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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 318

HIGH VELOCITY WIND TUNNELS.

(Their Application to Ballistics, Aerodynamics and Aeronautics.)

By E. Huguenard.

From "La Technique Aéronautique," Nos. 37-38,
November 15, and December 15, 1924.

June, 1925.

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HIGH-VELOCITY WIND TUNNELS.*

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By E. Huguenard.

The researches I have undertaken since 1917 for the production and experimental study of swift air currents have enabled me to define the conditions under which a high-velocity wind tunnel can now be operated.

The object of this article is to set forth the particular properties of swiftly-moving air, how these affect the installation of a wind tunnel, the experimental results already obtained, the possible applications of such a tunnel, and what can be easily accomplished at the present time.

In order to indicate the difficulties encountered in trying to increase the velocity of the wind in the tunnels, I will first recall the principal devices employed in aerodynamic laboratories. The direct determination of the forces exerted by the air on an automobile, an airplane, or an airship presents considerable difficulties, which have generally exceeded the means of the experimenters confronted by them. The principal importance of wind tunnels is to supply experimenters with conditions of facility and comfort which can be obtained in no other way. Instead of flight tests, they make it possible to substitute experiments

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with a model under the eyes of the experimenter, on a firm foundation and in an air current more regular than the natural wind. The increased speed of airplanes and the ideas adopted on the Reynolds number have resulted in the testing of larger models in air currents of high velocity.

Thus, to speak only of French plants, we have seen the diameter of the air stream of the Eiffel aerodynamic laboratory pass from 1.5 to 2 meters (4.92 to 6.56 feet) and the air velocity increased from 20 m (65 ft.) per second to nearly 30 m (98 ft.). The same progress was made at the aerodynamic institute of Saint Cyr where the velocity of the air stream (of 2 meters diameter) was increased to 40 m (131 ft.) per second. Lastly, the S.T.Aé. wind tunnel, at Issy-les-Moulineaux, can produce an air stream of 3 m (9.84 ft.) diameter with a velocity of over 80 m (262.5 ft.) per second, figures which have never been attained anywhere else.

As to what conditions limit the velocity of the air in the tunnel, a few figures will show. The flow of any gas (which we will assume to be atmospheric air in all that follows) is caused by a difference in pressure. In ordinary low-velocity wind tunnels, as in all the aerodynamics of airplanes and airships, the air has a pressure very near that of the atmospheric pressure in a fluid at rest. Also the laws of its flow are practically the same as if it were nearly incompressible, like a liquid. The simple theorem of Bernouilli gives the velocity V of an air current produced by an over-pressure h, measured by the weight of a cylindrical air column of the height h and a cross-section of one square centimeter.

$V^2 = 2\ gh$, g being the acceleration due to gravity. If we express, as is customary, the pressure in millimeters of water, instead of the column of air, the formula becomes

$$V_{m/s^2} = 2g_{m/s^2}\ p_m \frac{e}{a},$$

e being the specific gravity of the water, under the conditions of the experiment, and a the specific gravity of the air under the same conditions, whence $V_{m/s^2} = 16\ H_{mm}$ and $V = 4\sqrt{H}$, H being the evaluated pressure in millimeters of water. The values of V and H for the different wind tunnels are:

	V	H
Eiffel	30 m/s	56 mm water
St. Cyr	40 "	100 " "
Issy	80 "	400 " "

The work done in communicating the velocity V to one cubic meter of air is expressed numerically in kilograms by the number H, since the fan must transmit to this cubic meter a pressure reduction H. This work increases as the square of the velocity to be obtained, so that, while the energy acquired by the air traversing the experiment chamber of the Eiffel wind tunnel is only 56 meter-kilograms, it attains 400 mkg at Issy-les-Moulineaux. Since, moreover, the time required for this cubic meter to pass is proportional to its velocity, or since, in other words, it is necessary to make just so many more cubic meters pass in order to obtain a greater velocity, it is evident that the energy of the air stream, represented by VH, becomes very great at high velocities. For an air stream of one square meter cross-section, we thus obtain:

1680	mkg per second for	V = 30 m/s
4000	" " " "	V = 40 "
32000	" " " "	V = 80 "

On taking into account the 3 m^2 cross-sectional area for the Eiffel and St. Cyr tunnels and 7 m^2 for the Issy tunnel, we obtain for each one respectively 5280, 12560 and 224000 mkg. The powers required to operate the three wind tunnels, allowance being made for the power lost in the propellers, are therefore:

5280/75 = 70 HP. for the Eiffel tunnel;
12560/75 = 156 HP. " " St. Cyr "
224000/75 = 3000 HP. " " Issy "

The designers of the first wind tunnels, impelled by the necessity of producing swift air streams of large cross-section and limited in the means at their disposal, soon thought of the scheme of collecting the air as it left the experiment chamber and conducting it back to the propeller, whose role would thus be reduced to maintaining the motion of a mass of air in a closed circuit, the motor having only to offset the losses occasioned by friction, eddies, etc. They thus produced a sort of air fly-wheel revolving in a confined space and requiring only sufficient energy to overcome the various passive resistances. With a given power, it is thus possible to produce in a closed tunnel an air flow, which would require a power ρ times as great in an open tunnel, the number ρ representing the "coefficient of utilization" or efficiency of the tunnel.

Diagrams (1) and (2) in Fig. 1 represent the first types of wind tunnels in which the air was simply sucked or forced through. Diagram (3) of the same figure represents a closed tunnel, which was employed by Prandtl at Göttingen and which, in spite of great losses in the circulation, gave a value of the number ρ a little above 1.

This type has one very great disadvantage. All the losses of energy of the propeller, all the friction, eddies, etc., transform mechanical energy into heat, which is absorbed by the air in the tunnel, whose walls constitute the only means of cooling. The consequent rise in temperature is sufficient to render it impossible to obtain a stable adjustment of the apparatus, without some automatic device acting on the electric motor which drives the propeller, so as to insure constancy not only of the velocity, but also of the action of the air current on any obstacle or on a manometer.

The other device, invented by Eiffel and more generally employed, consists in drawing the air stream, as it leaves the experiment chamber, into a divergent cone, where the air expands as it loses velocity (Fig. 1, diagram 4). The propeller then has only to impart a pressure reduction h to the mass of air and requires less power. The ratio $H : h$ represents the "efficiency" of the tunnel. It often attains values of 3 to 4 and sometimes even more. There will therefore suffice for operating the three above-mentioned wind tunnels, which are all of the Eiffel type:

35 HP.	for	the	Eiffel	tunnel,	which	has	an	efficiency	of	2;
50	"	"	St. Cyr	"	"	"	"	"	"	3;
750	"	"	Issy	"	"	"	"	"	"	4.

Since the propellers are not perfect, these figures will have to be raised to about 50, 66, and 1000 HP., corresponding to values of ρ respectively, equal to 1.4, 2.4 and 3.

Obviously, if we wish to increase the velocity of the air, it is necessary to increase the pressure reduction in the constricted portion of the air stream. This reduction amounts to 40 cm (15.75 in.) of water at Issy-les-Moulineaux and 100 inches at McCook Field in the first American high-velocity wind tunnel. The latter, of the Eiffel type, has a diameter of one foot at its smallest part, through which the air is drawn by a helicoidal fan or propeller driven by a 200 HP. motor.

Under these conditions, Bernouilli's formula would give $V = \sqrt{16 \times 2500} = 200$ m/s (or 656 ft./sec.) for the velocity of the air stream. This is incorrect, however. Since the pressure varies from 1 to 0.75, the work done by the expanding air sets in motion a fluid, whose density diminishes in passing from the atmosphere into the experiment chamber, at the same time that its temperature is lowered. We will see farther on what correction must be added to the above number, which is too small.

