GALCIT

THE FIRST TWENTY-FIVE YEARS

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THE GUGGENHEIM AERONAUTICAL LABORATORY OF THE CALIFORNIA INSTITUTE OF TECHNOLOGY:

The First Twenty-Five Years

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I

HISTORY AND BASIC POLICIES

THE BIRTH DATE of the modern era of heavier-than-air flight is generally given as December 17, 1903, when the Wright Brothers made their first successful but unheralded flights. Fifty years later their achievement was honored at celebrations throughout this country and abroad. At the time of these celebrations the Guggenheim Aeronautical Laboratory of the California Institute of Technology, usually referred to by the less unwieldy abbreviation GALCIT, was well into the twenty-sixth year of its active life, which by then had spanned just over half the period of modern aeronautics. It has seemed appropriate, therefore, to review the history and contributions of the GALCIT over the 25 years of its existence.

The story really begins some ten years before the construction of the Guggenheim Laboratory itself. The January, 1917, Catalogue of the Throop College of Technology (which later became the California Institute of Technology) contains the following:

> Just as this catalogue goes to press, generous and wise friends of the college have undertaken to provide facilities for research in the science of Aeronautics, with every prospect of the cooperation of the United States Government. A wind tunnel will immediately be built and equipped in the best fashion, and a graduate course will probably be provided for students desiring to specialize in this branch of physics and engineering.

Between $5,000 and $6,000 was made available for these purposes, and during the subsequent year a small NPL type wind tunnel was constructed having a maximum wind velocity of 40 miles per hour. The Throop Catalogue for the following year contains the first mention of two staff members concerned with matters aeronautical. Mr. A. A. Merrill, one of the very early American pioneers, whose active participation in aviation dates back to the 1890's, appears as Research Assistant; he was given the responsibility for designing, supervising the construction of, and operating the wind tunnel. (He also doubled in brass as Instructor in Accounting.) Dr. Harry Bateman, a brilliant Cambridge-trained mathematician, is listed as Professor of Aeronautical Research and Mathematical Physics. The catalogues of the next few years list a number of aeronautical courses given by these two staff members. However, the number of students must have been very small, and there was no Aeronautics Department, nor were any aeronautical degrees awarded. By the mid-nineteen-twenties the aeronautical activities at the California Institute, into which Throop had been transformed, included only the wind tunnel experiments of Mr. Merrill, assisted by occasional students, and advanced courses in Theoretical Hydrodynamics and Elasticity given by Dr. Bateman from time to time to post-graduate students in physics and mathematics.

At about this time there were two developments of great importance to the future of aviation. The Daniel Guggenheim Fund for the Promotion of Aeronautics was established, having as one of its principal objectives the stimulation of advanced teaching and research in aeronautics. Second, it was becoming increasingly apparent that Southern California was destined to become one of the country's greatest centers of aviation industry. Dr. Robert A. Millikan, Chairman of the California Institute's Executive Council, realized the potential significance of these two factors to the future of the California Institute, and succeeded in October 1926 in obtaining a grant of $300,000 from the Guggenheim Fund for the construction of a laboratory and the establishment of a graduate school of aeronautics at the Institute. The eminent applied mathematician, scientist, and engineer, Dr. Theodore von Kármán, was brought to this country under the auspices of the Guggenheim Fund and visited many educational and research institutions with aeronautical interests. In particular, he spent the fall of 1926 at the California Institute advising its staff regarding the educational policies and experimental facilities of the new graduate school and laboratory. During this visit the essential features which characterized their subsequent development were largely worked out under Kármán's leadership. A cooperative arrangement was also made with the Douglas Aircraft Company whereby the airplane design courses would, at least initially, be given by engineers from its staff.

During the next two years the laboratory was designed and constructed, having as its major research facility a 200 mile per hour wind tunnel with a 10-foot test section; and the instructional course material was developed. In the fall of 1928 the laboratory was completed, and the GALCIT began its active career in aeronautical instruction and research. The academic staff consisted of Professors Harry Bateman and Theodore von Kármán (the latter as Research Associate, dividing his time between Aachen and the Institute), Assistant Professors Arthur L. Klein, Clark B. Millikan, and Arthur E. Raymond, and Instructor Albert A. Merrill. Raymond, then an engineer and later Vice-President of the Douglas Aircraft Company, served in a part-time capacity and was responsible for the aircraft design courses. Two years later Dr. von Kármán became Director of the GALCIT on a full-time basis and assumed the continuing leadership of its educational and scientific program.

The program of instruction and research which was announced as the GALCIT began its life is outlined in the 1930 Catalogue of the California Institute:

1. A comprehensive series of theoretical courses in aerodynamics and elasticity with the underlying mathematics and mechanics.
2. A group of practical courses in airplane design.
3. Experimental and theoretical researches on
   (a) The basic problems of flow in real fluids with regard to the scientific foundations of technical hydro- and aero-dynamics;
   (b) practical problems in aerodynamics and structures, especially as applied to aeronautics.

Far more important than the specific program outlined above was the fundamental concept of modern Applied Mechanics which Kármán brought to the new graduate school and which has ever since dominated its thinking and guided its activities.

Modern Applied Mechanics was founded by the German mathematician, Felix Klein, late in the last century. Its aim is the application of the methods of pure science to the treatment of engineering problems. Originally it involved the use of the most advanced mathematical techniques in the theoretical analysis of such problems and the application of the physicists' methods to their experimental study. More recently other scientific techniques, especially those of chemistry, have effectively been utilized. It is not surprising that analytical and scientific methods first replaced the older empirical or "cut-and-try" procedures in new branches of engineering like aeronautics rather than in the older and more established fields. During the past 25 or 30 years, however, the methods of Applied Mechanics have played an ever increasing role in the development of all aspects of engineering. Kármán, a pupil and later a colleague of Klein's, not only imbued the new graduate school with the spirit of Applied Mechanics but himself has been one of the most significant and prolific contributors to its literature.

It is a basic tenet of the Institute's educational policy that formal classroom instruction and research be closely associated, particularly in the graduate school. This policy has been followed in the aeronautics graduate school from the beginning. The next section of this survey outlines the major research activities and accomplishments of the GALCIT and, correspondingly, also indicates the fields which have been primarily emphasized in the instructional curriculum. During the student's first graduate year he normally takes introductory courses in Aerodynamics of the Airplane and in Airplane Design, as well as intensive courses in Engineering Mathematics and in Mechanics and Thermodynamics of Fluids. Since, in accordance with general Institute policy, the first-year graduate student also takes a course in the field of Humanities, there is normally no time for him to engage in any extensive research. Following the successful completion of these first-year courses the student receives the degree of Master of Science. In his second year the graduate student selects a research problem and spends nearly half his time on it. All students take a course in Experimental Methods in Aeronautics and in addition two or three courses selected from a list of electives, which includes advanced courses in Aerodynamics, Fluid Mechanics, Elasticity, Solid Mchanics, and Aircraft Design. There is also a special option in Jet Propulsion with its appropriate group of elective courses. Towards the end of this year the student and faculty jointly decide whether he wishes and is qualified to proceed with more advanced study leading to the doctorate. If he is not to continue, he prepares a thesis on his research, and, if this is accepted and the other academic requirements are fulfilled, he receives the degree of Aeronautical Engineer. Students with interest in and qualifications for further study do not normally take the engineer's degree but are admitted to work towards the degree of Doctor of Philosophy, which usually requires an additional one or two years. Essentially this pattern has been followed for the past 25 years, although there have been minor variations from time to time, and the list of advanced courses offered is in a continuous state of review and modification. Further details on the numbers and types of students together with some comments on their subsequent careers are given in a later section.

The GALCIT has, from the beginning, maintained a close contact with the aircraft industry. There have also been continuing and intimate relations with military and other government agencies since the early days of the laboratory. Furthermore, members of the laboratory staff have been instrumental in creating and developing organizations and facilities which have later become independent of the GALCIT, but with which close association continues to be maintained. These aspects of the laboratory's activities are discussed in later sections of this review.

A few highlights will serve to bring the GALCIT's history up to date. The number of enrolled students increased from three in the first class of 1928-29 to a wartime and post-war peak of well over a hundred, and now appears to be leveled off at about eighty. An addition to the original building was constructed in 1947 to furnish the classroom, office, laboratory, and shop space to cope with this expansion. The academic staff has also increased from the initial six, of whom all but two were part-time, to the present eighteen. The latter figure does not include the large number of graduate fellows and assistants. In 1942 Dr. von Kármán was called to Washington to serve as special assistant to General Arnold and later as Chairman of the Air Force Scientific Advisory Board. Dr. Clark Millikan became Acting Director of the Laboratory in 1945 and in 1949 was appointed Director, when Kármán became Professor Emeritus.

The following sections discuss in more detail some of the laboratory's activities and achievements which have been indicated above. The individual sections have been prepared by various members of the staff and hence differ somewhat in approach and style.

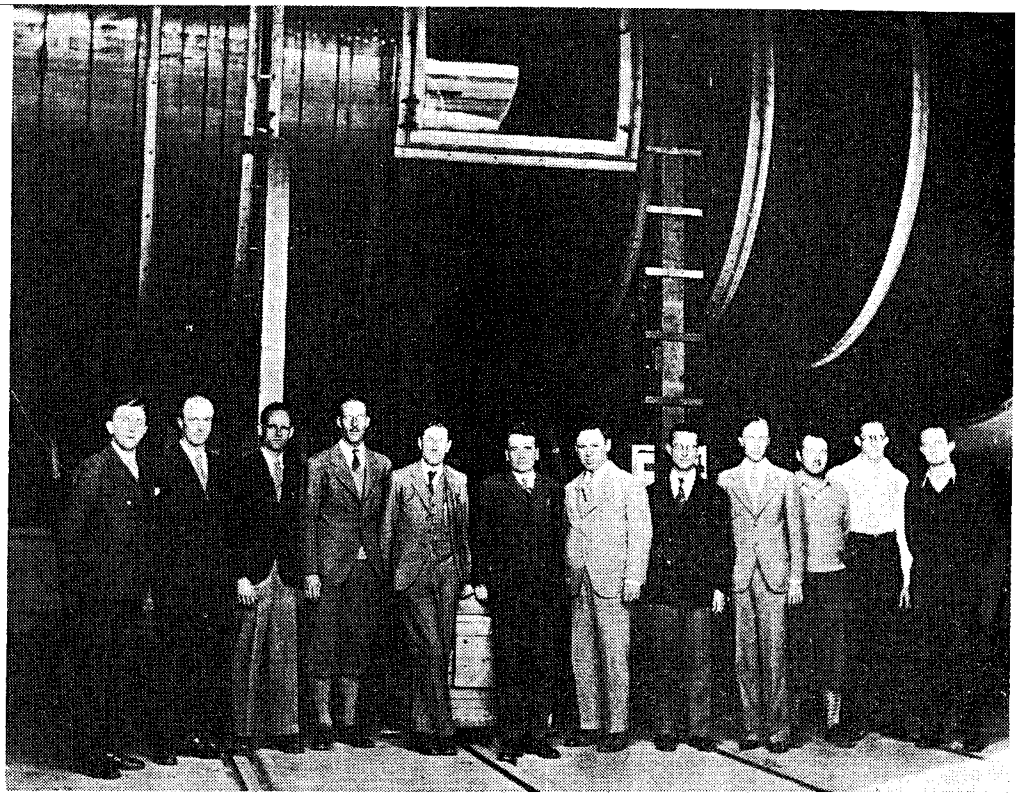
II

STAFF OF THE GRADUATE SCHOOL AND LABORATORY

SECOND ONLY TO KÁRMÁN as a guiding force in the early development of graduate study was Dr. Harry Bateman, who came to the Institute in 1918 as Professor of Aeronautics, Theoretical Physics, and Mathematics. Bateman's death in 1946 and Kármán's retirement in 1949 ended their activities in the GALCIT, but their influence continues strong, and will, it is hoped, remain so for as long as the laboratory exists. Before listing the present staff members, a basic policy which has prevailed since the first years of the GALCIT should be mentioned. This is the practice of inviting distinguished scientists to visit the graduate school and work with its staff members and students. In some cases the visits are short, but often they have been extended over a term or even a full academic year. Among the visitors in the fields of Fluid Mechanics and Aerodynamics have been Professors L. Prandtl, G. I. Taylor, J. M. Burgers, S. Goldstein, W. Tollmien, L. Howarth, J. Kampe de Feriet, I. Tani, M. Lighthill, G. Batchelor, K. Stewartson, and many others. In Solid Mechanics, Elasticity, and Structures, S. Timoshenko, J. N. Goodier, K. O. Friedrichs, L. H. Donnell, W. Prager, W. Wittrick, N. Minorski, J. A. van den Broek, C. B. Ling, and others have participated in the laboratory's activities. The new viewpoints which these and other distinguished scientists have brought and the interchange of ideas which their presence has made possible have been of inestimable value to the GALCIT group.

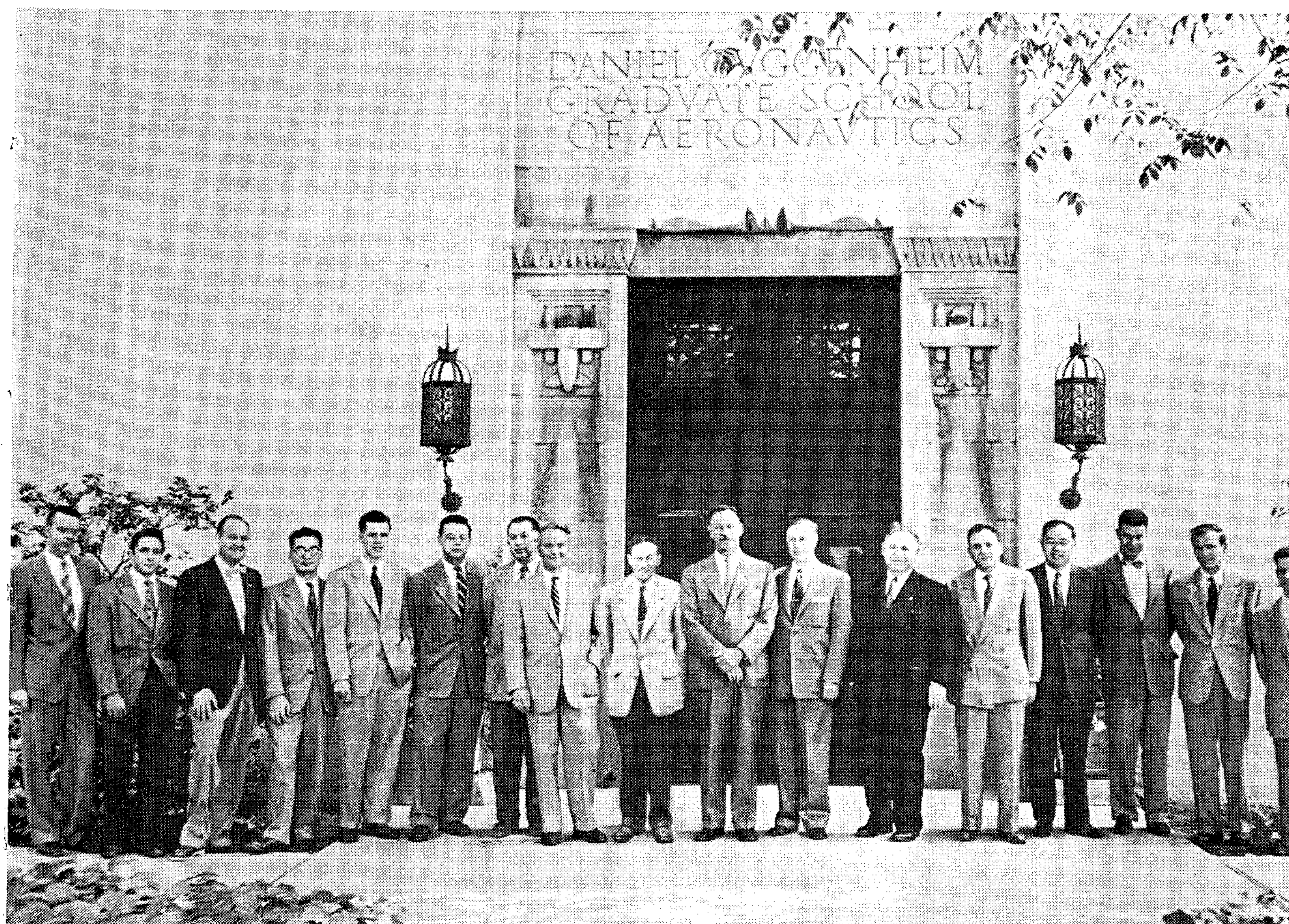
The present active staff members are listed below, together with their major responsibilities and fields of interest.

