this size (1000 lbs) of as much as three quarts of propellant per second. Major problems are to select fuel and oxidant combinations that give large thrust per unit weight flow and volume flow and still have properties that permit their handling and use, to prevent failure of the engine from the thousands of degrees of temperature attained by the reaction products, and to achieve efficient combustion in the smallest possible unit.

NACA activity in rocket engine combustion embraces the major problems. Both theoretical and experimental research is conducted to evaluate propellant combinations. The combinations shown by thermochemical calculations and other considerations to be of high interest for rocket propulsion are rated experimentally in different small scale rocket engines of 100 and 1000 lbs thrust such as these (show). This chart of relative range versus the lbs of thrust per unit weight flow of propellant, shows the range now under investigation by NACA. Ranges of about 1200 miles are possible now with single-stage rockets.

In order to prevent destruction of the chamber and nozzle when high energy propellants are used, particularly in long duration runs, ways and means of cooling the inner walls of the rocket chamber and nozzle have been studied. So hot are rocket reactions that jacketing the engine is not always good enough. A promising line of attack investigated has been one which provides for cooling the walls with a film of inert liquid such as water stratified along the walls. Apparatus such as this rocket engine (show) has been used to evaluate this technique. Water from these jets flows along the inside walls of the chamber. Other apparatus is in use to determine quantitative data on the heat transfer phenomena with a liquid film interposed between the hot gases and the wall. Propellant injection (show) is also a factor, in that proper design can keep the very hottest parts of the reaction away from the walls.

Propellant injection is, as you might suspect, a big factor in combustion and in the length of engine required for good combustion efficiency. High speed photographs of the rocket combustion process taken through this transparent-walled engine (show) are revealing considerable information about the overall combustion process in the rocket.

FUNDAMENTALS

The solution of practical problems encountered in the application of the combustion process to aircraft engines requires the results and conclusions from basic and fundamental studies. In design considerations for combustion chambers, for example, it is of great value to know the effect of such factors as turbulence, mixing, inlet-air conditions, fuel atomization, etc., on combustion characteristics such as combustion stability, combustion efficiency, and flame speed. While research in actual combustion chambers such as just described to you will answer many of these questions, other studies, frequently conducted in apparatus not even closely resembling combustion chambers are required to contribute to an understanding of the entire mechanism of combustion.

The laboratory is conducting research on the chemistry of combustion in an effort to learn the rate controlling factors. The dynamics of fuel droplet evaporation is under intensive investigation, because research has shown that the fuel spray is a significant factor in combustion chamber performance. Additional research is aimed at learning how aerodynamic factors, such as turbulence and gas stream mixing influence flame propagation.

CONCLUSION

A synthesis of fundamental knowledge and the results of systematic empirical research should provide the information needed to employ the combustion process most effectively for flight propulsion.

Walter T. Olson, Chief,
Combustion Branch.

WTO:yet

Files

Cleveland, Ohio,

AUG 30 1949 100.64

From Lewis
To NACA Headquarters Attention: Mr. E. E. Miller. A86793

Subject: 1949 Inspection.

1. There are transmitted herewith revised copies of the talks to be presented by the speakers of the Compressor and Turbine Research Division at the 1949 Inspection. The talks have been revised in accordance with the comments of the NACA and of NACA Lewis personnel, and differ from the initial drafts in three main respects:

a. The results achieved since last year are brought out more clearly.
b. The blade cooling demonstration has been shifted to the experimental turbine cooling talk. It is felt that it logically belongs in the experimental rather than in the theoretical discussion.
c. A more detailed summary of all the material presented has been added at the conclusion of the turbine cooling talk.

2. The accompanying charts are illustrative of the material to be presented, although they are not revised to conform to Inspection illustration standards. The final charts are in preparation.

Edward R. Sharp

Edward R. Sharp,
Director.

IAJ:lje
WHH
OWS

Enclosure:
1. 1 copy of subject talks.

Mail & Files

URGENT

U. S. GOVERNMENT ESSENTIAL AIR MAIL

Cleveland, Ohio.

