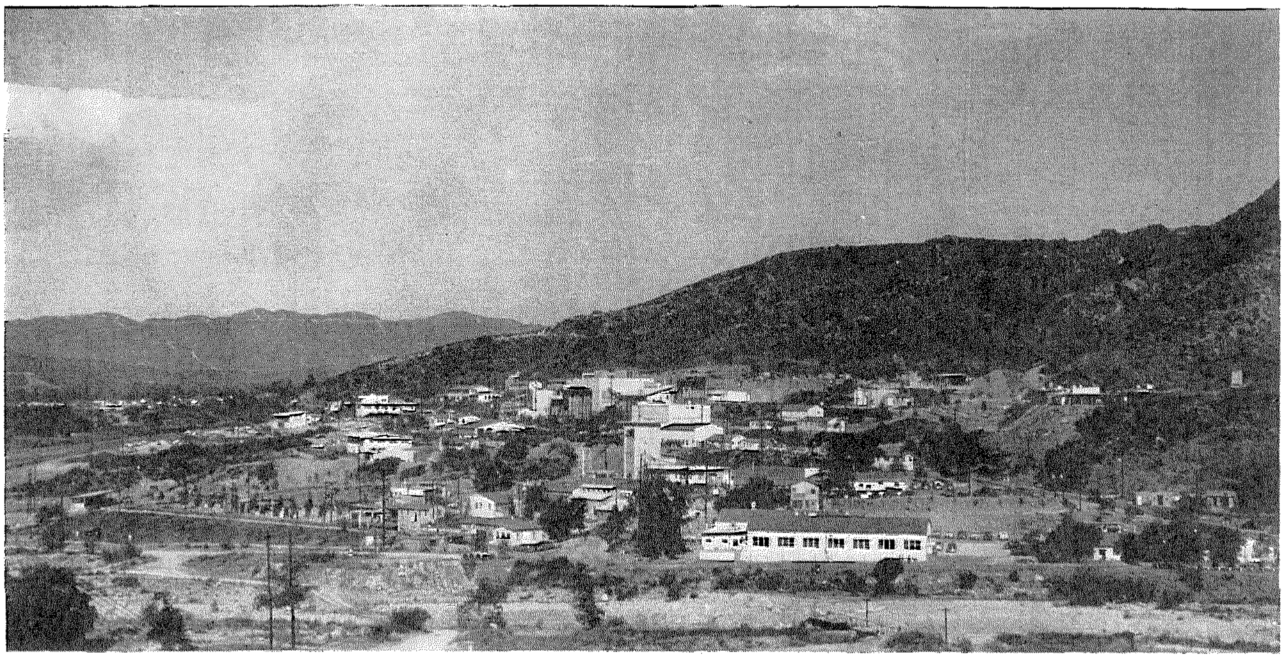


The Jet Propulsion Laboratory, three miles north of the Rose Bowl in Pasadena, now covers 64 acres

THE JET PROPULSION LABORATORY

What it is, what it does — and how it does it

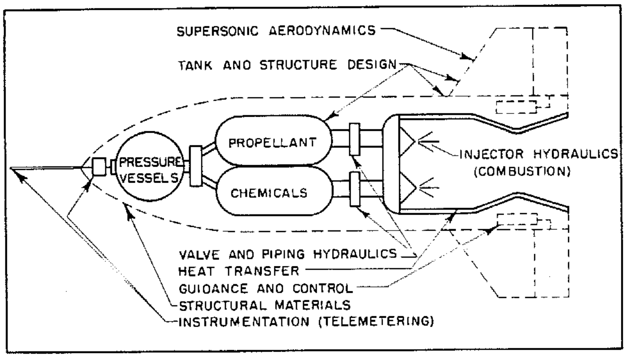
By HOWARD S. SEIFERT

WORLD WAR II, the "Physicists' War," naturally inspired a number of defense activities at the California Institute of Technology. Although this war has now receded almost a decade into the past, one defense project, the Jet Propulsion Laboratory, has proved itself to be of such continuing value that it has not only survived, but has grown tremendously.

The need for a propulsion plant for the assisted take-off of aircraft and for sounding rockets brought the Laboratory into existence in 1940, as an extension of work begun in 1936 by a small group of Caltech students under the direction of Dr. Theodore von Karman.

Starting from this specific practical problem, the interests of the Laboratory have extended in many directions. What was once a program to develop a simple thrust-producing device has grown to include aerodynamic tests of missile configurations in special supersonic wind tunnels, development of electronic guidance equipment, and fundamental research in fluid dynamics, combustion, chemistry, and materials.

It has been found wise to share the time of the staff between the preparation of immediately useful hardware and the acquisition of ultimately useful information in the sciences related to jet propulsion. The interaction between the applied and fundamental research has been to their mutual advantage. Practical experience turns up new problems of broad significance, and the solution to these results in new applications.



