AERONAUTICS

FIRST ANNUAL REPORT

OF THE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1915

THIRD EDITION

WASHINGTON
GOVERNMENT PRINTING OFFICE
1916

SUBMITTED BY MR. LODGE.

IN THE SENATE OF THE UNITED STATES,
January 31, 1916.

Resolved, That the report of the National Advisory Committee for Aeronautics, transmitted with the President's message of December fifteenth, nineteen hundred and fifteen, be printed as a Senate document, together with the accompanying appendices and illustrations.

Attest:

JAMES M. BAKER,
Secretary.

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REPORTS.

LETTER OF SUBMITTAL.

National Advisory Committee for Aeronautics,
State, War, and Navy Building,
Washington, D. C., December 9, 1915.

The President:

In compliance with the provisions of the act of Congress approved March 3, 1915 (naval appropriation act, Public, No. 273, 63d Cong.), the National Advisory Committee for Aeronautics has the honor to submit herewith its annual report for the period from March 3, 1915, to June 30, 1915, including certain recommendations for future work and a statement of expenditures to June 30, 1915.

The committee was appointed by the President on April 2, 1915, and held its first meeting for organization on April 23, 1915. On June 14 the President approved rules and regulations which had been formulated by the committee for the conduct of its operations.

By the act establishing the committee an appropriation of $5,000 a year for five years was made immediately available. Of the appropriation for the first year, ending June 30, 1915, there was expended a total of $3,938.94, as shown by the itemized statement in the accompanying report, and the unobligated balance of $1,061.06 was covered into the Treasury as required by law.

In order to carry out its purposes and objects, as defined in the act of March 3, 1915, the committee submits herewith certain recommendations and an estimate of expenses for the fiscal year ending June 30, 1917. The estimates in detail were submitted through the Secretary of the Navy.

Attention is invited to the appendixes of the committee's report, and it is requested that they be published with the report of the committee as a public document.

It is apparent to the committee that there is a large amount of important work to be done to place aeronautics on a satisfactory foundation in this country. Competent engineers and limited facilities are already available and can be employed by the committee to advantage, provided sufficient funds be placed at its disposal, as estimated for the fiscal year 1917.

What has been already accomplished by the committee has shown that although its members have devoted as much personal attention as practicable to its operations, yet in order to do all that should be done technical assistance should be provided which can be continuously employed. There are many practical problems in aeronautics now in too indefinite a form to enable their solution to be undertaken. The committee is of the opinion that one of the first and most important steps to be taken in connection with the committee's work is the provision and equipment of a flying field together with aeroplanes and suitable testing gear for determining the forces acting on full-sized machines in constrained and in free flight, and to this end the estimates submitted contemplate the development of such a technical and operating staff, with the proper equipment for the conduct of full-sized experiments.

It is evident that there will ultimately be required a well-equipped laboratory specially suited to the solving of those problems which are sure to develop, but since the equipment of such a laboratory as could be laid down at this time might well prove unsuited to the needs of the early future, it is believed that such provision should be the result of gradual development.

The investigations which the committee proposes in its program for the coming year can only be carried out to a satisfactory degree, with the limited facilities already existing, provided sufficient funds are made available. The estimates of the committee are based on such line of action, and on the assumption that a flying field can be placed at its disposal on Government land. If, however, such facilities be not practicable at this time, some progress may still be made by the utilization of the facilities of the Government aeronautic stations at Pensacola and San Diego.

The estimate of expenses for the fiscal year ending June 30, 1917, is as follows:

For carrying into effect the provisions of the act approved March third, nineteen hundred and fifteen, establishing a national advisory committee for aeronautics, there is hereby appropriated, out of any money in the Treasury not otherwise appropriated, for experimental work and investigations undertaken by the committee, including technical and clerical assistants and the necessary unskilled labor, equipment, supplies, office rent, and the necessary traveling expenses of the members and employees of the committee, personal services in the field, and in the District of Columbia: *Provided,* That an annual report to the Congress shall be submitted through the President, including an itemized statement of expenditures, $85,000.

The committee, therefore, submits its report, recommendations, and estimates to your favorable consideration.

Very respectfully,

George P. Scriven,
Brigadier General, Chief Signal Officer of the Army,
Chairman.

ANNUAL REPORT OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
STATE, WAR, AND NAVY BUILDING,
Washington, D. C., December 9, 1915.

To the Congress:

The members of the National Advisory Committee for Aeronautics were appointed by the President on April 2, 1915, in pursuance of the following provision in the naval appropriation act (Public, No. 271, 63d Cong.), approved March 3, 1915:

An Advisory Committee for Aeronautics is hereby established, and the President is authorized to appoint not to exceed twelve members, to consist of two members from the War Department, from the office in charge of military aeronautics; two members from the Navy Department, from the office in charge of naval aeronautics; a representative each of the Smithsonian Institution, of the United States Weather Bureau, and of the United States Bureau of Standards; together with not more than five additional persons who shall be acquainted with the needs of aeronautical science, either civil or military, or skilled in aeronautical engineering or its allied sciences: *Provided,* That the members of the Advisory Committee for Aeronautics, as such, shall serve without compensation: *Provided further,* That it shall be the duty of the Advisory Committee for Aeronautics to supervise and direct the scientific study of the problems of flight, with a view to their practical solution, and to determine the problems which should be experimentally attacked, and to discuss their solution and their application to practical questions. In the event of a laboratory or laboratories, either in whole or in part, being placed under the direction of the committee, the committee may direct and conduct research and experiment in aeronautics in such laboratory or laboratories: *And provided further,* That rules and regulations for the conduct of the work of the committee shall be formulated by the committee and approved by the President.

That the sum of $5,000 a year, or so much thereof as may be necessary, for five years is hereby appropriated, out of any money in the Treasury not otherwise appropriated, to be immediately available, for experimental work and investigations undertaken by the committee, clerical expenses and supplies, and necessary expenses of members of the committee in going to, returning from, and while attending meetings of the committee: *Provided,* That an annual report to the Congress shall be submitted through the President, including an itemized statement of expenditures.

APPOINTMENT OF COMMITTEE.

Under the authority of the statute the President appointed the following members of the committee:

Prof. Joseph S. Ames,
Johns Hopkins University, Baltimore, Md.
Capt. Mark L. Bristol, United States Navy,
Director of Naval Aeronautics, Navy Department.
Prof. William F. Durand,
Leland Stanford Junior University, Stanford University, Cal.

Prof. John F. Hayford,
Northwestern University, Evanston, Ill.
Prof. Charles F. Marvin,
Chief, United States Weather Bureau.
Hon. Byron R. Newton,
Assistant Secretary of the Treasury, Treasury Department.
Prof. Michael I. Pupin,
Columbia University, New York, N. Y.
Lieut. Col. Samuel Reber, United States Army,
Officer in Charge Aviation Section, War Department.
Naval Constructor Holden C. Richardson, United States Navy,
Navy Department.
Brig. Gen. George P. Scriven, United States Army.
Chief Signal Officer, War Department.
Dr. S. W. Stratton,
Director, United States Bureau of Standards.
Dr. Charles D. Walcott,
Secretary, Smithsonian Institution.

RULES AND REGULATIONS.

The approved rules and regulations for the conduct of the work of the National Advisory Committee for Aeronautics, as approved by the President on June 14, 1915, are as follows:

RULES.

1. The committee may exercise all the functions authorized in the act establishing an advisory committee for aeronautics.
2. The committee, under regulations to be established and fees to be fixed, shall exercise its functions for the military and civil departments of the Government of the United States, and also for any individual, firm, association, or corporation within the United States: *Provided, however*, That such department, individual, firm, association, or corporation shall defray the actual cost involved.
3. No funds shall be expended for the development of inventions, or for experimenting with inventions for the benefit of individuals or corporations.

REGULATIONS FOR CONDUCT OF COMMITTEE.

Article I.

MEETINGS.

1. The annual meeting of the advisory committee shall be held in the city of Washington, in the District of Columbia, on the Thursday after the third Monday of October of each year. A semiannual meeting of the advisory committee shall be held on the Thursday after the third Monday in April of each year, at the same place.
2. Special meetings of the advisory committee may be called by the executive committee, by notice served personally upon or by mail or telegraph to the usual address of each member at least five days prior to the meeting.
3. Special meetings shall, moreover, be called in the same manner by the chairman, upon the written request of five members of the advisory committee.
4. If practicable, the object of a special meeting should be sent in writing to all members, and if possible a special meeting should be avoided by obtaining the views of members by mail or otherwise, both on the question requiring the meeting and on the question of calling a special meeting.
5. Immediately after each meeting of the advisory committee a draft of the minutes shall be sent to each member for approval.
6. There shall be monthly meetings of the executive committee.

Article II.

OFFICERS.

1. The officers of the advisory committee shall be a chairman and a secretary, who shall be elected by the committee by ballot, to serve for one year.
2. The chairman shall preside at all meetings of the committee and shall have the usual powers of a presiding officer.
3. The secretary shall issue notices of meetings of the committee, record its transactions, and conduct the correspondence relating to the committee and to the duties of his office.

Article III.

COMMITTEES.

1. There shall be an executive committee which shall consist of seven members, to be elected by the advisory committee by ballot from its membership, for one year. Any member elected to fill a vacancy shall serve for the remainder of his predecessor's term. The executive committee shall elect its chairman.
2. The executive committee in accordance with the general instructions of the advisory committee, shall control the administration of the affairs of the committee, and shall have general supervision of all arrangements for research, and other matters undertaken or promoted by the advisory committee; and shall keep a written record of all transactions and expenditures, and submit the same to the advisory committee at each stated meeting; and it shall also submit to the advisory committee, at the annual meeting, a report for transmission to the President.
3. The executive committee is authorized to collect aeronautical information, and such portion thereof as may be appropriate may be issued as bulletins or in other forms.
4. There may be subcommittees appointed by the executive committee, the chairmen of which shall be members of the advisory committee, and the other members of which may or may not be members of the advisory committee.
5. All officers and all members of committees hold office until their successors are elected or appointed.

Article IV.

FINANCES.

1. No expenditures shall be authorized or made except in pursuance of a previous appropriation by the advisory committee, or by authority granted by the advisory committee to the executive committee.
2. The fiscal year of the committee shall commence on the 1st day of July of each year.
3. The executive committee shall provide for an annual audit of the accounts of the advisory committee, and shall submit to the annual meeting of the advisory committee a full statement of the finances and work of the committee, and a detailed estimate of the proposed expenditures for the succeeding fiscal year.
4. The Paymaster General of the Navy shall be the disbursing officer for such funds as may be appropriated for the use of the advisory committee. The chairman of the advisory committee, or the chairman of the executive committee, if authorized by the advisory committee, shall approve all accounts for the disbursement of funds.
5. Contributions of funds or collections for any purpose for aeronautics may be made to the Smithsonian Institution, and disbursements therefrom shall be made by the said institution.

Article V.

AMENDMENTS.

1. Amendments to these rules and regulations may be made at any stated meeting by a two-thirds vote of the advisory committee, subject to approval by the President.

ORGANIZATION OF COMMITTEE.

Pursuant to a call of the Secretary of War, by direction of the President, the members of the Advisory Committee for Aeronautics met in the office of the Secretary of War on April 23, 1915. The first meeting was called to order by the Secretary of War, and a temporary organization was effected. Brig. Gen. George P. Scriven, United States Army, was elected temporary chairman, and Naval Constructor Holden C. Richardson, United States Navy, temporary secretary.

In conformity with the designation in the call for the first meeting, issued by the Secretary of War, the word "National" was prefixed to the terms "Advisory Committee for Aeronautics."

Under the authority of the rules and regulations the organization was completed by the election of officers for one year as follows:

Brig. Gen. George P. Scriven, United States Army, chairman.
Naval Constructor Holden C. Richardson, United States Navy, secretary.

OFFICERS AND MEMBERS OF EXECUTIVE COMMITTEE.

OFFICERS.

Dr. Charles D. Walcott, chairman.
Naval Constructor H. C. Richardson, secretary.

MEMBERS.

Prof. Joseph S. Ames.
Capt. Mark L. Bristol, United States Navy.
Prof. Charles F. Marvin.
Prof. Michael I. Pupin.
Lieut. Col. S. Reber, United States Army.
Dr. S. W. Stratton.

WORK OF THE COMMITTEE.

The executive committee was directed to consider a program of investigation and procedure intended to carry into effect the purposes of the act creating the advisory committee, and to report the same with recommendations. The recommendations and the report of the executive committee were approved by the general committee at the annual meeting, and are incorporated in this report.

The authority of the advisory committee was given to the executive committee to institute special investigations that promised to be of service to aviation. The results are shown in the reports forwarded herewith as appendices. The limited time and the limited funds available both combined to prevent the accomplishment of additional work of importance, which might otherwise have been undertaken.

The executive committee instituted an investigation of facilities available in various colleges, technical and engineering institutions, and among manufacturers and various aeronautic societies, for the carrying on of aeronautic investigations. It was found that limited facilities were available for attacking various problems of aeronautic design, and that same could be made available to the committee, provided funds were available to carry out the necessary experiments, or to engage competent engineers on different phases of the work. A number of institutions have available mechanical laboratories and engineering courses capable of application to aeronautics, but only the Massachusetts Institute of Technology and the University of Michigan so far offer regular courses of instruction and experimentation. Worcester Polytechnic Institute has conducted experiments on full-sized propellers mounted on a whirling table turning on a pivot in the middle of a pond. The arms of the whirling table are provided at one end with a dynamometer for measuring the torque and thrust and revolutions of the propeller, and at the center a control stand for controlling the speed of the propeller. The speed of the rotating arm is controlled by means of a drag in the water, attached to the opposite end of the rotating arm. While there are objections to this method of testing in a circular path in the open, the method is ingenious and the results obtained should be valuable, particularly for comparison. In general, however, it appears that the interest of colleges is more one of curiosity than that of considering the problem as a true engineering one, requiring development of engineering resources and, therefore, as not yet of sufficient importance to engage their serious attention. Manufacturers are principally interested in the development of types which will meet Government requirements or popular demand, but which will not involve too radical or sudden changes from their assumed standard types.

As a result of the investigations of the facilities available in this country, and of the problems requiring solution, it is found that many problems exist requiring careful and thorough investigation, which could be attacked with facilities which can be placed at the disposal of the committee, provided sufficient funds are made available. Considerable work has already been accomplished in aeronautics with which the general public is not acquainted. This covers lines of development and investigation which if published would save money and effort on the part of individual investigators and inventors who are now duplicating investigations already made by others. Some of these investigations have resulted in improvement; others have shown the futility of development on certain lines. Some of this information is already embodied in reports which are only accessible to a few interested parties who know of its existence. Much can be accomplished by making the results of such investigations accessible, either in a reference library or in the form of reports.

PROBLEMS.

Of the many problems now engaging general attention, the following are considered of immediate importance and will be considered by the committee as rapidly as funds can be secured for the purpose:

A. *Stability as determined by mathematical investigations.*—The reduction to practical form of the analytical methods of determining the stability of aeroplanes from design data, without necessarily requiring wind-tunnel tests or full-sized tests of same.

(*a*–1) This will require first a thorough investigation by competent mathematicians and physicists of the work so far accomplished by different authorities of prominence in this country and abroad. The publication of many valuable treatises which have already been prepared is not sufficient, as many of these treatises are presented in such highly technical manner that they are not in form to be comprehended by designers and manufacturers who are otherwise fitted for practical accomplishments in aeronautical work.

(*a*–2) Another phase of these investigations is the natural tendency on the part of designers and constructors to assume that mathematical theories are of use only to those who are mathematically inclined; and there is objection, frequently based on good ground, that in order to arrive at solutions of the complicated equations involved, mathematicians necessarily make certain assumptions which are not always based on actual conditions, and though the conclusions drawn are logical, based on the assumptions made, there is reasonable doubt if the resulting conclusions apply to a complete machine. Until such distrust is overcome, true engineering progress in the design of air craft will be hampered and progress will depend, much as in the past, on "cut and try" methods. However, when the mathematician can explain by a correct application of mathematical analysis why certain things occur in practice, for which no satisfactory solution has been found, a start will be made toward the removal of the distrust of mathematical formulæ and real progress begin. As an instance of such application attention is invited to the report of Hunsaker and Wilson, of the Massachusetts Institute of Technology (Report No. 1), in which it is shown that although an aeroplane is designed so that statically it is stable to a satisfactory degree, it does not necessarily follow that the machine is dynamically stable; and in fact in the case investigated it was found that while within certain limits the machine was dynamically stable, the limits of dynamic stability were much smaller than supposed, and at low speeds dynamic instability existed to such a degree as to require correction in the design. Such instability has probably been the cause of a large number of accidents, and yet constructors and designers were at a loss to explain the cause until demonstrated by the test of a model of an actual machine in a wind tunnel.

B. *Air-speed meters.*—An important problem to aviation in general is the devising of accurate, reliable, and durable air-speed meters and other aeronautic instruments for the navigation and control of air craft.

(*b*–1) The most important of these problems is that of the prevention of "stalling" of aeroplanes. The committee considers "stalling" responsible for a very high percentage of aeroplane accidents. It is believed that at present the possibility of stalling exists in all machines, except a few which have been specially designed to have a high degree of inherent longitudinal stability; but it appears desirable and necessary to use machines of a normal type, because of certain considerations affecting the methods of using these machines in warfare and also because of certain restrictions involved in the performances of machines of the inherently stable type. The best means of preventing stalling is the development of a reliable air-speed meter, which by its indications will give warning of the approach to those conditions which produce stalling. A number of such meters already exist in different forms, but none so far developed or brought to the attention of the committee is considered to be satisfactory or reliable.

(*b*–2) The Bureau of Standards is now engaged in investigation of such meters, and attention is invited to the report of Prof. Herschel and Dr. Buckingham of the bureau on Pitot tubes. (Report No. 2.) In addition to the investigation by the Bureau of Standards referred to, a number of manufacturers and individuals are already engaged in the development of air-speed meters. The development of other forms of aeronautical instruments is in a more satisfactory condition and is progressing steadily.

C. *Wing sections.*—The evolution of more efficient wing sections of practical form, embodying suitable dimensions for an economical structure, with moderate travel of the center of pressure and still affording a large range of angle of attack combined with efficient action.

D. *Motors.*—The development of high powered aeronautic motors of the lightest possible construction consistent with reliable operation and the maximum economy of fuel and oil consumption.

(*d*–1) The committee is of the opinion that with proper encouragement, satisfactory types of aeroplane motors can be developed which will rival in efficiency and certainty of operation the automobile motors of to-day and the best aeronautic motors which have been developed abroad. This will require that manufacturers having capable organizations at their disposal shall become interested in aeronautic development and see a market for their products. In the meantime, both the War and Navy Departments are already engaged on this problem and may be expected to contribute valuable information in the near future. By employing some of the most competent engineers of this country on investigations of the many complicated details of design of gas engines, the committee should be able to make substantial progress on these lines.

(*d*–2) An efficient form of radiator is needed, which will provide satisfactory cooling for water cooled motors, without involving too much weight or resistance, and it is desirable that the principles of design should be carefully investigated with a view to the development of a type which will embody the different qualities required in such a manner as to have the least unfavorable effect on the aerodynamic efficiency of aircraft.

(*d*–3) An efficient form of muffler for internal combustion engines is necessary for military aircraft. An attempt by the committee to obtain a report on this subject has so far been unfruitful, though it is hoped that satisfactory progress can be made in the near future. The problem is not a simple one on account of the high power of the motors used.

E. *Propellers.*—The development of more efficient air propellers, which will hold their efficiency at high values over a large range of speed of advance. Also improvements in design of propellers relative to materials and details of construction, leading toward reduced weight and greater permanence of form, together with provision for ready repairs and moderate cost of construction.

(*e*–1) It is considered that this country has available a number of competent authorities on propellers for water craft, who are thoroughly equipped to place the design of aeronautic propellers on a satisfactory basis, and it is advisable that the committee should have at its disposal funds to engage such talent on the development of propeller design. A great deal of work has already been accomplished abroad and is available for use, and though high efficiency of design has been attained abroad, the progress on these lines in this country has been limited.

F. *Form of aeroplane.*—Improvements in the form of aeroplane leading toward natural inherent stability to such a degree as to relieve largely the attention of the pilot while still retaining sufficient flexibility and control to maintain any desired path, without seriously impairing the efficiency of the design.

G. *Radio-telegraphy.*—It is exceedingly desirable that the committee should investigate the question of apparatus to be used in sending messages from aeroplanes in order that there may be sure means of communication between the aeroplane and fixed base stations.

PHYSICAL PROBLEMS.

Beside the more general problems, the following problems of a physical rather than aeronautical nature are of particular interest:

A. *Noncorrosive materials.*—The availability of noncorrosive materials for construction details and fittings; such materials to have qualities comparable with those attainable in different grades of steel, both as to physical properties and as to reliability.

(*a*–1) Work on this line is already well in hand at the Bureau of Standards.

B. *Flat and cambered surfaces.*—A complete investigation of the effects of combinations of flat and cambered surfaces joined by hinges, as is usual in the construction of rudders.

(*b*–1) No extended work on these lines has yet been carried out, though facilities exist at the Washington Navy Yard and at the Massachusetts Institute of Technology.

C. *Terminal connections.*—The development of reliable terminal connections for truss wires, which will develop, if practicable, the full strength of the wire without involving too much bulk or weight, and without involving danger due to unusual care being required in attaching same; that is, the solution must be a practical and not a laboratory one.

(*c*–1) A valuable contribution to this question is submitted in the report volunteered by the John A. Roebling's Sons Co. (Report No. 3.)

D. *Characteristics of constructive materials.*—An accurate and authentic determination of the physical characteristics of all classes of woods, metals, and fabrics which enter into the present-day types of construction.

(*d*–1) Considerable information on these lines is undoubtedly available in the laboratory records of various technical institutions, but is not generally accessible. The Bureau of Standards is well equipped for this line of work.

E. *Generation of hydrogen.*—The generating of hydrogen economically at sea on a ship rolling in a seaway is a problem to be solved.

(*e*–1) There are many systems of generating hydrogen on land, but many of these would be defective if installed aboard ship. Any installation for this purpose aboard ship should combine capacity, compactness and economy, and certainty of operation to the highest degree.

F. *Standardization of nomenclature.*—The standardization of aeronautical nomenclature is most desirable for the whole country.

(*f*–1) This question has already been attacked by the Army and Navy, and the reports of these branches of the service should form a good basis for the work of the committee.

G. *Standardization of specifications.*—Standardization of specifications for aeroplane materials for use of the Government and people of this country.

(*g*–1) A proposition on these lines from a prominent manufacturer has already been received, and the committee has taken steps toward the development of such specifications.

H. *Bibliography of aviation.*—Revision and continuation of the bibliography of aviation.

I. *Collection, revision, and issuance of reports* and bulletins covering the state of the art of aeronautics, the primary purpose being to avoid as far as possible unnecessary duplication of work which has already been well done.

J. *Limitation of size.*—Determination of the present upper limits with regard to size and carrying capacity, with special reference to the means by which those limits may be extended, it being very important to know approximately the present limitations in size and carrying capacity and to what elements these limitations apply, and why.

K. *Causes of accidents.*—Securing and carefully compiling of reports of causes of accidents in aeronautics.

(*k*–1) While conditions have changed decidedly from the early days of aeronautics in this country, there is still evidence of carelessness in the design and operation of aeroplanes. It would appear as coming within the province of this committee that legislation should be enacted toward obtaining control of this feature at an early date. However, any such legislation should be most carefully considered and the views of those interested should be obtained. This is particularly necessary, as already a number of attempts have been made toward legislation in different States, with the result that in one State, at least, experimental work is practically prohibited, not because inventors and constructors can not comply with the law, but because the operation of the law requires facilities which do not exist in the State in which the laws have been passed. With a view toward determining the requirements of such legislation, it is proposed that a beginning be made by requesting that all accidents be reported to the advisory committee on forms to be published by the committee, embodying a set of categorical questions, the answers to which may lead to a determination of the principal causes of accidents. In cases where such accidents result in the maiming or killing of spectators or flyers, such questions should be answered by the investigating authorities. The word "request" is used in view of the possible conflicts of State and Federal authority and jurisdiction; and whereas it is very probable that both State and Federal authorities would be willing and glad to cooperate in this work in response to a request, it is not clear that such cooperation would follow legislation, unless carefully worked out.

STANDARDS OF WORK.

While the functions of the committee are not considered directly to be concerned with the question of preparations for defense, in the opinion of the committee it is of greatest importance that the manufacturers of aircraft and the War and Navy Departments, at present the principal consumers, should come to a definite agreement as to the standards of work necessary to facilitate production and repairs. Of the most importance in this line is the preparation of standard specifications for materials and tests. In this manner the producers and consumers will have a clear understanding on which to base contracts, and under the stress of war conditions the multiplication of aircraft would be greatly facilitated.

IMPORTANCE OF WORK TO ARMY AND NAVY.

The importance of aircraft to the War and Navy Departments, in view of the utilization of such craft in the present war in Europe, is so evident that no further comment is offered. It is, however, strongly recommended that every consideration should be given toward the provision of adequate facilities for initiating and conducting the important experimental work necessary for the efficient development of both branches of the service on aeronautical lines.

QUARTERS FOR COMMITTEE.

By courtesy of the Secretary of War, the first meetings of the advisory committee and the executive committee were held in the reception room in the office of the Secretary of War, and the annual meeting was also held in that room. In accordance with the instructions of the advisory committee, the executive committee attempted to obtain quarters in the State, War, and Navy Department Building, but found that each of these departments was so crowded for space that none was available. However, through the courtesy of the Secretary of War, the meetings of the executive committee have been held in the private office of the officer in charge of the Aviation Section, War Department, and the office work of the committee has been temporarily conducted and the files have been kept in a portion of a room adjoining the same office. While such improvised quarters for the committee served their purpose, such temporary quarters are not satisfactory or suited to the needs of the committee. Suitable quarters can be obtained at moderate cost in one of the several office buildings centrally located in the city of Washington. It is for this reason the committee recommends that provision for suitable quarters be made in the next appropriation act.

EXISTING FACILITIES FOR AERONAUTIC INVESTIGATION IN GOVERNMENT DEPARTMENTS.

For the conduct of the work outlined, limited facilities already exist in different Government departments about as described in general terms in the following. These facilities can be augmented by the facilities described as existing in the different technical institutions, etc., previously referred to:

A. The Bureau of Standards is well equipped for carrying on all investigations involving the determination of the physical factors entering into aeronautic design, and is prepared to take up such matters as are of sufficient general interest to warrant same.

B. The Navy Department is equipped with a model basin and wind tunnel at the Washington Navy Yard, with adequate shop facilities for carrying on the work in a limited way, and is also constructing at the Washington Navy Yard a plant for the testing of aeronautic motors and devices involved in their operation, which will be in commission at an early date. Also, under the Navy Department steady progress is being made in attacking practical problems involved in the development of the Navy aeronautic service at its station at Pensacola, and theoretical and practical designs are in hand in the Bureaus of Construction and Repair and Steam Engineering.