A86655

100.64

From Lewis
To NACA Headquarters - Attention: E. E. Miller

AUG 25 1949

Subject: 1949 Inspection, LFPL

SPECIAL DELIVERY

1. Enclosed are copies of revised talks on Stresses and Vibration and Automatic Controls which supersede the versions submitted to you on August 23. We would appreciate having your comments on these as soon as possible.

2. As per your request of this morning we are also enclosing the essence of Mr. Kemper's talk on the state of the art which is to be presented in the auditorium part of the program. Mr. Kemper's talk is in outline form with the lead sentences of each paragraph indicated. The talk will be amplified based on these sentences as soon as Mr. Kemper learns that the outline and subject matter are acceptable.

3. Revisions are actively in progress on the fuels, high temperature heat transfer, and supersonic propulsion talks and it is expected that revised copies of these talks will be forwarded to you early next week.

4. We want to know in advance that all of the material submitted will have suitable security clearance and will expect you to advise us in this matter as soon as possible.

Edward R. Sharp

Edward R. Sharp,
Director.

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CLEVELAND

WHH WHH:mlm
AS

Enclosures

cc: Mr. Hunter
XXXXXXXXXX
Mail & Files ✓

Files

A87957

100.64

September 27, 1949.

Mr. Karl J. Fairbanks,
Hotel Leamington,
3rd Ave., 10th and 11th Streets,
Minneapolis 2, Minnesota,

Dear Karl:

Thanks for your note of the 26th. I am sending Ralph a copy of our brochure as you suggested. It was nice to have been able to see you if only for a minute when you were here at the time of our Inspection. Those days are busy ones for me and I'm sorry I couldn't spend more time with you.

Kind regards,

Sincerely yours,

Edward R. Sharp

Edward R. Sharp,
Director.

Eastern
Daylight
Saving
Time

1949 INSPECTION
LEWIS FLIGHT PROPULSION LABORATORY
NACA CLEVELAND
September 20, 21, 22, 1949

9:00 am	Busses leave Cleveland Hotel for Laboratory
9:40	Registration in lobby of Administration Building; baggage checked in Room 111.
10:00	Opening Session for 1949 Inspection - Auditorium, Administration Building
10:30	Inspection of Laboratory in 8 groups designated by colors

	RED	WHITE	BLUE	GREEN	GOLD	BROWN	BUFF	GRAY
Compressor & Turbine Aerodynamics W-6, W-10 Eng. Res. Bldg.	*10:40	*10:40	11:50	11:50	**2:25	**2:25	3:35	3:35
Turbine Cooling W-2 Eng. Res. Bldg.	11:25	11:25	12:35	12:35	3:10	3:10	4:20 ***	4:20 ***
Heat Transfer; Turbojet Fuels CW-5 Eng. Res. Bldg.	11:50	12:25	10:40	11:15	3:35	4:10 ***	2:25	3:00
Rocket Research Rocket Component Test Laboratory	12:25	11:50	11:15	*10:40	4:10 ***	3:35	3:00	**2:25
Supersonic Propulsion Systems 8- x 6-ft. Supersonic Wind Tunnel	**2:25	3:35	3:35	**2:25	*10:40	11:50	11:50	*10:40
Inspection & Demonstration of 8- x 6-ft. SWT 8- x 6-ft. SWT	3:12	4:22 ***	4:22 ***	3:12	11:27	12:37	12:37	11:27
Turbojet Operation Problems Altitude Wind Tunnel Shop	3:35	**2:25	3:00	4:10 ***	11:50	*10:40	11:15	12:25
Materials, Stresses, and Vibrations CE-6 Eng. Res. Bldg.	4:10 ***	3:00	**2:25	3:35	12:25	11:15	*10:40	11:50

*Start first demonstration **Resume demonstrations after luncheon

═══ Luncheon in Auditorium begins at 1:00 ***Busses go to picnic area and leave for downtown starting 5:00pm EDT

NACA - Lewis

Cleveland, Ohio.
September 19, 1949.

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	Barnett	Jonas
CE-6	Deutsch*	Ault*
	Manson	Brown
AWT Shop	Fleming*	Dr. Gibbons*
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Director.

WHH:mlm

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Edward R. Sharp

Edward R. Sharp,
Director.