Clark B. Millikan has been a member of the staff since 1928 and became Director upon Dr. von Kármán's retirement in 1949. As Professor of Aeronautics his teaching and research activities have been primarily in the fields of Fluid Mechanics and Aerodynamics. He has been responsible for developmental wind tunnel testing and serves as Director of the Cooperative Wind Tunnel and Chairman of the Advisory Board of the Jet Propulsion Laboratory.



GALCIT *personnel in 1930. Faculty members Millikan, Bateman, Kármán, and Klein are flanked by visiting scientists and graduate students.*

The GALCIT *academic staff in 1954 (from left to right: Coles, Yoler, Felberg, Fung, Williams, Cole, Stewart, Lagerstrom, Liepmann, Millikan, Sechler, Klein, Lees, Nagamatsu, Willmarth, Roshko, Kaplun. Valleri not present.).*



E. E. Sechler joined the staff as Instructor in 1930 and has been Professor of Aeronautics since 1946. He is responsible for the instructional and research program in Solid Mechanics, Elasticity, and Structural Design, and has contributed greatly to the development of experimental apparatus and instruments. He is a consultant to the Cooperative Wind Tunnel.

A. L. Klein has been a member of the staff since 1928 and is now Professor of Aeronautics on a part-time basis. (He is also a member of the engineering staff of one of the major aircraft companies.) He teaches advanced airplane design and laboratory instrumentation, and has been responsible for much of the design work involved in the development of the Laboratory's equipment. He is also a consultant to the Cooperative Wind Tunnel.

H. W. Liepmann came to the GALCIT as Research Fellow in 1939 and has been Professor since 1949. His major fields of interest have been Fluid Mechanics and experimental Aerodynamics, and he has been responsible for developing and leading a large group of colleagues and graduate students who have worked in these fields.

H. J. Stewart, Professor of Aeronautics, has been on the staff since 1938 and has worked in theoretical Aerodynamics and Meteorology. He is currently on a part-time basis, since he also serves as Chief of the Research Analysis Section at the Jet Propulsion Laboratory.

P. Lagerstrom joined the staff as Assistant Professor in 1947 and is now Professor of Aeronautics. His field is theoretical Fluid Mechanics, and he has led a group of colleagues and students in both basic and applied researches in this subject.

L. Lees came as Associate Professor in 1953 to work in theoretical Fluid Mechanics after association with GALCIT much earlier as Research Assistant. He is currently devoting much of his effort to problems in hypersonic flow.

J. Cole, who was appointed Assistant Professor in 1951, also has theoretical Fluid Mechanics as his main field of interest.

Y. C. Fung joined the staff as Assistant Professor in 1951. His field is Solid Mechanics and Structural Design, with particular emphasis on problems of Aeroelasticity.

M. L. Williams also became Assistant Professor in 1951. His primary interest is Elasticity and Structural Design, but he is also involved in teaching and theoretical research on Flight Testing and Rotary Wing Aircraft problems.

H. Nagamatsu has been Senior Research Fellow since 1949 and has had responsibility for the development and use of the hypersonic research facility.

F. Felberg is Lecturer in Aeronautics on a part-time basis, teaching the introductory course in Aerodynamics of the Airplane. He is also a senior member of the staff of the Cooperative Wind Tunnel.

A. Roshko is Senior Research Fellow, carrying on research and supervising the work of a number of graduate students in Fluid Mechanics.

D. Coles is now spending his second year as Research Fellow, and *S. Kaplun, W. Willmarth, Y. Yoler*, and *S. R. Valluri* are also Research Fellows. The first four are working in Fluid Mechanics while the last is in Solid Mechanics.

III

MAJOR RESEARCH FIELDS–ACCOMPLISHMENTS AND FACILITIES

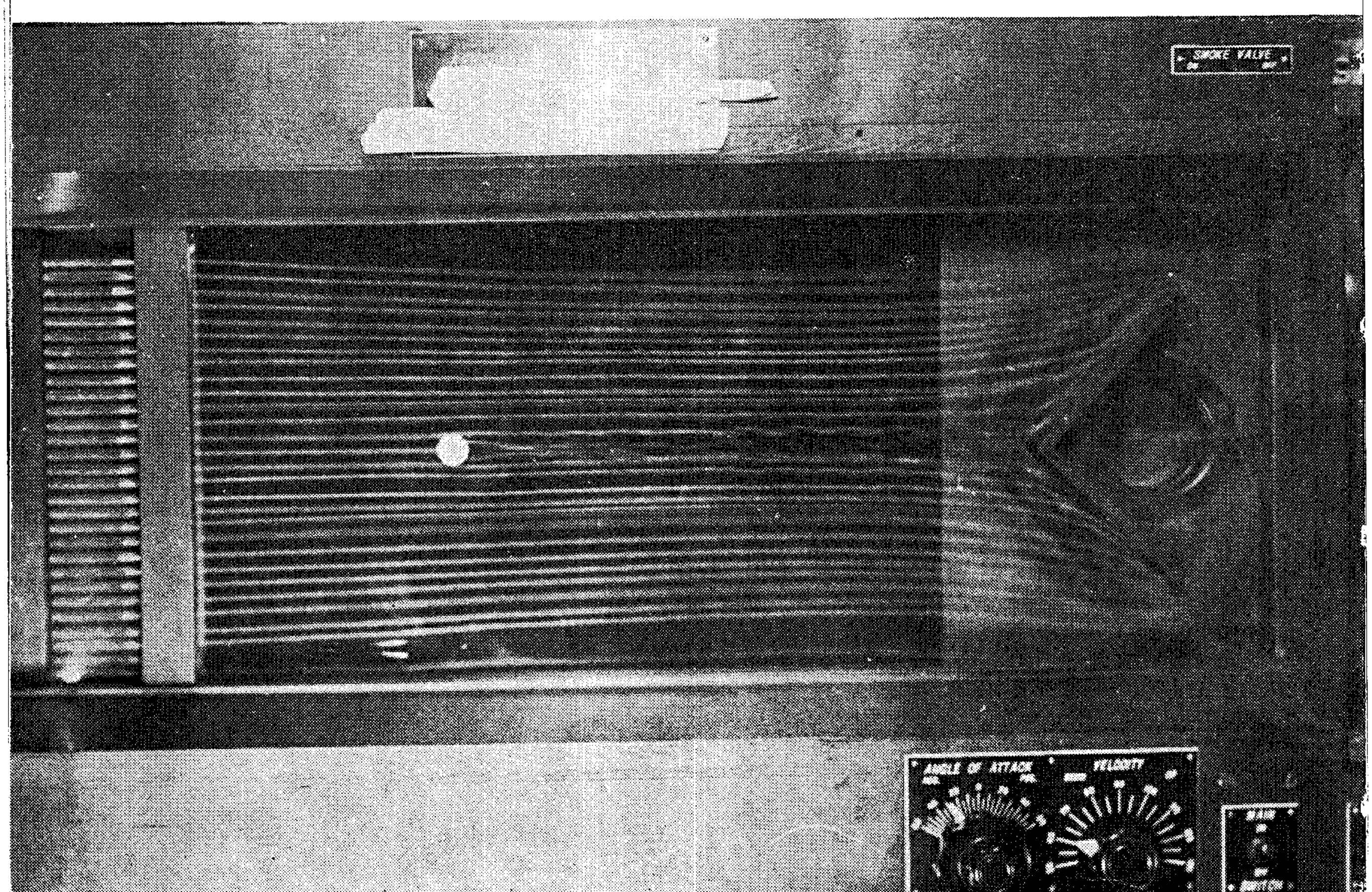
1. *Fluid Mechanics*

A VERY LARGE PART of the research activities at the GALCIT has always been occupied with work on the fundamental aspects of fluid mechanics. Now, 25 years after the foundation of the Laboratory, the list of publications on fluid mechanics constitutes a considerable part of the staff bibliography, and it is difficult indeed to select out of these the most important, original, or influential contributions.

In the early years the problems of paramount interest centered around boundary layer flow and turbulence. The interest in these two fields has persisted until the present, but has been supplemented by work in the fields of transonic, supersonic, and hypersonic flow and their host of new problems.

Prandtl's concept of mixing lengths and Kármán's general similarity approach governed the thinking in turbulence work during

Flow about circular cylinder in low-speed smoke tunnel.



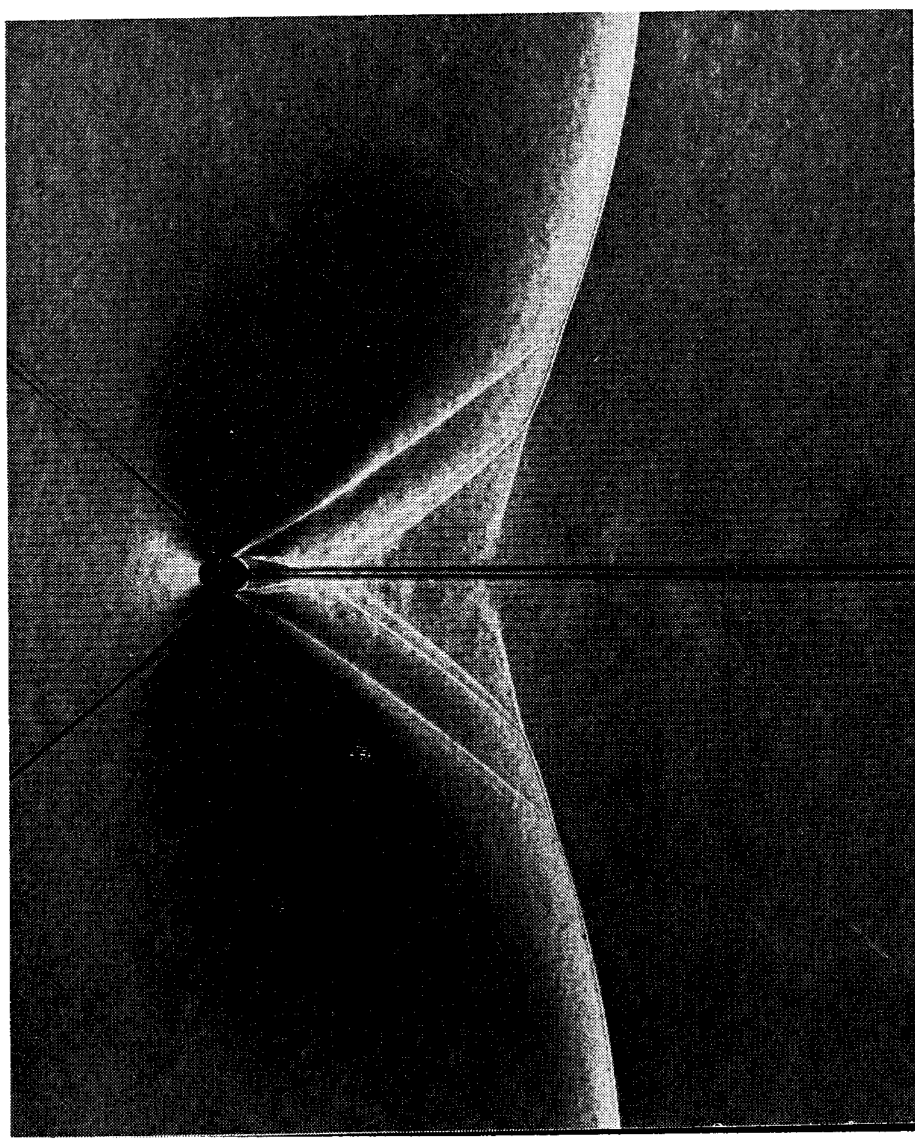
the late twenties and early thirties. To this area the GALCIT contributed much with papers by Kármán, Millikan, Tollmien, Kuethe and others. In the late thirties G. I. Taylor's concept of isotropic turbulence stimulated considerable work at GALCIT in this field. The now classical paper of Kármán-Howarth on isotropic turbulence appeared, followed by further theoretical and experimental work at the Institute. At nearly the same time renewed interest was taken in boundary layer transition and laminar instability. Transition by transverse contamination was discovered at the GALCIT by Charters, and the classical experiments of Schubauer and Skramstad at the Bureau of Standards were supplemented by Liepmann's work on the effect of curvature on laminar instability and transition. At about the same time C. C. Lin completed an extensive revision and clarification of the theory of laminar instability and together with Lees extended stability investigations to compressible fluid flow. The first detailed measurements of the structure of turbulence in free shear layers were carried out by Corrsin and Laufer at GALCIT, in the course of which the very important phenomenon of "intermittency" was first observed.

Interest in turbulence and related fields is still strong at the GALCIT today. Indeed, Roshko's recent work on vortex streets deals with a problem which was first studied by Kármán in 1912, and which is still not completely solved. D. Coles in recent papers has re-examined the phenomenological approach to the turbulence shear problems and extended the work of Prandtl, Kármán, and Millikan, thus connecting the early work at the GALCIT with the present. The impact of supersonic flight has also renewed interest in skin friction, and Dhawan and Coles have made very significant contributions to the present knowledge of high speed skin friction. This work is now being extended to the hypersonic range by Nagamatsu and his co-workers. The interest in turbulence has also led to studies of the modern theory of probability and its application to various statistical problems in fluid dynamics and aeronautics. In this connection Liepmann's approach to the buffeting problem has proved extremely fruitful.

Research on compressible flow began here as early as the thirties. In a classical paper, presented at the Fifth Volta Congress in Rome in 1935, Kármán made a penetrating analysis of some of the main problems in compressible flow. A subsequent paper by Kármán and Tsien made a more detailed analysis of the problem of the effect of compressibility on skin friction. Beginning with the 1932 paper of Kármán and Moore on the resistance of slender bodies of revolution in supersonic flow, there was continuous activity in the linearized theory of the supersonic motion of an inviscid fluid. The more important applications of this theory to engineering problems are summarized in the next section. Here it need only be mentioned that significant contributions to the basic foundations of the theory were made by Hayes and Lagerstrom, and second order corrections were studied by Van Dyke.

The difficulties encountered with fast aircraft near the speed of sound in the early parts of the war focused much attention on the problem of transonic flow. At first it appeared that the search for

Schlieren photograph at low supersonic speed in the transonic tunnel showing flow past circular cylinder. (The horizontal and diagonal dark, straight lines are support wires outside the airstream.)