C. The War Department has limited facilities at the flying school at San Diego, for investigations of interest to that branch of the service, and is able to carry out in a limited way experiments of interest to the service on full-sized machines, for which work it has the assistance of technical experts.

D. The Weather Bureau is well equipped for the determination of the problems of the atmosphere in relation to aeronautics, and Prof. Marvin, a member of the advisory committee, is the chairman of a subcommittee engaged on this problem. The work, however, will necessarily be limited until the necessary funds for more extensive work become available. There is already available in the records of the bureau much information of value which requires compilation in a form suited to aeronautic requirements, and this work is the subject of a preliminary report included in the annual report of the committee.

E. The Smithsonian Institution has been engaged for a number of years on the compilation of the bibliography of aeronautics, and is prepared to continue this work for at least two years more with the funds at its disposal. The institution has also contributed funds toward the development of the work of the subcommittee of the Weather Bureau in its investigation of the problem of the atmosphere in relation to aeronautics.

Itemized statement of expenditures under appropriation "Advisory Committee for Aeronautics, 1915."

No.	Payee.		Amount.
1150	J. F. Victory		$26.67
1155	Underwood Typewriter Co		67.50
1156	Union Envelope Co		4.23
1157	Andrews Paper Co		.79
1158	Municipal Supply Co		7.00
1159	Roberts Numbering Machine Co		2.40
1160	Globe-Wernicke Co		1.75
1161	E. J. Murphy Co		2.05
1162	Shaw-Walker Co		10.32
1163	do		9.16
1229	Transfer (supplies drawn from navy yard)		51.26
1420	A. B. Dick Co		75.00
1435	Postal Telegraph Cable Co		3.89
1436	Western Union Telegraph Co		20.39
1550	Joseph N. Snellenburg		67.00
1615	Prof. Michael I. Pupin		21.80
1617	do		21.80
1640	Massachusetts Institute of Technology		800.00
1641	Columbia University		1,500.00
7669	Prof. John F. Hayford		26.25
7670	Prof. William F. Durand		213.10
7775	Prof. Joseph S. Ames		3.70
			2,936.06
	OBLIGATED.		
	Cornell University	$1,000.00	
	United States Rubber Co	1.00	
	Goodline Manufacturing Co	1.88	
			1,002.88
	Total expended and obligated		3,938.94

A statement showing the expenditures of the committee is submitted herewith.

Summary of expenditures under appropriation "Advisory Committee for Aeronautics, 1915."

Clerical services	$26.67
Office furniture	67.00
Stationery and equipment	233.34
Members' traveling expenses	286.65
Telegrams	24.28
Technical reports from Massachusetts Institute of Technology, United States Rubber Co., Columbia and Cornell Universities	3,301.00
Total expended and obligated	3,938.94
Unobligated balance turned into Treasury	1,061.06
Amount of appropriation	5,000.00

CONCLUSIONS.

From the above, it will be apparent that utilizing all facilities at present available, the progress that can be made will be fragmentary and at best lack that coordination which is necessary to accomplish in a direct, continuous, and efficient manner, and as rapidly as practicable, the important work now in sight. If the committee is to be prepared to keep pace with the increasing needs of the very rapid development already under way, stimulated by the unusual conditions existing in Europe, the facilities and technical assistance recommended are essential. While the needs at present are principally those which have an important bearing on military preparedness, the committee is of the opinion that aeronautics has made such rapid strides that when the war is over there will be found available classes of aircraft and a trained personnel for their operation, which will rapidly force aeronautics into commercial fields, involving developments of which to-day we barely dream.

Respectfully submitted.

George P. Scriven,
Brigadier General, Chief Signal Officer of the Army,
Chairman.

REPORT No. 2.

IN TWO PARTS.

INVESTIGATION OF PITOT TUBES.

BY THE UNITED STATES BUREAU OF STANDARDS.

Part 1.—THE PITOT TUBE AND OTHER ANEMOMETERS FOR AEROPLANES.

By W. H. HERSCHEL,

Part 2.—THE THEORY OF THE PITOT AND VENTURI TUBES.

By E. BUCKINGHAM.

CONTENTS OF REPORT NO. 2.

REPORT NO. 2.

PART 1.

THE PITOT TUBE AND OTHER ANEMOMETERS FOR AEROPLANES.

By W. H. Herschel.

1. INTRODUCTION.

The air pressures on the wings of an aeroplane, and therefore the sustaining power of the wings and the stresses to which the whole structure is subject, depend on the speed of the machine relative to the air through which it is moving. The measurement of this speed—particularly near the lower limit where the sustaining power becomes deficient and there is danger of stalling, or at very high speeds where any movement of the controls may give rise to dangerously large stresses—is evidently a matter of importance, and the use of a reliable anemometer or speedometer is highly desirable. The aim of the following paper is to describe the principles of operation of some of the instruments which have been devised or used for this purpose and to discuss their characteristics, so far as it can be done from a general point of view or on the basis of available information, without undertaking new experimental investigations.

Since the Pitot tube is the instrument which has been most commonly used in the United States and Great Britain as a speedometer for aeroplanes, it will be treated first and somewhat more fully than the others.

2. GENERAL REMARKS ON THE PITOT TUBE.

The speed-measuring device known, after its inventor,[1] as the Pitot tube contains two essential elements. The first is the dynamic opening, or mouth of the impact tube, which points directly against the current of liquid or gas of which the speed is to be measured, and receives the impact of the current. The second is the static opening for obtaining the so-called static pressure of the moving fluid, i. e., the pressure which would be indicated by a pressure gauge moving with the current and not subject to impact. To avoid the influence of impact, the static opening points at right angles to the dynamic opening. If the two openings are connected to the two sides of a differential pressure gauge, the gauge shows a head which depends on

[1] Origin and Theory of the Pitot Tube, H. E. Guy Engineering News, June 5, 1913, p. 1172.

the speed and density of the current in which the tube is placed, and which may be used as a measure of the speed of the fluid past the Pitot tube.

If the fluid is a liquid and the two openings are connected to a U gauge containing the same liquid, the gauge shows a head h and the usual formula for computing the speed S is

$$S = C\sqrt{2gh} \tag{1}$$

in which g is the acceleration of gravity and C is the "coefficient" or "constant" of the given instrument. If the head h is read on a gauge containing a liquid of density d while the density of the fluid (either gas or liquid) in which the Pitot tube is immersed is ρ, equation (1) takes the modified form:

$$S = C\sqrt{2g\frac{d}{\rho}h} \tag{2}$$

According to the elementary theory as usually given, C should be exactly 1, and in practice it is in fact in the neighborhood of unity, when the instrument is properly designed and used with suitable precautions.

As regards design, it may be said that numerous recent investigations have shown that almost any sort of dynamic opening is satisfactory, but that the static opening must be designed with great care in order that the coefficient C may be set equal to unity without involving any sensible error in the result of using equation (2). Rowse,[1] for example, has made an extensive comparison of various forms of Pitot tube, which confirms previous results obtained by White,[2] Taylor,[3] Treat,[4] and others. With the most satisfactory tube tested, the experimental error in S was found to be not over 0.2 per cent. whether the static pressure was taken from a piezometer ring,[5] or from the static opening of the tube as supplied by the maker. The standard of comparison was a Thomas electric meter, which was assumed to give correct readings.[6]

It may therefore be concluded that by proper construction the Pitot tube can be made to have a coefficient so near unity that for all ordinary purposes the equation

$$S = \sqrt{2g\frac{d}{\rho}h} \tag{3}$$

may be regarded as sensibly accurate.

3. ERRORS WHICH MAY OCCUR IN THE INTERPRETATION OF PITOT-TUBE READINGS.

The simple theory which leads to equation (3) assumes that the tube is always pointed exactly against the current and that the observed head, h, is due to the instantaneous value of the speed S.

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[1] W. C. Rowse, Trans. A. S. M. E., 1913, p. 633.
[2] W. M. White, Journal Association of Engineering Societies, August, 1901.
[3] D. W. Taylor, Society of Naval Architects and Marine Engineers, November, 1905.
[4] Chas. H. Treat, Trans. A. S. M. E., 1912, p. 1019.
[5] The piezometer was simply an air-tight annular space about the pipe, connected with the interior of the pipe by six small holes.
[6] For accuracy of Thomas meter see C. C. Thomas, Journal Franklin Institute, vol. 172, p. 411, and Proceedings Am. Gas Inst., vol. 7, 1912, p. 339. For more recent experimental verifications of equation (2) without use of the Thomas meter, see F. H. Bramwell, Report of British Committee on Aeronautics, 1912-1913, p. 35, and Wm. Cramp, Manchester Memoirs, vol. 58, part 2, sec. 7.

These assumptions are never exactly fulfilled in ordinary practice and accordingly exact results may not be obtained, even when no fault is to be found with the instrument itself.

In the first place, it is impossible to read the gauge instantaneously; furthermore, there is always a time lag between the openings and the gauge. Accordingly, even when the current does not change in direction, if its speed varies rapidly all that can be observed is the mean value of h over a certain time interval, and this value does not correspond to the arithmetical mean value of S over the same interval, even if the interval is long compared with the time lag, as has been shown experimentally by Rateau.[1]

Disregarding the time lag, the value of S computed by equation (3) will be the root-mean-square speed, which is always larger than the arithmetical mean speed. Hence if, for example, the Pitot tube is being used to determine the discharge through a steam main feeding a reciprocating engine, the computed discharge will be greater than the true discharge. This error is not likely to be very large. If, for instance, the speed varies sinusoidally with time from 0.5 to 1.5 times its arithmetical mean value, the linear speed computed by equation (3) will be 1.0607 times the arithmetical mean speed which determines the total flow, or a trifle over 6 per cent. too large.

A second cause of error is rapid variability in direction of the current, which makes it impossible to keep the tube pointed correctly even when mounted on a vane. If, as is usually the case, it is desired to measure merely the component velocity in a fixed direction, the eddies which almost always exist may introduce a considerable error when this component velocity is computed by equation (3). If the variations of direction are small, the error is due almost entirely to the effect on the static opening and not to change of the direction of impact on the dynamic opening.[2]

This source of error is much reduced in the Dines tube, a form of Pitot tube in which the static opening consists of a number of round holes or longitudinal slits in a hollow cylinder placed with its axis perpendicular to the direction of the impact tube and to the plane in which the variations of direction are expected to occur. When this instrument is employed as an anemometer, its principal use, the cylinder is of course vertical.

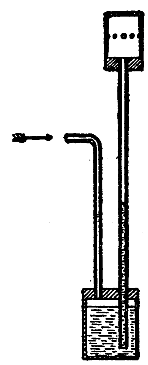
The heads given by the Dines tube are sensibly independent of errors in direction up to about 20° on each side of the mean. To offset this advantage, the instrument is somewhat less sensitive than the ordinary Pitot tube, the coefficient C being greater than 1. Furthermore, each tube must be calibrated separately, and it is not even certain that the coefficient is strictly constant for each tube. Data by Dines[3] show a constant coefficient $C=1.53$. Jones and Booth[4] find values from 1.20 to 1.70 for different tubes. Zahm[5] finds values from 1.42 to 1.50, depending on the speed.

It has sometimes been doubted whether the coefficient C of a given Pitot tube was dependent solely on the relative speed of the fluid and the tube, the suggestion being that a tube standardized by mov-

[1] Annales des Mines, 1898, p. 341.
[2] L. F. Moody, Proceedings Engineers' Society of Western Pennsylvania, May, 1914.
[3] Quarterly Journal, Royal Meteorological Society, vol. 18, 1892.
[4] Aeronautical Journal, July, 1913, p. 195.
[5] Physical Review, 1903, p. 410.

ing through a quiescent medium, as with a whirling arm in air, may not give correct results when used to determine the velocity of a fluid past a fixed point. It is difficult to see how the Pitot tube can respond to anything but velocity relative to itself. At all events, experiments by Fry and Tyndall[1] have shown that while there was some apparent disagreement at speeds below 11 miles per hour (17.7 kilometers) where the experimental errors were large, for higher speeds, up to 36 miles per hour (58 kilometers) both methods of standardization gave the same result.

Which method of standardization should be adopted—motion of the tube or motion of the fluid—may, nevertheless, depend on the purpose for which the instrument is intended. It is impossible in practice to set up an artificial current of fluid which shall have a high speed and not be turbulent and full of eddies; and the only conditions to which equations (1) and (2) refer are, in strictness, those of steady stream-line flow or steady motion of the tube in a quiescent fluid. If



Dines anemometer.

the tube is to be used in a very turbulent medium, as, for example, in measuring the discharge from a fan, it should be standardized in a stream of fluid in which the turbulence is about the same as it will be under the working conditions. It might very well happen that a given tube when tested on the whirling arm or by moving through still water gave a coefficient $C=1$, while if the tube were tested in a turbulent current some other value of C was obtained. If the tube were to be used to measure the average speed of a similarly turbulent current, this second coefficient should be used and not the value $C=1$.

Apparent errors and inconsistencies in the results obtained by equations (1) and (2) have probably been due in part to disregarding the foregoing obvious considerations.

4. WORKING FORMULAS FOR PERFECT PITOT TUBES.

It will be convenient to collect here, for reference, certain practical working forms of equation (3) for the perfect or ideal Pitot tube, that is, for a tube having the coefficient C equal to unity. If the tube does not satisfy this condition, whether on account of its design or from

[1] J. D. Fry and A. M. Tyndall, Philosophical Magazine (6), vol. 21, p. 348 1911.

the necessary circumstances of practical use, the value of C must be determined by experiment, and the values of S given by the following equations are then to be multiplied by the observed values of C.

We start by inserting the value $g=32.17$ ft./sec.^{2} or 9.81 m./sec.^{2} in the general equation (3), viz:

$$S=\sqrt{2gh\frac{d}{\rho}} \tag{3}$$

in which S = the speed of the current,
h = the head on the differential gauge,
d = the density of the liquid in the gauge,
ρ = the density of the current.

From this we obtain special equations for practical use.

(A) *Any two fluids.*—d and ρ may have any values but are to be measured in the same units. The value of S is given by the equation

$$S=X\sqrt{h\frac{d}{\rho}} \tag{4}$$

with the values of X shown in Table 1 for various methods of expressing S and h.

TABLE 1.—*Values of X for equation (4).*

h measured in—	S measured in—	X.
Inches of liquid of density d	Ft./sec	2.316
	Ft./min	138.9
	Mile/hour	1.579
Mm. of liquid of density d	M./sec	.1411
	M./min	8.404
	Km./hour	.5043

(B) *Any moving fluid, gauge liquid water.*—The value of S is given by the equation

$$S=Y\sqrt{\frac{h}{\rho}} \tag{5}$$

with the values of Y shown in Table 2.

TABLE 2.—*Values of Y for equation (5).*

h measured in—	ρ measured in—	S measured in—	Y.
Inches of water at 68° F.=20° C	Lbs./ft.^{3}	Ft./sec	18.28
		Ft./min	1097
		Mile/hour	12.46
Mm. of water at 68° F.=20° C.	Kgm./m.^{3}	M./sec	4.426
		M./min	265.5
		Km./hour	15.93

When the Pitot tube is to be used in air, the air density ρ for use in equations (4) and (5) may be found as follows:

Let B = the barometric pressure.

Let t = the temperature of the air.

Let P = the pressure of saturated steam at $t°$, from the steam tables.

Let H = the relative humidity.

Then in English units, if B and P are in inches of mercury and t in degrees F.,

$$\rho = 1.327 \frac{B - 0.376PH}{460 + t} \text{ lbs./ft.}^3 \tag{6}$$

or in metric units, if B and P are in millimeters of mercury and t in degrees C.,

$$\rho = 0.464 \frac{B - 0.376PH}{273 + t} \text{ kgm./m.}^3 \tag{6a}$$

All the numerical data given in this section are accurate enough to permit of computing the speed to within 0.1 per cent. Actual values computed from equation (6) may be found from Table 7, section 13. The calculations required by equation (6) may be avoided by the use of diagrams given by Rowse[1] and Taylor.[2] Hinz[3] gives a diagram showing the gas constant of moist air, which may be used in place of equation (6a).

5. ERRORS OF THE PITOT TUBE AT VERY HIGH SPEEDS.

The theory of the action of the Pitot tube, as given in Part 2 of this paper, shows that the equations given in the preceding sections must be expected to require a correction if the observed pressure difference is enough to compress the fluid sensibly. This will never occur when liquids are in question, though when the instrument is used for measuring the speed of a gas the correction required to allow for compressibility might become sensible at high speeds. But for the highest speeds attained by aeroplanes, say 130 miles per hour, the correction computed from the theory is less than 0.5 per cent., an amount which is altogether negligible in comparison either with the errors of observation or with the uncertainties of the theory itself, which is far from convincingly rigorous.

6. GENERAL REMARKS ON RESISTANCE ANEMOMETERS.

When a fixed obstruction is placed in a current of fluid, it experiences a force in the direction of flow which depends upon and may be used as a measure of the speed of the current. The force depends on the relative motion and is the same, at the same relative speed, when the fluid is at rest and the body moves through it, the force then appearing as a resistance to the motion. It is the resultant of forces exerted on the elements of the surface of the body (*a*) normally by the pressure, which varies from point to point; and (*b*) tangentially

[1] Loc. cit., p. 690.
[2] Loc. cit., p. 39, and plates 33 and 34.
[3] Adolf Hinz, Thermodynamische Grundlagen der Kolben und Turbokompressoren, p. 42.

by skin friction of the fluid moving along the surface. Since we are now interested only in devices which may be used as anemometers, we may as well, for the future, say "air" instead of fluid, and "wind" instead of current.

As regards the pressure, there is always, on the windward or upstream side, a region of increased pressure, i. e., of excess above the general static pressure of the air; while on the leeward or downstream side there is a deficiency. In the Pitot tube, the obstruction consists of the impact tube with its open mouth at the upstream end. This receives the excess pressure and transmits it to the gauge. The instrument deals solely with the excess pressure on the upstream side, of an obstruction of particularly simple form, the drag due to skin friction and the suction on the downstream side having no effect on the reading of what we have called a perfect Pitot tube.

The next simplest case is that of a thin flat plate of regular outline set normal to the wind. The skin friction forces balance one another and the whole normal force on the plate is the surface integral of the excess of pressure on the front, over that on the back. If the plate is mounted so that the force of the wind on it can be measured, it constitutes a "pressure-plate anemometer."

Various devices which are in practical use may be regarded as intermediate between the Pitot tube and the pressure plate anemometer. Among these are the Dines tube (see p. 82), the "Stauscheibe," and the Pneumometer. The Stauscheibe is a metal disk about 1 cm. in diameter with holes in the centers of its two faces from which the pressures are led to the two arms of the U gauge, through the disk and through the support by which the disk is held prependicular to the current. The Pneumometer differs from the Stauscheibe only in details of construction. For both these instruments the coefficient of equation (1) has the value 0.854, the observed pressure difference being influenced by the suction at the downstream face as well as by the impact pressure on the upstream face.[1]

In the case of pressure plate anemometers, it is usually the total force acting on the obstruction in the wind that is measured, rather than a manometric pressure, although Stanton [2] used a diaphragm and air pressure to transmit the force acting on a plate to a manometer 50 feet away.

If the solid obstruction is anything else than a thin flat plate normal to the wind, skin friction as well as pressure contributes to the resultant force; and if the body is not symmetrical about an axis parallel to the wind, the resultant force will not in general be parallel to the wind, but the body will receive a side thrust in addition to the resistance in the direction of the wind, as, for example, when the wing of an aeroplane has both lift and drift. Any body mounted so that the force on it can be measured, provides a means of measuring the speed of the wind and may be used as an anemometer; but if the body is to be held in a fixed orientation with respect to the wind, it is evidently simplest, mechanically, to avoid side thrust by making the body symmetrical about the wind direction, preferably a figure of revolution about that axis. The resistance offered to the wind by a symmetrical body of given maximum section normal to the wind

[1] Rowse, loc. cit., p. 677 and 684. A. Gramberg, Technische Messungen, third edition, 1914, p. 99. Cramp, loc. cit., p. 14.
[2] T. E. Stanton, Collected Researches, National Physical Laboratory, Vol. V, 1909, p. 169.

depends greatly on its shape, being less for a sphere than for a flat plate normal to the wind, and still less for a somewhat elongated spindle-shaped body.

Whatever the shape of the body may be, unless it is a sphere its resistance to a given wind depends on its presentation, and by a suitable choice of shape this variation of the force with the orientation may be made quite large. The operation of the Robinson, or cup anemometer, depends on the fact that the resistance of a hemispherical cup is greatest when the concave side is pointed to windward, so that a wind blowing in the plane of rotation of the cups always produces a torque. In the so-called "bridled" form of this anemometer, the torque is measured statically and the instrument is then merely a rather complicated form of pressure-plate anemometer. In the ordinary form of the instrument, in which the cups are allowed to revolve freely, the speed of the wind is measured indirectly by observing the speed of rotation, the action of the wind on the cups being then still more complicated.

From the fact that the pressure recorded by the Pitot tube is proportional to the square of the speed, it might be surmised that the total force observed with a pressure-plate or other static resistance anemometer would probably also be nearly proportional to the square of the speed; and this is confirmed by experiment. The analogy between these anemometers and the Pitot tube is a very close one, the Pitot tube being in principle only a particularly simple kind of resistance anemometer.

We have next to speak somewhat more in detail of some special types of resistance anemometer.

7. THE WIND RESISTANCE OF FLAT PLATES.

The resistance of a flat plate normal to a wind of velocity S is nearly proportional to S^2 and this relation is sometimes represented by writing

$$P = KS^2 \qquad (7)$$

in which P is the force per unit area of the plate. The coefficient K is approximately proportional to the density of the air, but it varies with the size and shape of the plate. The independence of Pitot tube readings of the size and nature of the dynamic opening would lead us to expect that the pressure at the center of the front of the plate would be independent of the size and shape of the plate, and Stanton's[1] experiments confirm this expectation. But the suction on the back depends on size as well as speed, thus accounting for the variability of K and showing that P is only a fictitious pressure with no physical significance.

We shall confine our attention to square and round plates, for which the laws of the distribution of pressure are more simple than for very oblong rectangles.[2] When giving numerical values in "English units" pressure will be in pounds per square foot and speeds

[1] Loc. cit., p. 192.
[2] G. Finzi and N. Soldati, Engineering, Mar. 31, 1905, p. 397.

in miles per hour, while in "Metric units" pressure will be in kilograms per square meter and speeds in meters per second.

A. *Square plates.*—According to Eiffel [1] the value of the coefficient K of equation (7) in English units varies from 0.00266 for plates 4 inches square to $K=0.00326$ for plates 40 inches square or larger. The temperature and pressure of the air during the tests are not given. The corresponding metric values are 0.065 and 0.08. Bairstow and Booth [2] after analyzing the available data give the equation

$$F=0.00126\ (S\ l)^2+0.0000007\ (S\ l)^3$$

in which F is the total force in pounds, S is the speed in feet per second, and l is the length of side in feet. The equation refers to air at 760 mm. and 15° C. or 59° F. If S is measured in miles per hour the equation becomes

$$F=0.00271(Sl)^2+0.0000022\ (Sl)^3$$

and if put into the form (7), for the sake of comparison with Eiffel's results, it may be written

$$P=0.00271(1+0.0008\ Sl)S^2$$

the coefficient K depending on both S and l.

B. *Circular disks.*—For a circular disk 30 centimeters, or 11.8 inches, in diameter, Eiffel gives the value $K=0.00276$ English, or 0.0675 metric. Stanton [3] found the values $K=0.0027$ English (0.066 metric) by using a 2-inch disk. On the whole, Eiffel's results seem preferable, because the size of disk used by him is more nearly the desirable size for an anemometer.

As regards the relative importance of the front and back of the plate, it may be noted that in a wind of 10 meters per second or 22.4 miles per hour, Eiffel found that the front of his 12-inch disk accounted for 72 per cent of the whole resistance. Zahm [4] has pointed out that if a plate be surrounded by a sufficiently broad guard ring there will be no suction on the back, while the pressure on the front will be uniform and the same as indicated by a Pitot tube at the same speed.

Table 3 shows the force on a 12-inch disk for different wind velocities, the total resultant force being calculated from Eiffel's value of $K=0.00276$ English (0.0675 metric), and from Bairstow and Booth's formula for square plates, assuming, as some but not all experimenters have found, that the average pressure would be the same for a circular plate with a diameter equal to l, as for a square of side l.

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[1] G. Eiffel, The Resistance of the Air, p. 35.
[2] Report, British Advisory Committee for Aeronautics, 1910–11, p. 21.
[3] T. E. Stanton, Proceedings Inst. C. E., Vol. CLVI, 1903–4, part 2, p. 78.
[4] A. F. Zahm, Journal Franklin Institute, vol. 173, January–June, 1912, p. 256.

TABLE 3.—*Wind forces in pounds on a 12-inch disk.*

Wind speed S miles per hour.	Force in pounds according to Eiffel.	Force in pounds according to Bairstow and Booth.
30	1.94	1.97
40	3.47	3.50
50	5.40	5.53
60	7.80	8.00
70	10.60	11.01
80	13.88	14.48
90	17.55	18.48

TABLE 3A.—*Wind forces in kilograms on a 30-centimeter disk.*

Wind speed S kilometers per hour.	Force in kilograms according to Eiffel.	Force in kilograms according to Bairstow and Booth.
48.3	0.86	0.87
64.4	1.53	1.55
80.4	2.38	2.44
96.5	3.44	3.53
112.8	4.68	4.87
128.8	6.13	6.39
145.0	7.75	8.15

8. RESISTANCE OF SPHERES AND HEMISPHERES.

Next to thin plates and hemispherical cups the sphere has been most frequently employed in static resistance anemometers as the obstruction opposed to the wind. In addition to the fact that a sphere is symmetrical about all diameters, so that the indications of a sphere anemometer may be made independent of changes in wind direction, the sphere has the further advantage of simplicity of form so that it may readily be duplicated. A disadvantage of the sphere, as compared with thin plates, is the lower value of the coefficient K of equation (7).

According to W. H. Dines, as quoted by Lanchester,[1] K has a value of 0.00154 English for a sphere 6 inches in diameter, or 0.0378 metric for one 153 millimeters in diameter. Dines's tests were made with a velocity of 21 miles an hour (34 kilometers). Eiffel[2] gives K as 0.00045 (0.011 metric) and explains the difference between his value and that of 0.00112 (0.0275 metric) found at Göttingen, as follows: K decreases with an increase of velocity until a certain critical velocity is reached, after which K remains nearly constant at 0.00045 for the three spheres experimented upon. This critical velocity was found to be about 27 miles an hour for a 6-inch sphere, 16 miles for a 10-inch sphere, and 9 miles for a 13-inch sphere (12,

[1] F. W. Lanchester, Aerodynamics, p. 25.
[2] La Technique Aeronautique, 1913, p. 146.