WHH:mlm

Annual Inspection Sept. 1948

PROGRAM

1 Auditorium

Welcome and Introduction

2. Compressor Laboratory, Compressor and Turbine Research Wing

Compressor research

Centrifugal
Subsonic axial flow
Supersonic axial flow

3. Turbine Laboratory, Compressor and Turbine research Wing

Turbine research

Cooling
Aerodynamics

4. Jet Propulsion Static Laboratory

Materials and stresses research

High-temperature materials
Turbine disks

5. Combustion Laboratory, Engine Research Building

Combustion research

6. Fuels and Lubricants Building

Fuels research

7. Engine Propeller Research Building

Engine control research

8. Altitude Wind Tunnel

Altitude operational problems
Turbojet icing-research
Thrust-augmentation research
Altitude Wind Tunnel

9. Eight-by-Six-Foot Supersonic Wind Tunnel
Supersonic ram jets
Supersonic boundary-layer study
Eight-by-Six-Foot Supersonic Wind Tunnel

1. - INTRODUCTION

The National Advisory Committee for Aeronautics, at its three principal laboratories, is engaged in the fundamental study of the problems of flight. It is the function of the Lewis Flight Propulsion Laboratory to carry out one important phase of this over-all research program, that of solving the problems associated with the propulsion of aircraft. All phases of propulsion are included in this research program.

Because current aviation problems are primarily concerned with high-speed aircraft, the emphasis in propulsion research is on systems that are capable of producing high power in a compact, light-weight package, such as the ram-jet, turbojet, turbine-propeller, and rocket engines. In the development of these powerful propulsion units, which are continually required to operate at higher temperatures and faster speeds, the problems are many and varied.

For example, the nucleus of the gas-turbine engine is formed by the compressor, the turbine, and the combustor; the success of the over-all power plant is dependent on the proper operation of each of these components. The aerodynamics of flow through compressors and turbines is particularly being investigated. Inasmuch as turbines are subjected to intense heat and high rotating stresses, methods of developing turbines and turbine materials that can withstand high temperatures are also under investigation.

The generation of hot gases is the primary function of gas-turbine and rocket engines; therefore problems of combustion require careful study. An associated problem is that of obtaining fuels and propellants that burn efficiently and deliver maximum heat energy.

The use of these various types of engine necessitates the solution of a variety of control and operational problems. Because supersonic flight gives rise to additional problems unique to this speed regime, the supersonic operation of propulsion systems is also under investigation.

The propulsion-system research being conducted at the Lewis laboratory is closely coordinated with the aerodynamic research being conducted at the Langley and Ames laboratories, to form the integrated NACA program of flight research. This booklet briefly relates the research trends that are being presented at this 1948 Inspection of the Lewis Flight Propulsion Laboratory.

2. - COMPRESSOR RESEARCH

Analysis of gas-turbine power plants has shown that the compressor must take in large quantities of air and efficiently compress it to the required density in order to produce high engine powers. The compressor must also be reliable, compact, and easily manufactured. From the consideration of high speed aircraft, these characteristics must be obtained in a unit having a minimum frontal area.

The two compressor types in general use today are the centrifugal compressor and the axial-flow compressor. The centrifugal type of compressor, in which the air is compressed by centrifugal action, has the advantages of simplicity, reliability, ease of manufacture, and high pressure ratio per stage, and the axial-flow compressor has the advantages of high flow capacity and efficiency.

The development of the centrifugal compressor has been somewhat handicapped by a lack of mathematical theory and fundamental data on the nature of flow through the complex passages of the impeller. The NACA is currently attempting to supply this information by actually making measurements of flow within the rotating passages of a 48-inch diameter centrifugal impeller. In conjunction with this investigation, a mathematical method of theoretically determining the flow characteristics in the impeller passages has been developed. The correlation of these two studies is expected to point out the source of losses and indicate the design modifications required to improve both the efficiency and flow capacity of this type of compressor.

The axial-flow compressor is essentially a series of rotating airfoils. When high over-all pressure ratios are desired, a large number of stages are required. Research on this type of compressor is therefore directed at increasing the pressure ratio per stage and thus obtaining a more compact and less expensive compressor of high air flow capacity and high efficiency. Theoretical studies of airfoil blade sections capable of producing high pressure ratios are being made. Experimental studies have indicated that a pressure rise per stage of the order of two to three times that of conventional designs can be obtained.

