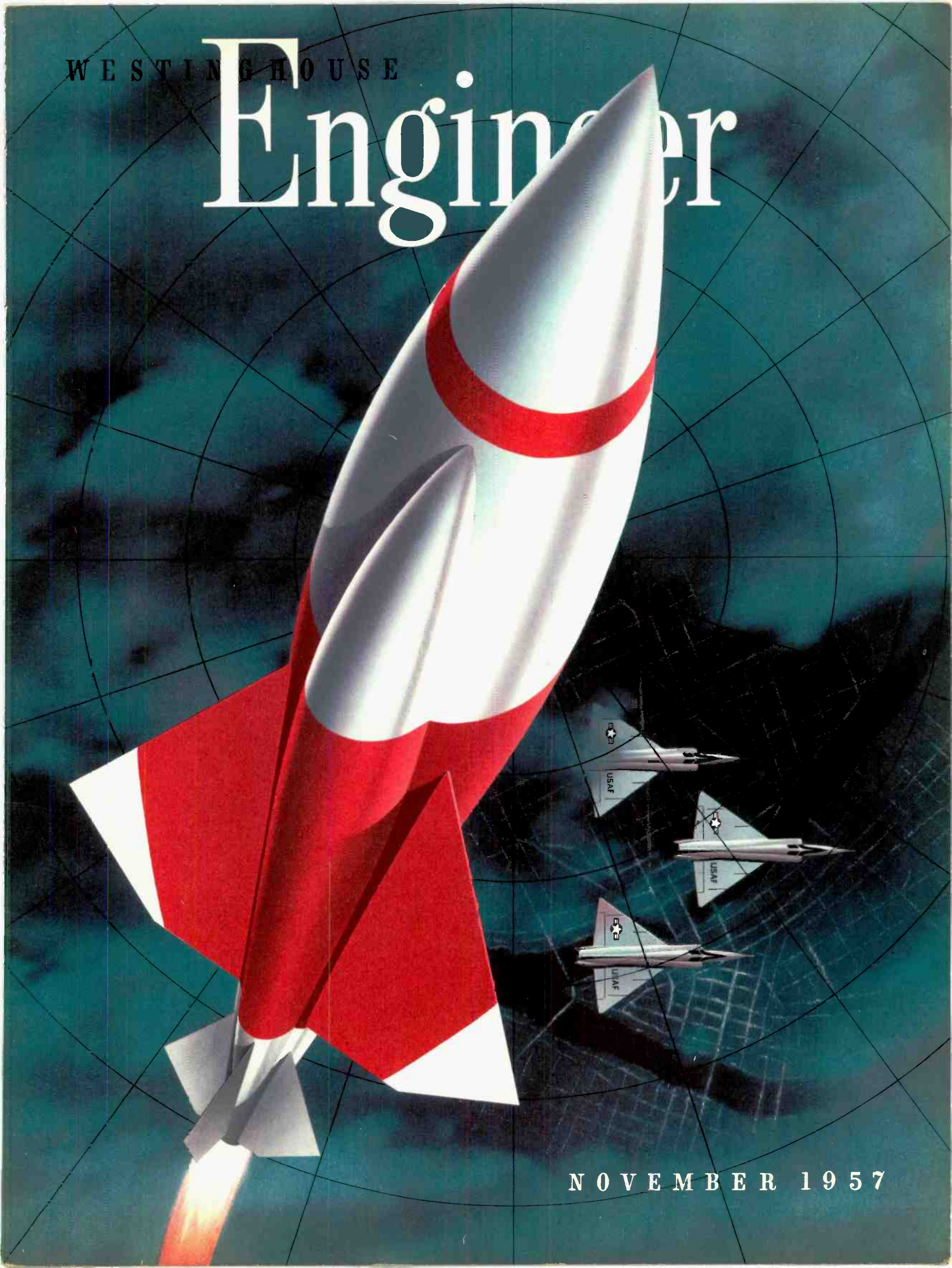
WESTINGHOUSE

Engineer



NOVEMBER 1957

THE ROLE OF INDUSTRY IN DEFENSE

INDUSTRY has always played an essential role in national defense. Wars cannot be won without the tools of warfare. Today, however, industry's role in national defense has changed drastically.

In every war to date, the major part of industry's participation in military affairs has been to *help win a war* already in progress. Today, industry's role is to *help prevent a war*. This has brought about many changes in the approach to the problem, and produced some dramatic results. Among other things, emphasis in defense has shifted from manufacturing to research and development.

An important new fact is that industry is more and more frequently called upon to develop a complete system, rather than a product as such. A guided missile, for example, is not merely a self-propelled bullet. It must be launched accurately, guided to a target; it may even have to "think" for itself. The development of a guided missile thus becomes the problem of creating a complete *weapons system*. The same holds true for many other military projects.

As a preface to this special issue about military aviation, a review of industry's role in defense is appropriate. For one thing, the changing pattern of defense means that defense work must now be conducted as a business, rather than as an interruption of business, as in the past. One obvious question is: Why does an industrial company undertake defense work? The basic reasons are simple, and probably obvious. One is to make a profit, which is basic to entering any business; another is that industry has an obligation to contribute its know-how to the defense of the country.

A second question is: What does industry contribute to national defense? The most apparent thing is the end product—an airplane, a tank, or a ship. But, of course, the public does not see many developments, and others are too complex to be generally appreciated.

Three things that industry contributes are often overlooked. These are technical experience and know-how, highly trained manpower, and efficient organization. The influence of these three factors on successful accomplishment of a project cannot be overestimated.

Experience is a frequently misunderstood factor. Often, military projects are considered so different from normal industrial projects that the two bear little relationship. Nothing could be further from the truth. In fact, without the available background of experience in industrial fields, defense engineering would be virtually impossible. And in a large, diversified organization such as Westinghouse, experience in nearly every field is relatively easy to find. Somewhere in such an organization is at least one man with knowledge of a specific field, and some background on any subject.

Perhaps the extent of industry's contribution to defense and the problems involved can best be realized by considering a specific example. Suppose, for example, an industrial company is given a contract to develop a guided missile. As mentioned, this is basically the problem of developing a complete *system*. It approximates the task faced in developing a complex industrial system, but with important differences. Like its industrial counterpart, the missile system requires work in many varied technical areas, although the areas themselves are quite different. Supersonic aerodynamics, structural and mechanical design, heat transfer, propulsion, guidance and control, explosives and detonation, and all the ramifications of each are involved in missile design.

With the continued urgency of most defense projects, another characteristic comes into play. This is the necessity for parallel advances in many different technical fields. The newest discoveries of pure science must be put to practical use quickly and efficiently, and critical areas of applied research must be judiciously planned. In many cases *invention must be scheduled*—a dangerous but necessary gamble.

Interwoven with these problems is a third characteristic, the complex interrelationships among all technical problems and decisions. A missile has a single purpose, and every device, every element of the missile system, contributes to that ultimate purpose. Therefore every decision and every change made on any one element of the system must be weighed in respect to every other part of the system.

Development of a missile system requires organization along system lines. With the ever-increasing complexity of weapons systems, the systems organization must contain experts in many different fields. But this in itself is not enough; it must also be able to draw upon experience from industry's storehouse.

This issue of the *Westinghouse* ENGINEER, devoted exclusively to various aspects of military aviation, suggests some of the problems and some of the solutions involved in defense work. It is not meant to be an all-inclusive survey of military aviation; also, of course, some of the best stories are cloaked in military secrecy, as they must be. However, we hope that this issue will suggest some of the vast problems being tackled by American industry, as well as some of the problems that lie ahead. Westinghouse is proud of the part it plays in national defense, and looks forward to other challenging roles in the future.

L. E. Lynde

L. E. LYNDE
VICE PRESIDENT
DEFENSE PRODUCTS

COVER DESIGN: Is it a plane or a missile? As aircraft fly higher and faster, and missile designs become more and more sophisticated, the two begin to show more than just a family resemblance. Herewith, cover artist Dick Marsh's interpretation of the synthesis.

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NEW AGE OF FLIGHT

Military aviation is in the midst of a fantastic period of development. Urged on by the world political situation, and supported by a multibillion dollar budget and some of the best technical brains in the world, the aviation industry has performed near miracles in the past few decades.

But as it grows in achievement, military aviation is becoming increasingly complex. In the beginning, military aviation was a plane and a pilot. In 1907 the Wright brothers were awarded a contract to construct the first powered aircraft for the Signal Corps, at a total cost of $25 000. The following year that plane set a world endurance record by staying aloft a few minutes more than an hour. The reception was something less than enthusiastic, but military aviation was here to stay.

In the decades that have followed, development has been in spurts, with the world situation dictating the time, effort, and money put into development. For most of the past two decades, however, world tension has dictated a constant intense effort in military aviation, and the results have been nothing short of spectacular.

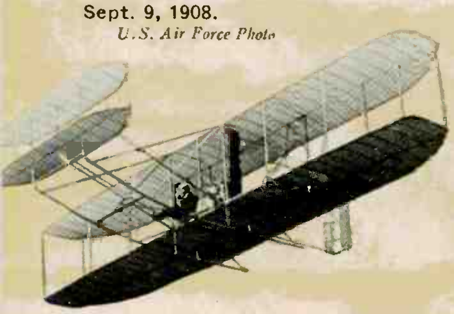
The Air Force's B-58 *Hustler,* with detachable pod under its fuselage.

changing concepts

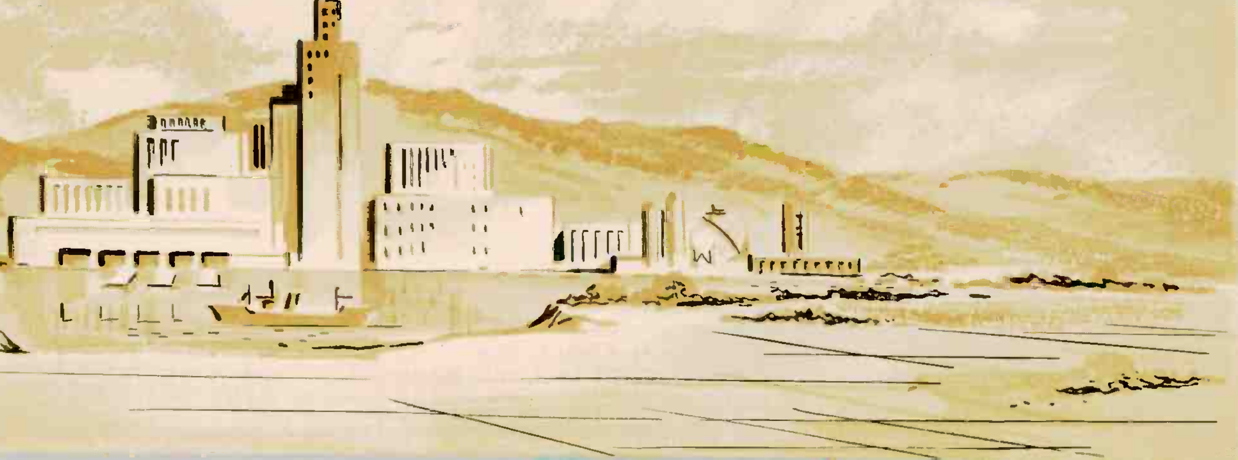
The simple concept of a plane as an airframe and an engine is no longer useful; today's plane is not a device, but a complete and intricate system. In addition to the airframe and the engine, the modern airplane is a complex of equipment designed to make it operate better, to enable it to get to its target and back, to enable it to find its target and hit it, to enable it to fly with a minimum crew and with minimum attention, and to help it defend itself against attacks from any quarter.

As airplanes have increased in speed, and complicated electronic equipment brought to bear to control them, they have become marvels of accuracy and efficiency in carrying out their assigned mission. But for every offense there is a defense, and this part of aviation has grown apace. The problems, however, are complex. Modern planes for example, can literally hide behind the curvature of the earth, and thus escape radar detection until they are within a few minutes—at supersonic speeds—from their target. This is typical of the problems that air defense faces, but by no means the most difficult. Thus the whole picture of military aviation

This article is based on information supplied by P. Conley of the Westinghouse Baltimore Divisions, and H. A. Gunther and A. F. Young of the Westinghouse Air Arm Division.



Orville Wright in a Wright type A airplane at Fort Myer, Virginia, Sept. 9, 1908.
U.S. Air Force Photo



COMPARISON OF WORLD WAR II AND MODERN BOMBERS

B-17 *Flying Fortress*
MAXIMUM SPEED (mph)—295 (at 30 000 feet); **ENGINES**—4 (reciprocating); **ENGINE POWER** (each)—1200 hp; **WING SPAN** (approximately)—104 feet; **LENGTH** (approximately)—75 feet; **WEIGHT**—55 000 pounds (loaded), 32 720 pounds (empty); **CREW**—10; **COST**—$190 000; **ENGINEERING MANHOURS**—200 000.

B-52 *Stratofortress*
MAXIMUM SPEED (mph)—650 plus; **ENGINES**—8 (jet); **ENGINE POWER** (each)—10 000 pounds thrust; **WING SPAN** (approximately)—185 feet; **LENGTH** (approximately)—157 feet; **WEIGHT**—400 000 (gross); **CREW**—6; **COST**—$7 million.

B-58 *Hustler*
MAXIMUM SPEED (mph)—supersonic; **ENGINES**—4 (jet); **WING SPAN** (approximately)—55 feet; **LENGTH** (approximately)—95 feet; **CREW**—3; **ENGINEERING MANHOURS**—9.3 million.

is a picture of moves and countermoves, by offense and defense, in addition to strict attention to maximum performance of individual units.

The increasingly complex situation has given rise to the consideration of systems rather than components. An airplane is no longer merely a vehicle for carrying bombs or guns—it is a complete weapon, or more exactly a weapons system. Further, it is itself part of a vast attack or defense system. Defense against enemy aircraft likewise is no longer a matter of a series of weapons, but a vast, interlocked network of devices and equipment to detect and destroy an aggressor.

These concepts are so intricate, so difficult, that they are full of problems that require the highest degree of imagination. And they are so vast that they require the brains and manufacturing skills of scores of companies, all working toward a common end, but with totally different problems. Consider then, some of the background of modern aviation.

aviation in the modern era

Today, the world is experiencing a period of accelerated technological advancement caused, not by war itself, but by the threat of immediate attack on the heartland of the nations by any aggressor. Unlike previous conflicts, any future conflict will be fought with the forces *in being at that time.* There is no time between a peace force and a war force. Oceans are no longer bulwarks of defense in time and depth. The ever-expanding third dimension is here to stay.

No longer are the new devices of aviation emerging from the bicycle shops and the basement tool benches, but are the products of well-equipped and expertly staffed research and development laboratories and highly efficient industrial manufacturing plants.

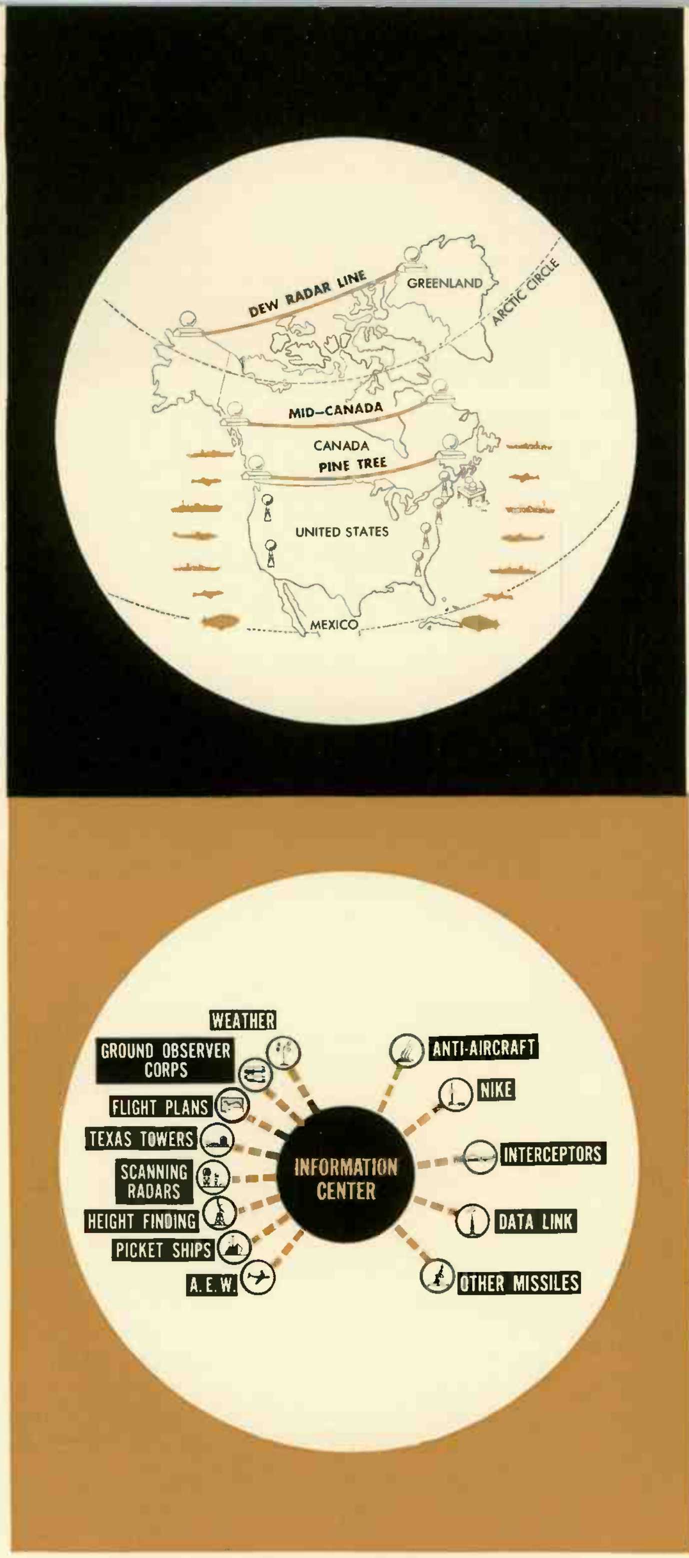
Standard production aircraft have flown at speeds of more than 1000 miles per hour. A manned, rocket-powered craft has climbed to an altitude of 20 miles and set an unofficial world speed record of 2000 miles per hour. Guided missiles are in operational use. In development are hypersonic intercontinental and intermediate range ballistic missiles, while research continues on chemical and atomic-powered aircraft.

For 1958, the aviation picture is bright—and expensive. Current programs (aviation related) indicate an estimated $12 billion gross new order total, one of the largest in the industry's history. Of this amount, $7 billion will be applied to military aircraft, engine, and associated equipment, $3 billion for guided missiles and $2 billion for military ground-based electronics equipment and related weapons. By the end of the fiscal year 1957, the U.S. military aircraft inventory will total 43 226 as compared with the 949 military planes operated by the United States twenty years ago.

But the increase in total cost is not just a matter of increased numbers. The Wright brothers' first plane for the Army cost $25 000; a World War II heavy bomber cost about $200 000; but the modern B-52 bomber runs close to $7 million. One solid reason is complexity. A B-17 required but 200 000 engineering man-hours; the B-58 Hustler, 9 million.

Unlike the specifications required of the Wright brothers' first aircraft, today's aircraft and missiles must withstand every environmental torment known to man—and then some. Modern aerial warfare demands aircraft and equipment that will operate reliably under extreme vibration, in freezing weather, or in the torrid, humid tropics. They must withstand desert storms or the salt spray of choppy seas, and are subjected to rapid flights from sea level to altitudes well over 50 000 feet.

An increasingly difficult problem confronting science is that of extreme high surface temperatures of the airframe encountered at sustained speeds of Mach 3 and above in stratospheric flight; at this speed surface temperatures may be 600 degrees F. With current programs now in process, continued speeds of this nature for manned aircraft will be achieved within 5 or 6 years. Ballistic missiles will also experience problems of extreme high temperatures upon reentry into the earth's atmosphere. The need for a solution to this problem is at hand. Propulsion systems are also making great strides. Turbojets currently in production are capable of propelling an aircraft at Mach 2 or greater and operating at



In any defense system, communications is a key element. Information from many sources, such as radar lines, picket ships, and Texas Towers (top diagram) must be collected, sorted and communicated to necessary defense installations. Instantaneous handling and use of all information is a "must."

altitudes of 72 000 feet. Rocket motors, too, are reaching greater and greater capabilities. In this area, speeds of 3500 mph and altitudes of 126 000 feet have been attained.

Missile guidance and control systems face even more severe hardships. Usually faster than manned aircraft, the missile's extremely high blast-off shock, in-flight temperatures, and periods of vibration provide a constant challenge for electronics equipment that must provide accurate and instantaneous guidance and control at all times.

Electronics for manned aircraft is also faced with many difficult problems in this new age. Packaging greater range, additional capabilities, and higher reliability in smaller and smaller "boxes" is a constant struggle.

air-defense systems

The magnitude of the tasks confronting the military and the aviation industry becomes more apparent when looked at in more detail. Consider, then, the general problems encountered in an air-defense system. While actual plans for air defense are classified, a hypothetical example can be drawn.

In the simplest sense, the function of an *air-defense system* is to prevent the fall of enemy bombs upon specified surface targets. The surface targets may include groups of Navy ships, Army units, Air Force ground installations, or civilian populated areas to name a few. For reasons of economy, it is more practical to consider defense of specific targets than, say, the North American continent. The defense system can function by destroying the bomb-launching vehicle, by destroying the bomb in flight, or by presenting such an impenetrable barrier that the enemy is discouraged from pressing or even initiating an attack. Air-defense systems are, in general, to be distinguished from *harbor defense*, *submarine defense*, and other closely related defense systems.

The air-defense system consists of means for detecting the approach of the enemy's weapon system, for identifying it as hostile, and for intercepting it with the defensive weapons systems at hand. Extensive coordination means must be provided to insure that the widely dispersed elements of such a system function effectively as a whole, and that loss of some elements will not seriously impair the efficiency of the remaining ones. The speed and accuracy of communications and decisions are paramount in the success of the system.

The threat posed by the enemy can be roughly divided into three categories. He may employ high-altitude bombers—similar to our B-52's—armed with free-falling bombs or air-to-surface guided missiles; or he may use low-altitude bombers armed with bombs or rockets; and, in the future, he can be expected to use long-range missiles of the Inter-Continental Ballistic Missile (ICBM) variety. An enemy could be expected to use all of these weapon systems together to attack different targets simultaneously. Any of the weapon systems mentioned could be used for delivery of nuclear weapons, which complicates the problem further, since one aircraft armed with one bomb can wreak terrible damage.

The approach of the enemy's weapons may be guided by his radar, by passively homing upon our communications or radar signals, or by celestial or inertial navigation. He can be expected to carry jammers to disrupt detection and communication systems.

Before any steps can be taken to counter the enemy's airborne threat, his approach must first be detected. The importance of accomplishing detection at long range becomes more and more important as aircraft speeds increase. If the enemy's speed is Mach 1, detection at 300 miles allows roughly 30 minutes to identify him, determine course and speed, decide what interceptors to use, get them off the ground and to enemy's altitude, and perform the interception air battle. At speeds of Mach 2, which have already been attained, this time is cut in half. If the enemy aircraft is armed with an air-to-surface missile, the aircraft must be destroyed before it reaches the launching range—possibly 50 to 100 miles from the target—or the much more difficult problem of intercepting the missile itself is faced. Of course, for any long-range missile such as ICBM, the increased speed places even greater emphasis on long-range detection.

Since radar follows more or less line-of-sight paths, detection of distant targets is limited to those sufficiently high to avoid the "shadow" of the earth's curvature. For surface radar, this implies a maximum range of no more than a few hundred miles on any but ICBM targets. To provide adequate detection range on conventional aircraft thus requires a radar network. The addition of large airborne-radar detection equipment also acts to extend the detection horizon for lower-flying manned aircraft. Such considerations have led to the establishment of extensive radar networks in Canada, our offshore "Texas Towers," radar picket ships in naval formations, and also airborne early-warning radar patrols.