Schematic diagram of a guided missile shows which components are the subjects of research investigations

I. THE RESEARCH PROGRAM

The field of jet propulsion embraces most of the engineering sciences. As a result, the research program at JPL covers many diverse problems—all related in some way, however, to propulsion, guidance or fabrication of missiles. The schematic diagram of a rocket vehicle, above, shows the locus associated with some of these problems, which may be classified under the following headings:

A. Chemistry of Propellants
B. Combustion
C. Fluid Dynamics
D. Heat Transfer
E. Materials
F. Mechanical Design
G. Instrumentation
H. Guidance and Control

A. Chemistry of propellants

The ideal liquid rocket propellant should release the maximum possible heat into combustion products of the lowest possible molecular weight, in order to provide maximum momentum in the exhaust jet. It should be stable against shock and temperature changes. It should ignite quickly and burn rapidly, in order to reduce the necessary volume and weight of the combustion chamber. It should have a high density to permit small storage tanks, and a low vapor pressure to avoid the need for thermal insulation. If it is to be used as a coolant, its specific heat and thermal conductivity should be high. In addition, it would be convenient if it were non-toxic, non-corrosive, available in large quantities, and cheap.

Although no one fluid exists with all these desirable properties, several possess enough virtues to be acceptable. The search for such substances, and the measurement and modification of their properties, are the chief concern of the chemistry research program. The oxidizers nitric acid, hydrogen peroxide, and liquid oxygen, reacting with the fuels aniline, alcohol, ammonia, gasoline, and hydrazine, have been among the most promising systems studied.

Solid propellants, because of the simplicity of their use, are no less interesting than liquids. The ideal solid propellant should possess most of the qualities of the ideal liquid. In addition, the rate at which the surface burns away should be controlled within wide limits. There should be no smoke, and the charge should retain good mechanical properties under extremes of temperature, stress, and acceleration.

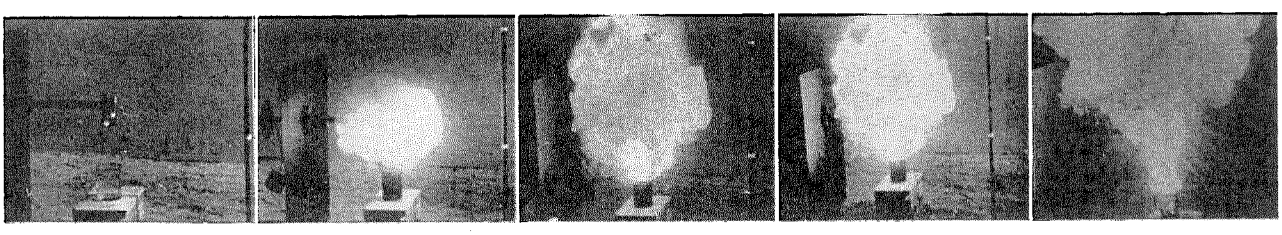
Originally, JPL solid propellants were made of simple mixtures of potassium perchlorate, asphalt, and lubricating oil. Present-day propellant production is more sophisticated, and involves careful process control.

B. Combustion

The general phenomena of combustion have long received the attention of investigators, but understanding of the subject is far from complete. Rocket combustion is particularly complex. In a typical liquid rocket the propellant enters in the form of a number of small streams travelling with a speed of about 100 ft/sec. The reaction begins immediately at the interface between the two liquids, which soon evaporate from the heat of the already established flame. The reaction is completed in the vapor phase at a pressure of several hundred pounds per square inch, and at temperatures ranging from 3,500° F to 5,000° F.

Pictures taken through a window in the combustion chamber show that the interior space distribution of temperature and velocity is quite irregular. Superimposed on this turbulent holocaust is a time variation, an oscillatory rise and fall in pressure which may range in frequency from twenty or thirty cycles per second to many thousands, and which is in part responsible for the rocket's notorious efficiency as a source of sound. As one British investigator put it, "What goes on in a rocket chamber is just nobody's business."

Experimental work at JPL on combustion includes interior measurement of rocket temperature patterns with movable probes, and extraction of gas samples with these



The ideal liquid rocket propellant should ignite quickly and burn rapidly — as in this spontaneous contact ignition of red fuming nitric acid and aniline. The consecutive pictures above were taken at intervals of 1/64th of a second.

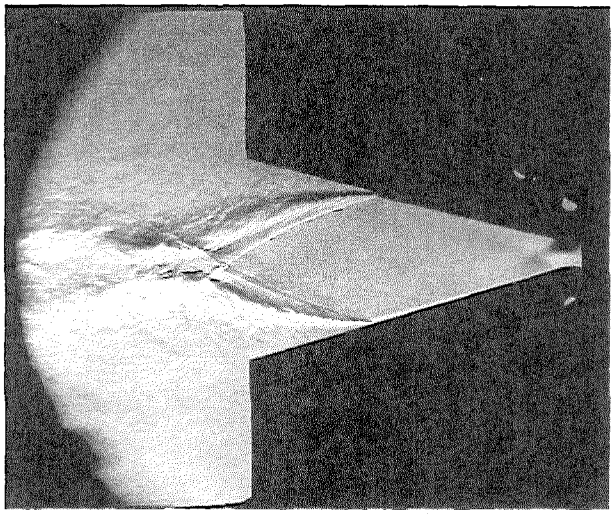
same probes for subsequent analysis in a radio-frequency mass spectrometer. Studies of the kinetics of the individual steps in the reaction of HNO_3, for example, have shed light on the time required for combustion to be completed. Spectroscopic study of the absorption bands of various rocket combustion products has led to independent means for estimating the temperature of the reaction.