Further gains in pressure ratio per stage are offered, however, by the supersonic type axial-flow compressor. This type of compressor utilizes the same shock waves to compress the air that have proved a limitation to the speed of aircraft. Supersonic velocities exist relative to the rotating blades, with a confined shock wave occurring within the blades. Because the velocity of sound does not provide a limitation, extremely high pressure ratios may be realized. The successful development of efficient high pressure ratio stages will mean that current multistage axial-flow compressors, which are large and costly to manufacture, can be replaced by compact and relatively inexpensive compressors.

ILLUSTRATIONS

1. Pictorial sketch of 48-inch centrifugal compressor installation. Legend - "The 48-inch centrifugal compressor provides a

means of obtaining detailed measurements of flow characteristics in the rotating impeller."

2. Pictorial sketch of supersonic compressor with schematic diagram of flow through the blading. Legend - "The supersonic type of axial-flow compressor utilizes the shock phenomenon to obtain compression of the air."

3. - TURBINE RESEARCH

In current gas turbine engines, the temperature limitations imposed by turblades and turbine parts permits only one-third of the air that passes through the engine to be burned, the remainder being used to dilute and moderate the hot mixture. Analysis of the effects of various parameters on the power output of the turbine-propeller-type engine has shown that very large gains can be obtained by increasing the turbine inlet temperature, particularly if the pressure ratio of the unit is also increased. Because the temperature attainable in gas turbines using currently available fuels is of the order of 3500° F, methods of building turbines that can withstand these temperatures are at present an urgent objective of NACA study. Considerable effort, therefore, has been expended to develop methods of turbine cooling. Much valuable information has been obtained from an analytical study of various methods of air or liquid cooling. Results obtained on liquid-cooled aluminum research turbines, which have been successfully operated at gas temperatures over 2000° F, indicate that this cooling of turbines not only offers considerable promise for attaining high-temperature operation but also offers promise for using nonstrategic materials for turbines.

In applying turbine cooling to blades, it may be necessary to use shapes quite different than those now in use, so that cooling passages can be accommodated. In order to utilize high gas temperatures efficiently, it will also be necessary to increase the pressure ratio per stage. These modifications must be realized, however, without impairing the efficiency and flow capacity of turbines. The NACA is conducting extensive research on the nature of flow in turbine blades. One of the research methods in use utilizes cold-air turbines for the investigation of various turbine design parameters. A two-dimensional cascade tunnel provides a further facility for obtaining fundamental data on the flow around turbine blades.

The realization of the objectives of this research will enable turbines of high power to be manufactured from readily available and easily machined materials.

Illustrations

1. Bar graph showing increase in power obtainable with increased gas temperatures. Pressure ratios and specific fuel consumptions are given. Legend - "Power output of the turbine-propeller engine can be substantially improved by increasing turbine inlet temperatures."

2. Pictorial view of two-dimensional cascade tunnel. Legend - "Two-dimensional cascade tunnel used to investigate the flow around turbine blades."

4. - HIGH-TEMPERATURE MATERIALS

Substantial increases in operating temperatures, which are required for improving the power output and decreasing the specific weight of gas turbines, can be achieved by obtaining materials for turbine blades that can operate successfully at these high temperatures. One phase of the research effort to improve the high-temperature characteristics of turbine-blade materials has included a thorough study of materials of very high melting points, including refractory metals, ceramics, and ceramic-metal mixtures (ceramals). Of these, ceramals seem to offer the most promise for future use.

The major load on a turbine blade rotating at high speed is the centrifugal force. Because the ability to withstand these extreme rotative stresses depends on both the strength and the density of the material, turbine materials are therefore evaluated by the strength-to-weight ratio. A promising ceramal investigated at this laboratory showed a strength-to-weight ratio at 1800° F that was 1.5 times as high as that of a high-temperature alloy of metal in wide current use. The ceramal blade has the additional advantage that the raw materials are domestically available and low in cost, in contrast to the strategically critical, high-cost metal alloys.