Once the approaching enemy is detected, the number of units must be evaluated and their individual courses and speeds plotted with high accuracy, so that the proper type and number of interceptors can be directed into positions for the kill. As the raid approaches the point of interception, the tracking accuracy requirements increase sharply. At this point, range, while still important, is subordinated to tracking accuracy and high data rate. In general, a different group of surface-radar equipment is called into play for the three-dimensional function of target tracking and interceptor control. Equally important, interceptors must be located relative to the enemy so that the interceptors can be directed into an advantageous position. Manned interceptors and some of the surface-to-air missiles contain short-range radars for the final approach to the target and control of air-to-air weapons.

The coordination of information flow in an extensive air-defense system is a problem of staggering proportions. In the detection phase, plots of numerous search radars must be compared and combined with reports from sky-watchers, intelligence data, the flight plans of thousands of friendly aircraft, and the results of electronic identification procedures. Since time is crucial, as much as possible of this comparing and combining can be done in large electronic computers after the various bits of data have been assembled by means of an extensive communications network. At least the initial phases of target tracking also can be accomplished by remotely-located computers. The situation at any instant must be readily displayed for command decision and action. In the same location must be displayed the recent history of targets, interceptors, and current status of both.

When the enemy raid approaches the interception point, the tracking function must be transferred smoothly from the search radars to the more accurate tracking and interceptor control radars. Again, a complex communication function is required to avoid confusion and possible track loss. The accurate output of the track radars is employed in an intercept computer to determine the optimum attack course for the interceptor. The output of the intercept computer guides the interceptor, either by direct communications link or by voice link to the interceptor. At some point in its approach to the enemy, the interceptor's radar will make contact for the final approach. If it is a manned interceptor, a computer solves the fire-control problems for the interceptor's weapons.

Since the entire tableau described must be accomplished in a few minutes, the requirement for automatic communication, computing, and display is obvious, as is the necessity for immediate decision on action to be taken, and communication to the proper weapons system. A wide variety of communication links are employed, ranging from common telephone lines to the most advanced single-sideband, digital-data links. Wherever possible, the flow of information from source to communication system to receiver must be without human intervention and resultant delay.

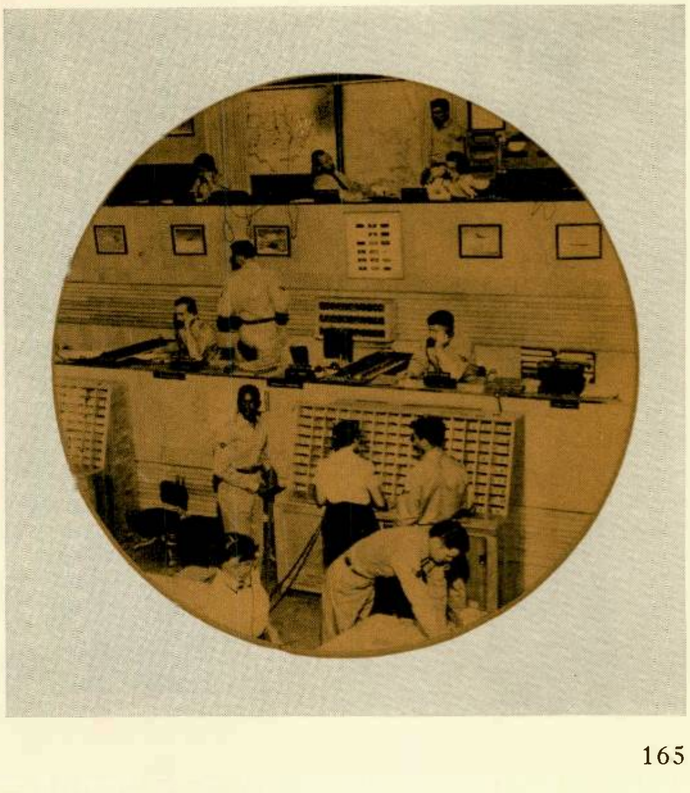
aviation—in what direction?

Modern advancements in military aviation are currently directed toward the establishment of a tremendous deterrent force that will make a potential enemy of the free-world hesitate before committing an act of aggression. Secondly, American science is directed at the attainment of a military force so powerful that a blow in retaliation to an aggressive act would cause that nation to be incapable of carrying out any further acts of war.

Aviation, in this new Age of Flight—born of war and nourished by threats of war—will lead man to a whole new world heretofore only seen through the eyes of a telescope. Some experts predict man's conquest of space will occur in five years, others say twenty-five, but most agree that man will set foot upon the moon or another planet before the close of this first century of air power. Nations will maintain strategic bases on manned satellites orbiting the earth.

Fantastic as these predictions seem, they are no more fantastic than the thought of aircraft speeds of 2000 miles per hour, or the idea of an earth satellite orbiting the earth 300 miles up would have been to Orville and Wilbur Wright. As Kitty Hawk spelled the beginning of aviation as we knew it yesterday, scientists, military leaders and the world's industry today are ushering in the second half-century of aviation to a truly remarkable and great new age of flight. ■

Military personnel working at the Air Defense Control Center in Colorado. *U. S. Air Force Photo*



MODERN AERODYNAMIC PROPULSION SYSTEMS

ARNOLD H. REDDING
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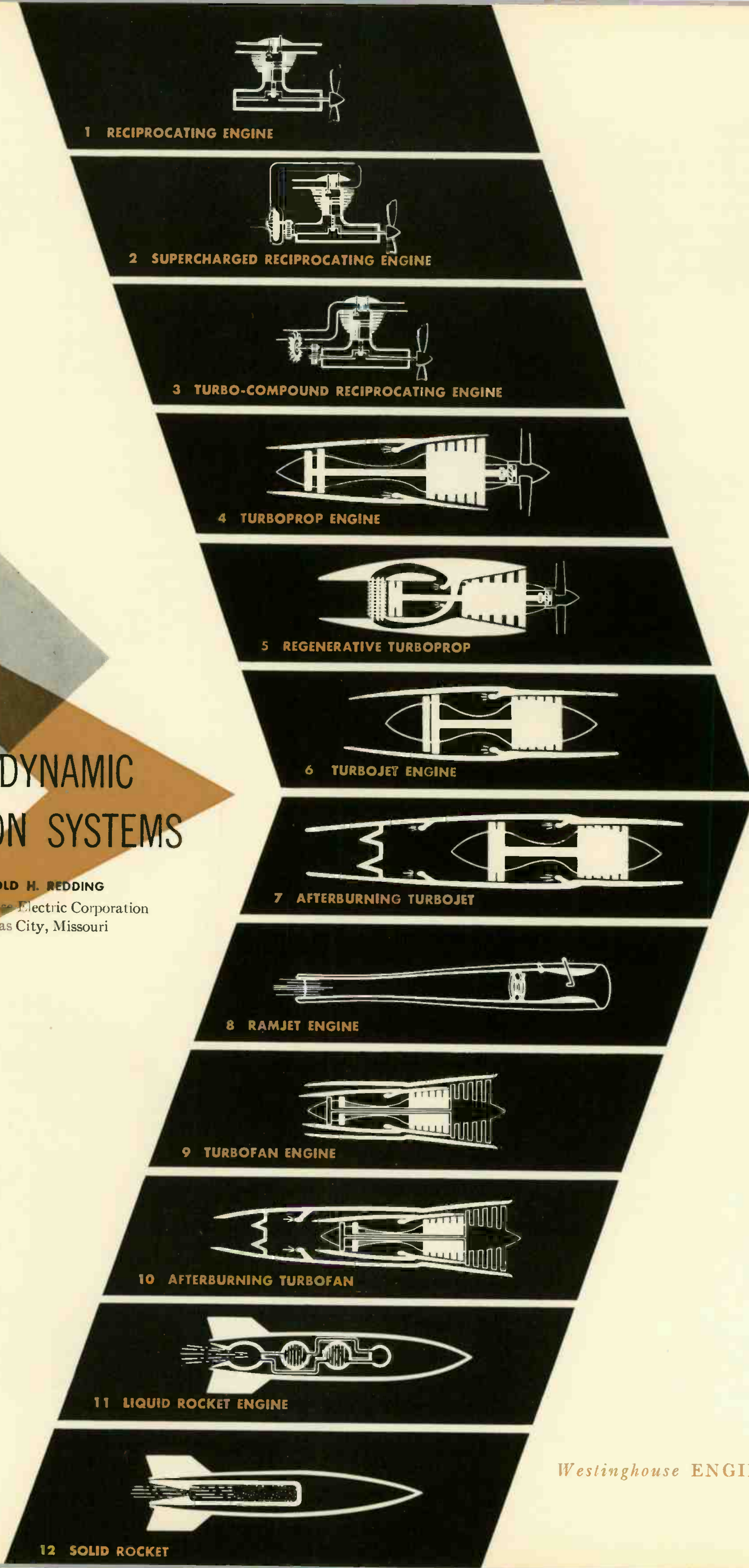


PROPULSION SYSTEMS

1 RECIPROCATING ENGINE The reciprocating engine is familiar and needs little comment. Because the cylinder and piston is alternately a compression and an expansion device and cooling of the metal parts is quite feasible, the piston engine operates at almost ideal fuel air ratios with very high cycle temperatures. This gives good efficiencies. **2 SUPERCHARGED RECIPROCATING ENGINE** The reciprocating engine basically has low volume flow and therefore is a heavy engine. As altitudes increase and the air becomes thinner its power goes down considerably. Mechanical friction, which remains constant with altitude, generally reduces efficiency. The use of a centrifugal supercharger driven by engine shaft power or exhaust gases, increases the swallowing capacity and power of the reciprocating engine and increases its efficiency at altitude with a relatively small weight increase. **3 TURBO-COMPOUND RECIPROCATING ENGINE** Combustion gases, because they are hot, have not expanded to atmospheric pressure at the end of the power stroke. This is particularly true for a supercharged engine. In the turbo-compound engine considerable additional power is obtained by directing engine exhaust gases through an expansion turbine geared to the crankshaft. **4 TURBOPROP ENGINE** The gas turbine engine uses a cycle similar to the reciprocating engine. However, it employs a separate compressor combustion chamber, and an expansion device or turbine. Because the turbine gases are always hot, and cooling is difficult, the maximum temperature ahead of the turbine must be kept much lower than in the reciprocating engine. This makes equivalent efficiencies difficult to achieve and reduces the work per pound of cycle fluid to about one-fourth that of the reciprocating engine. However, the nature of the kinetic gas-turbine engine is such that it will handle many times more air. A modern gas turbine develops efficiencies of 32 percent at cruising altitudes. However, the losses of the propeller bring the net efficiency to 27 percent in the kinetic energy leaving the propeller. The Froude efficiency of a modern propeller is in the order of 96 percent so a net propulsion efficiency of 26 percent can be achieved. This results in the consumption of about 0.5 pound of fuel per hour per thrust horsepower. **5 REGENERATIVE TURBOPROP** A heat exchanger, using some of the waste heat leaving the turbine to preheat the compressed air before it enters the combustion chamber, increases efficiency. The weight of this heat exchanger has not yet justified any but experimental applications. **6 TURBOJET ENGINE** The modern aviation gas turbine generates about 100 Btu of useful work per pound of working fluid. If the propeller, the reduction gear, and that portion of the turbine used to drive the propeller are eliminated, and an expansion nozzle substituted, at approximately 1000 feet per second or 680 miles per hour, a Froude efficiency of about 60 percent is achieved (page 168). This compares with a 68 percent utilization of the same energy if the efficiency of turbine, reduction gear, and propeller are considered. However, the power plant is much simpler and lighter. **7 AFTERBURNING TURBOJET** Because of turbine material limitations, only about one quarter of the air is burned in the combustion chamber of the turbojet engine. Additional fuel can be injected in an afterburner. Because the pressure here is considerably lower than that ahead of the turbine, this fuel addition results in lower thermal efficiency at low flight speeds. At 1000 feet per second a four-fold increase in fuel flow only increases the jet energy by about 2½ times. In addition, the Froude efficiency is reduced by about 20 percent, so that a four-fold increase in fuel gives only twice as much thrust. However, this is still an attractive means of getting short-time thrust boosts. As flight speeds increase, the pressure level in the afterburner increases greatly, due to the ram compression. This, along with the higher temperature, gives, at 3000 feet per second flight speeds, higher thermal efficiency than the turbojet. At this speed the energy added will be in excess of 400 Btu per pound, which gives a very reasonable Froude efficiency of 70 percent. **8 RAMJET ENGINE** At high flight speeds, normal to ramjet operation, the compression due to ram is sufficiently high that good thermal efficiency can be obtained without additional compression by a mechanical compressor. The ramjet, at 3000 feet per second, gives approximately the same performance as an afterburning turbojet engine. As the flight speed of the ramjet is reduced, the thrust reduces rapidly and is zero under static conditions. Ramjet vehicles usually have a very narrow speed and altitude range over which they can operate, and are boosted to this speed and altitude by other types of power plants. **9 TURBOFAN ENGINE** The non-afterburning turbojet engine develops its highest over-all efficiency at about 1500 feet per second. Modern airplanes maintain good aerodynamic efficiency up to about 900 feet per second. Modern propellers fall off rapidly in efficiency at flight speeds over 800 feet per second. The turbofan engine is a cross between the turbojet and turboprop engine that fits best between this speed range. In the turbofan engine, about half the energy left over after driving the main compressor is removed by a turbine that drives an auxiliary compressor. By this means the propulsion air is doubled and the Froude efficiency is increased without adding too much weight **10 AFTERBURNING TURBO FAN** If an afterburner is added to the turbofan, the thrust is greatly increased at high flight speeds. The afterburning turbofan falls between the afterburning turbojet and the ramjet in its thrust-versus-speed characteristics. However, with the afterburner turned off it has better subsonic cruise efficiency than either the turbojet or ramjet. **11 LIQUID ROCKET ENGINE** Liquids can be pumped up to high pressures without much difficulty. In the liquid rocket engine, fuel and oxidizer (for example, gasoline and liquid oxygen) are pumped into a combustion chamber at high pressures and the combustion gases expanded through an exhaust nozzle. This is a very efficient thermodynamic cycle and efficiencies of over 40 percent can be obtained. However, the absence of neutral nitrogen results in a very high velocity energy per pound of fluid (approximately 1800 Btu per pound). At all but extremely high flight speeds this results in a very low Froude efficiency, which, when coupled with the relatively low heat content of the fuel that must be carried (because of the oxidizer), does not give very good results. However, when very high flight velocity is required, especially in the absence of atmospheric air, the rocket is without peer. **12 SOLID ROCKET** The solid rocket, by using a fuel resembling a slow burning gunpowder, is a very much simpler power plant than the liquid rocket engine with its tanks, pumps, etc.

▪ Behind the tremendous revolution in military aircraft are many important technical developments. But a basic factor—and perhaps the most important—is the striking progress made in engines to hurtle the planes through the sky at ever-increasing speeds.

In 1942, competent airplane designers said that man would never be able to travel at 1000 miles per hour. Their reason was the tremendous power required. Their reason was right—but they underestimated the engineer's ability to produce the necessary power.

Looking for more specific reasons for the tremendous advancements of the last 15 years, first came the spark that is the turbojet engine of Frank Whittle, which indicated that it all could be done. Second, the wherewithal—the many billions of dollars spent on aeronautical research since 1942 (hundreds of times the amount spent before that time). And third, came the method, which in the case of the propulsion system has been the ability to break the system into individual component parts and recombine them in the best possible method. This has permitted a scientific approach that was never quite possible with a reciprocating engine, where the thermodynamics, aerodynamics, and mechanical design were all mixed up into one frustrating whole.

Heat engines are still the only aircraft propulsion method of today; therefore no time will be spent here on such weird and wonderful devices as photon and ion propulsion (probably next generation's standard means). Although there is nothing new in the thermodynamics of heat engines or the types of processes, new components are available to accomplish these processes. Also, a change in thinking has occurred as to what defines the useful output of a heat engine.

the heat engine

Nearly every heat engine obtains its motive force from the expansion of a fluid in the gaseous state at a relatively elevated temperature from a high pressure to a lower pressure. This fluid in expanding can do work through a mechanical machine to develop power, or can be accelerated through a nozzle to create a high-velocity jet of gas that gives a thrust.

The fluid arrives at the high pressure from which it expands in one of four ways. It can be: (1) pumped up in a liquid phase (steam turbine); (2) in a chemically different liquid phase (rocket); (3) compressed in the gaseous phase by a compressor (reciprocator, positive-displacement rotary, centrifugal or axial); or (4) compressed by utilizing the relative kinetic energy or flight (ram). The spent gas is discharged to the atmos-

AEROTHERMODYNAMIC COMPONENTS

I. For Compression

A. The Inlet:
At Mach 3 the theoretical pressure recovery across the inlet corresponds to a pressure ratio of 37:1. In all high-speed air-breathing engines this is a very important part of the compressor cycle.

B. Kinetic Compressors:
Centrifugal and axial compressors handle large volumes of air at good efficiencies and remain the heart of moderate speed air-breathing engines.

C. Positive displacement compressors, which are of little interest except when used as part of the combustion and expansion cycles, as in the reciprocating engine.

II. For Heat Addition

A. Direct fuel combustion chambers (These can be designed to burn fuel over a wide range of fuel-to-air ratios).

B. Heat exchangers for use of waste heat or indirect heating of working fuel (indirect fired combustion chambers).

C. Nuclear Heat Sources

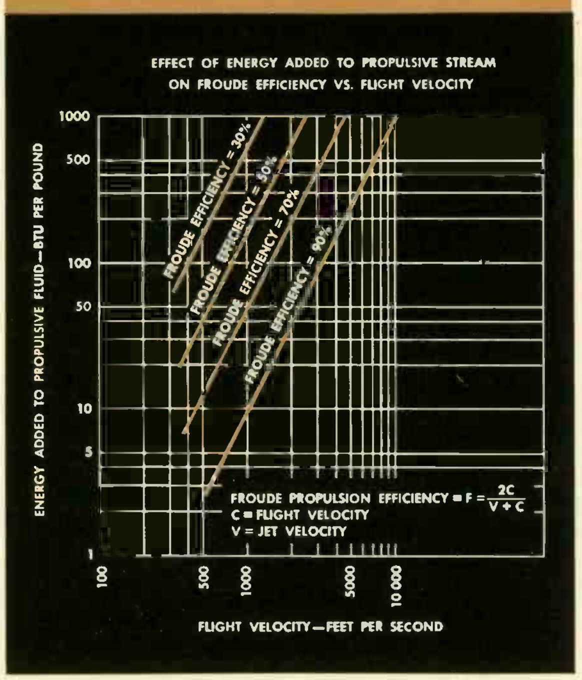
III. For Expansion

A. The kinetic turbine, primarily axial flow.

B. The exhaust nozzle for converting pressure energy into velocity to achieve the propelling momentum.

IV. The propeller, a special unshrouded case of the compressor, is admirably suited to convert shaft power into moderate increases in velocity of larger amount of air to give excellent propulsion efficiency at low speeds.

V. The happy combination of functions which is the reciprocating engine.



phere, sucked away by a compressor after suitable cooling, or cooled and condensed to a liquid state and pumped away (steam turbine).

Before the expansion, heat must be added to the working fluid. This can be done by direct firing of fuel into the fluid if the working fluid will support combustion, by indirect firing as in a steam boiler, or by heat transfer from a nuclear reactor.

Before looking further, consider the tools the aeronautical propulsion system designer has at his disposal. They are:

A. Fuels
B. Aerothermodynamic components
C. Materials, mechanical design, and manufacturing techniques

Fuels include the well-known hydrocarbons, which in general have a low heating value of 18 700 Btu per pound, weigh 6 pounds per gallon and require 15 pounds of air or 3 pounds of oxygen per pound for complete combustion. This means a maximum of 1160 Btu per pound of products when burned with air.

Then comes a wide range of rocket fuels. One of the best is pure hydrogen burned with pure oxygen. While hydrogen has a heating value of 51 000 Btu per pound, the mixture that must be carried has a combined heating value of only 5700 Btu per pound. A principal characteristic of rockets is that while the combustion mixture has a high heat per pound of mixture, the necessity of carrying the oxidizer reduces the total heat energy that can be carried by a factor of four or more when compared to air-breathing engines. Many chemical fuels are under investigation for both rocket and air-breathing engines.

The aerothermodynamic components available to the designer are indicated in the table at left.

The third tool is the great background of engineering materials, mechanical design methods, and manufacturing techniques.

The design of any aircraft propulsion system is a compromise between weight and fuel economy. The fuel economy is in itself a product of (1) the heating value per pound of fuel (2) the thermal efficiency of transferring the heat of combustion into the propelling jet (whether from a propeller, air-breathing jet engine, or rocket) and (3) the efficiency with which the jet propels the vehicle according to Froude's Law (see curve at left).

If the goal is the design of a spectrum of propulsion systems to operate at a propulsion efficiency of 70 percent over a range of flight speed from 500 to 5000 feet per second, the range of the energy added to the air is 100 to 1.

The efficiency with which the energy in the fuel or the heat released by a nuclear reactor is transformed into kinetic energy in the jet varies with the type of cycle used, the efficiencies of the components, and the maximum temperature. Using modern technology a wide spectrum of propulsion systems can be designed with thermal efficiencies defined in this manner varying from 27 percent in the case of the turboprop to 40 percent with liquid-fueled rocket. In general, the less work added per pound to the propulsion fluid, the lower is the thermal efficiency.

Where are we going? The past fifteen years have seen a terrific exploitation of the research of the past century. In many areas of propulsion the "state of the art" is pushing to the limits of known basic science. Many people in the industry feel that large-scale progress will have to wait on further basic scientific discoveries. However, nobody believes that progress will stop or even slow up. ■

Navajo
missile

McDonnell
Banshee F2H

Douglas X-3

JET ENGINE DEVELOPMENTS

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Advanced Development & Performance

R. A. NEAL, Section Engineer
Controls

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The development of the aviation gas-turbine engine has been directly responsible for the remarkable revolution in military aviation that has taken place since World War II. The acceptance of this new propulsive device has been so complete that no new reciprocating engines or piston-engine powered military or large commercial aircraft are now under development.

The reciprocating engine provided the prime source of propulsive power for the first 50 years of man's flight history, during which over 1 000 000 engines were built. But already over 90 000 aircraft gas-turbine engines have been built in the United States and many industry experts predict that jet propulsion will be the basic source of aircraft power for the next 50 years.

early turbine engine history

The history of the modern aircraft gas-turbine engine began in the early 1930's when British and German scientists began their development. This work went relatively unheralded until the great superiority of jet-powered military aircraft was demonstrated during World War II. England flew an engine, as conceived by Frank Whittle, in 1941. Before the end of the war, a production version of this engine was powering the Gloster *Meteor* on interceptor missions against the German V-1 buzz bomb.

In 1941, the United States Army Air Corps had a British Whittle engine shipped to the United States and gave an order for the Bell Aircraft Company to build the P-59A aircraft, using two Americanized Whittle engines. The maiden flight was made on October 1, 1942.

