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Development of High-Speed Water-Based Aircraft

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SUMMARY

Outstanding progress has been made in recent years in the field of seaplane hydrodynamics which has done much to bring the faltering seaplane up to modern standards of aerodynamic performance and design efficiency. In fact, extensive research programs, utilizing the dynamically similar model technique, promise to place consideration of water-based aircraft high on the program of current defense planning.

This paper outlines the salient features involved in the development of the dynamic model and associated research techniques into a practical, accurate research tool for designing water-based aircraft that demand little, if any, compromise with contemporary aerodynamic design. New seaplane design criteria are discussed, and their application to high-performance water-based aircraft is analyzed. With the high-speed propeller-driven seaplane now an actuality, attention is drawn to the solution of the supersonic water-based problem.

It is concluded that adequate design criteria and technological experience are available to meet satisfactorily or to exceed any aircraft requirement with a suitable water-based configuration.

INTRODUCTION

From its inception, the technical development of the airplane has been rapid. However, in recent years, it has been virtually land-bound, unless one was willing to accept the large performance penalties that accompanied adaptation to water operation. Because of these performance deficiencies, the seaplane for many years was restricted to only those functions where water-based operation was mandatory and outweighed other performance considerations. This left to the land-based airplane the principal task of securing and maintaining the mastery of the air—even over the seas—in spite of the hazards of forced landings and the restricted freedom of action imposed by the necessity for elaborately prepared terminal and auxiliary landing facilities.

This situation was not always true. Dating from the first practical seaplane developed by Glenn Curtiss in 1911, seaplane design progressed rapidly through the first World War. As a matter of fact, water-based development outstripped contemporary landplane design during that period to such an extent that, by 1938, all long-range transport was still accomplished by flying boats and the world's speed record was held by a seaplane. From a hydrodynamic point of view, this early development period culminated in the design and construction of the famous NC flying boats in 1918. The hull of the NC was 45 ft. long with a beam of 10 ft., and it was this hull that influenced basic seaplane design and hydrodynamic criteria for the following 20 years, during which period little research was directed toward the improvement of hull design.

During this static period, seaplane development centered about a few fundamental design criteria that had gradually evolved from trial and error and long experience. While it was recognized that basic improvements in hydrodynamic design were no doubt possible, research had lagged to the point where aircraft manufacturers were not justified in deviating, nor could they afford to deviate, far from established trends. Limited progress continued, but this was largely due to costly flight-test programs and the incorporation of improved air-frame and engine installations. This situation resulted from the fact that there was no satisfactory research procedure available for the rapid and accurate determination of the complex discontinuous variables involved during simultaneous operation in two media—i.e., air and water.

The introduction in this country of the dynamically similar model technique of research (by the author in July, 1938[1]) for the first time presented the airplane designer with a practical research tool for designing the hull of a seaplane which was complementary to, and as

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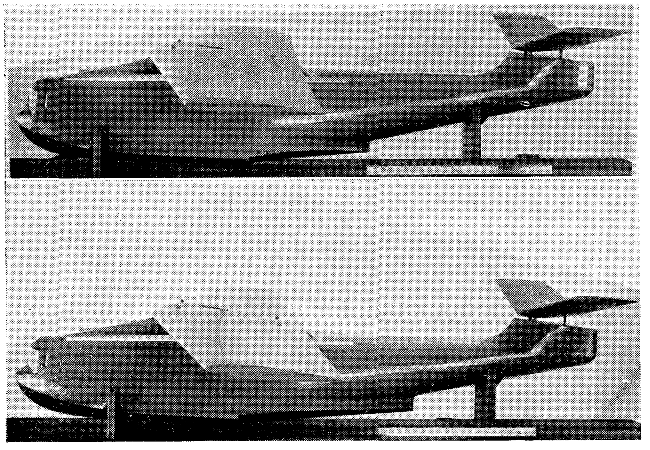


FIG. 1 (*top*). Original configuration of the XPB2Y-1 which gave an operational gross weight limit of 40,000 lbs. (*Bottom*). The revised XPB2Y-1 hull which resulted in an operational gross weight of 86,000 lbs.

modern in concept as, his science of aerodynamics. With this versatile scientific tool available, extensive hydrodynamic research programs were initiated during the past war to meet the ever increasing demands for increased seaplane efficiency and reliability. For example, the Coronado, a large four-engined patrol bomber flying boat, was increased from a maximum operational gross weight of 40,000 lbs. to a weight of 86,000 lbs.—over double—solely through the application of an intensive dynamic model research program. Fig. 1 shows the modification that eventually was found necessary in this case, and it is obvious that such an extensive revision of lines would not have been discovered by the costly time-consuming procedure of full-scale cut and try. The model tests, on the other hand, indicated a complete solution to the problem in 3 weeks of testing. In a like manner, the performance and efficiency of the famous Convair Catalina, Martin Mariner, Boeing Clipper, and other World War II seaplanes were greatly increased at a most critical period of the war effort.

With this outstanding confirmation of the effectiveness of the dynamic model in rapidly solving complex hydrodynamic problems and in spite of the urgency attached to improving existing seaplanes during the war, considerable effort was directed toward applying this new research technique to the fundamental solution of basic hydrodynamic criteria. The war was demanding that the range and load-carrying ability of seaplanes be improved. The only known method at the time was to overload continually these aircraft to the point where seaworthiness and water-handling characteristics were greatly impaired, attempt to refine the existing design still further, and then overload again. It was imperative, therefore, that some other fundamental means be found whereby the desired seaworthiness could be attained without impairing the load-carrying ability while at the same time allowing marked improvements in performance, which at best was dangerously low.

In searching for a fundamental concept that would allow radical improvement in hull performance, an *N.A.C.A. Technical Memorandum*[2] was recalled which briefly abstracted some experiments conducted by Sottorf in Germany. This report presented meager resistance and spray information on a series of high length-beam ratio hulls which, when carefully analyzed, held considerable promise for a solution to the problem just discussed. The brief summary presented in the N.A.C.A. publication was insufficient, however, for a thorough analysis, and the complete reports were ordered from DVL in Berlin. These reports, which were actually received after outbreak of war in Europe, were completely translated by Convair[3] and were found to contain a complete account of the German experiments.

More thorough analysis of these later data confirmed preliminary theoretical studies that high length-beam ratio hulls held out a definite promise for marked hydrodynamic improvement. However, it was also realized that these studies were based on a series of resistance-type tank models and that many more data, particularly on the stability and relationship of secondary design parameters, were required before utilization of the basic principles embodied in these hulls could be realized.

A Navy research authorization was granted to Consolidated Vultee, and, under the direction of Convair hydrodynamicists, carefully planned and integrated dynamic model research programs were organized at the N.A.C.A. Towing Tank, Stevens Institute Towing Tank, and Convair's own Hydrodynamics Research Laboratory. This resulted in a new family of hull forms of superior performance. It was through the application of basic design criteria obtained from this intensive research program that the XP5Y-1, the Navy's newest flying boat, was developed. This high-speed turboprop seaplane, shown in Fig. 2, represents the first water-based design in this country to deviate radically from the pattern established by the outmoded NC flying boats of World War I.

Like the NC boat, the XP5Y-1 has a beam of 10 ft. Fully loaded, the NC had a gross weight of 28,000 lbs., whereas the XP5Y-1 demonstrates excellent hydro-

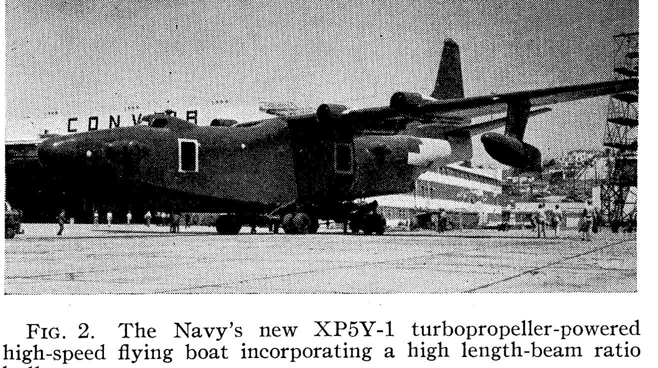


FIG. 2. The Navy's new XP5Y-1 turbopropeller-powered high-speed flying boat incorporating a high length-beam ratio hull.

dynamic characteristics up to 150,000 lbs. The increase in efficiency of the new high length-beam ratio hulls does not, however, stop with load. Hydrodynamic instability, such as porpoising and skipping, has been brought under control through the use of dynamic models and no longer restricts the operation of new seaplane designs to a narrow band of stable limits; hence, the versatility, safety, and seaworthiness of the modern flying boat were greatly increased. High hull fineness ratio, which allows the incorporation of easy buttocks and sharp waterlines, has done much to minimize the problem of spray and greatly increase seaworthiness and rough-water performance. This same feature has resulted in hulls of low frontal area, representing large decreases in aerodynamic drag. In conjunction with such design innovations as multicellular watertight integrity, propeller-turbine engine developments, and automatic mooring and docking techniques, the seaplane designer is now able to put a high-performance propeller-driven seaplane into the air which fully meets the exacting requirements of modern design and yet takes full advantage of the inherent strategic advantage of water-based aircraft from the operational standpoint of mobility and dispersion of forces.

If seaplane development were not to falter again, as it did after the first World War, it was obvious that the successful development of high-speed propeller-driven seaplanes would provide only temporary respite unless steps were taken to develop the water-based aircraft into an efficient and dependable transonic, and eventually supersonic, aircraft. The adaptation of transonic aircraft design to water-based operation, without sacrificing any of the high standards of hydrodynamic performance which have been introduced into seaplane design during the past few years, posed what at first appeared to be an insurmountable problem. It was apparent from the outset that extensive aerodynamic refinement of known hydrodynamic forms of high quality would merely result in poor hydrodynamic performance without ever fully obtaining the aerodynamic cleanliness required for transonic flight. It appeared logical, therefore, to start with an ideal aerodynamic configuration and, by means of extensive dynamic model research, develop new hydrodynamic principles and applications that, though different in concept, would result in the same degree of seaworthiness and stability normally associated with the best hulls of conventional form.

In line with the above reasoning, it was obvious that the basic "in-flight" configuration must consist of a smooth, unbroken form, utilizing high critical Mach sections throughout. In order to secure elementary floatation, it was necessary to supply sufficient volume of body so that engines, air inlets, jet exhausts, and personnel would not be inundated. The combination of these two fundamental requirements led logically to the blended-wing-hull configuration as the most promising approach to the basic problem.

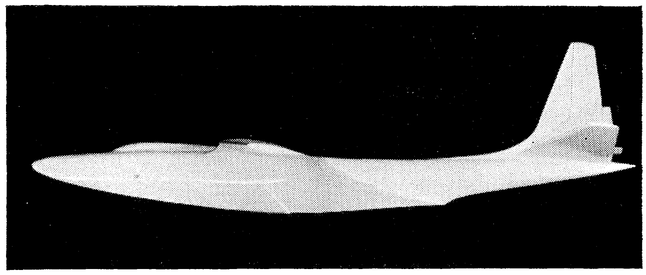


FIG. 3. A dynamically similar flying model of the first jet-propelled, blended-hull configuration to be developed for a transonic water-based aircraft.

By proceeding in this logical manner, a large number of transonic hydrodynamic configurations were designed and tested as free-body dynamic models—some were catapulted, others were towed, and many were actually flown, self-propelled with their own jet engines. It became increasingly apparent that a true aerodynamic form could meet adequately, or in some cases exceed, the established design criteria for satisfactory hydrodynamic performance. The first in this long series of transonic water-based configurations is illustrated in Fig. 3. Continual refinement has radically altered the appearance of these high-speed aircraft over that shown in this figure. However, the new research philosophy out of which it was conceived is firmly established, and the little dynamic model shown in Fig. 3 may well represent, in the years to come, the real rebirth of sea power. For, with the transonic water-based aircraft a practical reality from a technical standpoint, the revitalized hydrodynamic research program at Convair is already well into the problems of water-based supersonic flight.

The following sections of this paper will outline the development of the dynamically similar model and its associated research techniques. Within the limits of security classification, the more important hydrodynamic design criteria that have been obtained from the above research will be discussed.

DYNAMIC SIMILARITY

Fluid Resistance

Before discussing the various research techniques, equipment, and design criteria that have been developed around the use of dynamically similar models, it is believed desirable to review briefly the basic theoretical background upon which this versatile applied science is based. Classical hydrodynamics considers the perfect fluid that is defined as incompressible and nonviscous—i.e., there is no resistance to shearing between the elements. Water is, for all purposes, incompressible; however, it has viscosity and other characteristics such as surface tension which require special attention and cannot be neglected. The general resistance equation for the force acting on a body in motion, partly or wholly immersed in an imperfect fluid such as water, can be expressed in the following form:

$$R = (\rho V^2L^2)f\left[\tau, \frac{V^2}{gL}, \frac{\rho VL}{\mu}, \frac{V}{a}, \frac{l}{L}, \frac{v}{V}, \frac{V^2L}{\gamma}, \frac{L}{b}\right] \quad (1)$$

where the variables are density of the fluid, ρ; velocity of the body, V; linear size of the body, L; trim or angle of attack, τ; gravity, g; coefficient of viscosity, μ; compressibility of the fluid, V/a; surface roughness, l/L; texture of the fluid flow or turbulence, v/V; surface tension, γ; and fineness or aspect ratio, L/b.

The term ρV^2L^2 is the main term of the expression and is recognized as the force due to density. We are accustomed to the use of a single nondimensional coefficient of resistance instead of the complex function in the brackets. It must be borne in mind, however, that such a single coefficient, when used, varies with, and attempts to be, the equivalent of the terms listed. Some of these terms may be negligible, but all are subject, to some extent, only to experimental determination.