As the starting motor revolves the engine, the turbine blades move in a stream of cool air. When the fuel is injected and ignited, the blades are suddenly bathed in a gas stream several hundred degrees hotter than the normal operating temperature. The outer surface heats rapidly, expanding with respect to the still cool interior, momentarily creating severe stresses. This condition has been defined as thermal shock. A good ceramic, at 1800° F, has a strength-to-weight ratio twice that of a representative high-temperature alloy, but has a low resistance to thermal shock, such as to be of little immediate value for turbine blades. Addition of metal to the ceramic, producing a ceramal, greatly increased the thermal shock resistance.

The high-temperature parts of a gas-turbine engine are always surrounded by gas containing a great deal of oxygen. The combination of this oxygen with turbine-blade material may produce changes in shape or result in a new material of inferior properties. The solution to this oxidation problem therefore requires the choice of materials that either resist oxidation or that protect themselves by confining the oxidation to the surface. Ceramal compositions have been investigated that have excellent oxidation resistance up to 2400° F. The problem remains, however, of finding suitable ceramal compositions that combine good oxidation resistance with high strength-to-weight ratio and good thermal shock resistance.

Illustrations

1. Figure showing variation in strength-to-weight ratio and thermal shock resistance with percentage of metal in the ceramal. Legend - "The resistance to thermal shock and the strength-to-weight ratio of ceramals, which are major factors in turbine operation, are dependent upon the amount of metal present in the ceramal."

4. - TURBINE DISKS

At its rated take-off speed, the wheel of a typical turbine has more energy than the average automobile contains at a forward speed of 100 miles per hour. Fragments of such a wheel burst in a spin pit at about twice rated speed have been known to penetrate more than 8 inches of steel. Because of the obvious danger to pilot and aircraft, insurance against failure of the wheel in flight is one of the prime objectives in turbine design.

Whereas design analysis of rotating wheels is an integral part of present engineering work, the disk of the gas turbine presents new problems. The tendency of expansion of the hot rim relative to the cooler central region introduces thermal stresses that combine with the centrifugal stresses of rotation, producing thereby a complex total stress system. Uncertainties as to the magnitude of the thermal stresses and their importance relative to the centrifugal stresses have led, in many cases, to overdesign, making the disk an unnecessarily heavy component. Before optimum design can be achieved, a number of basic questions must be answered.

First, the relative importance of the various mechanical properties of the disk material must be evaluated. For example, ductility can usually be achieved only at a sacrifice of tensile strength. The insistence on an unnecessarily high ductility may therefore result in a weaker disk than if the significance of ductility and tensile strength were properly balanced. The relative importance of other high-temperature properties must also be determined.

Second, the thermal stresses must be better understood. These stresses, which are part of an internally balanced system, may differ in their effect from the centrifugal stresses, which are developed to resist an effectively external force. The theory of thermal stresses in rotating disks must be enlarged to include effects of plastic flow, and experiments must be conducted to determine the effects of these stresses on the rupture strength of disks. Special attention must be directed to the rim, which operates at high temperatures and stresses.

Considerable experimentation has already been conducted to evaluate ductility and tensile strength. For the thermal-stress problem, a large spin pit has been built. Disks can be rotated at any desired speed while heated to any desired temperature gradient. In this manner, the centrifugal and thermal stresses can independently be adjusted to arbitrary values and their relative importance in causing bursting can be determined.

Illustrations

1. Chart showing stress system in turbine disks. Legend - "Turbine disks are subjected to centrifugal stresses of rotation and to thermal stresses resulting from temperature gradients, resulting in a complex total stress system."

2. Photograph of burst turbine disk. Legend - "Results of bursting a turbine disk in the spin pit."

5. - COMBUSTION RESEARCH

The major problem of engine combustion is to release efficiently heat energy from the fuel in a small volume and in a short period of time. Important attendant problems are a low pressure loss, light weight and durable combustion equipment; flexibility of operation (especially at "off-design" points), and, when a turbine is employed, proper distribution of temperature across the combustor-outlet area to avoid subjecting the turbine blading to harmful hot zones.

Research on the ram jet at conditions simulating different flight speeds and altitudes has shown that the ram-jet combustor has a limited range of operation. In order to widen the operable region of ram-jet combustors, current research is aimed at learning basic design principles for flame holders and fuel injectors.