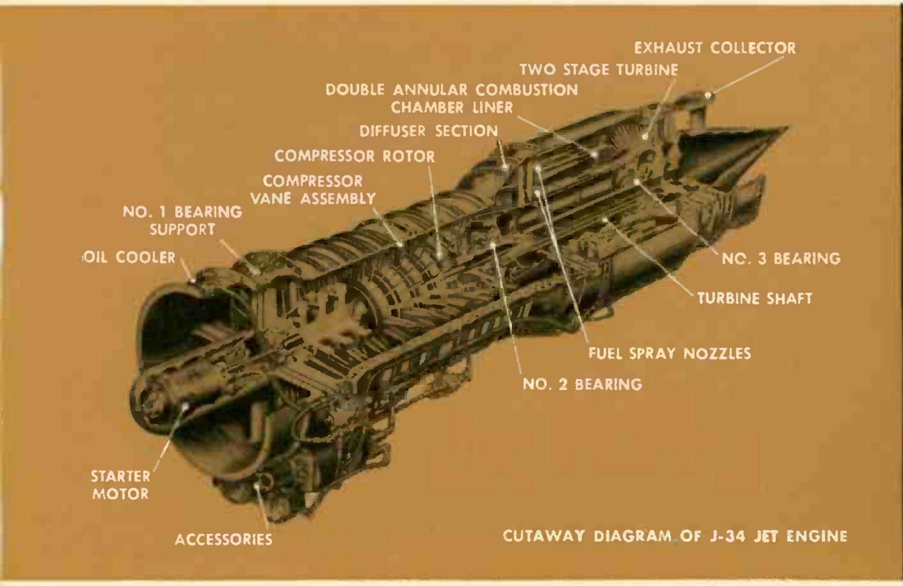
Also in 1941, the day following Pearl Harbor, an order was placed with Westinghouse for design and development of the first all-American designed jet engine. The resulting engine—known as the 19A *Yankee* engine—was first run on March 19, 1943 and first flown in January 1944. A more advanced version—the 19B engine—powered a McDonnell FH-1 *Phantom* during the first flight of a jet aircraft from a carrier, in 1946.

The development of the 19A and B engines was followed closely by the Westinghouse 24C or J34 engine, first produced in 1947. This engine is an excellent example of the reliability and performance possible even at an early stage in jet-engine history. The J34 has seen extended service in applications such as the Navy's F2H *Banshee* and F3D *Skyknight* fighters, and was recently selected for use in the North American T2J—the first Navy all-jet basic trainer. The J34 engine has also been used in several interesting experimental concepts, such as the XF-85 *Goblin* parasite-fighter, the XF2Y *Sea Dart* water-based fighter, and the X-3 high-speed research aircraft.

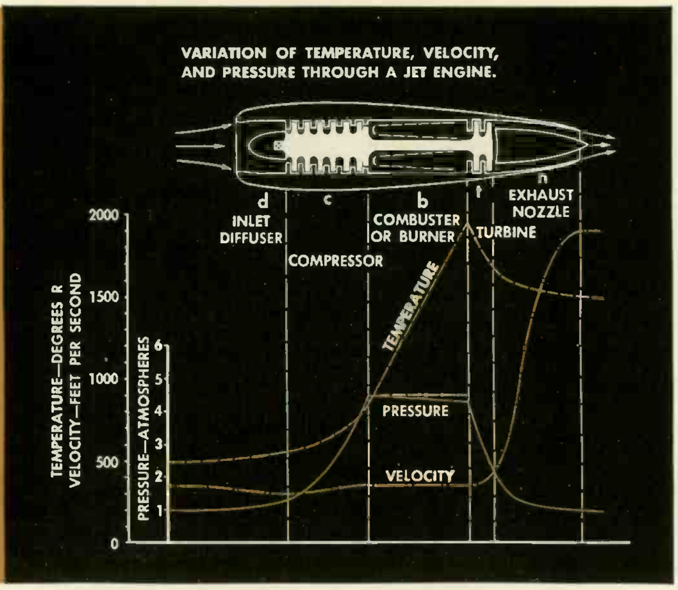
The new J54 engine represents the most recent state-of-the-art in designing for lightweight and low specific fuel consumption, and is well suited to a number of applications. This company-sponsored engine program has made use of the combined design techniques of Westinghouse and Rolls-Royce, Ltd., of England, made possible by an engineering information exchange agreement between these two companies.

modern development of turbine engines

Development of the turbine engine has been very rapid. Engines have been improved to produce more thrust more efficiently by greatly reducing the Specific Fuel Consumption (S.F.C.—pounds of fuel per hour per pound thrust) and the specific weight (pounds of engine weight per pound of thrust). These improvements have been primarily a result of increased compressor pressure ratio and turbine inlet temperature. Continual development of the engine components such



CUTAWAY DIAGRAM OF J-34 JET ENGINE



VARIATION OF TEMPERATURE, VELOCITY, AND PRESSURE THROUGH A JET ENGINE.

as the compressor, combustor, and turbine have made these gains possible. In addition, advances in metallurgy to permit lighter construction, application of afterburning (burning additional fuel after the turbine) to provide greater thrust, better mechanical arrangements, and improved control principles have contributed to this rapid development.

Today, engineers speak of 40–60 000 pound sea-level static thrust. New engines would permit some 2000-mph speeds at 70 000 feet and above. Already several engines are being developed in the 20–30 000 pound static thrust class.

development status of components

Compressor Development—The axial-flow compressor, pioneered in the U. S. by the Westinghouse 19A, is used in virtually all modern engines. This compressor has advantages over the centrifugal type—used in some early engines—of higher flow per unit frontal area and higher efficiencies. The axial-flow compressor consists of alternate rows of rotating and stationary air-foil shaped blades, which are carefully oriented to turn the flow in such a way that air-flow velocity is reduced and the pressure thereby is increased after each stage. Axial-flow gas-turbine compressors normally have from 10 to 20 stages depending on the design pressure ratio.

One way to improve engine efficiency is to increase the compressor pressure ratio. Engine designers have accomplished this by several means. One method is improved aerodynamic design of each individual compressor stage, although this has a practical limit. The next method is to increase the number of compressor stages; early engines used 8 to 10 stages, modern engines use 15 to 20 stages.

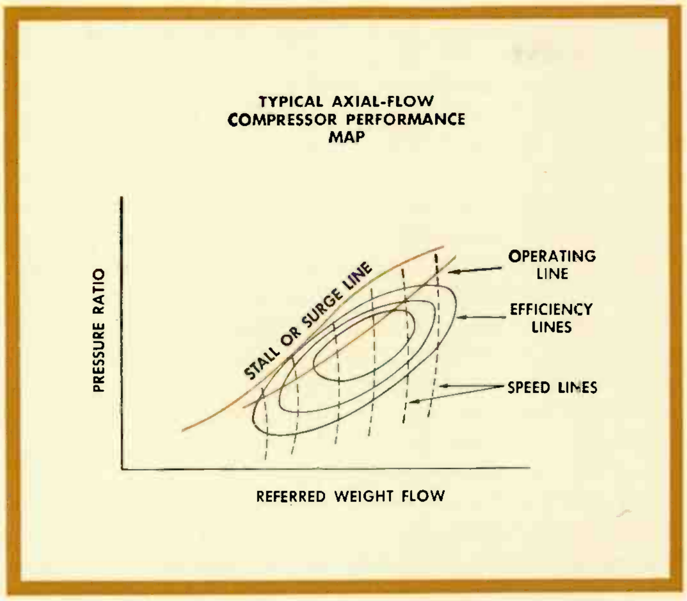
Compressor design is limited by the necessity for a wide range of stable operation and the rapid accelerations required for aircraft operation. Increasing the pressure ratio usually leads to serious mismatching of the stages at the front and the rear of the compressor when the engine is being operated under off-design conditions. At low rpm, the front stages are heavily loaded and are in or near stalling conditions while the rear stages are very lightly loaded. The reverse is true for high rpm operation, where the rear stages are heavily loaded. The degree of mismatching is a direct function of the design pressure ratio. This imposes a practical limit to the pressure ratio that can be obtained with a simple fixed-geometry axial-flow compressor design.

There are two ways around this problem. Higher compressor pressure ratio can be obtained by splitting the compressor into a two-compressor or twin-spool design, and selecting a different rpm for each of the two parts to produce improved matching at all conditions. Another means of obtaining the same result is to vary the air flow in the compressor such that the front stages are operated at a more optimum condition when they are likely to stall. This is accomplished by varying the swirl of the inlet air to obtain a more favorable angle of attack on the front stages. This swirl can be created by mechanically varying the angle of the stationary inlet guide vanes in the compressor. It has also been found that bleeding air from the compressor at an intermediate stage is helpful in rematching at low rpm. A combination of the variable-angle compressor inlet guide vanes, and a mid-stage compressor bleed permits higher compressor pressure-ratio designs without the complication of a twin-spool engine design.

Early jet engines were designed with "fixed geometry" compressors at pressure ratios from 4:1 to 5:1, while modern engines, utilizing the "variable geometry" features described above are running at pressure ratios from 8:1 to 13:1. The difference in pressure ratio between 4 and 13 results in a specific fuel consumption improvement of approximately 25 percent at a typical altitude-cruise condition.

Compressor stall and surge problems probably will continue for some time. Compressor stall occurs when one or more blades in the compressor stall in a manner similar to any airfoil section. This usually is not serious enough to reduce the engine airflow; however, these disturbances can cause serious vibration problems in the engine that in time can cause structural failure from fatigue. Compressor surge is a severe stall of one or more stages of the compressor with a drastic reduction in the air pumping capability of the compressor. The compressor surge results in greatly reduced efficiency and the drop in air flow to the combustor may result in serious overtemperature in the hot zone of the engine. As shown on page 171, the compressor should be operated close to the stall or surge line for best efficiency, but care must be taken to assure that transients caused by the pilot in changing the engine power setting, or airflow interruptions caused by aircraft maneuvering will not put the compressor in the stall or surge region.

The temperature of the air being rammed into the engine inlet during flight at higher Mach numbers forces the com-



pressor to operate in the thermal "thicket." This is not abrupt like the sound "barrier" and the temperature problem is going to be difficult to solve. As a result of the ram temperature rise, the temperature at the outlet stages of the compressor will reach values found in the turbines of currently flying jet engines.

For slow and moderate flight speeds there is considerable incentive for increasing the overall compressor pressure ratio to obtain improved S.F.C. This is not so for high Mach number flight since the ram pressure rise can be used to partially compress the air. To keep the number of compressor stages to a minimum, increased pressure ratio per stage will still be required in the interest of light weight.

Combustor Developments—The function of the jet-engine combustor is to heat the air coming from the compressor and deliver it to the turbine with a specified temperature level and distribution and with minimum pressure loss. A maximum of one-fourth of the available oxygen is generally consumed in the main combustor. The combustor usually consists of a diffusing section where the air is slowed to a velocity suitable for the combustion; a primary combustion zone where approximately one-fourth of the air is mixed with the metered fuel and combustion takes place; and a secondary mixing zone where the remaining three-quarters of the air is admitted and mixed with the combustion gases, thereby providing the desired temperature level and distribution. The designer's aim is to get the greatest heat release in the smallest volume, with the lowest pressure drop at the highest efficiency, and provide the hot gas to the turbine in a predetermined temperature and distribution pattern. Combustor design in early engines took two forms, still used in current engines—the annular and the can type.

The *annular* combustor design is so named because the combustion zone is arranged as an annular ring around the engine. The secondary or cooling air flows inside and outside of the combustion zone and is mixed with the hot combustion gases through properly placed holes in the combustion liners. The combustion liners are cooled by the flow of a film of cool air along their surfaces. By proper design of the mixing holes and slots, the desired distribution can be obtained at the turbine entrance.

The *can* type combustor consists of a number of combustion cans of duplicate design spaced around the engine. The cans may number from 6 to 16. Each is equipped with a fuel-admission device and has a symmetrical combustion liner, similar to that in the annular combustor, where the cooling air is mixed with the hot combustion gases prior to admission to the turbine. Tubes interconnect the cans so that the combustion process can be started from one or two of the cans.

A recent trend has been the combination of the two types to form a *canular* combustor. This type places the can-type combustion liners in an annular space in the engine and the cooling air is brought into the combustion chamber through this annular space.

The condition of the fuel as admitted to the combustor is important to good combustion design. Two methods have been employed, atomizing spray nozzles and vaporizing flame tubes.

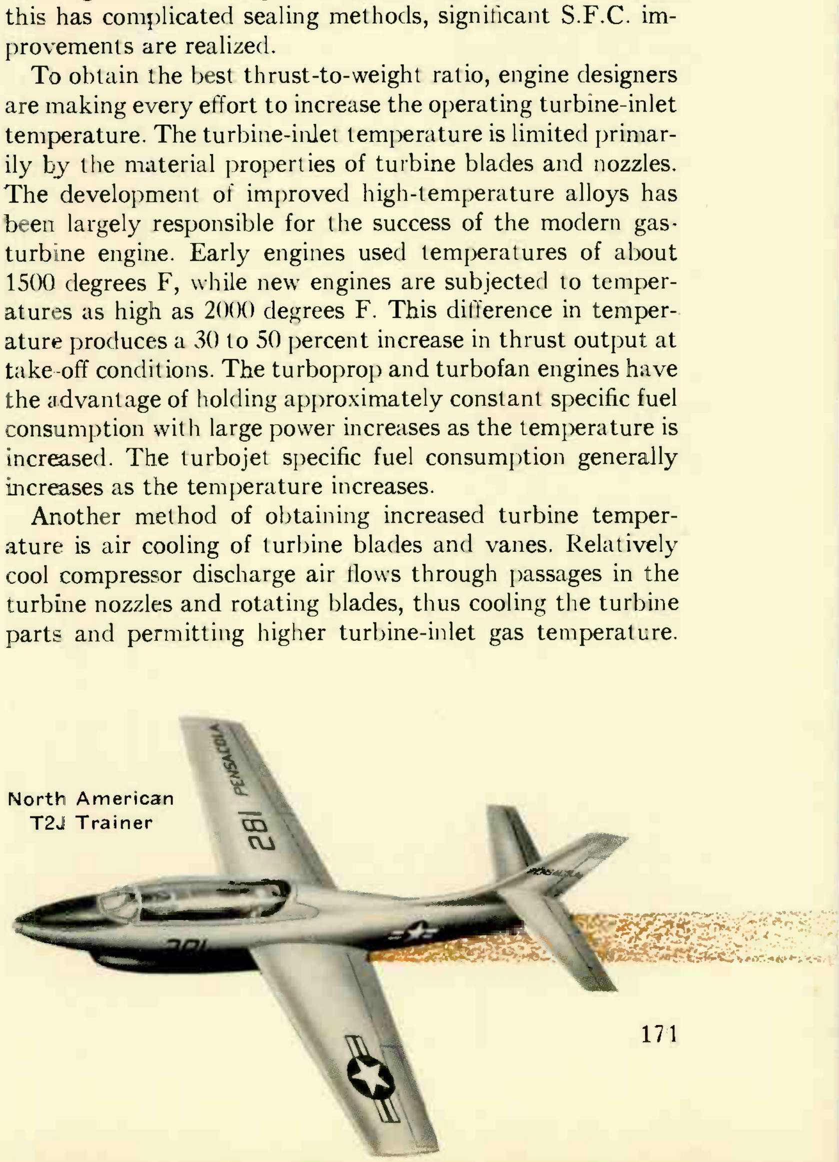
Turbine Developments—The axial-flow turbine consists of one or more stages, each having a row of stators or nozzle vanes and a row of rotor blades. The air is expanded through the stationary blading and then directed against the rotor to produce the desired power.

A source of improvement of turbine efficiency that has received close attention is the sealing around the various stages. Since the turbine is located at the highest pressure point in the engine and has the highest temperature, leakage paths become important. Hot gases that leak through the turbine distort the aerodynamic shape of the gas path through the turbine and also they cause a loss when they mix with the cooler gas that has passed through the turbine. These losses show up as increased Specific Fuel Consumption. Much work has been done to keep this leakage to a minimum by using shrouded rotating blades, rubbing seals, and multiple-pass seals. While this has complicated sealing methods, significant S.F.C. improvements are realized.

To obtain the best thrust-to-weight ratio, engine designers are making every effort to increase the operating turbine-inlet temperature. The turbine-inlet temperature is limited primarily by the material properties of turbine blades and nozzles. The development of improved high-temperature alloys has been largely responsible for the success of the modern gas-turbine engine. Early engines used temperatures of about 1500 degrees F, while new engines are subjected to temperatures as high as 2000 degrees F. This difference in temperature produces a 30 to 50 percent increase in thrust output at take-off conditions. The turboprop and turbofan engines have the advantage of holding approximately constant specific fuel consumption with large power increases as the temperature is increased. The turbojet specific fuel consumption generally increases as the temperature increases.

Another method of obtaining increased turbine temperature is air cooling of turbine blades and vanes. Relatively cool compressor discharge air flows through passages in the turbine nozzles and rotating blades, thus cooling the turbine parts and permitting higher turbine-inlet gas temperature.

North American
T2J Trainer



Ceramic coatings can also be used to insulate the turbine parts from the higher temperatures. Other means of cooling are effusion cooling, film cooling, and circulation of cooling liquid in blades. In some applications, such as missiles, a shorter life may be acceptable, thus allowing higher temperatures.

Afterburner Developments—A common modification to the basic turbojet-engine cycle is the addition of a reheat process after the turbine. Reheat, or afterburning as it is commonly called, produces the large thrust augmentations often required for take-off and high-speed flight. The afterburner usually is a cylindrical casing, into which fuel is injected and mixed with the turbine outlet gases and burned to produce as high a gas temperature as possible.

The apparent simplicity of the afterburner by no means indicates a lack of development problems. As much fuel as possible must be burned for brief high-thrust operation, with the result that temperatures of about 3200 degrees F are produced. Special care must be taken in the design to assure proper cooling of all surfaces to prevent metal part burnouts.

Burning at these high rates has created a high-frequency vibratory phenomena called "squeal," from its audible sound. This vibration is very destructive, causing mechanical failures in a matter of minutes. The exact mechanism of squeal is not fully understood but the addition of a baffle in the burning section of the afterburner has generally solved this problem.

To make proper use of the afterburner, the engine must generally be equipped with a multiple-area exhaust nozzle. The least number of areas required is two—one, a minimum area for non-afterburner operation, and the other, a larger area for afterburner operation. Most efficient operation of the engine can be achieved by making the jet nozzle area infinitely variable from the closed to open area. This complicates the exhaust nozzle design and the control system for operating it.

At higher Mach numbers the efficiency of the afterburner cycle approaches that of the ram jet, which is important to applications where sustained high Mach number flight is required. Afterburners, therefore, are likely to remain an essential part of the turbojet and turbofan engines in the foreseeable future.

optimum engine designs for different applications

The art of designing aircraft to utilize gas-turbine engines has progressed rapidly. At first, the high subsonic speeds made possible by the higher power of the turbojet were exploited and the sacrifice in range due to the high fuel consumption was necessarily accepted. Detailed designs are now made to produce the optimum combination of engine and aircraft design parameters for a specified aircraft mission. This, in some cases, will mean that an engine is initially designed and developed to meet the needs of a particular application, rather than as a general-purpose configuration. Examples of this could be a lightweight, low-pressure ratio, afterburning turbojet engine for missile or high-speed fighter application, and, conversely, a high-pressure ratio non-afterburning turbofan for subsonic or low supersonic long range, or high endurance aircraft.

The use of recently developed high-speed digital computing equipment is contributing heavily to improved design and analysis techniques. More accurate and thorough calculations can be performed on computers. A system has been developed to permit the large mass of engine performance data required by the airframe designer to be delivered to them in the form of magnetic tapes, which can be used directly on a high-speed computer.

summary

In summary, the aviation gas-turbine engine is truly a limit design device. That is, the urgent need for aircraft that are capable of higher speeds, longer range, shorter take-off and landing and higher load-carrying capacity put increasing demands on the engine designer. He must develop more efficient cycles, higher airflow and compressor pressure ratios, increased turbine temperatures, more efficient components, lighter weight, wider range of operation and increased reliability. These factors force the engineer to design to the limit of available information and to continually search for better materials and methods in the fields of thermodynamics, aerodynamics, mechanical design, controls and metallurgy. The success of this search will pace the advances in both the military and commercial aircraft engines of tomorrow. •

TURBINE ENGINE DEVELOPMENT HISTORY

1930 *Whittle took out first patent applying the gas turbine to jet propulsion.*

1933 *Whittle started practical development of jet engine.*

1937 *In April, the first Whittle designed engine ran successfully.*

1939 *First order placed for jet propelled aircraft with the Gloster Aircraft Co., Ltd.*

1939 *First turbojet flight by German He 178 with Dr. Von Ohain He S3b engine.*

1940 *First flight of Caproni-Campini jet propelled monoplane of Italian design using reciprocating engine to drive compressor.*

1941 *First flight of Gloster E28/39 turbojet propelled aircraft in Great Britain with Whittle W-1 engine.*

1941 *Bell Aircraft Co. given order to build P-59 using two American-built Whittle engines.*

1941 *Order placed with Westinghouse for development of all-American design jet engines.*

1942 *Maiden flight of P-59 in U.S.A.*

1943 *Initial operation of first American-designed turbo-jet, the Westinghouse 19A.*

1946 *First jet flight from aircraft carrier by McDonnell FH-1.*

AIRCRAFT DETECTION SYSTEMS

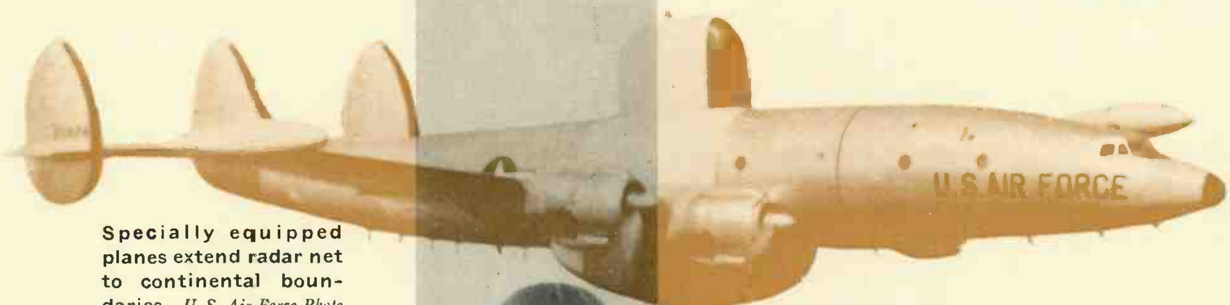
K. M. MACK — Electronics Division

C. E. McCLELLAN — Air Arm Division

Westinghouse Electric Corporation
Baltimore, Maryland

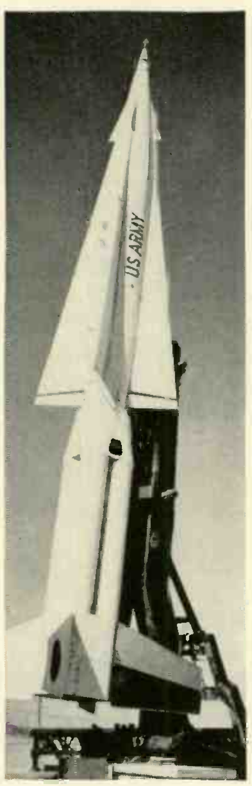
Detection systems are the eyes of a defense system. The characteristics of the defense system are extremely broad. At one extreme is the compact, self-sufficient system to permit a manned interceptor to locate and destroy an enemy; at the other are fixed defensive systems covering hundreds and thousands of square miles and involving dozens of detection systems.