7, and 4 meters per second, respectively, for the 16, 24, and 33 centimeter spheres). The high value of the Göttingen coefficient is, according to Eiffel, due to the fact that velocities of over 23 miles an hour (36 kilometers) can not be obtained at that laboratory. It will be noted that even for a 6-inch sphere the critical velocity is well below the lowest flying speeds used in practice.

Table 4 shows values of K for hemispherical cups, according to Dines.

TABLE 4.—*Values of K in equation (7) for hemispherical cups.*

	English.	Metric.	English.	Metric.	English.	Metric.
	Diameter of cup.					
	2½ in.	64mm.	5in.	127mm.	9in.	229mm.
Cup facing wind	0.00597	0.146	0.00386	0.095	0.00402	0.099
Cup with back to wind	.00239	.059	.00168	.041	.00138	.034

Since Dines used only the one speed of 21 miles an hour, there is a doubt whether his values would hold for higher speeds. It appears that with a cup there would be little if any reduction in diameter as compared with a plate giving an equal force, though the cup would have the advantage of greater strength for a given force and weight. The difference in the force acting on the cup in its two positions, which is the driving force of the Robinson anemometer, is clearly indicated by the table.

9. PRACTICAL FORMS OF RESISTANCE ANEMOMETER.

Maxim[1] used a pressure plate anemometer consisting of a disk with a spring resistance. His arrangement had the advantage of fairly uniform graduations of the scale, the spring acting indirectly, with variable leverage on the pressure plate.

In the pressure-plate anemometer of Dines[2] the variable resistance is furnished by a float partly immersed in water, the pressure on the plate being equal to the weight of a volume of water equal to that of the part of the float raised above the water level.

The 1914 catalogue of Aera, Paris, shows a pressure plate anemometer which is merely a speed indicator. It is supplied with three disks, so that it may be set for any speed between 50 and 75 miles an hour (80 and 120 kilometers). The pointer will then show whether the actual speed is above or below the normal. Aera also make an anemometer using a sphere, in the form of a pendulum. This instrument reads only to 45 miles an hour (72 kilometers) and has graduations coming closer together at higher speeds. It would be very inaccurate without some means for holding it vertical.

The Davis Lyall air speed indicator, made by John Davis & Son, of Derby, England, is a bridled anemometer of the screw type which should be held with its back to the wind, though the manufacturers

[1] H. Maxim, Natural and Artificial Flight, p. 70.
[2] Quarterly Journal, Royal Meteorological Society, vol. 18, 1892, p. 167.

do not provide it with an air vane to do this automatically. This defect is remedied in the Aera bridled anemometer. Concerning the Davis Lyall instrument, it is stated:

To avoid undue oscillation of the pointer a damper is provided—either magnetic or air. Such a damper is rendered necessary in measuring velocities in a natural wind which varies within wide limits.

When it is desired to investigate the gusty character of natural winds, the sensitiveness of a bridled anemometer becomes an advantage. Concerning a bridled anemometer consisting of five hemispherical cups attached to a vertical spindle by short arms, Stanton[1] says that this instrument is more sensitive to momentary gusts than any of the other recording instruments in common use.

10. THE ANEMO-TACHOMETER.

When anemometers of the screw type are used for high velocities, there is danger that the vanes will be deformed and the velocity indications become unreliable, and for this reason cup anemometers are more suitable for out-door work. Wilhelm Morell, of Leipzig, has placed on the market an anemo-tachometer illustrated in the Deutsche Luftfahrer.[2] This is a Robinson anemometer with tachometer attached for aeronautical purposes, the tachometer being an instrument, usually actuated by centrifugal force like a steam engine flyball governor, so that velocities may be read at a glance from the position of a pointer. It will be noted that with a tachometer, in contrast to a revolution counter, no measurement of a time interval is required. The anemo-tachometer also has the advantage of all Robinson anemometers that the wind vane may be dispensed with.

According to a communication from Morell, his anemometers are calibrated in a wind tunnel, built in accordance with designs of Prof. Prandtl of the University of Göttingen, in which air currents up to 78 miles per hour (125 kilometers), can be obtained. It is stated that some of these instruments have been in constant use for two years without needing recalibration.

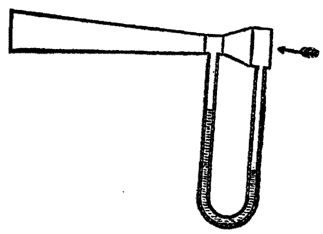
The anemo-tachometer, as well as other anemometers, should be attached to the aeroplane in such a manner that its indications are not influenced by the irregular and indeterminate wash of the machine and propeller. It has been proposed to lengthen the distance between the cups and the casing, so as to bring the cups above the upper supporting plane, while keeping the dial on a level with the pilot's line of vision. The objection to this lengthening is that it might change the friction and hence the indications of the instrument, and necessitate a special calibration.

What appears at first sight to be a solution of the difficulty, would be to provide the anemometer axis with a small electric generator, and use the electric voltage, thus generated to indicate speed of rotation by means of a voltmeter. We should anticipate, however, that electric indicating instruments, as at present constructed, would not long retain their accuracy when exposed to the vibrations on an aeroplane.

[1] Collected Researches, National Physical Laboratory, Vol. V, p. 174.
[2] Apr. 2, 1913, p. 168.

11. THE BOURDON-VENTURI ANEMOMETER.

The Venturi tube consists of a short converging inlet followed by a long diverging cone, the entrance and exit diameters being usually equal so that the tube may be inserted as a section of a pipe line. There is generally a short cylindrical throat. The converging part has somewhat the shape of a vena contracta, but its exact form is of little importance. The exit cone has a total angle of about 5°, this being found to give the minimum frictional loss for a given increase of diameter.



Venturi tube.

When a current of fluid passes through the tube, the pressure in the throat is less than at entrance to the converging inlet, by an amount which depends on the ratio of entrance to throat area, the density of the fluid, and the speed of flow. If the tube is provided with side holes and connections to a differential gauge by which this pressure difference may be observed, it constitutes a Venturi meter. The area ratio is a known constant for a given tube, so that when the density of the fluid is known the observed pressure difference may be used as a measure of the speed of flow. When the pressure difference is expressed as the height of a water column, it is known technically as the "head on Venturi."

Such an instrument may be used as an anemometer by pointing it so that the wind blows directly through it, and the observed head may then serve as a measure of the wind speed. Bourdon[1] employed the Venturi tube for this purpose in 1881, and it has been used recently as an aeroplane anemometer.

At a given speed, the observed head increases with the ratio α of entrance to throat area and the instrument may be made to give a much larger head than a Pitot tube. This is illustrated by the figures given in Table 5 for a tube in which $\alpha = 4$, the throat having half the diameter of the entrance. The data are for air at atmospheric pressure and 70° F. Column (2) gives the head which would be observed with a Pitot tube; column (3) that observed by Bourdon; and column (4) the ratio of (3) to (2).

[1] Annales des Mines, September and October, 1881; Comptes Rendus, 1882, p. 229.

Table 5.—*Comparison of Pitot and Venturi heads for $a=4$.*

(1) Wind speed.		(2) Pitot-tube head.		(3) Head on Venturi according to Bourdon.		(4) $\frac{\text{Col. 3.}}{\text{Col. 2.}}$	(5) Theoretical head on Venturi.	
Miles hour.	*Meters sec.*	*Ins.*	*Mm.*	*Ins.*	*Mm.*		*Ins.*	*Mm.*
10	4. 47	0. 05	1. 3	0. 17	4	3. 4	0. 7	18
20	8. 94	. 19	4. 8	. 80	20	4. 2	2. 9	74
30	13. 41	. 43	10. 9	2. 30	58	5. 3	6. 8	173
40	17. 88	. 77	19. 6	4. 0*	102*	5. 2	12. 3	312
50	22. 35	1. 20	30. 5	6. 6*	168*	5. 5	20. 0	508
60	26. 82	1. 73	43. 9	10. 0*	254*	5. 8	30. 0	762
70	31. 29	2. 35	59. 7	15. 0*	381*	6. 4	45. 0	1, 143
80	35. 76	3. 07	78. 0	20. 0*	508*	6. 5	63. 0	1, 600
90	40. 23	3. 89	98. 8	25. 0*	635*	6. 4	90. 0	2, 286

In figure 1 the line *H G* represents Bourdon's observations and the starred values in column (3) of Table 5 were read from the dotted extension of this curve. While this extrapolation can make no claim to accuracy, it appears from column (4) of Table 5 that a Venturi tube with a 2 to 1 diameter ratio would probably give at least five times as much head as a Pitot tube at ordinary aeroplane speeds.

The curve *F E* of figure 1 and the numbers in column (5) of Table 5 were found from equation (27) of Part 2, which is known experimentally to agree closely with the facts when the Venturi meter is inserted in a pipe line instead of being used as an anemometer with both ends free. Upon introducing the known values of k and ρ for air at one atmosphere and 70° F., equation (27) reduces to

$$S=1720\sqrt{\frac{r^{\frac{10}{7}}(1-r^{\frac{2}{7}})}{\alpha^2-r^{\frac{10}{7}}}}\text{ miles per hour.}$$

If the 1720 is replaced by 769, the result will be in meters per second.

What part of the great discrepancy between columns (3) and (5) of Table 5, or between *E F* and *G H* of figure 1, is to be ascribed to friction or other circumstances which make the Venturi tube act differently as an anemometer and as a flow meter, and what part to Bourdon's experimental arrangements and possible errors of observation, can not be decided without further investigation; but in any event, it is obvious that with the Venturi tube a much larger head is available than with a Pitot tube.

Since Bourdon wanted an anemometer for very low speeds, he increased the available head still farther by using two concentric tubes, the exit end of the inner one being at the throat of the outer, so that the suction there increased the speed through the inner tube and the fall of pressure at its throat. The proportions of the tubes which were adopted as giving the best results were as shown in Table 6.

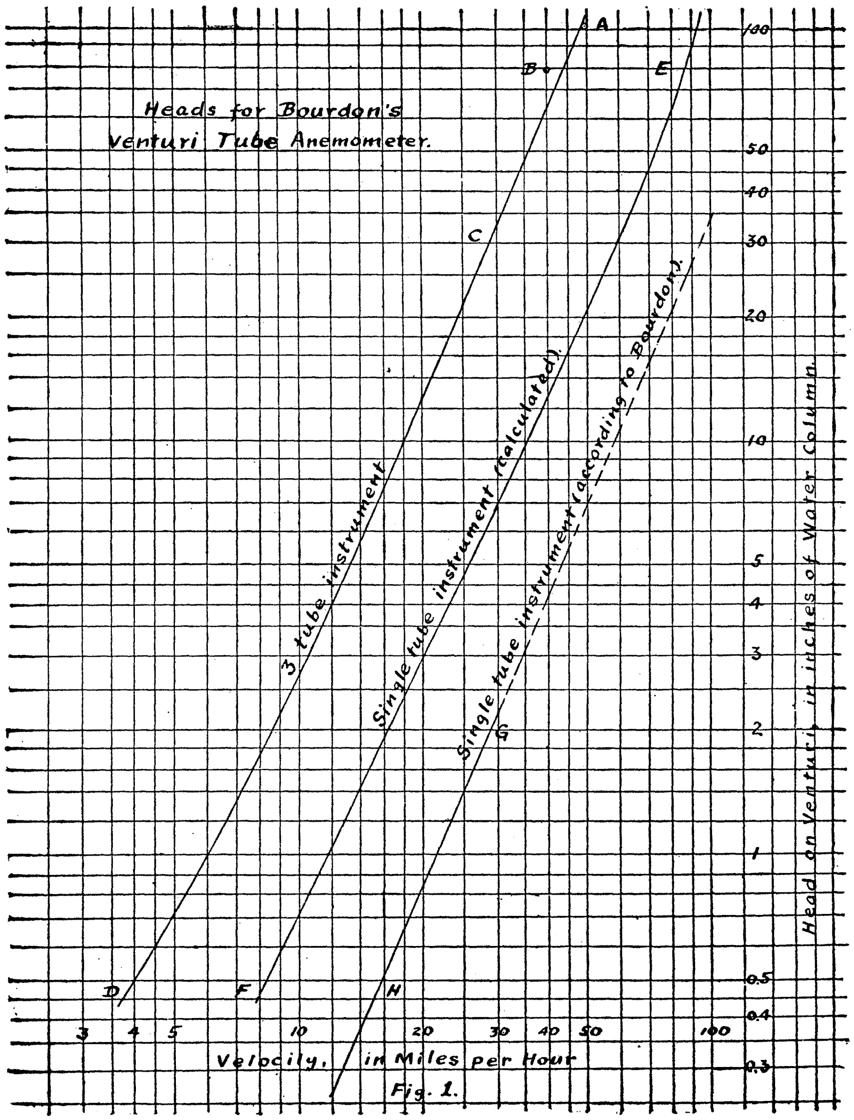


Fig. 1.

TABLE 6.—*Proportions of Bourdon's double Venturi tube anemometer.*

	Inner tube.	Outer tube.
Ratio of minimum to maximum diameter:		
(*a*) Of converging cone	0.31	0.56
(*b*) Of diverging cone	0.45	0.60
Double angle:		
(*a*) Of converging cone	34° 15	21° 38
(*b*) Of diverging cone	3° 45	4° 50
Relative throat diameters	1.0	6.2

No cylindrical throat piece was used with either tube, the converging and diverging cones being connected directly.

Bourdon also used a similar arrangement of three concentric tubes. The heads obtained with this, at various wind speeds, are shown on figure 1 by the curve *D C* and by the isolated point *A*. The point *B* is from tests of a 3-tube instrument by Brown Boveri & Co.[1]

The proportions of single-tube anemometers as used in modern French practice seem to be somewhat like those of Bourdon's inner tube. (See Table 6.) The length of tube in the anemometer made by Aera, of Paris, is 6.3 inches (160 mm.) or nearly the same as the length of the diverging cone of Bourdon's inner tube. Dorand[2] gives, without dimensions, a section of a Venturi-tube anemometer which indicates a ratio of throat to entrance diameter of about 0.2. The proportions proposed by Toussaint and Lepère[3] as a result of recent experiments are very similar to those of Bourdon's outer tube. (See Table 6.)

12. REMARKS ON THE SPECIAL CONDITIONS TO WHICH AEROPLANE ANEMOMETERS ARE SUBJECT.

A. *Weight and head resistance.*—These must both be small—the smaller the better. Accordingly we need not consider any essentially heavy instruments, such as those which require the use of electric batteries, nor instruments like large pressure plates which offer a head resistance of several pounds.

B. *Robustness.*—The very severe conditions of vibration preclude the possibility of using instruments which are not mechanically strong or which can not be made so without too great weight. Both the anemometer head proper, and the transmitting and indicating parts must be simple, light, strong, and free from the need of delicate adjustment or frequent testing.

C. *Position.*—The head must, so far as practicable, be out of reach of irregular currents and eddies and therefore at some distance from the indicator or dial in front of the pilot. The available positions are (*a*) in front of the center of the machine, (*b*) well above the upper planes over the pilot's head, (*c*) near one wing tip. Position (*a*) might be practicable and satisfactory in some cases but there is a possibility, unless the head were very far in front, that the readings might not be the same, at a given speed, during normal flight as when planing with the motor stopped. We have no information on this point. The influence of the body extends some distance ahead, a fact which should not be overlooked.[4] Position (*b*) would often require the construction of a special support, increasing the weight and head resistance. Position (*c*) seems the natural one to adopt if a transmission of the requisite length can be made satisfactory; but here again it should be noted that the disturbance due to a strut or wing begins some distance ahead of the leading edge.[5]

D. *Orientation.*—While most anemometers have to be pointed directly into the wind if they are to indicate its resultant velocity,

[1] Zeitschr. d. Ver. Deutscher Ingenieure, 1907, p. 1848.
[2] E. Dorand, La Technique Aeronautique, Nov. 1, 1911, p. 252.
[3] Rep. Brit. Adv. Com. for Aeronautics, 1912–13, p. 396.
[4] See, for example, the results of experiments on the Marienfelde-Zossen high-speed electric railway, The Electrician, June 17, 1904.
[5] See E. F. Relf, Rep. Brit. Adv. Com. for Aeronautics, 1912–13, p. 133.

what is needed in aviation is primarily the relative wind speed along a direction fixed with regard to the axis of the machine. The undesirable complication of mounting the anemometer head on a wind vane is therefore unnecessary and the head may be fixed. If information is required about motion perpendicular to this direction, it may be got from a wind vane.

E. *Independence of gravity.*—On account of the very considerable angles of heeling and pitching, it seems useless to consider any instrument which depends for its action on weights or liquid manometers. Any required forces must be applied by springs; or if pressures are to be registered, it must be by spring gauges. Furthermore, all parts of the instrument must be so balanced that the readings are not affected at all by gravity. This remark applies to the transmission and the indicator as well as to the head.

F. *Vertical acceleration and centrifugal force.*—Vertical acceleration acts merely as a change of the intensity of gravity. It will, therefore, have no effect on an instrument which is properly constructed in accordance with E, above.

Centrifugal force must be allowed for in a similar way by careful balancing of all movable parts so that the lateral acceleration of the whole machine during curved flight shall not influence the readings. This balancing in the transmission is equally necessary, whether forces are transmitted by rods or wires or pressures by fluids in tubes.[1]

13. DENSITY CORRECTIONS.

Before considering the effects of changes of air density on the indications of particular types of anemometer it will be well to see how great these variations are likely to be under working conditions. For this purpose we consult equation (6) of section 4, viz,

$$\rho = 1.327 \frac{B - 0.376\,PH}{460 + t} \qquad (6)$$

in which

ρ = the density of the air in pounds per cubic foot.
B = the barometric pressure in inches of mercury.
t = the temperature of the air in degrees Fahrenheit.
P = the pressure of saturated steam at $t°$ in inches of mercury.
H = the relative humidity ($H = 1.0$ for saturated air).

The ranges we shall assume are: $B = 30$ to 20 inches, corresponding to a rise from sea level to about 10,000 feet altitude; $t = 0°$ to $90°$ F.; $H = 0.0$ to 1.0, i. e., from complete dryness to saturation.

We may first consider the term $0.376\,PH$. Taking P from the steam tables we have

at	$t = 50°$	$70°$	$90°$
$0.376\,P =$	0.136	0.278	0.533
$0.376\,P \times 0.5 =$	0.068	0.139	0.267

[1] For a discussion of the effect of vertical acceleration and centrifugal force on liquid manometers the reader may be referred to an article by H. Darwin, Aeronautical Journal, July, 1913, p. 170.

If we assume a constant relative humidity $H=0.5$, while in fact the humidity varies all the way from 0.0 to 1.0, the maximum error we can make in the value of 0.376 PH is 0.376 $P\times 0.5$, of which the values at 50°, 70°, and 90° are shown above. To find the percentage error which this assumption can introduce into the computed value of ρ, we must compare these errors with the value of B. The following table shows the maximum per cent. errors in ρ at 50°, 70°, and 90° F. and at 20 and 30 inches pressure which can be caused by assuming $H=0.5$.

	$t=50°$	$t=70°$	$t=90°$
$B=20$ inches	0.34%	0.70%	1.33%
$B=30$ inches	0.23%	0.46%	0.89%

Since a temperature of 90° F. will seldom or never prevail at an altitude where the pressure is as low as 20 inches, we may regard 1 per cent. as about the maximum possible error, and in the vast majority of cases the actual error will be less than 0.5 per cent. Now with the anemometers we need to consider, a given percentage error in the density causes only about half as much error in the speed S; and furthermore, an accuracy of 1 per cent. in measuring the speed of an aeroplane may be regarded as satisfactory. Hence the assumption of a constant relative humidity of 50 per cent. ($H=0.5$) is quite approximate enough for our purpose, and we adopt this assumption and thereby simplify equation (6) to the form

$$\rho=1.327\frac{B-0.19\,P}{460+t}\text{ pounds per cubic foot.} \tag{8}$$

From equation (8) we may now compute a table of approximate values of the air density at various values of the barometric pressure B and the temperature t. It will be convenient to have the values expressed, not in pounds per cubic foot, but in terms of a standard air density, and for this the value $=0.07455$ has been chosen. This is the density at $B=29.92$ inches, $t=70°$ F., and $H=0.5$, conditions which are a fair average representation of those which are likely to prevail during anemometer tests. The values are shown in Table 7.

TABLE 7.—*Relative density D of air at B inches pressure, t° F., and 50 per. cent relative humidity, referred to air at 29.92 inches pressure, 70° F., and 50 per cent. relative humidity.*

$B=$	20″	22″	24″	26″	28″	30″
$t=0°$ F....	0.773	0.851	0.928	1.006	1.083	1.160
10°.....	.757	.833	.908	.984	1.060	1.135
20°.....	.741	.815	.889	.963	1.037	1.112
30°.....	.725	.798	.871	.943	1.016	1.088
40°.....	.710	.781	.853	.924	.995	1.066
50°.....	.696	.766	.835	.905	.975	1.045
60°.....	.681	.750	.818	.887	.955	1.023
70°.....	.667	.734	.801	.868	.935	1.003
80°......	.653	.719	.785	.850	.916	.982
90°.....	.639	.703	.768	.833	.897	.962

We have next to consider how these variations of density may affect the readings of an anemometer which has been tested under standard conditions.

A. *The Pitot tube.*—The Pitot tube formula may be written

$$S = \text{const} \times \sqrt{\frac{p_1 - p_2}{\rho}}$$

or for a standard density ρ_0

$$S_0 = A_0 \sqrt{p_1 - p_2}$$

At any other density, $\rho = D\rho_0$, we have

$$S = \frac{A_0}{\sqrt{D}} \sqrt{p_1 - p_2} = \frac{S_0}{\sqrt{D}} \qquad (9)$$

If the tube has been standardized at the density ρ_0 and the constant A_0 determined, or if the gage has been provided with a speed scale or a table for converting its readings at the standard density ρ_0 into speeds, the true speed at any other density ρ is found by multiplying the indicated speed by $\frac{1}{\sqrt{D}}$. Values of $\frac{1}{\sqrt{D}}$ computed from Table 7 are given in Table 8.

TABLE 8.—*Values of* $\frac{1}{\sqrt{D}}$ *for use in equation (9).*

$t°$ F.	Barometric height B in inches of mercury.					
	20″	22″	24″	26″	28″	30″
0..........	1.137	1.084	1.038	0.979	0.961	0.928
10..........	1.149	1.096	1.049	1.008	.971	.938
20..........	1,162	1.108	1.061	1.019	.982	.948
30..........	1.174	1.119	1.072	1.030	.992	.958
40..........	1.187	1.131	1.083	1.040	1.003	.968
50..........	1.199	1.143	1.094	1.051	1.013	.978
60..........	1.212	1.155	1.106	1.062	1.023	.989
70..........	1.225	1.167	1.117	1.073	1.034	.999
80..........	1,238	1,180	1.129	1.084	1.045	1.009
90..........	1.251	1.193	1.141	1.096	1.056	1.020

If the purpose of reading the anemometer is not, primarily, to ascertain the speed, but to judge of the wind pressures on the machine which determine the lift and the stresses, then the density correction should *not* be applied. For at any given angle of attack, the wind forces are very nearly proportional to the Pitot pressure; when the gauge shows a given reading, the wind forces are always the same; and from the standpoint of sustaining power and strength it is immaterial how the forces arise. Hence from the point of view of the aviator who is concerned with the safety of his machine, the speed readings of the Pitot-tube anemometer correct themselves automatically—if the machine flies safely at a given speed and in air of a given density, it will be equally safe in air of any other density, regardless of pressure, temperature, and humidity if the Pitot-tube gauge gives the same reading.

B. *Pressure-plate anemometers.*—It would naturally be supposed that the readings of pressure plate anemometers would be affected by variations of air density in the same way as those of Pitot tubes. The theory of the subject, however, is not entirely clear, and it is difficult to interpret some of the experimental results which have been obtained.[1] In the absence of further investigation it would seem safest to make the density correction, when necessary, exactly as is done for the Pitot tube. If the readings are taken only for the sake of estimating the wind forces on the machine, the density correction is to be omitted, just as with the Pitot tube.

C. *The Bourdon-Venturi anemometer.*—If the results of Bourdon's experiments agreed closely with computations from the theoretical equation of the Venturi meter, we should feel justified in using that equation to compute density corrections to be applied to the readings of an instrument which had been tested at a standard air density. But the discrepancies shown by curves GH and EF of figure 1 are so large that we can not trust the theoretical equation at all for a Venturi tube used as an anemometer. It appears that further experimental investigations of this instrument are needed.

D. *Rotary anemometers.*—Regarding rotary anemometers, Jones and Booth[2] say:

> The principal advantage possessed by instruments of this type is that they read the actual travel through the air independently of variations in density.

It seems likely, however, that this independence is only approximate and not complete. The ratio of cup or vane speed to wind speed depends on the value of the least wind speed which will just keep the anemometer turning against friction. And since each vane or cup when moving very slowly acts as a pressure plate, it seems that the wind speed required in order to furnish the torque for very low speeds of rotation must depend on the air density. Hence it seems probable that at higher speeds the action of instruments of the Robinson or of the screw type is somewhat influenced by air density. Exact information on this is lacking.

14. COMPARISON OF TYPES OF ANEMOMETER.

Anemometers in general might be compared from various points of view; but since our purpose is strictly practical, we shall at once exclude from the discussion any instrument which can not be made satisfactory on the score of (*a*) robustness combined with lightness, (*b*) independence of gravity, and (*c*) flexibility of transmission, permitting the head to be placed at a distance from the indicator in front of the pilot's seat. There seem then to remain for discussion the Pitot tube, the pressure plate, the Venturi tube, and the Robinson anemometer.

A. *The Pitot tube.*—This has been the most studied, and we can speak of it with more certainty than of the others. The head is

[1] See Rayleigh, Rep. Brit. Adv. Com. for Aeronautics, 1910–11, p. 26.
[2] Aeronautical Journal, July, 1913, p. 192.

simple and may be placed in any position; and the transmission of the pressure through tubes presents no obvious difficulties. The prime defect of the instrument is the smallness of the pressure available for actuating the indicator. While sensitive liquid gauges may be used under some circumstances, anything but a spring gauge seems out of the question for all-round use. The problem with the Pitot tube is to make a satisfactory spring gauge which shall at the same time be sufficiently sensitive and so robust as to be reliable. The problem looks difficult, but may not be insoluble.