Another aspect of combustion which is important for jet propulsion generally is *air-fuel combustion.* The technique of introducing fuel into a rapidly moving airstream in such a manner as to complete its burning in the shortest possible time, and to maintain this flame over wide variations of stream velocity, pressure, and air-fuel mixture ratio, is essential to the operation of a ram-jet propulsion plant. At JPL experimental work is being carried out on the properties of the low-pressure (few mm) flame, which spreads out the combustion zone and reduces its temperature, enabling a study of its structure and sampling of the chemical species present. In addition studies are being made of the effect of turbulence on flame propagation, and the mechanism of "flame-holding"—i.e., stabilization of a flame front in the vicinity of a solid surface submerged in a flow field.

C. Fluid dynamics

It is obvious that a device which propels itself through a gaseous environment by the expulsion of gas will present many problems in fluid dynamics. Let us consider the aerodynamic and hydrodynamic problems separately.

1. *Aerodynamics.* Rockets travel at supersonic speeds, and the necessary empirical information on lift, drag, interference effects, and the like is scarce and expensive to acquire. Quantitative theoretical analysis is difficult to perform. New physical effects become important, such as aerodynamic heating of the skin of the vehicle. The vehicle now travels not at a relatively uniform speed, as does an airplane, but is constantly accelerating or decelerating. In the course of a single flight it may travel through air whose density varies from standard sea-level value to zero, and during this time the weight of the vehicle may reduce to 25 percent of its original value, with corresponding troublesome changes in the relative position of its center of gravity and center of pressure.

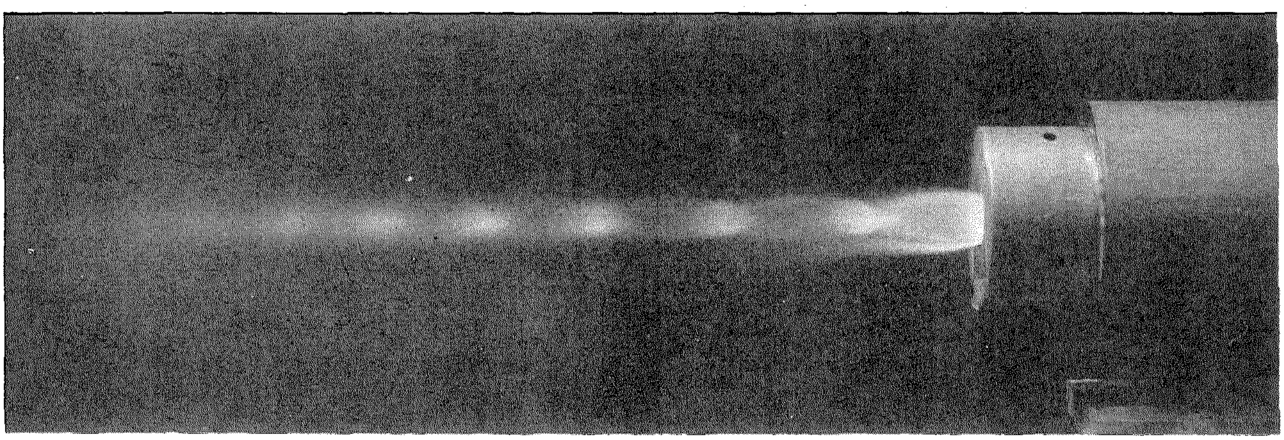


Schlieren photograph of the separation of flow of cold gases in the expanding portion of a deLaval nozzle.

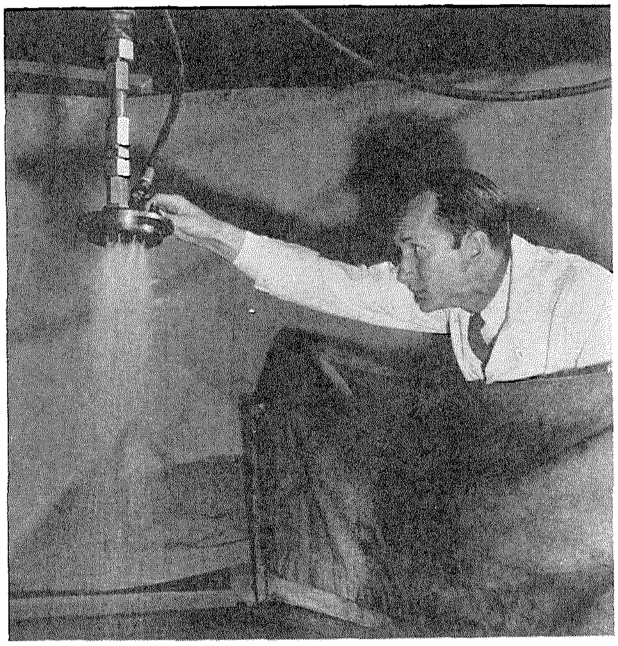
JPL is fortunate in possessing two large supersonic wind tunnels—one of 12-inch-square working area, and the other of 20-inch-square working area. Both have air velocities in the vicinity of four times the speed of sound. With these a considerable amount of "routine" measurement of aerodynamic coefficients is done for military contractors. However, a significant fraction of the operating time is devoted to basic study of boundary layers (skin friction), heat transfer, turbulence, and the behavior of simple wing shapes in supersonic streams.