In hydrodynamic experimental testing, it is necessary to determine $f_1(\tau)$ or the variation of resistance coefficient with trim. Because of the gravity effects associated with wave-making, the term $f_2(V^2/gL)$, or Froude Number, must be met. Because of the dependence of frictional resistance on viscosity, $f_3(\rho VL/\mu)$, or Reynolds Number, must be calculable or an allowance made. As we are dealing with incompressible water, the compressibility term $f_4(V/a)$ may be neglected. If tests on two models do not agree, the surface roughness $f_5(l/L)$ may not bear the same relation in the two cases. This function has a strong bearing on frictional resistance as does $f_6(v/V)$, which is the stream turbulence as represented by the ratio of the average lateral turbulence velocity to the measured axial velocity. Surface tension represented by $f_7(V^2L/\gamma)$ can, in most cases, be neglected, except possibly in accurate studies of spray formation. Experiments have been conducted where this term is eliminated by the introduction of Aerosol, or some other commercial wetting agent, to the water. Finally, it is apparent in aerodynamics, and is becoming increasingly so in hydrodynamics, that fineness or aspect ratio, represented by $f_8(L/b)$, cannot be neglected. In hydrodynamics, this becomes the ratio of the planing bottom fineness or length to beam ratio. These are by no means all of the dimensionless combinations that may be written, but they comprise what are usually considered the most important.

Using this typical example of the numerous factors influencing fluid resistance, three important facts can be derived which apply equally well, though varying in detail, to all other quantities for which scale reproduction is desirable:

(1) Theoretically, no model test can completely represent a full-scale condition unless all of the dimensionless ratios are held constant.

(2) It is impossible to hold all of these ratios constant at the full-scale value in a model test, for some of them are contradictory.

(3) The dimensionless ratios may not have equal weight, but theory does not show it.

Experience tells us, however, that the angle of attack or trim is the most important of all the terms given and that for hydrodynamic work the Froude Number should be held constant. It is obvious from this discussion that experimental research on models, in an attempt to determine or predict full-scale behavior, is not a cut-and-dried procedure but is a series of compromises based on judicious judgment and experience. Even the meticulous matching of Froude Number does not assure similarity. For the lower speed régimes where wave-making predominates, it will give close approximations, but, as the speed increases to high-speed planing on the water, the function of Reynolds Number becomes more and more predominant. While the above discussion appears to present a pessimistic picture of experimental model testing, it should be pointed out that, by comparison, the theoretical or analytical solution to hydrodynamic problems, particularly those concerned with stability, is practically hopeless, with no prospect of improvement. On the other hand, rapid progress has been made toward the solution of the problems associated with dynamic similarity, and it appears that the full application of this relatively inexpensive and direct approach to the solution of discontinuous complex variables is virtually unlimited. Later sections of this paper will discuss in more detail the specific deviations from theoretical similitude and the remarkable degree of accuracy that can be obtained from the modern dynamic model when it is properly designed and operated.

Froude's Law of Comparison

In the previous section on fluid resistance, it was stated that Froude Number, V^2/gL, must be held constant in all cases of experimental hydrodynamics when anything but the specific full-scale configuration itself is being investigated. It was further stated that, with calculated reservation, the holding of this function constant would most nearly result in model experiments producing quantitative data directly commensurate with full scale. As these statements contain the heart of all hydrodynamic research and analysis, it is advisable to become more familiar with the character and limitations of this function.

In 1867, William Froude had constructed what is generally conceded to be the first modern towing tank, and, by 1879, when he died, he had contributed volumes to the science of naval architecture. Of greatest significance was his famous Greyhound tests, where a 172-ft. boat named the "Greyhound" was towed by

H.M.S. "Active." By duplicating the full-scale tests in his towing tank with a $^1/_{16}$-scale model and by applying appropriate coefficients of friction to both full scale and model, from data previously determined in the tank, he was able to separate that portion of the total resistance due to gravitational wave formation and eddies. By analysis of these data, Froude determined that, if any full-scale speed was divided by $\sqrt{16}$ (the square root of the model scale), the wave and eddy resistance of the model at that speed was equal to the corresponding resistance of the full-scale ship divided by 16^3 (the model scale cubed). This relationship Froude called the "Law of Comparison." By referring to Eq. (1), we see that the second function in the bracket, V^2/gL, previously called Froude Number, demands that V vary as the square root of the linear dimension L if model comparison is to be valid.

As pointed out, this relationship applies only to residuary resistances and wave formation. If we were limited to ideal fluids, Froude's Law of Comparison would be sufficient. However, the functions of viscosity, surface tension, and other properties of water are such that any attempt to bring them into a law of similarity requires the introduction of Reynolds Number as well. The conditions where Reynolds and Froude agree exist only at full scale. If the frictional component is small, as is usually the case in the larger tank models of conventional speed seaplanes, it is possible to neglect its effect and proceed under Froude's comparison and scale total resistance directly to the scale cubed. In most cases this will result in a degree of full-scale conservatism which will cover items of surface roughness and protuberances not usually present in the model tested. If, on the other hand, we are dealing with small models of extremely high-speed planing craft, gravitational resistance may be small or negligible, and large errors will result if the frictional resistance is not separately treated at the proper Reynolds Number as in aerodynamic theory. Fortunately, the majority of critical items of hydrodynamic performance, such as stability, spray formation, seaworthiness, etc., occur at low speeds in the range of transition from displacement to planing and thereby closely follow Froude's Law. For emphasis it should be pointed out again that one will find all of the standard coefficients and parameters of seaplane design based on Froude's Law of Comparison and, unless the research engineer is fully aware of the limitations and treatment of this function, that serious inconsistencies will result, particularly as the trend for higher speed water-based aircraft continues.

Dimensional Analysis

Inasmuch as experimental research is the foundation of all applied hydrodynamics for the seaplane designer, it is necessary that the engineer understand the dimensional test equivalents for all factors encountered full scale. In the two previous sections, we have discussed the components of hydrodynamic resistance and how this force varies with linear scale. In this section, with Froude's Law as a basis, we will develop the relationship of many other interrelated physical functions of dynamics and mechanics to linear scale. Keeping in mind the inherent, but calculable, discrepancy of Froude's fundamental Law of Comparison, we can establish mathematically how every other physical quantity must vary to keep the total dimensionally correct.

In the early days of seaplane research and ship design, the designer was primarily occupied with the resistance of his hull forms, and, consequently, the basic law of comparison, as stated by Froude, dealing with the relation of resistance to speed with varying scale was adequate. However, with increasing knowledge of hull form and the rapid development of powerful engines, resistance was gradually, but steadily, subordinated to the more critical studies of dynamic stability on the water and the factors affecting spray formation and seaworthiness. As stated previously, the most direct approach to these problems is through the use of dynamically similar scale models. To obtain accurate results for these complex dynamic problems, it is necessary for the models to be dimensionally correct in all respects to the full-scale prototype—i.e., they must not only be geometrically to scale, such as a wind-tunnel model or resistance-tank model, but it is also required that they have, among other things, gross weight, inertia, power, accelerations, and all aerodynamic forces and moments to scale. It is obvious, therefore, that, if this can be accomplished throughout for every factor, we have in effect a flying miniature of the full-scale airplane that will perform every maneuver of the full-scale aircraft and at a rate of movement directly to scale. *In effect, the dynamic model becomes a complex integrating mechanism that automatically picks up every known or unsuspected force, in the proper magnitude, point of application, direction, and sequence; integrates all these reactions instantaneously; and provides the observer with the resultant motion and rate.* Even if there were no unknown transient forces, the task of integrating all known forces in a complex dynamic reaction by analytical means, for just one speed point, is enormous. It is this goal of tremendous simplification of integrating all forces on a free body which has made the problems associated with the attainment of such a model seem inconsequential by comparison.

Because the dynamically similar flying model represents the ultimate in experimental research at reduced scale, we shall develop the principal scale relationships involved in its design and analysis. It is apparent that, if sufficient basic factors are dimensionally correct, other minor dependent variables will automatically follow. Therefore, the derivations and relationships that follow are the principal functions involved and should be sufficient for most analyses. The engineer will find it a simple matter to derive certain other functions not specifically listed in this compilation.

In the following derivations we will consider that the symbol for scale, λ, represents the whole number—i.e., if $\lambda = 8$ then the linear scale is $^1/_8$ or λ^{-1}. As the linear or geometric scale, λ^{-1}, is usually given, it is desired to get all other physical relations in terms of this one value. It is obvious, therefore, that, if the linear scale is a ratio of lengths L, then L varies directly as $1/\lambda$ or λ^{-1}, written $L \propto \lambda^{-1}$. Following this procedure, it is plain that an area is made up of a length times a length or L^2. Therefore, area, or L^2, varies as the linear scale squared —i.e., area $\propto \lambda^{-2}$. In a similar manner, it may be reasoned that a volume or mass is an area, L^2, multiplied by thickness or height, L, giving L^3. Hence, volume, weight, or, as Froude determined, force $\propto \lambda^{-3}$. As the moment of a force is that force multiplied by an arm, L, we may extend our reasoning to show that moment $\propto L^4$, or λ^{-4}. Similarly, the moment of inertia is a mass multiplied by the arm squared, or moment of inertia $\propto \lambda^{-5}$.

Since our system of similarity is based on Froude's Law of Comparison and since we have seen from Eq. (1) that this expression depends upon the speed varying with the square root of the linear dimension, it follows that velocity $\propto \sqrt{L}$ or $\lambda^{-1/2}$. As distance is a linear dimension, L, and velocity varies as the $\sqrt{L}$, then time, which is distance divided by velocity, or $L/\sqrt{L}$, must also vary with $\sqrt{L}$. Hence, time $\propto \lambda^{-1/2}$. Now that we have the basic variations of mass, length, time, and velocity, it is a simple matter to substitute in the expressions for any physical function and derive its variations with linear scale. For instance, revolutions per minute is revolutions, which are nondimensional, divided by time, or $1/\sqrt{L}$, which gives us the relation r.p.m. $\propto \lambda^{1/2}$. Likewise, acceleration is feet per second squared, or $L/(\sqrt{L})^2$, giving acceleration $\propto 1$, or unity; hence, it becomes nondimensional. This means that all model linear accelerations will be identical to the full-scale accelerations in magnitude. On the other hand, if we consider angular motion, we find that angular velocity is nondimensional radians divided by seconds, or $1/\sqrt{L}$, giving, as in the case of r.p.m., $\omega \propto \lambda^{1/2}$. As angular acceleration is radians per second squared, or $1/L$, we have simply $\alpha \propto \lambda$ for this quantity. Whereas we found that linear acceleration is identical to both model and full scale, we see that angular acceleration will be the whole number λ times as great in the model as the full-scale value. The fact that linear accelerations do not vary with scale is fortunate, inasmuch as the value g, which is the acceleration due to gravity, is a constant over which we have no control and corrections would be extremely difficult at best, if not impossible.

Continuing our derivations into the more complex functions, we recall that power is defined as the work accomplished per unit of time, where work is the product of a force times the distance through which it acts. Following the previous line of thought, we can consider that force, L^3, times the distance of action, L, causes work to vary with the fourth power of linear scale—i.e., work $\propto \lambda^{-4}$ and power will therefore be $L^4/\sqrt{L}$, which gives $L^{7/2}$ or power $\propto \lambda^{-7/2}$. That these relationships are dimensionally correct can be quickly checked by substituting these derived values into any formula defining some nondimensional coefficient and thereby demonstrate that the numerical value of the coefficient does not change with scale. For this demonstration we can pick such an expression as the following, which defines the well-known nondimensional power coefficient, C_P:

$$C_{P_{(\text{full scale})}} = \frac{5 \times 10^{10} \times \text{b.hp.}}{(N)^3 \times (D)^5} \tag{2}$$

where b.hp. is the brake horsepower, N is the propeller revolutions per minute, and D is the propeller diameter in feet, all full-scale values. From our previous discussion we know that the C_P for the model would be

$$C_{P(\text{model})} = \frac{5 \times 10^{10} \times (\text{b.hp.} \times \lambda^{-7/2})}{(N \times \lambda^{1/2})^3 \times (D \times \lambda^{-1})^5} \tag{3}$$

and, solving for the variation of λ, we find

$$C_{P_{(\text{model})}} \propto \frac{\lambda^{-7/2}}{\lambda^{3/2} \times \lambda^{-10/2}} = \frac{\lambda^{-7/2}}{\lambda^{-7/2}} = 1 \tag{4}$$

Therefore, the ratio of $C_{P(\text{full scale})}$ to $C_{P(\text{model})}$ is unity.

For convenience, Table 1 is presented which summarizes the principal relationships in condensed form, giving, in addition, a typical set of values for an assumed value of $\lambda = 8$ giving a linear scale of $^1/_8$.

TABLE 1
Dimensional Conversion for Linear Scale

Unit	General Conversion	$^1/_8$ Scale, $\lambda = 8$
Linear dimensions	λ^{-1}	1/8
Area	λ^{-2}	1/64
Volume, mass, force	λ^{-3}	1/512
Moment	λ^{-4}	1/4,096
Moment of inertia	λ^{-5}	1/32,768
Linear velocity	$\lambda^{-1/2}$	1/2.83
Linear acceleration	Constant	1
Angular velocity	$\lambda^{1/2}$	2.83
Angular acceleration	λ	8
Time	$\lambda^{-1/2}$	1/2.83
R.p.m.	$\lambda^{1/2}$	2.83
Work	λ^{-4}	1/4,096
Power	$\lambda^{-7/2}$	1/1,446
Wing loading	λ^{-1}	1/8
Power loading	$\lambda^{1/2}$	2.83

The interesting fact to note in closing this brief discussion of dimensional analysis is that all of the factors listed in Table 1 have been experimentally checked on numerous occasions by constructing and testing models of existing airplanes for the purpose of positive correlation. For instance, in the case of the Navy's XP4Y-1, a $^1/_8$-scale, radio-controlled, dynamically similar model (Fig. 4) was constructed and thoroughly correlated with the full-scale airplane, as well as wind-tunnel and towing-basin, tests. With accurate scale propellers set at the actual full-scale blade angle and with the r.p.m. adjusted to 2.83 times the full-scale value (see Table 1), the engine power was measured on a dynamometer and was found to be 1/1,446 the full-scale value, and the thrust developed was 1/512. With this power and a model weight of 1/512 full scale, the model was found to become air-borne at a time and speed equal to 1/2.83 that observed during flight tests. Linear acceleration at the hump and getaway was found to be the same on model and full size. Additional description and results of these correlation studies, particularly with regard to the more complex functions involved in the stability derivatives, are covered in more detail in reference 4.

Research Techniques

Towing Tank Testing

The oldest and most usual form of dynamic model testing is in a towing tank. Prior to the introduction of dynamic models, these towing tanks were used primarily to tow solid resistance models through the water, much as William Froude did in the late 1800's. These resistance models were attached to a towing carriage through a dynamometer linkage such that resistance and moments at fixed trims or free to trim resistance at various speeds could be recorded. The results were similar to those obtained in a wind tunnel, inasmuch as forces and moments due to form only were the principal products of the testing.