B. *The pressure plate.*—By an increase of size, the pressure plate may be made to give as large a force as is desired, the limit being set by the amount of head resistance which it is considered permissible to devote to an anemometer. Transmission by wires under tension might be practicable but would be liable to get out of order and to be seriously disturbed by vibration. Transmission by means of liquid pressure might be managed but would introduce complications, and the development of the instrument in this form would demand a great deal of experimentation. In spite of its attractiveness and apparent simplicity at first sight, the pressure plate does not, on the whole, seem very promising as a practical aeroplane instrument.

C. *The Bourdon-Venturi anemometer.*—The Venturi tube furnishes a pressure difference and the transmission problem is simple, as it is with the Pitot tube. But the pressure difference may be made so large that the problem of making a satisfactory spring gauge is vastly simpler than with the Pitot tube, and should not present any insuperable difficulties. A more important doubt arises in connection with the density correction. Since it is impracticable to test an anemometer at low-air densities by the ordinary methods, and since Bourdon's results differed greatly from what might have been expected on theoretical grounds, the instrument should be used with caution, if high altitude flights are in question, until we know more about its practical behavior. On the other hand, it appears to be satisfactory at ordinary air densities,[1] and it seems to be an instrument of great promise and one of which the practical development should be pushed along.

D. *The Robinson anemometer.*—The weak point of the Robinson anemometer is lack of flexibility in the transmission. In the form of Morell's anemo-tachometer it indicates speed through the air nearly independently of the air density. But since the main purpose of knowing this speed is for finding the total distance traveled, it would seem as if the ordinary method of registering the total number of turns would, in practice, be more useful than the attachment of a tachometer to give instantaneous speeds.

Having now discussed some of the mechanical characteristics of the four types of instrument we may take another standpoint and, assuming that a mechanically satisfactory instrument of each type can be constructed, ask whether one presents any advantages over another. The answer to this question depends on why we want to know the speed.

If what is wanted is to estimate the distance traveled through the air, some form of Robinson anemometer seems to be the thing to use, because it is independent of air density, to a first approximation, at

[1] See Eiffel, The Resistance of the Air, p. 234.

all events. The other three types of instrument will all require to have a density correction applied to their readings, if the air density is far different from that during standardization, and they are thus at a disadvantage.

But it appears that the speed through the air is, in general, not itself the important quantity sought; for at best it does not tell us the speed over the ground until it is compounded with the speed of the wind which may happen to be blowing. A more important use of the anemometer is not properly as a speedometer but as a dynamometer, i. e., as an instrument for indicating the air forces on the machine. For this purpose, any instrument such as the anemo-tachometer which gives the speed without reference to the density will require a density correction to its readings, whereas the Pitot tube gives just what is wanted, the allowance for density being already present in its uncorrected readings, so that equal readings mean equal pressures, whatever the density may be. The pressure plate falls in the same class as the Pitot tube. Of the Bourdon-Venturi anemometer we can say very little until the instrument has been further studied, but it seems likely that it also will act rather as a dynamometer than as a speedometer, if its readings are not corrected for variations of air density.

Still another question which may be asked is, What sort of mean speed does a given anemometer indicate when exposed to a gusty wind? In regard to this question, the four types under consideration fall into the same grouping as before. With the Pitot tube, the pressure plate, or the Venturi tube, the pressure difference or the force depends on the square of the wind speed, and the mean reading of any of these instruments in a wind of varying speed will therefore give not the arithmetical mean speed but the root-mean-square speed, which is what determines the mean wind forces on the aeroplane. The anemo-tachometer, on the other hand, will probably indicate something between the arithmetical mean and the root-mean-square speed. If it had no inertia it might be made to indicate the arithmetical mean, but the effects of inertia in causing lag or lead will probably make the mean reading of the instrument in a wind of variable strength somewhat higher than it would be in the absence of inertia. The fact that this might result in a slight overestimate of the total travel will hardly be of any moment, in view of the impossibility, for the aviator, of measuring and allowing for the true velocity of the wind with respect to the earth's surface.

REPORT No. 2.

PART 2.

THE THEORY OF THE PITOT AND VENTURI TUBES.

By E. Buckingham.

1. THE ENERGY EQUATION FOR STEADY ADIABATIC FLOW OF A FLUID.

Let a fluid be flowing steadily along a channel with impervious and nonconducting walls, from a section A to a section A_1, the areas of the sections perpendicular to the direction of flow being also denoted by A and A_1. By saying that the flow is "steady" we do not mean that it occurs in stream lines and without turbulence. We mean merely that it is "sensibly" steady; i. e., that such variations of speed, direction of motion, pressure, etc., as may occur at any point in the stream as a result of turbulence are so rapid that our measuring instruments do not respond to them, but indicate only time averages; and that these time averages are constant at any fixed point within the channel. Values of a property of the fluid, or of any other quantity such as speed, "at a point," are therefore to be understood as time averages over a time which is long compared with the speed of variation of the quantity to be measured, though it may appear short in the ordinary sense.

Let θ, p, v, ϵ, T, respectively, be the absolute temperature, static pressure, specific volume, internal energy per unit mass, and kinetic energy per unit mass, at the entrance section A. By the "static pressure" is meant the pressure which would be indicated by a gauge moving with the current. Let θ_1, p_1, v_1, ϵ_1, T_1 be the corresponding quantities at the exit section A_1. Both sets of values are to be understood as averages over the whole section, as well as time averages in the sense explained above. The two sections shall be at the same level, so that the passage of fluid from A to A_1 does not involve any gravitational work.

As a unit mass of fluid crosses A, the work pv is done on it by the fluid following; and as it crosses A_1 it does the work p_1v_1 on the fluid ahead. Since the walls of the channel are nonconducting, no heat enters or leaves the fluid between A and A_1; hence the total energy, internal plus kinetic, increases (or decreases) by an amount equal to the work done on (or by) the fluid, and we have

$$pv - p_1v_1 = (\epsilon_1 + T_1) - (\epsilon + T)$$

or

$$T - T_1 = (\epsilon_1 + p_1v_1) - (\epsilon + pv) \qquad (1)$$

So far no assumptions have been made and equation (1) is rigorously correct for adiabatic flow between two sections at the same level. Internal heating by skin friction or the dissipation of eddies is merely a conversion of energy from one form into another and not an addition of energy; hence it does not affect the validity of equation (1) and need not appear in it.

2. INTRODUCTION OF THE MEAN SPEED INTO THE ENERGY EQUATION.

Let Q be the volume of fluid which crosses the section A per unit time, and let $S=Q\div A$; then S is the arithmetical mean, over the section, of the component velocity normal to A and along the channel. Let Q_1 and S_1 be the corresponding values at A_1. Measuring kinetic energy, as well as work and internal energy, in normal mass-length-time units, we then set

$$T-T_1=\frac{1}{2}\,(S^2-S_1^2) \tag{2}$$

and proceed to substitute this expression for $(T-T_1)$ in equation (1).

This substitution is indispensable to further progress, but it involves an assumption which destroys the rigor of all further deductions. The deductions are, nevertheless, very approximately confirmed by experiment, and it is therefore worth while to examine the assumption.

If there were no turbulence and if the speed were uniform over each section, we should have the two separate equations

$$\left.\begin{aligned} T&=\frac{1}{2}S^2 \\ T_1&=\frac{1}{2}S_1^2 \end{aligned}\right\} \tag{3}$$

and equation (2) would be exact. If there is no turbulence but the speed of flow is nonuniform, approaching zero at the walls, as it must where the channel has material walls, equations (3) will not be satisfied, but we shall have $T>\frac{1}{2}S^2$ and $T_1>\frac{1}{2}S_1^2$, because the mean square speed, which determines the kinetic energy, is always greater than the arithmetical mean speed S when the distribution over the section is not uniform. With a round pipe and nonturbulent flow $T=\frac{2}{3}S^2$ instead of $\frac{1}{2}S^2$.

In nearly all practical cases the flow of fluids is turbulent and the relation of the whole kinetic energy, including that of the turbulence, to the arithmetical mean normal component of the speed at the given section will depend on the amount of turbulence. It is impossible to say what the relation will be further than that the kinetic energy of eddies and cross currents tends to increase the error which would be involved in assuming equations (3), while, on the other hand, the fact that with increasing turbulence the speed becomes more nearly uniform over a cross section tends to decrease the difference between the mean square and the arithmetical mean of the component normal to any section.

The assumption involved in using equation (2) is not, however, so violent as that which would be involved in using equations (3) separately. For equations (3) are equivalent to

$$T-\tfrac{1}{2}S^2=T_1-\tfrac{1}{2}S_1^2=O$$

whereas equation (2) is satisfied if

$$T-\tfrac{1}{2}S^2=T_1-\tfrac{1}{2}S_1^2 \tag{4}$$

no matter what the value is. Equation (4) and its equivalent (2) are satisfied if the error in assuming equations (3) to hold is the *same* at both sections without vanishing or even being small. This will occur if the kinetic energy of turbulence is the same at both sections and if also the speed distributions over the two sections are such that the arithmetical mean normal speed is the same fraction of the mean-square normal speed at both. While therefore it is evident that the use of equations (3) separately might lead to conclusions at variance with facts, equation (2) may nevertheless be nearly fulfilled in practice. The agreement with observation of deductions from equations (2) and (1) shows that in many ordinary cases the error committed by treating equation (2) as exact is in reality quite insignificant.

For geometrically similar channels, the percentage error of equation (2) depends only on $\frac{DS}{\nu}$, in which ν is the kinematic viscosity of the fluid and D a linear dimension of the channel. With a given fluid in a given channel increasing S increases the turbulence, but it is not evident how this will affect the percentage error, $\frac{2T-S^2}{S^2}$, if at all. Hence, it seems possible that although turbulence increases with $\frac{DS}{\nu}$, the *percentage* error in assuming equation (2) may not increase but remain constant or even decrease. On the other hand, at a given speed S, if $\frac{DS}{\nu}$ is increased by increasing D or diminishing ν, the turbulence and the value of $\frac{2T-S^2}{S^2}$ will be increased and there will be a greater chance that equation (2) may be sensibly in error. At a given mean axial speed S we must therefore be prepared to find greater discrepancies between experiment and results deduced from equation (2) for large channels and fluids of low kinematic viscosity than for the opposite conditions.

We shall now proceed as if equation (2) were rigorously exact, and by combining it with equation (1) we obtain

$$\tfrac{1}{2}(S^2-S_1^2)=(\epsilon_1+p_1v_1)-(\epsilon+pv) \tag{5}$$

an equation which serves as the point of departure for the theory of the Pitot tube, the Venturi meter, the steam-turbine nozzle, and various other devices in which a stream of fluid is retarded or accelerated adiabatically.

3. ISENTROPIC FLOW OF AN IDEAL GAS.

If the physical properties of the fluid have been sufficiently investigated and if a sufficient number of quantities are measured at each of the two sections, the value of $(\epsilon + pv)$ may be computed for each section and the value of $(S^2 - S_1^2)$ found from equation (5), to the degree of approximation permitted by the assumptions which have been discussed above. A process somewhat of this nature is pursued in the design of steam-turbine nozzles, $(\epsilon + pv)$ being then the quantity known as the total heat of steam.

But when the fluid is a gas, it is usual to proceed with deductions from equation (5) by the aid of two further assumptions which enable us to compute variations of ϵ and v from observations of p alone. The first of these assumptions is that the fluid behaves sensibly as an ideal gas defined by the equations

$$pv = R\theta \tag{6}$$

$$\epsilon = \epsilon_o + C_v\,(\theta - \theta_o) \tag{7}$$

in which C_v is the specific heat at constant volume, and ϵ_o is the internal energy at the standard temperature θ_o. The properties of ordinary gases, such as air, carbon dioxide, or coal gas, when far from condensation, are nearly in conformity with equations (6) and (7), and for such fluids no serious error is involved in making the assumption mentioned, unless very great variations of pressure and temperature are under consideration. Equations (6) and (7) imply also the relation

$$C_p = C_v + R \tag{8}$$

in which C_p is the specific heat at constant pressure.

The second assumption is that during the simultaneous changes of pressure and temperature in passing from A to A_1 the familiar isentropic relation for an ideal gas, viz,

$$\frac{\theta_1}{\theta} = \left(\frac{p_1}{p}\right)^{\frac{k-1}{k}} \tag{9}$$

remains satisfied, k representing C_p/C_v. This assumption is, of course, not exact, for while we have stipulated that the flow shall be adiabatic, the internal heating, due to viscosity causes an increase of entropy. The assumption amounts, therefore, to assuming that this irreversible internal heating is not enough to cause any sensible increase of the temperature at A_1 over what it would be if there were no internal heating at all.

The foregoing assumptions enable us to put equation (5) into a more available form. By substituting from (6) and (7) into (5), and using (8), we have

$$\frac{1}{2}\,(S^2 - S_1^2) = C_p\,(\theta_1 - \theta) \tag{10}$$

By means of (9) and (6), this may be written

$$\frac{1}{2}\,(S^2 - S_1^2) = \frac{C_p}{R}\,pv\left[\left(\frac{p_1}{p}\right)^{\frac{k-1}{k}} - 1\right]$$

and by (8) we get $C_p/R=\frac{k}{k-1}$ so that we have

$$\frac{1}{2}(S^2-S_1^2)=\frac{k}{k-1}pv\left[\left(\frac{p_1}{p}\right)^{\frac{k-1}{k}}-1\right] \qquad (11)$$

which is the usual form of equation (5) for isentropic flow of an ideal gas. If the speed is known at either section, equation (10) enables us to find the speed at the other from a knowledge of C_p and an observation of the difference of temperature; while equation (11) gives us similar information in terms of the pressures at A and A_1 if the density and the ratio k are known. We shall apply this equation to both the Pitot tube and the Venturi meter.

4. THE THEORY OF THE PITOT TUBE.

To treat the Pitot tube, we consider the fluid which is approaching the dynamic opening. Starting at a point so far upstream that the presence of the Pitot tube produces no sensible disturbance there, a particle of fluid approaches the dynamic opening, slows down, and mixes with the permanent high-pressure cap of nearly stationary fluid, which covers the dynamic opening and communicates with the differential gauge through the impact tube. The same particle, or another indistinguishable from it, emerges from the cap and, being accelerated by the now positive pressure gradient, flows on along the impact tube, finally acquiring a sensibly constant speed when it has reached a region of sensibly constant pressure. We wish to apply equation (5) to this motion if we can find a plausible way of doing so.

Starting with the contour of a small plane area, in the undisturbed current and perpendicular to its general direction, we construct, in imagination, a tubular surface of which the sides are at every point parallel to the mean direction of motion of the fluid past that point, as found by averaging with regard to time. If the motion is not turbulent, this tube is a tube of flow and no fluid passes in or out through its sides. If the motion is turbulent, as it nearly always is in practice, the *same* fluid does not flow continuously along the tube as it would if the walls were impervious. On the contrary, particles of fluid are continually leaving the tube in consequence of the turbulent time-changes of the direction of motion at any fixed point; and these particles are continually replaced by others, of the same total mass, which enter from without the tube. But on the whole, the particles which enter have the same average component velocity along the tube as those which leave; for unless this were true we could, merely by *imagining* the tubular surface, generate within the fluid a particular filament which was moving, on the whole, faster or slower than the surrounding fluid. We conclude that the net effect of turbulence is the same as if the imaginary tube walls were made rigid and perfectly reflecting for mechanical impact without exerting any skin friction on the fluid flowing along them.

If the whole current of fluid is at a sensibly uniform temperature across its general direction, no heat passes in or out through the tubular surface, and equation (5) may be applied as though we had an impervious nonconducting channel to deal with. Furthermore, if the tube is of small section, the axial speed, averaged with regard to time, will be the same at all points of any one cross section. Hence the application of equation (5), involving the assumption of equation (2) or (4), is better justified than for a material tube in which skin friction would cause the axial speed to be nonuniform over any section.

We now consider such an imaginary tube, starting in the undisturbed fluid some distance upstream from the dynamic opening of the Pitot tube, passing into the high-pressure cap over the opening and emerging again at the edge of the opening, to continue its course along the side of the impact tube. The portion of the imaginary tube which passes through the high-pressure cap may be regarded as an enlargement of cross section at which the mean axial speed is so reduced that its square is negligible in comparison with the square of the speed at distant points. If we let A be a section at some distance upstream and A_1 be the section of the tube where it passes through the high-pressure cap, S_1^2 is negligible in comparison with S^2 and equation (5) gives us

$$S=\sqrt{2[(\epsilon_1+p_1v_1)-(\epsilon+pv)]} \tag{12}$$

in which S is the speed of the undisturbed current; ϵ, p, and v refer to conditions in the undisturbed current; and ϵ_1, p_1, v_1 refer to conditions in the dynamic opening. The static pressure, which the static opening is designed to receive and transmit to the gauge, is p; while the pressure received by the dynamic opening is that in the permanent high-pressure cap, or p_1.

Equation (12) is the general form of the Pitot tube equation for any fluid, whether compressible or not. In the case of a liquid, the internal energy and specific volume are not appreciably affected by the very small pressure variations involved, so that we have $\epsilon_1=\epsilon$ and $v_1=v$ and equation (12) reduces to

$$S=\sqrt{2v\ (p_1-p)}=\sqrt{2\,\frac{p_1-p}{\rho}} \tag{13}$$

ρ being the density of the liquid. If the pressure difference is expressed as a head h of liquid of density d, we have $p_1-p=ghd$ and equation (13) takes the form

$$S=\sqrt{2g\,\frac{d}{\rho}\,h} \tag{14}$$

the usual form of the Pitot tube equation for a perfect or ideal tube.

Even when the fluid is a gas, if S is small and (p_1-p) therefore also small, ε_1 and v_1 are nearly the same as ε and v so that equations (13) and (14) remain approximately correct—admitting all the assumptions made—though it is not evident how close the approximation will be. But if the speed and the pressure difference are great enough to cause sensible compression, we must return to equation (5) and introduce the conditions for adiabatic flow of a gas, as was done in section 3 in arriving at equation (11). The fact that equation (14) does agree well with observations on gas currents at moderate speeds, shows that no great error is involved in neglecting compressibility and justifies us in going on to find a closer approximation by treating the gas as ideal and thereby using an approximation to the compressibility.

Assuming, then, that equation (11) is applicable to the imaginary current tube now under discussion, we have, by setting $S_1^2 = O$, the equation

$$S = \sqrt{\frac{2k}{k-1}\frac{p}{\rho}\left[\left(\frac{p_1}{p}\right)^{\frac{k-1}{k}} - 1\right]} \qquad (15)$$

If we now set $\frac{p_1}{p} = 1 + \Delta$ and $\frac{k-1}{k} = n$ we have

$$\left(\frac{p^1}{p}\right)^{\frac{k-1}{k}} - 1 = n\Delta\left\{1 + \frac{n-1}{2}\Delta + \frac{(n-1)(n-2)}{1\cdot2\cdot3}\Delta^2 + \text{etc.}\right\}$$

Setting the $\{\ldots\} = X^2$, substituting in equation (15), and noticing that $n\,\Delta = \frac{k-1}{k}\,\frac{p_1 - p}{p}$ we have

$$S = X\sqrt{2\,\frac{p_1 - p}{\rho}} \qquad (16)$$

which differs from equation (13), obtained by disregarding compressibility, only in the correction factor

$$X = \left\{1 + \frac{n-1}{2}\Delta + \frac{(n-1)(n-2)}{1\cdot2\cdot3}\Delta^2 + \frac{(n-1)(n-2)(n-3)}{1\cdot2\cdot3\cdot4}\Delta^3 + \cdots\right\}^{\frac{1}{2}} \qquad (17)$$

The quantity $\Delta = \frac{p_1 - p}{p}$ is the fractional rise of pressure at the mouth of the impact tube: hence it is, in practice, always a small quantity. The value of k for gases is always between $\frac{5}{3}$ and 1, so that $n = \frac{k-1}{k}$ is always between $\frac{2}{5}$ and 0. Accordingly the terms of X containing Δ are alternately negative and positive and when Δ is small the series converges rapidly, the sum of all the terms in Δ being nearly equal to the first term alone, so that if the first is negligible the sum is negligible and X may be set equal to unity.

The ratio of the specific heats of air is 1.40. Hence $n = \frac{2}{7}$ and we have

$$X = \left\{1 - \frac{5}{14}\Delta + \frac{10}{49}\Delta^2 - \frac{95}{686}\Delta^3 + \text{etc.}\right\}^{1/2} \qquad (18)$$

If an error of y per cent. in S is permissible, an error of y per cent. may also be allowed in the correction factor X and the value of Δ may be, at most, such as to make $\frac{5}{28}\,\Delta = \frac{y}{100}$ or $\Delta = 0.056y$. For any assigned values of the error y per cent. in the speed, the value of S can be found from equation (13).

Let us suppose, for example, that the Pitot tube is to be used for measuring the speed of an aeroplane and that an accuracy of 0.5 per cent. is sufficient. Then we have $\Delta = 0.028$ and $p_1 - p = 0.028\ p$. To find what speed would give this head on the differential gauge, we set $p = 1$ atmosphere $= 1.013 \times 10^6$ dynes/cm.^{2} and $\rho = 0.0013$ gram/cm.,^{3} and substitute in (13), the result being $S = 66.1$ m./sec. $= 212$ ft./sec. $= 148$ miles/hour. Since an accuracy of better than 1.0 per cent. can hardly be demanded of an aeroplane speedometer, it is evident that for all ordinary speeds of flight, no correction for compressibility is needed and equations (13) and (14) may be used.

It is of course a simple matter to compute values of the correction factor X for various speeds; but in view of the uncertainties and assumptions involved in the theory, the results would have a misleading appearance of accuracy and would not in fact be worth the labor of computation. What has been shown is sufficient, namely, that if a Pitot tube does not measure the speed of an aeroplane correctly the error is not due to neglecting the compressibility of the air.

5. THE THEORY OF THE VENTURI METER.

The Venturi meter is a channel of varying cross section, and we may apply to it the general equations of flow which have already been developed. In doing so, we shall let A be the entrance section of the meter where p is measured, and A_1 be the throat section at which the diminished pressure p_1 is observed. We have to use equation (5).

If the meter is used for measuring the flow of a liquid of density ρ we may set $\epsilon_1 = \epsilon$ and $v_1 = v$ as we did in treating the Pitot tube, and equation (5) then gives us

$$S_1^2 - S^2 = 2\,\frac{p - p_1}{\rho} \tag{19}$$

Neither S nor S_1 vanishes; but in addition to (19) we have the equation of continuity which for a fluid of constant density may be written

$$S_1 A_1 = SA \tag{20}$$

and (19) and (20) together enable us to find either S or S_1. If we represent the area ratio by a single symbol

$$\frac{A}{A_1} = \alpha > 1 \tag{21}$$

we have

$$S = B\sqrt{2\,\frac{p - p_1}{\rho}} \tag{22}$$

where

$$B = \sqrt{\frac{1}{\alpha^2 - 1}} \tag{23}$$

and B is a constant characteristic of the given meter.

Comparing (22) with (13), the equation for the Pitot tube in a liquid, we see that they differ only by the factor B which depends on the area ratio α. If $\alpha = \sqrt{2}$, $B = 1$ and the observed Venturi pressure difference $(p - p_1)$ will be the same as would be shown by a Pitot tube with its dynamic opening in the entrance of the meter. For various values of the ratio $\frac{D}{D_1}$ of entrance diameter to throat diameter we have the following values of B:

$\frac{D}{D_1}=$	1.5	2.0	2.5	3.0	4.0
$\alpha=$	2.25	4.00	6.25	9.00	16.00
$B=$	1.569	3.874	6.170	8.944	15.77

Evidently, the Venturi pressure difference may easily be made much larger than the Pitot pressure difference at the entrance speed and the gauge reading be made much more sensitive.

If the fluid is a gas instead of a liquid, compressibility will still be negligible at sufficiently low speeds, as for the Pitot tube, and equation (22) may be used; but in general the compressibility must be allowed for. To treat the flow of a gas, we have to make the same assumptions as in section 3, namely, that the gas is sensibly ideal and that the flow from the entrance section A to the throat A_1 is sensibly isentropic, the combined effect of heat conduction to or from the walls of the meter, and of internal heating in the gas itself, being insignificant. We then have to apply equation (11) to the case in hand, and if for simplicity we represent the pressure ratio by a single symbol and write

$$\frac{p_1}{p} = r < 1 \tag{24}$$

we have by equation (11)

$$S_1^2 - S^2 = \frac{2k}{k-1} \frac{p}{\rho}\left[1 - r^{\frac{k-1}{k}}\right] \tag{25}$$

ρ being the density of the gas at the pressure p as it crosses the entrance section.

To combine with (25) we have the equation of continuity

$$S_1 A_1 \rho_1 = SA\rho$$

and if we remember that during isentropic compression or expansion of an ideal gas pv^k remains constant, the equation of continuity may be written

$$S_1 = \frac{\alpha}{r^{1/k}} S \tag{26}$$

By using (26) to eliminate S_1 from (25) we now obtain the equation

$$S = \left\{\frac{2k}{k-1} \frac{r^{2/k}}{\alpha^2 - r^{2/k}} \frac{p}{\rho}\left(1 - r^{\frac{k-1}{k}}\right)\right\}^{1/2} \tag{27}$$

by means of which the entrance speed S may be computed from the observed pressure ratio $r = p_1/p$ when the area ratio α and the properties of the gas are known. Since we are treating the gas as ideal, p/ρ is, for any given gas, proportional to the absolute temperature θ at the entrance section, and we may write $\frac{p}{\rho}=\frac{p_o}{\rho_o}\frac{\theta}{\theta_o}$, ρ_o being the density of the gas at the standard pressure p_o and temperature θ_o.

For air, $\frac{C_p}{C_v}=k=1.40$ and if we insert the known value of ρ_o at 1 atmosphere and 0° C. and set

$$S=Y\sqrt{\frac{\theta}{\theta_o}} \tag{28}$$

where

$$Y=\left\{\frac{2k}{k-1}\cdot\frac{r^{2/k}}{\alpha^2-r^{2/k}}\left(1-r^{\frac{k-1}{k}}\right)\frac{p_o}{\rho_o}\right\}^{1/2}$$

we have the values of Y shown in the following table for various pressure ratios r and for meters in which the throat diameter is $\frac{1}{2}$, $\frac{1}{3}$, or $\frac{1}{4}$ of the entrance diameter, i. e., $\alpha=4$, 9, or 16. If t is the temperature at entrance, on the centigrade scale $\frac{\theta}{\theta_o}=\frac{273+t}{273}$ while if t is measured on the Fahrenheit scale,

$$\frac{\theta}{\theta_o}=\frac{460+t}{492}$$

THE VENTURI METER FOR AIR.

Values of Y in $S=Y\sqrt{\frac{\theta}{\theta_o}}$

S=Speed at entrance to meter $\alpha=\frac{A}{A_1}=\frac{\text{entrance area}}{\text{throat area}}$

r=throat pressure÷entrance pressure=p_1/p θ=absolute temperature of air at entrance.

θ_o=absolute temperature of ice point.