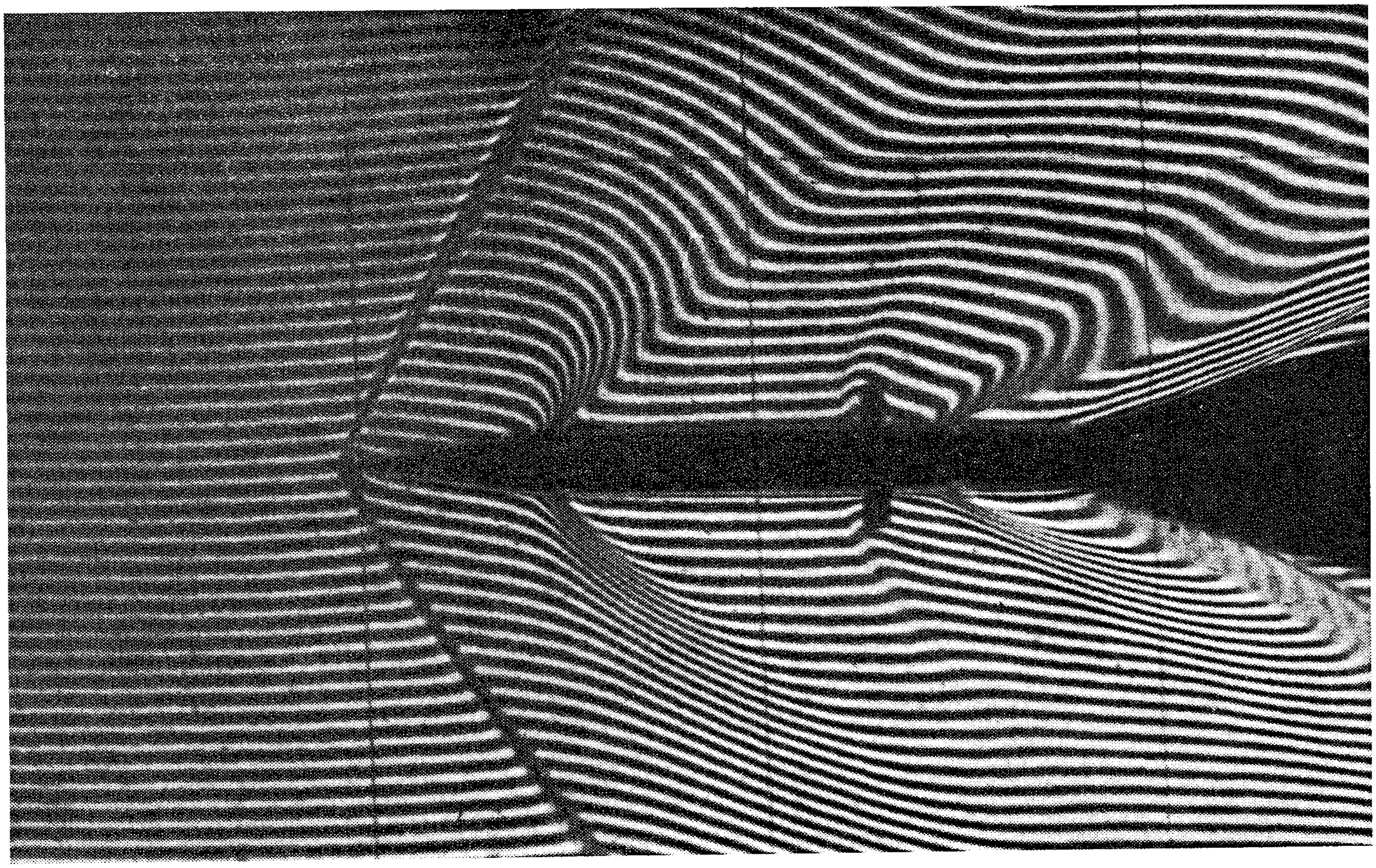


potential solutions, that is, shock-free solutions, was of paramount importance and the concept of the "limiting line," discovered in the middle of the thirties by F. and M. Clauser at the GALCIT, attracted much attention. Later, the presence of shock waves had to be accepted as a characteristic feature of transonic flow, and the emphasis shifted. In this recent development Kármán's general transonic similarity rules, the experimental work of Bryson and the theoretical work of Cole are important contributions which have come from the GALCIT.

Some of the earliest GALCIT publications are papers by Millikan (1929) on viscous flow. The boundary-layer theory of viscous flow was also investigated during the thirties by Kármán and Millikan. A paper by Kármán and Tsien in 1938 dealt with the effect of compressibility on boundary-layer flow. In high speed flow many new problems of viscosity and turbulence arise. In particular, new types of interaction between shock waves and boundary layers were noted during the forties and were studied experimentally and theoretically by Liepmann, Roshko, Dhawan, Cole and others. The research effort on problems of this type is at present continually extending. The problem of shock-wave boundary-layer interaction becomes even more pronounced at hypersonic speeds. Contributions toward an understanding of this interaction have been made recently by Lees and by Nagamatsu and Li. Molecular phenomena become important in flows at low pressures. In this latter field a survey paper by Tsien was important in drawing the attention of aerodynamicists to the application of kinetic theory of gases to their problems.

The difficulties in obtaining a theoretical understanding of viscous phenomena at high speeds also led to studies of the fundamental aspect of the equations for viscous flow, incompressible as well as compressible. Research in this field was done by Lagerstrom, Cole, Trilling, and Wu. This work included, in particular, a critical re-examination of the nature of the boundary layer approximation in papers by Lagerstrom, Van Dyke, Latta and Kaplun.

The development of research equipment and instrumentation for the experimental investigation of Fluid Mechanics problems is discussed in a later section, and has played an important part in the GALCIT's contributions to this field.



Interferometer photo showing shock wave and density variations in flow over a wedge at low supersonic speed.

2. *Applied Aerodynamics*

An important part of the research effort at the GALCIT has been, and is, connected with applied aerodynamics. The theoretical phases of this work have been concerned primarily with the development of mathematical techniques by which the principles of fluid mechanics and dynamics can be applied to engineering problems. The experimental phases have been concerned with the development of laboratory instrumentation and test procedures which can be used to investigate airplane and missile development problems. A large part of the experimental work has been concerned with the design, construction and operation of the various GALCIT wind tunnels, the Cooperative Wind Tunnel, and the supersonic wind tunnels at the Jet Propulsion Laboratory. Since wind tunnel testing has been such an important portion of the research activities, this work is summarized later in a separate section.

The numerous investigations in applied aerodynamics can be grouped into the following broad categories: airfoil and wing theory, the linearized theory of supersonic wings and bodies, non-stationary wing theory, wind tunnel techniques, and those topics which couple dynamics and aerodynamics, e.g., performance, stability and control. In addition, various staff members have presented broad surveys covering many of these special topics. The best known of these survey papers are the 1935 Volta Congress paper by Kármán, the Third Wright Brothers Lecture, presented by Millikan in 1939, and the Tenth Wright Brothers Lecture, presented by Kármán in 1946.

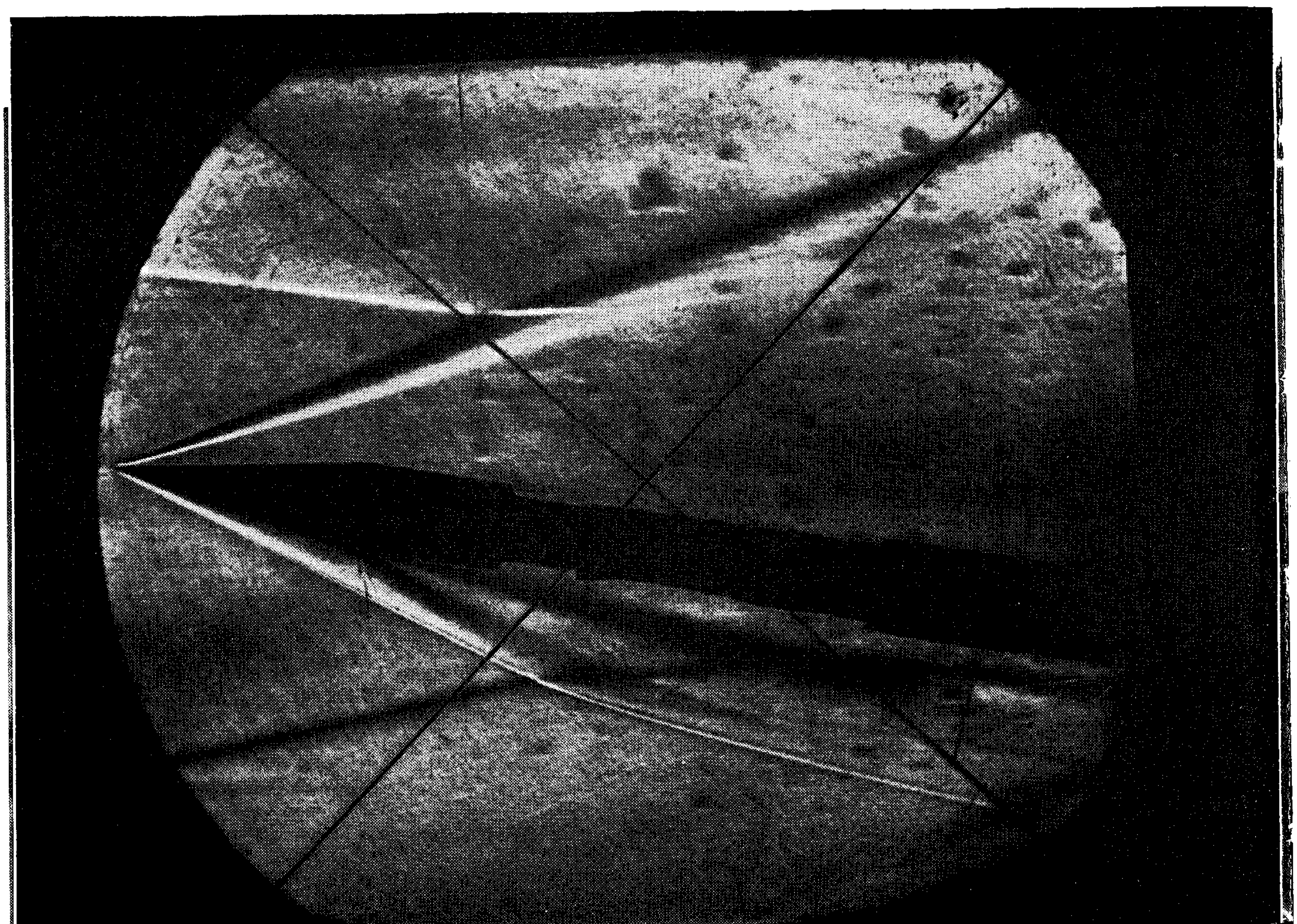
The contributions of the GALCIT group to airfoil and wing theory started with Millikan's work on the classical theory of thin airfoils in 1930. Further developments of this theory were presented by Stewart in 1942. A formulation of the Prandtl and lifting surface wing theories in terms of Fourier integrals was given by Kármán in 1935. A theory of wings of very low aspect ratio was developed by W. Bollay (1937, 1939). The aerodynamics of airfoils and wings in a non-uniform flow field was studied by Tsien and Kuo (1943) and by Kármán and Tsien (1945). The aerodynamics of an axially symmetric wing was studied by Stewart (1944).

As interest in high speed and supersonic flight increased, applied aerodynamics research was correspondingly concentrated in the field of compressible fluid aerodynamics and resulted, as mentioned in the preceding section, in the development of linearized theory for widespread engineering use. The first application of this theory, by Kármán and Moore to the problem of the resistance of slender bodies moving with supersonic speeds, was presented in 1932. The problem of lift in this case was studied by Tsien (1938). The application of the linearized theory to subsonic aerodynamic problems was discussed by Lees and Tsien (1945). The theory was applied by Puckett and Stewart (1946, 1947) to the calculation of the lift and drag of delta wings at supersonic speeds and, following Busemann's work, to the development of the theory of conical flows. The application of the conical flow theory and other techniques to many supersonic wing and interference problems has been carried out by Lagerstrom and co-workers since 1947.

The problem of wing flutter caused an interest to develop in the aerodynamics of wings in non-stationary motion. The first investigation at the GALCIT was a joint work by Kármán and Sears in 1938. This two-dimensional incompressible fluid theory was further developed by Sears (1938 to 1940) and by Biot (1942). An experimental investigation of the response of an airfoil to a gust was carried out by Sears and Kuethe (1939). The extension of Evvard's linearized supersonic wing theory to non-stationary problems was studied by Li and Stewart (1950 to 1953). Froehlich (1951) calculated the non-stationary response of delta wings with supersonic leading edges and of the corresponding class of "purely supersonic" wings. The non-stationary slender body theory was studied recently by Cole (1953).

Since the 10-foot wind tunnel at GALCIT was one of the first wind tunnels to be used extensively for the development testing of airplanes, many of the early research investigations were concerned with the development of laboratory equipment and testing procedures for investigating various special design problems. Work in this category includes that of Klein (1932) on wing fillets, of Millikan (1934) on the effect of turbulence on the maximum lift

Shock waves about a cone in the hypersonic wind tunnel at a Mach Number of 5.8. (The crossed wires are not in the airstream.)



of wings, of Russell, McCoy and Millikan (1936) on the effects of the propeller slipstream, of Millikan (1936) on the stalling of tapered wings and of Rumph and Shairer (1940) on the application of boundary layer and wake survey measurements.

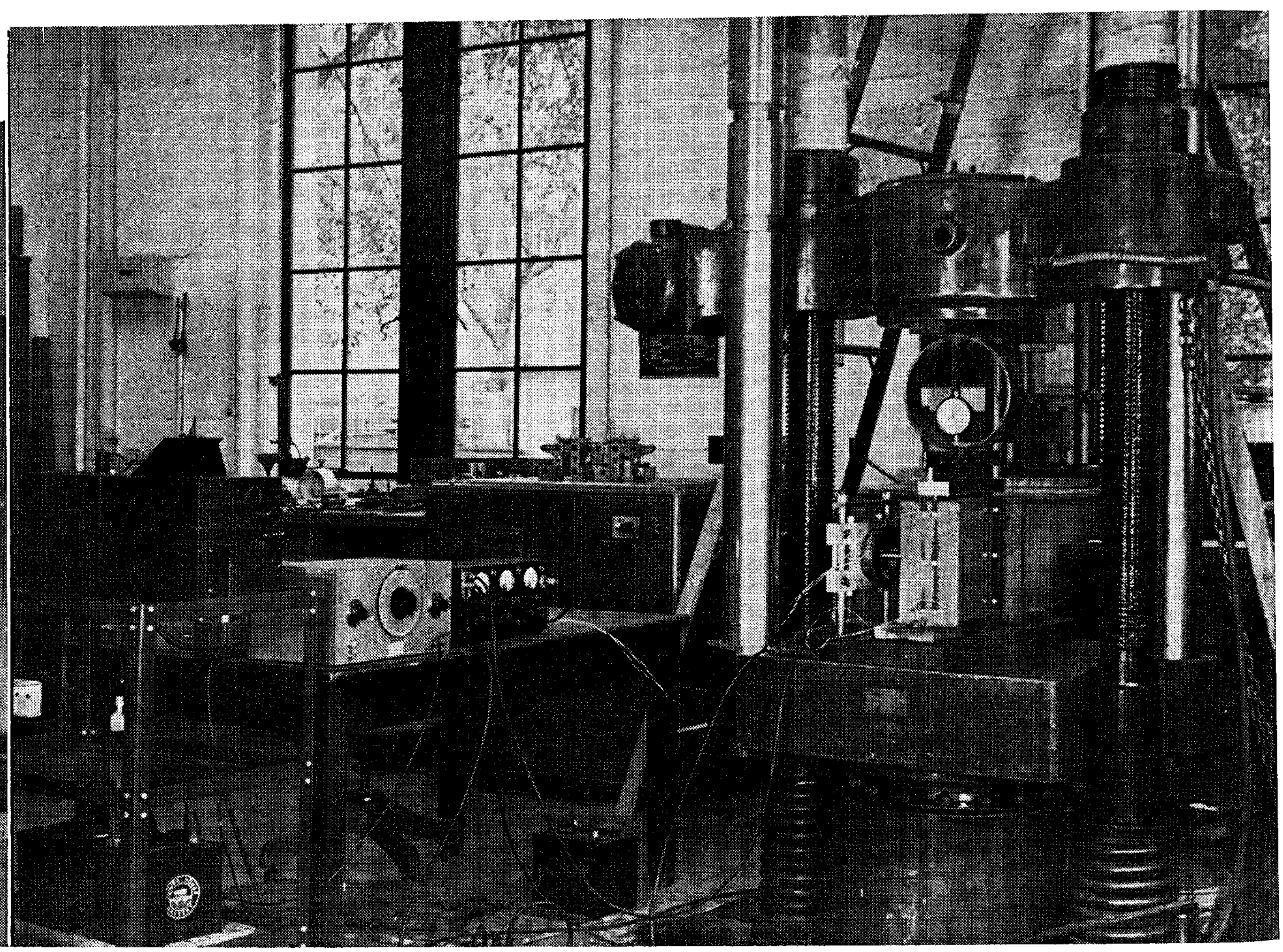
A related group of theoretical investigations was concerned with the calculation of the corrections which must be applied to wind tunnel test results in order to determine the corresponding free flight conditions. These investigations included those of Millikan (1932) on the effect of the wind tunnel walls on the lift distribution of wings, of Biot (1933) on the corrections to rolling moments, and of Stewart (1939) on the corrections to yawing moments and (1941) on the effects of the wind tunnel walls on the stalling characteristics of wings.