With the introduction of dynamically similar scale models in 1938, it became necessary to revise all the old procedures and equipment of tank testing in order to take advantage of the unlimited opportunities afforded to investigate the dynamic effects of hydrodynamic stability and its interrelated influence on the associated aerodynamic parameters of the aircraft as a whole. The towing tank became a free-stream turbulence wind tunnel, as well as a water channel, and the models had to be given as many degrees of freedom as physically possible in order that resultant motion would be unrestrained. Inasmuch as pitching and heaving motions associated with the cyclic hydrodynamic stability problem known as porpoising were of immediate concern and because of the fact that the towing channels were narrow, precluding lateral deviations from a course down the center of the tank, it was customary to mount the models so that they had freedom in pitch and rise but were restrained in yaw, roll, and freedom along the longitudinal axis.

This is accomplished in a manner illustrated in Fig. 5, which shows the $^1/_{10}$ scale powered model of the

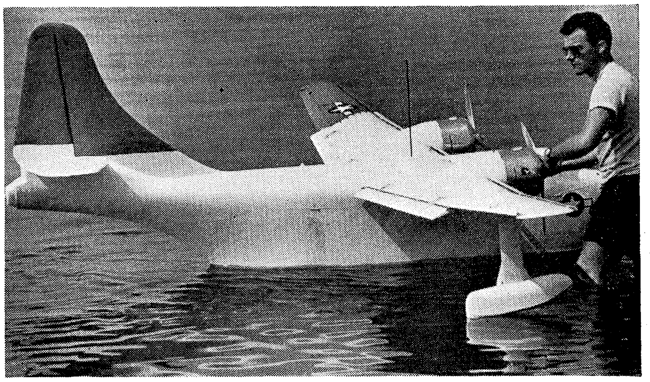


FIG. 4. The first completely free-body, self-propelled dynamically similar model to be flown by remote radio control. A $^1/_8$ scale model of the XP4Y-1.

XP5Y-1 attached to the towing carriage of N.A.C.A. Tank No. 1 at Langley Air Force Base, Va. The rectangular towing staff is pivoted at the center of gravity of the model and allows freedom in pitch while restraining the model in yaw and roll. The staff is machined on all faces and rides in a roller cage attached to the carrier. The roller cage restrains the staff in yaw and holds it to a vertical position but allows complete freedom in rise. It will be further noted in Fig. 5 that the roller cage is mounted to the carriage truss through a dynamometer linkage so that resistance and/or thrust may be measured during the run.

Early experiments were conducted with unpowered models, and the towing force or thrust was transmitted to the model through the towing staff to the model center of gravity. While this procedure was providing many results theretofore unattainable, true dynamic similarity was not obtained, and every effort was made, in conjunction with the N.A.C.A. staff, to improve continually the efficiency of dynamic models and their technique of testing. In 1940, it became obvious that the models should incorporate scale power and running propellers in order to further enhance and refine the ex-

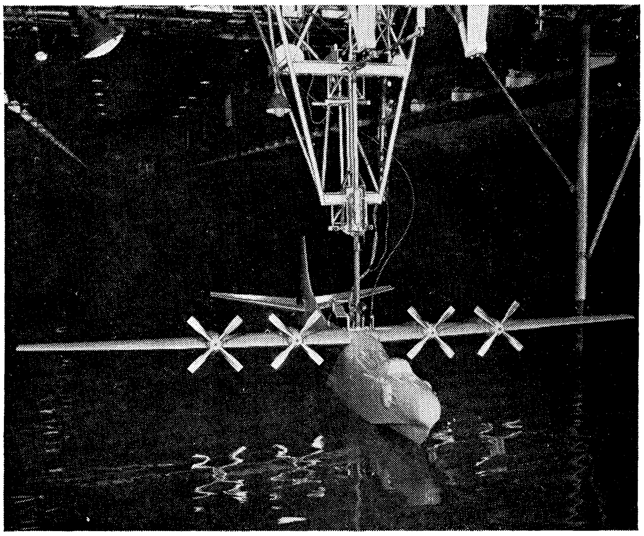


FIG. 5. The $^1/_{10}$ scale XP5Y-1 dynamically similar powered model in the N.A.C.A. towing tank at Langley Air Force Base.

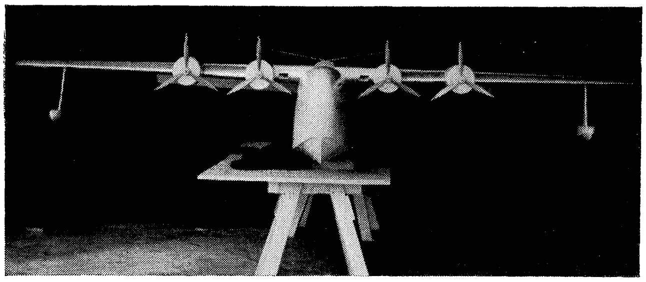


FIG. 6. The 1/8 scale Coronado powered dynamically similar towing tank model.

cellent data being obtained. Convair was given a contract by the Navy to design and install variable frequency power equipment in the N.A.C.A towing tank, along with associated development of lightweight electric motors, adjustable-pitch metal propellers, and other equipment involved in going to power operation. A 1/8 scale dynamic model of the Convair Coronado, shown in Fig. 6, became the first model to be tested with this equipment.

The absence of complete freedom of motion still restricted the scope of testing and precluded any study of directional problems. Various attempts were made to incorporate additional degrees of freedom of a limited nature, mostly without success. One important result of these studies was the development of a rail system for the roller cage which allowed an appreciable amount of fore and aft freedom. With careful control of model and carriage power, it became possible to operate the model truly self-propelled for short periods of time. However, except for certain special constant-speed runs, the basic towing tank technique consists of towing a powered model, rigidly attached to the towing carriage through the center of gravity pivot and having freedom in only pitch and rise.

There are four basic testing techniques utilized in tank-testing of dynamic models which will be briefly discussed:

(1) *Constant Speed Run.*—The constant speed run is not a dynamically similar function inasmuch as the important acceleration parameter is neglected. Nevertheless, this technique is valuable for establishing certain fundamental hydrodynamic criteria such as trim limits of stability, resistance, underwater flow photographs, and spray patterns. Because of the ease in duplicating test conditions and the time available for observation, the influence of extremely small variables may be detected.

(2) *Accelerated Run.*—The accelerated run, where the model is accelerated at a constant rate from standstill to getaway, most nearly simulates full-scale operation. While the actual take-off run of a seaplane is not made at a constant acceleration rate, it is not feasible to vary this factor in the towing tank because of the high inertia and complicated speed control of the towing carriage. It is customary to set a constant rate equal to the acceleration of the aircraft during the critical speed range at the hump and maintain this rate constant to getaway. An even more serious drawback to accelerated runs in the towing tank is the inability of any present-day equipment to match the accelerations being studied for modern high-speed water-based aircraft, which are approached $^1/_3g$ in some cases. The accelerated run technique is used in all cases for evaluating the stability range, aerodynamic control, and spray characteristics of a specific design configuration.

(3) *Landing Run.*—This technique involves getting the model up to stabilized flight as rapidly as possible in order that a landing from the flight attitude may be made. The majority of these landings are made with the model attached to the towing carriage, which is decelerated from flight speed at a constant rate. Here again, in most cases, it is not feasible to decelerate the heavy towing carriage at a rate commensurate with full scale, and, being rigidly attached, the predetermined rate of the carriage is impressed upon the model regardless of the varying decelerating forces it may experience. In certain cases where the model is small, it has been found practical to launch the model from the carriage in free flight. Landings under these conditions are dynamically similar and, consequently, are much more desirable in that they overcome the above objections to the rigid attachment. Obviously, control and instrumentation is complicated considerably by this latter technique.

(4) *Generalized Similarity.*—This last towing tank procedure is commonly called the "Stevens Method," inasmuch as it represents the unique testing technique employed by the Experimental Towing Tank at Stevens Institute of Technology. Fig. 7 illustrates the Stevens towing carriage with a dynamic model attached. Here it will be noted that the aerodynamic parameters and derivatives are introduced through calibrated weights, springs, and dash pots. While all of the full-scale parameters must be known in order to set up their equivalents on the model system for specific

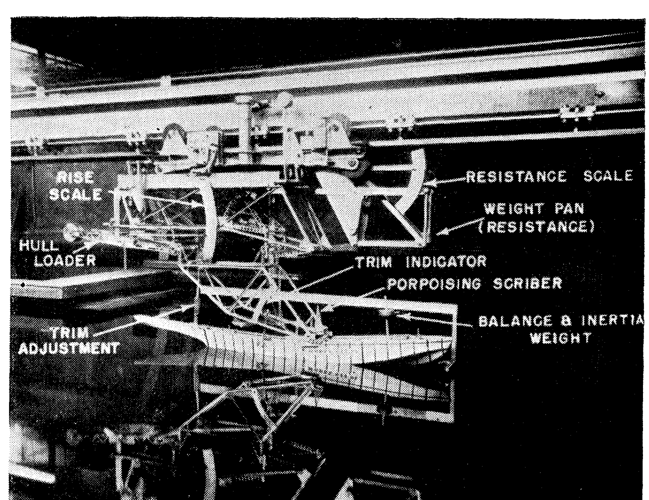


FIG. 7. The Stevens Institute of Technology towing tank and dynamic model towing carriage.

tests, this method does prove versatile for generalized problems where it is desirable to introduce the aerodynamic derivatives as independent variables. It is difficult to determine a specific evaluation by this method, such as is possible with the accelerated run technique; however, for rapid comparative study of many variables, this technique is superlative.

Steady progress has been made in the continual effort to minimize or eliminate inaccuracies in the scale-testing of dynamically similar models in the towing tank. Obviously, the ideal situation is to have a fully instrumented, self-propelled free body under the positive control of an operator. Such a model would inherently produce the proper variation of acceleration and unrestrained motion in space. In spite of the physical limitations and compromises of the towing tank, this equipment produces accurate results in the hands of experienced analysts who fully recognize, and allow for, the deviations from dynamic similitude.

Free-Body Testing

During World War II, the facilities at the N.A.C.A. and other towing tanks in this country became crowded, and many high priority developments were suffering long delays. To alleviate this condition and at the same time obtain for the first time the optimum condition previously mentioned (that of having complete free-body operation), Convair started to develop a system of free-body dynamic model research. The heart of this development is the large, natural outdoor towing basin available in the form of the U.S. Naval Training Station Estuary, illustrated in Fig. 8. This ideal testing facility is an arm of San Diego Bay, and it is completely contained in the center of a military reservation, which provides excellent security protection. Located adjacent to Convair property, its smooth sand beaches and calm protected water allow dynamic models to be operated by the contractor at his plant, thus ensuring uninterrupted research and development.

As discussed previously, the problems associated with complete free-body operation are numerous. The models must be propelled and be under positive control, and, to be of any value, technical test data must be accurately and rapidly available. This has resulted in the development of many new pieces of test equipment and of new research techniques. However, as in the early development history of the dynamic model itself, the potential rewards in the form of versatility, speed of results, and accuracy outweigh the purely mechanical problems associated with the attainment of this goal. For instance, unlike the inherent restrictions of the towing tank, the free-body model produces unrestrained resultant motion about all axes, allowing complete studies to be made of directional stability, water-looping, low-speed maneuvering and control, drifting in seas, course-keeping, and other specified problems, in addition to the standard straightaway run. Take-off time

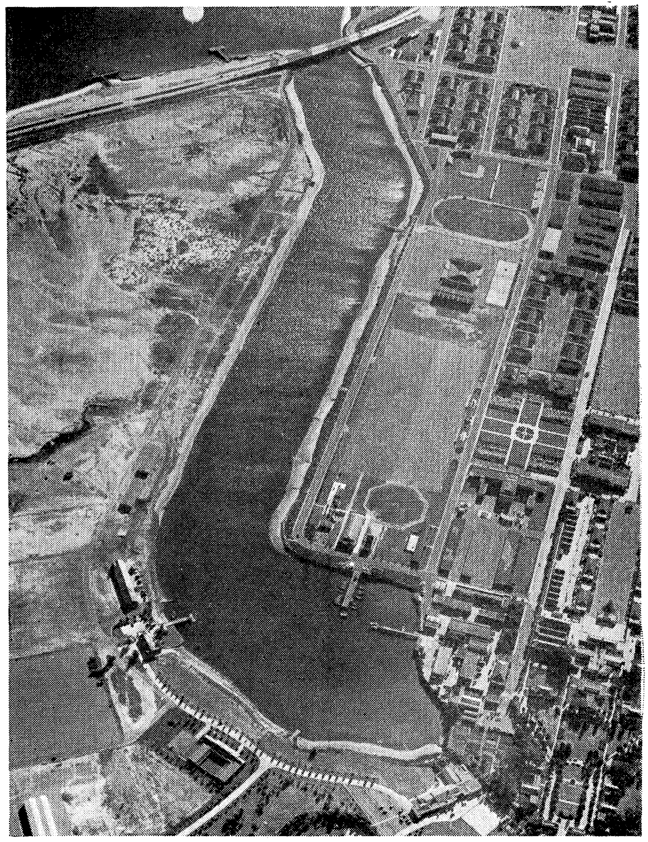


FIG. 8. The San Diego Naval Training Station Estuary used by the Convair Hydrodynamics Laboratory for open-water free-body testing of dynamically similar models.

and distance under all conditions of varying seas, wind, and loading can be determined immediately without recourse to the complicated take-off integral. Perhaps of greatest value, however, is the ability to operate in an environment as natural as nature itself. The towing tank has always presented a problem when evaluation or study of the influence of rough or mixed sea conditions is desired. Inasmuch as an actual seaplane rarely operates in a flat calm, the entire field of typical service operational problems has received but cursory examination. The waves propagated in a towing tank always meet the model head-on, which is the most hazardous and least recommended procedure for landing a full-scale seaplane in rough water. To make matters more difficult, the assisting stiff head wind invariably present in head-on seas of the type generated in a towing tank is not duplicated, which allows the model to encounter these heavy seas with extremely excessive speeds. On the other hand, at the outdoor estuary the gradually rising mid-day and afternoon breeze provides a daily testing period from 3 to 4 hours of flat calm in the morning, for precision laboratory type of testing, to scale head winds of 30 to 40 knots in the early afternoon. By judicious selection of time of day, any degree of full-scale operational conditions may be obtained. Likewise, heading and sea condition may be varied at will. With the desired wind and heading selected, artificial seas of any desired pattern and com-

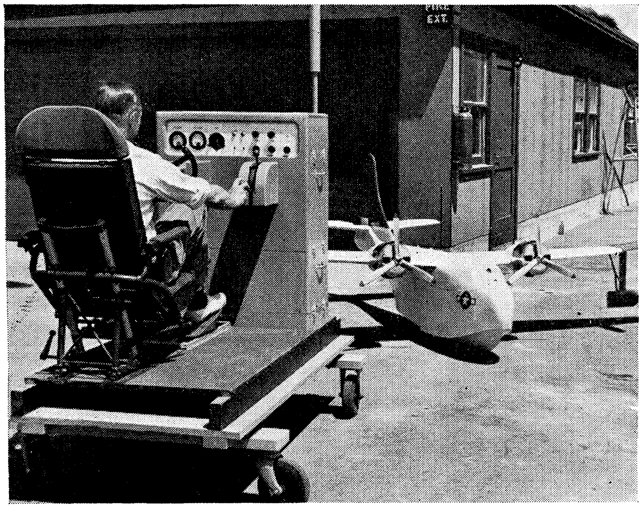


FIG. 9. The $^1/_8$ scale XP4Y-1 radio-controlled model and the seven-channel proportional control transmitter developed by the Convair Hydrodynamics Laboratory.

plexity can be generated in the path of the model by external sources. With the models under remote control and free of all restraint, valuable information can be obtained concerning characteristics most difficult and hazardous to secure full scale and impossible to secure in the towing tank.