Values of Y.

r	$\alpha=4$			$\alpha=9$			$\alpha=16$		
	M./sec.	Ft./sec.	Mile/hour.	M./sec.	Ft./sec.	Mile/hour.	M./sec.	Ft./sec.	Mile/hr.
0 9998	1. 44	4. 74	3. 23	0. 626	2. 05	1. 400	0. 350	1. 150	0. 784
. 999	3. 23	10. 60	7. 23	1. 40	4. 59	3. 13	0. 784	2. 57	1. 753
. 995	7. 21	23. 65	16. 13	3. 12	10. 24	6. 98	1. 75	5. 74	3. 91
. 99	10. 16	33. 34	22. 7	4. 40	14. 11	9. 85	2. 47	8. 09	5. 52
. 98	14. 3	46. 48	32. 0	6. 19	20. 3	13. 85	3. 47	11. 38	7. 76
. 95	22. 2	72. 8	49. 6	9. 62	31. 6	21. 5	5. 39	17. 7	12. 06
. 90	30. 4	99. 8	68. 0	13. 2	43. 4	29. 6	7. 41	24. 3	16. 57
. 80	40. 2	131. 7	89. 8	17. 5	57. 5	39. 2	9. 82	32. 2	22. 0
. 60	48. 1	157. 9	107. 6	21. 1	69. 3	47. 2	11. 86	38. 9	26. 5

Computed on the assumptions $pv=R\theta$, C_v=constant, $\frac{C_p}{C_v}=1.400$.

$p_o=1.01323\times10^6$ *dyne/cm²*.

$\rho_o=0.0012928$ gm cm³ at 760 mm. and 0° C

REPORT No. 4.

PRELIMINARY REPORT ON THE PROBLEM OF THE ATMOSPHERE IN RELATION TO AERONAUTICS.

By PROF. CHARLES F. MARVIN.

REPORT No. 4.

PRELIMINARY REPORT ON THE PROBLEM OF THE ATMOSPHERE IN RELATION TO AERONAUTICS.

UNITED STATES WEATHER BUREAU,
Washington, D. C., November 9, 1915.

GENTLEMEN: The particular work comprising the subject of this report has been undertaken pursuant to an allotment by Dr. Charles D. Walcott, Secretary of the Smithsonian Institution, of $2,500, made available through the Secretary of Agriculture to the Chief of the Weather Bureau. At the meeting of the executive committee held June 11, 1915, the chairman, Dr. Charles D. Walcott, was authorized to designate Charles F. Marvin, Chief of the Weather Bureau, as chairman of a subcommittee to investigate and report upon the problem of the atmosphere in relation to aeronautics. He was requested to select other members of the subcommittee, not to exceed four, and Profs. William J. Humphreys and William R. Blair, of the United States Weather Bureau, subsequently consented to act as members of the subcommittee.

At the meeting of the executive committee held August 5, 1915, a proposal of work to be undertaken was outlined by the chairman of the subcommittee on the atmosphere in relation to aeronautics, the substance of which is briefly quoted as follows:

The Weather Bureau is already in possession of an immense amount of data concerning atmospheric conditions, including wind movements at the earth's surface. This information is no doubt of distinct value to aeronautical operations, but it needs to be collated and put in form to meet the requirements of aviation. The bureau also has a considerable amount of determinations of atmospheric conditions in the free air. Most of these observations were made at Mount Weather, but others have been made at a few points in the West, such as Huron, S. Dak.; Fort Omaha, Nebr.; Avalon, Cal.; and a few aboard the Coast Guard cutter *Seneca*, during the past summer while this vessel was engaged on ice patrol off the Newfoundland coast. Portions of these data also are undoubtedly valuable to aviation, but it is quite apparent that but a small fraction of the material needed to meet the requirements of aeronautical work throughout the United States is available, and that therefore much additional observation work is necessary.

In considering the work that should be done along these lines, further cooperation is needed by the Weather Bureau with those actually engaged in aeronautical operations, and with this need in view Prof. Blair, a member of the subcommittee, has already been in conference with Mr. F. R. McCrary, acting director of naval aeronautics. It is proposed to utilize the fund made available by the Smithsonian Institution to undertake a careful compilation of the data already available in the Weather Bureau records, this compilation to be along lines that will make the data available to aviation; also that additional observations be undertaken to gain information concerning atmospheric conditions by means of pilot balloons, the position and motions of which are recorded by theodolites and such other apparatus as the work may require. It may be proper to state at this point that the Weather Bureau is already conducting aerial investigations of direct interest to meteorology, and that the new work herein proposed will be supplementary and in addition to the work the Weather Bureau is already performing. Embarrassment has been experienced in the progress of this work since the European war on account of the inability to procure serviceable rubber balloons. A manufacturer in Ohio has undertaken to supply these, and has submitted a considerable number of samples and full-sized balloons. So far, however, the results have been almost a complete failure, on account of the seeming inability to secure the necessary strength and gas tightness at the seams. Work is still in progress, however, on the manufacture of the balloons, and we are hopeful of more favorable results in the future.

The following outline indicates approximately the subject matter of a meteorological character it is expected to include in the proposed publications:

ATMOSPHERIC CONDITIONS IN RELATION TO AERONAUTICS.

1. INTRODUCTION.—Brief presentation of a few fundamental principles and data relating to general atmospheric conditions and motions and forming a basis for the subsequent discussion of relations of temperature pressure and motions of the atmosphere.

CHAPTER I.—General meteorological and climatological data selected and classified with respect to its bearing on aeronautics. The data should show general surface conditions of weather, temperature, sunshine, rain, thunderstorms, humidity, and wind velocity and directions; also comprise as full information concerning average free-air conditions as the scanty data available permit.

CHAPTER II.—A discussion of particular and local atmospheric conditions as affecting aviation.

CHAPTER III.—General presentation of free-air conditions arranged with relation to surface conditions.

CHAPTER IV.—Instruments with special reference to aviation.

CHAPTER V.—Miscellaneous useful material not otherwise included.

APPENDIX.—Formulæ and practical tables.

The practical closing of European markets for certain instrumental supplies has prevented procuring recording theodolites of special construction needed in studying atmospheric motions by means of pilot and sounding balloons. A type of instrument of this kind has been designed and efforts are being made to secure the manufacture in the United States of a small supply for the Weather Bureau work.

Difficulties are still encountered in procuring in the United States a good quality of rubber balloons for atmospheric explorations.

Mention is made at this point of a special form of camera adapted to make a photograph on a single plate of the entire sky from horizon to zenith. This has been developed and tried out by Mr. Fred W. Mueller, with the advice and assistance of Dr. O. L. Fassig, both of Baltimore, Md. The instrument is fully described and illustrated in the Monthly Weather Review.

Since the publication of that paper I am informed by Dr. Fassig that Mr. Mueller has greatly improved the mechanical arrangements of the camera, so that the same results can be obtained in a simpler manner. It is believed the device may have some special use in aeronautics as well as meteorology.

C. F. MARVIN,
Chairman, Subcommittee on the Atmosphere in Relation to Aeronautics.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
Washington, D. C.

REPORT No. 6.

IN TWO PARTS.

INVESTIGATIONS OF BALLOON AND AEROPLANE FABRICS.

By THE UNITED STATES RUBBER COMPANY, GENERAL LABORATORIES.

Part I.—BALLOON AND AEROPLANE FABRICS.

By WILLIS A. GIBBONS and OMAR H. SMITH.

Part II.—SKIN FRICTION OF VARIOUS SURFACES IN AIR.

By WILLIS A. GIBBONS.

CONTENTS OF REPORT No. 6.

PART 1.

BALLOON AND AEROPLANE FABRICS.

APPENDIX.

PART 2.

SKIN FRICTION OF VARIOUS SURFACES IN AIR.

REPORT No. 6.

PART 1.

BALLOON AND AEROPLANE FABRICS.

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Note.—Although usually associated, for obvious reasons, balloon and aeroplane fabrics have actually become so dissimilar in many respects, such as materials of construction and requirements for satisfactory results, that for the most part the two will be discussed separately. The tearing and surface friction tests, being common to both, are exceptions to this rule. The plan followed as far as possible in this report has been to give first the results of the various parts of the investigation, with such descriptive matter, data, and plates as are necessary to make the results clear. The data and other details are given in the appendix. For convenience the data is grouped somewhat differently in the appendix, without, it is thought, causing any confusion.

SUMMARY.

The following conclusions are drawn from the results of our tests hereinafter described. It must, however, be remembered that they are based almost entirely on experiment, so care must be used in applying them extensively until they have been tried in actual practice.

COATING MATERIALS.

(1) By proper treatment fabrics can be made noninflammable even though coated with cellulose nitrate varnish followed by spar varnish.

(2) The ordinary cellulose acetate dopes do not make fabric fireproof, although themselves noninflammable. This applies particularly in the case of fabrics doped, then coated with spar varnish.

(3) Fabrics coated on one side with rubber, with the other side doped, would probably give a satisfactory tightening effect and at the same time resist damp weather better.

(4) Maximum efficiency can apparently be best obtained by not stretching the cloth too tightly on the wings before coating.

(5) Stretching and tearing tests give valuable information regarding the suitability of fabrics and should be considered in addition to the tensile strength. The area inclosed by the stretch-load, curve, representing the work done to break the strip, gives an idea as to its resistance to shocks, etc.

BALLOON FABRICS.

(1) Permeability increases greatly with temperature—about 4 per cent per degree C. for samples tested.

(2) Tests made on fabrics with varying weights of rubber indicate that permeability is not directly proportional to the thickness of the layer.

(3) Tearing tests show a great superiority of bias over parallel doubled fabrics.

SURFACE FRICTION TESTS.

(1) For very smooth surfaces the surface friction varies with the 1.8–1.85 power of the velocity; the exponent increases with the roughness, approaching 2 for fabrics with nap on the surface.

(2) Varnished fabrics have nearly as low a resistance as plate glass. The resistance increases greatly as the surface becomes rougher from the presence of loose fibers.

Part I.—AEROPLANE FABRIC.

I. MATERIALS USED.

By far the greater part of the aeroplanes in use to-day have wings made of a textile fabric, usually linen, coated with a more or less waterproof, practically nonelastic varnish. This is ordinarily some form of cellulose acetate, or less frequently cellulose nitrate, with more or less softening material added, and some suitable solvent.

It is ordinarily the practice to apply three or more coats of this varnish, rubbing down with sandpaper after the coating is dry, after which one or two coats of high-grade linseed oil varnish, preferbly a spar varnish, are applied.

1. COATINGS.

The cellulose acetate or nitrate lacquer is chiefly useful because it acts as a sort of waterproof sizing, which shrinks the cloth more or less, and prevents it from changing in tension with the hygroscopic conditions of the atmosphere. The spar varnish protects this layer, which often shows a tendency to peel, and makes the wing more waterproof.

This form of treatment is convenient, and the materials fairly easy to obtain. On the other hand it could hardly be called permanent; the varnish or dope, as it is commonly called, must be applied to the wings of a machine every few weeks, if the machine sees much service.

Another defect noted probably more by the United States military branches than abroad, is that due to deterioration of the underside of the fabric from moisture and bacteria. The dopes owe their shrinking action to the fact that they are colloids, and as such, when applied to the cloth, do not penetrate but remain on one side. As the solvent evaporates, the gel decreases in volume. The most evident decrease is of course in the thickness of the layer, but there is naturally a tendency for the other two dimensions of the layer of drying varnish to decrease, causing the well known shrinking effect. Other colloids produce the same effect; for example, glue. Another example is the common gummed label, which being unable to shrink, curls up. At Vera Cruz it was found that there was considerable tendency for the uncoated side of the wings to rot, owing to this lack of penetration. On the other hand, those varnishes which penetrate do not produce the shrinking effect.

2. FABRICS.

Of the fabrics linen is the most satisfactory. Ramie and cotton have been used to some extent, but the former is difficult to obtain and the latter does not take the varnish so well as the linen and tears much easier.

Practically all of the linen suited for this purpose comes from abroad, chiefly from Ireland. An investigation of the relative weights and strengths obtainable is, particularly at the present time, rather difficult to make complete. Added to this there is the difficulty of obtaining material of exactly the same grade from time to time. The fabrics in general use weigh $3\frac{3}{4}$ to $4\frac{3}{4}$ ounces per square yard, and have a tensile strength, tested at about 65 per cent humidity, of from 60 to 70 pounds per inch for the lighter weight to 100 pounds per inch for the heavier weight.

In the following experiments we have used two grades of linen, No. 1, called high grade, being about the best material immediately obtainable in sufficient quantities for our work, and No. 2, medium grade. The No. 1 weighs 4.6 ounces per square yard and has a tensile strength of about 90–95 pounds per inch warp and 60 pounds filling. The No. 2 medium grade weighs about 3.8 ounces per square yard and has a strength of about 65 pounds warp, 50 pounds filler.

DOPES.

The varnishes or dopes used were three representative products obtained in this country. The cellulose acetate varnishes are probably far from perfect, owing to the difficulty of obtaining a satisfactory product in this country. We understand that the latest European material of this sort is a vast improvement on anything heretofore produced.

The solvents for cellulose acetate commonly used are acetone or tetrachlorethane. The latter is said to be rather dangerous on account of its poisonous properties, and care should be used to allow the vapors, which are heavier than air, to pass through ventilating openings in the floor.

Mention must also be made of a material, the use of which in Europe has been mentioned in news reports. This is a transparent celluloid made of cellulose acetate compounded with a camphor substitute and used in the form of a thin, transparent, noninflammable sheet. These are used for wings instead of cloth, and are said to be very difficult to see at a height of a few thousand feet. Whether this is so or not there is of course this advantage, that the pilot can have a much wider field of view than with ordinary wings.

We were fortunate in obtaining sheets of this material. They are of practically the same strength in both directions.

Thickness.	Weight (ounces per square yard).	Tensile strength (pounds per inch), about—
10/1000	9.33	55
64/1000	59	325

Complete data are given elsewhere.

While the thickest sheets are of course too heavy for wings, they might be used for other purposes as, for example, flooring.

II. STRENGTH, STRETCHING, AND AGING TESTS.

1. STRENGTH.

The samples on which these tests are based were made in two ways: (1) The method used in most cases, except when otherwise specified: The linen was stretched moderately on a frame about 3 by 4 feet, and fastened by tacking. The dopes, etc., were applied to this. (2) The second way (used only in special cases): The linen was doped without first being stretched on a frame.

(1) In general there is a gain in tensile strength due to the dope. No added effect was observed from the varnish.

(2) With a high-grade linen No. 1, the increase in strength amounted to about 10 to 15 per cent. With a medium grade, the increase, particularly in the filler, was much higher, about 40 to 60 per cent.

(3) Tests made on high-grade linen No. 1, coated without being stretched on a frame, showed a much higher tensile increase—in the neighborhood of 40 per cent in some cases. In the first samples, stretched fairly tight before coating, there was evidently not much shrinkage, in the latter samples the cloth shrunk at will, in some cases 3 or 4 per cent. In specifying the increase in strength due to dopes, the method of coating is therefore of importance. The first tests probably approach more nearly the conditions of use on the aeroplane.

(4) Linen coated with rubber, with or without dopes, is stronger than uncoated linen.

(5) Medium-grade linen shows a greater increase in tensile than high-grade linen, in some cases about twice as great an increase being observed.

2. STRETCH.

The stretch at different loads was measured for several different samples and curves plotted. The following points were noted:

(1) The stretch is less up to a certain load with coated fabrics than with the same fabric uncoated.

(2) There is no decided difference between cellulose acetate and cellulose nitrate dopes. The latter is usually supposed to give less shrinking than the acetate. It is possible that this view arises to some extent at least from the fact that fabrics coated with the

nitrate varnish are often more flexible than the others, and therefore appear, on a frame, less taut.

(3) Spar varnish slightly decreases the stretch.

(4) Linen coated with rubber has a greater stretch than the linen without rubber, the latter being, for example, 13 per cent at 96 pounds break, the former 16½ per cent at 100 pounds.

(5) Medium-grade linen, while it acquires a relatively greater strength increase due to coating, has both coated and uncoated a lower ultimate stretch.

	Break.	Stretch.
	Pounds.	*Per cent.*
High-grade linen No. 1	90–95	13¼
High-grade linen No. 1 coated with varnish 1877	100	14½
Medium-grade linen No. 2	65	11
Medium-grade linen No. 2 coated with varnish 1877	78	[1] 10.7

[1] By extrapolation.

3. EFFICIENCY.

While it is desirable to have a wing material which will not easily sag, at the same time it is also important to have a fabric yield rather than break under load. A material which has this ability will often by yielding reduce the stress, and so stand usage which would otherwise be disastrous.

A convenient index of this, which for want of a better term we call the efficiency of the fabric, is the work required to break a piece say 1 inch wide and 12 inches long. This is represented by the area included by the stress-stretch curve. We have calculated this value for the various materials examined. The details and data are given elsewhere, but the following points may be mentioned here, observations being based on breaking in the direction of the warp, since the fillers do not show such marked differences.

(1) When the linen is fastened to a frame under fairly strong tension, as would ordinarily be done in covering a wing surface, and then coated, the work required to break a piece of given dimensions is not sensibly greater than that to break the uncoated material, in spite of the fact that the actual tensile strength of the linen seems to be higher after coating. This holds for high and medium grade linens.

(2) Linen coated under no tension required about two and one-half times as much work to break as uncoated linen. The greater stretch and increased tensile strength are both responsible for this.

In view of this the suggestion is made that there is probably some advantage in not using any more tension than is necessary in fastening the fabric to the frames before coating. The dopes have considerable shrinking power, measured linearly, and by allowing the cloth to shrink a certain amount the slack will be taken up and at the same time a greater efficiency obtained. A stress from collision, etc., will then have a chance to exhaust itself without breaking the cloth, since the cloth can "give" and thus adjust itself to decrease the amount of the stress.

We understand that one manufacturer of the varnish at least recommends this. We have also been told that in some cases, as when a wing collides with an obstruction in landing, a dent may be formed in the fabric without breaking, this dent later disappearing. Since the varnish coating is noncrystalline, and can really be considered in a sense a supercooled liquid, it seems quite likely that there may be some flowing action permitting a slow readjustment of this sort.

(3) The use of spar varnish seems to have no decided effect on the efficiency.

(4) Rubber on one side of the linen with various coatings showed an efficiency about 75 per cent higher than that of linen without rubber, coated on frames. This is of course partly due to the greater stretch of such a fabric, as already noted. It would be interesting to find by practical experiment whether a fabric with rubber on one side can be made to shrink sufficiently for use on a wing. From our small experiments it seems likely that it would be satisfactory. If so, it would have the advantage of being protected on the under side, a matter of consequence in certain localities, as already shown.

4. AGEING.

Samples subjected to continuous exposure for three weeks in a location such that the material felt the full effect of sun and weather throughout the day gave the following results on tests:

(1) The tensile strength was 66 to 75 per cent of the original.

(2) In all cases samples had been greatly affected by the weather, in appearance and feeling. Spar varnish coatings cracked and pealed; samples doped but not coated with spar were more or less scrubbed off by the weather and had evidently deteriorated.

(3) In several cases samples doped and varnished with spar varnish showed a smaller decrease in tensile than those unvarnished, but the effect was not so pronounced as would be expected.

(4) Cellulose acetate coatings seemed more affected by the ageing than cellulose nitrate. This is probably due to the hygroscopic character of the former material, and to the ease with which oils are blended with the latter, making it more waterproof.

III. ABSORPTION OF WATER.

Samples were first weighed, then dried at 95–100° C., and reweighed, after which they were tested. One piece of each was soaked in water at an average temperature of 25° C., another was hung in a saturated atmosphere at the same temperature—for two weeks in both cases. The samples were removed, surface water wiped off the ones that had soaked, after which they were weighed in a weighing bottle. They were then dried at 95–100° C., and reweighed. These data gave the amount of moisture normally present, the amount of water taken both by soaking, and by standing in moist air, and the amount of material washed out by soaking in water. The following results were obtained:

(1) Loss from soaking amounts to 3 to 7½ ounces of the weight of the sample.

(2) Compared with dried samples, fabrics exposed to saturated atmosphere showed 6 to 13 per cent moisture.

(3) Soaking caused the samples to take up 30 to 60 per cent of water.

(4) Cellulose acetate coatings suffer more from soaking than cellulose nitrate.

(5) Fabrics coated with rubber on one side, and doped on the other side, show a smaller absorption of water on soaking, and a smaller increase in weigh due to moisture taken up on standing in a saturated atmosphere than unrubberized fabrics. The effect of spar varnish, in preventing the absorption of water was here very apparent.

IV. FIREPROOFING.

Tests on fire resisting properties of various fabrics were made, to find the effect of the different coatings, and to investigate the possibility of impregnation of fabric with fireproofing materials.

Method of test.—A strip of the fabric ¾ inch wide, was held horizontally, coated side up, and the end touched to a Bunsen flame for a distance just sufficient to ignite. The time required to burn back for a distance of 3½ inches was observed; in cases where the flame was extinguished before this point was reached, the actual distance was noted. Care was taken to avoid drafts.

(1) All coated fabrics not otherwise treated were inflammable; that is, the piece continued to burn after the source of heat was removed.

(2) Spar varnish seemed to retard the burning of fabric coated with cellulose nitrate, and to accelerate it in the case of fabric coated with cellulose acetate.

(4) Fabrics impregnated with ammonium chloride and ammonium phosphate were more fireproof than those impregnated with boric acid. In every case the first two prevented the flame from being self-propagating even when the fabric was doped with cellulose nitrate.

(5) It is interesting to note (see appendix) that fabric impregnated with ammonium chloride has an increased initial tensile strength, but deteriorates more rapidly on exposure. This is probably on account of hydrolysis of the cellulose (fabric). These experiments lead one to believe that by further investigation a thoroughly statisfactory material may be found, which will make fabric fireproof and at the same time not injure it.

Part II.—BALLOON FABRIC.

I. MATERIALS.

Cotton is the most widely used fabric for balloons, in spite of the fact that it is one of the weakest textile fabrics. Silk, the strongest textile fabric, is used to some extent in France and Italy, when lightness is the most important feature. In Germany, it is usually considered dangerous, owing to its electrostatic properties. Its high cost is another objection, when large amounts are needed, as in a Zeppelin type dirigible.

Ramie has been used, but is reported to be unsatisfactory, owing to the difficulty in rubberizing.

Linen has been used, with success, and on account of its greater strength possesses considerable advantage over cotton. The greater tearing resistance of this material as compared with cotton is particularly important. On the other hand, as already stated, it is more difficult to obtain, made according to specifications, than cotton.

In large balloons, rubber is used almost without exception. Other materials are less permeable to hydrogen, but none possess the same properties of adhesion, ease of working, and flexibility. Several layers of fabric can be used, thus increasing the strength and gas-tight properties of the material, whereas oiled fabrics are ordinarily used in a single layer, and to keep this tight a thin closely woven fabric must be used. Furthermore, oiled fabrics are subject to change from heat and cold and must be handled with care. They are, however, cheaper than rubberized fabrics.

We have obtained various cotton fabrics suitable for use in balloon cloth, and from the tests on these, and also from published data of tests made in Europe, have endeavored to establish some relation between the weight and maximum strength obtainable at that weight. Differences in testing conditions, such as humidity and method of testing, not usually specified, cause a certain variation, so the probable limits of strength of each weight are given.

Until recently it was very difficult to obtain a satisfactory fabric made in this country. Labor and other conditions in Europe have permitted a greater concentration upon the spinning and weaving of such fabrics. The results have been that until recently no cotton fabrics comparable to those made in Europe could be obtained.

Recently there have been produced in this country fabrics which from the standpoint of weight and strength are probably as good as those made in Europe. It is to be hoped that the same perfection in spinning and weaving may also be obtained.

In the former operation cotton manufacturers usually admit the superiority of European material, but probably in time this can be met. This point is important, in order to get a fabric as free from flaws as possible.

The mean results of our tests and those from abroad would indicate the following:

Weight of fabric.	Strength warp and filler.
Ounces per square yard.	*Pounds per inch.*
2	30
2½	42
3	53
3½	65
3¾	74

II. STRENGTH AND AGEING TESTS.

(1) *Effect of structure.*—Ordinarily balloon fabrics are made of two or more cloth layers, one of these usually on the bias. A layer of rubber is between each ply of fabric and a layer on the face of the fabric which comes in contact with the gas. The outside surface may or may not be coated with rubber and is sometimes treated after the balloon is made with cellulose acetate varnish. Parallel fabrics—that is, two or more layers of fabric with the warp threads all running in the same direction—have been used to some extent in France. They are supposed to be stronger, but tear more easily. Since cotton tears quite easily under ordinary conditions, it seems highly desirable to adopt some such method as biasing to prevent tearing. While the biased fabric does not show so high a tensile strength test, it must be remembered that the stresses on a dirigible balloon which cause trouble are not the simple ones due to internal pressure, weight of load, etc., but those localized in one area due to sudden pulls on ropes, etc. It is important to have a fabric that will not continue to tear after a tear is once started.

Tensile strength tests made on 1-inch strips showed that the strength of a 2-ply parallel fabric was not necessarily twice that of the single ply of uncoated fabric. On the other hand, double bias fabrics show a greater strength than that of the single ply of fabric when the stress is parallel, for example, to the warp of the unbiased piece.

	Balloon cloth made from—	
	Fabric No. 1.	Fabric No. 2.
Strength of fabric, uncoated warp	70	50
Strength of 2-ply parallel fabric warp	125.5	92.6
Strength of fabric 2-ply bias warp of unbiased ply	85	66
Tensile strength by bursting test, 2-ply bias	100	85

Ageing for 13 weeks, the samples being continuously exposed to the weather, caused a decrease in tensile strength of about 5 per cent. The samples were exposed during the winter months, from January 1 to about April 1.

Other samples exposed for one month, from August 20 to September 20, showed a decrease of about 8 to 10 per cent in tensile strength in the warp and from 0 to 6 per cent in the filling. The rubber was apparently unaffected.

III. PERMEABILITY OF BALLOON FABRICS.

The permeability was measured by the chemical method similar to that used at the National Physical Laboratory of Great Britain. In this method the fabric is held in a cell, which is divided by the fabric into two compartments. Dry purified hydrogen at a pressure of 70 millimeters of water is passed through one side, while air is drawn through the other, dried and passed through an electric furnace, which burns the hydrogen present in the air from diffusion to water, which is absorbed and weighed. The cell is kept at constant temperature by immersion in a thermostatic bath. The permeability is expressed in liters of hydrogen, measured at 0° C., 760 millimeters per square meter of fabric per 24 hours.

In France the Renard-Sourcouf balance is ordinarily used. This measures the net volume of gas lost by diffusion through the fabric. It does not in reality measure the loss of hydrogen, since air passes in while hydrogen passes out. According to T. Graham,[1] the relative rates of diffusion of nitrogen, air, and hydrogen are as follows:

Diffusion through rubber.