An aircraft's course, altitude, and speed is plotted by radar, and relayed to controllers for the purpose of identification. *U.S. Air Force Photo*



Specially equipped planes extend radar net to continental boundaries. *U.S. Air Force Photo*

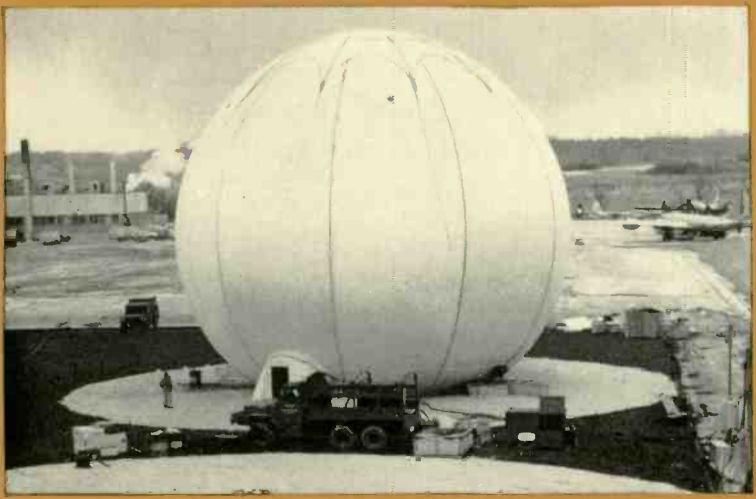
Strung out along the far reaches of Alaska and the Arctic are a series of small Air Force outposts, referred to as "Early Warning Stations" or radar sites. These sites, remotely situated and with only radio contact to the outside world, operate 24 hours a day. *U.S. Air Force Photo*



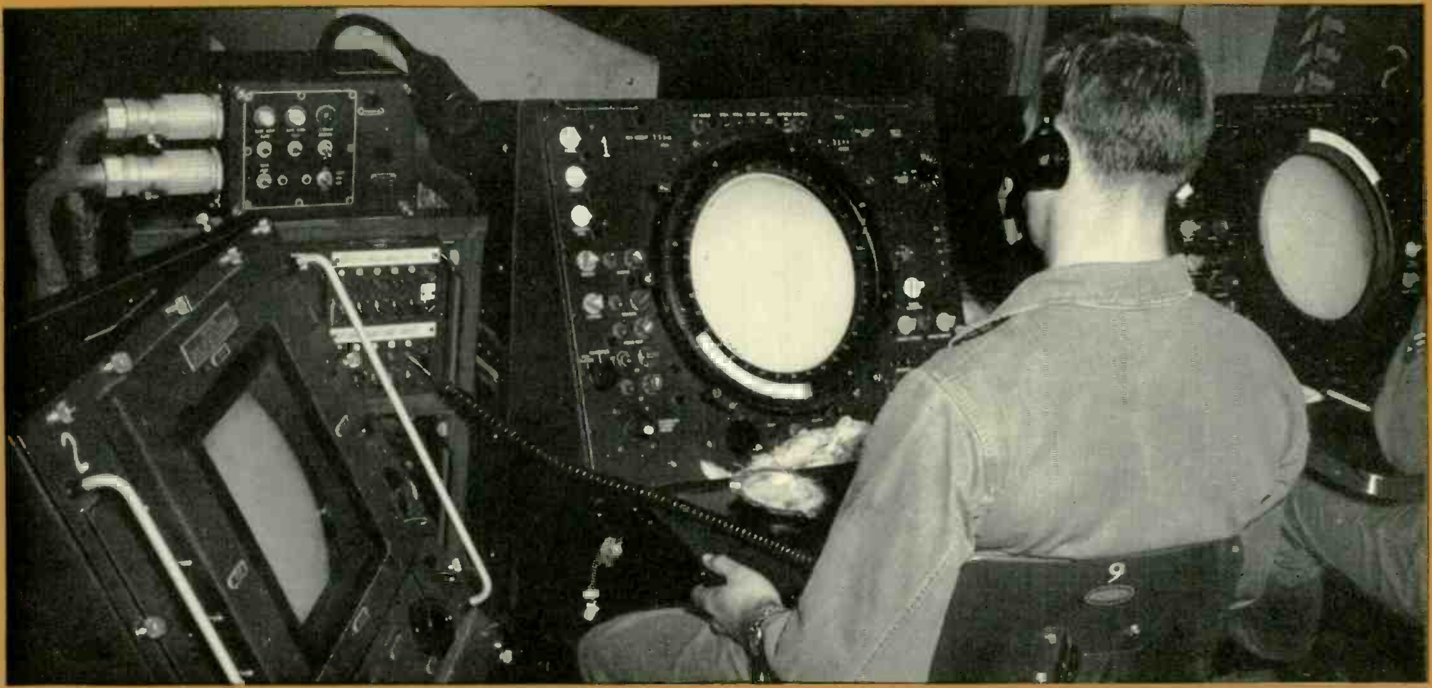
The Nike-Hercules, the U.S. Army's new surface-to-air guided missile, on launcher at White Sands Proving Ground. *U.S. Army Photo*

As a basic part of military operation, detection systems are constantly subject to the struggle between offense and defense. It is characteristic that a weapon or a method of attack is first presented and then defense weapons or strategies devised to nullify or minimize the offensive technique. Illustrative of this is the introduction of jet aircraft in the latter stages of World War II and in the immediate post-war period. It has been known for some time that a major portion of the energy returned to a radar detection system from an aircraft was reflected by the propeller. In addition, the engine configuration, particularly for the very large horsepower engines of the advanced propeller-type fighters, demanded large-diameter fuselage design even for small fighters. On such targets, the returned energy was sufficient with the techniques available to provide adequate warning for the speeds available. The jet aircraft, however, provided immediately a major increase in target velocity and slender propellerless fuselages. The overall result of these two changes was to reduce the effective range of detection systems by at least a factor of four and warning time by a factor of eight to one. As a result, nearly all of the radar systems so painstakingly developed during World War II were made obsolete, and development had to begin again. These difficulties are being further extended by the advent of supersonic aircraft with an even smaller echoing area, and a velocity so great that the horizon-limited range of radar may be insufficient. This is especially true in view of the tremendous destructive potential of even a single military plane carrying nuclear weapons.

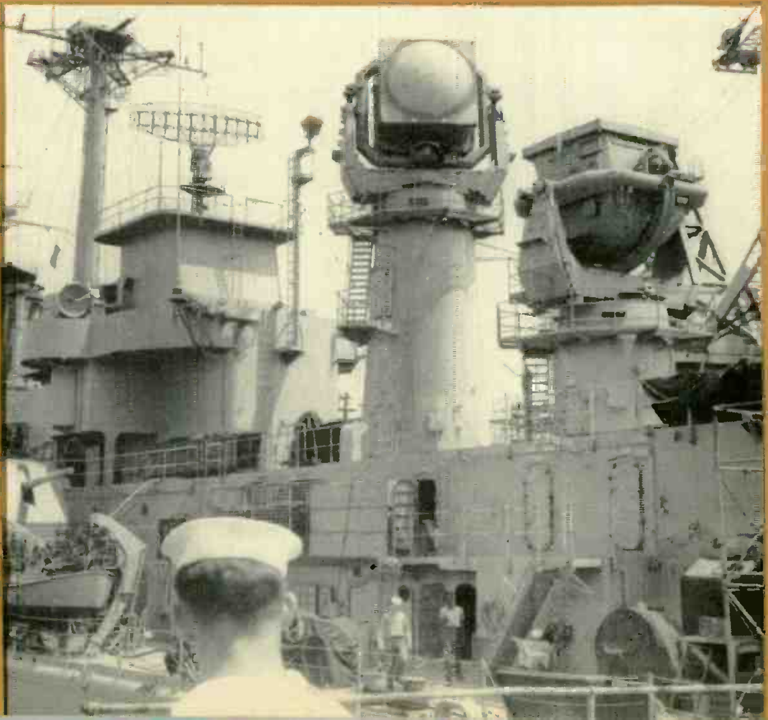
The next evolutionary step is already in the making. The introduction of ballistic-type missiles as offensive weapons not only introduces a further increase in target velocity with a virtual minimum of radar-detection area, but detection systems must also provide information on the precise location of the target at longer distances. A satisfactory detection system to meet this problem is only one part of the series of problems that a defensive system must solve to meet the ballistic-missile threat.



An Air Force tactical radar station, which includes a Paraballoon air-supported antenna, is housed in this air-inflated radome. The enclosed "three-dimensional" radar station on test furnishes range, azimuth, and altitude information for all targets within its 360-degree coverage range. This is a truly mobile, high-power, tactical radar set. All components, including the Paraballoon antenna, can be dismantled into 200-pound pieces.



The radar observer aboard a Texas Tower (the tower unit of an Aircraft Control and Warning Squadron) must keep constant watch on radar screen to detect radar echoes from aircraft, which show up as illuminated dots or "blips." *U. S. Air Force Photo*



Super radars for guidance of Terrier missiles installed aboard the guided missile cruiser *U.S.S. Canberra*. The radars have massive, turret-like antennae and resemble giant searchlights. *U. S. Navy Photo*

detection systems

Systems of special interest are those useful for aircraft detection, or for use in aircraft. The senses of human observers still form an important part of the defense system, but electronic devices are the basic detection systems. Although the detection process is the keystone of the system, associated computers and other equipment for effectively utilizing the information obtained are also part of the overall detection system.

Electromagnetic radiations covering the spectrum from radio to infrared are utilized in electronic detection systems. Various frequencies have their individual advantages and disadvantages. In general, the lower frequencies yield higher power, more sensitive receivers, and greater freedom from atmospheric attenuation. The higher radio frequencies favor higher antenna gain, smaller size and finer target discrimination and detail.

Active Systems—The usual detection system consists of transmitting high-frequency radio signals from a directional antenna and determining target position by noting the time for reflected echoes to return and the antenna direction. Transmission can be in the form of sharp pulses with relatively long listening periods between, which is the most common and most generally useful method. Another approach is to transmit and receive simultaneously and continuously. This system has advantages in simplicity and reduction in peak power requirements although it is poorly adapted to accurate ranging. Combination systems now under development may take advantage of the virtues of both systems.

Passive Systems—Systems that do not depend on radiation from the detection system are called passive systems. More limited in ability than active systems, they are valuable because of their "invisibility" to the target, since active systems cannot operate without betraying their presence to a target equipped with suitable detectors.

The airborne target may be forced to radiate radio signals to perform its mission. This permits ready detection by a simple receiver. While this gives direction rather than range, several ground-based stations can triangulate, and airborne detectors can frequently get rough range from the strength of the returned signals or triangulation along the flight path.

Infrared detection has great promise for detection purposes. Jet engines, rocket motors, and the skin of high-speed missiles are all strong sources of infrared radiation. Since infrared wavelength is extremely short, a few ten thousandths or an inch or less, precision optical systems are possible and provide accurate direction and crude range finding. A most promising system appears to be a combination of infrared for detection and direction finding, with short bursts of active radar for ranging.

special considerations

A number of special developments are pertinent to the application of detection systems:

Moving Target Indicators—Many times detection systems observe numerous targets, although only those that move, such as vehicles and aircraft, are of interest. To eliminate the confusion of numerous stationary targets, circuits have been designed to differentiate between moving and stationary targets. If the radar system itself is in motion, this motion is generally accurately known and its effect on the path length can be canceled out. Selection of moving targets only greatly increases the operator's ability to detect a target.

Automatic Alarm—The strain and monotony of ceaseless observation of detection-system indicators is fatiguing to the observer and results in a lowered performance efficiency. Circuits can be provided that determine when a new target moves into the field of observation, and actuate an alarm to alert the observer, eliminating the need for continuous scrutiny of the indicator. The importance of such a mechanism occurs in two areas. First, the reduction of the number of operators required and secondly, the increase in reliability of target detection.

The design of automatic alarm circuitry involves a statistical consideration of the noise or natural disturbances present in all electronic equipment. These disturbances are completely random and are in fact, generated by electron motion in the circuit components in the input stages of the radar detection system receiving elements. Such random fluxations can easily exceed a weak signal. This can be avoided if system performance is sacrificed. However, to avoid this sacrifice a technique of *signal integration* is frequently employed. In this circuit, the radar return from a given direction is added to previous returns from that direction. Since the noise fluxations are entirely random, the effect is to reduce peak fluxations in comparison with the desired signal returns that are repetitive and therefore accumulate.

Countermeasures—The violent impact of detection systems on the art of warfare has naturally placed high priority on the development of techniques for thwarting their effectiveness. These techniques come under the general heading of countermeasures.

Countermeasures can be divided into two general categories—those in which the target emits energy for the purpose of disabling or misleading the detection system, and passive systems that depend upon the dissemination of false reflection targets to confuse the detector.

In the first category the obvious and well-known technique is to transmit a powerful noise signal on the detecting system frequency to either block the receiver or at least obscure the radar echo. The system can be effective but has the disadvantage of being readily recognized, which permits the detection system to take corrective steps, such as an abrupt frequency shift. Much more subtle are systems in which a portion of the signal illuminating the target is amplified by the target and modified before transmission back to the detecting system, so that the detector will make an inaccurate determination of target position. This inaccuracy does not have to be large to completely protect the target from an unguided weapon.

One of the earliest but still effective passive confusion devices is the ejection from the target of large numbers of tiny foil reflectors, which are quickly disbursed in the aircraft slip stream and become an effective target of very large reflecting power that can obscure and protect the target.

airborne detection systems

Detection systems, primarily radar at present, have taken to the air. In all combat aircraft, radar eyes are a necessity. Transport aircraft, both commercial and military, are rapidly adopting radar to avoid severe weather. Military applications, however, heavily dominate in numbers, investment, and variety.

Airborne equipment is subject to many restrictions that make compromise necessary. Weight and space are at a premium, since every pound of electronic equipment requires ten pounds of airplane and fuel to carry it around. Antennas are limited in size to fit within the aerodynamic contour of the aircraft. Since the gain and target resolution of an antenna increases with the frequency of the radiation, short wavelengths must be used although both transmitter and receiver performance would be better at longer wavelengths. At wavelengths of one centimeter and shorter, severe atmospheric absorption of radiation exists. As an optimum compromise, most airborne radar equipment operates in the range of wavelengths between one and ten centimeters.

Reliability is of supreme importance in airborne equipment. Simplicity spawns reliability and yet the additional functions constantly being added to the detection systems imply added complexity. Consequently, design of airborne equipment challenges the engineer to obtain maximum results from the simplest possible circuits.

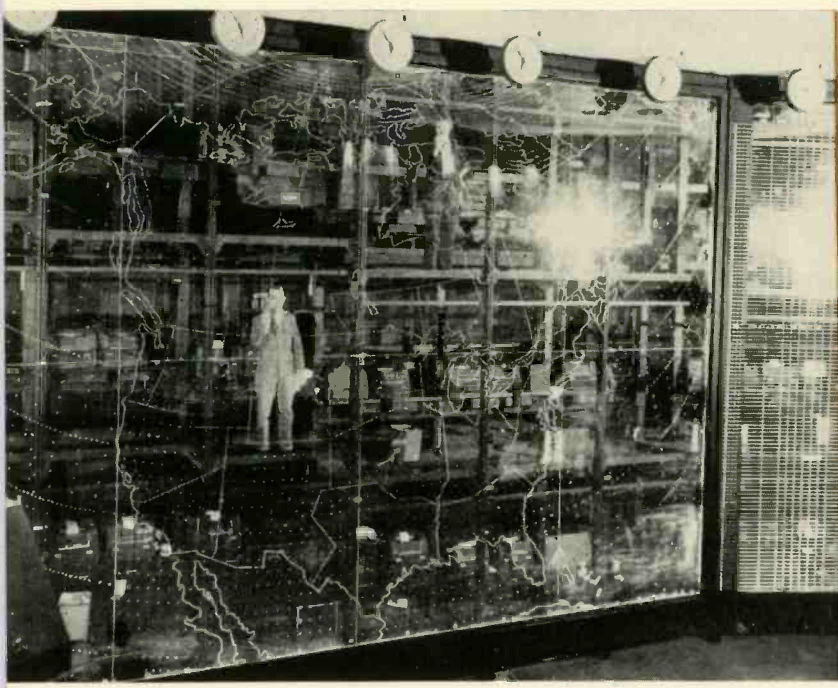
Airborne equipment is subject to extreme and rapidly varying environmental conditions. It is only minutes from the rarefied atmosphere of the stratosphere, where cold parts get colder and hot parts get hotter, to the penetrating humidity on a carrier deck. Protection from the shock of catapult take-offs and arrested landings competes with protection from the destructive high-frequency vibrations set up by a jet engine.

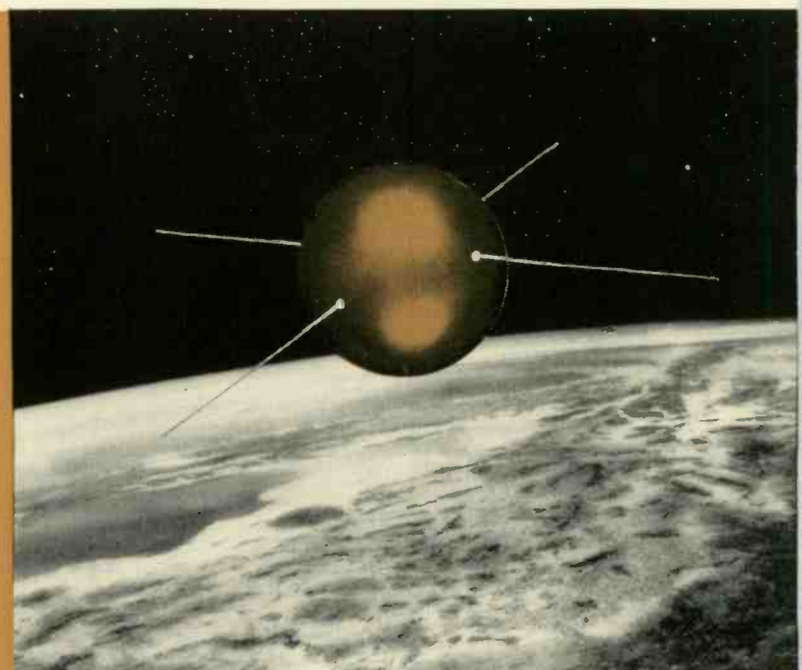
when other instruments were damaged or failed. The ability of radar to spot obstacles ahead and avoid hitting mountains through errors in course or altitude is well established.

Reconnaissance is a natural military application of mapping capability. Since specialized aircraft can devote much more space and weight to the radar than can a fighter or airliner, the quality of the information can be vastly improved. Modern equipment can accurately map large areas showing in fair detail such features as city streets, farm houses, and small boats.

Early warning of the enemy aircraft approach is accomplished by aircraft modified to carry large antennas and high-power detection systems. Such planes regularly patrol much of the coastline of our country.

Collision prevention with other aircraft is an important but as yet unsolved problem. The weight of the equipment and the aerodynamic drag of the antennas that are required by the present state-of-the-art constitute uneconomical penalties at this time. These technical difficulties will undoubtedly be solved in the future and this function made an important radar application.





uses of airborne detection systems

Airborne detection systems have a multitude of uses, peaceful and military. Leading the commercial applications is the use of radar to avoid turbulent and dangerous atmospheric extremes. This is made possible by the reflection of radar signals from precipitation that is present in such conditions. Radar enables the pilot to select routes that skirt areas of really violent turbulence.

Another valuable capability of radar, both commercial and military, is its ability to observe terrain being traversed in spite of darkness or poor visibility. Of course, the picture is not of optical detail but the portrayal of distinguishing terrain features is adequate for many applications. This also makes navigation possible with radar, provided that rivers, mountains, cities, lakes, coastlines, or other distinguishing features are present. Many a pilot has navigated safely home by radar

military combat applications

Any device that can do accurate ground mapping from an airplane is obviously a potential bombsight. Radar has been used for this purpose from its early days in World War II. Improvements in range and accuracy plus day and night all-weather capability have given radar a secure hold as the most important type of bombsight.

Of all military applications of radar, the radar-equipped interceptor is perhaps most appealing to the imagination, if any phase of war can be called appealing.

Directed to the target by long-range surface detection equipment, the pilot seeks and finds the enemy by radar and is guided on a suitable attack course by a computer that uses radar signals to analyze the attack situation. Operating strictly on electronic equipment, a pilot can destroy a plane he never sees. This was done for the first time in the Korean conflict using detection and guidance equipment designed and built by Westinghouse.

ground detection systems

One of the major characteristics of ground-based detection systems is the necessity to establish such systems as portions of rather extensive defense networks. In the days of World War II it was possible to operate on a point-defense concept, and hence a detection system could be associated with the immediate users of such information. The advance in aircraft capabilities and the necessity of achieving very high attrition rates because of the nuclear capabilities of enemy aircraft make isolated ground-based detection systems insufficient.

This point is clearly illustrated by the establishment of the DEW (Distant Early Warning) line of detection systems for the defense of the North American continent. For this line of outposts to be useful, the information gathered must be rapidly transmitted to a central point where effective warnings can be issued for all active and passive defense measures, including retaliation. The SAGE (Semi-Automatic Ground Environment) system further illustrates the necessity of networking detection system information. For not only is this information necessary for warning purposes but the actual defense mechanisms are dependent on such information for their effectiveness.

Combat operations center at Continental Air Defense Command headquarters at Ent Air Force Base, Colorado Springs. *U.S. Air Force Photo*

Artist's concept of the man-made scientific earth satellite passing over the lower part of the southeastern United States and Northern Mexico. The photographic background, which covers part of several states, was taken by the U.S. Navy from a Viking 12 rocket at an altitude of 143.4 miles. *U.S. Navy Photo*

To provide the information inputs that such defense networks require, the associated detection systems have been evolved along certain specialized lines.

Long-Range Search, Early-Warning Radars—In these detection systems, design parameters have been compromised to provide maximum range sensitivity. In general, they are characterized by lower frequencies of operation, lower space scanning rates, large pulse-widths, large ponderous antennas, and relatively poor definition of target information.

"Control" Radars—Here, different design parameters have been made to emphasize the accuracy or definition of the information obtained, usually at the expense of range. The necessity of looking frequently at targets that may be maneuvering has further imposed relatively rapid space-scanning rates. These radars are further characterized by relatively narrow pulse-widths and higher frequencies of operation.

Height-Finding Radars—Some systems are specifically designed to produce information on the angle of elevation or altitude of a target. Particular attention is paid to achievement of a specially shaped antenna pattern in the vertical plane, to provide accurate information. This separate class of radars imposes a serious problem of coordination and control, since the defense system must obtain height information with reference to specific desired targets.

Combined Three-D Radar Systems—These are essentially control radars that have integrally incorporated means to determine target height. This integration has imposed severe problems demanding the greatest skill in selection of design parameters and has unfortunately demanded an increase in radar complexity. A measure of this increase can be obtained by considering that a control radar normally handles about 100 000 pieces of information per complete space scan, and that imposition of height requirements multiplies the information content by at least a factor of 10, and perhaps by 100. It is nevertheless in this general direction of integrated systems that future progress can be foreseen. Where design compromise cannot provide sufficient or satisfactory performance, invention is required. Illustrative of this is the Paraballoon antenna, which by utilizing an entirely new technique has provided large radar antennas that can economically meet and resolve the dilemma of high-accuracy, high-performance systems. This solution has provided a springboard for further developments in ground-radar systems.

Commercial applications of the above types of equipment are largely concerned with the direction or control of air-traffic. For this task not only the radar systems but many of the other techniques of the defense system are well suited.

future

The evolution of detection systems will continue. As weapons technology advances, so will the means for detecting and defeating these weapons. Looking into the future, there are at least two discernible directions for this evolution. It appears that a natural result of the attempts to establish an earth satellite will be a series of detection systems mounted in space platforms, which can keep unfailing watch on all corners of the earth. The design problems associated with this type of system are tremendous. While nature supplies the vacuum, thus eliminating the restrictive confines of man-made vacuums and envelopes, the problems of weight, size, and reliability assume an importance an order of magnitude larger than at present. While today's aircraft requires nearly ten pounds of airframe and fuel to carry one pound of electronic equipment, a space station will probably need 100 to 1000 pounds of fuel and airframe to deliver this same pound of electronic gear. Since space platforms may well be unmanned, electronic equipment failure would result in an aborted mission costing hundreds if not thousands of times today's aircraft missions.

The second direction is concerned with man's age-old desire to "see in the dark." Research scientists, working with conductive solid-state devices and various means to amplify images are approaching this dream. Although no device can actually see in total darkness, the amount of light produced in the night-time sky is entirely sufficient for foreseeable devices to produce high-definition images.