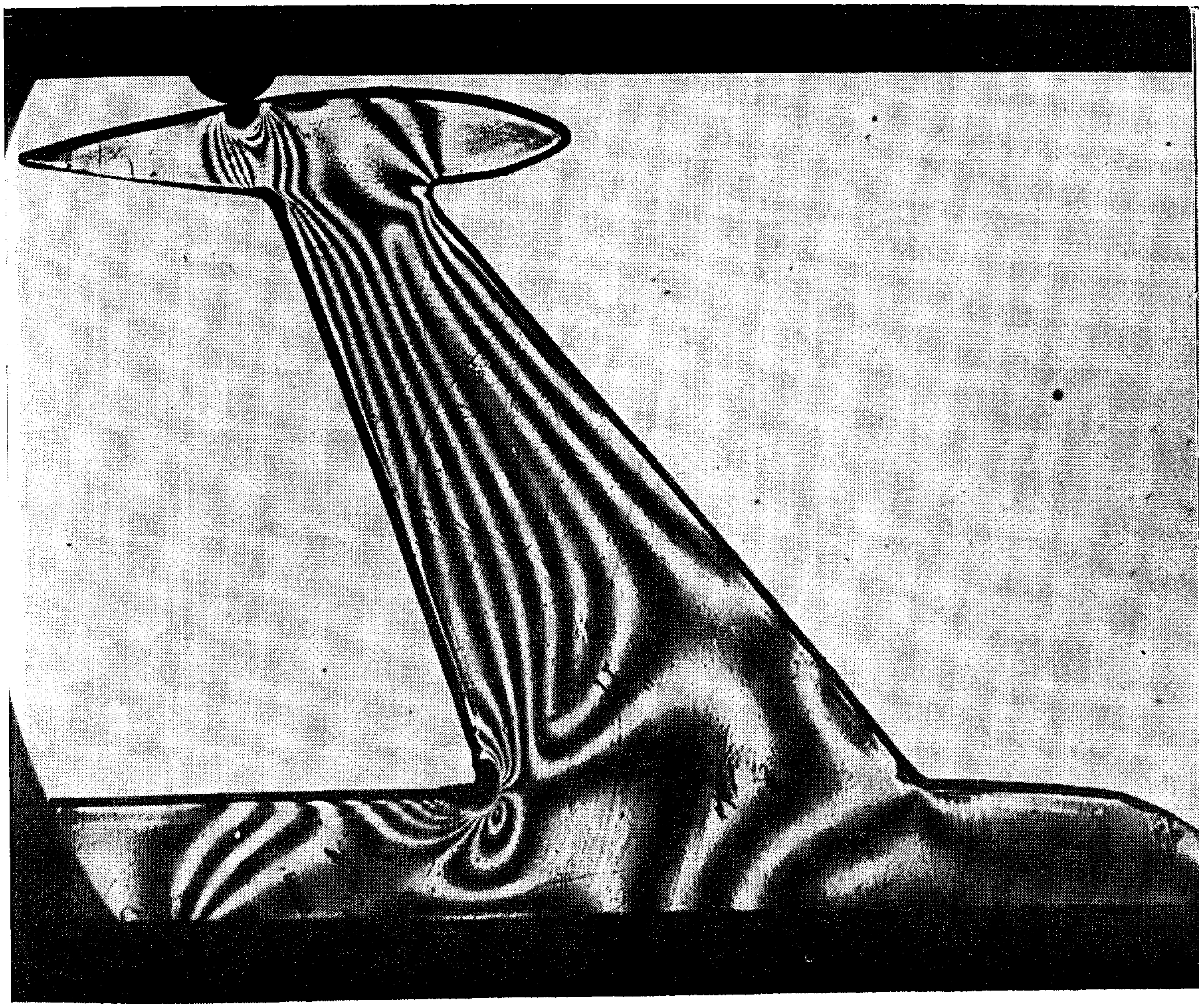
In an overall sense aerodynamics is of importance in the design of an airplane or missile primarily through the influence of the air forces on the motion in flight, i.e., on the performance, stability and control. One group of investigations was concerned with airplane performance problems. This group includes the work of Millikan (1929) on a simplified approach to performance problems, which was further developed by Oswald (1932), by White and Martin (1936) and by Rockefeller (1937, 1939). Problems in determining the optimum flight paths, particularly for high altitude transport operation, were studied by Rockefeller and Moore (1935, 1936). Another group of research projects was concerned with problems of stability and control. These include the work of Jenney (1935) and Bolster (1937) on static longitudinal stability, of Albach and Miller on static directional stability, of Root (1934) on dynamic longitudinal stability, and of Goode (1943) on maneuverability in turns. The special effects of high speed flight, particularly in the transonic speed range, on stability and control were investigated by Kármán (1947).

It is natural that the aerodynamic study of airplane wings should stimulate corresponding investigations in the field of turbomachinery, where the individual blades behave like wings in a non-uniform flow field. The initial step in this direction was taken by Kármán in 1944, when he extended the actuator disk theory of propellers to describe the flow across turbine blade rows. The technique was developed by Rannie to the point where it constitutes a recognized design tool for axial compressors and turbines. The limitation of this calculation, which gives the flow field only in the plane of the actuator disk and far downstream, was removed by Marble, who calculated the entire flow field not only for actuator disks but for blades of finite chord. This work, originally valid for axial turbomachines, was generalized by Marble and Michelson to turbomachines of different geometry.

The problem of blade losses, which cannot be treated from the actuator disk viewpoint, was first investigated by Tsien in 1944 in his calculation of the field induced by an infinite set of non-uniform lifting lines. The extension of this treatment to the case where the flow approaching the cascade is not uniform was made possible through the development, by Kármán and Tsien, of the theory for a lifting line in non-uniform approach flow. Modification of this analysis for problems of axial compressors was begun by Fejer, who discussed the flow about a single blade between parallel walls when the approaching flow was non-uniform.

Testing column stability of frame members by determining natural frequency as a function of loading.





Photoelasticity photograph showing stress distribution in model of aircraft fuselage, swept wing, and tip tank.

3. *Elasticity and Structures*

At the beginning of the GALCIT it was decided that one of the major fields of study to be emphasized was that of aircraft structural analysis and design. Early instruction in this subject was given by A. E. Raymond of the Douglas Aircraft Company and A. L. Klein. An abstract of the subject matter of these early courses in design indicates the relatively primitive types of structure used in the aircraft of that time. Beams, columns, trusses, and simple tension members were the structural elements, and, while there is reference to tie rods, strength of X4130 steel, and fabrics, little mention is made of sheet metal structures or the aluminum alloys.

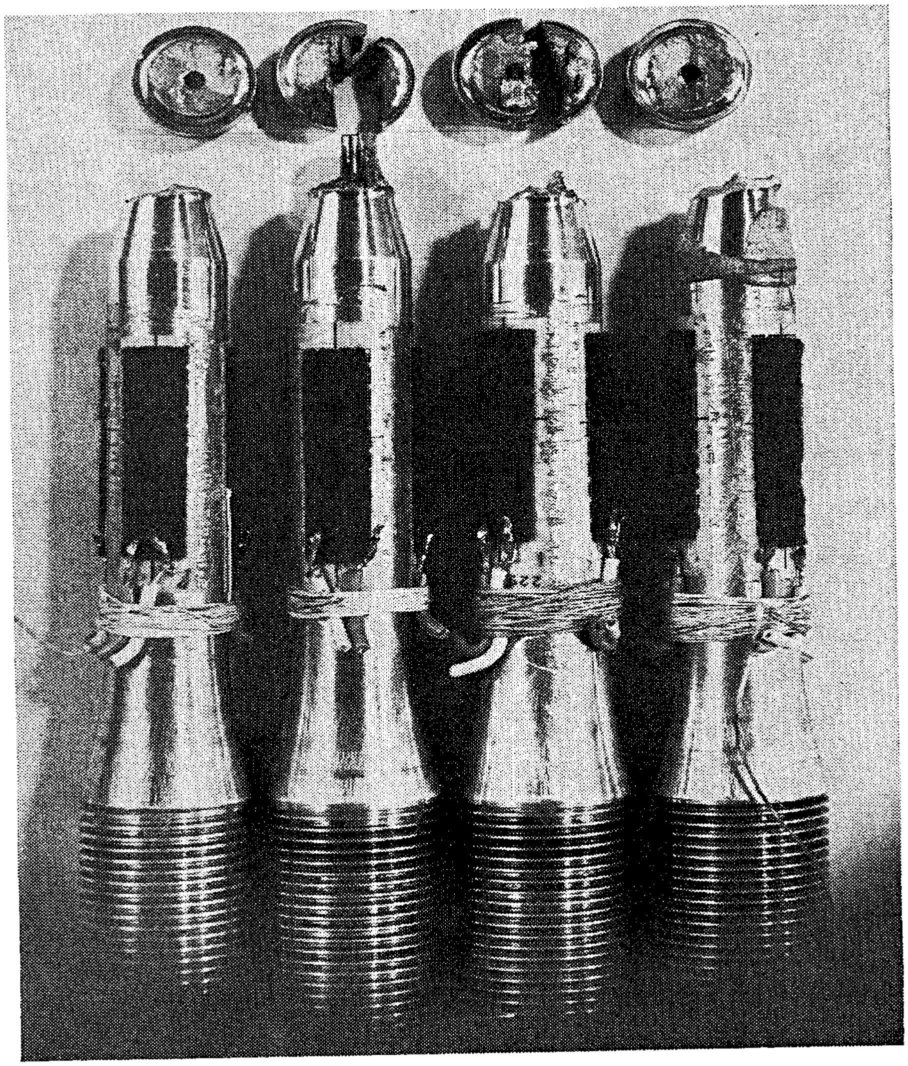
The proper utilization of metals in sheet form for aircraft construction was given a considerable impetus between 1930 and 1935 by the work of Kármán and Sechler, who developed the concept of an "effective width" of sheet acting with stiffeners in compression, even though the sheet between stiffeners was in a buckled state. The idea of using any structural element beyond the stability limit was revolutionary in nature since, up to that time, the buckling load had been considered to be the ultimate allowable load of both plates and columns.

During this period, courses in theoretical and applied elasticity were started because it was found that the ordinary "strength of materials" approach to the problems of aircraft construction was lacking in some of the essential background necessary for a solution of the more advanced structural problems. These courses were given by Kármán, since the field of applied elasticity was one of the many in which he was outstanding. Here, as in other disciplines in the department, his approach was that of fundamental Applied Mechanics, in which the physical problem was emphasized in order to formulate properly the required theoretical techniques.

The research programs of the early 1930's reflected the new interest in sheet metal construction, and there were many publications and theses concerned with buckling and ultimate stress problems in thin metal elements. Researches into riveting techniques and the methods of transferring concentrated loads into distributed sheet structures were also given considerable attention. Coupled with these programs, which were largely experimental, were a number of theoretical investigations—for example, a study by Biot of transient oscillations in elastic systems (the first GALCIT Ph.D. thesis in the structural field).

Important contributions to non-linear elasticity problems were made by Kármán and Tsien. The buckling of thin cylindrical and spherical shells was treated, and methods of calculating large deflections of thin shells were formulated.

The new thinking concerning structures which was developing in aeronautics also had its impact on other engineering fields. As a result we find Biot making important contributions to the structural problems of buildings subjected to earthquake vibrations, and other members of the Laboratory staff were concerned with the design



Aluminum alloy fatigue test specimens after failure.

of the dome for the 200-inch telescope on Palomar Mountain. The theoretical and experimental work on this dome, which is a thin sheet metal construction having an R/t ratio of over 2500, was carried out by Bollay and Sechler with the assistance of graduate students in the Guggenheim Laboratory. More recently, problems connected with the Southern California Cooperative Wind Tunnel have been studied; in particular, R. R. Solverson has investigated by photoelastic techniques the stress concentration in fillets as used in the hold down shoulders of the fan blades of the tunnel, and S. R. Valluri is presently engaged in research into the fatigue properties of the fan blade material at elevated temperatures.

Close contact with industry has always been the policy of the GALCIT, and a review of the papers and theses in structures not only shows a continuing effort in fundamental research but also an interest in the current problems of the airframe companies. Thus we find research on the brinelling of small ball bearings, column properties of open, thin sheet sections, properties of aluminum alloys under impact, and general instability properties of large stiffened shells. The names of Donnell, Tsien, Duwez, and Dunn will be found on many of the papers, in addition to those of graduate students and other research workers who made important contributions to the progress in this field.

During Kármán's leave of absence as head of the Scientific Advisory Board of the Air Force, Sechler gradually assumed responsibility for the structural and applied elasticity program of the GALCIT. Under his supervision, the program has continued to emphasize fundamental research, which is guided towards the solution of future as well as present problems of the airframe designer and stress analyst.

The past ten years have seen radical changes in the entire field of aeronautics. Increased speeds have required thinner wings, which have quite different behavior under load than the older, thicker wing structures. Swept wings have become necessary for certain types of aircraft, and one of the recent major efforts of the GALCIT structures group has been a survey of the entire field of swept wing design. This survey had the aim of establishing analysis methods for such structures by theoretical and experimental research into the problem. Two of the younger members of the laboratory staff, Fung and Williams, have made important contributions in this field.

Increased speeds and thin swept wings have also increased the importance of treating the airplane as a flexible rather than a rigid body. Since the wing deflection and the load influence each other, the fields of aerodynamics and structures can no longer be separated, and the treatment of such problems is the basis for new course work and research in aeroelasticity, a field in which Fung has made significant contributions.

Other new difficulties arise from aerodynamic heating due to high speeds and from fatigue, which may occur either from aerodynamic buffeting, gusts, or landing loads. Thus, aeroelasticity, thermal elasticity, and the fundamentals of fatigue failure are of current interest, and they promise fertile fields for research for some time to come.

Visiting scientists and research workers have always been welcome at GALCIT. Such scholars as N. O. Mykelstad, C. B. Ling, and W. H. Wittrick have contributed extensively, not only to the research and publications in the field of structures and applied elasticity, but also to the educational program through their cooperation in seminars and research conferences. Furthermore, the Solid Mechanics seminars furnish a common focal point for all groups interested in the broader and more fundamental aspects of solid state physics and are attended not only by the GALCIT structures group of staff and students but also by interested members of other Institute departments, representatives of local industry, and visiting scientists.

4. *Jet Propulsion and Rockets*

Interest in rocket propulsion at the California Institute of Technology started as early as 1935 when members of the GALCIT faculty and graduate students began experimental and theoretical studies in the field of rocket propulsion.

Through the efforts of Kármán the first substantial outside support for this program was obtained through the National Academy of Sciences in 1939. Because of the possible application of rocket propulsion to assisted takeoff of aircraft, the Army Air Force became interested in the program and in 1941 took over sponsorship of the work. At this time the effort was organized and known as GALCIT Project No. 1.

The organization of the Project drew heavily on the GALCIT faculty, and during its initial phases the staff was made up almost entirely of GALCIT personnel. F. J. Malina was particularly active, and his name appears on most of the early GALCIT publications in the field.

By 1941 the scope of both theoretical and experimental work had been greatly extended. In August, 1941, the first practical solid propellant had been developed, and the first successful assisted-takeoff tests were made. These first rocket motors shortened takeoff distances of small aircraft by as much as 50 percent. After the development work was completed and the assisted-takeoff motors went into extensive service use, large-scale production was undertaken by the Aerojet Engineering Corporation, which was subsequently acquired by the General Tire and Rubber Company and has recently become the Aerojet-General Corporation.