Nitrogen	1
Air	1.149
Hydrogen	5.5

With the Renard balance, while 5.5 volumes of hydrogen pass out, according to the above figures, 1.149 volumes of air pass in, giving a net change of 4.351 volumes. In other words, for an apparent loss of 10 liters per 24 hours per square meter, we should have an actual loss of 12.6 liters, as measured by the chemical method. (We have not had an opportunity to test fabrics measured by the gas balance method.) The volume loss is of course important, and if on further investigation it is found that there is much variation in the ratios given by the Graham experiments for different kinds of rubber it would be well to make both tests standard. In fact, the introduction of auxiliary coatings of cellulose esters, etc., makes this of immediate interest.

(1) EFFECT OF VARYING AMOUNTS OF RUBBER.

The permeability decreases with increasing weight of rubber as a general rule, but does not seem to be proportional to it.

Weight of rubber between plies (ounces per square yard).	Permeability at 15° (by extrapolation).
1.65	50
3.11	9
5.11	9

This is in accord with the observation of Austerweil,[2] who found that the permeability of two rubber membranes, 918 and 1,675 grams per square meter respectively, was practically the same for the first 100 hours. The rates diverged up to 400 hours, after which they were again constant. This, according to Austerweil, marked the point when both membranes were saturated. Between 100 and 400 hours the thinner membrane became saturated more rapidly than the other, and so showed a greater rate of diffusion.

[1] Phil. Trans., 1866, p. 399.

[2] Die Angewandte Chemie in der Luftfahrt, p. 67.

(2) EFFECT OF TEMPERATURE.

Experiments conducted in England at the National Physical Laboratory[1] show that the permeability rises rapidly with the temperature. For two samples they found the following results:

Diagonally doubled, 3 layers rubber	15.5° C.— 6.71 1 22.1° C.—10.84 1
Parallel doubled, 2 layers rubber	15.5° C.—12.3 1 22.1° C.—21.5 1

These figures show more than 9 per cent increase in permeability per degree.

We have made tests at approximately 20, 30, and 40° C., and found in every case a marked temperature coefficient. If the values of permeability and temperature are plotted, it will be noted (fig. 9, appendix) that the curve rises more rapidly with increasing temperature. Our results show a temperature coefficient about one-half that given in the data just cited. It may be that the nature of the rubber compound has considerable bearing.

This high temperature coefficient is of peculiar importance in this country, where the aeronautic activities of both Army and Navy are centered in the South. It seems advisable that this be considered in specifying the minimum gas leakage allowable when contracting for dirigible balloons, and that some temperature be stated, since a balloon tested at Pensacola would, without extra precautions, show a higher loss than one in the vicinity of New York. A correction to a standard temperature could probably be made.

This also shows the advisability of providing adequate arrangements to prevent too high a temperature in hangars. I understand that in Europe double roofs, with fans and other suitable cooling devices are used.

(3) EFFECT OF COATING CLOTH WITH CELLULOSE ESTER LACQUERS.

It has been the practice in Europe for some time, apparently, to coat the outside of balloons with some sort of varnish. These are sold under various names, but in general are cellulose acetate lacquers. They are used to cut down wind resistance, to protect the fabric, and to render it gas tight in cases where the rubber has deteriorated.

Samples were given four coats of cellulose nitrate and cellulose acetate lacquers 1876 and 1877, respectively, the lacquer being applied to the cloth. In both cases the improvement in permeability was definite, though small, amounting to from 1 to 1½ liters per square meter per 24 hours.

(4) EFFECT OF COATING RUBBER WITH CELLULOSE ESTER LACQUERS.

It seemed likely that the small improvement noted above was due to the fact that cloth offers a poor surface for obtaining a tight coat, at least for a thin film. To verify this tests were made with the same

[1] Tech. Report Adv. Committee for Aeronautics, 1910-11, p. 60.

materials in the same amounts on the rubber side. The improvement was very marked here, amounting to 50 per cent or more of the value found for the same fabric uncoated. In one case there was a reduction from 11 liters at 20° C. to 4 liters at the same temperature. Unfortunately these lacquers are not suited for use on rubber surfaces since they peel off. It is to be hoped that a marked improvement may be made in them, since their use for this purpose seems very promising. The inflammability of cellulose nitrate is of course a drawback, but obviously a balloon filled with hydrogen must be carefully protected from fire, however noninflammable the material used in its construction. It is, moreover, a simple matter to obtain cellulose nitrate blended with oil to give a flexible coating.

(5) EFFECT OF COATING RUBBER WITH GELATIN COMPOUNDS.

A flexible gelatin compound on the rubber surface in about the same amounts as the coatings used in (4) and (5) was tested and found to give a very low permeability:

Original permeability at 20° C., 11 liters per square meter per 24 hours.
Permeability after coating with gelatin compound at 20° C., .8 liter approximately per square meter per 24 hours.

Part III.—TESTS ON BALLOON AND AEROPLANE FABRICS.

I. TEARING TESTS.

To obtain some knowledge of the behavior of aeronautic fabrics under stresses somewhat similar to those existing in aeroplanes and balloons, the test used by the National Physical Laboratory [1] was employed.

Method.—A piece of fabric is clamped in the jaws, and in the center of this a slit of definite length is cut perpendicular to the line of pull. When stress is applied, the cut opens, and if the load is increased the tear widens in a direction perpendicular to the stress and the sample finally breaks. The threads parallel to the line of stress bend inward on either side of the slit; those perpendicular to the strain bend away from the cut. The localization of strain on the thread at the ends of the slit is evidently caused by the pull being transmitted from the longitudinal threads to the transverse threads, due to the take-up in weaving. The general effect of stretching coated and uncoated fabrics is shown in the photographs taken of tests. (Appendix, Plates I–VI.) The wrinkling of the coated fabric around the cut, producing a poor impression, is particularly of interest, showing how the disturbance is more localized than in the case of uncoated fabric.

A fair index of the ability of fabrics to resist tearing may be obtained by plotting the results for the point at which the tear starts to widen and where rupture occurs against the size of cut. The factor found by dividing the breaking load by the width of slit gives a means of comparison which seems to have some value. (See appendix for data and curves.)

(1) The load to break falls off more rapidly with increasing size of slit in the case of a doped fabric than with an undoped fabric.

(2) Cotton is much inferior to linen.

[1] Tech. Report of Adv. Com. for Aeronautics, 1910-11, p. 72.

(3) Parallel double balloon fabric tears more easily than bias doubled fabric, particularly for small cuts. Furthermore, a parallel fabric tears evenly in a straight line, while in the case of the bias a general rending of one layer occurs, while the other is distorted rather than torn. It can be readily seen that the effect of tearing on the parallel fabric in a balloon would be much more disastrous.

II. SURFACE FRICTION TESTS.

Tests on the resistance of various fabrics were made in the wind tunnel at the Washington Navy Yard.

The method used was to suspend vertically a glass plate about 34 inches wide and 9 feet long so that its long edge is in the direction of the air flow. The following edge of the plate is connected with the balance, allowing the horizontal moment about one knife edge to be measured.

Corrections were found and used for the wires suspending the plate. The ends of the plate fitted into slots in struts of stream line form. The wind passing the slot into which the leading edge fitted caused a diminution in pressure, giving the effect of a thrust on the plate against the wind. The wind caused a compression in the slot in which the following edge fitted, likewise giving the effect of a thrust against the wind. The amount of pressure developed in each slot was observed with a hook gauge manometer, and from this and the area of the edges could be calculated the correction to be added for each speed.

The resistance of the plate glass was taken as standard and found at 30, 40, 50, 60, and 70 miles per hour. Various samples of fabric were then attached, covering both sides of the glass completely in each case, and the resistance measured at different speeds.

Complete data will be found elsewhere, but the following general points may be mentioned here. Taking, for example, the resistance of plate glass as 1, at 70 miles per hour, we have the following comparative resistances at this velocity:

Experiment No.	*At 70 miles per hour.*	
1	Plate glass	1.000
5	Linen No. 1 (high grade)	1.362
2	Linen No. 1 (high grade), 1 coat varnish No. 1876	1.162
3	Linen No. 1 (high grade), 3 coats varnish No. 1876	1.108
4	Linen No. 1 (high grade), 3 coats varnish No. 1876, 1 coat spar varnish	1.061
6	Linen No. 1 (high grade), 3 coats varnish No. 1877	1.085
7	Linen No. 1 (high grade), 3 coats varnish No. 1877, 1 coat spar varnish	1.081
8	Linen No. 1 (high grade), 3 coats varnish No. 1877, 2 coats spar varnish	1.078
9	Balloon fabric No. 3, cloth outside, double parallel	1.965
10	Balloon fabric No. 3, cloth outside, double parallel, freshly singed	1.654
11	Balloon fabric No. 3, cloth outside, double parallel, singed and coated once, No. 1876	1.345
12	Balloon fabric No. 3, cloth outside, double parallel, singed and coated three times, No. 1876	1.107
13	Balloon fabric No. 3, cloth outside, double bias	1.902
14	Balloon fabric No. 3, cloth outside, double bias, freshly singed	1.762
15	Balloon fabric No. 6, cloth outside (specially woven fabric), double bias	1.528
16	Balloon fabric No. 6, cloth outside (specially woven fabric), double bias, freshly singed	1.372
21	Aeroplane fabric, rubberized, No. 23	1.079
22	Aeroplane fabric, aluminum coated, No. 24	1.101

I. From these figures it will be seen that we may roughly divide surfaces into groups as to wind resistance.

(1) Those which are what might be called continuous; in this case the resistance probably increases simply as the surfaces deviate from a true plane due to lumps and other unevennesses. Plate glass, doped, varnished, and rubberized fabrics come in this class. The resistance does not exceed 1.20, glass being 1.

(2) Those which have a discontinuous surface, i. e., such as would be presented by a perfectly smooth woven material, as a wire gauze; linen and singed cotton approach this. Here the resistance is between 1.35 and 1.7.

(3) Those which have a discontinuous surface to which is added other roughnesses, such as arise from nap. Unsigned cotton is in this class, and the resistance is 1.5 or more.

II. It is interesting to note the great improvement produced on balloon fabric by the use of one or more coats of some sort of varnish.

III. The *difference* in resistance between an uncoated fabric of class (3) and plate glass is very appreciable at high speeds, being about 0.013 pound per square foot at 70 miles per hour. This would mean a total head resistance in a large machine of about 18 pounds, or a decrease in lifting power of 150–180 pounds. However, as can be seen from the list, it is fairly simple to cut down the resistance until it approximates that of glass.

APPENDIX

TO

REPORT No. 6, PART 1.

[Containing details, data, and plates.]

LINEN FABRICS.

Linen is the most widely used material for aeroplane wings, on account of its great strength and toughness. The grades now on the market have weights and strengths as shown:

	Weight (ounces per square yard).	Strength.	
		Warp.	Filler.
I	3. 67	65. 0	54. 4
II	3. 78	69. 5	49. 2
III	3. 87	80. 7	79. 0
IV	4. 04	86. 9	74. 0
V	4. 09	90. 2	82. 7
VI	4. 48	82. 9	100. 1
VII	4. 60	95. 0	60. 0
VIII	4. 86	90. 4	102. 5

In Great Britain there has recently been adopted the method of testing the sample wet, after soaking some time. This is to avoid error due to humidity changes. While this method may seem somewhat arbitrary, it is convenient and nearer the conditions of use than a test on absolutely dry material. They figure that this test corresponds to what could be expected at a theoretical humidity of 111 per cent.

Tests on transparent cellulose acetate sheets.

No.	(1) Thickness.	(2) Weight (ounces per square yard).	(3) Tensile strength (pounds per inch).		(4) Maximum difference in tests (in per cent of average value).	
1	10/1000	9. 33	55. 3	57	10. 8	10. 5
2	16/1000	15. 49	106. 3	85. 8	14. 1	8. 1
3	24/1000	22. 96	127. 1	130	30. 6	25. 2
4	32/1000	30. 35	178. 6	187. 7	21. 2	2. 6
5	64/1000	59. 02	326	345. 8	10. 7	. 8

Tests made on Riehle machine, 1-inch strips, 1-inch jaw, 3 inches between jaws; speed, 18 inches per minute.

The strength was measured both ways on each sheet, since it was thought that the material might show a grain, such as often occurs in materials in sheet form which have been made by a calendering process. Except in the case of No. 2, there is no perceptible difference in strength. The material runs fairly uniform in strength except for the one sheet No. 3. Column 4 shows the difference between the highest and lowest tests, compared to the average.

The material is quite flexible, in thin sheets, and can be bent double several times in one place without cracking. On the other hand, it tears very easily when once cut. It is noninflammable.

STRETCHING TESTS.

Figures 1–4 show the relation between load and per cent stretch. The numerical values for the tests are given on page 155 and need little comment.

The tests were made on a Riehle fabric-testing machine, and measurements were made on an initial distance of 20 inches, so the results are probably quite accurate. The jaws moved apart at a rate of 6 inches per minute.

It is interesting to note that the rate of stretch is usually low in doped fabrics up to 10 to 20 pounds load, after which it rises more rapidly. On the other hand, the uncoated fabrics tend to be just the opposite of this—that is, there is a considerable stretch at first under light load, up to say 20 pounds, then the "slack" having been removed from the fibers, the stretch is much slower. It will be noticed that this holds true even for samples when the total stretch of the coated fabric greatly exceeds that of the uncoated, as in figure 2, Curves VIII, IX, X, XI, when the fabric was not stretched on a frame without coating. The stretch of the coated fabric only becomes equal to that of the uncoated at loads of 12 to 20 pounds.

The application of this seems to lie in the fact that ordinarily even at high speeds the loading due to wind pressure is very light. According to Austerweil [1] even at highest speeds the load would not amount to more than 145.5 kilograms per meter, or about 8 pounds per inch. Ordinarily it would be much less. It would seem therefore that from the standpoint of keeping the fabric taut against stretching just as good results could be obtained by putting it on loosely enough to allow shrinkage, and get the benefit of increased tensile strength and efficiency shown by the fabrics in Curves VIII–X, inclusive.

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[1] Die Angewandte Chemie in der Luftfahrt, 179.

Stretch of aeroplane fabric.

Fabric.	Curve.	Stretch under load of (pounds per inch)—											Efficiency—in (1-inch by 12-inch strip) foot-pounds.
		10	20	30	40	50	60	70	80	90	100	110	
Linen No. 1:													
Untreated warp	I	3.65	7.10	8.30	9.35	10.10	10.65	11.15	11.55	12.05	(96) 12.35	......	8.67
Untreated Filler	I	1.62	2.37	2.90	3.37	3.75	4.16	......	......	......	......	......	......
Varnish 1875—W	II	1.25	3.75	6.66	9.25	10.58	11.83	12.92	13.75	14.75	......	......	7.77
F	II	.80	1.68	1.86	2.12	2.66	3.19	3.73	4.36	......	......	......	......
Varnish 1876—W	III	1.17	3.58	7.50	9.92	11.50	12.58	13.50	14.12	14.50	15.00	......	9.62
F	III	.75	1.58	2.58	3.42	4.11	4.42	5.25	5.62	6.00	......	......	......
Varnish 1877—W	IV	1.75	4.7	7.42	9.35	11.25	12.00	12.83	13.33	14.12	14.50	14.75	10.93
F	IV	.75	1.75	3.00	3.50	4.00	4.75	5.25	6.00	(86) 6.75	......	......	......
Varnish 1875 and Spar—W	V	1.17	3.42	5.92	8.00	9.33	10.62	11.50	12.08	13.00	(95) 14.00	......	7.54
F	V	1.00	1.75	2.75	3.33	4.25	4.62	5.33	6.00	(86) 6.50	......	......	......
Varnish 1876 and Spar—W	VI	1.10	3.5	6.42	8.80	10.30	11.25	12.16	13.00	13.53	14.00	......	8.75
F	VI	.83	1.75	2.75	3.75	4.33	4.92	5.33	5.92	6.37	(96) 7.00	......	......
Varnish 1877 and Spar—W	VII	1.75	4.00	6.50	8.75	10.50	11.75	12.12	12.50	13.00	(96) 14.2	......	7.32
F	VII	1.04	1.99	2.85	3.55	3.81	4.08	4.60	4.86	......	......	......	......
Linen No. 1, coated, without prestretching, coated with—													
Varnish 1875—W	VIII	5.00	6.89	11.44	15.33	17.55	18.89	20.00	21.17	21.75	22.67	120–23.67 23.33	19.41
F	VIII	2.20	3.33	4.33	5.07	5.76	6.33	7.00	7.37	(88) 8.13	......	......	......
Varnish 1876—W	IX	3.16	7.83	12.00	15.08	17.08	18.08	19.66	20.42	21.17	22.00	120–23.83 22.50	19.11
F	IX	2.00	3.80	4.77	5.25	6.00	6.37	6.50	7.00	......	......	......	......
Varnish 1877—W	......	2.81	10.43	15.00	17.50	18.75	19.75	20.43	21.06	21.56	22.12	22.83	18.19
F	......	1.83	3.08	4.16	4.58	5.16	5.66	6.16	6.37	......	......	......	......
Linen No. 1:													
Rubberized—W	IR	7.42	11.25	12.44	13.44	14.06	14.56	15.06	15.56	15.92	16.50	......	12.89
F	IR	2.25	3.50	4.00	5.25	5.8	6.25	......	......	......	......	......	......
Rubberized—Varnish 1875—W	......	1.92	5.58	8.58	10.92	11.66	13.08	13.92	14.42	14.92	15.33	16.25	11.77
F	......	1.92	2.81	4.00	5.12	5.62	6.37	6.50	7.00	......	......	......	......
Varnish 1876—W	......	2.56	7.25	10.37	12.12	13.19	14.00	14.6	15.19	15.6	16.19	120–17.25 16.75	15.16
F	......	1.37	3.00	4.00	5.12	5.5	6.00	6.57	6.81	......	......	......	......
Varnish 1877—W	......	2.75	7.08	10.5	12.25	13.33	14.17	14.92	15.5	15.92	16.37	16.70	13.46
F	......	1.62	3.19	4.19	5.08	5.66	6.17	6.50	6.92	7.25	......	......	......
Varnish 1875—Spar—W	......	1.75	6.75	9.25	11.50	12.66	13.21	14.06	14.69	15.44	15.5	......	12.25
F	......	1.33	2.42	3.50	4.50	5.16	5.58	6.00	6.16	......	......	......	......
Varnish 1876—Spar—W	......	2.50	7.94	11.06	12.81	13.77	14.69	15.37	16.00	16.37	16.62	17.00	13.64
F	......	1.37	3.06	4.44	4.62	5.19	5.56	6.19	6.31	......	......	......	......
Varnish 1877—Spar—W	......	2.66	6.66	9.83	11.5	12.92	13.83	14.58	15.08	15.58	16.06	16.5	12.66
F	......	1.33	2.42	3.58	4.42	4.92	5.33	5.50	5.87	......	......	......	......

Stretch of aeroplane fabric—Continued.

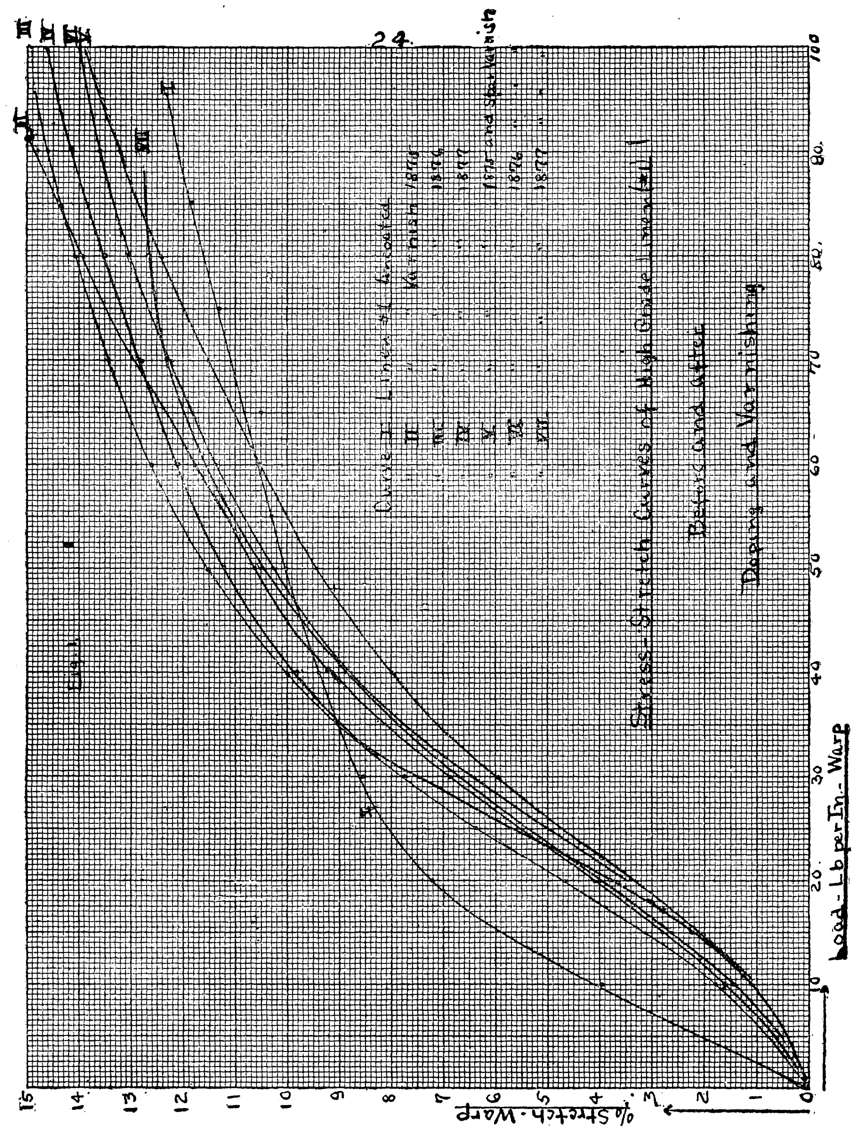
Fabric.	Curve.	Stretch under load (pounds per inch).										Efficiency in (piece 1 by 12 inches) foot-pounds.
		10	20	30	40	50	60	70	80	90	100	
Medium-grade linen No. 2:												
W	IM	5.08	7.42	8.42	9.16	9.50	10.12	......	......	......	......	4.51
F		3.75	5.00	5.75	6.12	......	......	......	......	......	......	....
Linen No. 2:												
Varnish 1875—												
W	IIM	1.58	4.16	6.42	8.67	9.92	10.62	11.50	......	......	......	4.77
F		.67	1.42	2.33	3.16	3.83	4.42	5.00	5.12	5.50	......	....
Varnish 1876—												
W	IIIM	1.33	3.08	5.08	6.58	7.50	8.33	8.75	9.50	......	......	4.56
F		1.17	2.50	3.83	4.92	5.83	6.50	7.12	......	......	......	....
Varnish 1877—												
W	IVM	1.66	3.92	5.92	7.58	8.50	9.42	10.12	......	......	......	4.18
F		1.42	3.00	4.25	5.67	6.25	6.87	7.50	......	......	......	....
Varnish 1875 and spar—												
W	VM	1.17	2.75	4.83	6.33	7.33	8.75	8.83	9.58	10.00	......	5.50
F		1.19	2.50	3.58	5.00	5.75	6.42	6.83	7.17	7.75	......	....
Varnish 1876 and spar—												
W	VIM	1.50	3.50	5.50	6.92	7.75	8.58	9.25	10.00 (75)	......	......	4.82
F		1.00	2.16	3.17	4.08	4.75	5.25	5.83	6.00	......	......	....
Varnish 1877 and spar—												
W	VIIM	1.33	3.33	5.00	6.58	7.75	8.50	9.16	9.75 (75)	10.25	......	5.68
F		1.58	2.66	3.50	4.83	5.42	6.08	6.58	6.75	......	......	....

TEARING TESTS.

In these tests wooden jaws were used, fitted to a Riehle fabric testing machine. The jaws moved apart at a speed of approximately 6 inches per minute.

The Plates I–VI were made by setting up the machine in a dark room, putting the sample under tension, and holding a dry plate against the sample. An electric bulb on the other side of the sample furnishes light for the exposure. In the case of cotton fabrics the small size of the yarn and its transparency gave poor definition; this difficulty was removed by first coloring the sample with a yellow naphtha soluble dye. The photographs are therefore actual size, and show up the conditions of the threads quite clearly.

The factor obtained by dividing the breaking load for a 1-inch cut by that for the uncut fabric gives some idea as to the relative tearing resistance of various materials. This, with the actual tensile, should furnish a good basis for comparing fabrics as to suitability.