The nature of the supersonic flow through deLaval nozzles has been studied experimentally, using both hot and cold gases. Also, an analytical group works in conjunction with the wind tunnel and missile design groups, calculating trajectories, drag coefficients, heat transfer and similar quantities.

2. *Hydrodynamics.* The large amount of "plumbing" associated with liquid propellant rockets gives rise to a number of special problems. The proper performance of a rocket system depends upon accurate knowledge and



Various supersonic flow phenomena are studied experimentally at the Lab, using hot gases (as in this picture) and cold gases (picture at top of page). Here is the shock wave pattern in the jet of a small 25-lb. thrust test rocket.



Workers in JPL hydraulic lab run water tests to check the accuracy of impingement of rocket injector jets.

control of all hydraulic flow parameters. There is no margin for inefficiency in a guided missile. At JPL a large hydraulic laboratory is devoted to checking and measuring the performance of valves, injectors, and similar components.

The operation of the "injector"—the set of orifices through which jets of propellant are introduced into the combustion chamber—presents many complex problems. At JPL studies are made of the spatial distribution of the atomized spray resulting from two impinging jets (as shown in the picture above), as well as the distribution of droplet sizes and the degree of "mixing" or intermingling of the propellant components.

D. Heat transfer

There is no ordinary furnace hotter than the combustion chamber of a rocket and, even though only two or three percent of the propellant energy passes through the walls as heat, its removal poses a difficult question. About three BTU/in^2-sec (or 1.5×10^6 BTU/ft^2-hr.) pass through the throat region of a rocket nozzle. Thus, guiding the exhaust gases through the nozzle throat is somewhat like asking a snowman to swallow a cup of hot coffee. Cooling is usually accomplished by circulating part of the propellant outside the combustion chamber. This coolant often reaches the boiling point. At JPL considerable work has been done on the study of boiling and the mechanism of boiling heat transfer, concerning which little information is available, particularly for propellant liquids.

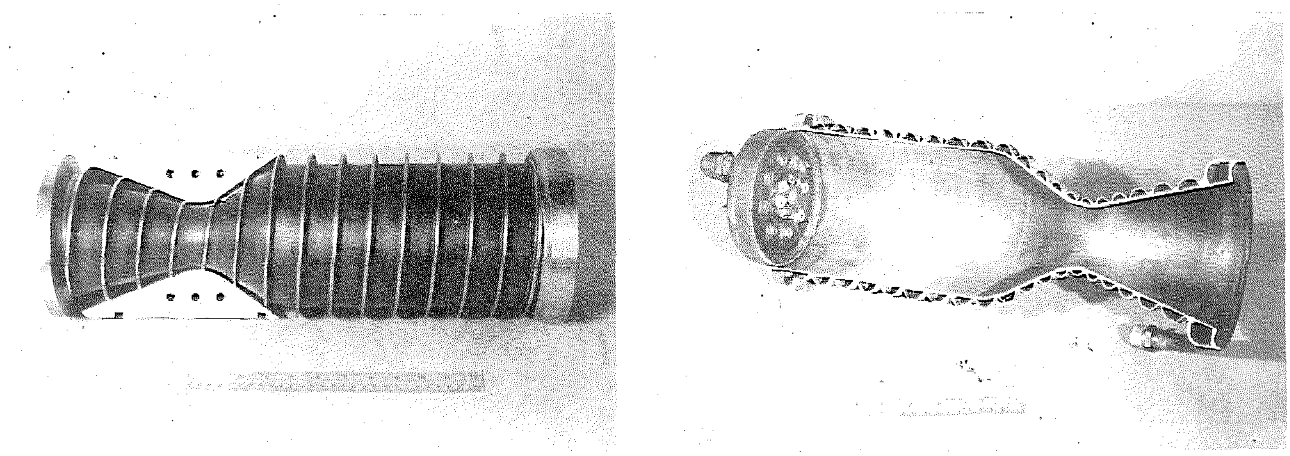
Other techniques of fluid cooling, such as the introduction of liquid films on the interior surface through small orifices (a technique used by the Germans in the V-2 rocket) and the "oozing" of a coolant fluid through porous metal walls, have also been investigated experimentally at JPL.

E. Materials

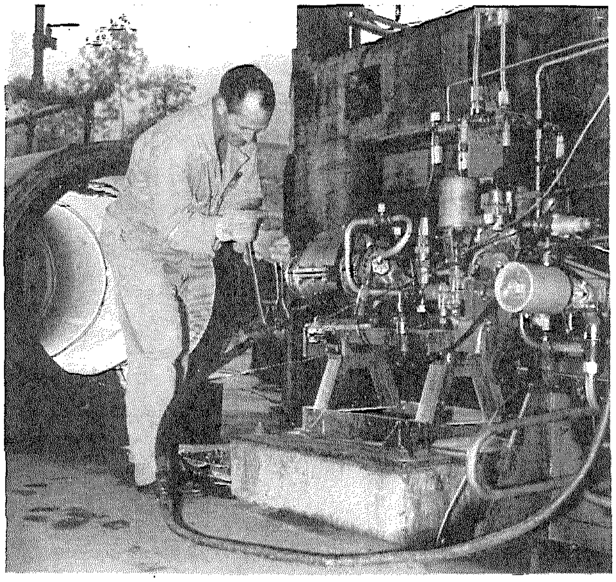
The high melting-point, strength, and corrosion resistance required in jet propulsion applications directs the rocket engineers' attention to refractory substances. The materials program at JPL particularly emphasizes the *fundamental* aspects of refractory research. Recent materials studied at JPL include titanium and titanium alloy systems, in particular those containing chromium, molybdenum, vanadium, and a few of the more complex ternary systems. Also investigated was the crystal structure of new intermetallic compounds in various titanium and zirconium alloys.