It is already possible, however, to perceive the great disadvantage of this device for producing air streams for aerodynamic tests, namely, that the density of the air will continue to decrease as the velocity increases, so that very high velocities will only be possible with a very rarefied gas. Now the Reynolds number relative to the air stream is proportional to this density and it is easy to see that, beyond a certain pressure reduction, this Reynolds number diminishes when the velocity of the indrawn air is increased, the reduction in the density offsetting the gain in velocity. Excepting when it is just a matter of verifying the effect of this Reynolds number on the laws of aerodynamic similitude or of studying the rarefied air of high altitudes, this great velocity becomes useless, if we hold to the present conceptions of similitude.

In order to eliminate this difficulty, it is necessary to increase the pressure so that, after expansion, the air can retain a pressure whose value is near what it normally is in the atmosphere, i.e., to use compressed air.

The idea of utilizing the flow of a mass of compressed air for obtaining a swift current of air enabling the study of certain physical phenomena relative to a projectile immersed in it, was explicitly stated in an article by the Austrian physician and mechanic, E. Mach, in 1889 ("Wiener Berichte"). It does not, however, appear to have been developed, unless its application to the study of projectiles was kept secret.

The idea was taken up again in 1916, at the suggestion of Mr. Chilowsky, by Mr. Langevin, for the purpose of verifying certain phenomena of combustion in very violent artificial winds comparable to the relative winds encountered by gun projectiles in their trajectories.

Its rudimentary installation formed the basis of the high-velocity wind tunnel constructed by me in 1917, in collaboration with Mr. Sainte Lague, and which rendered it possible to obtain the results given farther on.

Before describing it, we must see how the air flow is obtained and when the pressure variations (and consequently the density variations of the air) are no longer negligible. We will consider the case where the air flows from one atmosphere at a pressure of p_1 into another atmosphere at a pressure of p_2. The pressures p_1 and p_2 are supposed to be invariable and we also assume that no constraint is imposed on the gas during its expansion, i.e., that it receives no exterior energy, nor undergoes any friction, nor exchanges any heat with the medium surrounding the air stream. This problem is classic. The air being considered as a perfect gas, let p be the pressure of the air in kg/m² at the given instant; v, its specific volume in m³/kg; T, its absolute temperature; w, its velocity in m/s; s, the cross-sectional area of the air stream.

The corresponding data relative to the mass of air taken from the original atmosphere are indicated by the index 1; the data of the final atmosphere, by the index 2. These data are related according to the formulas:

$$\begin{cases} pv = RT & R = 29.3 \\ pv^{\gamma} = C^{te} & \gamma = 1.44 \\ \dfrac{W^2}{2g} = p_1\ v_1 - pv + \displaystyle\int_{v_1}^{v} p\ dv. & \end{cases} \tag{1}$$

In the calculation, we will frequently introduce the quantity $\omega = 1/\gamma = 0.71$.

By considering the temperature T_1 and the pressure P_1 as known, we readily find the expressions for the temperature and velocity of the gas after an expansion which brings the pressure of this gas to a fraction $z = p/p_1$ of the initial pressure:

$$\begin{cases} T = T_1\ z^{1-\omega} \\ W^2 = \dfrac{2g\ R}{1-\omega}\ T_1 \cdot (1 - z^{1-\omega}) \\ S^2 = P^2\ \dfrac{T_1}{p_1^2}\ \dfrac{R\ (1-\omega)}{2g}\ \dfrac{1}{z^{2\omega}\ (1-z^{1-\omega})} \end{cases}$$

P being the output of air in kg/s and g the acceleration due to gravity.

If V denotes the velocity of sound in air at the temperature T_1, the first two formulas can be written:

$$\begin{matrix} W = \alpha\ V \\ T = \beta\ T_1 \end{matrix} \quad \text{in which} \quad \begin{matrix} \alpha = \sqrt{4.9\ (1-z^{0.29})} \\ \beta = z^{0.29} \end{matrix}$$

Fig. 2 gives the various values of V as plotted against the initial temperature T_1 of the air.

Fig. 3 contains the curves representing the values of the two functions α and β for the values of the ratio of expansion z, which concerns us here. It is then very easy to determine the flow velocity and the exit temperature of the air.

Let us take, for example, the wind tunnel at McCook Field, for which $p_1 = 1$ kg/cm², $p_2 = 0.75$ kg/cm², $T_1 = 20^\circ$. The velocity of sound in air at 20°C (68°F) is $V_{20} = 345$ m/s (1132 ft./sec.). The value of z is 0.75/1 = 0.75. The corresponding values of α and β are 0.63 and 0.90, from which we deduce: $W = 345 \times 0.63 = 217$ m/s (712 ft./sec.) and $T_2 = 0.9\ (273 + 20) = 264^\circ C = -9^\circ$ absolute temperature.

Let us now consider the case of compressed air. Let us expand, e.g., air at 20°C from the absolute pressure of 6.5 kg/cm² to the atmospheric pressure of 1 kg/cm². The value of z is then 1/6.5. The corresponding values of α and β are respectively, 1.45 and 0.57. The velocity of sound at 20°C is $V_{20} = 345$ m/s, from which we derive $V_2 = 1.45 \times 345 = 500$ m/s and $T_2 = 0.57\ (273+20) = 167^\circ C = -106^\circ$ absolute temperature.

The output is easily calculated. In the chosen example we obtain 9.9 kg/sec. and per dm² of the cross-sectional area of the air stream. The energy required per second to produce this output into the atmosphere is also easily calculated and is found to be about 177,500 mkg. The power required for maintaining the flow would be about 2500 HP. The magnitude of this figure shows immediately what an enormous waste of energy is caused by the use of a simple tube allowing such a mass of air to flow without any recovery, though giving, however, an air stream of only 11.3 cm (4.45 in.) diameter. No account has yet been taken of the efficiency of the compressor, nor of the manner in which the compression is effected. It would be necessary to count on a power of 3000 HP. per dm^2 of the air stream moving at the rate of 500 m (1640 ft.) per second.

A wind tunnel of 50 cm (19.7 in.) inside diameter, or 20 dm^2 cross-section, would therefore absorb about 60,000 HP. It would doubtless be possible, by recovering the air on its exit from the experiment chamber, to save 3/4 of the power. Even then 15,000 HP. would be required, which would be extremely burdensome. We will see, farther on, that this outlay is needless.

Now that we are in a position to contemplate the production of winds of 500 m/s, we can ask ourselves what limit it would be possible to reach in this manner. If we temporarily disregard the question of cost, we find there are two available methods for increasing the velocity of the air stream:

1. To diminish z and consequently increase α;
2. To increase T_1 and consequently V.

The first method is not very efficacious, since, if z passes from 1/6 to 1/30, α passes from 1.4 to only 1.75. Moreover, the temperature of the air stream falls enormously. This is due to the fact that, since the internal energy of the air is constantly diminishing, the expansion becomes constantly more difficult.

On the other hand, it is very important to raise the value of V, i.e., to heat the air before it expands or, if preferred, to prevent the air from cooling during its expansion.

If, e.g., we heat the air to 273°C, the velocity of sound at this temperature is 480 m (1575 ft.) per second. An expansion of 2.5 : 1 is sufficient to give a velocity of about 500 m (1640 ft.) per second. An expansion of 6.5 would give a velocity of 480 x 1.45 = 700 m (2297 ft.) per second. The absolute temperature of the air after expanding is then 546 x 0.57 = 312°C = 39°C.