Stress-Stretch Curves of High Grade Linen
Before and After
Doping and Varnishing
Load - Lb per In. - Warp
% Stretch - Warp

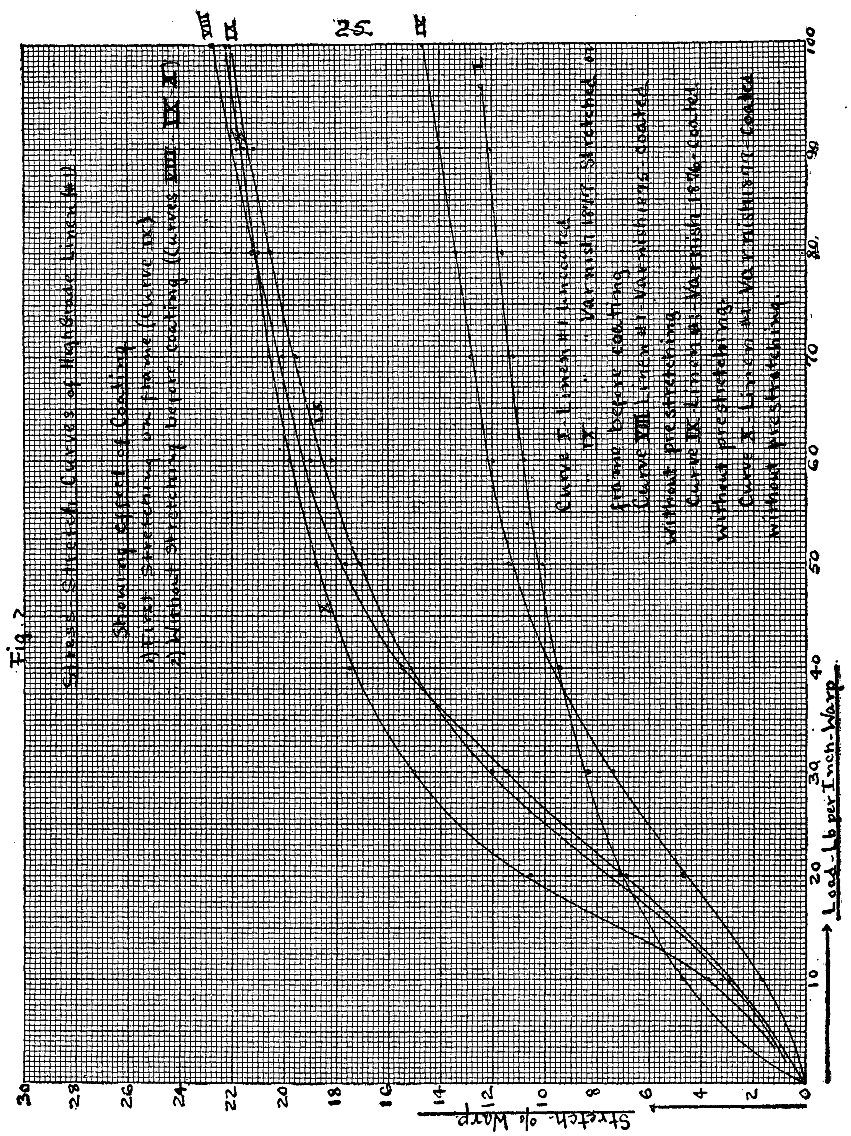


Fig. 2
Stress Stretch Curves of Highgrade Linen (#1)
Showing effect of Coating
1) First Stretching on frame (Curve IX)
2) Without Stretching before coating (Curves VIII IX X)
Curve I. Linen #1 Uncoated
" IX " " Varnish 1877 Stretched on frame before coating
Curve VIII Linen #1 Varnish 1875 Coated without prestretching
Curve IX Linen #1 Varnish 1876 Coated without prestretching
Curve X Linen #1 Varnish 1877 Coated without prestretching
Stretch % Warp
Load Lb per Inch Warp
VIII
IX
X
IX
I
25

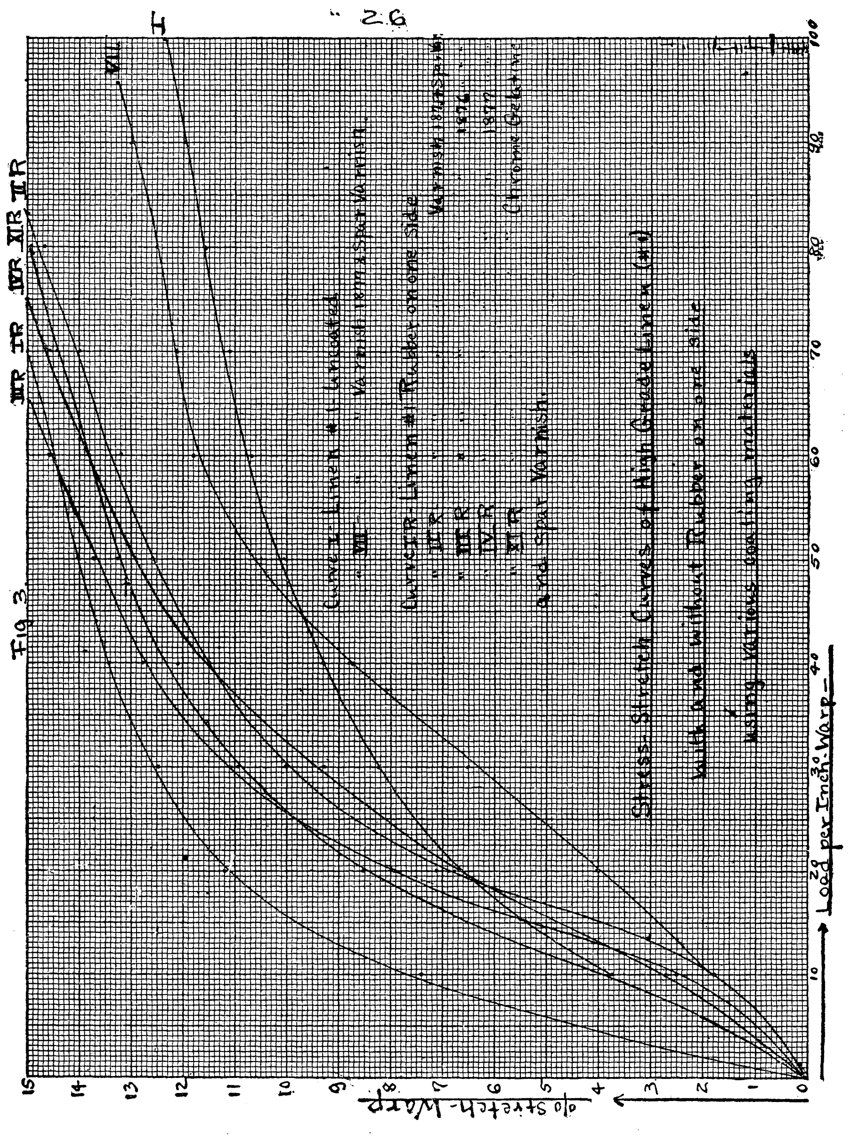


Fig 3.
Stress Stretch Curves of High Grade Linen (#1)
with and without Rubber on one side
using various coating materials
Load per Inch: Warp
% Stretch-Warp
Curve I Linen #1 Uncoated
Curve I R Linen #1 Rubber on one side
and spar varnish.

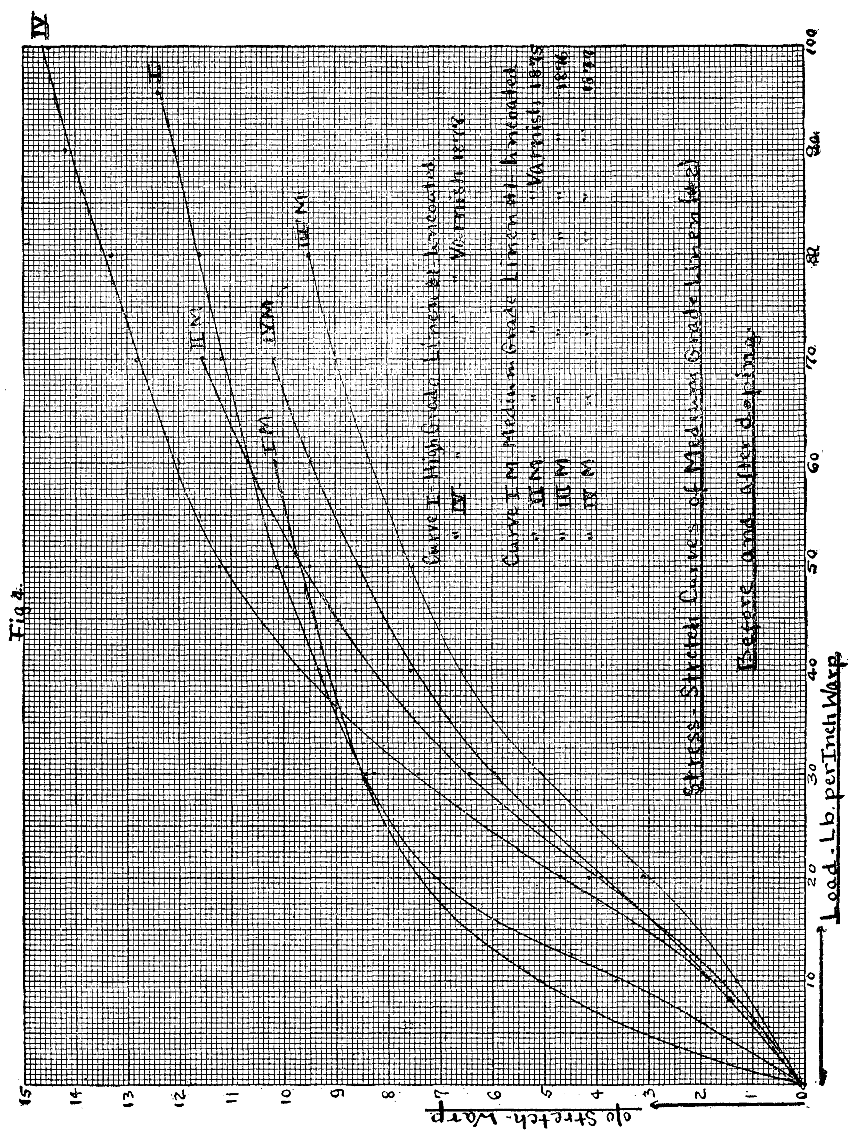

Stress-Stretch Curves of Medium Grade Linen (#2)
Before and after doping
Load - Lb. per Inch Warp
% Stretch - Warp

Fig 4.

	Tensile strength (pounds per inch).		Tearing factor.	
	Warp.	Filler.	Warp.	Filler.
Linen No. 1, high grade:				
Uncoated	100	59	0.50	0.52
Doped	106	86	.29	.44
Linen No. 2, medium grade:				
Uncoated	65	45	.67	.57
Doped	85	75	.58	.58
Cotton, light weight:				
Uncoated	37	49½	.48	.36
Doped	45	45	.38	.37
Balloon fabric:				
Double parallel	85	70	.36	.33
Double bias	65	....	.66	....

From the above figures it will be seen that the lower grade of linen is relatively more difficult to tear than the high grade. This is probably because the higher grade fabrics, both linen and cotton, owe their greater strength for a given weight to the greater number of yarns per inch. These are of necessity smaller, and since tearing depends to a considerable extent on the strength of the individual threads, we find that strong, closely woven fabrics tear more easily in proportion than weaker ones. A good example of this is the filler of the cotton fabric, compared with filler of No. 2 linen. The actual tensile strength of the cotton is higher, but the effect of a cut much greater, giving the factors as shown: 0.36 for the cotton and 0.57 for the linen.

Tearing tests on aeroplane and balloon fabrics—Load required to start tear, and to break, for slits of various sizes.

Fabric.	Size slit.									
	0 inch.		¼-inch.		½-inch.		1-inch.		1½-inch.	
	Load per inch.									
	Tear.	Break.	Tear.	Break.	Tear.	Break.	Tear.	Break.	Tear.	Break.
Linen, No. 1, high grade, uncoated:										
Warp	100	100	66½	74	48½	66	36	50	27	49
Filler	59	59	40	44	34	42	23½	31	18	29
Linen, No. 1, high grade, coated, 1875 var.:										
Warp	106	106	74	90	49	70	31	45	26	43
Filler	86	86	51	68½	37½	45½	30	38	27	31
Linen, No. 2, medium grade, uncoated:										
Warp	65	65	49½	51	32	50	28	44	21	42
Filler	45	45	29½	35	26	30	20	26	17	25
Linen, No. 2, medium grade, coated, 1875 var.:										
Warp	85	85	57	74	41	64	23	50	21	49
Filler	75	75	55	62	38	46	29	43½	25	36
Cotton, light weight, uncoated:										
Warp	37	37	16	18	10½	18	10	18	9	18
Filler	49½	49½	18	20	14	18	10	18	(8)	(15)
Cotton, light weight, coated, 1875 var.:										
Warp	45	45	23	26	18½	22	15½	17½	14	18
Filler	45	45	20½	22	15	16½	11½	(17)	11	14½
Balloon fabric, double, parallel:										
Warp	85	85	41	46	30	37	23	31	20	25
Filler	70	70	34	36	23	29½	17½	23½	14	20
Balloon fabric, double bias	65	65	53	57	47	52	30	43	20	34

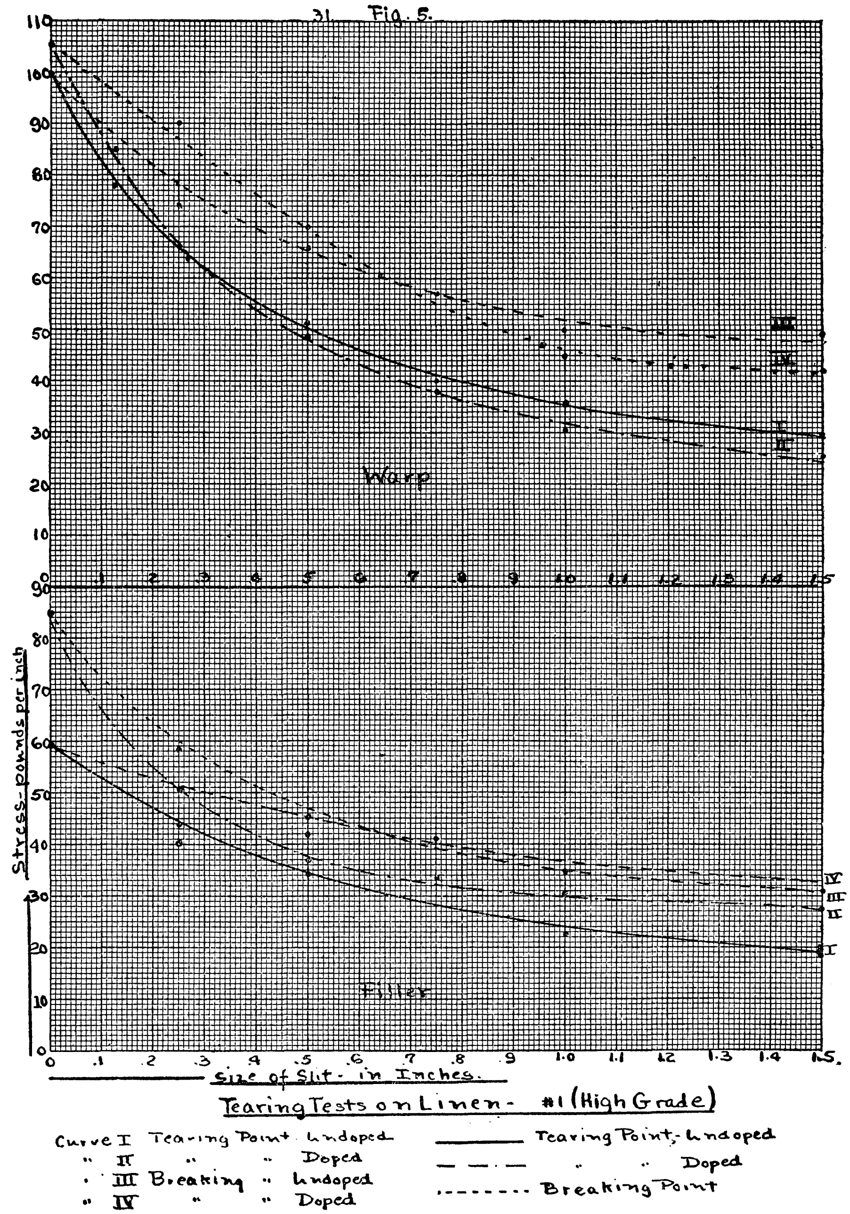
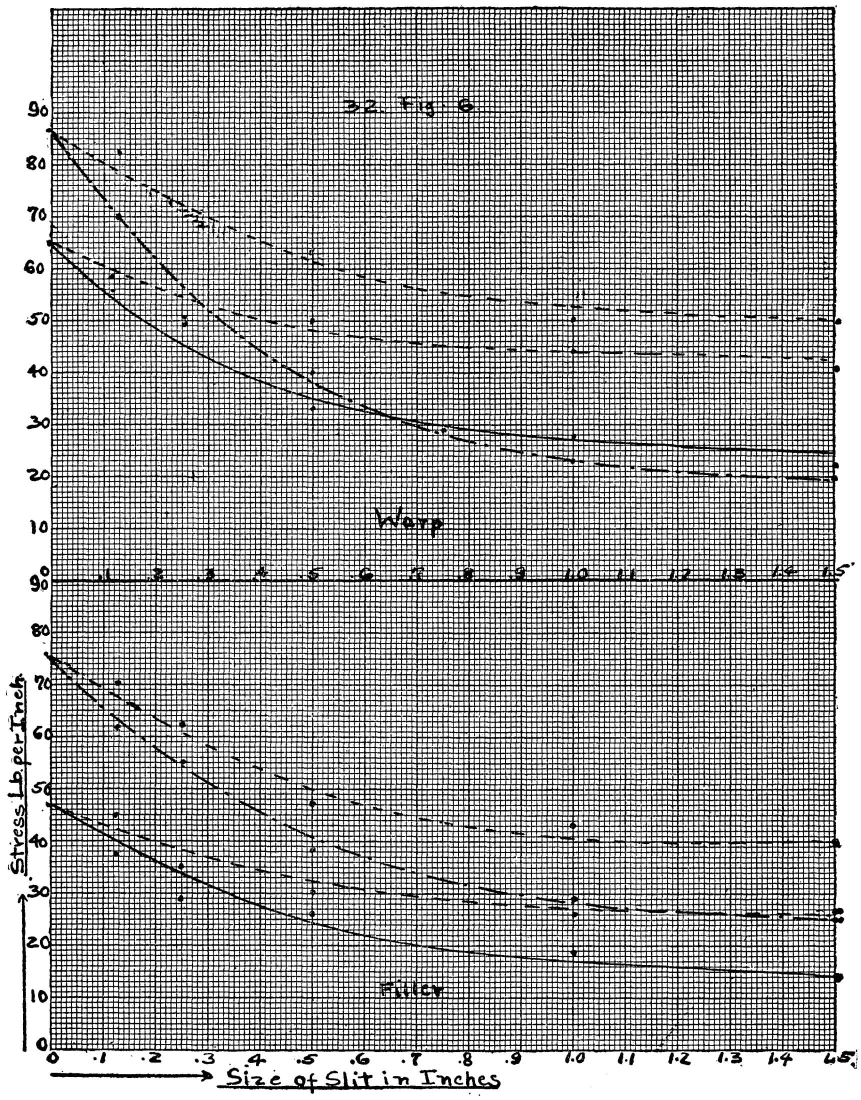


Fig. 5.
Stress - pounds per inch
Warp
Filler
Size of Slit - in Inches.
Tearing Tests on Linen - #1 (High Grade)
Curve I Tearing Point Undoped
" II " " Doped
" III Breaking " Undoped
" IV " " Doped
Tearing Point, - Undoped
" " Doped
Breaking Point



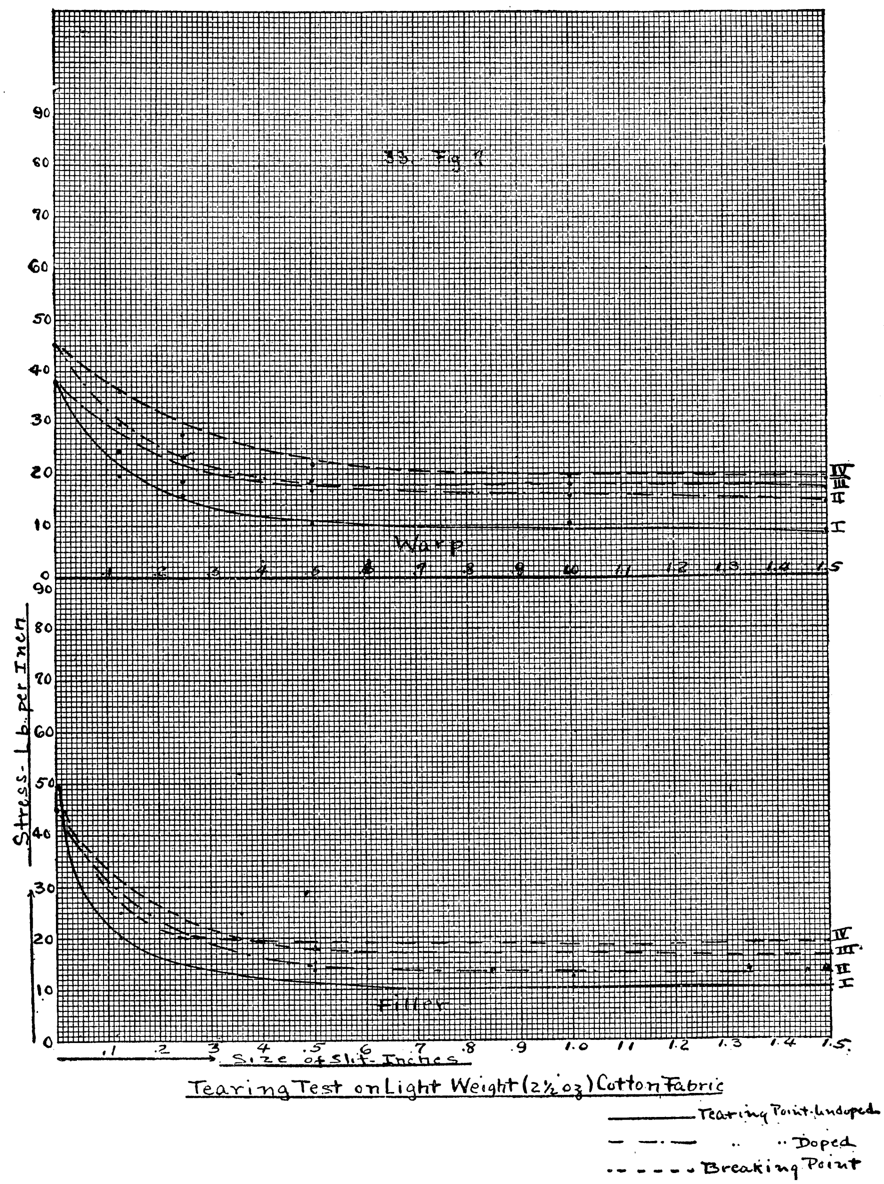
Tearing Tests on Linen #2 (Medium Grade)

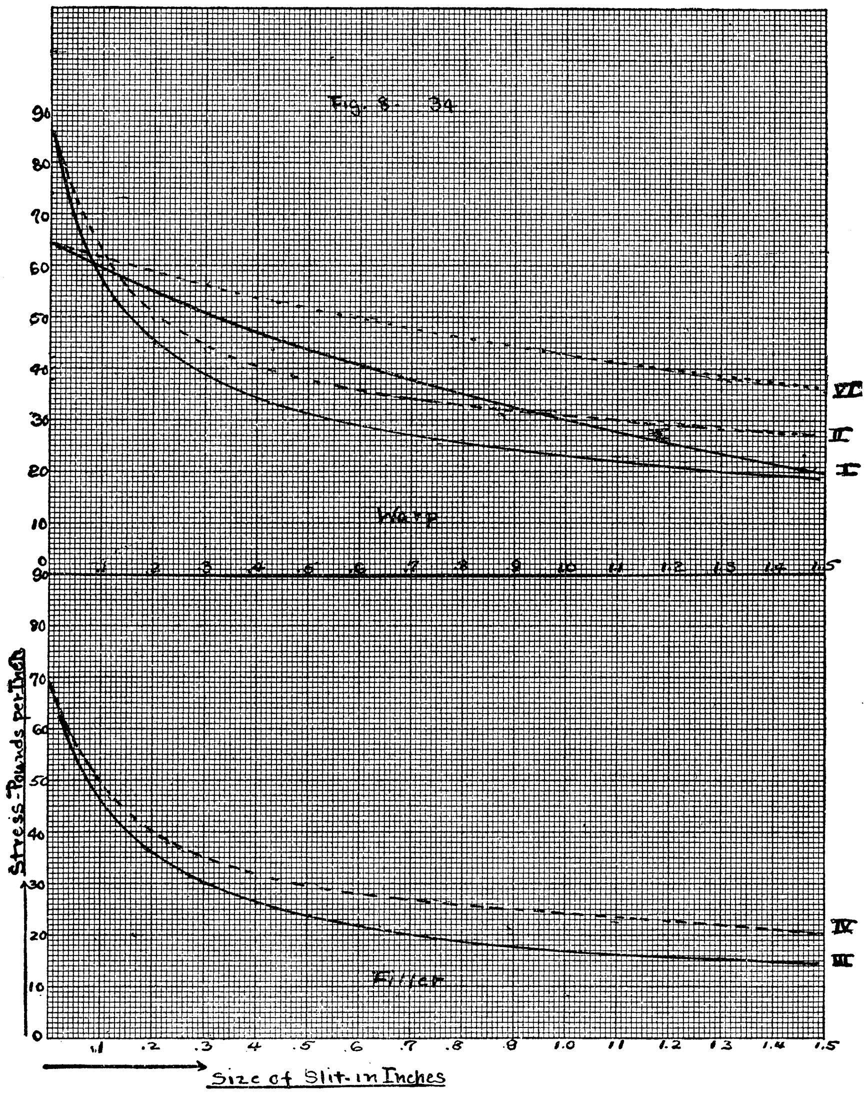
Curve I - Tearing Point - Undoped ——————— Tearing Point. Undoped

" II. " " Doped —·—·— " " Doped

" III Breaking - Undoped - - - - - - - Breaking Point.

" IV " " Doped


Warp
Filler
Stress - Lb. per Inch
Size of slit - Inches
Tearing Test on Light Weight (2½ oz) Cotton Fabric
Tearing Point. Undoped.
" " Doped
Breaking Point



Tearing Tests on Balloon Fabric.

Curves I & III. Tearing points Double parallel balloon fabric. Warp & Filler resp.
" II & IV. Breaking " " " " " " "
" V & VI Tearing and Breaking Points. " " Double bias.

COTTON FABRICS.

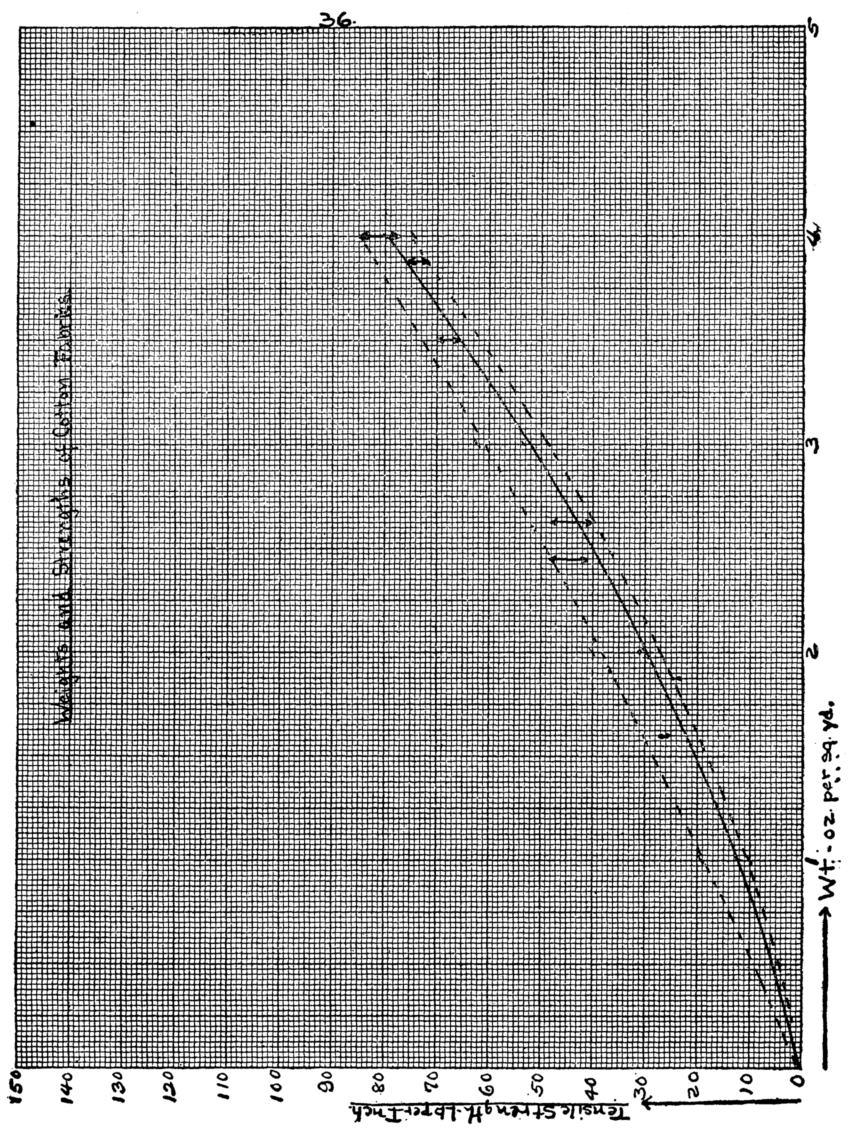
Sea island or Egyptian cotton, preferably the former, should be used for fabrics intended for use in making balloon fabric. In general the fabrics should be as nearly as possible of the same strength in both directions. Ordinary fabrics intended for clothing are, of course, usually much stronger in the direction of the warp than in the direction of the filling, because the strain comes mostly on the warp, and such fabrics are softer. Another item is, of course, the expense, since the fillers represent a greater manufacturing outlay.