The combustion problem for the gas turbine engine differs from that for the ram jet in that not only must fuel be burned efficiently in a fast flowing air stream and with low pressure loss, but combustor-outlet temperatures in the turbine engine must not exceed values harmful to the turbine.

Early investigations by the NACA on the operating characteristics of a number of turbojet combustors disclosed that combustion efficiency decreased with altitude, and that turbojets had a combustion-imposed altitude operational limit. Research revealed the causes of these phenomena and further systematic research effected satisfactory solutions. But raising the ceiling imposed by combustion aggravated another problem, that of combustor-outlet temperature distribution. It is essential to the life of the turbine blading that hot spots on the blading not be caused by faulty distribution of temperature from the combustor. Currently, research is being directed at ways and means of achieving preferred temperature profiles from gas-turbine combustors.

The rocket engine operates on fuel and oxidant that are carried in tanks and thus requires no outside air. The fuel and oxidant react so vigorously upon mixing in the combustion space that no flame-retaining devices are required. The major problems for the rocket engine are to select fuel-and-oxidant combinations that give large thrust per unit weight flow and volume flow and still have properties that permit their handling and use, to prevent failure of the engine from the thousands of degrees of temperature attained by the reaction products, and to achieve efficient combustion in the smallest possible unit.

The solution of practical problems encountered in the application of the combustion process to aircraft engines requires the results and conclusions from basic and fundamental studies. The NACA is conducting research on the chemistry of combustion in an effort to evaluate the factors that control the combustion rate. The dynamics of fuel-droplet evaporation is under intensive investigation, because research has shown that the fuel spray is a significant factor in combustion-chamber performance. Additional research is aimed at learning how aerodynamic factors, such as turbulence and gas-stream mixing, influence flame propagation.

Illustrations

1. Curve showing operable range of ram-jet combustors as a function of inlet-air velocity and fuel-air ratio. Legend — "In the ram-jet combustor, a range of fuel-air ratios and inlet-air velocities exists where the combustor will operate; outside of this range, no operation is possible."

2. Photographs of combustion in three rocket combustors. Legend — "High-speed photographs of the rocket-combustion process, taken through a transparent-walled engine, are revealing considerable information about the combustion process in the rocket."

6. - FUELS RESEARCH

The first turbojet engines developed in this country were designed to operate on high-octane aviation gasoline or on a special kerosene-type fuel that can be produced only in limited quantity.

The projected use of turbojet, turbine-propeller and ram-jet aircraft in large numbers for both military and commercial applications has indicated the need for a jet fuel that will be available in large quantities. Representatives of the petroleum industry have indicated the types of fuel that can be made available in the maximum quantity.

The Air Force, the Buereau of Aeronautics, Department of the Navy, and the NACA have undertaken the task of evaluating the performance of such fuels in jet engines. The NACA is evaluating the fuels on the basis of altitude operational limits, carbon deposits, combustion efficiency at altitude, starting at both sea level and altitude, and other operating characteristics. On the basis of these evaluations, it will be possible to establish what types of fuel can be used in current engines and to estimate what quantities of fuel will be available for current engines. It will also be possible to determine what changes have to be made in current engines so that fuels available in the greatest quantity can be used.

A second aspect of the problem is to determine which components of hydrocarbon fuels give the best performance in jet engines. It is a well-known fact that fuels derived from petroleum contain hundreds of individual hydrocarbons. It is important to know the performance of the individual components in jet engines. In reciprocating engines, the individual hydrocarbons vary in their knock-limited performance from below zero to above 350 and research to date indicates that marked differences also exist in their performance in jet engines.

A third problem that is receiving continued research emphasis at the NACA is the matter of fuels to extend the flight range of jet aircraft. Such airplanes are streamlined for high-speed operation and the space for fuel storage is very limited. It is therefore, important to use fuels that will deliver the maximum heat energy per unit volume. The NACA is investigating hydrocarbon fuels that will deliver 30 percent more energy per unit volume than aviation gasoline. Investigations are also underway to utilize solid metals as aircraft fuels. If aluminum metal could be utilized as an aircraft fuel, it would deliver over 2.5 times as much heat energy per unit volume as aviation gasoline and other metals could deliver almost 4 times as much gasoline.