If instead of expanding the air from 6.5 kg to the atmospheric pressure, we should expand it to 0.5 atm., the velocity obtained would be 480 x 1.56 = 750 m/s (2460 ft./sec.) and the exit temperature would be 546 x 0.48 = 262°C = -11° absolute. We thus see that it would be possible, under these conditions, to obtain air-stream velocities up to 700 m (2297 ft.) per second, the temperature of the expanded air being practically the same as that of the surrounding medium.

In short, to obtain a current of air for a high-velocity wind tunnel, it is first necessary to heat the compressed air sufficiently so that the desired velocity shall be less than the velocity of sound in this air and then procure an expansion rate which shall bring the exit temperature of the air to the vicinity of the desired value.

Difficulties arise only when it is necessary to provide the output of a tunnel of large dimensions. At 700 m/s, 1 dm^2 of the cross-sectional area delivers 7 m^3/sec., or about 9 kg/s. Let us note, in passing, that the tunnel suffers from this cause a recoil of $\frac{9}{9.81} \times 700 = 640$ kg. Our tunnel would therefore constitute a good reaction propeller.

The production of the compressed air would require, however, a very powerful and very costly compressor, the establishment of which cannot now be contemplated. The problem can be solved otherwise, if we restrict ourselves to the use of some existing plant and to a combination of measuring instruments reducing the duration of the experiments to a minimum. This is the solution proposed by Mr. Sainte Lague and myself in 1917.

There are two large compressed-air stations in the world: the one belonging to the C.P.A.C. (Compagnie Parisienne de l'Air Comprimé) which has compressors with a total power of 12,000 HP. supplying air at a pressure of about 6.4 kg per cm^2 and a temperature of 40°C; the other, of 100,000 HP., is at the mines of the Rand in South Africa.

As already mentioned, Messrs. Chilowsky and Langevin had installed in the factory of C.P.A.C. crude apparatus consisting of a tank holding 6-7 m^3, which could be filled with compressed air at 6.5 kg/m^2 and emptied into the atmosphere by means of a quick-acting valve opening a converging-diverging tunnel 80 mm in diameter at its smallest cross-section and 120 mm at its outer end.

The experimenters assumed that the exit velocity of the air was its theoretical velocity of about 485 m/s. In reality, it was barely 350 m/s, due to the too rapid divergence of the exit cone of the tunnel.

With the aid of Messrs. Sewall, Delcourt and Comte, we were able to modify the plant, in order to investigate the Chilowsky shells, so as to obtain a velocity of over 450 m/s and experimental results which will be given farther on.

The plant consisted of the same tank and valve, but another tunnel with a smaller angle (6°) and an exit diameter of 98 mm and, facing it, a dynamometric registering device with a high-pressure piston. Fig. 4 is a diagrammatic representation of these devices. The projectile P, to be tested, was held in front of the tunnel T, on a dynamometric support, streamlined to lessen its effect on the air current. The thrust on the shell was communicated to the piston p of the dynamometer which compressed the oil in a tube C terminating in a metal recording manometer M. The dynamometric period of the system was about 1/50 of a second.

Impressed with the unique resources, which offer, in an intellectual center like Paris, the powerful factory of the C.P.A.C., we then conceived the idea of developing this primitive plant into a veritable high-velocity aerodynamic laboratory. Owing to the kindness of Mr. Guiard, chief engineer of the C.P.A.C., we were able to assemble the necessary materials quickly and we outlined our project in two short communications to the "Direction des Inventions" (Huguenard and Sainte Lague, "Rapports sur un laboratoire aérodynamique à la Direction des Inventions," October 27, and December 15, 1917). The project was abandoned on the signing of the armistice.

The results obtained with the original plant, as also the general lines of the project, were included in a report by the American Lieutenant Sewall, to the United States War Department (S. Sewall, "Report on high-velocity wind tunnels." November 12, 1918).

The project comprised four principal parts:

1. A simple continuous wind tunnel;
2. An intermittent wind tunnel;
3. Plants for preliminary investigations;
4. Devices for recovering and heating (aerothermal wind tunnel).

1. Continuous wind tunnel.- This consists simply of a tube connected with the compressed-air tank, with all the requisite measuring devices. The diameter of the air stream is evidently limited by the output of the factory compressors and cannot exceed 30 cm (11.8 in.), unless expansion is produced below the atmospheric pressure by means of a divergent cone after the experiment chamber.

. . . .

2. Intermittent wind tunnel.- After adjusting the measuring instruments in a continuous wind tunnel, we can then employ, for

most of the aerodynamical experiments, blasts produced by the discharge into the atmosphere of a large tank of compressed air. A 250 m^3 tank assures the obtention of air streams of 60 cm diameter. The flow can be regarded as permanent, if we consider the length of the air column, which strikes the object under test for a period of one second, and if we employ, as in our original plant, quick-action instruments, like oil dynamometers,

3. <u>Plants for preliminary investigations</u>.-can be constructed at small expense, always near the C.P.A.C. factory.

4. I now come to the most important part of the project, that upon which the researches must depend. I have referred to the importance of heating the air before its expansion. This is how it may be done.

In a tank charged at 6.5 kg/cm² at 20°C (68°F) and then heated, e.g., by means of superheated steam, to 250°C (482°F), the pressure of the air would mount to $6.5 \times \frac{250 + 273}{293} = \frac{523}{293} \times 6.5 = 11.6$ kg/cm². Expansion to the atmospheric pressure would then give, for $z = 1 : 11.6$,

$$\alpha = 1.58 \qquad \beta = 0.49 \qquad V = 460 \text{ m/s}$$

and, consequently, $W = 728$ m/s and $t = -17°$.

Another method can be used, which consists in incorporating a small quantity of water vapor in the air of the tank heated to 100 - 120°C (212-248°F). I will not dwell on this very simple method, which I proposed in 1919, and which renders it easily possible to approximate 700 m (2297 ft.) per second, while keeping the expanded air at a temperature near that of the surrounding media, due to the enormous quantity of heat given out by steam in condensing.

As already mentioned, it is very important to allow the gas to expand below the atmospheric pressure, in an experiment chamber similar to those in tunnels of the Eiffel type, and then to increase the pressure reduction in the mass of air by means of a divergent exit cone opening into the atmosphere. This affords a very easy way to increase the value of z and, consequently, of the exit velocity. Lastly, it is now possible to conceive of a recuperation plant, in which the heating of the air before expansion, aided by the cooling of the air stream before and during its recompression in the exit cone, would enable the circulation of the air without any mechanical device. The data for establishing such a project are still incomplete. I hope to be able to obtain them soon by experimentation.

I now come to the practical part of my article, namely, the utilization of wind tunnels of very high velocity. It is doubtless important to have masses of air moving at 500-600 m (1640-1968 ft.) and even 1000 m (3280 ft.) per second, with possible temperatures ranging, e.g., between -100° and 100°C (-148 and 212°F). Here is, apparently, an important field for physical research.

I will first give the results obtained in the very modest C.P.A.C. plant during the war, results which were disconnected and recorded at random, in the midst of work having an entirely different object.

Ballisticians are most directly interested in wind tunnels of very high velocity, since only firearm projectiles attain the velocities under consideration. Furthermore, excepting very large calibers, experimentation is possible on the full-sized projectiles.