The famous liquid-propellant combination of red fuming nitric acid and aniline had been discovered elsewhere in 1940 and resulted in April, 1942, in the first successful assisted takeoff of aircraft using liquid-propellant rocket units.

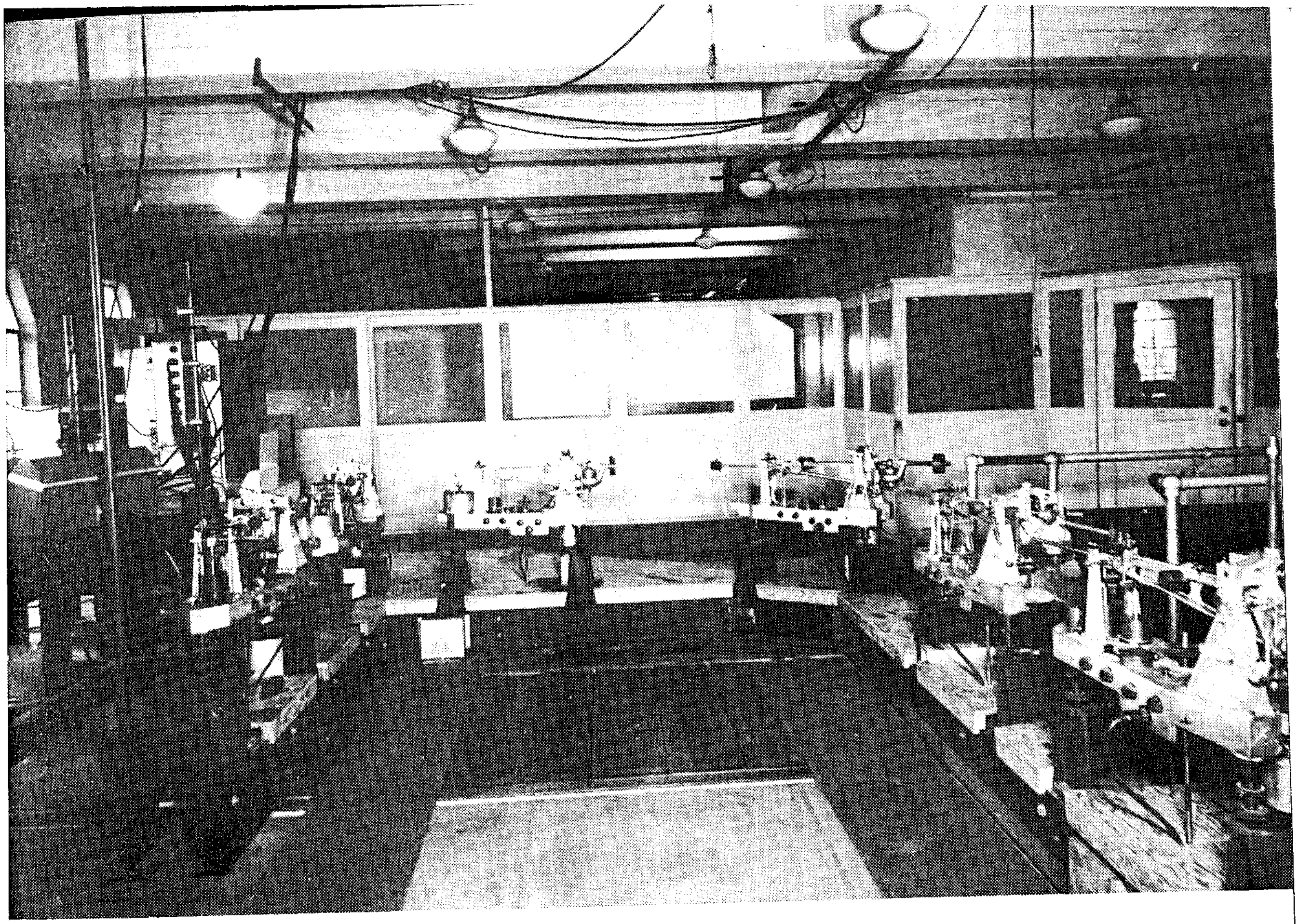
These major developments by the GALCIT Project, in addition to its extremely important basic research studies of the period 1935-44, contributed to a large extent in the formation of the basic technical framework of the present guided-missile industry.

In 1944 the first long-range rocket research and development program in the United States was started. By this time the size of the Project had increased to a point where the organization of a separate laboratory seemed desirable. Accordingly on November 1, 1944, the Project separated from the GALCIT and became known as the Jet Propulsion Laboratory, the subsequent history of which is given in a later section.

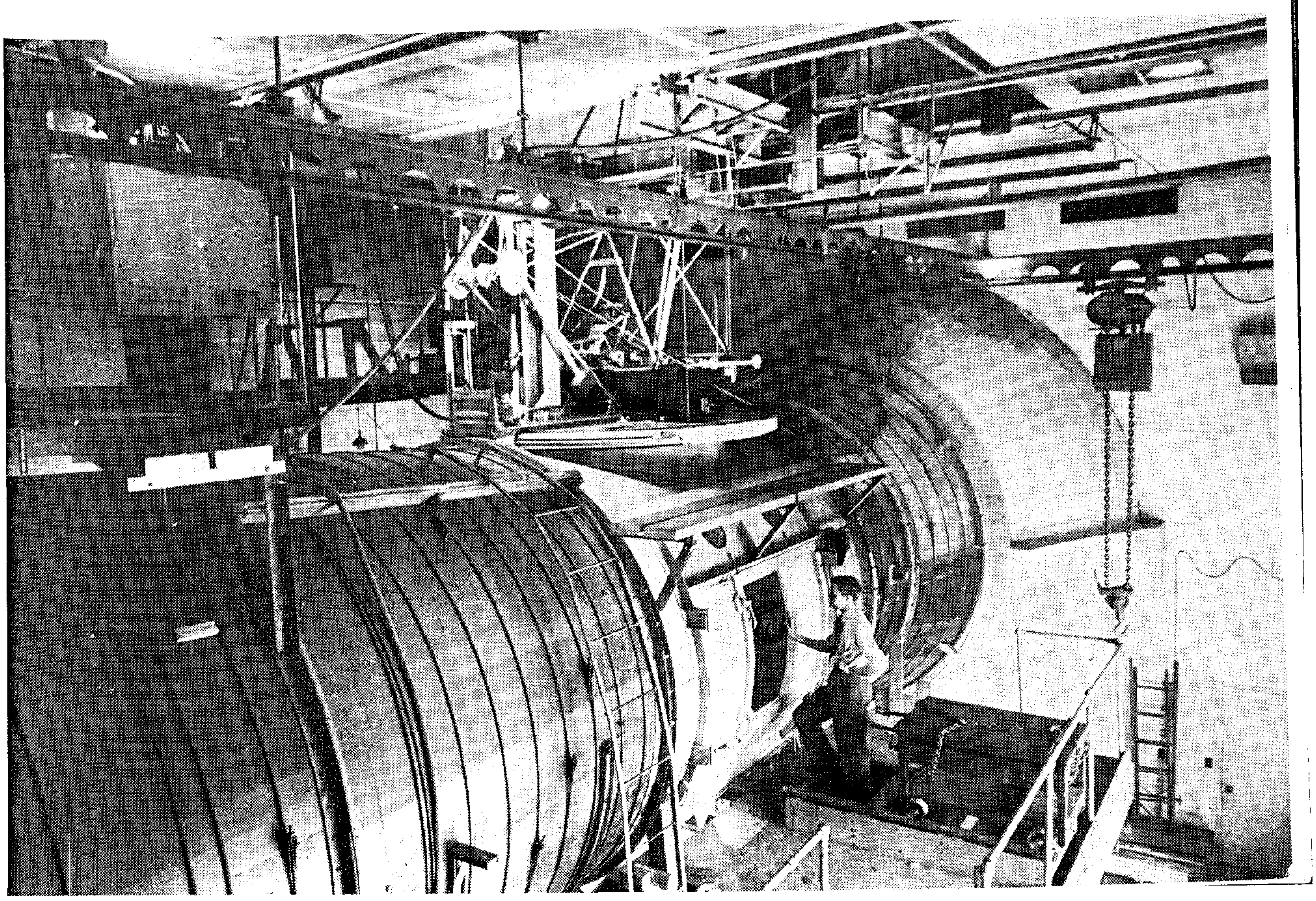
Through the formative years of the Jet Propulsion Laboratory and down to the present time, members of the GALCIT staff have played an important part in the organization of the Jet Propulsion Laboratory. As a continuing policy, close cooperation is maintained in fields of interest common to the two organizations, particularly in the field of supersonic aerodynamics.

5. *Wind Tunnels—Research and Industrial Testing Tools*

Wind tunnels have always been a dominant feature of the GALCIT. The largest experimental facility in the laboratory as originally constructed was a 200 mile per hour wind tunnel with test section 10 feet in diameter. When it was placed in operation in 1929 it was one of the highest performance wind tunnels in existence, and it has continued to render yeoman service even to the present. It was originally expected that about half of its time would be occupied with research problems pursued by members of the staff and students, while the other half would be available for the testing of models of aircraft



10-Foot Wind Tunnel showing model suspension system, with balances and control desk above.

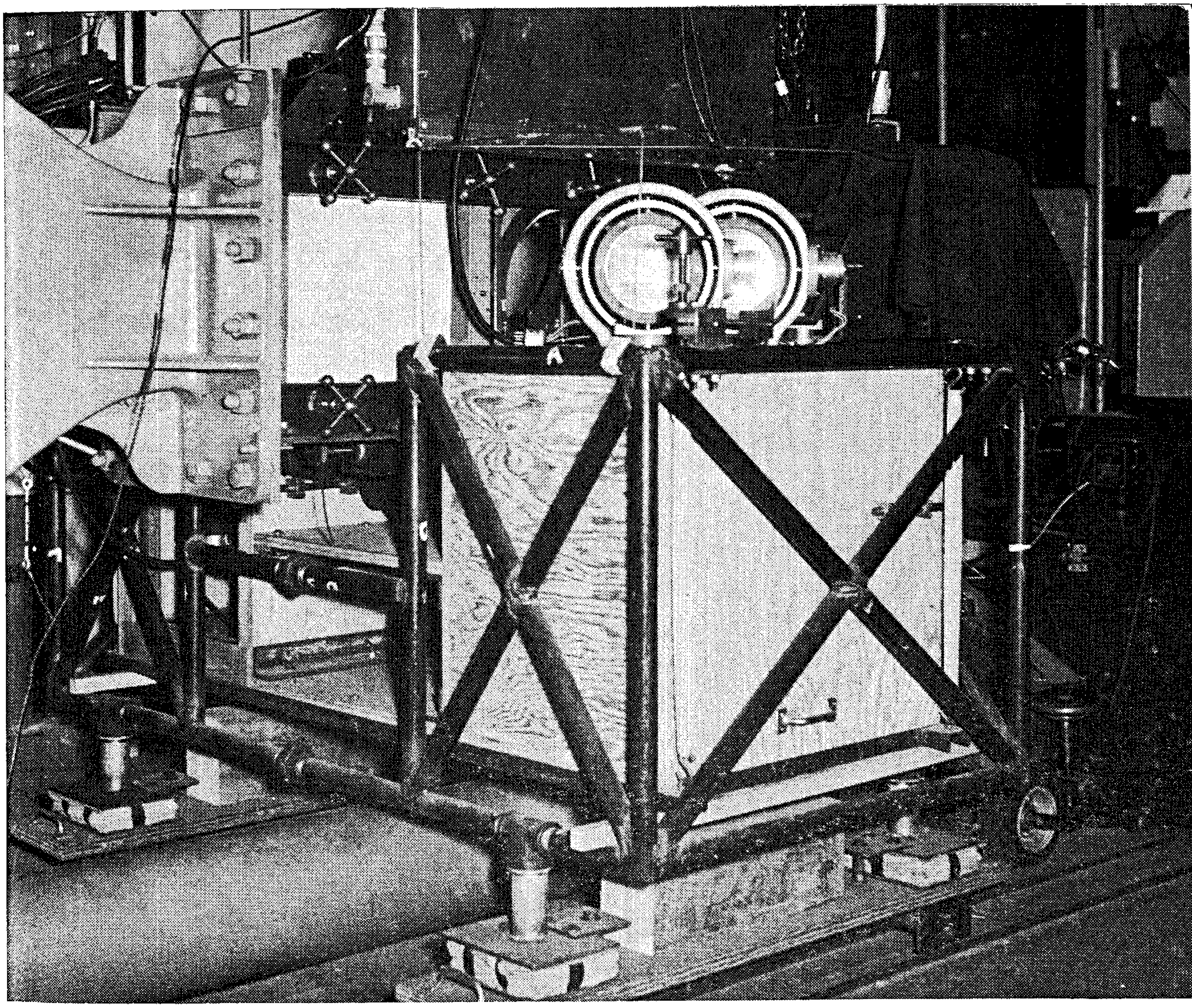


under development by industry and government. Actually some 24 of the GALCIT publications listed in the bibliography deal with tests in the 10-foot tunnel or with techniques and theoretical calculations associated with it, and a large number of theses involved its use. The majority of these research activities occurred during the first ten or twelve years of the tunnel's life, for during the World War II emergency the wind tunnel was completely occupied with testing of models for urgently needed military aircraft. During all of this period it was operated on a basis of two shifts six or seven days a week. Since the war, the demand for this type of industrial and governmental testing has remained high, and most of the academic wind-tunnel researches have been carried out in smaller special-purpose tunnels as will be further discussed below.

A few statistics in connection with the industrial and govermental testing activities of the GALCIT 10-foot wind tunnel are of interest. As of May, 1954, a total of 790 separate wind-tunnel test programs have been carried out and over 700 formal reports issued. These cover tests on over 550 distinct aircraft types for some 35 United States and foreign aircraft companies, as well as investigations for 6 government agencies. Although the tunnel's performance is now greatly exceeded by many more recently constructed facilities, its operation on an overtime basis is still required.