The future for detection systems will be built on problems arising from weapons improvement, to be solved by the inventions and discoveries of the electronics industry. ■

AVIATION COMMUNICATIONS AND NAVIGATION ...TODAY AND TOMORROW

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■ The growth and progress of many services vital to air transportation must keep pace with the accelerating growth of air transportation if full aircraft potential is to be realized. One of these services is electronic communication and navigation, without which aircraft are limited to fair weather excursions. Today with accurate navigation and airport approach equipment available, commercial flights move regularly through all but the worst weather conditions. Some military planes equipped with the latest devices take off, perform their mission, and land in practically zero ceiling and visibility conditions. With further refinement and cost reduction, this type of operation will be possible for commercial carriers.

Compared to 165 airport radio stations operating in 1935, the US Civil Aeronautics Administration today operates over 575 airways communication stations and airport control towers, 365 four-course radio ranges, and 400 omni-directional range stations. In addition, the scheduled airlines operate through the services of Aeronautical Radio Incorporated over 500 communications stations along US domestic air routes. These services do not include an equally impressive number of stations operated by the military services for their flights.

Functions of navigational equipment

The services provided by electronic communications and navigational equipment can be grouped into three basic functions: *navigation*, *air-traffic control*, and *general operational traffic*.

Navigation—Navigation includes those devices that provide information to help the pilot determine his location with respect to a known point or points, and to guide him to his destination. The most basic navigation method is still faithfully followed by most pilots even in the most modern aircraft; this consists of plotting a course by dead reckoning from a known origin, using time of flight, estimated speed and course, supplemented by observation of ground check points where visual reference to them can be maintained. For long distances, over water or clouds, celestial navigation is possible. However, more and more dependence is placed on electronic navigation devices that can give continuous independent checks of position automatically, and further, can be utilized to actuate plane controls to automatically guide the plane.

Electronic navigation is performed by one of two basic principles. The first is to obtain by *radio direction-finding techniques* relative bearings from the plane of two or more identified points, such as broadcast or range stations. The intersection of the radio bearings establishes the plane's location within the accuracy of the observation. Direction-finding equipment is still carried on most commercial and military aircraft and can be tuned to CAA range stations or commercial broadcast stations; however, it is used more and more as auxiliary or back up to more modern and automatic methods.

A more modern version of this principle is the LORAN

(Long Range Navigation) system often used to provide navigational data to aircraft over the ocean. In LORAN, a master and slave transmitter each radiate carefully synchronized pulses in the 1.7—2.0 megacycle range. A radio receiver measures the time difference between reception of these two pulses. This time is translated into a hyperbolic locus of possible positions with respect to the two transmitters. Measurement of another pair of pulses from a second master-slave transmitter combination at different locations from the first pair produces a second locus; the intersection of the loci defines receiving point position. Positions can usually be determined within a few miles at distances of 1000 miles from the transmitters. Other similar systems operating at other frequencies and even higher accuracies are in use or are being developed, such as *Gee*, *Cylac*, *Decca* and *Radux*.

The second basic electronic navigational method is the *rho-theta* method where the relative bearing (*theta*) and the distance (*rho*) from a single known point establishes aircraft location. This method is in general use today in the form of VOR (Very-High-Frequency Omnidirectional Range) combined with DME (Distance Measuring Equipment). The VOR, operating in the 100–120 mc frequency range, transmits a characteristic signal over a line-of-sight range from the station. The characteristics of the signal received at a given point depend upon the relative bearing of that point from true north. In the United States, 1230 VOR stations are scheduled for installation, each on a separate (non-interfering) frequency with coded identification. This large number is required because VHF range is limited to line-of-sight, which is only 130 miles for an aircraft flying at 10 000 feet. DME operates at ultra-high frequency (in the vicinity of 1000 mc) from the same location as the VOR transmitter. To use DME, the aircraft transmitter sends out periodic interrogation pulses that trigger responding pulses from the DME station back to the aircraft. The round-trip time of each pulse is used to calculate distance between the aircraft and the DME transmitter.

Another similar system, called TACAN, has been developed by the military and combines both bearing and range functions of VOR and DME. *Navarho* is still another system of this type operating at low frequency (90–118 kc), which has been developed by the Air Force and provides *rho* and *theta* information as well as high reliability over long distances. Present indications point to an ultimate combination of the *theta* function of VOR and the distance function of TACAN, forming a VORTAC system for future official CAA use.

Air-Traffic Control—The second major function of aviation communications lies in the area of air-traffic control. With the tremendous amount of traffic using present day airspace, especially around air terminals, the air-traffic control problem becomes more critical daily. In brief, air-traffic control can be classified into two basic functions—enroute control, and terminal and ground-approach control. In each case, the object of the control agency is to move as much traffic as possible without running undue risk of collision or accident. To carry out this function, the control agency maintains tight control over the entire airspace under conditions of poor weather and visibility when instrument flight rules apply. During good weather, visual flight rules apply, and only the immediate terminal area is controlled. When instrument flight rules are in force, flight plans are adjusted by the control agency to allow adequate airspace around each flight to prevent collision. To continually check on flight progress requires frequent communication with the plane. In terminal areas the plane is constantly observed by radar, and voice instructions are issued by radio to guide it into the landing pattern.

Under instrument landing conditions, a plane can be brought down to the runway by ILS (Instrument Landing System) in which the pilot guides his aircraft by a pattern of signals radiated from the ground and displayed on his instrument panel to indicate his position and altitude with respect to the glide path to the runway, or by GCA (Ground Controlled Approach) in which the pilot is talked down by a radar observer.

The large number of planes in the terminal vicinity at one time and the relatively large amount of information that must be exchanged between planes and ground-control points make the communications problem critical. Further, the need for a much higher capacity traffic-control system for both military and civilian aircraft has become painfully obvious; yet the widely differing types of aircraft, speeds, and practices makes this a baffling technical and organizational task.

General Operational Traffic—The third category of communications covers general operational traffic, which includes identification for civil and military purposes, exchange of weather information, passenger and airline information, and emergency communications in any phase of flight. In military operations this phase of communications can involve a considerable amount of data of a widely varying nature. Although some data-link equipment is now used by USAF fighters, the vast majority of air/ground/air traffic is voice. In general, airlines use vhf while the military use uhf. Over 1750 channels, 100 kc wide, are assigned to aircraft use in the uhf band.

problems of communication and navigation

As can be gathered from previous discussion, a multitude of problems are associated with every phase of aircraft communication and navigation. In general, these problems might be grouped into several broad categories; in each, the practical answers are of great importance to the furtherance of air transportation and national defense.

Reliability—First is the need to discover or develop a method of transmission that is extremely reliable in the face of interference from a variety of sources. With the safety of a high-speed airliner dependent upon the split-second accuracy of information being exchanged with the control agency in a densely traveled terminal area, communications must be impervious to noise, harmonics, fading, and interfering signals.

To meet this problem of reliability a number of approaches offer promise. A better understanding of electromagnetic radiation phenomena derived from actual propagation tests will continue to add to our knowledge of circumventing natural radio transmission impediments. Westinghouse is operating a terminal of a 2000-mc tropospheric scatter link for the US Air Force and investigating propagation characteristics of this new multichannel communication means. In the future, scatter communication from ground to plane may be utilized.

Another approach has been brought to light by communication theory developments which indicate that the communication channel efficiency can be improved in the presence of noise by the manner in which the message is encoded and the form of transmission symbols used. The usual type of analog information (continuously varying signals) can be translated into discrete elements of binary information or "bits." These bits can be transmitted in a variety of forms or waveshapes, designed to achieve an optimum match to the transmission medium and to the type of detector. The symbols used (combination of bits to form letters) can be coded with some redundancy to make possible error detection at the receiver.

Another interesting approach to improved reliability is deliberate use of transmission redundancy by the technique of space, frequency, and time diversity. This technique combats degradations in the transmission medium by sending information simultaneously along two paths in space, or on two frequency channels, or by simply sending the information in the same channel several times. These methods are quite effective in overcoming multipath fading, produced by canceling signals arriving at the receiver from different transmission paths. However, they are not as effective in overcoming jamming or large-scale ionospheric disturbances.

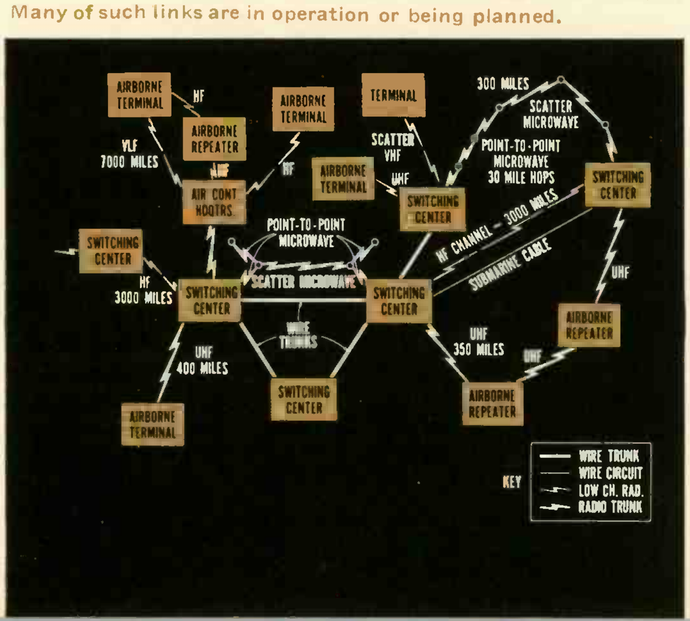
Still another effective method of combating interference lies in the method of modulating or adding intelligence to the radio carrier. Recent developments have shown single-sideband modulation to be superior to other methods under conditions of marginal signal strengths, multipath transmission, and enemy jamming. Along this line the present Westinghouse development program of single sideband for uhf scatter communication for the Air Force represents one of the firsts in the art, and is expected to materially improve long-range communications at that frequency (2000 mc).

Increased Information—A second basic need for airborne communication is an increase in information passed between the aircraft and the ground in a given time, but at the same time, a material simplification in the communicating process. This need is rapidly becoming more urgent with the increasing aircraft complexity and speed, and the increasing traffic handled in the terminal area.

Data Links—These problems point to the need for data links between the plane and ground, to automatically and reliably transmit required information at high speed. Data is sent with a discrete address to activate only the intended receiver. The information is prepared and transmitted in digitalized form, and utilized at the receiver to automatically activate the necessary functions or make appropriate indications. Identification, navigation data, traffic-control data and instruction, and other operational communications can be carried simultaneously in the data message. Systems are appearing that can exchange all the information needed to handle 120 aircraft on the same frequency in the vicinity of the station. The information from the plane might include identity, distance, bearing, altitude, heading, and speed.

The data link appears to be an important part of any general air-traffic control and navigation plan. An exchange of plane- and ground-gathered information on the plane location can be accomplished enroute, along with continuous review and alterations on flight instructions as a result of computer comparisons of the flight plans and progress of other planes within the area. *Rho-theta* type data on aircraft location will eliminate the necessity of expensive radar installation in all but the congested terminal areas. Extremely high-speed visual display and printing devices can display the data received from the link at rates of up to 10 000 characters per second.

This chart illustrates the many different types of transmission media used to achieve a world-wide communications network. Many of such links are in operation or being planned.



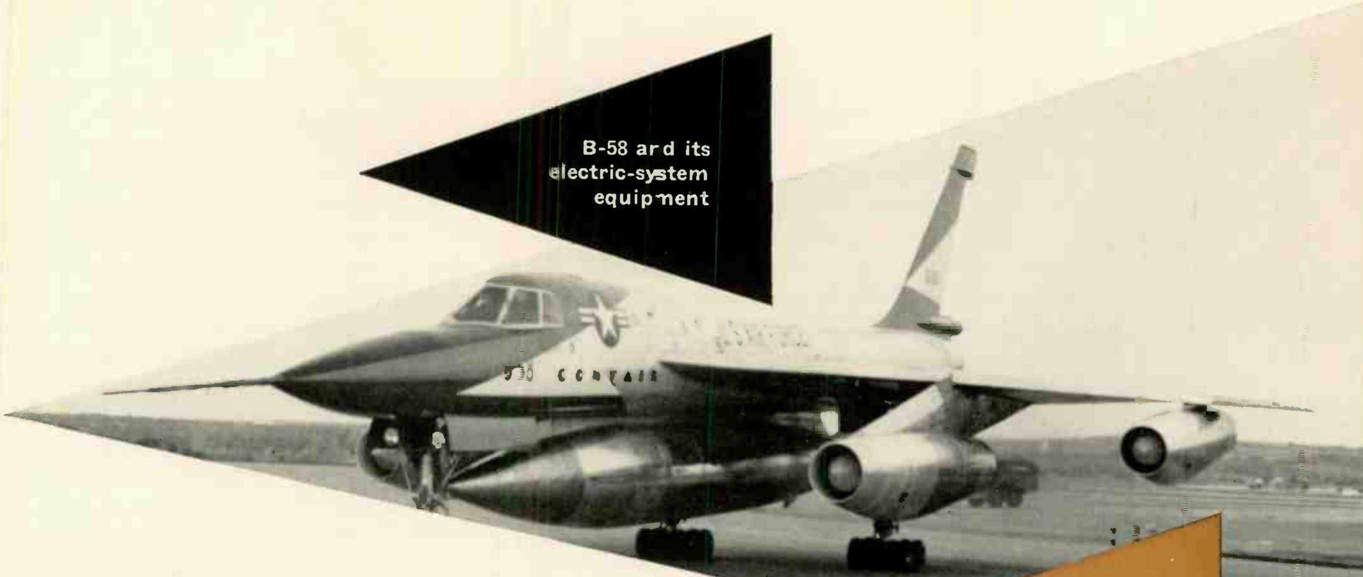
Major needs facing the industry in this general field are: an increase in the rates of data transmission without excessive increases in frequency band-width; high reliability without a serious reduction in information capacity; a universal data-link system that fits the needs of both military and civilian aircraft, but uses the same terminals and facilities; and airborne communications and navigation equipment that will not require extensive operator attention when switching from one terminal or route facility to the next.

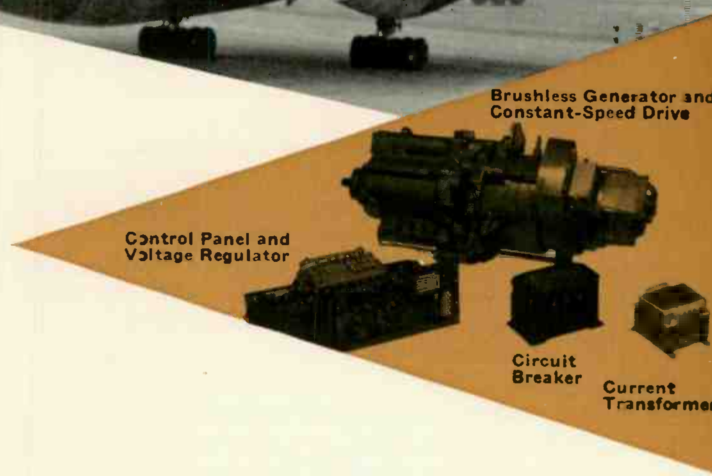
Long-Distance Communication—With the advent of long-range aircraft and global military strategy, extremely reliable long-distance communications from this country to US planes in various parts of the world is an urgent requirement. Many factors conspire to make this a most difficult task—atmospheric noise, solar magnetic storms, aurora borealis, size and dielectric limitations on aircraft antenna and power amplifiers, and, of course, the possibility of enemy jamming. Some of the new techniques discussed under increased reliability such as coding and new modulation methods should help the problem. However, the basic fact remains that distances are often too great to be traversed with known techniques. The use of very low frequencies and high power can achieve adequate communications from ground to air; but the long antennas and high power required make the return air-to-ground path impossible for any significant distance.

One interesting approach to this problem is the possibility of aerial relay stations carried in interposed aircraft where long-range communication is necessary. A series of interesting experiments were conducted a number of years ago by Westinghouse, Glenn L. Martin, and the US Army with an airborne relay station for re-transmitting television signals (Stratovision) at 250 mc and communication signals at 750 and 3300 mc. Investigations of this and other new methods of achieving 5000- to 10 000-mile communication channels from air-to-ground and ground-to-air are a part of Westinghouse long range major development programs.

Single Sideband—With the increasing demand for communication channels, the available frequency spectrum is rapidly diminishing. This has given great impetus to development of new techniques to utilize the spectrum more efficiently—to squeeze more communications into smaller channels. The most significant method recently introduced is single-sideband transmission, as compared to conventional double sideband or frequency modulation. Requiring only half the bandwidth needed for present amplitude-modulated signals, the channels available can be doubled, provided that accompanying stability problems can be solved. Recognizing the need for a quickly retunable, highly stable frequency source to capitalize on the narrower single-sideband signal, the Stacot exciter was developed. It can produce signals in one-kilocycle steps and with stabilities in the order of one part in 100 million for use both at high frequencies (2–30 mc) and at very high frequencies (225–400 mc).

With the tremendous importance presently accorded to military air power and commercial air transportation, and the pressing problems faced today in connection with communication and navigations to support each, an urgent demand exists for material progress in the art. This poses an opportunity for new ideas and superior products. The coming of the missile age with unmanned missiles replacing to a large extent manned military aircraft will increase pressure for larger capacity and more reliable communications over longer distances. ■





WEAPONS SYSTEMS PHILOSOPHY DICTATES AIRCRAFT ELECTRIC SYSTEMS

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The concept of weapons systems has dominated all military planning recently, since it affects aircraft and aircraft equipment. The starting point is the mission requirement; then the air vehicle is developed, along with its equipment and its ground support to carry out that mission. The chief impact this has on aircraft equipment, including aircraft electric systems, is conflict between the desire for highly specialized, special-purpose equipment on the part of the weapons-system contractor and the desire for economy and standardization on the part of both the equipment manufacturer and those responsible for logistic support of aircraft.

A partial solution to this dilemma is to make a distinction between *systems* and *equipment* requirements. Such a distinction is hard to maintain, since better performance of equipment and systems are always inextricably interwoven. The distinction is readily grasped, however, if the assumption is made that the electric system designer has available any standard component he could possibly require in setting up a system to meet the requirements of the basic weapons system. The standard components can always have better performance than the system minimum requirements, so long as the penalty for better performance does not compromise the performance of the weapon system. Thus, an infinite number of systems could be designed and supported by a large but finite number of equipment components.

By convention, the term "aircraft electric system" refers to a primary system delivering power to one or more main buses—not to the multitude of secondary electric systems. The primary power system on all modern United States military aircraft (i.e., those designed since 1955) and on all large transport aircraft (subsequent to the DC-7 and to the Constellations) is three-phase alternating current. The universal objective of all electric system designers is to assure continuity of power at the main bus. From this point on, no two systems are designed to meet exactly the same requirements. (See table on page 182).

Consider the problem confronting the electric-system designer, neglecting for the time being all problems of equipment design. Assume that the weapons-system contractor has not been selected, and that several potential contractors are working up proposals.

The factors entering into a system design proposal are:

1. *Preferences.* Different for each weapons-system vendor.
2. *Amount of power under various flight conditions.* Depends on weapons-system vendor's selection of other subsystems.
3. *Mission profile.* Flight speeds and durations at various altitudes—determines cooling conditions primarily.
4. *Heat sinks available.* Extremely important as speeds increase, since aerodynamic heating becomes significant at the speed of sound and increases as the second power of speed.
5. *Accuracy of frequency and voltage required.* This depends largely on the electronic subsystems chosen. In some cases frequency can be allowed to vary directly with engine speed, and in other cases frequency must be held so that the long-time cumulative error is less than five parts per million. Some equipment will tolerate plus-or-minus five percent voltage accuracy, while other equipment requires voltage held to plus-or-minus one percent and recovery within 25 milliseconds from transient disturbances.
6. *Performance required under fault conditions.* Requires evaluation of possible faults, probability factors, damage evaluation, separate evaluation of effect on mission and effect on return to base.
7. *Automatic features required.* Small crews and high-speed performance dictate minimum attention under all conditions.
8. *Weight and space.* The weapons system allows the contractor almost a free hand; previous practice was to use standard government-procured equipment.
9. *Shock and vibration.* Both are becoming more severe as a result of high-thrust engines and aerodynamic loads at high speeds, hence a trend to static devices.

The systems required on modern aircraft run the gamut from hovering aircraft (helicopters), VTOL (vertical take-off and landing), STOL (short take-off and landing), through subsonic aircraft such as the B47, B52, and commercial jet transports, to the supersonic vehicles such as the century fighters (F102, F104, F105), supersonic bombers (B58), and the intercontinental ballistic missiles (Atlas and Titan). The systems designer has to provide for speeds from zero to over 15 000 miles per hour, altitudes from a few feet to over 50 miles, from the crude power needed for de-icing to the precision power required for elaborate inertial navigation systems, and for magnitudes of a few kilowatts to perhaps 5000 kilowatts someday for nuclear-propelled craft.

In actual practice, the development of mission requirements, system requirements, and apparatus go hand-in-hand, with considerable interplay or "feedback." Aircraft can attain high speed only at high altitude; brushes do not maintain lubricating properties over a wide range of altitude and so brushless generators were developed. Air is extremely rarefied at high altitude and not very effective for cooling; it is still less effective when heated by high speed, and so new cooling schemes must be developed. High speed implies high thrust and aerodynamical buffeting; both cause extreme vibration so that calibrated electromagnetic relays are no longer suitable for control functions and static devices must be developed. Closer and closer limits are set on the electronic devices. Electronics engineers demand perfect voltage, frequency, wave form, phase angle, and transient performance; the weapons-system manufacturer has to work out the best compromise between the perfect and the possible.

The new watchword is *reliability*. Long a pious generality, this word has now assumed real mathematical significance. An oversimplified definition of percent reliability is the number of successful missions per 100 attempts. Reliability criteria for each subsystem must be fed into the computations in achieving satisfactory overall weapon reliability.

Because, for most mission requirements, a-c systems give higher overall weapons system reliability, they have replaced d-c systems. D-c power generation once was assumed to have an insurmountable advantage in ease of accomplishing parallel operation, but ten years of experience on the B36 and subsequent aircraft have proven parallel operation of a-c generators both practical and reliable.

Historically, the decision to provide the B36 with an a-c system was dictated by its intercontinental mission, and the success of the airplane program was staked on the ability of industry to make the hydraulic drive a reality. Although now there are other practical ways to obtain constant speed, such as, for example, the engine-bleed air turbine used on some B52 airplanes, the hydraulic drive is still predominant, both as to number of units in use and number of airplane types on which it is installed. Ratings at present cover a range from about 10 to 60 kva. Significantly, a-c systems with hydraulic constant-speed drives were chosen by the first three American manufacturers to develop commercial jet transports.

The B36 airplane was not only the first operational airplane with a primary a-c electric power system, it was the first with what might be called an "engineered" electric system. Operation under both normal and fault conditions was studied thoroughly and fault protection provided to a degree that represented a major breakthrough from all precedents.

Even so, the salient features of the B36 system were largely dictated by state-of-the-art limitations of equipment as visualized about 1945. The 40-kva generators were two-bearing machines, with integral exciters, fairly "stiff" electrically—all features that have stood the test of time. Ability of generators to withstand increasingly severe environments has been improved considerably, but about the only improvement affecting system electrical characteristics directly has been reduction in harmonic voltages to a present value in the order of two percent total rms harmonics in the line-to-neutral voltage wave.