Everybody knows how a projectile travels. Its mass, suddenly launched at a high velocity by the combustion of powder, contains a supply of kinetic energy sometimes mounting into the thousands or even millions of meter-kilograms. It is this energy which enables the projectile to overcome the resistance offered by the air. It is to this particular method of propulsion that we owe the formula by which ballisticians represent the resistance of the air to a projectile:

$$R = m\ c\ F(v),$$

m being the mass of the projectile, $F(v)$ a function of the velocity and c the ballistic coefficient, defined by

$$c = i\ \Delta\ \frac{a^2}{p},$$

in which Δ is the weight of a cubic meter of air, a the caliber in meters, p the weight of the projectile and i a coefficient called the index of shape. We must make a little exertion to extract from these symbols the air resistance with the coefficients K_x or C_x familiar to aeronautic engineers. If we adopt the notation of the "Committee on Standardization," we will write $R_x = C_x \, S \, \Delta \frac{V^2}{2g}$, on conserving Δ so as not to confound it with a, S being equal to $\pi \frac{a^2}{4}$. A comparison of the two formulas yields the expression $C_x = \frac{8}{\pi} \times i \, f(v)$, or $K_x = \frac{1}{16} C_x = 0.16 \times i \, f(v)$, $f(v)$ being the function $\frac{F(v)}{V}$. This enables us to determine the aerodynamic fineness of an artillery projectile. For a 75 mm (2.95 in.) projectile of 1914, $i = 0.74$.

The function $f(v)$ of artillery has a value of 0.12 for this or a similar form of projectile at low velocities, whence $K_x = 0.16 \times 0.12 \times 0.74 = 0.014$. Now, we know that well faired bodies have a coefficient $K_x < 0.003$ at aviation velocities. The best projectiles seem to correspond to $i = 0.31$ (about), which again gives $K_x = 0.006$.

With Mr. Sainte Lague, I obtained (by methods concerning which I will shortly say a few words) $i = 0.12$, which gives $K_x = 0.0023$, a value near those furnished by the best profiles tested in wind tunnels.

From the resistance at small values of v, we pass to the resistance at any velocity whatever by multiplying the resistance calculated by the customary aerodynamic formulas by the value of $f(v)$ corresponding to the velocity under consideration.

Fig. 5 assembles the various curves of theoretical or experimental origin which are utilized for representing this function. There are given, first, the function $f(v)$ of the Gavre Committee, then that of Siacci and, lastly, the one obtained by the theoretical law and the one for spherical projectiles. Fig. 6 gives, with the profiles of the corresponding projectiles, the value of $f(v)$ according to Cranz. It is known that the curves vary with the shape of the projectile, but how were they obtained, since the author does not indicate whether they are of experimental origin? On the method of studying the function $f(v)$, I will quote a passage from a note of August 25, 1919, by the chief engineer of naval artillery, Mr. Anne, who was vice-president of the Gavre Experimental Committee.

"In this formula, i and $F(v)$ are required by the experiments. The law of $F(v)$, or rather of $f(v) = \frac{F(v)}{V^2}$, was established by means of special firing experiments in which we measured the velocities V_1 and V_2 at two points far enough apart, but near enough to the muzzle of the gun, about 1800 m (5905 ft.) maximum at Gavre, from which we derived the value of the function $f(v)$ corresponding to the mean velocity $\frac{V_1 + V_2}{2}$, by assuming a half-theoretical, half-empirical law for the resistance of the air. By operating at a great number of velocities, we were able to determine points of the curve of the function $f(v)$. With the aid of these points (which, moreover, formed, in certain regions, a "milky way" of considerable width and, in other regions, were very rare and isolated) we traced, on a large sheet of white paper, a compensative curve which we assumed to represent the function. It would appear that the study of the law of $f(v)$ must be entirely remade."

Is it not possible to proceed in any other manner? Artillery engineers assume that the function $f(v)$ holds good for all calibers of the same form index, but has a particular value for each form. Let us, therefore, take a projectile, place it on a dynamometer, in a blast of air issuing from a tank, and note simultaneously the velocity of the air and the force exerted on the projectile. In 15 seconds we obtain a drawing from which we derive the function $f(v)$.

The determination of i is more difficult (because this quantity includes terms which depend on the behavior of the projectile in its trajectory), but the interpretation of the firing results is very easy when we already know the resistance offered by the projectile to an air current striking it directly in front.

I do not insist on this method, but, if we multiply the cost of one cannon shot by the number of points of the "milky way" cited by Mr. Anne and if we compare the product thus obtained with the cost of the thousand cubic meters of compressed air (about 15 francs) required for the experiment, it is obvious that the establishment of a wind tunnel would effect a considerable saving.

Fig. 7 shows the records obtained in our original plant, by causing a blast to act on two 75 mm (2.95 in.) projectiles. The dynamometer pen recorded, in ordinates, the forces exerted on the projectiles by the wind. These forces can be evaluated by employing the fifth line, which represents the action of known forces on the dynamometer piston. The paper recording strip was moved at a uniform speed and a chronograph made marks every 1/5 second on the upper part of each diagram. Since the law of variation of the wind velocity can be determined as a function of the time from the beginning to the end of the blast, we can thus obtain, for every point of the dynamometric line, the value of the force R exerted on the projectile by a wind of the velocity V. The curve f(v) is thus determined for all velocities below the maximum velocity of the blast.

The two upper lines of Fig. 7 relate to the same shell of ancient form. The experiment was tried twice, in order to show the regularity of registration. The third and fourth lines relate to a recent shape of the projectile. The diminution of the resistance is especially large, when the wind velocity is over 450 m (1476 ft.) per second.

It is interesting to find that, in spite of the smallness of the air stream, the resistances measured are in nearly the same ratio as those deduced from actual firing.

Great difficulty was encountered during the experiments in measuring the velocity of the air stream, but it was found possible to overcome this by using Pitot tubes previously calibrated in air currents of known velocity. I have already referred to a method which enables the measurement of these velocities by measuring the acceleration of a sound wave in the blast.

Fig. 8 shows, on the right, the photograph of a sound wave in still air. The wave is exactly centered on the sphere (at the top of the vertical rod) forming the electric terminal from which the electric spark jumped in producing the sound. The photograph on the left represents a sound wave accelerated toward the right by a wind of only 14 m (46 ft.) per second. The measurement of the eccentricity of the wave and interval of time separating the sonorous spark from the spark producing the photograph furnish the desired velocity.

I now pass to another example of the application of high-velocity wind tunnels, namely, the study of shells with flame, as invented by Mr. Chilkowsky. This inventor proposed to act on the resistance which the air opposes to the motion of projectiles by diminishing the density Δ of this air by heating by means of a flame driven forward in the axis of the projectile. I replaced this axial flame by a transverse flame.

Fig. 9 shows diagrams of such projectiles, in which the arrows indicate the approximate position of the flame. The action of this flame on the resistance of the air is shown in diagrams, Figs. 10 and 11, obtained with the same shells which furnished the lines of Fig. 7 and which were charged with phosphorus, whose combustion was intended to diminish the density of the air. We see that the resistance of the air can be considerably diminished by this method. Moreover, the results obtained in the wind tunnel made it possible to increase the range about 25% for the flame shells. This gain was about 23% in the first actual firing.

Shells with ogive flame which I constructed, with Mr. Sainte Lague, for the naval artillery, gave, in firing, a form index of less than 0.3 during their entire trajectory, which no ordinary type of projectile was able to obtain. Other shells gave, at the beginning of their flight in the air, a form index of only 0.12, the flame having reduced the air resistance more than 80%. The mode of action of this flame has, moreover, nothing in common with the idea on which the invention was based.

I now come to the results obtained in our small plant, which have especially to do with aerodynamics. Everybody now knows that a projectile having a velocity greater than the velocity of sound in the air where they are both propagated, is surrounded with a shock wave and leaves a wake similar to that left by a boat on water. Very delicate experiments have made it possible to photograph this phenomenon, owing to variations in the transparency of the air produced by compression by the projectile.