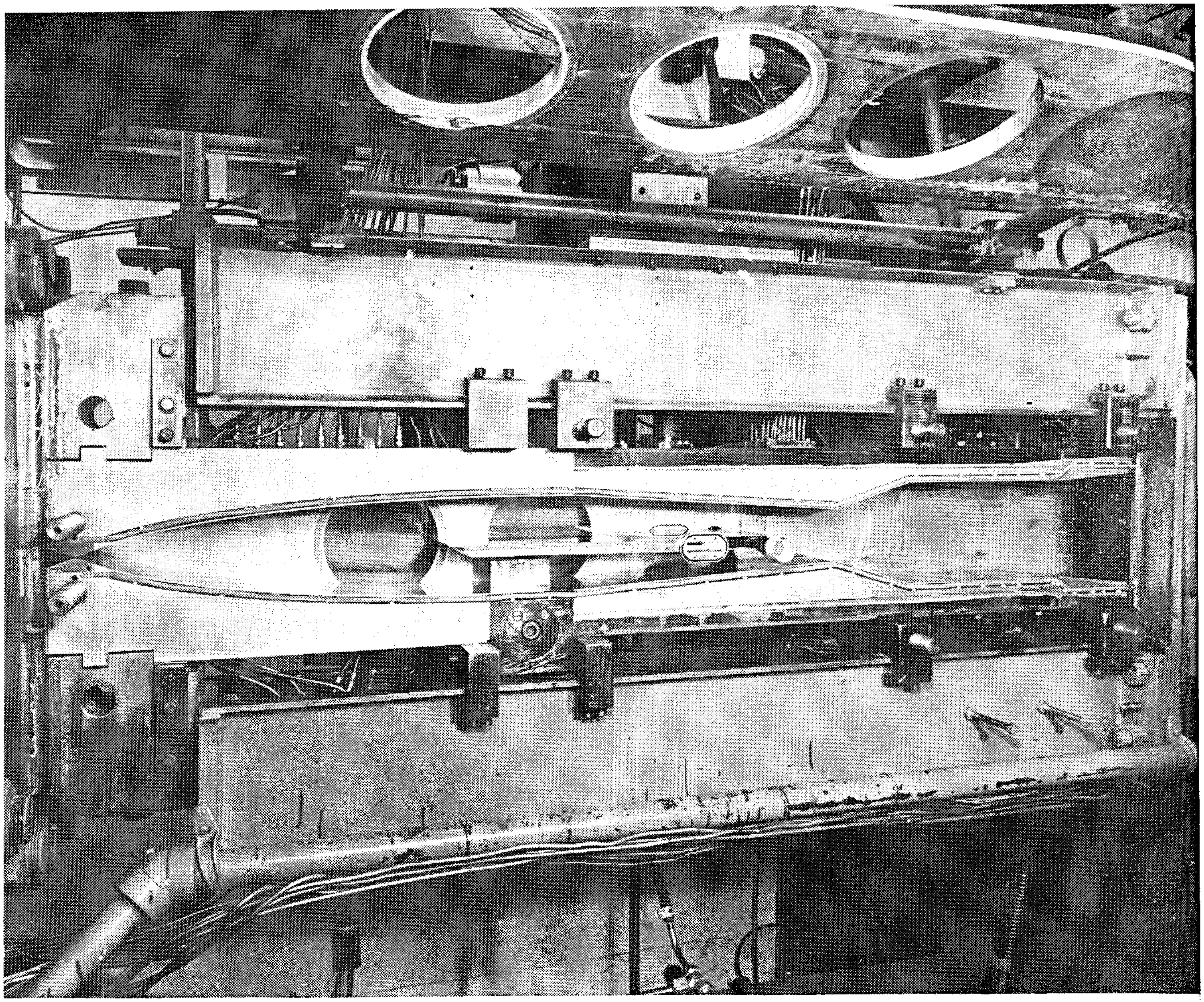
Not only has this wind tunnel contributed greatly to the development of military and commercial aircraft, but it has also played a vital role in the academic life of the GALCIT. Since 1930 it has been the policy to employ students on a part-time basis for its operation. In this way large numbers of students during their academic aeronautical training were brought into close contact with the practical problems of designing and developing actual aircraft. Also many students without the financial resources to support themselves unassisted were enabled to earn the funds necessary to complete their professional training by working in a field immediately related to their course of study. Many of the leading aerodynamicists and engineers in industry, government, research laboratories, and academic institutions are ex-members of the GALCIT 10-foot wind-tunnel staff.

Although this first wind tunnel is the largest in the GALCIT, it is far from being the only one. Over half-a-dozen small, low-speed tunnels have been constructed for specific research investigations,



The small transonic wind tunnel showing the portable interferometer.

especially in connection with the low-speed boundary-layer and turbulence researches mentioned earlier; and several of these are still in active use. A small transonic tunnel has been used by Liepmann's group to produce important and fundamental data on flow characteristics in the neighborhood of the speed of sound. The first continuously operating, supersonic tunnel in this country to reach Mach numbers above four was designed jointly by Tsien and M. Serrurier, and constructed some years ago under the sponsorship of the Army Ordnance Corps. Puckett carried out many investigations using the tunnel as a pilot or model tunnel for a much larger wind tunnel built subsequently at the Ballistic Research Laboratory at Aberdeen Proving Ground. It continues to be a valuable research



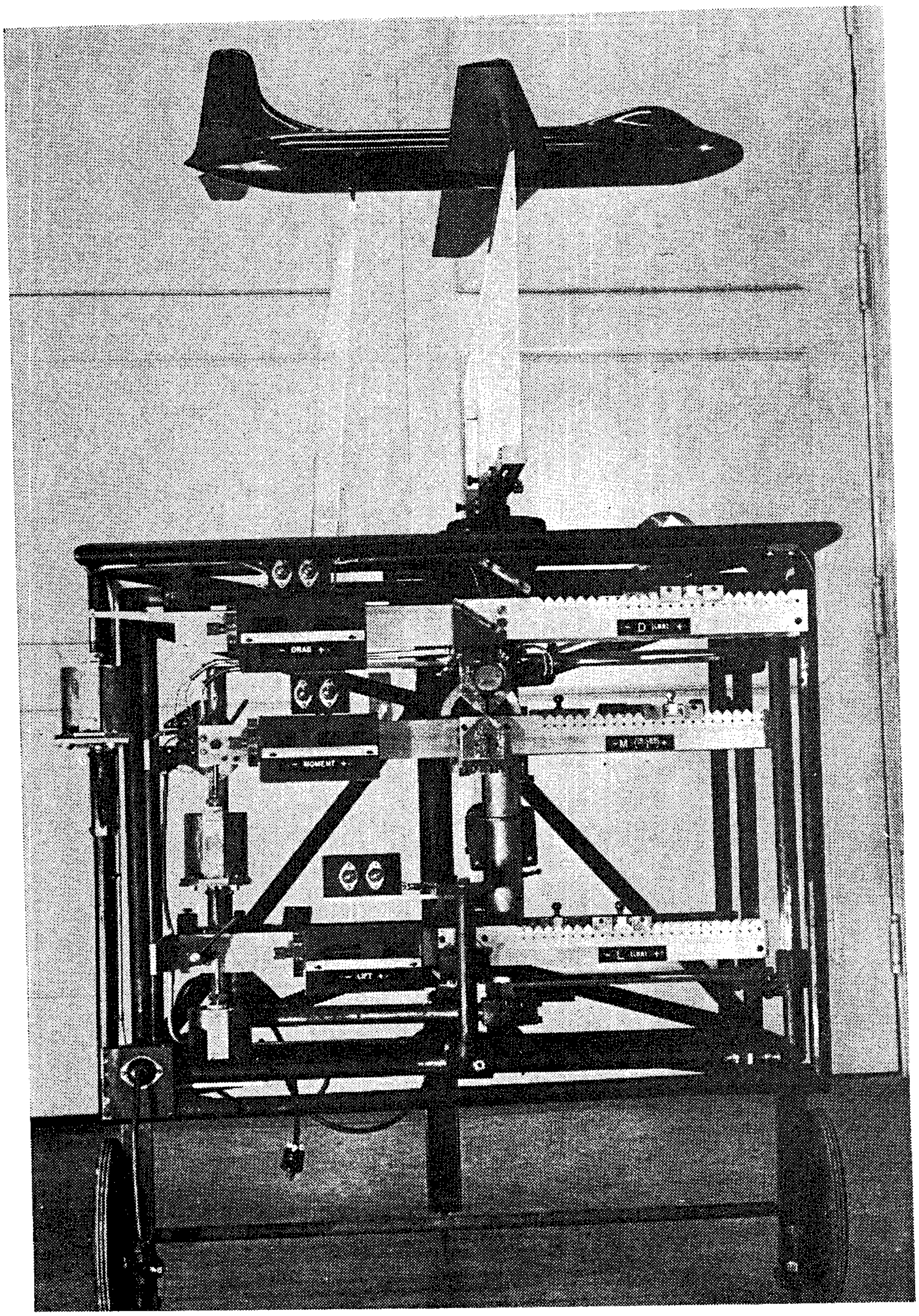
A flat plate for boundary-layer investigations, installed in one of the two hypersonic tunnel test sections. The rear side wall has been swung up out of the way so that the nozzle, test section, and diffuser are visible.

tool. A hypersonic test facility has also been constructed at the GALCIT, with Army Ordnance and Air Force support, where Mach numbers of over 10 have been reached. This is currently being used very intensively in the exploration of the new and important field of very high Mach number flow. Finally, a 175 mile per hour wind tunnel with 3-foot by 4-foot test section was installed in 1950 to be used primarily for student instruction and thesis research. This was dedicated to A. A. Merrill in recognition of his pioneering work in aeronautics at the Institute in pre-GALCIT days, and is known as the Merrill Tunnel.

6. *Research Equipment and Instruction*

In any branch of science and engineering in which experimental research plays an important role, many of the most significant advances result from the development or invention of powerful experimental tools or of ingenious and precise instruments and techniques. This section outlines some of the GALCIT contributions in these fields which have resulted from the continuous and intensive attention which has been devoted to them over the past 25 years.

The portable balance and model support system of the Merrill Tunnel with a Navy fighter model ready for test.



The largest items of GALCIT research equipment are the wind tunnels described earlier. These, as well as the still larger tunnels at the Jet Propulsion Laboratory and the Cooperative Wind Tunnel to be discussed below, were conceived and basically designed by members of the GALCIT staff and former California Institute students (especially H. Ashkenas, A. E. Puckett, P. V. H. Serrell, J. E. Smith, and H. F. Richards). The model support and balance systems were designed by Klein, Sechler, and Serrell for the larger tunnels and by Liepmann, Puckett, and Nagamatsu for the smaller high speed tunnels. In addition, a number of model supports and balances have been designed, and in some cases constructed, by research students who needed specialized equipment.

For studies in fluid mechanics the group under the direction of Liepmann has made notable contributions to hot wire techniques for measuring turbulence, has developed counting methods for the statistical analysis of turbulent flows, and has conceived and constructed a simple and inexpensive, but extremely precise, interferometer having many ingenious features for the study of supersonic flows. Recently, new techniques in the use of a glow anemometer for turbulence measurements at supersonic velocities have been developed. Also in the supersonic and hypersonic fields a contribution of major importance was made by Dhawan, Coles, Korkegi, and Eimer with the design and development of a direct means of measuring skin friction on an element of a test body in high velocity flow.

In fields other than aerodynamics the tilt-meters at the Cooperative Wind Tunnel should be mentioned. These instruments are used to keep the basic model support system level, and can detect an out of level of the order of one-eighth of an inch in a mile. Such devices were originally developed by the Seismological Group on the campus and were modified and adapted by Klein, Sechler, and others for their present task.

In structures, the use of large numbers of strain gages made necessary the design and construction of a rapid and accurate set of switching panels for changing from one gage to another. These panels, along with many other electronic devices developed in the Laboratory, were the result of work by Jessey of the GALCIT staff. Also in structures, the use of mirrors instead of large, expensive lenses made large fields possible for photoelastic studies. This technique was first used by the late J. Brahtz when he was a graduate student at the GALCIT.

Important instrumentation developments have also been made. Recently an electronic contouring device was designed by Bartsch and Jessey which makes it possible to mill contoured shapes for wind tunnel throats in hours rather than the days required by previous methods. Many other useful and ingenious contributions by the machine shop and electronics laboratory have made it possible for the research worker to obtain results and accuracies in his studies which were previously unattainable.

7. *Meteorology*

Many important phases of the science of meteorology are concerned with fluid dynamics, and one of the most important fields of application of meteorology has been in the operational use of aircraft. For these reasons research and instruction in the field of meteorology were undertaken as part of the activities at the Guggenheim Aeronautical Laboratory in 1932 under the leadership of Dr. Irving P. Krick. This work was primarily concerned with developing and applying the methods of analyzing the atmosphere as a three-dimensional fluid dynamics system. These methods were introduced into meteorology during World War I by the Norwegian group of meteorologists. The older forecasting procedures were not satisfactory for periods of more than about 24 hours, and the efforts of Krick's group were primarily concerned with the development of techniques for extending the forecasting period.

At the onset of World War II the air forces of both the Army and Navy required the services of large numbers of trained meteorologists, and the California Institute of Technology became one of the five principal training centers for this military activity. Because of the magnitude of this program, a separate department of meteorology was organized under Dr. Krick's leadership in 1944, and since that time only a small amount of research in the field of meteorology has been carried out at the GALCIT.

IV

THE MOST IMPORTANT PRODUCT–GRADUATES

IN JUNE, 1929, the first two degrees were awarded by the Guggenheim Graduate School of Aeronautics: master's degrees to E. E. Sechler and A. E. Lombard. Both of these men subsequently received doctor's degrees and went on to aeronautical careers. Dr. Sechler is now Professor of Aeronautics at the California Institute, and Dr. Lombard is Scientific Advisor in the Directorate of Research and Development, Headquarters U.S.A.F. Since that time, through June, 1953, a total of 964 graduate degrees have been awarded. Of these, 544 were fifth-year or master's degrees, 330 were sixth-year or "professional" degrees, and 90 were doctorates. The total number of students corresponding to these degrees is 744, since the same man often takes two degrees consecutively.

The first Navy and Marine Corps students outside the 10-foot wind tunnel test section in 1933. From left to right: Hutchins, Jerome, Rassieur, Vosseller, Bridget.

In 1933 Captain Paul Kemmer of the Army Air Corps, who was the first student sent by one of the military services, received the professional degree. The next year four Naval officers and one Marine, who had been sent to the Institute from the Naval Postgraduate school, received their professional degrees. The subsequent history of these five men, C. B. Hutchins, F. J. Bridget, W. T. Rassieur, C. C. Jerome, and A. B. Vosseller is of interest: Hutchins was killed in an aircraft accident; Bridget died a hero's death leading the famous "Bridget Battalion" of irregulars at Bataan; Rassieur recently retired as a Rear Admiral and is now active in the aircraft industry; Jerome and Vosseller are currently on active duty, the former as a Marine Major General and the latter as a Rear Admiral.

Every year since 1934 has seen a group of officers from the Naval Postgraduate school working towards professional degrees at the GALCIT, and many Air Force officers have also been assigned to the graduate school for study. A total of over 250 officers from the United States armed forces have received degrees from the GALCIT during the past twenty years, and there have been a number of officers from foreign countries.

The majority of the civilian students have gone on to engineering positions in the aircraft industry, where many now occupy key technical and administrative positions. However, many others have entered academic life or research laboratories, and a considerable number are now in government service as research administrators or scientific and technical advisors.

The following GALCIT alumni are mentioned as examples of the large number who have attained distinction in a wide variety of activities. Three are now heads of aeronautics departments at major universities: W. R. Sears at Cornell, F. Clauser at Johns Hopkins, and M. Clauser at Purdue. H. S. Tsien is the Goddard Professor at the Jet Propulsion Center, and L. G. Dunn is Director of the Jet Propulsion Laboratory, both at the California Institute. Roy Marquardt is President of the Marquardt Aircraft Company; W. Bollay heads the Aerophysics Development Corp. Rear Admiral C. M. Bolster recently retired as Chief of the Office of Naval Research and is currently Manager of Research of the General Tire and Rubber Company. Lieutenant General D. L. Putt is Deputy Chief of Staff for Research and Development of the U. S. Air Force. Many other GALCIT alumni have attained positions of eminence in industry, as well as in science and education.

During the emergency of the last world war the Guggenheim Graduate School undertook instructional responsibility of unusual and abnormal kinds. There suddenly developed both in industry and in the armed forces a critical need for men with at least a minimum of aeronautical technical knowledge to handle jobs which had to be done as a result of the sudden spectacular increase in aircraft production and military air operations. In the spring of 1940 the Lockheed Aircraft Co. recruited 120 graduate engineers without aeronautics experience who were working in non-critical industries. The California Institute agreed to give these men an intensive eight-week course in aeronautics during that summer. The 120 men received a certificate at the completion of this course and went on to work for Lockheed. Shortly afterwards the U. S. Office of Education began its sponsorship of special training programs to meet the critical need for trained civilians and officers. The Lockheed course was somewhat expanded and given to many hundreds of civilians and officers over the period from 1941 to 1944. Persons completing these courses received a special certificate rather than a college degree. Although this program involved a considerable disruption in the GALCIT's work, the results more than justified the effort.

V

ACTIVITIES RELATED TO BUT NOT PART OF THE GALCIT

THREE MAJOR DEVELOPMENTS at the California Institute had their origins at the GALCIT and then grew into independent organizations. Although all are administratively quite separate from the GALCIT, close contact and cooperation are maintained with all three. They are discussed below in the order in which they were established.

1. *Jet Propulsion Laboratory* (*by Dr. L. G. Dunn, Director*)

During World War II, the California Institute of Technology was asked to contribute creative engineering talent to a number of defense research projects, among them the development of jet propulsion devices. The results of this effort were of such value to the Department of Defense that, in the latter part of the war, the Jet Propulsion Laboratory (JPL) was established to continue the program, under the administrative supervision of the California Institute of Technology.