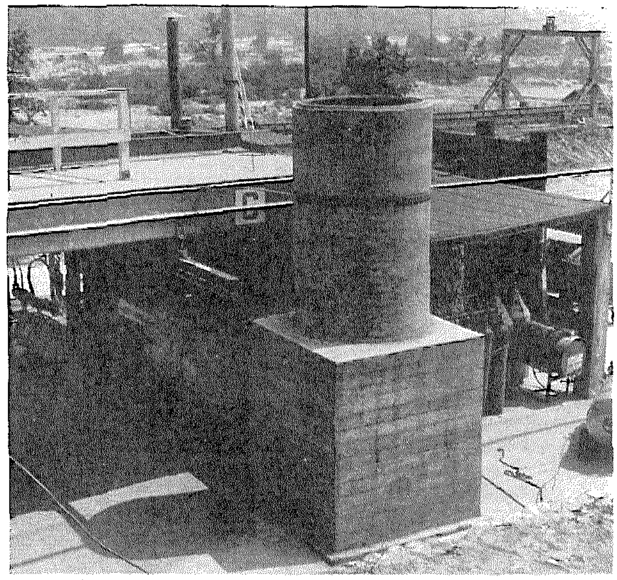
Additional high temperature substances studied were the chromium base alloys with iron, molybdenum, and vanadium (especially the brittle sigma phase). The properties of the ceramic zirconium oxide, stabilized with lime, magnesia, or other rare earth oxides, were also examined.

A particularly interesting application of materials research has been the development of the so-called "sweat cooling." This involves the preparation of a metal filled with connected pores, through which a coolant fluid can



Rocket motor development work reduced weight of this 1500-lb.-thrust rocket motor from 50 lbs. (left) to 12 (right).





Research information on rocket characteristics is acquired in elaborate test set-ups like this. Sound suppressor, shown behind worker in picture at left, is one of main features of rocket-firing test cells, as shown by exterior view at right.

be forced. By this technique a surface exposed to flame can be kept quite cool with only a small expenditure of fluid. At JPL the production of porous metals by powder metallurgy techniques was pursued vigorously. Related work was carried out on the mechanism of sintering and diffusion of mixed powders during alloying. Coordinated with this work was the study of the laws of liquid and gas flow, as well as heat transfer, through porous metals.

F. Mechanical Design and Development

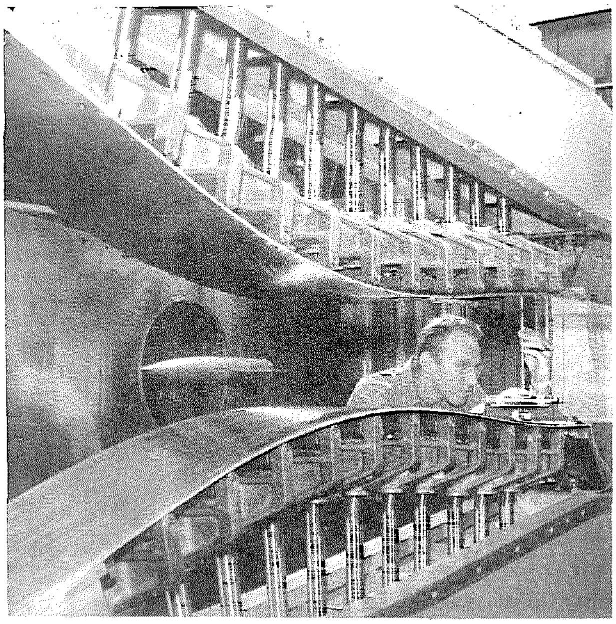
The producers of "hardware" at JPL are of two types. The first type is exemplified by the rocket research engineer, who wishes to know, for instance, whether a particular injector will operate well. He does not worry about the weight of his test motor, or whether it can be fuel-cooled. His attention is focussed on only one aspect of the problem, and his objective achieved when his data are secured. Of course, the information should not be allowed to lie dormant at this point. Before a rocket can be demonstrated to the military services, or transferred to commercial production, a prototype or "Mark I" version incorporating the new injector design, together with much additional information from other research engineers, must be synthesized by a "development" engineer. He is the second type of mechanical designer referred to, and his trials and tribulations are fully as great as the "research" man's.

Liquid rocket research at JPL involves devising and testing propulsion systems which combine some choice of cooling technique, materials of construction, combustion chamber configuration, propellant chemicals, injector design, and fabrication procedure. Shall it be a water-cooled liquid oxygen-alcohol motor using a shower-head injector in a cast spherical aluminum chamber with an inserted copper nozzle? Or, would it be preferable to use a fuel-cooled nitric acid-aniline system and impinging-jet injector in a spun steel cylindrical chamber with spot-welded cooling jacket? Since there are at least a dozen choices of each of the variables, a morphological array of all possible rocket motors would number at least several million. Obviously, some less ambitious number is selected as worthy of experimental investigation.