In our high-velocity wind tunnel, the shock wave is visible to the naked eye. In October, 1917, Mr. Saint Lague noticed that, during the beginning of the blast which struck a stationary projectile, the tip of the latter was covered with a sort of cap having the appearance of a glass globe, as seen against the greenish gray background formed by a damp wall. It was the shock wave. A photographic device, represented by Fig. 12 was quickly installed and enabled us to obtain the photographs reproduced by Figs. 13-16.

Fig. 13 shows the wave at a velocity of about 450 m (1476 ft.) per second. It is seen that the front of this wave is sharply defined and that there are several other waves in front of the shell or distributed along its surface. Figs. 13-16 show the wave at gradually decreasing velocities. In Fig. 15 the shell has been placed outside the axis of the air stream, so that the wind velocity on its right is lower than the velocity of sound, though still being higher than the latter on its left. The wave shock is still visible on the left, though it has disappeared on the right. It no longer exists in Fig. 16, the velocity being lower than that of sound. Figs. 17-21 show the shock wave in front of projectiles of various shapes.

These photographs were obtained by placing the plate in the position A of Fig. 12. If the plate is placed at B, a different result is obtained, the proportions of the various zones of the wave being modified as shown in Fig. 21, which wave was furnished by the same projectile and the same air stream as in Fig. 13.

The photographs give only faint images of the actual phenomenon, which, within a few seconds, shows all the successive modifications of the wave. In the blast of decreasing velocity, this wave, lying at first very near the projectile, opens gradually, after the manner of an umbrella, at the same time moving farther forward. When the wind velocity approaches the velocity of sound in the air stream, the wave, almost flat, moves toward the tube into which it seems to precipitate itself. We greatly regret that we were not able, in 1917, to kinetograph this phenomenon, which shows what resources can be furnished by a high-velocity wind tunnel for the study of aerodynamics. Although special devices are necessary, in order to show the eddies and separations at ordinary velocities, and although recourse must be had to very difficult methods, in order to view the phenomena which accompany a projectile moving through the air, we can here put our finger on the shock wave and introduce, with the greatest facility, a manometer for measuring the pressure.

We were thus able to find that the negative pressure at the center of the base of a projectile, at 450 m (1476 ft.) per second, was about 0.3 kg per cm^2, a number which accords with that furnished by certain theories and which would be very difficult to measure on a real projectile during its flight.

Coming to the application of such wind tunnels to aeronautics, it is evident that experiments performed at very high velocities can reveal properties which would not appear clearly at lower velocities and thus suggest fruitful ideas.

Thus, e.g., the effect produced by a flame in front of a projectile leads to the following remarks. A 75 mm shell at 500 m (1640 ft.) per second encounters an air resistance of about 50 kg/cm^2. In order to maintain this velocity, $50 \times 500 =$ 25,000 mkg are required per second, or 333 HP. The combustion of 10 grams (0.35 oz.) of well-placed phosphorus reduces the resistance to 25 kg and the requisite power to 166 HP. It could not be due to any reaction produced by a particular fuse, since, in order to obtain a reaction of 25 kg, it would, in fact, be necessary to launch the 10 g toward the rear at a velocity of more than 25 km (15.5 miles) per second, which is absolutely impossible with the dispositions adopted. It can only be the modification in the air flow about the projectile, which causes the observed diminution in the resistance.

Of course, this flame method is not directly applicable to the hull of an airship, but we can conceive of devices which, by reducing the pressure on the nose, to the advantage of the negative pressure on the stern, would enable the hull, equipped with its propeller, to offer an apparent resistance (or drag) much smaller than the resistance offered by the hull alone.

Of what applications to aeronautics can we now conceive for wind tunnels in which the air flows at several hundred meters per second?

At a meeting of the French Aerial Navigation Society, I once heard Mr. Rateau declare that anything which concerns the air, concerns aerial navigation. Without doubt, as the speed of airplanes is increased, we will see the velocity of propeller blades approach 300 m (984 ft.) per second and thus justify the construction of the McCook Field wind tunnel. I might also recall the turbo-compressors and their application to aviation at high altitudes where velocities of this order are current, but the real importance of high velocities is not there. Now that human flight is an accomplished fact, the only interest in aviation is speed. Most of the researches of aeronautical scientists have to do with the means suited for gaining a few kilometers per hour, for night flight and for increasing the safety, i.e., for gaining in ultimate speed by avoiding interruptions.

What is the maximum speed attainable? For some time, on the basis of the high altitudes attained, speeds have been contemplated, which still seem fabulous, 600-1200 km (373-746 miles) per hour, as in Jules Verne. We may now consider such speeds as realizable, not in a remote future, but immediately.

Alone among all the methods of transportation, aviation has shown, from its very beginning, an extraordinarily rapid increase in speed. Fig. 22 shows, year by year, the greatest speeds attained by airplanes. From about 15 m (49 ft.) per second in the first flights, we have progressed, in 27 years, to more than 120 m (394 ft.) per second, the speed doubling regularly every five or six years.

This is certainly not accidental. At each new performance, pessimistic calculators, accepting with more or less grace the results already obtained and arming themselves with formulas borrowed from other modes of locomotion, have somewhat advanced the limit they had previously set to the speed of aircraft, whereupon this new limit has been promptly exceeded.

This is because there is a profound difference between aerial and all other forms of transportation. An aircraft can choose, almost at will, the density of atmosphere in which to fly and the increase in power required for a given increase in speed is much less than in the case of land or water vehicles.

Since there is no indication of any change in the speed curve (aside from technical considerations, which have thus far amounted to nothing), we must logically expect aircraft to attain speeds of the order of 240 m (787 ft.) per second within five or six years.

In order to attain this speed, it will doubtless be necessary to find some other means of propulsion than the screw propeller now in use, which is not essential. Birds fly very well without it. Rockets, which are a special kind of aircraft, leave the ground much like an airplane and travel at very high speed. Considered as the means of carrying large projectiles, they open up interesting vistas and their application to aircraft can be contemplated from now on, provided they are not expected to move large commercial aircraft slowly.

The high-velocity wind tunnel will doubtless be an important factor in solving the problem as to what the new means of propulsion will be.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

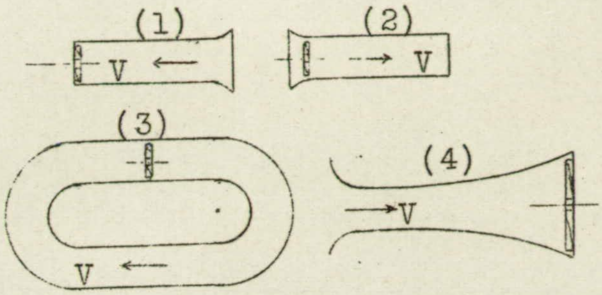


Fig.1 Wind tunnel diagrams. (1)Suction. (2)Blowing. (3)Closed. (4)Eiffel type.