There are four basic open-water, free-body research techniques currently being used to develop high-speed water-based aircraft; these will be discussed as follows:

(1) Radio Control.—As stated previously, to take full advantage of the great potentialities of the free-body research technique, it is necessary to have a self-propelled dynamically similar model under the positive control of an operator with an accurate system for recording test data. The precise development of any one of these requirements is a major undertaking when the small available weight and space allowances are considered.

In June of 1943, development was started of a $^1/_8$ scale dynamically similar model of the Convair XP4Y-1 twin-engined flying boat to be remotely controlled by positioning, multichannel radio. Scale requirements called for a gasoline power plant of $1^1/_2$ hp. at 4,250 r.p.m. and not to exceed a weight of 4 lbs. Ohlsson & Rice Manufacturing Company, of Los Angeles, produced this engine in 4 months after date of contract, and the first problem, that of self-propulsion with scale power, was solved.

To attain precision positive control, the Convair Radio Laboratory developed a seven-channel, positioning radio transmitter, lightweight receiver, and associated servomechanisms. The detail technical development of this interesting and elaborate system is fully described in reference 5 and will not be repeated here. With self-propulsion and a precise remote control system available, attention was directed toward developing an accurate phototheodolite tracking and film analyzer system for recording the motions and accelerations of the free body in space. The first completely instrumented, radio-controlled free-flight dynamic model was successfully demonstrated by Convair in August, 1944, just 14 months after initiation of the program. This original model is shown in Fig. 9 and a complete description of its development and correlation with full-scale flight tests and the towing tank is given in reference 4.

Following the successful demonstration of precision free-body control and analysis, a concerted program of research was initiated in an effort to overcome the serious seaplane problems discussed in the introduction to this paper and, once again, to place efficient, high-speed water-based aircraft in the forefront of defense planning. A total of 27 dynamically similar radio-controlled research model configurations were tested to determine the fundamental factors affecting hydrodynamic efficiency. Out of this intensive study came the full development of the remarkable high length-beam ratio hull, which resulted in the Navy's new turbopro-

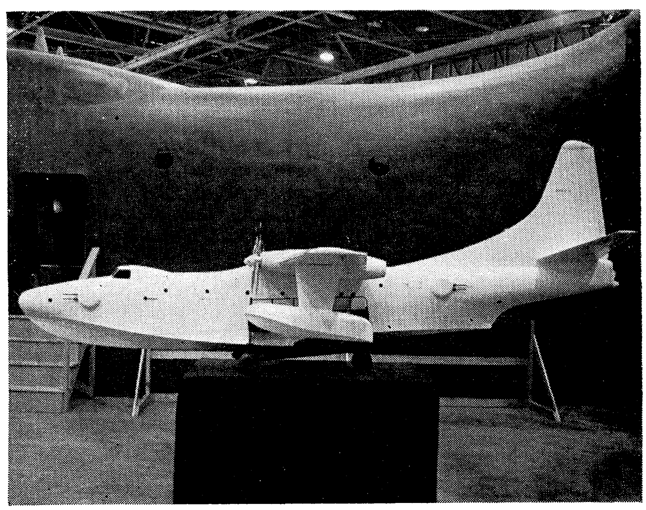


FIG. 10. The $^1/_{10}$ scale XP5Y-1 radio-controlled free-flight model sitting in front of the full-scale mock-up.

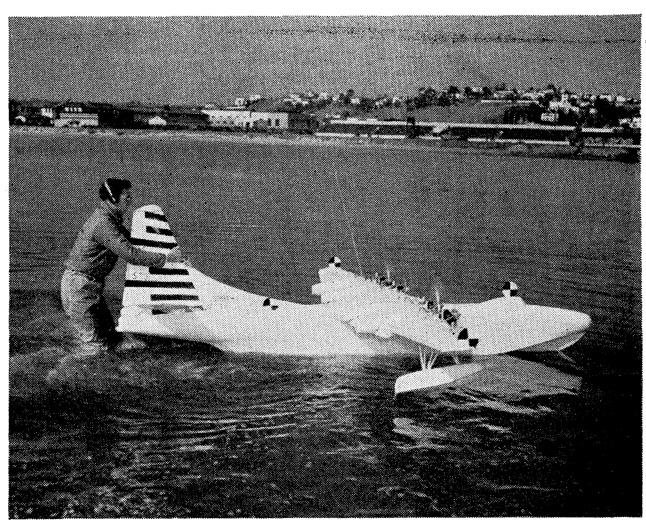


FIG. 11. The XP5Y-1 free-flight model just prior to being released for a self-propelled radio-controlled test flight at the estuary.

peller-powered XP5Y-1 previously discussed and shown in Fig. 2.

The $^1/_{10}$ scale radio-controlled dynamically similar model of the XP5Y-1 is shown in Figs. 10 and 11. This model has made over 2,000 test runs during the past 3 years and has completed the full hydrodynamic flight-test program scheduled for the full-scale aircraft. In addition to performing the functions normally expected of the full-scale aircraft, the model has thoroughly explored régimes, attitudes, and conditions considered far too hazardous to risk human life and costly equipment to investigate during flight testing. Many of these conditions, once investigated by the model, have proved to be satisfactory and thereby serve to enhance the operational safety and utility of the aircraft. Those that fail result in relative minor costs to repair the model, no one is injured, and valuable experience is gained.

Since the first radio-control system was developed in 1944, there have been many improvements in electronic control, recording equipment, and operating technique. For all precise, laboratory-type analysis of straightaway control and stability in calm water, it is now customary to utilize a fast-acting bang-bang type of radio control. As it is desired to accelerate to getaway on a straight course in smooth water with the principal controls treated as independent variables, the elevators, rudder, flaps, and throttles are fixed at their test settings and the bang-bang control is connected to only the ailerons and ignition so that slight corrections to maintain wings level and the "blipping" of port or starboard engines to maintain course are the only variables involved. Just after getaway, all ignition is cut and the run is terminated. For the more elaborate evaluations of seaworthiness, maneuverability, rough-water take-offs, and flight, the original seven-channel proportional control system is used which provides simultaneous precision control of the elevator, rudder, ailerons, and independent throttles, in addition to selective ignition cut-off.

(2) *Catapult Launching.*—While the radio-controlled powered model is used for the majority of conventional hydrodynamic tests, it is not desirable or necessary to employ these elaborate models for routine investigations of landing stability and impact. Through the use of a catapult and open-water conditions, where the heading and air speed relative to the water may be selected to match the conditions under study, the engines and radio equipment can be removed and their weight replaced with more elaborate recording equipment. For these tests the aerodynamic controls are preset prior to each run. Through the use of an accurate velometer to record wind velocity and direction, of calibrated catapult spring tension, and of a little experience in presetting the controls, it is possible to execute precise landings at any attitude and rate of sink within the capabilities of the aircraft configuration being tested.

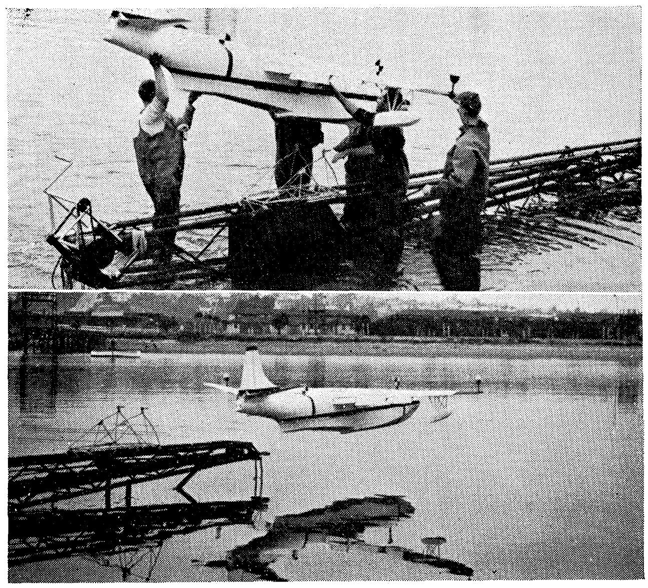


FIG. 12. The XP5Y-1 free-flight catapult model during landing stability tests at the estuary.

Fig. 12 shows a typical catapult launching of the $^1/_{10}$ scale XP5Y-1 catapult model. The equipment shown is a standard 30-ft. A-2 target drone catapult, which is capable of launching a 100-lb. model at a flight speed of 60 ft. per sec. The catapult is portable, and its heading and height above the water may be varied at will. For these tests, the models carry elaborate internal instrumentation, in addition to the phototheodolyte tracking equipment previously mentioned. When the lanyard is pulled, an inertia switch automatically turns on a 16-mm. gun camera mounted within the model. This camera records a continuous record of trim, air speed, relative wind, bow, step and sternpost contact with the water, and impact acceleration. Fig. 13 is a picture of the internal instrumentation installation.

The free-body catapult technique is used to obtain smooth- and rough-water landing stability, aerodynamic ground effect, landing impact, and water-looping characteristics. Here again, particularly in the study of rough-water impact and water-looping, attitudes and conditions that would never be attempted full scale can be thoroughly studied at no risk. Only in this way can the full capabilities of a new design be determined.

(3) *Bridle Tow.*—The bridle tow technique is used to good advantage in all those cases where it is desired to obtain resistance data, position the model close to the observer for detail study, determine preliminary stability and spray information from small survey models incapable of carrying power plants or radio, and constant speed running under controlled conditions. This procedure most nearly approaches the towing-tank method except for the fact that selection of heading, wind, and sea is still available to the operator.

Fig. 14 illustrates a typical bridle tow installation for a small jet-propelled research model. The launch tows the model through the thrust line from the end of

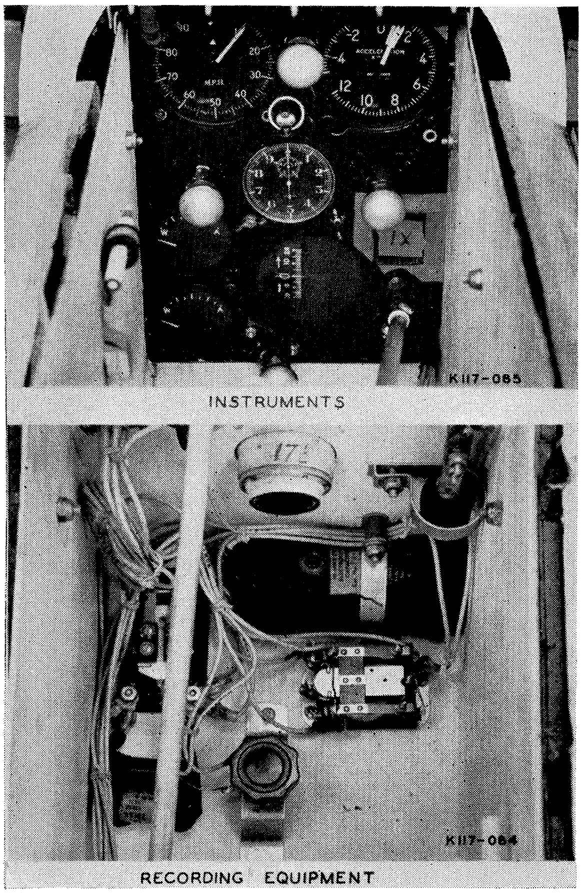


FIG. 13. Internal instrumentation in the XP5Y-1 dynamically similar free-flight model.

a towing boom that contains a resistance dynamometer. The instrumentation box on the launch contains the resistance and water-speed indicators, which are recorded by a camera. Just below the recording instruments, the model being towed is framed in an aperture that allows the image of the model, the shore line, resistance, and water speed to be recorded simultaneously. In this manner, complete trim tracks with a record of spray and resistance at any speed may be determined.

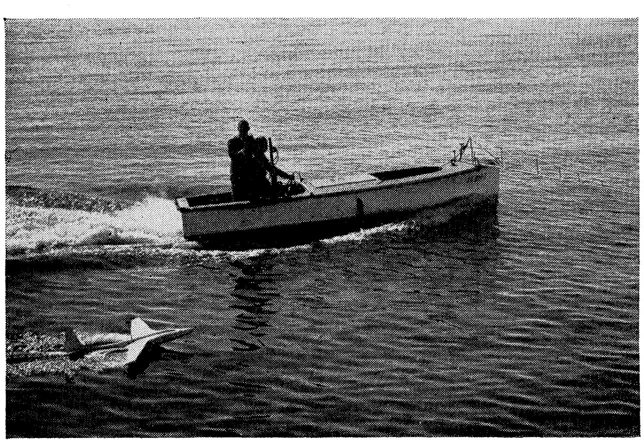


FIG. 14. The bridle tow technique developed by the Convair Hydrodynamics Laboratory for the testing of small unpowered survey models of supersonic water-based aircraft prior to self-propelled tests.