<u>Illustrations</u>

1. Bar graph showing amount of fuel available from a barrel of crude oil, for present and proposed fuel. Legend - "Only a very small quantity of current turbojet fuel is available from a barrel of crude oil; whereas almost half of a barrel of crude oil could be used as a jet fuel under the proposed fuel specification."

2. Bar graph showing comparative thrust for gasoline, aluminum, and beryllium. Legend - "The use of solid metals for aircraft fuels will result in an appreciable increase in thrust per unit cross-sectional combustor area over that available from aviation gasoline."

7. - ENGINE CONTROLS RESEARCH

The successful operation of gas-turbine engines, even with the attainment of desired component performance, is dependent on the engine-control system. In general, it is the function of an engine-control system to obtain optimum engine performance and to maintain engine operation within safe and stable operating limits. This general control criterion is difficult to achieve for controls systems applied to gas-turbine engines. Complete exploitation of the engine potentialities may be attained only through accurate adherence to finite limits of both engine speed and temperature, and response of the control system must be consistent and reliable for all the varying conditions of operation.

Successful application of controls to the gas-turbine engine requires a thorough knowledge of engine and control-system transient characteristics to enable the designer to match the response of both engine and control system. Matching of the response of engine and control system is essential, as it may determine such important performance characteristics as acceleration and deceleration rates. Maximum stresses in the reduction gearing of turbine-propeller engines, which may ultimately dictate the size and weight of this important component, will result from improper matching of engine and control-system response characteristics. Large torque fluctuations and dangerous overspeeding of the compressor and turbine components may be expected under certain conditions of operation when engine and control system are improperly matched.

Analytical and experimental control studies are being conducted at the NACA to determine the control system and necessary response characteristics required for each gas-turbine-engine type. Various stability and response criteria are being studied to enable control designers to match and evaluate response characteristics of any combination of engine and control system. In order to supplement bench and full-scale-engine test facilities, an electronic engine and control-system simulator will be used to study response characteristics of any combination of engine and control system.

Illustrations

1. Curve showing engine speed variation as a function of time, with proper and improper response curves. Legend - "Improper matching of the response of engine and control systems results in undesirable oscillations and instability of engine speed."

2. Schematic diagram showing analogy between operation of an engine and a spring-and-weight system. Legend - "The response of a controlled gas-turbine engine can be interpreted from the analogous response of a damped spring-and-weight system.

8. - GAS-TURBINE OPERATIONAL PROBLEMS

The use of gas-turbine engines for aircraft propulsion has created a new set of engine operational problems, most of which have been investigated in the altitude wind tunnel. For example, in high altitude flight, the danger of combustion blow-out has been found to fix the minimum rotational speed at which turbojet engines will operate and the allowable turbine temperature has been found to limit the maximum rotational speed. Another problem results from the fact that the inertia of large turbojet engines is so great that the engine can not respond quickly to throttle changes, particularly at high altitude. Because the ability to accelerate rapidly is essential for military applications, variable-area exhaust nozzles have been developed to provide a means of quickly increasing the engine thrust.

It has been found that multiengine jet airplanes will cruise at best economy if a few of the engines are operated near maximum thrust and the remainder are shut off. Under these conditions, it is important to prevent air from flowing through these idle engines because windmilling of the engine causes an increase in drag. Windmilling is required to start the engines again, however, and this gives rise to an additional problem. At high altitudes, the engine cannot be started again unless the airplane is flying at a very high speed.

The vulnerability of the turbojet engine to icing conditions is apparent from the rapid increase in tail-pipe temperature, the increase in specific fuel consumption, and the decrease in thrust that occurs when icing is encountered. Laboratory and flight studies of the icing problems have resulted in three methods of providing the ice protection that is essential to the safe operation of this type of engine.

The first method provides for surface heating of all inlet components exposed to icing either by electric heaters or by hot gas. The second method involves the bleeding of hot gas from the rear of the engine into the inlet, and it is now possible to design a system with good anti-icing characteristics using a minimum of bleedback. The third method removes water droplets from the inlet air by inertia separation; experimental investigations have provided sufficient data for efficient design. The most economical ice protection system for a specific aircraft installation may well incorporate combinations of these methods.