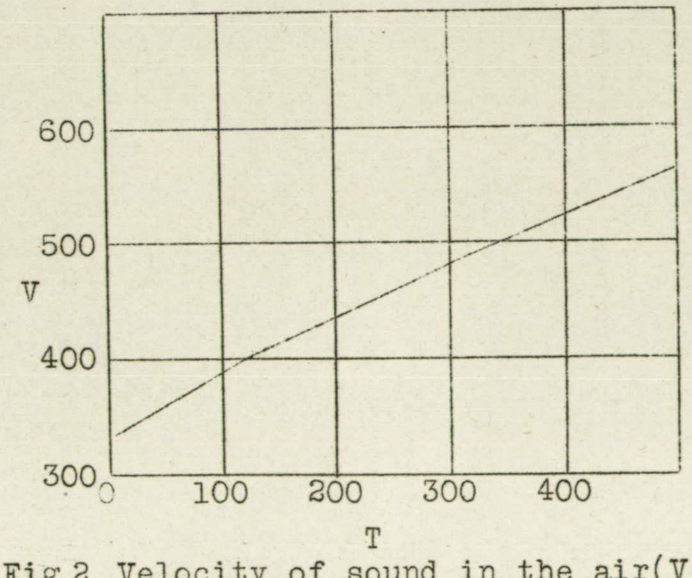


Fig.2 Velocity of sound in the air(V)plotted against absolute temp.(T)

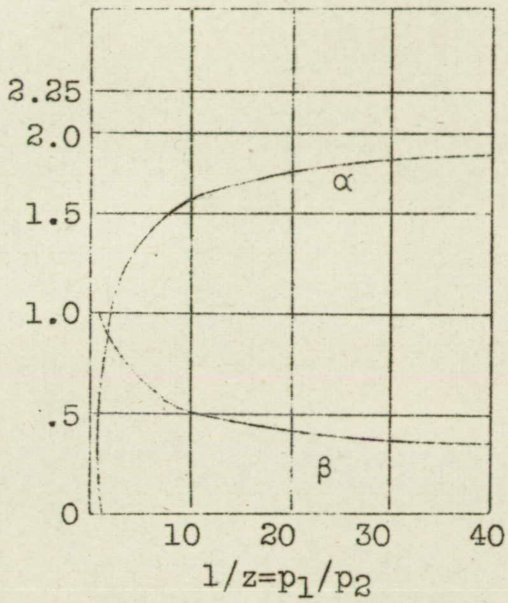


Fig.3 Flow of compressed air. Values of α & β plotted against z.

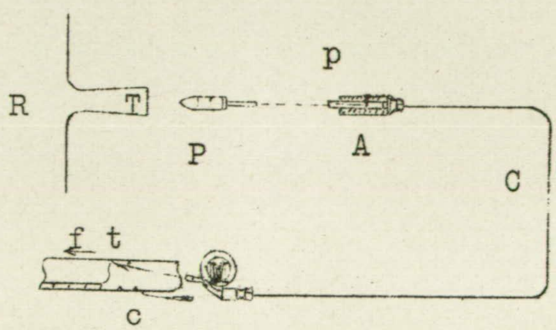


Fig.4 High-velocity wind tunnel for studying projectiles.

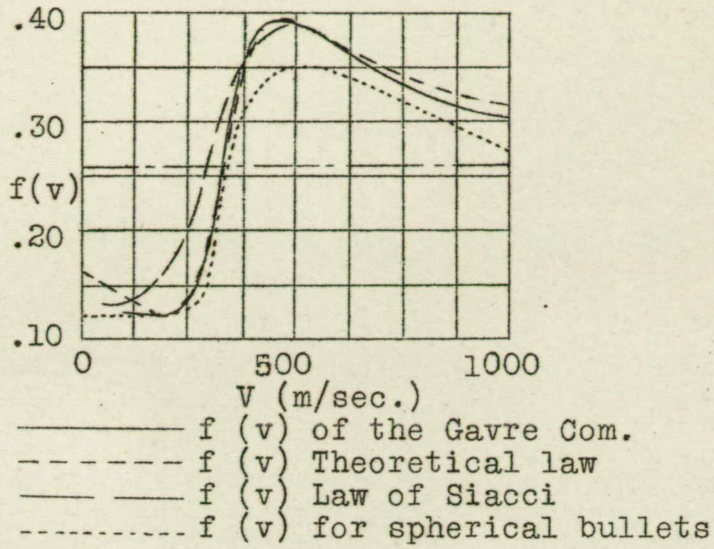


Fig.5 Curves of the function f(v).

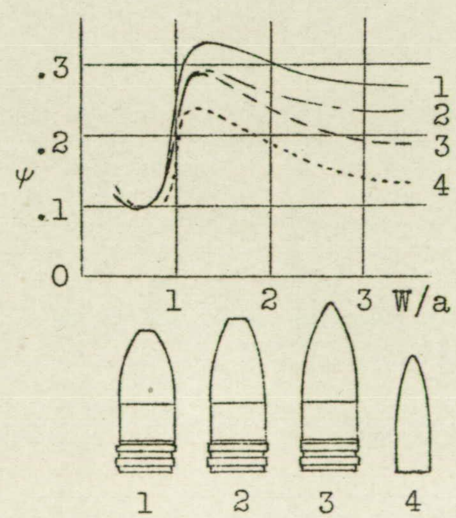


Fig.6.

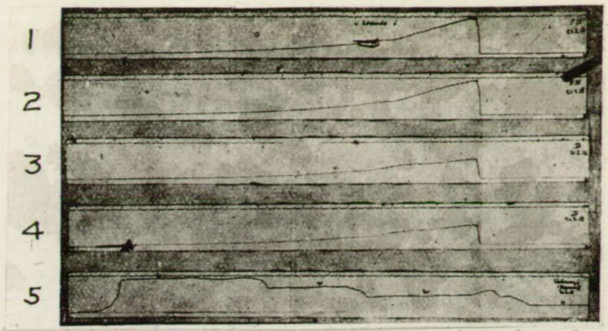


Fig.7 Air-resistance records obtained with a shell of ancient shape(1 & 2) and a shell D (3 & 4). (5) calibration of dynamometer.

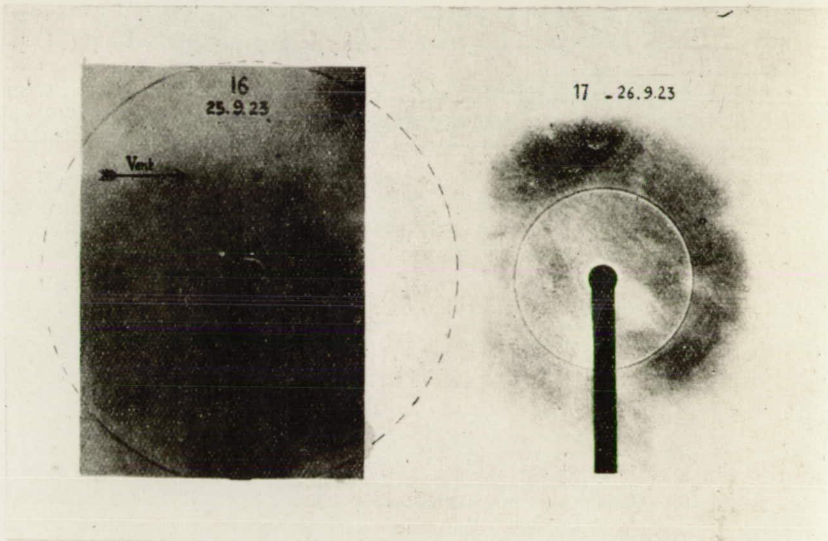


Fig.8 Measuring the velocity of an air current by photographing sound waves.