Carbon-pile regulators were used on the B36, and on many later airplanes. These regulators, thousands of which are still in use, are rugged and capable of excellent performance when properly maintained. The voltage regulator on an a-c parallel system must, of course, balance reactive load as well

DRIVE AND ELECTRICAL SYSTEMS FOR WESTINGHOUSE EQUIPPED PLANES

Note ① System Requires ±1 Volt Regulation and 400% 3 Phase Short Circuit Current

Note ③ System Requires Voltage Recovery to ±5% Regulation in 0.05 Second Following Load Switching

*Indicates Systems on Which Westinghouse Has Prime Responsibility for Drive as Well as Other Electrical System Components

AIRPLANE	MANUFACTURER	PAR.	ISOL.	DRIVE	GENERATOR	REG.
B-36	CONVAIR	●		SUNDSTRAND	4-40 KVA	CP
B-47	BOEING		●	ENGINE	2-20 KVA	CP
B-47E	BOEING	●		SUNDSTRAND	2-40 KVA	MA
B-52	BOEING	●		THOMPSON & GE ATM	4-60 KVA	CP
*B-58	CONVAIR		●	SUNDSTRAND	3-40 KVA	MA
F-102	CONVAIR		●	ATM	1-26 KVA	MA
F-103	REPUBLIC		●	AIR ATM	1-20 KVA	MA
F-105	REPUBLIC		●	AIR ATM	1-30 KVA	MA
C-130	LOCKHEED		●	ENGINE	2-40 KVA	CP
KC-135	BOEING	●		SUNDSTRAND	3-40 KVA	MA
CL-28	CANADAIR	●		SUNDSTRAND	4-40 KVA	MA
P5M	MARTIN	●		SUNDSTRAND	3-40 KVA	CP
XP6M	MARTIN	●		SUNDSTRAND	3-40 KVA	MA
*ZPG-3W	GOODYEAR	●		SUNDSTRAND	2-40 KVA	MA
*A3J	NORTH AMERICAN		●	SUNDSTRAND	2-30 KVA	MA
707 (40 KVA)	BOEING	●		SUNDSTRAND	4-40 KVA	MA
707 (30 KVA)	BOEING	●		SUNDSTRAND	4-30 KVA	MA
F-27	FAIRCHILD		●	ENGINE	2-15 KVA	CP
T-38	NORTHROP		●	ENGINE (GEAR BOX)	2-8 KVA	MA
SM-62	NORTHROP		●	SUNDSTRAND	1-60 KVA	MA
WV-2	LOCKHEED		●	ENGINE	2-30 KVA	CP
RC-121	LOCKHEED		●	ENGINE	2-30 KVA	CP

LEGEND
CP —Carbon Pile Regulator
MA —Magamp Regulator
OV —Overvoltage Protection
UV —Undervoltage Protection
OE —Overexcitation Protection
UE —Underexcitation Protection
US —Underspeed Protection
UF —Underfrequency Protection
AP —Automatic Paralleling

as maintain the system voltage level. There should be no interaction between real and reactive power sensing.

Elimination of all drift in regulator calibration was impossible and this limited the accuracy of reactive load division. The error amounted to about 24 percent of nominal rated capacity and theoretically, at least, reduced overall system capacity. By contrast, the modern static Magamp regulator has negligible drift. Reactive load division can be controlled to within six percent of the perfect value, and full theoretical system output is available without endangering synchronism or thermal limits.

Precise control of reactive load balance pays further dividends in fault protection. On the B36, a relatively crude exciter ceiling relay operated after a generator had put out maximum excitation for some rather unpredictable length of time. The generator was then taken off the line and the exciter circuit opened. Coordination was difficult, calibration uncertain, and the relay couldn't distinguish between a heavy overload and overexcitation resulting from a fault. All this is changed with the modern over-and-under excitation relaying system made possible by the precision Magamp regulator used on modern systems. Selective protection against excitation faults is positive and immune from false signals.

Another improvement that pays ultimate dividends in reliability is the so-called *isochronous governor* for the constant-speed drive. Originally, a speed-droop system was used for real load division on the B36. Nominal frequency was obtained at about 75 percent load when everything was in proper adjustment. From no-load to maximum overload, frequency shifted from about 420 to about 380 cycles. When speed droop is used for load division, a small error in speed setting causes a large shift in load between machines. Consequently, to make the error in load division tolerable, the shift in frequency as the load on the system changes must be considerable. Thus, poor load division might overstress the drive mechanism, and poor frequency regulation handicapped the performance of the electronic "black boxes." Perfection of a precision governor, sensitive to both absolute frequency and to load unbalance, has now made it possible to control steady-state frequency to plus-or-minus 0.25 percent (399-401 cycles). This makes the "black box" designers happy, makes automatic paralleling feasible, and helps eliminate the necessity for a flight engineer.

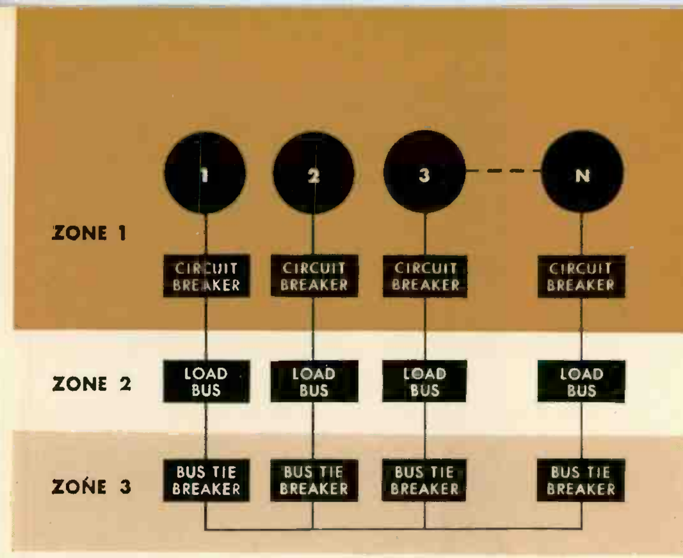


Fig. 1—Protection and control zoning for a parallel a-c system

The main bus on the B36 was of the so-called ring type. Each generator was tied to the bus through a single circuit breaker, and all loads were brought to the one bus. The modern parallel system uses the bus arrangement shown in Fig. 1. Parallel operation is obtained when the bus tie breakers are closed. Any load bus can be supplied through the tie breaker even though a fault in a generator or feeder has opened the generator breaker. Even a failure in a load bus does not cause serious trouble, since provision is made to transfer essential loads between buses. The generator associated with the defective bus is lost as a source of power, and it may be necessary to monitor some nonessential loads. All of the switching, however, is fully automatic and almost instantaneous, so that continuity of power is assured.

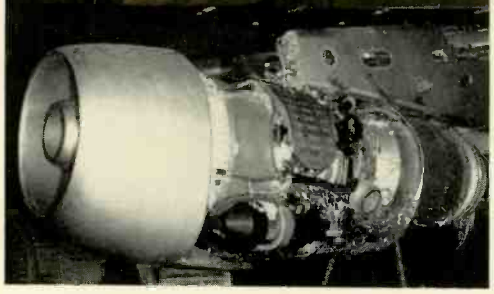
By modern standards the B36 had a large crew and it was not difficult to provide a flight engineer. The modern military airplane is designed to very different mission requirements. On a fighter, the crew may be a single pilot, and even on a

CONTROL AND PROTECTION													AUTO	MANUAL	REMARKS
OV	UV	OE	UE	US/UF	AP	PS	OP	DP	NS	EC	GCR	T-R			
								●		●	●			●	
●								●		●	●			●	
●	●	●	●	●	●	●		●			●		●		First Automatic Parallel A-C System
●	●			●				●		●	●			●	
●	●			●				●			●			●	First Oil-Cooled Brushless A-C System (See Note ①)
●								●			●	●		●	
●	●			●							●	●	●		Oil-Cooled Brushless System
●	●			●							●	●	●		
●								●			●	●		●	
●	●	●	●	●	●			●			●	●		●	
●	●	●	●	●	●		●	●			●	●	●		Westinghouse General System
●								●		●	●			●	
●	●	●	●	●	●	●	●	●			●	●	●		
●	●	●	●	●	●	●		●			●	●	●		Same as B-47 System
●	●			●			●	●			●	●	●		Oil-cooled Gen. with Pilot Exciter, Static Con., High-phase Takeover Reg. (See Note ②)
●	●	●	●	●	●			●		●	●	●	●		Brushless Air-cooled Generators, Static Controlled
●	●	●	●	●	●			●		●	●	●	●		Brushless Air-cooled Generators, Static Controlled
●	●								●		●		●		De-icing System Only
●	●			●							●	●	●		First Trainer A-C System, Air-cooled Brushless Generators, Static Control
											●			●	Missile Power System
●								●		●	●			●	
●								●		●	●			●	

PS —Phase Sequence Protection
OP —Open Phase Protection
EC —Exciter Ceiling Protection
DP —Differential Current Protection

NS —Negative Sequence Protection
GCR —Generator Control Relay
T-R —Control Power Transformer-Rectifier
ATM—Air Turbine Motor

Control and protective equipment on KC135 jet tanker



40-kva alternator and Sundstrand drive on KC135 jet tanker

supersonic bomber three men are all that can be carried. Hence, operation of the electric system must be practically automatic. If the system is to be paralleled, it must be done automatically, at the first instant frequency and phase relationships are correct. If a fault occurs, the system must evaluate the new conditions, decide what to do, and perform the necessary switching with negligible effect on the connected loads. For all practical purposes, the flight engineer is now replaced by a computer.

Basic system philosophy has reached a stage where it will remain status quo until a revolution occurs in the generation of power. Before speculating on such a revolution, consider some of the refinements in performance being developed.

The outstanding trend in the power-system field is the requirement for greater and greater environmental extremes with only nominal increases in weight, and with ever-improved performance. Consider generators, for example. The original 40-kva generator for the B36 weighed 75 pounds and used a magnesium housing; had no requirement for line-to-neutral harmonics; was rated on the basis of —40 degrees C cooling air at 35 000 feet; specified no limit for voltage unbalance with unbalanced loads; required an overspeed test at 9000 rpm; and possessed rather marginal brush performance at 50 000 feet. Operating at the same rated speed of 6000 rpm, the 40-kva generator for the Boeing 707 jet transport weighs 86 pounds, with no magnesium permitted; has less than 2½ percent harmonic content line-to-neutral; is rated on the basis of +120 degrees C cooling air at 50 000 feet; must have less than two percent voltage unbalance with a single-phase load of ⅓ rated line current; is given an overspeed test at 11 000 rpm; and operates without brushes. The 40-kva generator for the B58 is another advanced design. Not only is this machine brushless, it is "cooled" with oil entering at 150 degrees C.

The development of brushless generators deserves emphasis. Not only does this solve the impossible problem of compounding brushes to function over fantastic ranges of humidity, oxygen density, and temperature, it eliminates a major difficulty in matching generator and regulator characteristics. The environmental ranges cause variations in brush contact drops; these variations cause extreme and erratic changes in circulating currents, and the circulating currents change the gain of the excitation system. At the same time, independent variation in machine temperature can change the machine time constants by a factor of two to one. It is not surprising that high-sensitivity, fast-response regulation was nearly impossible before the brushless machine.

Static voltage regulators have already been mentioned. Not only does the Magamp regulator eliminate wear problems of the carbon discs in the carbon-pile regulator; it also eliminates erratic operation caused by excessive vibration on a magnetomechanical system, as well as the inherent insensitivity when calibration and power handling are combined in a single device. Another development appears close at hand. Experimental regulators have been built using transistors for controlling excitation; availability of high-power silicon or other high-temperature transistors will make possible a high-performance regulator with 25 to 30 percent the volume and weight of the Magamp regulator.

Other exciting new developments are the static decision-making or "logic-circuit" control and protective panels developed for use where excessive vibration made electromechanical relays useless. These panels are the "computers" mentioned previously. The reliability of static computing panels is such that they are rapidly replacing panels with conventional relays even where excessive vibration is not a problem. Although semiconductors are expensive at present, their cost is decreasing and a semiconductor scheme probably will be the ultimate choice.

Speculation on the future is always interesting. A recurrent dream is the achievement of controlled frequency independent of rotational speed. Most of the schemes proposed simply put power proportional to make-up speed into the drive system. This might be tolerable for small ratings and small speed variations, but is impractical for a two or three-to-one speed range and for any real capacity. The next most popular scheme is to generate d-c or rectify wild-frequency a-c, and then convert the d-c to a-c of controlled frequency. This has been done for small amounts of power. The problems in developing a full-scale system to operate on this principle are considerable, but probably not insurmountable.

The size of future electric systems depends on many complex factors that determine the proportion of secondary power handled electrically, pneumatically, and hydraulically. Total secondary power tends to go up with aircraft weight, probably about directly. It also goes up with speed, with some evidence in past experience indicating that the proportionality factor is at least speed squared. If the future continues the trends of the past, secondary power systems are going to involve thousands of horsepower in the next 10 to 20 years.

How can such amounts of power be generated? As long as conventional rotating engines are used, hydraulic drives can probably serve the purpose. A different method, say by solving the problem of static frequency conversion equipment, immediately introduces a generator problem. Large d-c generators will be impractical. Large a-c generators operating over a wide-speed range are far from simple engineering problems. Add temperatures reaching 800 degrees F or more, surroundings saturated with intense nuclear radiation, and it becomes apparent that engineers have some tough problems ahead.

So far, the existence of a prime mover has been assumed, but such an assumption is hardly justified. Best predictions are that no rotating engines will be used and that chemical or radiant energy will have to be converted to the desired electric energy, as directly and efficiently as can be accomplished. The electric systems designers of the next decade will be making science facts out of science fiction. ■

GUIDED MISSILES

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The *Bomarc* interceptor missile is hurtled into the air with a booster rocket; when the rocket burns out, two ramjet engines take over. *U.S. Air Force Photo*

From the primitive spear to the arrow to the gun, the trend of history has been toward faster and further-reaching missiles with greater lethality upon impact. The basic difficulty with all these devices was (and in some cases still is) the operator's lack of control over the projectile once it left the launching engine. Target motion during the missile flight, wind effects, deflections caused by air turbulence, and in the case of long-range projectiles, varying densities of air strata all contribute to inaccuracy of aim. The advent of anti-aircraft guns for shooting at fast targets intensified these problems and called for more elaborate schemes to anticipate target motion, and aim the projectile on an accurate interception course. Even with many advancements, the aim of an ordinary anti-aircraft gun or even field or naval guns is far from perfect. The obvious need was a device that could be controlled during flight, and its course corrected to account for the various disturbing factors—a *guided missile.*

The guided missile is basically a projectile, which includes a destructive warhead and devices for propelling it, guiding it to the target, and keeping it flying straight. The guided missile must also contain power sources for its various auxiliary services, and in some cases transmitters to enable its controller to locate the missile during flight.

Guided missile development had to await development of several basic components: First of all, the motor, then the aerodynamic know-how to properly design the airframe, and then a means for guidance.

Guided missiles today range in size from a few hundred pounds to 10 tons or more. Some employ simple guidance systems; others are very elaborate and require huge guidance installations. Modern missiles can be classified in several basic categories (Fig. 1), which include: (1) surface-to-surface; (2) surface-to-air; (3) air-to-surface; (4) air-to-air; and (5) special applications (air-to-underwater, surface-to-underwater, underwater-to-air, underwater-to-surface.

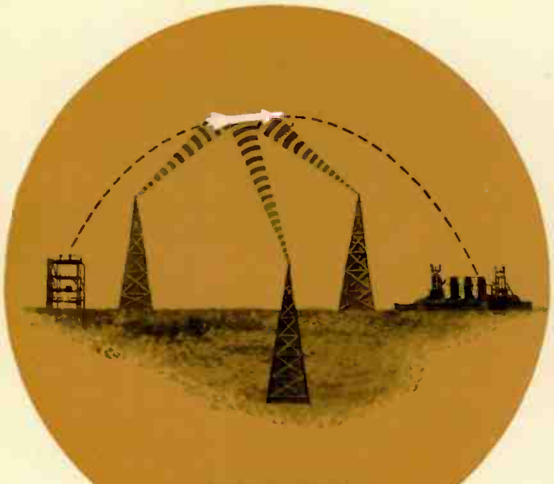
guidance systems

A primary technical problem in guided-missile design is the guidance system, without which the missile is little more than a cannon shell. Several basic guidance schemes are in existence:

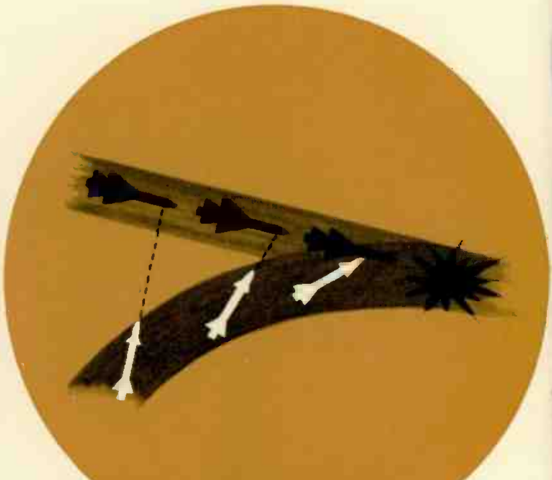
Guidance by wires—This system is used today in simple anti-tank missiles, particularly in a French version. The system was also employed by the Germans during World

1a—GROUND-TO AIR AND GROUND-TO-GROUND MISSILES

1b—AIR-TO-AIR AND AIR-TO-GROUND MISSILES


2—COMMAND GUIDANCE


3—BEAMRIDER


4a—PURE PURSUIT

War II in one of their air-to-air missiles, but is now practically abandoned because of the obvious difficulty of stretching a wire between the ground or the aircraft and the missile. In the French version of anti-tank missile, the operator fires the missile while keeping the target within the sights of the telescope. The operator keeps the missile centered on crosshairs by manipulating a control box that transmits appropriate signals to the missile control surfaces.

Command Guidance—This guidance method uses coded signals from the launcher (Fig. 2). Generally the method performs as follows: a ground radar tracks the target, and knows its bearing and range; the missile is fired, and guided by appropriate signals from the ground toward the target. The system is similar to wire guidance, with the wire replaced by a radio link. A related method used in the Matador missile provides continuous electronic signals that blanket the area between the missile launcher and the target. The missile is preset to fly in a certain path and derives its information from these radio signals. This system has the disadvantage that radio waves, especially over long distances, become easily distorted so that guidance information becomes decreasingly accurate as distance increases between the missile and launching station.

Beamrider—In this system, a radar tracks the target continuously and keeps locked on it (Fig. 3). The missile is launched in the radar beam and follows the beam until it hits the target.

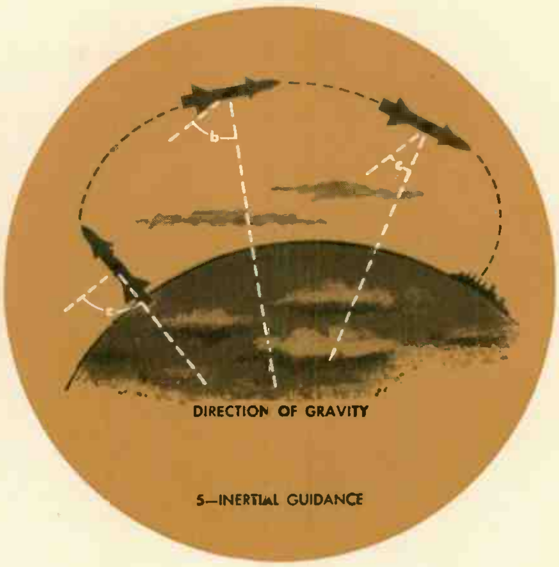
To achieve accuracy, the beam from the radar must be narrow. At the same time, the missile must be launched from a place somewhat removed from the radar to prevent burning the radar with exhaust flames. Therefore, the missile must be aimed to intercept the radar beam (be "captured" by the beam). With a narrow beam, this is difficult. Therefore, most systems use two beams—a narrow beam insures accurate guidance, and a broader beam centered with the narrow beam insures "capture." The missile is launched towards the beam without requiring excessive accuracy and is first captured by the broad beam, which then pulls the missile to the center of the narrow beam. The system is relatively simple and economical, and requires relatively little complication, within the missile or on the ground. But it has the drawback that the missile, towards the end of its flight, is forced into high lateral accelerations unless the target is flying directly toward or away from the radar. The system is also somewhat inefficient in utilization of the ground equipment.

"Homing" types of guidance—These are the most modern types and require a greater degree of intelligence in the missile than do the other systems. Homing type guidance systems are either *active* or *passive*. In the passive system, a radar illuminates the target and reflections from the target are "seen" by the missile. In the active type, the missile is equipped with its own radar, which illuminates the target and the missile zeros in on the return signal.

A homing missile can follow several types of trajectories: *Pure pursuit* (Fig. 4a), in which the missile constantly aims at the target. This system requires longer flight paths than other more modern systems. It was used in early German missiles but is now almost entirely obsolete. *Proportional navigation* (Fig. 4b), in which the missile is automatically aimed to achieve a collision course with the target. This is the most modern system and is widely used. Other guidance systems are *deviated pursuit* and the *constant-bearing courses*.

Inertial guidance—Some drawbacks exist with the guidance systems previously discussed, primarily because guidance occurs by means of radio signals, which can be detected by the enemy to reveal valuable information on attacker position. In addition, the enemy can use his own signals to attempt to jam or seize control of the missile. The other principal drawback is that electronic guidance by radar only works within line-of-sight; as soon as the distance becomes so great that the earth's curvature is involved, radar signals cannot follow the missile. To obviate these two difficulties in long-range surface-to-surface missiles, the *inertial* guidance system is used. This system is based on the use of gyros, spinning masses that maintain their attitude in space regardless of missile motion (Fig. 5). By comparing the direction of the force of gravity with the preset gyro direction, the missile can tell when it has reached the target. In theory the system is fool-proof, but it requires extremely accurate gyros, which are very delicate instruments. Furthermore, accurate knowledge of the direction of the force of gravity is difficult to obtain in a moving missile. Considerable effort is currently being expended by various agencies and companies to correct these drawbacks.

Guidance by stars—This type of guidance is similar to that used by ships. The missile is equipped with special



instruments that observe certain star positions, and compare these positions with force-of-gravity direction. When the right position is reached, the missile automatically dives to bomb the target. Again, the major difficulty is accurate knowledge of the direction of the force of gravity.

Combination guidance—A missile weapon system may involve combinations of the above types of guidance. For example, one ground-to-air missile system uses command guidance during the midcourse phase until the missile is in a position to "acquire" the target with its own active homing system for terminal guidance. Another guided missile system uses a modified beamrider and passive-homing-guidance combination.

missile components

A typical cut-away view of a missile is shown in Fig. 6. The following principal components are needed for a successful missile:

Motors—Numerous types of motors are used for guided missiles, ranging from jets to rockets. Use of any motor depends upon the application. Solid or liquid fuels are used for propelled rockets, pulse-jets for subsonic missiles, and ram jets for supersonic missiles. Some missiles employ a combination of rocket boosters to bring the missile to supersonic speed, after which a ram jet takes over.