Also, the condition of the sea at the moment is permanently recorded for future reference or evaluation. This system is extremely versatile and is used extensively during early survey investigations of a radical new design prior to constructing the large and more elaborate powered models.

(*4*) *Free Launch.*—The testing procedures discussed thus far have dealt primarily with gasoline engine propeller-driven models or models containing no power plants at all, such as the catapult and bridle tow techniques. To date, no large jet-propelled radio-controlled models have been tested comparable to the large propeller-driven types previously discussed. This is due to several causes: (1) suitable jet units for producing sufficient scale thrust have not been available; (2) the study of jet-propelled water-based aircraft is so new and the problems so diversified that emphasis has been put on a large number of small survey models in an effort to establish basic design criteria; and (3) the inherently greater speeds of the jet-propelled aircraft have posed the tremendous problem of speeding up pilot and servo reaction times beyond the point that is now critical. It will be recalled that, in dynamic similarity, time varies as the square root of the scale, so that on a $^1/_{10}$ scale model events occur roughly three times faster than the equivalent full-scale event. Operation in confined areas with extremely fast aircraft rapidly multiplies the problems of control reaction.

It was inevitable, however, that, if water-based aircraft were to keep pace in the aviation field, means to obtain powered dynamically similar research data, comparable to that being secured on conventional-type seaplanes, must be developed. The first step in this direction was the availability of an efficient, lightweight pulse-jet engine. Aeromarine Company of Vandalia, Ohio, produces such engines in $4^1/_2$ and 30 lbs. of thrust per unit ratings. For additional versatility, the $4^1/_2$-lb. thrust units may be manifolded together to produce an $8^1/_2$-lb. thrust unit.

With suitable power plants available, detailed studies of the many mounting, manifolding, cooling, and associated problems were started. Obviously, it was desirable to check out these many jet-power development problems with as small and economical a model as possible in view of the attrition rate anticipated. It was at this point that the free launch technique was evolved. It was reasoned that excellent results are attained from catapult launchings with preset controls and that with the accelerations anticipated the take-off run would closely approximate a catapult launching. In the original attempts at free launch, the fuel was metered closely, and progressively longer bursts were permitted as the trim and balance of the model proved satisfactory. This technique resulted in some exciting, inadvertent uncontrolled take-offs and climbs to high altitudes when combinations of factors became ideal; and, as a consequence, a light, single-channel, radio-controlled fuel shutoff had to be developed. This shutoff mechanism was so light that it could be easily installed in small 15-lb. models utilizing a pair of $4^1/_2$-lb. thrust units for propulsion. This complete installation, including radio, fuel tank and cutoff, and a pair of engines, is shown in Fig. 15.

Subsequent testing with the single-channel control of fuel shutoff has proved so successful that the free launch technique has become a standard test procedure, in spite of the fact that it was originally a temporary measure to expedite the development of jet power in free-body models. Completely satisfactory runs can be made up to getaway, and in many cases short straightaway flights may be accomplished in complete safety to the model. Inasmuch as the speed and acceleration of the towing launch is limited, this free launch procedure allows the survey studies of small models to be carried out to high planing speeds and actual getaway. When the larger jet-propelled models are constructed, it is likely that free launch techniques will be used with, possibly, the addition of aileron control and that the weight saved will be put into internal instrumentation.

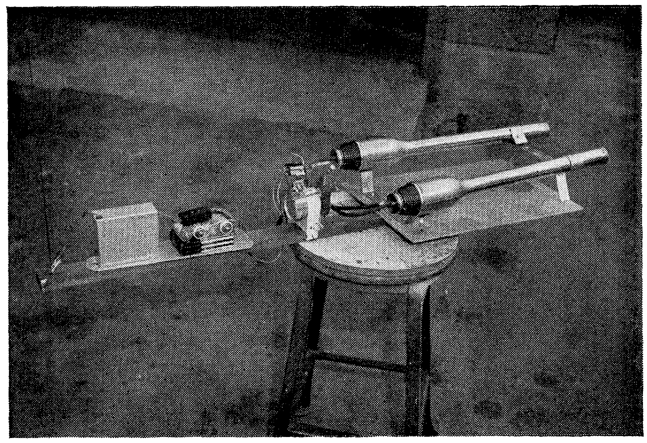


FIG. 15. The radio gear and power-plant installation for self-propelled radio-controlled models of jet-powered water-based aircraft.

Experimental Research

It has been pointed out in this paper that the introduction of the dynamically similar model and its associated research techniques has been responsible for breaking the period of passive development in the water-based aircraft field. This has been accomplished by supplementing design criteria established by the rule of thumb and gradual process of experience by full-scale trial and error, with fundamental information obtained from a direct experimental approach where all of the parameters affecting hydrodynamic performance and efficiency appear as configuration or test variables subject to evaluation and accurate study. While many new design criteria have been established since introduction of the dynamically similar research technique, it is not within the scope of this paper to present each study in detail. Rather, it is believed more desirable to discuss at some length the several broad basic concepts that contributed the most toward the radical resurgence of water-based aircraft.

Hull Loading

The load that must be supported by a flying boat hull or seaplane float is probably the most fundamental variable in the design of a water-based aircraft, since it fixes the basic overall size of the hull. This corresponds to the selection of the basic wing area for a new airplane design. As you recall, the wing area required is fixed by the maximum lift (or load) coefficient that can be attained and the landing speed desired. In effect, this determination is strictly a low-speed, maximum load-carrying criterion and is largely independent of the high-speed characteristics of the aircraft in question. As a matter of fact, as much research effort and expense has been devoted to developing the low-speed load-carrying ability of wings as any other phase of aerodynamic investigation. The analogy between basic hull size and wing area selection is interesting, inasmuch as both are a measure of the maximum load-carrying ability at the lowest speed where sustention is by dynamic forces. In the case of the hull, this speed occurs in the transition region between displacement and planing and is known as the hump. Just as aerodynamic stability and control reach a critical value near the stall and must be considered in the final selection of aerodynamic configuration, so do hydrodynamic stability and control reach their most critical values in the region of the hump. In addition, the water-based situation is further complicated by the generation of gravitational wave systems that reach their peak intensity in this region. The bow wave and spray produced often limits the loading to a value much lower than theoretically possible because of physical inundation of power plants and cockpit enclosures. It can be seen that the major problem facing the seaplane designer in his effort to make radical improvements in seaplane efficiency was to increase hull loading materially while at the same time to suppress the spray formation and maintain adequate stability. As mentioned previously in our discussion of Froude Number, these critical low-speed functions lent themselves admirably to investigation by dynamically similar models.

In hydrodynamic analysis, the hull loading is expressed in terms of the nondimensional load coefficient C_Δ, which is based on the hull beam as the characteristic dimension and is equal to Δ/wb^3, where Δ is the load on the hull in pounds, w is the density of water in pounds per cubic foot, and b is the maximum hull beam in feet. As the load on a hull continually varies with speed, due to the varying proportion of load carried by the wing, it is customary to compare hulls at their static load coefficient $C_{\Delta_0} = \Delta_0/wb^3$, where Δ_0 is the total gross weight of the airplane.

Up to and including the seaplanes in general use during World War II, the ratio of the length of the hull to

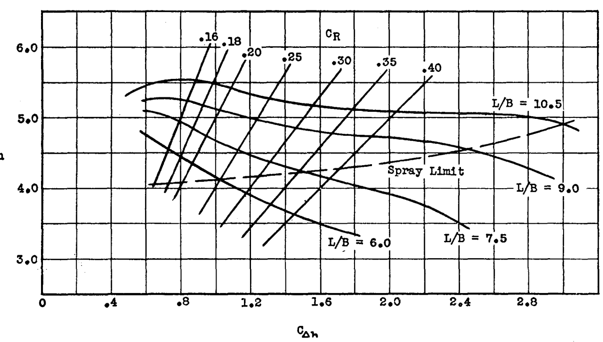


FIG. 16. Influence of length-beam ratio on the hull load and load-resistance ratio at hump speed. (Hydrodynamic effect of length-beam ratio; 25° deadrise.)

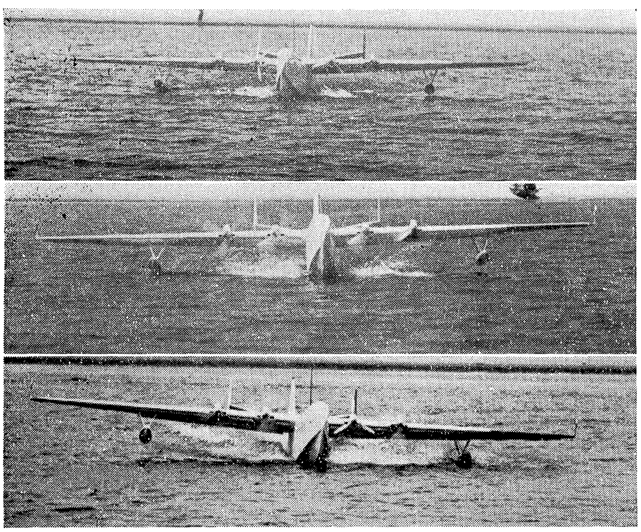


FIG. 17. The 21-ft. span powered dynamic research model from which the XP5Y-1 high L/b hull was developed. Note procedure employed for determining influence of power on spray.

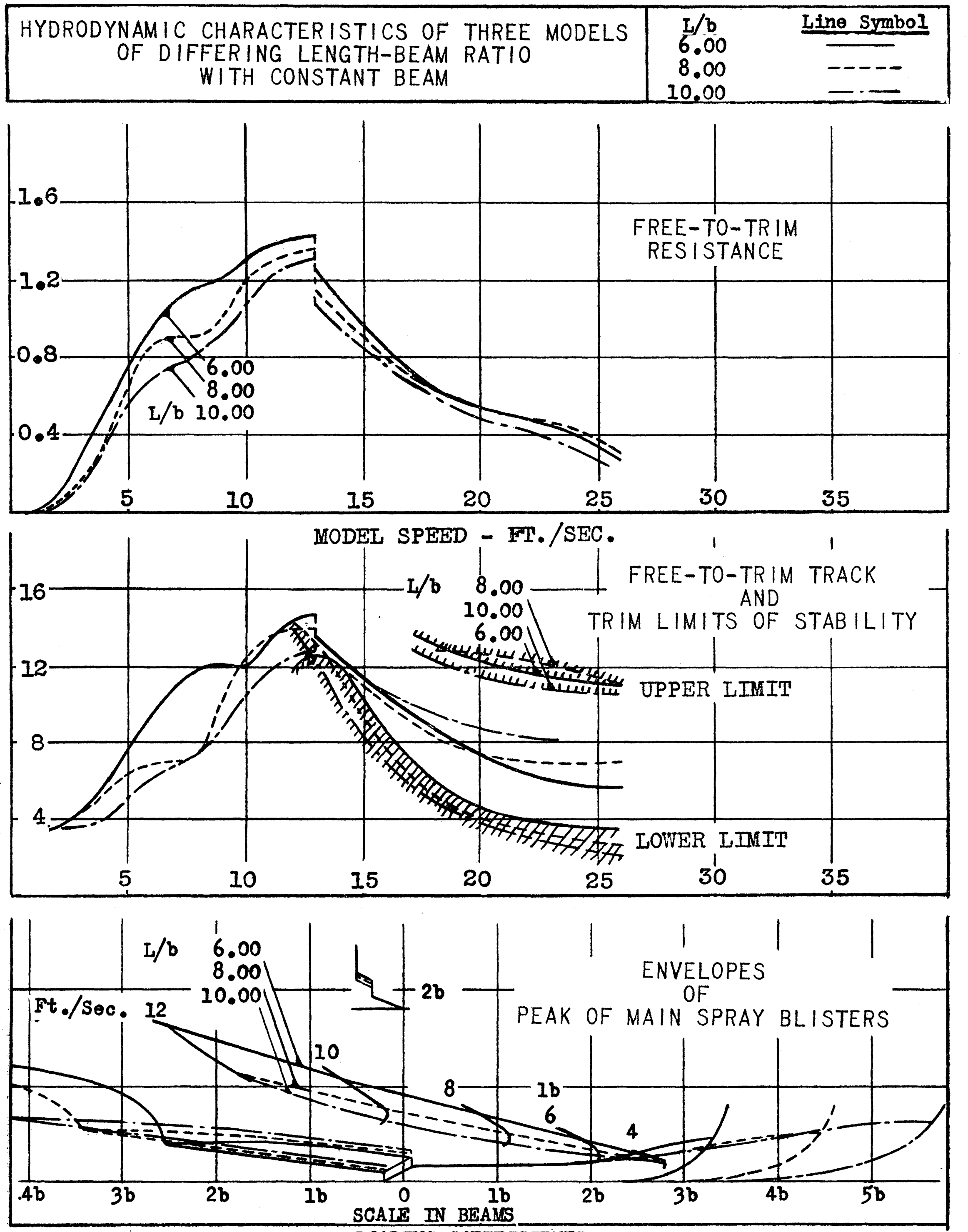
the beam was usually between 5.0 and 6.0, and it was well established that for such proportions it was valid to use C_{Δ_0} as a basis for loading comparison, regardless of size. In other words, any two seaplanes having the same general proportions of length and beam generally had the same hydrodynamic characteristics if the values of C_{Δ_0} were equal. Over a considerable period of years, experience had indicated a range of load coefficients to which could be assigned certain general characteristics of operation. For example, it was established that, for exceptionally good seaworthiness, short take-off time (low resistance), and clean running, a beam should be selected which gave a static load coefficient of not over $C_{\Delta_0} = 0.65$. Likewise, it was generally accepted that the upper limit of hull loading was around $C_{\Delta_0} = 1.0$.

To select the beam for a contemplated design, the designer had a choice, therefore, between these limits of load coefficient. With the condition of the ratio of length to beam more or less constant, it was established by experience that, increasing the load coefficient, (a) increased the trim and resistance at hump speed, (b) increased the height and intensity of the spray, (c) decreased the range of hydrodynamic stability during take-off, (d) had little effect on landing stability, (e) decreased low-speed maneuverability and control, and (f) reduced air drag by reducing the size of the hull relation to the load. Item (b) or (e) usually determined the maximum load that was practical for the design in question.