Work on solid propellants for rockets at JPL parallels in many ways the work done on weapon rockets at Eaton Canyon during the war — a project which was administered by Caltech for the National Defense Research Council (NDRC). Among the many research problems are how to control the burning rate, and the mechanical properties of the solid charge.

Turning from research engineers to design and development men, we see that their responsibilities are broad. At JPL these men perform the integrated function of design, development, fabrication, assembly, inspection, and check-out testing of complete missiles. Their tasks include aerodynamic, thermodynamic, heat transfer, vibration, and ballistic calculations. Their program also includes optimization studies; particularly reduction in weight of all components. The great importance of minimum weight in rocket flight may not be generally appreciated. A rocket which is 50 percent expendable fuel may have a range of 50 miles. If the rocket can be redesigned to have 90 percent of its initial mass expendable, the range will be extended to 500 miles! The smaller the percentage of dead weight left after the fuel has been burned, the farther this remnant will go.

Typical of the work of this group at JPL is the search for heat-resistant surface coatings for protection against the aerodynamic heating (temperatures to 1,000° F) which a missile experiences upon reentering the atmosphere at the end of its flight.



Lab's 20-inch supersonic wind tunnel features an adjustable throat section positioned by servo-controlled jacks.

Other problems include the design of light-weight pressure vessels, pressure regulators, special valves, and numerous structures and fixtures; for example, radio antennae. An outstanding example of their work was the design of the rocket separation mechanism for the Bumper WAC, the two-stage rocket which set the so far unbroken altitude record of 250 miles.

G. Instrumentation

The testing of a rocket, involving as it does high temperatures, pressures, and fluid flow rates, as well as ballistic flight, naturally creates a demand for measuring devices of high accuracy and short time resolution. The flood of data accumulated with these instruments in turn creates a demand for computing equipment which can reduce and plot data or solve complex systems of equations quickly.

Among examples of work on measuring instruments done at JPL are: a high-speed camera of the Kerr-cell shutter type, a recording potentiometer capable of 20 measurements per second to 0.1 percent accuracy, a counter for the measurement of the number and size of droplets in a spray, and a flowmeter for low-temperature liquids. Test cells at JPL are scattered over the plant at widely separated points. These have been interconnected with a telephone-type network capable of transmitting 22 channels of information to a central recording center. This system makes an expensive array of recording equipment (oscillographs, potentiometers), together with its operating crew, readily available to any test cell on short notice.

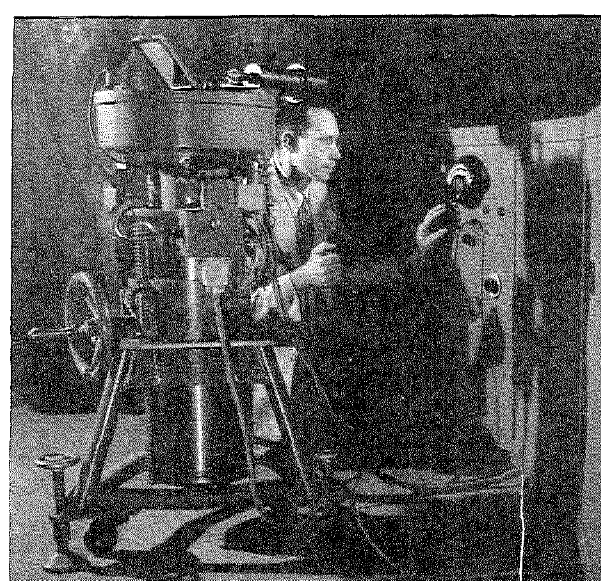
Computing equipment available at JPL includes a large Reeves analog computer (REAC). By now most engineers are aware that these computers make possible the solution of otherwise unmanageable differential equations, and bring forth solutions in a day which would otherwise require months of hand computation, and therefore would probably not be attempted. It should not be assumed that the operation of these computers is simple or routine. Each new problem is a challenge to the ingenuity of the operator, who must combine mathematical talent with the skill of an expert television repairman.

H. Guidance and control

Early in JPL's history, it became necessary to evolve an air-to-ground radio link, or telemetering system, for the transmission of data from the sounding rockets then being used to proof-test propulsion systems. Later the Department of the Army requested that a missile guidance and control system be evolved, which made it necessary to establish a complete research division devoted to electronics. Today a substantial part of the JPL engineering staff is devoted to this activity.

The stability of the missile in flight (its ability to maintain a more or less steady orientation, as well as its ability to change direction in response to signals) depends on the development of a suitable auto-pilot, resembling that used in conventional aircraft, but responding more rapidly than the aircraft type. This stability and maneuverability is what is accomplished by the "control" system of a missile.

In addition to the orientation of its axis, the position in space of the missile's center of gravity must be both measured and modified. This function is termed "guidance." Evidently a high degree of precision as well as rapid action will be demanded of the guidance system for a missile moving at supersonic speeds. Various techniques exist for achieving this end, some of which are described qualitatively in open literature.



Lab's high-speed camera lives up to its name by taking exposures of less than one-millionth of a second.