Another significant gas-turbine operational problem is that of increasing engine thrust for take-off and for short bursts of power at altitude. The injection and burning of additional fuel in the tail pipe of a turbojet engine is one attractive means of obtaining this added thrust. In this process, which is variously called afterburning, tail-pipe burning, or exhaust reheat, the exhaust gases issue from the jet nozzle at higher velocities and higher temperatures than can be tolerated in turbine-limited operation of the conventional engine. Afterburning can increase the engine thrust by as much as 35 percent for take-off and 60 percent at flight speeds of 500 miles per hour. This increased thrust, however, entails a loss in fuel economy. Research is in progress at the NACA to solve the problems of fuel control to maintain safe temperatures and good economy, the determination of optimum tail-pipe size, and the reduction of the losses in power due to the afterburner when it is not in operation.

Illustrations

1. Chart showing the speeds required for a windmilling start at various altitudes. Legend - "A turbojet engine using an axial-flow compressor requires very high flight speeds for a windmilling start at high altitudes."

2. Chart showing increase in thrust and decrease in take-off length resulting from the use of tail-pipe burning. Legend - "The use of tail-pipe burning improves the thrust and take-off characteristics of turbojet-powered aircraft."

9. - SUPERSONIC RAM JETS AND FLIGHT PROBLEMS

The ram jet possesses operating characteristics that make it ideal for flight at supersonic speeds. Compression of the air is accomplished in the ram jet without any moving parts by simply scooping in the air and utilizing the energy of flight to compress the air. Fuel is then injected and burned, and the resulting hot gases are expelled rearward to provide forward thrust.

Shock waves that occur ahead of the inlet of the ram jet cause serious energy losses and reduced engine power. In an attempt to reduce these losses, various improved inlet designs have been studied by the NACA. It has been shown that this energy loss may be minimized by appropriate design and that pressure recoveries within a few percent of the theoretical maximum are possible.

More recent investigations of complete ram jets operating in wind tunnels at supersonic speeds gave performance considerably below theoretical limits. Sensitive pressure pick-ups and high-speed photographs of the inlet disclosed a fluctuating pressure and a shock wave that oscillated at extremely high frequency between its design position and a position ahead of the inlet, thus accounting for the performance losses. The instability of combustion with ordinary fuels and acoustical resonance or "organ-pipe" frequency were found to be factors causing this shock oscillation. The NACA is continuing the study of the effect of these related problems of acoustics and combustion stability on the flow into the ram-jet inlets of varying geometric proportions.

Much larger ram jets have been studied at supersonic speeds with a ducted inlet in the altitude wind tunnel and in free flight with a series of ram jets launched from an airplane at high altitude. Results have shown the effect of ram-jet geometry on net thrust as speed is increased in the falling trajectory. This research on ram jets will be continued, with much of the work to be performed in the new eight-by-six-foot supersonic wind tunnel soon to be placed in operation. This new tunnel was built with the assistance of the Department of the Navy and marks a major addition to the supersonic research facilities of this country.

The viscosity or friction of air results in the build-up of a thin layer of stagnant air called boundary layer on air flow surfaces, a factor that complicates the solution of the aerodynamics of supersonic flight. Viscosity affects the separation of air flow from surfaces, the transition from smooth flow to turbulent flow in the boundary layer, the heat transfer at the surface, and the interaction of shock with the boundary layer. The growth of boundary layer on both the wind-tunnel walls and model surfaces complicates the interpretation of experimental data obtained from supersonic investigations. Special research techniques are being employed by the NACA in new facilities designed for the study of boundary-layer and heat-transfer problems as they relate to supersonic-wind-tunnel and propulsion-system design.

Illustrations

1. Pictorial sketch showing installation of a ram jet in the supersonic tunnel. Legend - "The installation of ram jets in specially equipped supersonic tunnels permits detailed study of operation."

2. Curve showing the falling off of ram-jet recovery when fuel is burned. Sketches showing the shock picture with and without burning are superimposed. Legend - "The burning of ordinary fuels in the supersonic ram jet causes the shock wave to pulsate between its design position and a position ahead of the inlet, resulting serious losses in pressure recovery."

3. The eight-by-six-foot supersonic wind tunnel.