Length-Beam Ratio

As discussed in the introduction to this paper, the first promising approach to the problem of loading was revealed in the reports covering the experiments conducted by the Germans on high length-beam ratio hulls.[2, 3] In aerodynamics, one of the fundamental measures of efficiency of a wing is the L/D or ratio of lift to drag. In hydrodynamics, this applies to a hull as well and is the ratio of load supported to the resistance, or Δ/R. A cross-plot of the German data, where the Δ/R at the hump, for various values of length-beam ratio, was plotted against hull load coefficient, showed the remarkable trend reproduced in Fig. 16. On this curve has been plotted the maximum spray limit considered acceptable by the Germans, and it is interesting to note the great area available for improvement in loading and Δ/R over the upper limit of conventional seaplane practice represented by the $L/b = 6.0$ curve. It appeared from study of these data that increasing length-beam ratio materially reduced the energy going into the parasitic gravitational wave-making system. This, in turn, reduced spray and resistance, both factors being conducive to higher allowable loadings.

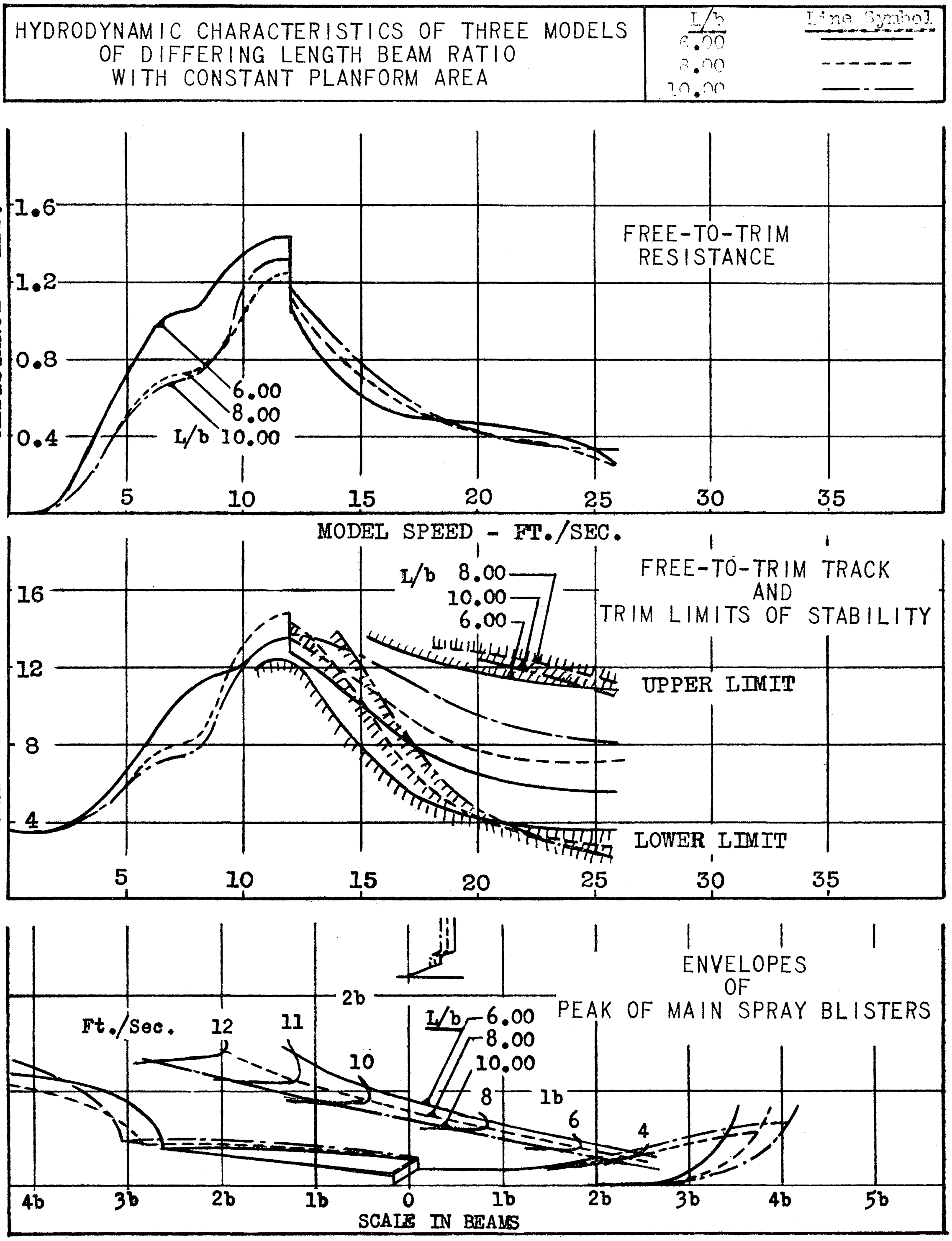
As these data dealt primarily with the effect of length-beam ratio on resistance, with the inference that spray reduction would also be realized, it was apparent that many more data, particularly regarding quantitative results of spray and stability, were required before correlated design parameters could be established. A broad research program consisting of a family of 21 dynamically similar model configurations, covering length-beam ratios of 6, 8, and 10, was initiated simultaneously by Convair, using free-body radio control, and Stevens Institute, employing the Stevens' method. The radio-controlled model with an L/b of 10.0 hull installed is shown in Fig. 17. These tests confirmed the fact that length-beam ratio has a powerful influence on the allowable magnitude of C_{Δ_0} which may be used and still maintain satisfactory spray. It was found also that, as the L/b ratio increases, the limiting value of C_{Δ_0} increases in direct proportion to the function L^2b, resulting in a smaller beam and, hence, overall size of hull for a given load. This was a fundamental finding of immense importance, for it established the fact that hulls of varying length-beam ratio will have equivalent resistance and spray characteristics if a load coefficient similar to C_Δ, but based on L^2b instead of b^3, is held constant. Dr. Davidson, of Stevens Institute of Technology, first presented this relationship[6] and calls this coefficient K_2, which is equal to Δ/wL^2b. Figs. 18(a–c)



LOADING COEFFICIENTS

L/b		6.00	8.00	10.00
C_{Δ_0}	(Constant)	1.00	1.00	1.00
$K_{3/2}$		0.068	0.044	0.032
K_2		0.028	0.016	0.010

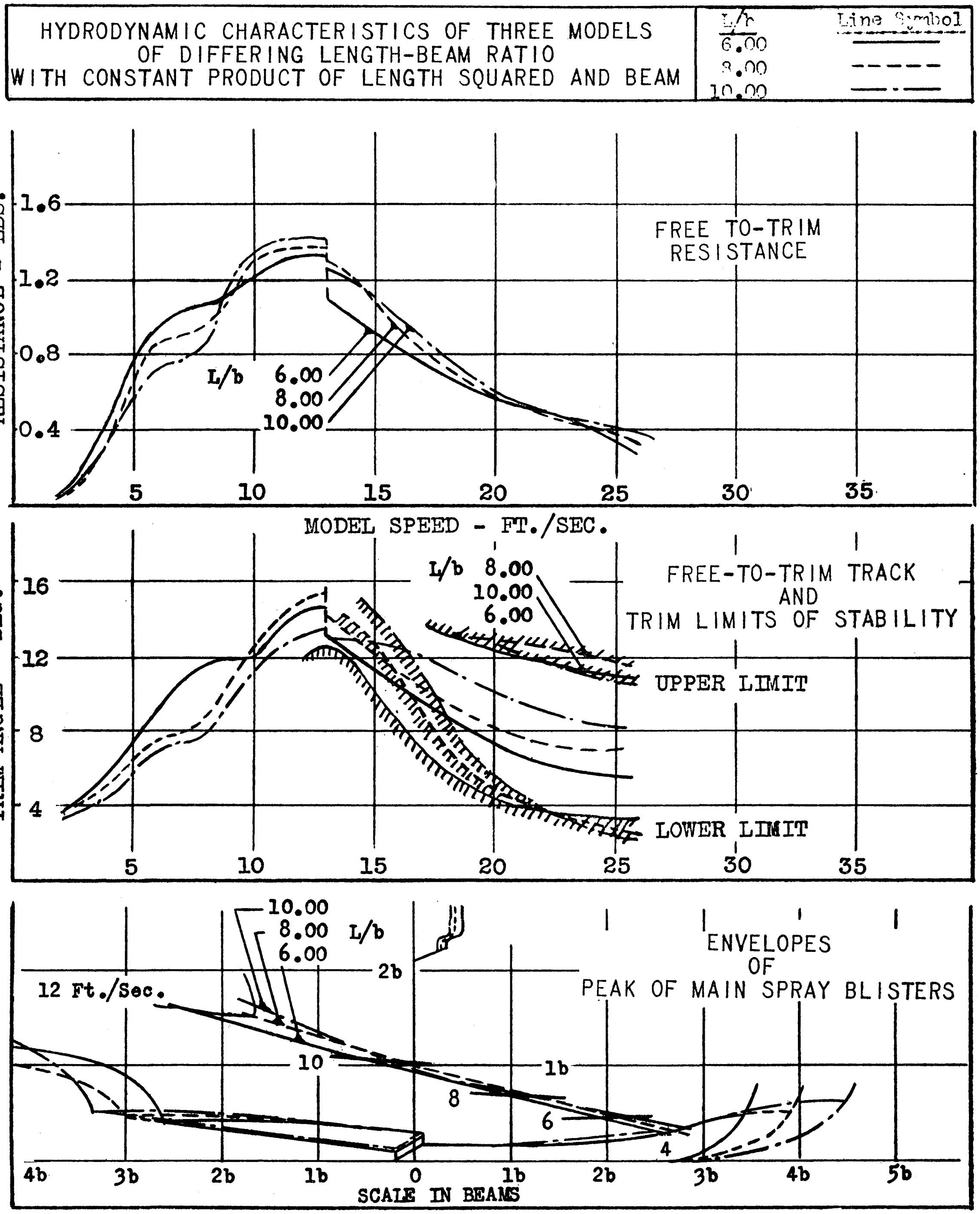
FIG. 18a. Influence of length-beam ratio on loading, resistance, stability, and spray while maintaining constant beam. Length increased by proportional increase in transverse section spacing along the keel.



LOADING COEFFICIENTS

L/b	6.00	8.00	10.00
C_{Δ_0}	1.00	1.54	2.15
$K_{3/2}$ (Constant)	0.068	0.068	0.068
K_2	0.0277	0.0241	0.0215

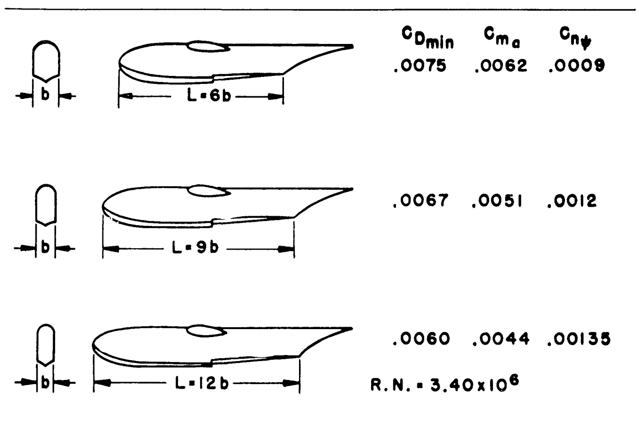
FIG. 18b. Influence of length-beam ratio on loading, resistance, stability, and spray while maintaining constant plan-form area (Lb = constant).



LOADING COEFFICIENTS

L/b	6.00	8.00	10.00
C_{Δ_0}	0.72	1.28	2.00
$K_{3/2}$	0.049	0.057	0.063
K_2 (Constant)	0.020	0.020	0.020

FIG. 18c. Influence of length-beam ratio on loading, resistance, stability, and spray while maintaining the product of (length)^2 $\times$ beam constant (L^2b = constant).



NACA LENGTH BEAM RATIO SERIES AND AERODYNAMIC RESULTS

FIG. 19. Influence of length-beam ratio on aerodynamic characteristics from the N.A.C.A. high L/b hull series.

summarize the results of this fundamental finding which first established a definite design relationship between the influence of length-beam ratio and physical hull size.

Fig. 18a shows the academic relationship of load, resistance, spray, and stability versus length-beam ratio where the beam is held constant and the length is increased by a proportional increase in station spacing along the keel. Here, it will be noted that marked reductions in spray and resistance are realized as the length increases, indicating that the higher length hulls can carry much more load; or, for constant loading, the size can be reduced while maintaining constant resistance and spray. In an effort to determine how much the load can be increased or the size reduced with increasing length-beam ratio, a comparison is made in Fig. 18b where the hull plan-form area is maintained constant as the L/b varies. Here again, the length is varied by proportional increase in hull spacing, while the beam is decreased at the same time to maintain plan-form area constant. It will be noted that the relationship is still conservative, indicating that further increase in load, or less size, can be tolerated for equivalent resistance and spray.

In Fig. 18c we find the relationship previously mentioned where the product of L^2b is maintained constant. Resistance and spray are observed to collapse substantially to a common curve, regardless of length-beam ratio, when compared at a constant value of the K_2 load coefficient proposed by Davidson. By studying the relations presented in Figs. 18a, 18b, and 18c, it can be noted that the influence of the planing bottom length has been progressively weighed against the effect of the beam. It is also apparent that, in the case of constant plan form, increasing length-beam ratio would maintain a hull of constant volume and decreasing frontal area, whereas, using the L^2b relationship, which has now been completely substantiated by all research facilities, a progressive decrease in hull volume, in addition to a rapid decrease in beam required, is made possible. This latter characteristic is of considerable importance from an aerodynamic standpoint, as indicated in Fig. 19, where it is noted that there is a 20 per cent reduction in hull drag in going from a length-beam ratio of 6.0 to 12.0.

To assist the designer in the selection of a beam for a new design and to establish clearly the interrelationship of loading, seaworthiness, and size, the selection chart of Fig. 20 has been prepared. This chart gives the relationship of static load coefficient (C_{Δ_0}) to length-beam ratio for equivalent hulls based on the L^2b or K_2 standard of loading. The introduction of this relationship between length and beam is of extreme importance to the designer, since a knowledge of its effects on the hydrodynamic characteristics of a hull permits greater choice in size and shape of hull to arrive at optimum dimensions to satisfy a particular design specification. Also, it permits data obtained on any one hull of a family to be expanded to any other hull of which it is a parent. It will be noted in Fig. 20 that certain values of K_2 have been assigned their characteristic influence on spray height; this characteristic, we have noted, is the fundamental loading design criterion. In the initial stages of a design, a value of $K_2 = 0.018$ should be assumed and a value of $K_2 = 0.022$ should never be exceeded, since the design loading of a new seaplane invariably increases somewhat as the design progresses.