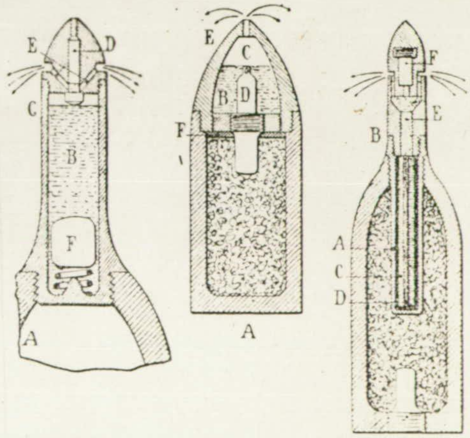


Fig. 9

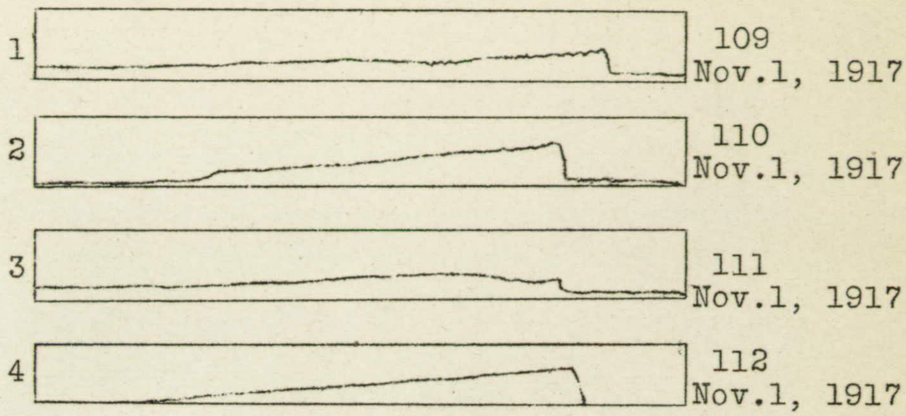
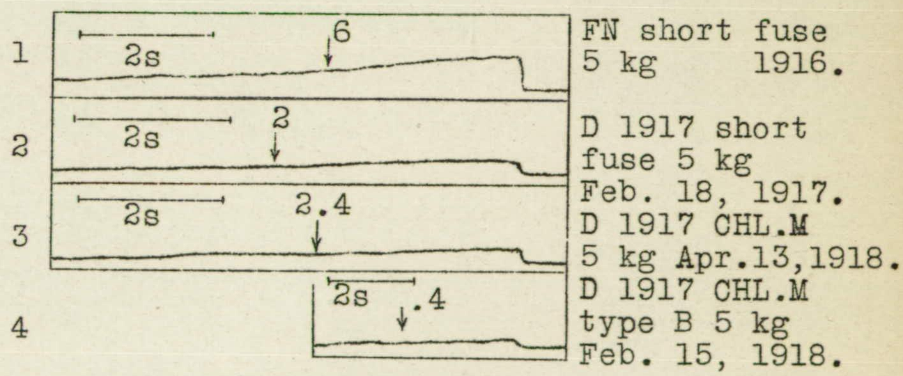


Fig. 10 Record of air resistance obtained with shells with flames (1 & 3) and without flames (2 & 4).

(Diagrams taken from half-tone cuts.)



The resistance of the shell FN in the air current (480 m/s about) is about 50 kg
That of shell D 1917 is about 21 kg (27.5)
" " " D 1917 CHL. " 22 kg (20)
" " " D 1917 CHL. " 8 kg (15)
At the end of 3 sec. in the region marked by the arrows the reduction of the air resistance attained 94% (V = 300 m/s).

Fig.11 Record of air resistance obtained with shells without flames (1,2,3) and with flames (4).

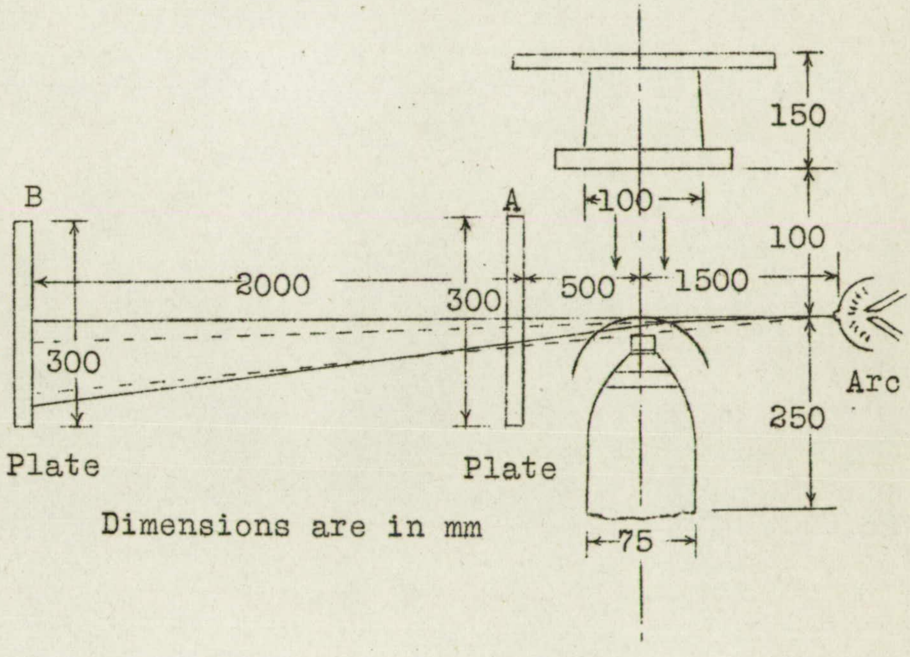


Fig. 12. Device for making photo of waves of shock.

Fig. 13 Shock wave of 75 mm shell.
Scale 0.9 V = 450 m/sec.

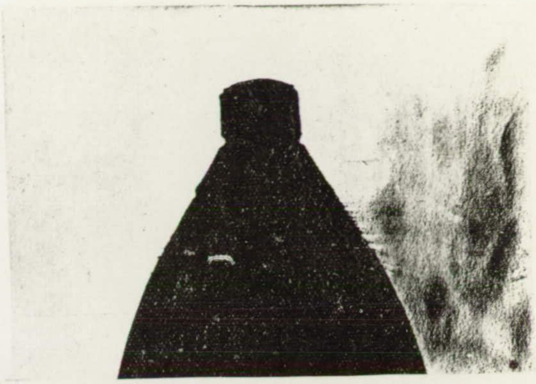


Fig.16 Shock wave of 75 mm shell.
Scale 0.75 V - 200mm/sec.

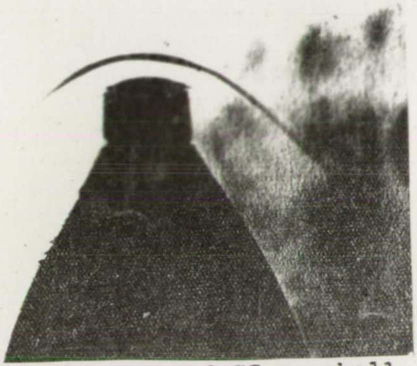


Fig. 14 Shock wave of 75 mm shell
Scale 0.75 V = 300 m/sec.

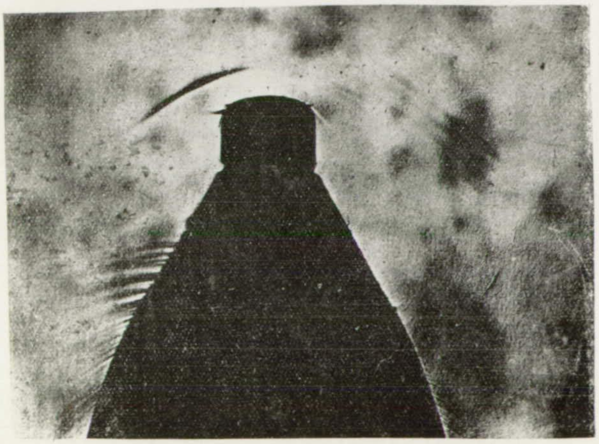


Fig. 15 Shock wave of 75 mm shell.
Scale 0.9 V = 280 m/sec.