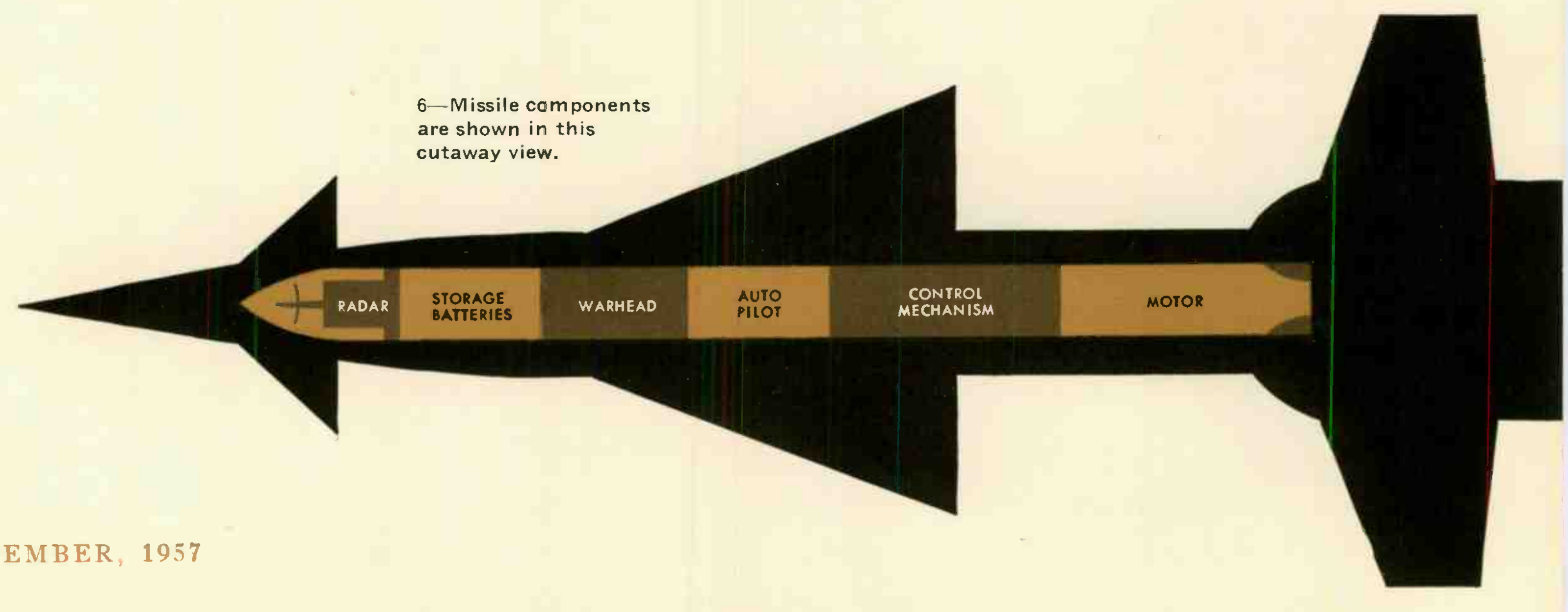
Warheads—This "business" load of the missile ranges from a few tens of pounds to hundreds of pounds. Generally speaking the efficiency of a missile in terms of warhead weight carried for a given missile weight is low. A typical medium-range missile carrying a hundred-pound warhead may weigh as much as 5000 pounds. Warheads perform their destructive action by means of fragments, pure blast, or by other devices now under study. In the future, most warheads will probably be of the nuclear type.

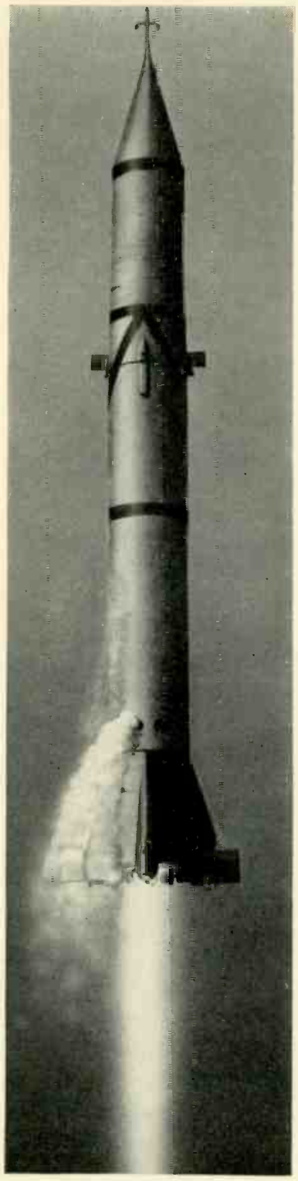
Autopilot—This mechanism is required to keep the guided missile flying straight, in the same manner that a pilot (or autopilot) is required for aircraft. In fact, while an aircraft should be able to fly all by itself after the course is set, any small disturbances (winds, changes in balance, etc.), would soon deviate the aircraft from its proper course unless they are properly corrected. The heart of the autopilot is the gyro. Appropriate equipment senses differences in aircraft attitude with respect to the gyro and commands rudders or control surfaces to correct the discrepancy.

current developments

A typical example of present missile development is the Bomarc, an Air Force surface-to-air guided missile capable

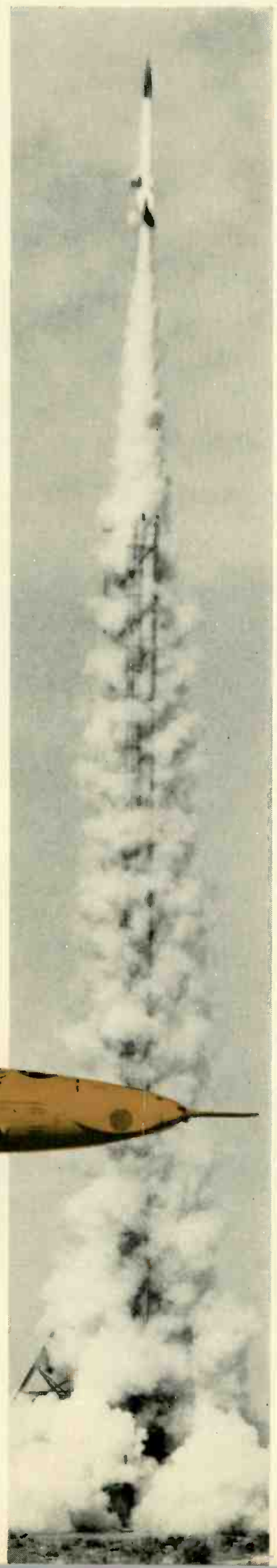
6—Missile components are shown in this cutaway view.





The Army's *Redstone* missile in flight.
U.S. Army Photo

Navy *Cougar* with *Sidewinder* missile.
U.S. Navy Photo



Launching *Aerobee* guided missile.
U.S. Air Force Photo

of destroying high-flying enemy bombers at considerable range. The ground guidance equipment uses ground-based radar data to guide the missile to a position from which the missile guidance unit can find the attacker, and then navigate to a collision path.

The ground-guidance system for the Bomarc is designed to realize maximum effectiveness from the entire weapon system. It provides a broad area defense so that many cities can be defended by each network of ground-guidance systems and missile bases. Studies are being made to optimize the weapon-system performance against targets that try to avoid Bomarc attack by flying "evasive" courses. Also techniques are being developed to minimize the effectiveness of enemy attempts to confuse the weapon system by electronically "blinding" ground and missile radars, or "jamming" the radio command link.

An indication of the high degree of know-how, and of the advanced thinking applied to the growing missile field can be gleaned from the quality and number of studies performed in recent months. Considerable time and effort have been expended on bomber defense, one of the most intriguing of current-day air-warfare problems. The bomber, in its attempt to reach the target, must defend itself against a wide variety of enemy countermeasures, which include interceptor aircraft and missiles of the Bomarc type. Defensive action, originating in the bomber's central data computer, or "brain," must select the weapon that will most effectively thwart the enemy. This may entail transmitting radar signals destined to "jam" enemy tracking devices; it may necessitate using false targets as a confusion aid; or as a last resort, launching a defensive missile.

The Air Force has asked for a bomber-defense missile system for the projected nuclear bomber. Navy interest in a defensive system for its heavy aircraft initiated another study that advocates a rather unconventional missile form for aircraft protection against rear attacks.

Both projects required intensive research into the basic concepts of air warfare, to achieve a system of the future capable of fulfilling its tactical requirements, but which is at once producible, reliable, and of low cost to the Armed Forces.

Weapon-system development has resulted in the extension of fire-control systems, formerly restricted to guns and rockets, to include missile capabilities. All-weather interceptors flying against enemy aircraft can now unleash long-range, highly accurate air-to-air guided missiles at safe distances and achieve a higher enemy attrition rate than was formerly possible. Tie-in of the fire control "brain" to an automatic flight control system (an advanced type "autopilot") has been accomplished to provide both stabilization and guidance of the aircraft while tracking the target—all without pilot aid.

The challenge of space flight has initiated many fundamental studies, including those directed toward improving inertial navigation systems, which are destined to answer the many problems of precision, long-range navigation. A missile navigation system that is invulnerable to enemy jamming, insensitive to weather, and completely independent of ground aids for navigation is the ultimate for long-range flight both over the earth's surface and in outer space. Out of these continuing studies will come solutions that will enable us to guide missiles, not merely as weapons of war, but as vehicles of peaceful transportation, to their solar destinations. ■

TESTING TOMORROW'S AIRCRAFT

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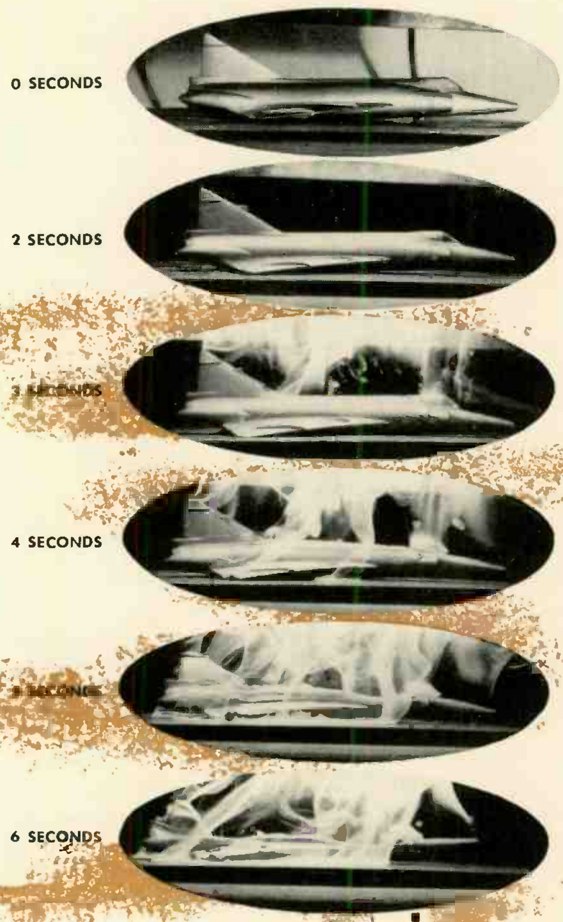


Maintaining America's qualitative air superiority has been described as "running like mad to stay in the same place." Much of this "running like mad" is done in the nation's aviation test facilities. Here research and development is carried on to make possible the tremendous aviation achievements that appear in the nation's headlines.

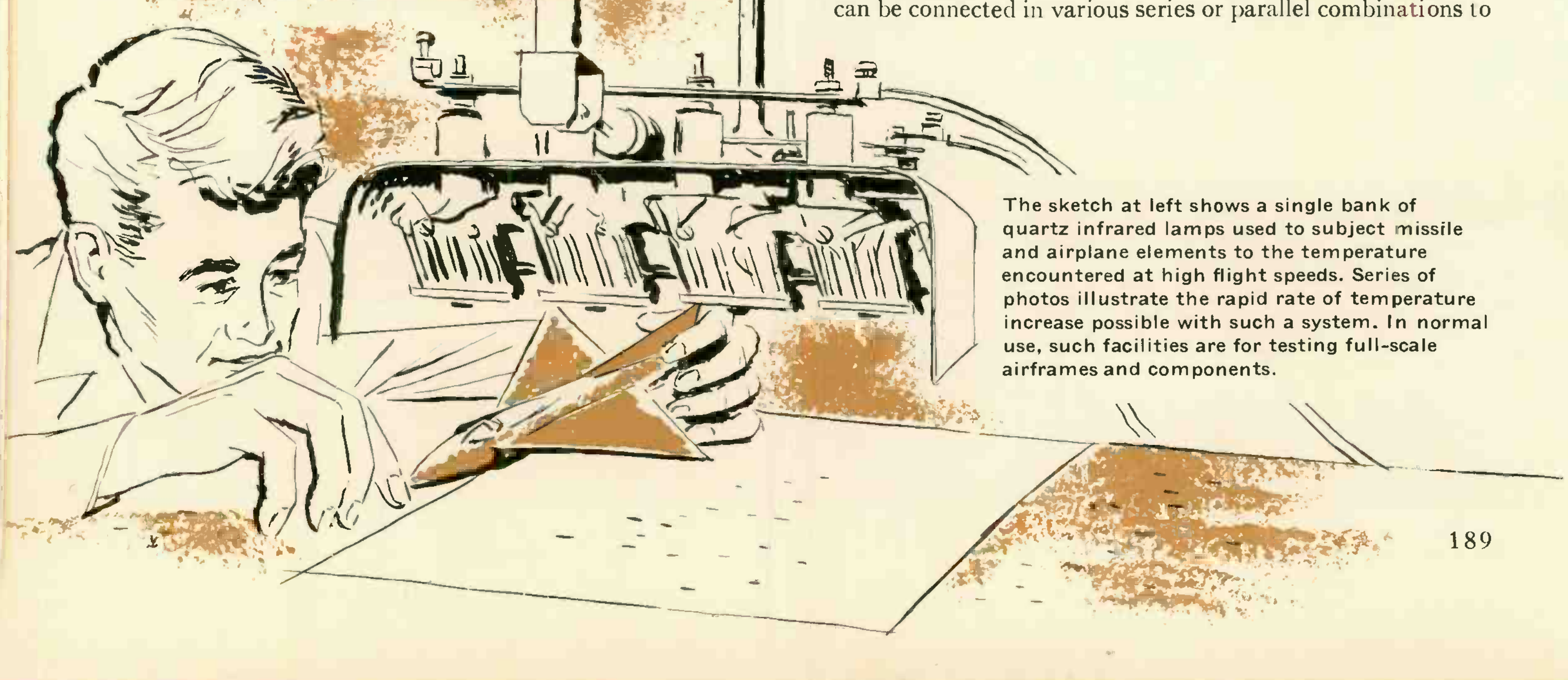
Today's aviation test facilities cover an almost inexhaustible range of types. Every structural member, component, engine, subassembly, and complete airframe or missile is tested in some form of a test facility. Successful design and performance prediction of airborne vehicles and component systems presents problems—literally by the thousands—that must be solved in these laboratories. Since research and development testing must precede actual flight of the aircraft or missile, the engineering for such facilities is clearly in the realm of "the wild blue yonder."

The "test facility" is a specialized system for *subjecting* the "test article" to certain postulated environmental and operational conditions and for *measuring* its reaction to these conditions in whatever manner and with whatever accuracy is required. The form and function of aviation test facilities is determined completely by the environmental and operational conditions that must be duplicated, and the type of vehicle they must test. They are also affected by the type of vehicle reaction to be measured and the required accuracy. These facilities may be broadly classified into "air-blowing" and "non-air-blowing" categories. The air-blowing facilities include engine test facilities and wind tunnels.

engine test facilities

Engine components and complete engines are tested in *test cells* of *engine test facilities*. The test cell began as a relatively simple "stand" for measuring engine thrust at sea-level conditions; no special efforts were made to duplicate environmental conditions at altitude. Engines are tested in elaborate totally enclosed cells supplied by a battery of compressors delivering air at the inlet to the engine at the proper velocity, pressure, and temperature to duplicate conditions at altitude and speed. The hot gas discharge from these closed test cells is removed by exhauster compressors, preceded by spray coolers to make the hot combustion gases suitable for handling by the compressors. By this means, the so-called internal aerodynamics and thermodynamics are investigated under operating conditions.

Facilities of this type usually require several individual compressors driven separately or in groups of two and three by individual drive motors or steam turbines. The compressors can be connected in various series or parallel combinations to



The sketch at left shows a single bank of quartz infrared lamps used to subject missile and airplane elements to the temperature encountered at high flight speeds. Series of photos illustrate the rapid rate of temperature increase possible with such a system. In normal use, such facilities are for testing full-scale airframes and components.

deliver air to a main supply header at various pressures and volumes. The main header is arranged, in turn, so that it can be isolated into one or more different sections, each section supplying one or more test cells operating at different flight conditions. The exhauster header and exhauster compressor battery is similarly arranged.

wind tunnels

The wind tunnel has been called man's largest precision instrument. Tunnels are characterized by many factors, such as the size of the test section, length of running time, the horsepower of the drive, the speed of the air flow, the temperature, the air density in the test section, and many others. Today's tunnels range from those with test areas of less than a square inch in cross-section, up to one 40 feet by 80 feet. Their test-section velocities range from stiff breezes at the subsonic speeds to hypersonic blasts reaching up to Mach 15.

Continuous-flow wind tunnels include the older low-speed tunnels in which even today's advanced aircraft types must be tested to determine landing and take-off characteristics. In these "subsonic" tunnels, control of test-section air speed is a direct function of the speed of the motor driving the fan and drive speed must be controlled with great accuracy.

As aircraft flight speeds pushed upward into the transonic, and ultimately into the supersonic range, tunnels were evolved in which control of test section speed ceased to be dependent upon control of drive system speed and became a function of the test-section expansion ratio or geometry. Much attention now centers upon the "fan," which has now become a multi-stage compressor, and upon control of the test-section air speed, which is accomplished by varying the shape of the flexible steel sidewalls.

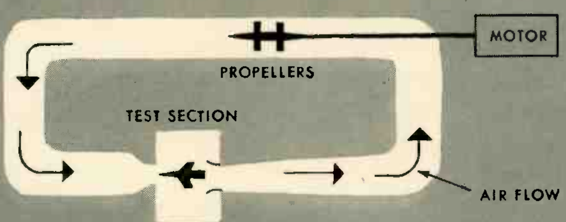
Just as the airframe and all its aerodynamic components are tested singly and in combination in a variety of tunnels, so the engine is tested. First its components separately, then the whole engine in an engine test facility, and finally the engine in its "pod," nacelle, or wing mount together with adjacent portions of the airframe is installed in the test section of a large *Propulsion Wind Tunnel* to study interactions between the adjacent airframe and the engine. These large test facilities are capable not only of aerodynamic testing in the ordinary sense, but also of testing the so-called "external aerodynamics" of full-size "burning" engines in their associated airframe structures. Outstanding examples of such facilities are the USAF PWT at Arnold Engineering Development Center with its 250-square-foot flow area, and the NACA PWT at Lewis Flight Propulsion Lab with its 100-square-foot flow area.

An example of a continuous tunnel whose unusual physical arrangement is uniquely determined by its function is the 12-foot vertical tunnel at Wright Field. From a distance, the tunnel resembles a huge silo. It is constructed as two concentric concrete cylinders. The inner cylinder contains the test section, approximately two-thirds of the way up the vertical height of the cylinder, with the fan located at the top. The fan pulls a vertical flow of air upwards, through the test section, and returns it outward and downward through the annulus between the outer and inner walls.

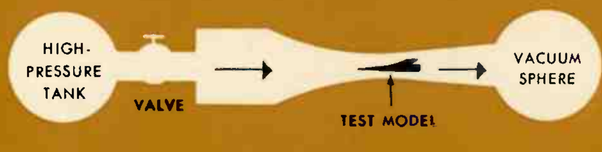
This tunnel is used for studying spinning characteristics of various aircraft types, models of which are tossed into the upward flowing air stream. Remote systems operate the tiny model control surfaces. Air speed is regulated, by controlling speed of the main fan, to just support the model in the field of view through the test-section windows.

Intermittent-flow tunnels include the blowdown tunnel, shock tubes, and electric-arc tunnels. In the *blowdown tunnel*, air is pumped into a storage vessel by a relatively low capacity compressor system over a period ranging from 15 minutes to a half hour. A special quick-acting flow-control valve is then opened, permitting the air to "blow" for a few seconds through the test section and out to atmosphere or to an evacuated chamber, depending on what "altitude" or Reynolds number is desired in the test section. Blowdown tunnels are usually designed for high supersonic speeds and obtain these with minimum investment. However, the short operating time during which usable data can be taken requires considerable attention to the design of the quick-operating control valves, high-speed measuring apparatus, etc. This type of tunnel has become popular with airframe manufacturers who need *some*, although not necessarily exhaustive, information about vehicle performance at the earliest possible date.

Among the most advanced intermittent wind tunnels in operation are those capable of producing the extremely high-speed and high-temperature flows associated with the re-entry of a ballistic missile into the earth's atmosphere. Various techniques have been used in an attempt to produce these extremely high temperatures and speeds. Among these are: the combustible-mixture shock tube, and more recently, the electric arc "tunnel." In the *shock tube*, a mixture of combustible gases is ignited while trapped behind a frangible disc or diaphragm, which can be ruptured at the precise moment necessary to permit an extremely intense detonation wave to sweep through the tube. The "thickness" of the detonation wave or pressure discontinuity is very small. But as this discontinuity sweeps over the small model, after passing through an appropriate converging-diverging nozzle section, it simulates, for a brief instant, conditions experienced by a missile re-



CONTINUOUS FLOW TUNNEL



BLOWDOWN TUNNEL

entering the earth's atmosphere at speeds of the order of Mach 10 and above. Interesting work is presently being done in several laboratories to increase the frequency with which such a shock wave can be produced, its effective duration, and the maximum Mach number that can be simulated.

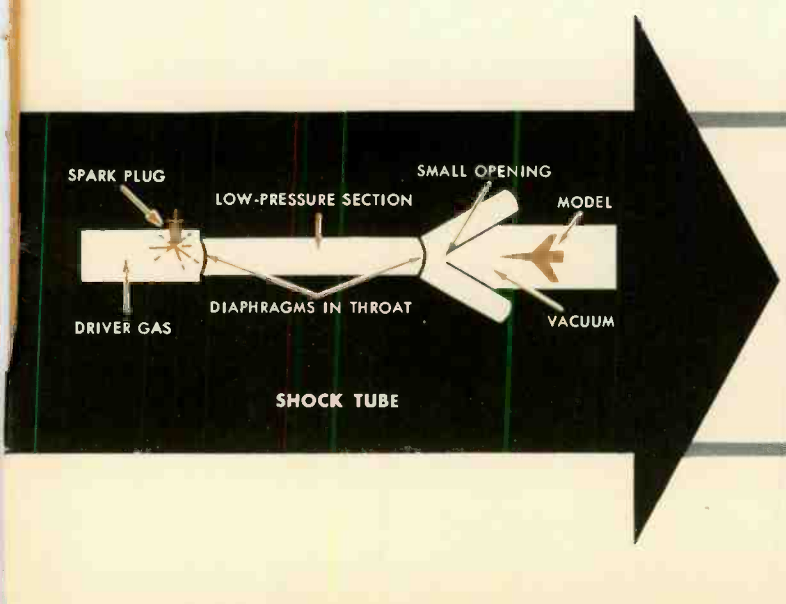
The *electric-arc tunnel* produces a blast of hot gas from an arc chamber, in which air is trapped behind a diaphragm prior to the initiation of a high-energy electric arc within the chamber. After the diaphragm ruptures, the hot gases issue from the arc chamber into the previously evacuated tunnel and into the test section proper. Various classes of energy storage apparatus have been considered for delivering the necessary energy into the arc. Among these are capacitors, induction coils, rotating machinery, and storage batteries.

wind tunnel auxiliary machinery

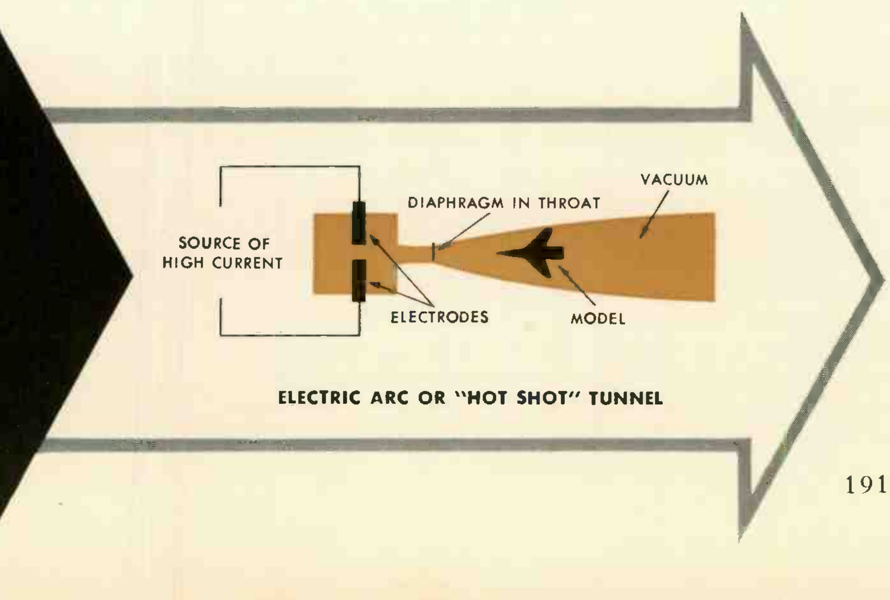
Boundary-Layer Systems—An important class of auxiliary machinery systems sometimes applied to transonic and supersonic tunnels is known as "boundary-layer removal systems." These systems reduce the thickness of the boundary layer of relatively stagnant air that builds up along the walls in a high-speed test section; this layer reduces the effective area of the test section to considerably less than the actual cross-sectional dimensions. Under certain flow conditions, this amounts to blockage or choking of the tunnel, and little or no effective testing can be done except on extremely small models. To prevent this, a so-called plenum chamber is installed around the test section flexible walls, so arranged that air from the main flow can be bled through holes or slots in the test section walls, thus introducing a secondary flow outward through these holes. To produce such a flow, boundary-layer compressors draw air from the plenum chamber and discharge it back into the tunnel at another location. The range of pressures and volume flows over which these boundary-layer compressors must operate is determined by the amount of suction necessary to remove the boundary layer under the various flow conditions and nozzle settings in the test section. These boundary-layer removal systems must operate over a relatively wide range of volume flows and compression ratios and in some cases must handle high suction temperatures. In some tunnels, the installed horsepower for this service approaches 50 percent of the total main drive horsepower requirement.