II. LABORATORY FACILITIES

A. Research equipment

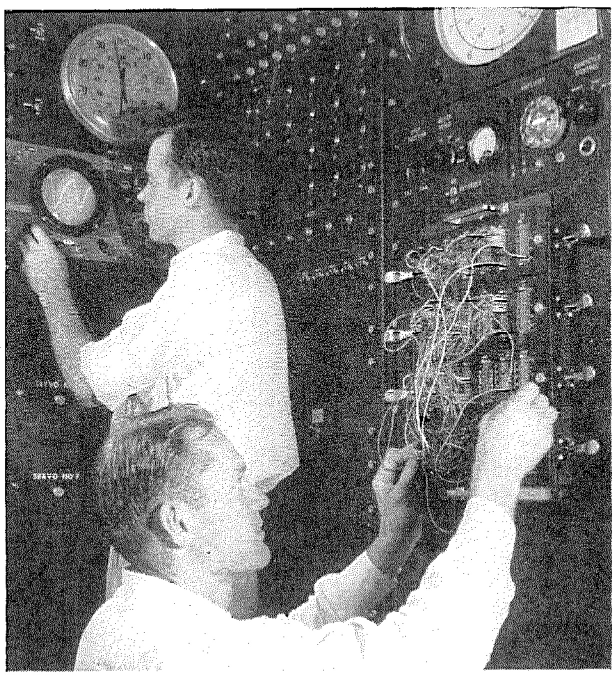
In the descriptions of experimental apparatus to follow, the problems in which they are used will not be discussed. The applications will be evident from the research program outlined above. The items chosen here by no means form a complete catalog.

Major pieces of equipment are the two supersonic wind tunnels and their associated balance and compressor equipment. These tunnels are of the unique flexible throat construction, which enables quick change in operating conditions and a rapid rate of collecting data. The tunnel air supply is also made available to air-fuel combustion test cells. Another major installation for fluid dynamics work is the hydraulics laboratory, which contains pump, valve, metering and reservoir equipment for large liquid flows and high pressure.

Two facilities of general utility are the shops, which have a number of large machine and sheetmetal power tools, and the library, which receives about 100 periodicals and is a repository for an extensive collection of technical reports.

Materials research is aided by two large hydraulic presses (the larger of 3.6 million lbs. capacity) for powder metallurgy work, as well as several X-ray diffraction units, an electron microscope, and high temperature furnaces of various types, as well as equipment for radioactive tracer research.

Combustion research is carried on with the help of a radio-frequency mass spectrometer of the type recently originated by the Bureau of Standards, which requires no fixed magnetic field. The spectroscope part of the work uses a Perkin-Elmer infra-red prism spectrometer (to 25 microns) and a Dietert 1½-meter concave grating spectrograph for the ultra-violet.



Lab's electronic computer quickly solves equations which would involve months of hand computation.

The JPL Administration Building — hub of the lab.

Instrumentation, guidance, and control activities employ a large amount of commercial electronic gear. One major piece of electronic equipment is the Reeves analog computer. It is planned to augment this with digital computing equipment, and work is currently proceeding on equipment to convert physical magnitudes from analog to digital form and back.

B. Buildings

JPL now possesses a considerable number of permanent buildings of high quality and substantial size. The total area of office and laboratory facilities today covers about 64 acres. Among major JPL structures are a large administration building, a modern cafeteria, and separate laboratories for fluid dynamics, combustion, chemistry, metallurgy, electronics and instrumentation. In addition there are central shop, assembly, and storage buildings as well as several minor shops and concrete test cells (equipped with sound-suppressingd evices) for small experimental rockets.

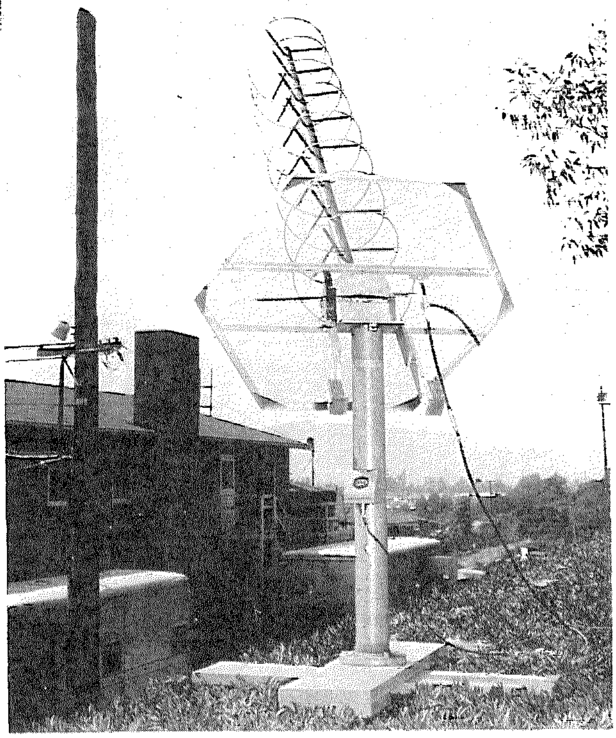
JPL also operates or administers three external facilities—a static test stand for large rockets in the desert north of Pasadena; a field test crew in New Mexico, to supervise actual flight tests; and a school for training military personnel in guided missile techniques.

III. PERSONNEL

A. Leadership

The original interest in rockets at Caltech was inspired almost sixteen years ago by Dr. Theodore von Karman. The early days of the "Galcit" (for Guggenheim Aeronautical Laboratory of the California Institute of Technology) project, as JPL was then called, were guided by Doctors F. J. Malina and H. S. Tsien of the Aeronautics Department, and by Dr. Martin Summerfield, a graduate of the CIT Physics Department.