Since the end of the war, the Laboratory has grown from a small group assigned to the task of developing a simple thrust-producing device for the assisted takeoff of aircraft to a completely equipped laboratory having a wide variety both of equipment and scientific talent. The staff currently numbers over 1,000 persons. Fundamentally, JPL is a research center whose efforts are directed toward the acquirement of basic information in the engineering sciences related to missile development and the various phases of jet propulsion. Especially in the field of aerodynamics, close liaison and cooperation are maintained with the GALCIT. Research and development are conducted under contracts with governmental agencies, and close liaison is maintained between JPL and the various military services.

The JPL directorship was assumed in 1945 by Dunn, at that time a member of the GALCIT faculty. Professional, operational, and administrative personnel, many of whom were formerly associated with GALCIT, are supplied by the California Institute of Technology. More than half the professional staff hold degrees which are be-

An aerial photograph of the Jet Propulsion Laboratory in Pasadena's Arroyo Seco.

yond that of Bachelor of Science, and approximately one-third are California Institute graduates.

Laboratory facilities, which are located in the upper Arroyo Seco near Pasadena, cover an area of 80 acres. Total Laboratory floor space is nearly 300,000 square feet. The value of buildings, utilities, installed property, and land is estimated at more than $12,000,000. There are two major external facilities: a static-testing area at Edwards Air Force Base, Muroc, California, for firing large rocket motors, and a field-testing operational unit at White Sands Proving Ground, New Mexico, for test flights of missiles.

The research program at the Jet Propulsion Laboratory covers many diverse problems, all of which are related in some way to propulsion, guidance, or missile development. The more important studies being undertaken include supersonic aerodynamic tests, development of electronic guidance equipment, and fundamental research in fluid dynamics, combustion, chemistry, and materials.

Chemistry and chemical engineering have played an important role in the development of all types of power plants based upon the principle of jet propulsion. Foremost has been the search for high-energy chemicals suitable for the operation of solid- and liquid-propellant rocket motors. The quest for such substances and the measurement and modification of their properties are the chief concern of the chemical research program at the Laboratory.

The application of chemical-engineering principles has refined to a high degree the manufacture of solid propellants. The first propellant developed at this Laboratory was widely used in assisted-takeoff motors during World War II. Present propellants have been greatly improved by using synthetic fuels having controllable properties. The search for better propellants continues, and new chemical compounds are being prepared. In addition to the search for ideal compounds, various new processing techniques are now employed in order to obtain propellants possessing better physical and ballistic properties.

Combustion within a rocket motor is a phenomenon which is only partially understood. The reactions involved take place at temperatures ranging from 3500 to 5000° F. and at pressures of several hundred pounds per square inch. The control and understanding of the release of heat energy under such extreme conditions are important factors in basic jet-propulsion research. Several detailed studies to elucidate the processes of combustion in rocket motors are under way at the Jet Propulsion Laboratory.

Experimentation is also conducted in the field of air-fuel combustion to aid in designing ramjets and similar types of power plants. Techniques for introducing fuel into a rapidly moving air stream are essential to the operation of the ramjet propulsion plant; burning must be completed in the shortest possible time, and the flame must be maintained over a wide variation of stream velocity, pressure, and air-fuel mixture ratios. In addition, the effects of turbulence on flame propagation and the mechanism of flame holding are of significance and are being studied.

Heat transfer through the walls of a rocket motor poses difficult questions that the rocket research engineer must answer. Cooling is often accomplished by circulating part of the propellant in a double-walled combustion chamber; however, this coolant often reaches the boiling point. Considerable pioneering work has been conducted at the Jet Propulsion Laboratory relative to the study of the mechanism of boiling heat transfer. Several other techniques of fluid cooling are also under investigation for rocket-motor application.

Materials which will withstand the rigorous test of rocket firings must have a high melting point, strength, and corrosion resistance. Titanium and titanium-alloy systems, in particular those containing chromium, molybdenum, and vanadium, are typical of the metals being studied. Ceramic materials, such as zirconium oxide stabilized with lime, magnesia, or rare-earth oxides, have also been included in the search for useful materials. Several X-ray diffraction cameras, an electron microscope, large hydraulic presses, high-temperature furnaces, and radioactive-tracer equipment are among the specialized tools which aid the materials research program.

At the Jet Propulsion Laboratory, the production of porous metals by powder-metallurgical techniques has received much attention. Related work has been carried out on the mechanism of sintering and diffusion of mixed powders during alloying. Coordinated with this work is the study of the laws of liquid and gas flow, as well as heat transfer, through porous metals.

Aerodynamic design of rocket-powered missiles which travel at supersonic speeds up to several thousand miles per hour is complicated by the need for empirical information on lift, drag, interference effects, and similar phenomena. The Jet Propulsion Laboratory has two large supersonic wind tunnels, one having a 12-inch test section and the other, a 20-inch test section. At present, both wind tunnels may be operated at air velocities of approximately four times the speed of sound. A significant fraction of the operating time of these installations is devoted to basic studies of skin friction, heat transfer, turbulence, and the behavior of simple wing shapes in supersonic streams.

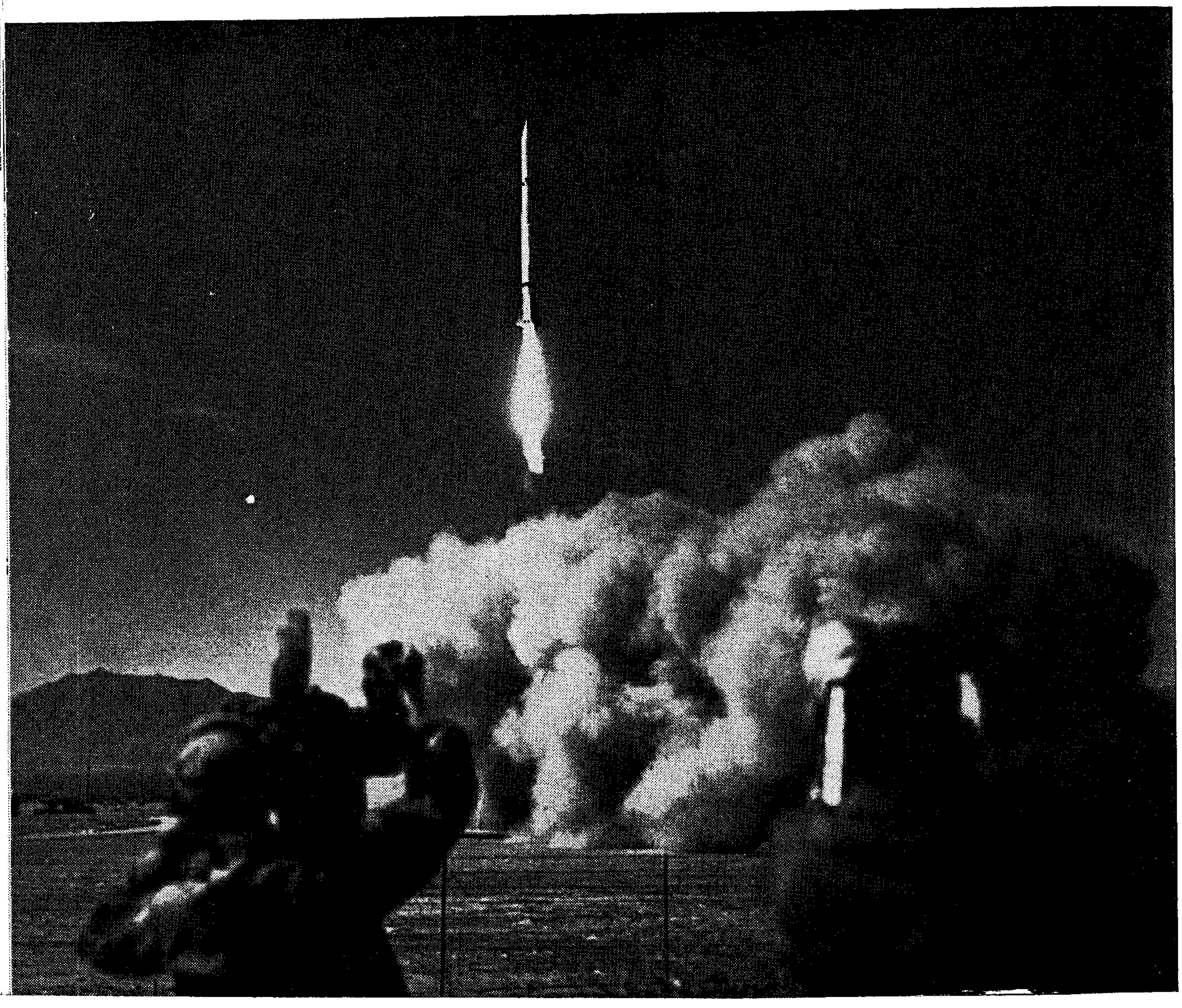
Electronics research and development have constituted an increasing proportion of laboratory activity as interests have expanded into the guided-missile field. The Jet Propulsion Laboratory was one of the pioneers in the field of radio telemetering, and the system developed has, with slight modifications, been adopted as a standard at all of the U. S. rocket test ranges. Guided-missile developments at JPL require electronic research in the fields of servomechanisms, computers, and radar. Frontier work in the statistical theory of communication, noise filtering, transistor circuitry, and reliability of electronic components is being carried on.

Instrumentation for recording data during testing of rocket motors is elaborate and expensive. These tests, which involve exceedingly high temperatures, pressures, and fluid flow rates, have created a demand for measuring devices of high accuracy and short time resolution. The flood of data accumulated with these instruments has made necessary the development and installation of computing equipment which can reduce and plot the data or solve complex systems of equations quickly. Test cells at the Jet Propulsion Laboratory are scattered over widely separated points. They are interconnected by means of a telephone-type network capable of transmitting twenty-two channels of information to one central location which contains an array of recording equipment.

Mechanical design and engineering for the development of liquid-propellant rocket motors involve the devising and testing of propulsion systems which combine some choice of cooling technique, materials of construction, combustion-chamber configuration, injector design, and fabrication procedure. Laboratory personnel perform the integrated functions of drafting-board design, fabrication, assembly, inspection, and testing. Thermodynamic, heat-transfer, vibration, and ballistic calculations are performed. Optimization studies, particularly directed toward reducing the weight of all components, are vital factors during the development stage. The proper performance of a liquid-propellant rocket motor depends upon accurate knowledge and control of the flow of propellants through the complicated maze of plumbing in the system. A large hydraulic laboratory is devoted to checking and measuring the performance of valves, pressurization systems, and similar components.

The design of a solid-propellant rocket motor is seemingly simpler than that of a liquid-propellant motor but is equally challenging and interesting. Research engineers are confronted with questions concerning the burning rates of solids, mechanical properties of propellant charges, propellant manufacture, and many other fundamental motor-design problems which are similar to those pertaining to liquid-propellant motors.

A JPL Corporal missile just after launching at the Army's White Sands Proving Ground.



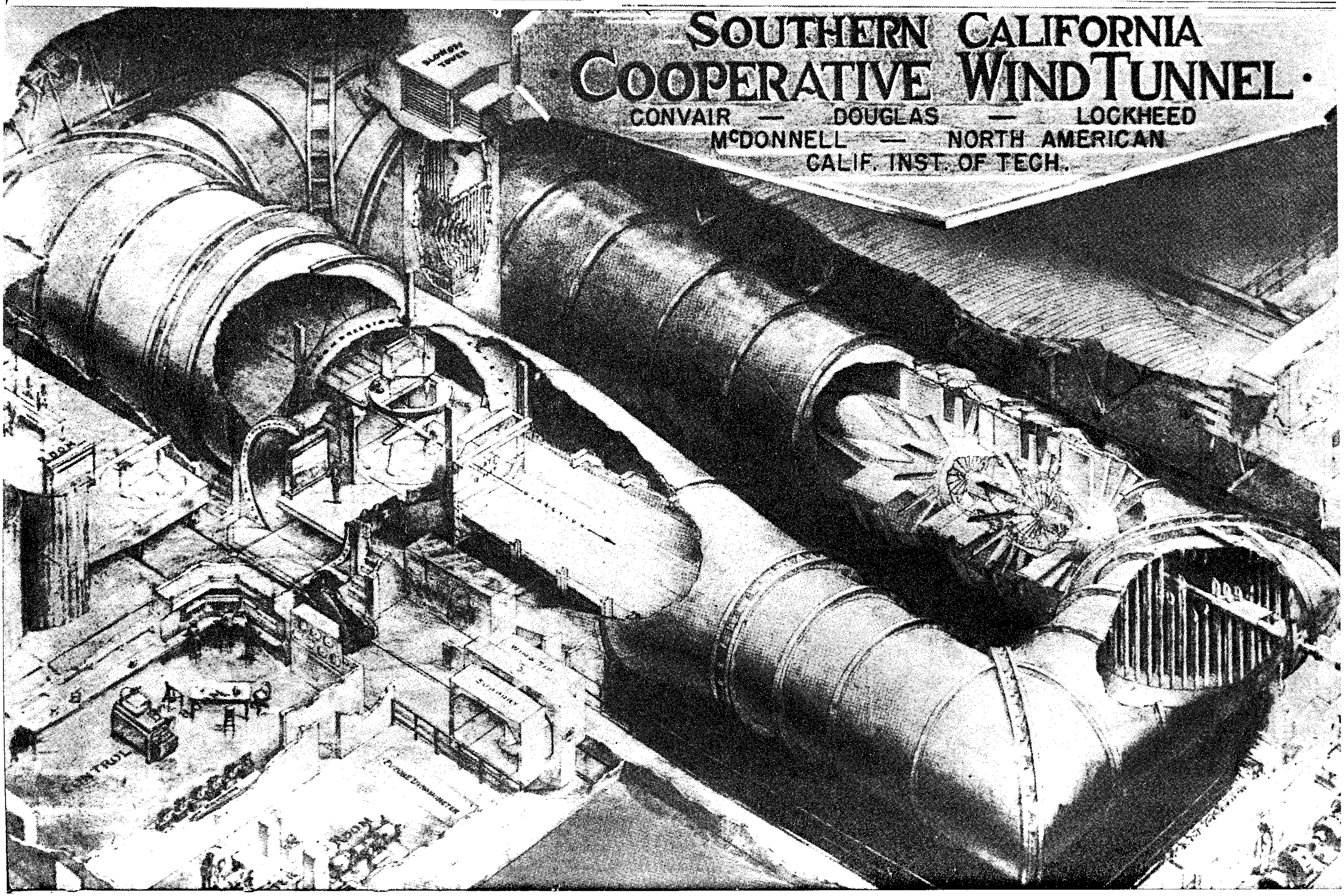
In addition to carrying out the early development of assisted-takeoff rockets for aircraft and the development of other rocket test vehicles, the Laboratory engineered and tested the Wac Corporal, the nation's first high-altitude sounding rocket. This rocket reached an American high-altitude record of 43.5 miles when it was first tested in September, 1945. In February, 1949, at White Sands Proving Ground, the Wac Corporal was launched from the nose of a German V-2 and attained a still-existing record altitude of 250 miles.

In April, 1954, the army disclosed that it had greatly increased its battlefield atomic firepower with the addition of the Jet Propulsion Laboratory's new Corporal, the first tactical long-range rocket missile to be produced and made available to the armed forces. This supersonic weapon, which is electronically guided and capable of destroying selected targets deep behind enemy lines, was developed for the Ordnance Corps of the Department of the Army.

2. *Southern California Cooperative Wind Tunnel*

By the late 1930's it was becoming apparent that before many years aircraft would be flying fast enough so that the effects of the air's compressibility would become important. Wind tunnel facilities capable of producing velocities up to the neighborhood of the speed of sound (approximately 1100 feet per second under standard sea-level conditions) were obviously going to be required for the development of such aircraft. The GALCIT 10-foot wind tunnel had proved extremely valuable for development testing, but its 200 mile per hour top speed would clearly be inadequate. What would be needed was a tunnel with test section dimensions comparable to those of the 10 foot tunnel but with a 750 mile per hour speed capability. Unfortunately these two requirements implied extremely large power for the drive and a construction cost running into several million dollars.