It should be pointed out that, in addition to obtaining a much smaller and cleaner hull aerodynamically, increasing L/b ratio at constant K_2 will materially reduce the hull weight because of reduction in hull volume and beam. Structural studies[7, 8] indicate that this weight trend continues up to a L/b ratio of approximately 15.0 or slightly higher. With further increase in L/b ratio, the hull bending moments become increasingly higher because of the added length of hull, and this trend begins to reverse. Just where this reversal occurs and how rapidly it will build up depend upon many functions related to the specific design. It is interesting to note that increasing length-beam ratio from 6.0 to 12.0 has resulted in reductions as high as 8 per cent in structural weight of the hull for equal performance.[8]

Forebody Proportion

Throughout this discussion of the parameters affecting hull loading, the conventional standard of using the overall length of the planing bottom, which includes both forebody and afterbody, is employed to determine the L/b ratio of the hull. It is important to note, however, that the forebody is the principal load-carrying portion of the hull and that in many respects it bears the most direct analogy to the wing of an airplane, being responsive to unit loading, proportion or aspect ratio, pressure distribution, and section. Being a surface that derives its lift from operation on the surface of a medium, it depends upon those dynamic forces that normally act on the lower surface of a wing at a finite angle of attack rather than the fluid circulation resulting from total submergence in a fluid. In spite of the loss of lift due to absence of circulation, the fact that it is operating in a fluid of approximately 800 times the density of air results in extremely great lift for nominal area. As a consequence of the high density of water and resulting high unit pressures, release in energy at the boundaries of the surface creates violent turbulence in the form of waves and spray; this must be controlled. As spray is the principal characteristic influencing the load that may be carried and since this characteristic is fundamentally a low-speed function, where the forebody wetted length is a maximum, it is reasonable to assume that it is the length of the forebody that furnishes the predominate influence in the overall length-beam ratio of the hull.

This assumption was investigated by Parkinson,[9] of the N.A.C.A., by correlating all existing full-scale and model information with respect to forebody fineness. Parkinson's analysis indicates that, when the static load coefficient, C_{Δ_0}, is plotted against forebody length-beam ratio, L_f/b, on a logarithmic scale, seaplanes having similar spray characteristics lie along straight lines having equations of the form $C_{\Delta_0} = k(L_f/b)^2$, where k has the following values:

Excessive spray	0.0975
Heavy, but acceptable for overload	0.0825
Satisfactory for normal operation	0.0675
Extremely light spray	0.0525

It will be noted that Parkinson's k is of the same order as Davidson's K_2, shown in Fig. 20, indicating that the factor L^2b is the correct fundamental characteristic for comparing equivalent hulls.

Most successful seaplane designs have incorporated a forebody length that varies from 55 to 60 per cent of the total planing bottom. Variations greater than this range have not proved entirely satisfactory, particularly from a stability standpoint. Research has shown that, where the above proportions of forebody and afterbody are maintained, either Davidson's K_2 or Parkinson's k will give substantially the same design load criterion. There has been a strong trend in modern seaplane research to separate the forebody and its functions from the afterbody and to treat these basic planing surfaces separately. This line of attack has resulted in the development of the planing tail and long afterbody form of hull. These types have shown some promise

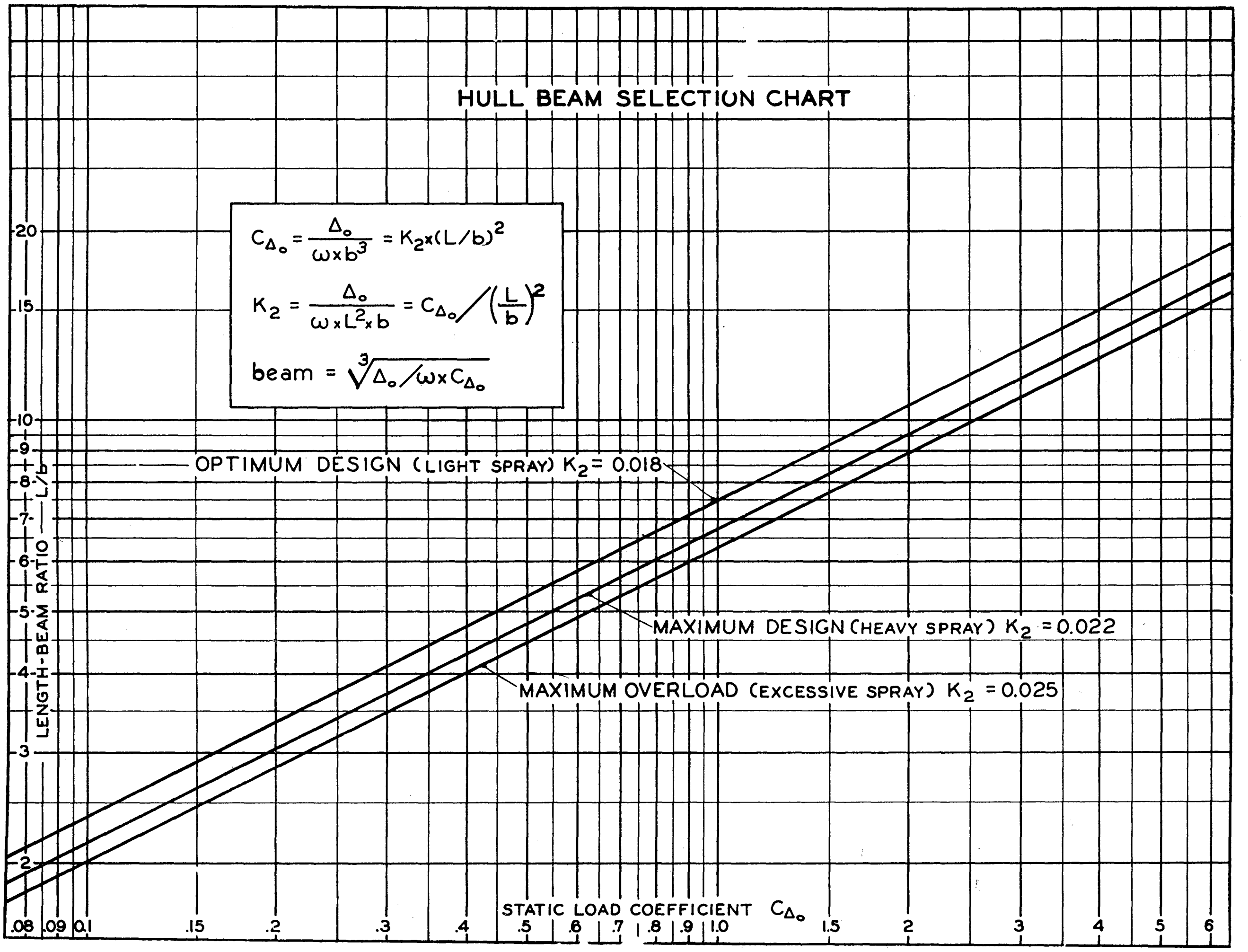


FIG. 20. Hull beam selection chart giving the relations between length-beam ratio and load coefficient for constant values of K_2 (L^2b = constant).

with regard to certain specific characteristics; however, evidence has shown that there are sufficient numbers of interdependent parameters to preclude the listing of completely independent criteria. While rigorous procedures for such a segregation may be developed in time in the laboratories, it is desirable for the designer to think of the planing bottom as a coordinated unit and to use the overall K_2 as a load criterion. He should keep in mind that, when comparing the load capacity of hulls of abnormal afterbody proportion, the additional length of afterbody over and above standard proportions contributes nothing to the characteristics that have been attributed to length-beam ratio in this paper. This is justified by the fact that it is the forebody that carries the load and generates the wave system, while the afterbody is merely a trimming device and the longer afterbodies are invariably set at a higher afterbody keel angle so that their effectiveness is still just the equivalent of the standard shorter afterbody. Serious inconsistencies will result if the total length of these abnormal hulls is used to determine the hull's L/b ratio for comparison with standard forms.

The selection chart of Fig. 20 has been set up for the standard hull proportion. For hulls of abnormal afterbody length, an equivalent length-beam ratio, L'/b, must be employed in all cases where length-beam ratio is used as a standard of comparison. The effective planing length, L', is the length that would result when the forebody of the hull in question is assumed to be 58 per cent of the total length, as in the expression $L_f = 0.58L'$, where L_f is the actual forebody dimension and L' is the total effective length for comparative purposes.

All of the parameters discussed thus far in this section have dealt with the fundamental problem of increasing the load-carrying capacity of a hull. Earlier in our discussion of hull loading, we found that, for years, established practice had dictated a design static load coefficient of $C_{\Delta_0} = 0.65$ with an absolute maximum of $C_{\Delta_0} = 1.0$, above which any further loading would increase resistance, spray, instability, or lack of maneuverability to unsatisfactory values. From our study of Fig. 20 we see that, through the results of dynamic model research, the powerful influence of length-beam ratio as a basic design parameter has made available to the designer as much as 300 per cent increase in this critical value with no loss of hull efficiency or seaworthiness.

Hydrodynamic Stability

Established design criteria, prior to the introduction of high length-beam ratio as a fundamental parameter, indicated that increasing the static load coefficient beyond a $C_{\Delta_0} = 1.0$ would increase trim, resistance, spray, and instability to unacceptable values. We have seen from Figs. 18 and 20 that, through the introduction of length-beam ratio as a basic design parameter, the major problem of greatly increased hull loadings was impressively solved with an actual overall improvement in trim, resistance, and spray. Stability, however, has been another story and has been purposely overlooked so far in this discussion because of the specialized research programs required for its solution. In returning to Figs. 18, it will be noted that, while resistance, spray, and trim could be controlled by appropriate length-beam ratio for a given increase in loading, the lower trim limit of stability increased rapidly, with any increase in loading, to values that would not permit a stable take-off to be made. During the early phases of length-beam ratio research, this persistent deterioration of stability promised to nullify all other gains in this development. Conventional hydrodynamic stability had been none too good, and it was desirable to improve this characteristic; further compromise with stability could not be tolerated.

To review for a moment, it will be recalled that, during the take-off of a seaplane, after it has passed the hump speed, the planing trim must remain between two limiting curves of trim or it will encounter instability known as "porpoising." Porpoising is a cyclic oscillation in pitch and rise, and, if allowed to persist, it may become divergent and result in destruction of the seaplane. These limiting curves are shown in Figs. 18 and consist of an upper and lower limit of trim, versus speed, between which the aircraft will be stable. It has been established that the upper trim limit is dependent upon, and is a function of, the afterbody form and position. The lower limit depends upon forebody lines. To satisfy the stability requirements for take-off, the designer must provide an adequate range of stable trims to accommodate the normal trim range of the hull when operating anywhere within the design range of center-of-gravity loading, flap, and elevator position. If the trimming moment available between the limiting curves is not sufficient to accommodate all normal operation conditions, the aircraft must be placarded for limited operation or modified to broaden the limits. It is obvious that the critical condition for upper limit is with maximum aft center of gravity, flaps up, power off, and up-elevator—or, in other words, conditions that produce a bow-up moment and, hence, high trim. Conversely, lower limit is critical for conditions that produce bow-down moments. Inasmuch as low trim is desirable from a resistance and spray standpoint and the take-off conditions of high power and flap deflection produce strong bow-down moment, the lower limit is of major importance during the heavily loaded take-off run. As we have noted, the lower limit of trim increases steadily to higher trims with increase in loading, which is directly opposed to the desired trend. It was found in the past that only moderate increases in loading raised the lower trim limit to such an extent that it was found necessary to reduce flap and limit the forward range of center-of-gravity position in order to take off. This, in turn, increased the resistance and left little up-elevator control available, which further decreased the load-carrying ability of the aircraft.

With the large increases in loading made available through the employment of high length-beam ratio, this trend approached intolerable proportions, which indicated that a stable take-off would be impossible. Inasmuch as the forebody of the hull determines the position and form of the lower trim limit, an extensive research program was initiated in an effort to isolate the forebody design parameters associated with lower limit stability. All there was to go on at the start of these studies was the knowledge that for satisfactory planing stability the forebody contacted by the water during planing must be free of all longitudinal curvature. At speeds just beyond the hump, where lower limit porpoising is most likely to be encountered, this wetted length had been found to extend approximately one and one-half beams forward of the step. As a consequence, it had been rigid design practice to maintain an area of constant deadrise for approximately one and one-half beams forward of the step. This region was commonly called the "forebody flat."

It will be recalled that, when the first families of hulls of increased length were investigated, the hulls were lengthened by proportionate increase in spacing between the transverse stations of a good low-length parent hull. This was an obvious method and was believed to be sound inasmuch as the flat was rigidly maintained, and actually lengthened, by this procedure. It was noted, however, that the static trim of these long hulls was increasing to extremely high values, indicating that the buoyant power of the forebody was increasing at a greater rate than the afterbody. In an effort to reduce this power by reducing the volume through increased deadrise forward of the step, it was found that the lower limit of stability also improved with reduced forebody effectiveness. In attempting to bring the lower trim limit down by cutting further back into the flat with increased deadrise, curvature was introduced and improvement ceased.