Nozzle Controls—Another function in both the continuous-flow type tunnel and the blowdown tunnel is control of the shape of the supersonic or transonic nozzle and test section. As mentioned, speed in transonic and supersonic test sections is controlled by variation of the geometry of the test section itself. All methods involve changing the shape of the flexible walls of the test section. Since both transonic and supersonic (but especially transonic) air flows are essentially "unnatural," in that they are very unstable and require special conditions to exist at all, the control of the test section geometry is a precise and meticulous operation. The walls are moved by large actuators, which must be capable not only of precise adjustment (resolution must be about one part in one hundred thousand) but, in most cases, must be capable of withstanding large compressive loads. The design of this actuating apparatus and its associated control equipment calls for the exercise of the greatest skill and ingenuity. Besides the precision with which the walls must be positioned, excessive local stresses must be avoided in the wall plates themselves. A further problem is that since tunnel testing time is extremely expensive, adjustments in nozzle and test-section contour must be made in the minimum possible time. To accomplish this, position data is stored by such means as punched cards and fed into automatic computing equipment. The computer controls the action of the individual actuator motors to achieve the desired contour change in the minimum possible time without either overstressing the plate or making errors in the final contour adjustment. Not all test section control equipment is this complicated, however, since many simpler forms are in successful operation. Among the simpler types is the sliding block or "asymetric" developed by NACA.

Model Support Systems—The most important final product of any wind tunnel or test facility is data on the reaction of the test article to test conditions. Knowledge of these reactions is obtained by sensitive apparatus of special design, which measures them and sends signals to read-out equipment. These are the so-called "model support systems" or "model balances." These devices support the model within the test section and provide a means for manipulating the model to simulate various flight attitudes and maneuvers. Also they bring out to measuring devices accurate indications of forces and moments imposed upon the model during these manipulations under the flight speed and altitude conditions existing in the test section. Model balances are classified in various ways depending upon the method of supporting the model, the number of measurements they are intended to make, etc. For instance, sidewall balances are attached to the side wall of the wind tunnel and support the model out in the air stream in the test section; pod balances support the engine in a pod mounting below an aircraft wing; sting supports support the model from a structure resembling a "stinger" in the tail of an insect, etc. All these devices are complex mechanisms of linkages, gears, small high performance syn-



SHOCK TUBE



ELECTRIC ARC OR "HOT SHOT" TUNNEL

The control system of the elevated temperature test facility at East Pittsburgh. The system, which can operate up to 2500 degrees F, includes an ignitron power controller, temperature sensing equipment, and a precision regulator (see also page 189).

chromotors and sensitive measuring devices, such as strain gauges and hydraulic pressure cylinders.

test "stands"

A large class of test facilities does not involve the "blowing of wind." In this category fall structural test facilities, generator test stands, acoustic noise facilities, "captive" rocket stands, rocket pump and turbine test stands.

Elevated Temperature Structural Test Facilities—As planes and missiles reach higher speeds, problems of the so-called thermal barrier or thermal thicket become increasingly pronounced. With the advent of supersonic, and the approach of hypersonic flight, and their accompanying aerodynamic heating and thermal loading effects, the need for elevated-temperature structural test facilities has become acute. In these facilities various temperature gradients and heat flows are produced within or on the surface of a structural member. In addition, it may be loaded to produce given stress gradients. This permits studies of the behavior of structural elements under the extreme temperature conditions expected.

Several means of heating have been used, such as: (1) electrical-resistance heating; (2) radio-frequency induction heating; (3) electric blankets; (4) solar radiation; (5) hot gases; (6) wind-tunnel testing; and (7) hot-body radiation.

Electrical-resistance heating is usually confined to the testing of small specimens of uniform cross-section. *Radio-frequency induction heating* is useful for the rapid heating of reasonably small test articles. It closely approximates the aerodynamic heating that takes place on the outer surface. A serious disadvantage in many instances is that different materials heat at different rates due to differences in electromagnetic permeability, thereby giving thermal gradients that do not duplicate the aerodynamic heating.

Conduction heating by an electric blanket is best suited for those applications requiring slow heating of large, irregular areas. The thermal inertia associated with the blankets prevents testing at the most rapid response rates.

Solar radiation can at present be used only where the spot to be heated is quite small. Approximately 420 Btu's per square foot per hour is the maximum direct radiation that can be obtained, but by parabolic mirrors, as used in a solar furnace, heat fluxes up to approximately 5 000 000 Btu's per square foot per hour can be obtained.

Hot gases were one of the first methods tried in an elevated-temperature structural test facility. Here, the heating of the material and the effects of oxidation and corrosion can be simulated. However, to accomplish the latter effect, the oxygen content must be of the same proportion as that of the atmosphere in which the test article is to fly. A device known as an "Aeroder" has been used to produce these effects. This consists essentially of a jet-engine combustion chamber supplied from an auxiliary air supply. The article undergoing test is exposed to the jet at the nozzle opening. The jet stream ranges between 1800 degrees and 2000 degrees F at a Mach number of 1.8. With afterburners, temperatures up to 3500 degrees F have been reached.

Wind-tunnel testing has not been used extensively to obtain temperature effects except for very small test articles in shock tubes and electric-arc tunnels where intermittent flow or discharge permits using the tremendous energy required.

Hot-body radiation is the most active technique presently used for elevated-temperature structural testing. Most elevated-temperature structural test facilities currently being considered use as a source of heat high-intensity incandescent lamps operated at voltages far exceeding their normal rating. These lamps can be controlled by computer equipment capable of sensing the temperature gradient being produced and deducing from this gradient whether or not the desired heat inflow per square foot of surface is being produced. If it is not, corrective action is computed and the necessary control signals initiated to control the lamps.

Aircraft Generator Test Stands—On these test stands, generators alone, and sometimes complete aircraft electrical systems are given tests under closely controlled conditions. These drives provide adjustable speed over a wide range and have ability to maintain a closely regulated speed at any selected point. This permits generator performance under many flight operating conditions to be duplicated on the ground. Such items as voltage regulation, transient response, overload capacity, paralleling operations with other generators, and shock loading can be simulated and accurately measured. These facilities save thousands of hours of flight testing and secure data that could be obtained in actual flight only with extreme hazard or difficulty.

Acoustic Noise Test Facilities—The aircraft industry is becoming acutely aware of the problems of acoustical energy and its effect upon man and materials. The effect of noise on the human being can range from the nuisance (such as creating temporary deafness) to the more sinister effect of acoustical energy transmitted directly to the flesh and bones, where it may be potentially injurious to the nervous system. Many strange effects of noise on the human have been noted; for example, a man within a thousand feet of a missile launching generally loses his latest meal due to the effect of acoustical pressure waves emanating from the tremendously noisy rocket discharge. Acoustical energy can produce vibration in structural members, causing early failure.

The noise produced by rockets and missiles comes close to being pure "white noise," as does the noise spectrum produced by a jet aircraft. White noise means that over the particular band of frequencies of audible noise produced, all frequencies are present and of equal intensity.

To further investigate the problems created by these airborne acoustical waves, the industry is beginning to install white-noise test facilities. Here high-energy acoustical pressure waves up to the order of 180 decibels can be produced electronically and transferred by suitable transducers into airborne pressure waves.

Static Rocket and Missile Test Stands—The airplane's close relative, the missile, has required new and often more vexing testing procedures for its development and production. One spectacular one is the static test stand, in which the missile power plant, or even the complete missile, is mounted for a full-thrust operational check-out of its propulsion system. Many such facilities are already in existence and still larger and more complex stands are now under construction. The larger test stands are capable of testing propulsion systems developing up to 1 500 000 pounds of thrust.

In the larger stands the power plant or complete missile is mounted vertically in a supporting steel structure resembling an oil-well derrick. The hot exhaust gases and flames from the propulsion system are deflected horizontally by steel and concrete flame deflectors over which thousands of gallons of water are poured during the test. Were it not for this water cooling, the steel and concrete of these deflectors would melt and erode in a matter of seconds. The control and instrumentation for these stands is housed in a reinforced concrete blockhouse built to withstand blast explosion. In these blockhouses hundreds of thousands of dollars of instrumentation and data reduction equipment is housed.

Missile Pump and Turbine Test Stands—Two of the most important components in a missile are the pumps and turbines used in the propulsion system. The pumps supply the fuel and oxidizing agent to the combustion chamber of the engine and are driven by a high-speed gas turbine. These pumps and turbines are high in both speed and horsepower, and by all normal industrial standards are extremely small in size but tremendous in performance. Their life span is extremely short, but during this time the utmost in performance and efficiency must be realized to obtain the ultimate performance from the missile.

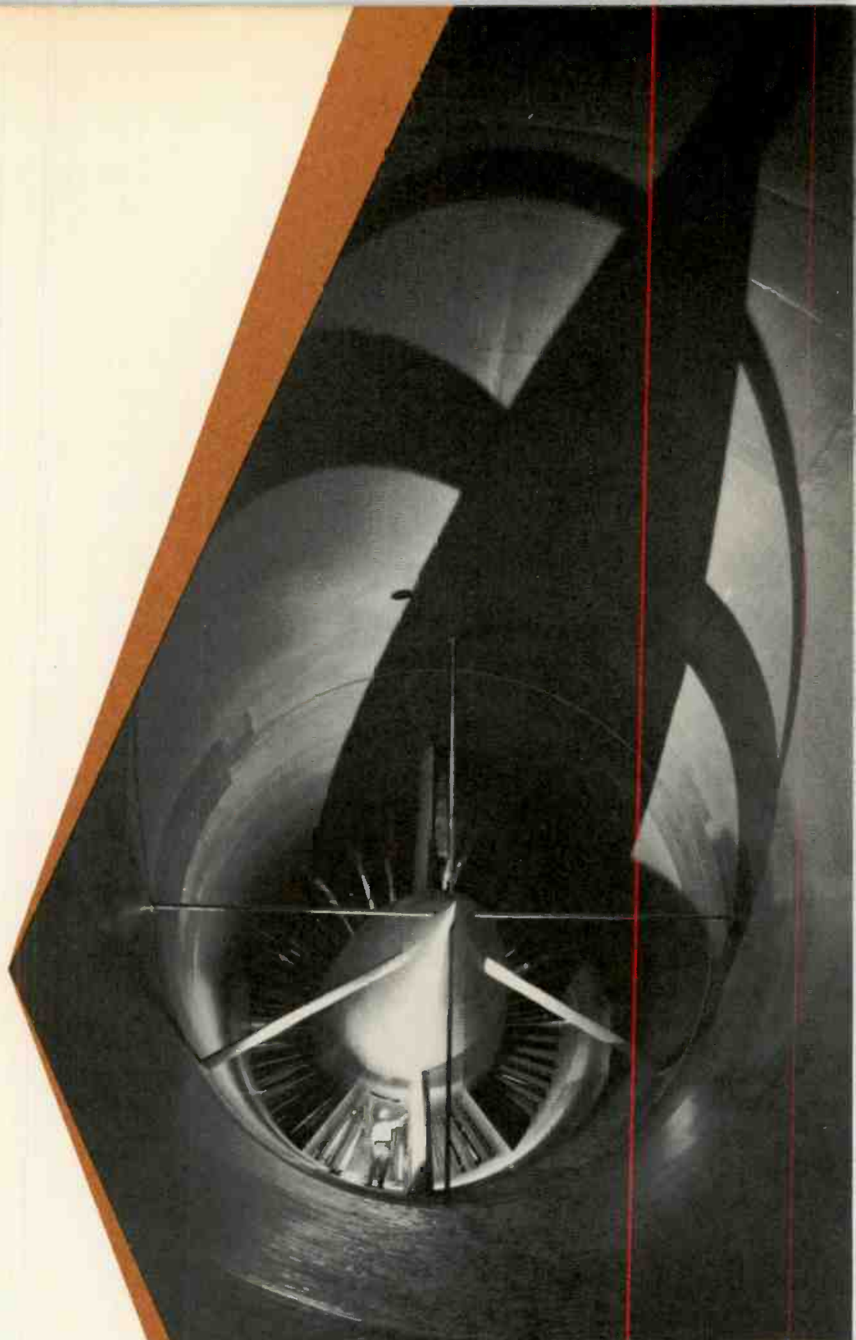
The pump test stand is essentially a motoring dynamometer. Since the pumps themselves are lubricated and cooled by the fuel or oxidizing agent, they can only be run with fuel or oxidizer flowing in the system. These pumps deliver prodigious quantities of fuel or oxidizer and for this reason the supply that can feasibly be stored lasts for only a few seconds. Therefore, the test runs are of very short duration. Generally speaking, a test stand of this nature must accelerate to full speed in 10 to 15 seconds and run at a closely regulated speed of about plus or minus one-tenth of one percent for the next 15 seconds and then shut down. Some of the larger stands under consideration have top speeds of 30 000 rpm and a full horsepower range of 30 000 hp. The precision required in torque measurement under these operating conditions imposes stringent design requirements on the speed controls for these test stands.

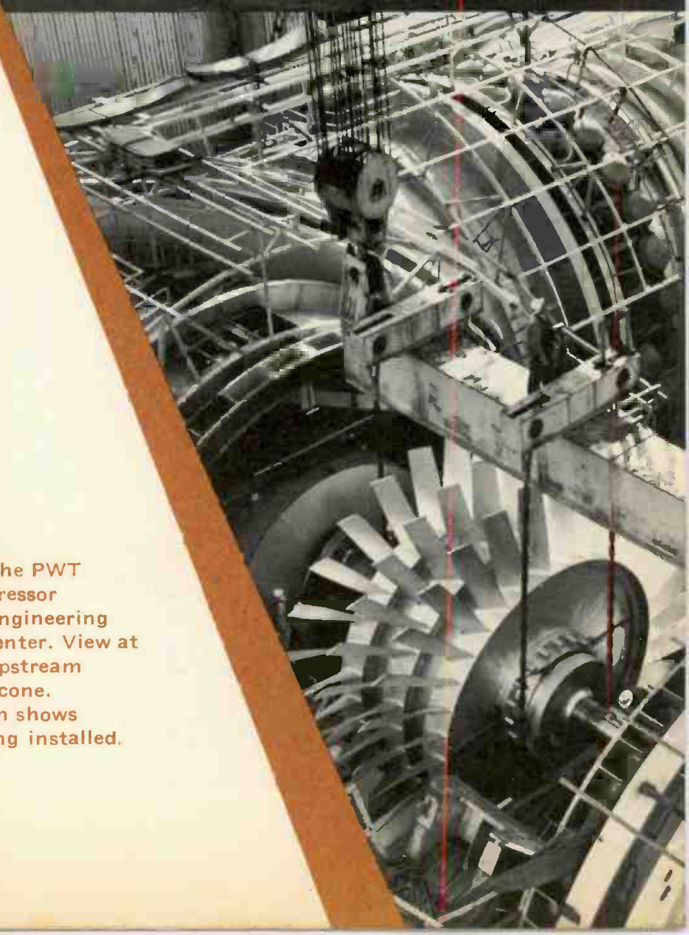
The turbine test stand is essentially an absorption dynamometer, and while it is able to run for a longer period of time than the pump, its speed regulation and other factors are much the same. Large stands currently under discussion will exceed 90 000 hp at 30 000 rpm.

No missiles now in production require pumps or turbines demanding the full rating of these proposed stands. However, the lead time necessary to engineer, design, and fabricate test stands like these is such that the planning must be done in advance if the tools are to be ready when needed.

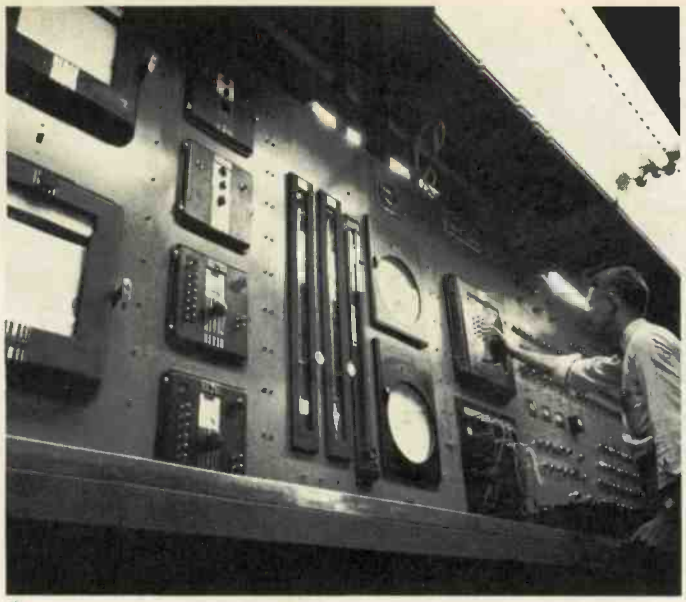
conclusion

The foregoing indicates what might be called the "chain of dependence" that connects the advanced requirements of tomorrow's aircraft with similarly advanced requirements for test facilities. The aircraft industry is perhaps unique in requiring an extremely high time rate of change of the state of art simply to stay abreast of the requirements for maintaining qualitative air superiority. This rate of change is so great as to require major breakthroughs at frequent intervals almost as a matter of routine. ■





Two photos of the PWT transonic compressor at the Arnold Engineering Development Center. View at top is looking upstream toward the tail cone. Photo at bottom shows compressor being installed.



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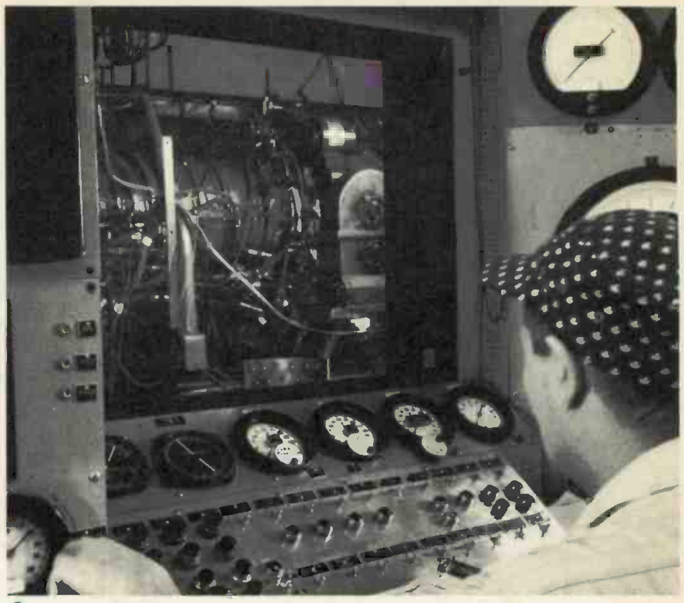

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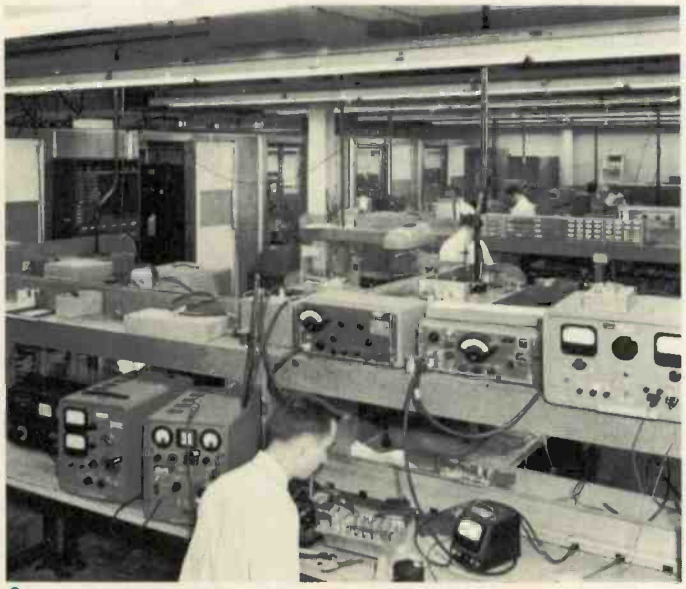

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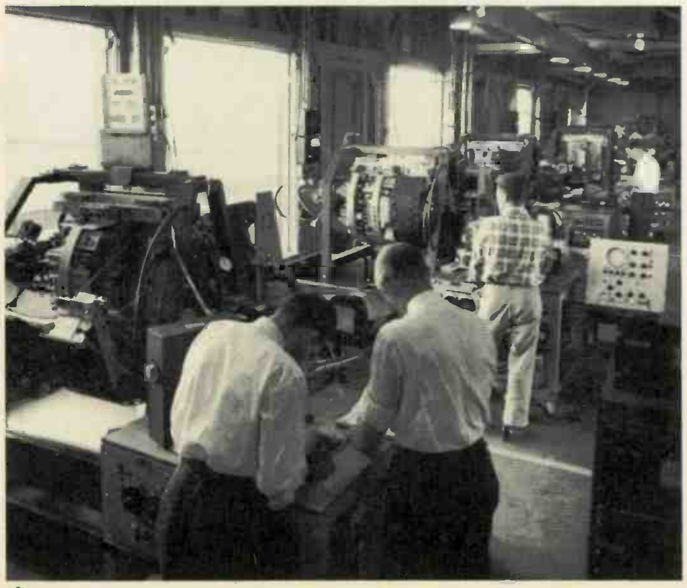
With the help of modern laboratory and testing facilities, aircraft components can be put through almost any environmental or operational condition that could be encountered in service. Engineering design and serviceability are thereby assured long before equipment leaves the ground. Only a sampling of the variety of facilities required is shown:

1 Control panel of a high-altitude chamber for environmental testing of aircraft generators, motors, and control equipment; 2 Jet-engine development test cell; 3 Development laboratory for communications equipment; 4 This "penthouse" test area provides both development engineering and production testing facilities for airborne military systems; 5 Full-scale test-flight facilities provide final performance analysis of airborne equipment.



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