Fig. 17 Shock wave of 37 mm projectile. Scale 0.75

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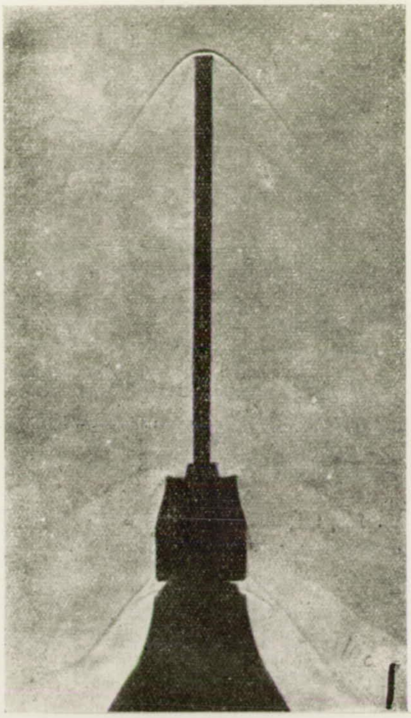

Fig. 18 Shock wave on a cylindrical rod

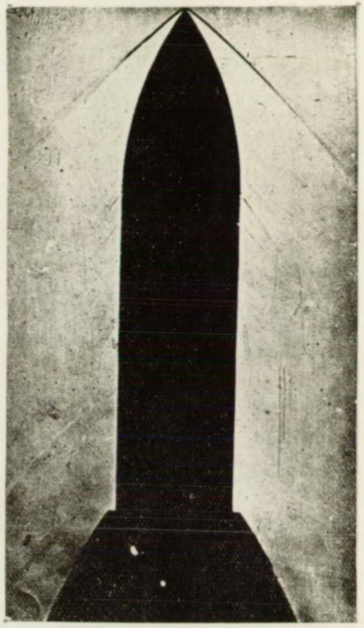

Fig.19 Shock wave of a shell with flame. Scale 0.667

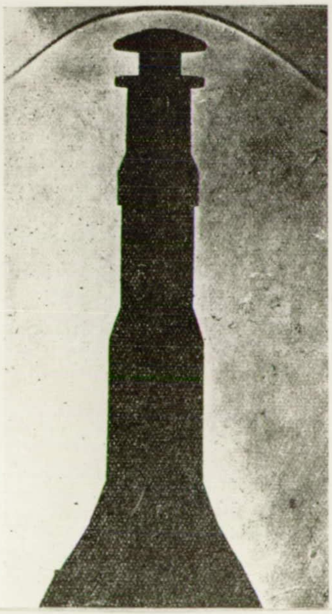

Fig.20 Shock wave of shell 1.A. Scale 0.667

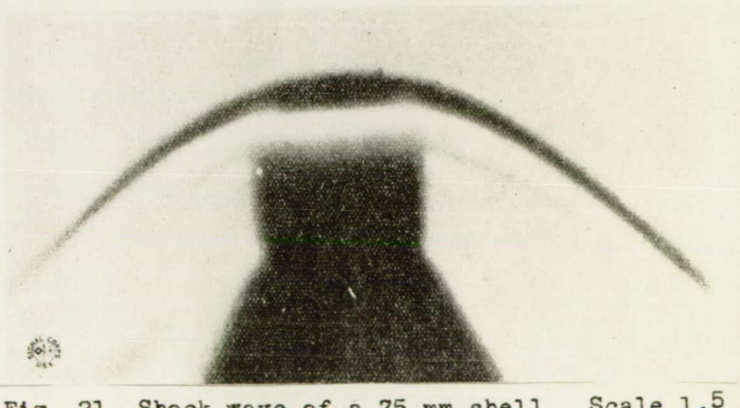

Fig. 21 Shock wave of a 75 mm shell. Scale 1.5

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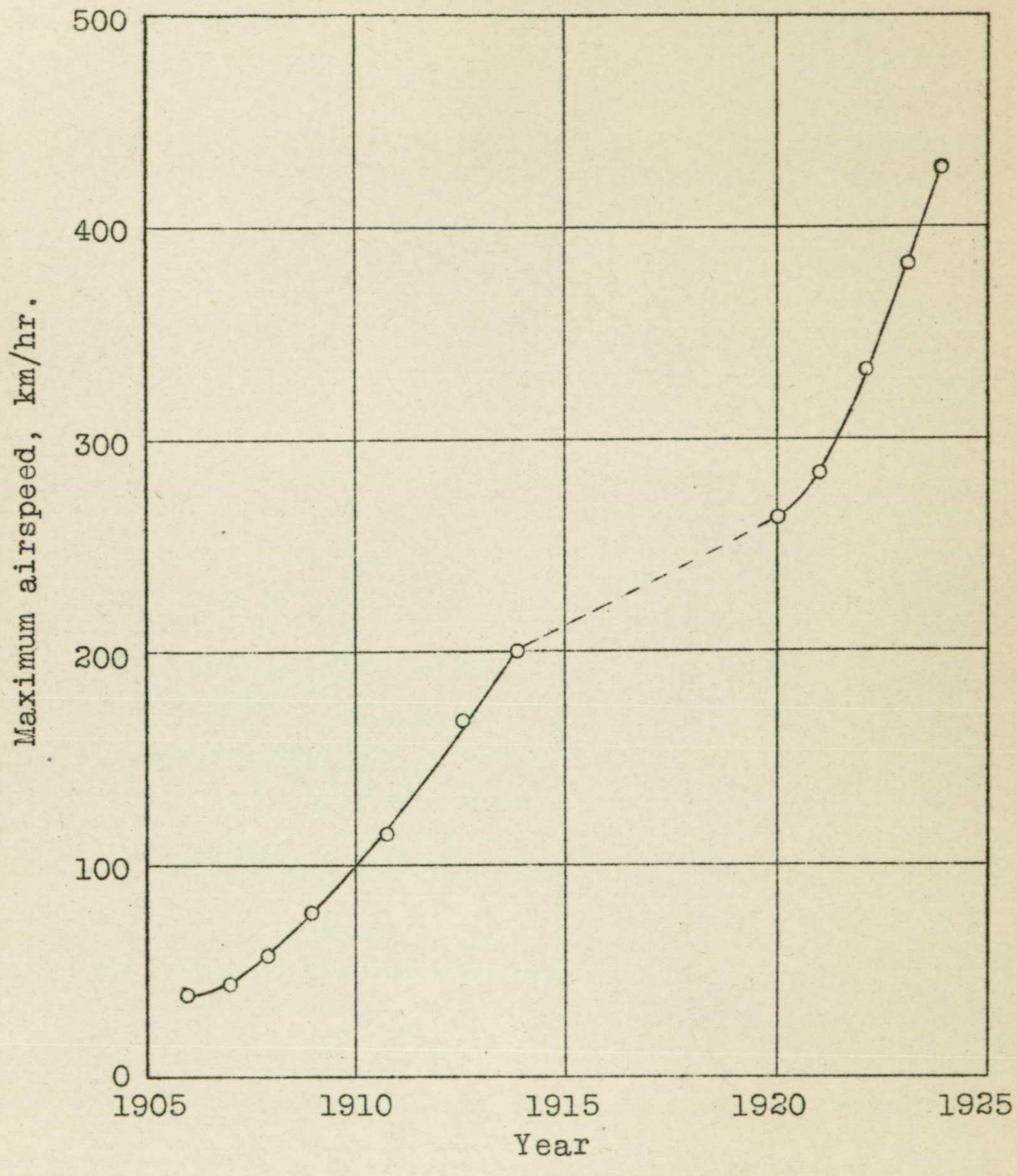

Fig. 22 Curve showing increase in maximum speed of airplanes.