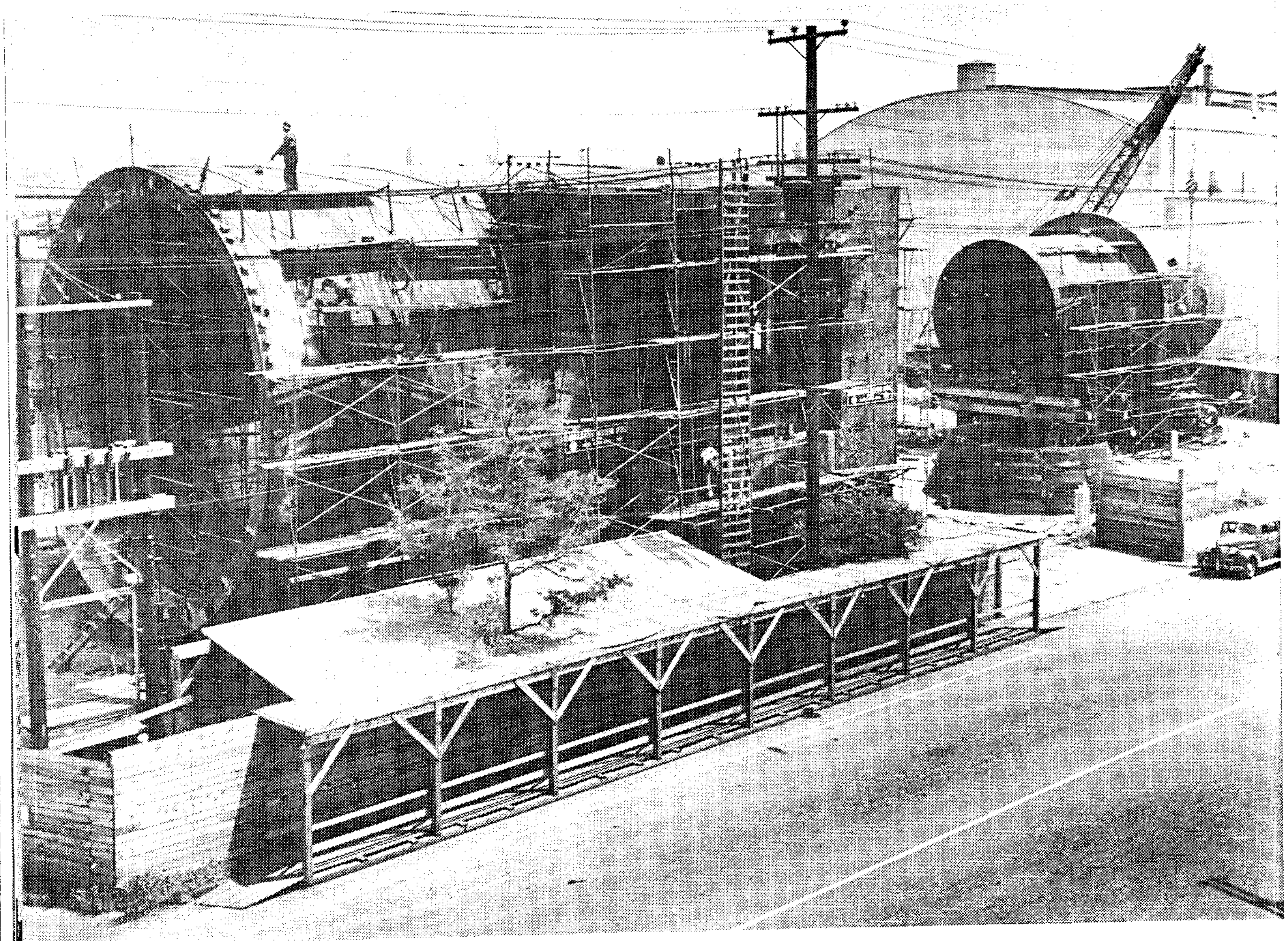
After much thought and discussion a group of aircraft companies decided to undertake a cooperative effort to produce such a facility. The Curtiss-Wright Corporation agreed to finance the construction of a wind tunnel at Buffalo and four Southern California companies, Consolidated-Vultee, Douglas, Lockheed, and North American, jointly undertook to sponsor one in Pasadena. Essentially the same


SOUTHERN CALIFORNIA
COOPERATIVE WIND TUNNEL
CONVAIR — DOUGLAS — LOCKHEED
McDONNELL — NORTH AMERICAN
CALIF. INST. OF TECH.

design was to be used for both. A design group was set up at the GALCIT under Millikan's leadership, and the project was started. Since the job to be done was quite specific, i.e., development testing of aircraft models, it was possible to include many unique features in the design. Some of the more important characteristics of the tunnels as they were constructed were a steel shell construction permitting variation in the pressure level in the tunnel between 1/10 and 4 atmospheres; an air-lock surrounding the 8½ by 12-foot test section so that access to the model could be had at atmospheric pressure while the remainder of the tunnel was under pressure or vacuum; three interchangeable test section "carts" so that two models could be prepared for testing while a third was being tested; 12,000 h.p. electric motors driving two 16-blade propeller type fans producing test-section velocities up to or a little greater than the speed of sound; elaborate force measuring equipment with provision for automatic recording and reduction of data.

The Pasadena tunnel, which is some three miles from the campus and adjacent to the Pasadena City Power Plant, was dedicated as the Southern California Cooperative Wind Tunnel in May, 1945, and shortly thereafter began routine operations. These have continued ever since on a two-shift basis. Some years ago the McDonnell Aircraft Co. purchased one-half of Consolidated-Vultee's interest in the tunnel, so that the CWT, as it is usually called, now has five owner companies. As of May, 1954, some 400 test programs had been completed, not only for the owner companies, but also for most of the other major aircraft companies of the country, as well as for numerous government agencies. The laboratory, with something over 150 employees, is operated by the California Institute under a management agreement, with an annual operating budget of over a million dollars. Millikan is Director on a part-time basis, and J. E. Smith, a GALCIT alumnus, serves as full-time Associate Director.

The unusual, if not unique, cooperative arrangement under which the CWT functions has worked remarkably well and has excited much interest elsewhere. A year or so ago the major British aircraft companies formed a cooperative organization patterned very closely on that of the CWT, and a British "cooperative wind tunnel" is now under construction. The French aircraft industry is currently in the process of forming a similar organization.



Air-lock or test section and motor section for the CWT modification being fabricated adjacent to the laboratory.

Less than ten years after the CWT was designed, aircraft performance had advanced so spectacularly that it was clear that supersonic speeds were soon to be matters of routine operations. The owner companies accordingly authorized an $8,000,000 modification program for the CWT. This will involve an increase in the drive power to 40,000 h.p. and make possible testing at speeds up to 1.8 times the speed of sound. Construction on the modification program is currently in active process and should be completed and the tunnel ready for operation in mid-1955.

3. *Guggenheim Jet Propulsion Center (by Dr. H. S. Tsien, Goddard Professor)*

The Jet Propulsion Center, an independent unit in the Division of Engineering of the California Institute of Technology, was established by the Daniel and Florence Guggenheim Foundation in 1948. Thus, on the occasion of the twenty-fifth anniversary of GALCIT, the Guggenheim Jet Propulsion Center was only five years old. Nevertheless, the Center is anxious to participate in this celebration for two reasons: jet propulsion is very closely associated with aeronautics; without aeronautics, there can be no jet propulsion. Secondly, the Guggenheim Jet Propulsion Center is an outgrowth of the activities of the Guggenheim Laboratory in the fields of rockets and turbomachinery which were encouraged and guided by GALCIT's founding director, Theodore von Kármán.

As early as 1935, W. Bollay, then a graduate assistant to Kármán, gave a discussion of the possibilities of the rocket powered airplane during one of the weekly Aeronautics seminars. With this as a start, the research and studies in rocket propulsion at the GALCIT grew into the present Jet Propulsion Laboratory. This part of the history has been traced in earlier sections of this survey. The purpose and guiding principle of the Guggenheim Jet Propulsion Center are quite different from those of the Jet Propulsion Laboratory; to quote the 1949 Institute Catalogue:

> This Center was created specifically to provide facilities for postgraduate education and research in jet propulsion and rocket engineering, with particular emphasis on peace-time uses. The objectives of this Center are to provide training in jet propulsion principles, to promote research and advanced thinking on rocket jet propulsion problems, and to be a center for peace-time commercial and scientific uses of rocket and jet propulsion.

An important part of this program is the Daniel and Florence Guggenheim Fellowships in Jet Propulsion. These fellowships carry a stipend up to $2,000 a year in addition to tuition.

But instruction in the new field of rocket and jet propulsion did not begin at the California Institute of Technology with the Guggenheim Jet Propulsion Center. It began in 1943 in the Guggenheim Aeronautical Laboratory. At the request of the Air Technical Service Command, Army Air Forces, during the academic year 1943-44 a course in jet propulsion was initiated, limited to officer personnel of the Army and Navy assigned to the Institute for graduate study. Lectures were prepared by members of the staff of GALCIT and by several outside specialists. The course was planned by Kármán, who was also instrumental in guiding the actual instruction during the year 1943-44. The course covered in a comprehensive manner the basic principles of all known rocket and jet propulsion systems and performance of jet propelled devices. This same course was repeated during the academic year 1944-45. During subsequent years, this course was continued with little change in content. The teaching load was then, however, carried mainly by the staff of the Jet Propulsion Laboratory. This special course was then open to civilian students; but the influence of the earlier history remained, and the military enrollment continued to be heavy. For instance, as late as 1953, out of a total of 18 students graduated with the engineer's degree from the entire Engineering Division, 10 studied in the Jet Propulsion Center and received the degree of Aeronautical Engineer. Out of these 10, 9 were service officers.

With the establishment of the Guggenheim Jet Propulsion Center in 1948, and the appointment of Tsien as the Robert H. Goddard Professor, responsible for the general supervision of the Center, the instruction program was reorganized and expanded. F. E. Marble, then an Instructor in Aeronautics, joined the Center in 1949, followed by S. S. Penner in 1950, both as Assistant Professors in Jet Propulsion. The Jet Propulsion Center occupies a somewhat autonomous place in the Engineering Division because the solution of the engineering problems in jet propulsion draws on the knowledge and practice of the older branches of engineering, in particular, mechanical engineering and aeronautics. Thus, the program of instruction in jet propulsion should properly include material from both of these engineering fields. Furthermore, it is expected in general that students entering the course work in jet propulsion will have had their undergraduate preparation in mechanical engineering or aeronautics. Thus, the program of instruction in jet propulsion has two separate options, allowing men from both aeronautics and mechanical engineering to follow their previous inclinations and developments. No academic degrees are given with the designation of jet propulsion. This again demonstrates the close ties between the GALCIT and the Jet Propulsion Center.

Dr. von Kármán, the first director of GALCIT, laid down the principle of scientific engineering as the unification of theory and practice. While the problems of engineering should be examined in their full context without oversimplification, the method of attack should be the most efficient, drawn from the advanced modern sciences. This basic principle is closely followed in the instruction and research at the Guggenheim Jet Propulsion Center. Three basic engineering courses are offered for the first year graduate students: Rocket, Thermal Jets, and Chemistry Problems in Jet Propulsion. For the second year graduate students, the subjects are more theoretical and fundamental in character, and include such topics as Theory of Stability and Control, High Temperature Design Problems, and Physical Mechanics. The first of these is a course in the application of modern physics and chemistry to predict the macroscopic properties of engineering materials from the atomic and molecular structure.

Research carried on in the Jet Propulsion Center also emphasizes the fundamental problems in rocket and jet propulsion engineering. Current activities proceed along four main lines: (1) fluid mechanics of turbomachinery, (2) basic combustion problems, (3) gas emissivities and application of modern spectroscopy to detailed analysis of combustion, and (4) theory of the control and guidance of complex systems.

Under the supervision of the staff of the Jet Propulsion Center and with the sympathetic cooperation of Dr. W. D. Rannie, Associate Professor of Mechanical Engineering, many theses have been written which have made important contributions to their respective fields. Among those who have received their doctor's degree in Aeronautics, Monroe and Holmquist, both of the U. S. Navy, made a valuable analysis of the compressible flow phenomena in high speed turbomachines. Mager made a detailed study of the laminar boundary layer with cross pressure gradient, a problem associated with the secondary flow in turbomachines. Knuth did extensive experimental work on the stability and efficiency of film cooling, a method of cooling for extremely large heat flux, and determined the optimum film thickness for least coolant expenditure. Meghreblian made a theoretical calculation of the thermodynamic functions of a dissociated gas consisting of polyelectronic atoms at high temperatures, for which the electronic energy levels of the atom give essential contribution to the total energy. Adamson determined theoretically the ignition of a cool stream of combustible gas by a neighboring hot stream of inert gas. Zukoski's detailed experiments on flame stabilization with bluff bodies helped greatly to elucidate this very important but hitherto obscure problem.

The preceding paragraphs summarize briefly the high lights of the Guggenheim Jet Propulsion Center, particularly those which have to do with its mother organization, the Guggenheim Aeronautical Laboratory. The Center is still in its early years. If it holds some promise now, this is in large measure due to the guidance by example it received from the GALCIT. Thus, it is only appropriate on this occasion of the twenty-fifth anniversary of GALCIT, for the Jet Propulsion Center to express this indebtedness and to wish the older organization an even more glorious future.

VI

CONTRIBUTIONS TO THE NATIONAL DEFENSE AND RELATIONS WITH THE GOVERNMENT

ONE OF THE GREATEST CONTRIBUTIONS which an academic institution can make to the defense of the country lies in the training which it can give to officer and civilian government servants so that they may better discharge their responsibilities. With the enormous increase since the beginning of the last war in the role of science in the armed forces, this is particularly true of a technical institution like the California Institute of Technology. In an earlier section some details have been given of this aspect of the GALCIT activities, both as a part of its normal postgraduate instruction and also in its war-time emergency training programs.

The GALCIT has also contributed by carrying out technical and scientific investigations at the request of the armed services. The setting up of the rocket program and later of the Jet Propulsion Laboratory are examples which have been discussed earlier. The members of the staff have also participated intensively in government activities. Kármán was for many years consultant to all three services, and after 1942 devoted most of his time to setting up and leading the Air Force Scientific Advisory Board. Millikan has served on advisory committees to the three services and was for three years Chairman of the Guided Missiles Committee of the Department of Defense Research and Development Board. Sechler has served on Air Force committees; he, Millikan, Lees, and Fung are currently active on such an assignment. Stewart has consulted with Army Ordnance and is a member of the Air Force Scientific Advisory Board. Millikan, Sechler, and Liepmann serve on subcommittees of the National Advisory Committee for Aeronautics.

These are examples of services by the GALCIT staff for government agencies. On the other hand, the Army, Navy, Air Force, and NACA have very wisely adopted policies of supporting research projects at universities. The researches mentioned earlier have for many years been supported to a large extent by these agencies, and there are currently active projects sponsored by all four. Much of the GALCIT's history of the past twenty-five years could not have been written had it not been for its close association with these agencies of the government.

VII

RELATIONS WITH INDUSTRY

In its relations with industry as with the government, probably the Galcit's greatest contribution has been the students it has trained and sent out. Of these the greatest percentage has entered the engineering departments of aircraft companies. As has already been mentioned, it has been a continuous policy that close contact be maintained with industry in the Galcit's day to day life. The first airplane design course was given by a practicing aeronautical engineer; and, ever since, one course each year is given by engineers from local aircraft companies.

The testing program in the 10-foot and Cooperative wind tunnels obviously results in intimate contacts between staff members and students and aircraft company engineers, and similar contacts are also frequent in other fields. Company engineers are invited to attend the Galcit seminars, of which there are several each week, and the invitations are frequently accepted. Members of the staff are encouraged to undertake part-time consulting responsibilities if they care to do so, and many avail themselves of the opportunity. Experience has shown that, with a strong and active program of fundamental research on the campus, such consulting activities actually contribute to the staff's creative work, rather than interfere with it. This is certainly due in part to the dynamic nature of the aircraft industry and to the number of problems whose solution requires the most advanced scientific knowledge and techniques.

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