In 1947 the directorship of the laboratory was assumed



This unique telemetering antenna, circularly polarized, is used to communicate with missiles while in flight.

by Dr. L. G. Dunn, and Chairmanship of the Board of Directors by Dr. C. B. Millikan, both of the Aeronautics Department. From that period on, a number of Caltech faculty members have shared their time with JPL, acting as Chiefs of JPL research sections. Among these are Dr. W. H. Pickering, Electrical Engineering; Dr. H. J. Stewart, Aerodynamics; Dr. Pol Duwez, Materials and Metallurgy; and Dr. Frank Marble, Applied Mechanics.

B. Professional staff

More than half of the large professional group at JPL hold degrees beyond the B.S. About one-third are Caltech graduates. The group is fairly evenly divided among mechanical, aeronautical, chemical, and electrical engineers, together with a somewhat smaller number of mathematicians and physicists.

It goes without saying that the JPL staff derives much profit from the proximity of the Caltech campus and the opportunity for attendance at seminars and ready exchange of ideas with men working on the campus.

C. Administrative and technical staff

For every professional employee, there are three staff members assisting him in various capacities such as computer, fabricator, test operator, clerk, editor, draftsman, accountant, or librarian. This group of men and women has its own news bulletin (*The Lab-oratory*) and has established a number of clubs and hobby groups, such as baseball, tennis, bridge, rod and gun, short wave radio, and sound recording. Evening classes for these employees are held at JPL in certain technical subjects. The professional staff is deeply indebted to the skill and integrity of this group for making possible the embodiment of scientific ideas.

IV. PUBLICATIONS

The necessity for preparing written reports of his work is usually irksome, if not actually painful, to a busy research man. JPL endeavors to alleviate this difficulty by providing a reports staff to assist the engineer in preparing figures, typing, and editing. During the year 1950-51 over 100 reports were published, of which approximately one-third were unclassified or presented in the open literature.

A small number of these publications are given herewith in a brief sample bibliography:

Altman, D., and D. Wise: The Measurement of Chemical Equilibria by Means of the Critical Flow Orifice, *J. Chem. Phys.*, Vol. 19, No. 4, April 1951.

Bowersox, R. B. and C. G. Hylkema: High-Speed Recording Potentiometer, *J. P. L. Memo* No. 20-69.

Dunn, L. G., W. B. Powell and H. S. Seifert: Heat-Transfer Studies Relating to Rocket Power-Plant Development, *Third Anglo-American Aeronautical Conference*, 1951.

Hibbs, A. R.: Optimum Burning Program for Rocket-Propelled Missile in Horizontal Flight, *J. Am. Rocket Soc.*, Vol. 22, No. 4, July-August 1952.

Lehan, F. W.: Expected Number of Crossings of Axis by Linearly Increasing Function Plus Noise, *J. Appl. Phys.*, Vol. 22, No. 8, August 1951.

Martens, H., and Pol DuWez: Phase Relationships in the Iron-Chromium-Vanadium System, *Trans. American Soc. Metals*, Vol. 44, 1952.

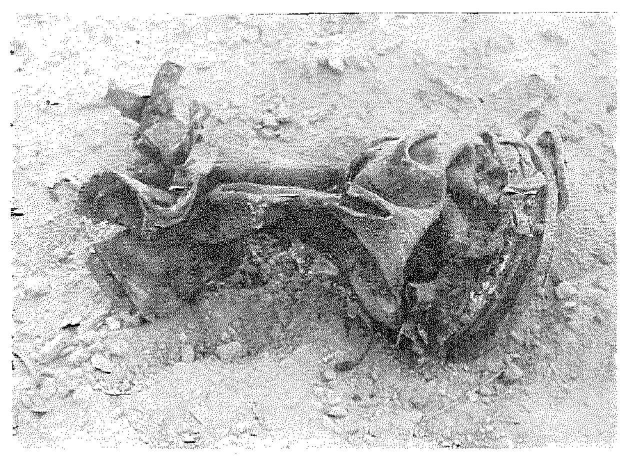
Penner, S. S. and D. Weber: Absolute Values for the Integrated Absorption of Diatomic Gases. I. Carbon Monoxide, *J. Chem. Phys.*, Vol. 19, No. 7, July 1951.

Seifert, H. S., M. M. Mills, and M. Summerfield: The Physics of Rockets, *Am. J. Phys.*, Vol. 15, No. 1, Jan-Feb. 1947; Vol. 15, No. 2, March-April 1947; Vol. 15, No. 3, May-June 1947.

Stewart, J. L.: A General Theory for Frequency Discriminators Containing Null Networks, *Proc. I.R.E.*, Vol. 40, No. 1, January 1952.

Stewart, R. M.: A Simple Graphical Method for Constructing Families of Nyquist Diagrams for Multi-Loop Control Systems, *J. Aero. Sci.*, Vol. 18, No. 11, November 1951.

Wright, F.: Measurements of Flame Speed and Turbulence in a Small Burner, *Phys. Rev.*, Vol. 81, No. 5, March 1, 1951.



Months of effort and hundreds of thousands of dollars go into every rocket firing — and this is the end result.