With this new trend to work on, it gradually became apparent that, while longitudinal curvature must be eliminated from the planing bottom ahead of the step, this need not be accomplished by maintaining a constant transverse section but could be a warped surface of varying deadrise so long as the longitudinal elements of this surface were straight lines for one and one-half beams forward of the step. Upon establishing the basic fact that the trim at which lower limit instability is encountered is dependent upon the linear rate of change of deadrise, or forebody warping, in the planing area, it became a relatively simple procedure to set up design criteria that would provide adequate stability for the various combinations of length-beam ratio and loadings previously established. Fig. 21 gives the linear variation of deadrise forward of the step in degrees per beam of forebody length required to give adequate lower limit stability for various forebody lengths. The degree of

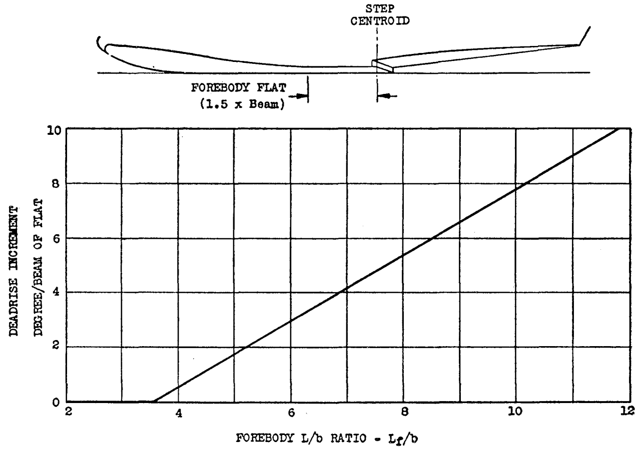


FIG. 21. Linear variation of deadrise forward of the step in degrees per beam of forebody length to maintain lower limit stability with increase in length-beam ratio.

warping given in Fig. 21 extends for only one and one-half beam-lengths forward of the step, at which point the buttock lines may then curve as gradually as possible to the deadrise required at the bow for the suppression of spray.

It will be noted in Fig. 21 that for a forebody L_f/b ratio of 3.5, which corresponds to an overall L/b ratio of approximately 6.0 for a hull of conventional proportions, the forebody flat has a zero rate of warp in degrees per beam, resulting in a flat area of constant deadrise which conforms to the old rule-of-thumb concept.

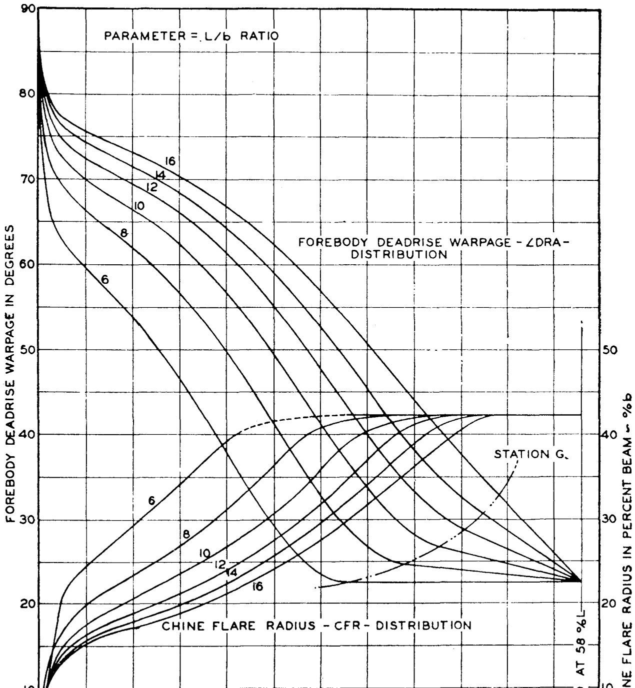


FIG. 22. Design chart for a family of hull forebodies of varying L/b ratio designed to give equal stability and spray for constant values of K_2 (L^2b = constant).

However, for all L_f/b ratios greater than this value, the gradual increase in warping, to maintain equivalent lower limit trim, results in no region of constant forebody deadrise. These criteria have been incorporated into the plot of Fig. 22 which shows the forebody deadrise variation for a typical family of hulls of varying length-beam ratio and standard proportion of forebody to afterbody. The dashed curve, labeled "Station G" in Fig. 22, represents the one and one-half beams of forebody flat or linear warp that must be free of longitudinal curvature. It is apparent that, because of the long forebody flat required for the lower L/b ratios, it is difficult to warp the bottom to the high sharp lines required at the bow without utilizing rapid buttock curvature. As the L/b ratio increases, it becomes increasingly easy to obtain the deadrise angles of the order of 70° to 80° at the bow which are desired from a seaworthiness and low bow buoyancy standpoint. It is this easing of the forebody lines with increasing length which results in the major increases in performance attributed to high L/b ratio hulls, and the proper use of linear warp will assure this performance without loss of stability.

It was stated earlier in this paper that no attempt would be made to cover the entire scope of research investigations since the advent of dynamic model testing. These detailed findings are adequately reported in applicable scientific literature and do not warrant repetition here. However, the discussions of increased hull loading contained herein are believed to be of such fundamental importance that any other studies may be classified as refinement and extension to this basic concept of modern hull design. Through the application of the broad design criteria summarized in Figs. 20 and 21, we find the water-based aircraft potential suddenly expanded many times. While detailed exploration and refinement will continue unabated, the foundation for a revitalized program of modern high-speed seaplane development is well established.

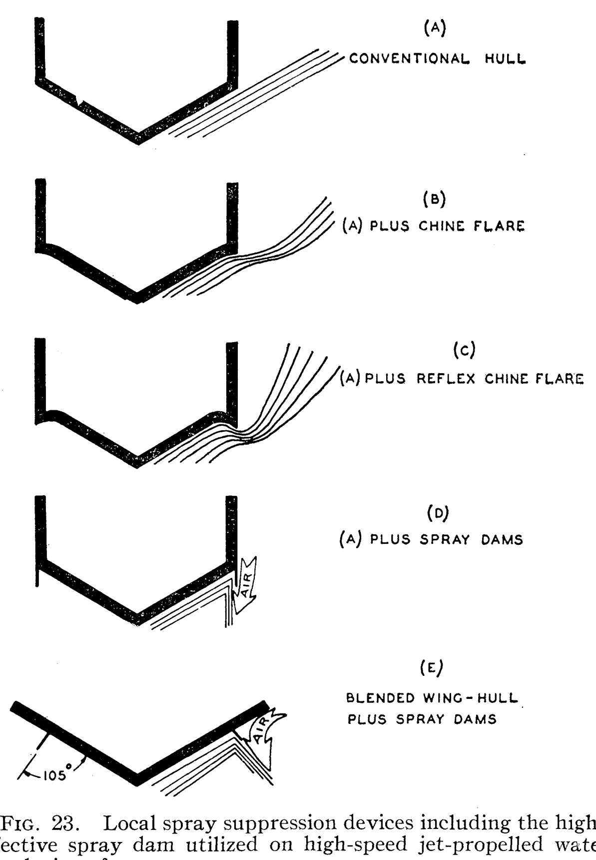


FIG. 23. Local spray suppression devices including the highly effective spray dam utilized on high-speed jet-propelled water-based aircraft.

Spray Control

During the course of the research investigations that have been discussed thus far and prior to the realization of the full impact that the high length-beam ratio studies would have on the course of seaplane design, many other approaches to the problems confronting water-based aircraft development were initiated. Inasmuch as excessive quantities of drenching spray was the principal factor restricting the loading of conventional seaplanes, the major effort was directed toward the development of improved spray suppression devices. Even though these studies proved to be of little value at the time and were eventually dropped in favor of full exploitation of the much more promising influence of length-beam ratio, one development during this period was found much later to have a most profound influence on the future course of transonic and supersonic water-based aircraft. For this reason, it is appropriate to discuss briefly localized spray suppression.

A conventional "V" bottom planing surface, such as shown in Fig. 23(A), is not satisfactory for a seaplane hull due to the great height to which the spray climbs upon leaving the chine; therefore, most conventional hulls have incorporated some form of transverse curvature in the bottom called chine flare, as indicated in Figs. 23(B) and 23(C). The most effective control through the use of flare is obtained by a generous radius that terminates with a horizontal or slightly downward direction at the chine, as shown in Fig. 23(B). If a radius that is too small or abrupt is used, only the layer of water adjacent to the hull is acted upon, and the inertia of the unaffected mass carries it by the local curvature with little change in direction. Likewise, if exaggerated flare is employed, as in Fig. 23(C), the adjacent layer will actually rebound from the unaffected mass and rise higher than if no flare at all had been used.

During the course of isolating the effect of downward deflection of the chine, a simple expedient was employed which consisted of attaching a metal strip to a hull without flare, such as shown in Fig. 23(A), and then progressively deflecting this strip and recording the spray height. As one would expect, there was no improvement beyond a few degrees of deflection at which point the reflected spray became progressively worse, as in the condition of Fig. 23(C). As in the course of many research investigations, the study was continued "ad absurdum" for the record and upon approaching a nearly vertical position, as shown in Fig. 23(D), an interesting phenomenon occurred in that marked reductions in spray height were noted.[10] It was concluded from these tests that the increased effectiveness is due to the sharp intersection of the strip with the bottom, which in effect acts as a dam. This powerful effect is lost where the lowered chine is faired by using reflex flare or a fillet of any nature. Because of obvious structural limitations, this highly effective vertical spray strip, shown in Fig. 23(D), was not considered feasible for application to conventional hulls and for many years remained principally of academic interest only.

With the advent of jet propulsion, which has encouraged the development of extremely low, blended-hull type configurations for seaplanes, the vertical spray strip (or spray dam as it is now commonly called) has shown great promise in being able to control effectively all spray without the necessity for any flare, any sharp chine, or, in fact, any discontinuity of any sort on the basic hull bottom. This form of spray dam has been extensively developed by the Consolidated Vultee Hydrodynamics Laboratory, and in a broad sense this device, as illustrated in Fig. 23(E), has made the high-speed jet-propelled water-based aircraft feasible. Because of the inherent unbroken form of the aerodynamically smooth blended-hull configuration, the spray dam feature may be maintained structurally by placing the structural depth to the dam on the outer face where it can be adequately tied into the continuing hull structure. By rotating the spray dam wedge about the upper inboard edge, it may be retracted flush in flight, leaving an unbroken blended wing and hull contour. The spray dam obtains its effectiveness by violently agitating the main spray blister and thoroughly mixing it with air. This aerated mass is deflected downward with great force in a high-velocity jet. Because of the high content of entrained air, this water mass penetrates the free water surface with little or no rebound or reflection, and the high velocity curtain generated effectively retains the mass of water not directly contacted by the dam.

An impressive example of the spray dam in operation is shown in the photograph of Fig. 24, which was taken at the speed for maximum spray. Here it will be noted that the bow wave is completely suppressed, and at no point does the spray reach a height greater than the dam itself. At a comparable loading, the bow wave on a conventional hull, utilizing a sharp chine and flare, would be going completely over the wing in the example shown. In combination with the powerful influence of high length-beam ratio, the application of the spray dam principle on a completely smooth aerodynamic form of high critical Mach

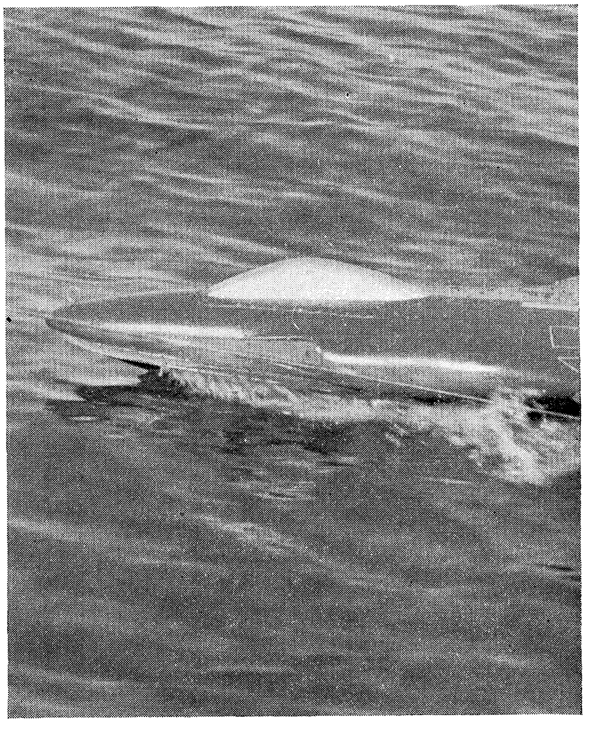


FIG. 24. The forebody of a supersonic water-based aircraft showing the action of the retractable spray dams at the speed for maximum spray and the relationship of the jet air intakes.

Number has made possible jet-propelled supersonic water-based aircraft incorporating hydrodynamic seaworthiness and stability comparable to the best propeller-driven seaplanes of conventional form. Security prevents a detailed analysis of the parameters and factors uniquely associated with the transonic and supersonic water-based problem. However, it suffices to say that recent hydrodynamic research, based upon the fundamental principles discussed in this paper, has placed the water-based aircraft high on the priority list of National Defense once again.

Conclusions

Extensive refinement of the dynamically similar model and its associated research techniques during the years since 1938, when this new concept was first introduced in this country, has established the science of seaplane hydrodynamics on a par with contemporary fields of aeronautical research and development. Extensive experience has indicated that the fundamental laws of dimensional similitude can be matched or compensated to the extent that accurate determination of the complex integrals of unrestrained motion, in discontinuous media, are possible with an economical and rapid experimental procedure.

One of the greatest contributions of the dynamic research program to the advancement of water-based aircraft design has been the establishment of hull length-beam ratio as a fundamental design parameter. Through the application of this basic criterion and its dependent variables, the hull loading of seaplanes has been increased over 300 per cent with an accompanying improvement in performance, seaworthiness, and stability. Design charts have been prepared which provide the designer considerable latitude in selection of optimum characteristics with a high measure of confidence.

Through a new blended wing-hull design approach, coupled with the development of an extremely effective spray suppression device known as a "spray dam," it has been possible to water-base idealized high Mach Number aerodynamic forms without compromising hydrodynamic performance, seaworthiness, or stability. By utilizing jet power, it has been demonstrated that water-based aircraft can be developed into efficient and dependable transonic and supersonic aircraft.

It appears reasonably certain that established research techniques, such as discussed in this paper, can keep the fundamental design of water-based aircraft abreast of current aerodynamic development. It is just as reasonable to assume that, without this unique development, water-based aircraft today would be relegated to nothing more than auxiliary craft, used in those few instances where operation on water became mandatory for a particular specialized mission.

Many of the principles and new design criteria discussed in this paper appear for the first time in the Convair XP5Y-1. This high-speed seaplane, constructed for the U.S. Navy, not only embodies exceptional hydrodynamic performance but also holds the distinction of being the first multiengined aircraft in the United States to be powered with propeller turbines. The technical mating of these two outstanding developments is indicative of the new role of water-based aircraft.

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Only the simplest formulas should be typewritten; all others should be carefully written in pen and ink. The difference between capital and lower-case letters and Greek symbols should be clearly distinguished.

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