It is difficult to establish any very definite relation between weight and maximum strength attainable, since the methods of manufacture play a very important rôle. A heavy tightly woven fabric may actually test much lower than one apparently not so strong, probably on account of a shearing or grinding action.

The fabrics examined are in general of single-ply yarns, the number of threads varying between 120 and 144 per inch, depending on the weight and strength. The data given represent samples made and tested in this country, and also test published abroad.

	Weight (ounces per square yard).	Strength (pounds per inch).	
		Warp.	Filler.
I	1.60	27.0	26.0
II	1.85	24.3	24.5
III	1.98	31.0	31.0
IV	2.44	41.5	49.0
V	2.67	40.9	49.2
VI	3.51	70.0	67.0
VII	3.86	72.0	75.0
VIII	4.05	84.0	78.0

The curve shows that considerable variation is to be expected, probably to a large extent owing to the great variation in methods of testing. Accordingly, two curves are drawn as limits, with a mean or average value. Any fabric whose tests would place it within the area included by these curves would probably be about as good as could be expected in that grade. This does not mean, of course, that fabrics falling below this area would be unsatisfactory. It simply gives a rough idea of the possibilities under best conditions.


Weights and Strengths of Cotton Fabrics.
Wt. oz. per sq. yd.
Tensile Strength lbs. per Inch
0
1
2
3
4
5
36.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Summary of various tests on aeroplane fabrics.

Fabric.	Weight (ounces per square yard).	Tensile strength (pounds per inch).				Effect of exposure (per cent strength of original.)		Fire test.		Water absorption.		Loss in weight from soaking.
		Original.		After 3 weeks' exposure.								
		Warp.	Filler.	Warp.	Filler.	Warp.	Filler.	Seconds to burn 3½ feet.	Distance burned.	In saturated atmosphere.	Soaking.	
									Inch.	*Per cent.*	*Per cent.*	*Per cent.*
1. Linen No. 1 (high grade), varnish, 1875	5.18	95	92	62	66.7	65.0	72.5	35.0	.....	12.94	44.2	3.96
Linen No. 1 varnish:												
2. 1875, and spar varnish	5.88	101	90	75	72	74.2	80.0	33.6	.....	12.90	43.6	3.33
3. 1876	5.49	100	88	68	57	68.0	65.0	23	.....	10.01	43.6	5.47
4. 1876, and spar varnish	6.18	98	92	71	70	72.8	76.5	22.6	.....	11.49	38.2	3.27
5. 1877	5.24	106	91	90	75	84.8	82.5	38.3	.....	13.74	51.9	3.94
6. 1877 and spar varnish	6.42	113	83	81	59	71.7	71.2	39.6	.....	12.14	60.9	4.03
7. Cotton (light weight) varnish, 1875	3.45	58	68	28	40	48.4	59.3	23.0	.....	8.7	32.4	.84
Cotton varnish:												
8. 1875, and spar varnish	4.62	51	59	38	40	74.0	68.0	20.6	.....	6.27	45.0	.75
9. 1876	3.43	50	62	24	23	48.5	36.6	9.6	.....	6.42	37.9	.31
10. 1876, and spar varnish	4.07	55	63	29	40	49.8	63.2	10.0	.....	5.66	34.3	.79
11. 1877	3.24	51	59	44	44	87.2	74.2	22.0	.....	8.03	40.0	.96
12. 1877, and spar varnish	4.18	51	53	43	43	85.2	82.0	18.3	.....	7.41	42.1	.71
Linen No. 1, Am. chloride varnish:												
13. 1875, and spar	7.16	97	95½	52	58.4	53.5	61.0	.....	1.6	.....	.....	.....
14. 1876, and spar	6.90	117	100	79	60.2	67.5	60.2	.....	1.3	.....	.....	.....
15. 1877, and spar	7.57	107	96	58	54	54.2	56.3	.....	1.4	.....	.....	.....
Linen No. 2 (medium grade) varnish:												
16. 1875	4.17	88.8	74.9	.....	.....	.....	.....	.....	.....	.....	.....	.....
17. 1875, and spar	5.50	100	86	.....	.....	.....	.....	.....	.....	.....	.....	.....
18. 1876	4.15	92	79	.....	.....	.....	.....	.....	.....	.....	.....	.....
19. 1876, and spar	5.50	91	77	.....	.....	.....	.....	.....	.....	.....	.....	.....
20. 1877	4.23	78	78	.....	.....	.....	.....	.....	.....	.....	.....	.....
21. 1877, and spar	5.39	91	82	.....	.....	.....	.....	.....	.....	.....	.....	.....
Linen No. 1 (rubberized) varnish:												
22. 1875	7.37	121	104	.....	.....	79.2	75.0	.....	.....	7.73	63.5	4.34
23. 1875, and spar	8.44	116	99	.....	.....	89.0	86.0	.....	.....	8.18	39.4	3.27
24. 1876	7.63	120	94	96	78	87.5	78.7	.....	.....	8.53	44.3	3.38
25. 1876, and spar	8.89	119	96	103	85	94.5	100.0	.....	.....	10.69	38.9	2.82
26. 1877	7.57	119	91	105	74	93.2	95.5	.....	.....	8.32	55.3	5.92
27. 1877, and spar	8.94	119	97	113	96	96.5	86.7	.....	.....	6.04	39.0	5.23
Linen No. 1 varnish:												
28. 1875	5.18	95	92	111	87	89.5	92.3	.....	.....	.....	.....	.....
29. 1875, and spar	5.88	101	90	115	84	90.0	91.0	.....	.....	.....	.....	.....

NOTE.—Samples Nos. 22 and 29 were exposed 2 weeks to weather; all others, 3 weeks. Varnish, 1876—cellulose nitrate; varnishes, 1875 and 1877—cellulose acetate.

PERMEABILITY TESTS.

As already stated in the main body of the report, the method used was similar to that of the National Physical Laboratory of Great Britain, in which the hydrogen diffusing through the fabric is burned to water and weighed.

Owing to the limited time at our disposal, the tests were each two hours in length. Several tests were made on each sample at each temperature, and ordinarily agreed within a few per cent, when the slight temperature differences were allowed for. (To save time the thermostat was not run always at the same temperature, but simply kept constant at one temperature for each run. As the room temperature varied greatly from day to day during the period in which the tests were made, this made the operation of the thermostat more simple, and in addition gave in many cases a further check on the temperature effect.)

The diameter of the cell was 220 millimeters.

The hydrogen was run through one side of the cell at a rapid rate for several hours at the start of an experiment, to insure the expulsion of air. The proper rate for the passage of the air was found by experiment; it was noted that above a certain point, even with increased absorption apparatus, the total weight of water absorbed did not increase, indicating that the hydrogen was swept out practically as soon as it entered the cell. In the interval between tests on the same fabric, the air side was continually swept out, to prevent the accumulation of hydrogen on the air side. For this purpose a three-way stop-cock was introduced, and connections with trap-bottles made so that the furnace and cell could be swept out separately with air. It was found that in some cases the furnace contained small amounts of moisture that had not been all removed during the experiment, so at the expiration of the time by turning the cock the cell was swept out in preparation for the next run, while dry air was drawn from without through the furnace and absorption tubes for 10 to 15 minutes.

Specimen tests are shown.

Permeability tests on various fabrics.

Fabric.	Temperature (° C.).	Permeability (liters per square meter per 24 hours, at 760/0°).
No. 1 balloon fabric, 2-ply parallel (9.25 ounces per square yard):		
1.65 ounces per square yard rubber between plies	21.2	54.99
1 ounce per square yard rubber on inside face	22.07	56.37
	29.68	63.4
	30.01	65.3
	40.08	79.1
	40.09	79.4
No. 2 balloon fabric, 2-ply parallel (10.81 ounces per square yard):		
3.11 ounces per square yard rubber between plies	20.45	11.64
1 ounce per square yard rubber on inside face	21.65	11.29
	29.87	16.8
	30.71	17.32
	32.27	18.79
	38.58	24.35
	39.19	25.34
No. 3 balloon fabric, 2-ply parallel (93.2 ounces per square yard):		
5.51 ounces per square yard rubber between plies	20.04	11.2
1 ounce per square yard rubber on inside face	20.23	11.7
	39.48	25.25
	39.63	25.55
	40.14	26.37
Balloon cloth No. 3, 4 coats varnish No. 1876 on cloth (about 2 ounces per square yard)	21.42	10.86
	21.91	11.8
	22.00	11.34
	29.99	15.44
	31.68	17.11
	40.51	24.73
	40.75	25.25
Balloon cloth No. 3, 4 coats varnish No. 1877 on cloth (about 2 ounces per square yard)	20.81	11.18
	20.85	11.34
	21.28	11.5
	30.51	16.90
	30.57	17.15
	39.09	24.13
	39.74	24.22
Balloon cloth No. 3, gelatin compound on rubber (2 ounces per square yard)	20.2	1.4
	20.01	.8
	21.29	1.4
	38.91	5.6
	38.95	6.6
Balloon fabric No. 3, varnish No. 1876 (2 ounces per square yard), on rubber	20.02	4.5
	20.22	5.0
	20.46	5.6
	38.96	10.2
	39.24	11.2

Permeability tests on various fabrics—Continued.

Fabric.	Temperature (° C.).	Permeability (liters per square meter per 24 hours, at 760/0°).
Balloon cloth No. 3, varnish No. 1877 (2 ounces per square yard), on rubber	19.91	4.55
	20.25	4.15
	37.45	10.85
	38.90	11.35
	38.96	12.7
Balloon cloth No. 19 (12 ounces per square yard)	20.3	11.2
	21.1	11.37

(1) It will be noted that gelatin compound gives very low permeability. The use of gelatin on fabric for balloons was suggested by Julhe.[1] Austerweil tried this and found[2] that at first there was practically no loss in volume, even a slight gain due to gases dissolved in the water. After 35 hours the membrane was apparently saturated and lost gas at practically the same rate as the comparison rubber membrane. On the other hand, although each of our tests was only two hours long, the total time in which the cell was filled with hydrogen, and the gelatin-rubber fabric in place, was 48 hours, yet at the end of that time, when the tests were made at 40° C., the permeability was only one-fourth that of the rubberized fabric alone. It is possible that in contact with dry rubber and dry gases, as in our apparatus, the membrane might act differently.

(2) Another point of interest is the test on fabrics 2 and 3 compared with fabric 19. The first two were experimental samples, and for convenience made parallel. The fabric 19 was bias, yet showed practically no difference in permeability. There has been some indication in tests made at the National Physical Laboratory that parallel fabrics were much more permeable. They state that probably the method of manufacture has a considerable effect. This has not been noticed in our tests, and the reason for any such difference is not apparent.

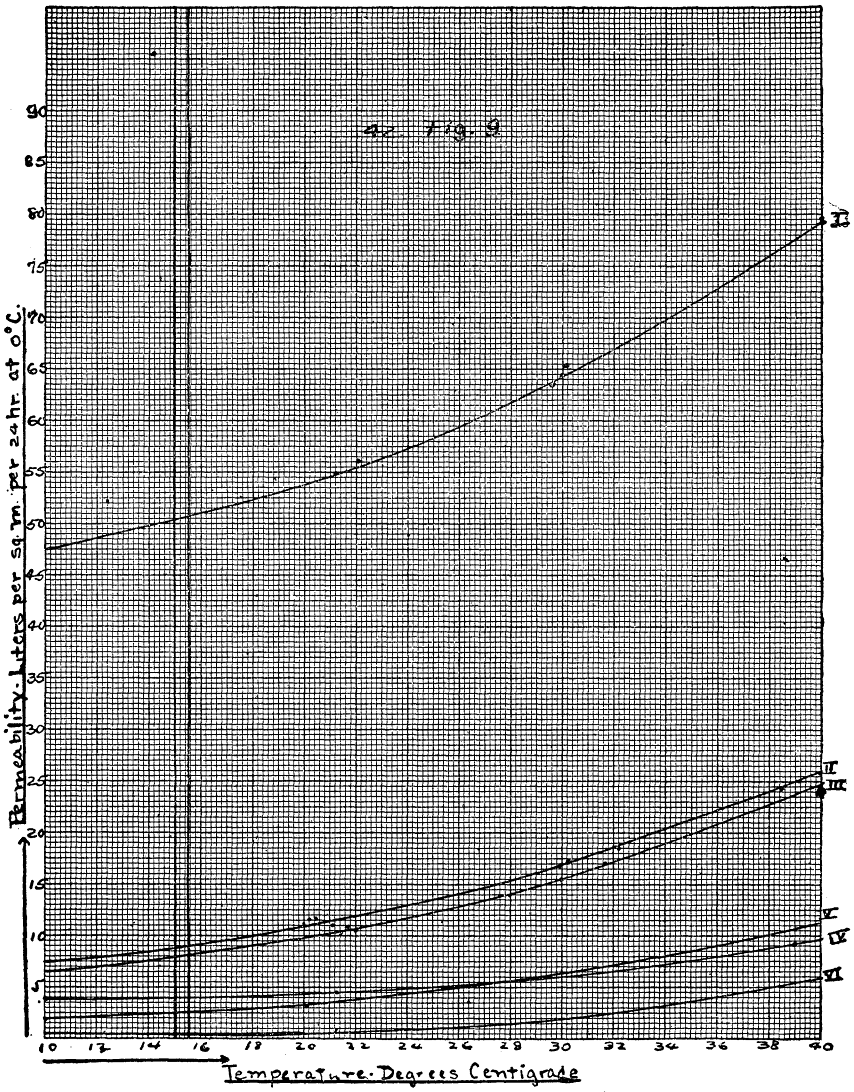
(3) *Temperature coefficient.*—This varies with the temperature and degree of permeability of the material. From our experiments we found the following values:

	Rate of increase at—		
	10–20° C.	20–30° C.	30–40° C.
	Per cent.	*Per cent.*	*Per cent.*
Rubber fabric, permeability at 15° C	4.4	4.6	4
Rubber fabric coated with 2-ounce gelatin on rubber	....	1.3	3.4

(4) *Effect of Weathering.*—On account of the limited time at our disposal for making this investigation, long weathering tests on these samples were not made. Aging by continuous exposure for one month caused no increase in permeability; in fact, one of our samples seemed improved. The rubber layers were apparently unaffected, so this improvement was not due to resinification which has been noted in England, but was more likely due to a slight variation in samples.

[1] C. R. Acad. Sc., 1912, Feb. 12.

[2] Die Angewandte Chemie in der Luftfahrt, p. 90.



Effect of Temperature on Permeability.

I. Balloon Fabric. 1.65 oz. Rubber between plies
II " " (s) 3.11 & 5.51 oz " " "
III " " 5.51 oz. rubber. Coated on cloth. with Aerovarnish. 2 oz
IV-V " " " " " " " rubber " " 1876 & 1877 resp. 2 oz
VI. " " " " " " " " " gelatine compound 2 oz

Surface friction of aeronautic fabrics at different wind velocities.

Condition and area (square feet).		Experiment No. 1. Plate glass.					Experiment No. 2. Linen No. 1, 1 coat varnish, 1876 (area, 50.35).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.384	0.404	0.0079	0	0	0.408	0.428	0.0085	0.0006	1.081
40	.031	.637	.668	.0131	....	....	.679	.710	.0141	.0010	1.080
50	.046	.969	1.015	.0199	....	....	1.046	1.092	.0218	.0019	1.098
60	.071	1.342	1.413	.0276	....	....	1.480	1.551	.0309	.0023	1.118
70	.094	1.768	1.862	.0364	....	....	2.040	2.134	.0424	.0060	1.162

Condition and area (square feet).		Experiment No. 3. Linen No. 1, 3 coats varnish, 1876 (area, 50.35).					Experiment No. 4. Linen No. 1, 3 coats varnish, 1876; 1 coat spar varnish (area, 50.35).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.394	0.414	0.00822	0.0003	1.042	0.389	0.409	0.0081	0.0002	1.031
40	.031	.665	.696	.0138	.0007	1.060	.649	.680	.0135	.0004	1.034
50	.046	.998	1.044	.0208	.0009	1.048	.981	1.027	.0204	.0005	1.028
60	.071	1.410	1.481	.0295	.0019	1.067	1.376	1.447	.0287	.0011	1.038
70	.094	1.919	2.013	.0403	.0039	1.108	1.854	1.948	.0387	.0023	1.061

Condition and area, (square feet).		Experiment No. 5. Linen No. 1, uncoated (area, 50.18).					Experiment No. 6. Linen No. 1, 3 coats varnish, 1877 (area, 50.18).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.457	0.477	0.0095	0.0016	1.205	0.390	0.410	0.0082	0.0003	1.034
40	.031	.778	.810	.0161	.0030	1.234	.652	.683	.0136	.0005	1.040
50	.046	1.204	1.250	.0249	.0050	1.254	.988	1.034	.0206	.0007	1.039
60	.071	1.738	1.809	.0361	.0085	1.305	1.392	1.463	.0292	.0016	1.056
70	.094	2.395	2.489	.0496	.0132	1.362	1.880	1.984	.0395	.0031	1.085

Condition and area (square feet).		Experiment No. 7. Linen No. 1, 3 coats varnish, 1877; 1 coat spar varnish (area, 50.18).					Experiment No. 8. Linen No. 1, 3 coats varnish, 1877; 2 coats spar varnish (area, 50.18).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.393	0.413	0.0082	0.0003	1.044	0.393	0.413	0.0082	0.0003	1.044
40	.031	.655	.686	.0137	.0006	1.049	.644	.675	.0134	.0003	1.026
50	.046	.977	1.023	.0204	.0005	1.028	.978	1.024	.0204	.0005	1.028
60	.071	1.384	1.455	.0288	.0012	1.041	1.367	1.438	.0286	.0010	1.033
70	.094	1.884	1.978	.0394	.0030	1.081	1.874	1.968	.0392	.0028	1.078

Surface friction of aeronautic fabrics at different wind velocities—Continued.

Condition and area (square feet).		Experiment No. 9.					Experiment No. 10.				
		Balloon fabric No. 3, double par. cloth outside (area, 49.6).					Balloon fabric No. 3 (same as 9), freshly singed (area, 49.6).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.672	0.692	0.0139	0.0060	1.766	0.493	0.513	0.0103	0.0024	1.311
40	.031	1.149	1.180	.0238	.0107	1.822	.883	.914	.0184	.0053	1.408
50	.046	1.764	1.810	.0365	.0166	1.838	1.403	1.449	.0292	.0093	1.470
60	.071	2.501	2.573	.0518	.0242	1.873	2.041	2.112	.0426	.0150	1.539
70	.094	3.452	3.546	.0715	.0351	1.965	2.898	2.992	.0603	.0239	1.654

Condition and area (square feet).		Experiment No. 11.					Experiment No. 12.				
		Balloon fabric No. 3 (same as 10); 1 coat varnish, 1876 (area, 49.6).					Balloon fabric No. 3 (same as 10); 3 coats varnish, 1876 (area, 49.6).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound, square foot.	Net excess.	Resistance factor.
30	0.020	0.446	0.466	0.0094	0.0015	1.180	0.394	0.414	0.0083	0.0004	1.056
40	.031	.783	.814	.0164	.0033	1.253	.661	.692	.0139	.0008	1.063
50	.046	1.199	1.245	.0251	.0052	1.264	1.009	1.055	.0213	.0014	1.072
60	.071	1.722	1.793	.0362	.0086	1.309	1.419	1.490	.0300	.0024	1.082
70	.094	2.332	2.426	.0490	.0126	1.345	1.904	1.998	.0403	.0039	1.107

Condition and area (square feet).		Experiment No. 13.					Experiment No. 14.				
		Balloon fabric No. 3, bias (area, 48.88).					Balloon fabric No. 3, bias, freshly singed (area, 48.88).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistance factor.
30	0.020	0.631	0.651	0.0133	0.0054	1.691	0.483	0.503	0.0103	0.0024	1.308
40	.031	1.078	1.109	.0227	.0096	1.739	.864	.895	.0183	.0052	1.402
50	.046	1.632	1.678	.0343	.0144	1.728	1.461	1.507	.0309	.0110	1.555
60	.071	2.343	2.414	.0494	.0218	1.782	2.157	2.228	.0457	.0181	1.651
70	.094	3.294	3.388	.0694	.0330	1.902	3.043	3.137	.0642	.0278	1.762

Condition and area (square feet).		Experiment No. 15.					Experiment No. 16.				
		Balloon fabric No. 6, double bias, special fabric (area, 49.34).					Balloon fabric No. 6, double bias, special fabric, freshly singed (area, 49.34).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistence factor.
30	0.020	0.468	0.488	0.0099	0.0020	1.252	0.423	0.443	0.0099	0.0020	1.139
40	.031	.858	.889	.0180	.0049	1.378	.744	.775	.0157	.0026	1.202
50	.046	1.343	1.389	.0281	.0082	1.414	1.170	1.216	.0247	.0048	1.243
60	.071	1.959	2.030	.0412	.0136	1.490	1.744	1.815	.0368	.0092	1.331
70	.094	2.648	2.742	.0556	.0292	1.528	2.378	2.472	.0500	.0136	1.372

Surface friction of aeronautic fabrics at different wind velocities—Continued.

Condition and area (square feet).		Experiment No. 21. Aeroplane fabric, rubberized, No. 23 (area, 48.8).					Experiment No. 22. Aeroplane fabric, aluminum coated, No. 24 (area, 48.6).				
Miles per hour.	Net correction, pound.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistance factor.	Gross force, pounds.	Net force, pounds.	Net force, pound/square foot.	Net excess.	Resistence factor.
30	0.020	0.382	0.412	0.0084	0.0005	1.070	0.394	0.414	0.0085	0.0006	1.078
40	.031	.653	.690	.0142	.0011	1.082	.657	.688	.0142	.0011	1.083
50	.046	1.004	1.050	.0215	.0016	1.083	.988	1.034	.0213	.0014	1.073
60	.081	1.379	1.460	.0299	.0023	1.081	1.375	1.456	.0299	.0023	1.081
70	.094	1.824	1.918	.0393	.0029	1.079	1.856	1.950	.0401	.0037	1.101

SURFACE FRICTION TESTS.

In the next to the last column of each experiment, pages 43–4, are given under the heading "Net excess" the numerical difference between the resistance in pounds per square foot of the material, and the resistance of plate glass. In the last column are given factors obtained by dividing the resistance of the material by that of glass at the same velocity.

In general the resistance of an object to the wind increases with the square of the velocity. The general form is, for unit area:

$$P = K V^2.$$

When P = pressure.
V = velocity.
K = a constant.

It has been found by Froude and others that surface friction varies with about the 1.87 power of the velocity.

Plotting the logarithms of the velocity against the pressure, we obtained from our results, in practically all cases, a straight line. The values at 70 miles per hour were a little off in most cases, indicating the pressure of another factor, possibly due to temperature.

The logarithms were plotted and from the values of the faired curves, the approximate exponents and coefficients were obtained algebraically for some of the most interesting cases.

General equation $P = K V^n$.

When P = pressure in pounds per square foot.
V = velocity in miles per hour.
n and K = constants.

		K	N
Experiment 1.	Plate glass	0.0000178	1.84
Experiment 2.	Linen No. 1, varnish No. 1876	.0000156	1.85
Experiment 5.	Linen No. 1, uncoated	.0000137	1.92
Experiment 9.	Balloon fabric No. 3	.0000192	1.93

It will be noted that in general the rougher materials have higher exponents, approaching 2 in the case of balloon fabric.

Absorption tests, balloon and aeroplane fabrics.

Fabric.	Atmospheric weight.	Dry weight.	Moist weight.	Normal moisture.		Moisture after suspension in saturated atmosphere.		Atmospheric weight.	Dry weight.	Wet weight.	Dry weight after soaking.	Normal moisture.		Water held in fabric after soaking.		Weight of material removed by soaking.	
				Ounces.	Per cent.	Ounces.	Per cent.					Ounces.	Per cent.	Ounces.	Per cent.	Ounces.	Per cent.
High-grade linen No. 1, untreated, weight 4.6 ounces:																	
Varnish 1875 (cell. acetate)	5.52	5.18	5.85	0.34	6.56	0.67	12.94	5.65	5.30	7.34	5.09	0.35	6.61	2.25	44.2	0.21	3.96
Varnish 1875 and spar varnish	6.26	5.88	6.57	.38	6.46	.69	12.90	6.09	5.71	7.93	5.52	.38	6.65	2.41	43.6	.19	3.33
Varnish 1876 (cell. nitrate)	5.71	5.49	6.04	.22	4.02	.55	10.01	5.71	5.49	7.45	5.19	.22	4.02	2.26	43.6	.30	5.47
Varnish 1876 and spar varnish	6.54	6.18	6.89	.36	5.83	.71	11.49	6.46	6.11	8.17	5.91	.35	5.44	2.26	38.2	.20	3.27
Varnish 1877 (cell. acetate)	5.61	5.24	5.96	.37	7.07	.72	13.74	5.72	5.34	7.79	5.13	.38	7.13	2.66	51.9	.21	3.94
Varnish 1877 and spar varnish	6.87	6.42	7.20	.45	7.01	.78	12.14	6.64	6.20	9.57	5.95	.44	7.10	3.62	60.9	.25	4.03
Rubberized (one side)	6.49	6.27	7.08	.22	3.51	.59	9.41	6.63	6.41	9.88	6.16	.22	3.43	3.72	60.4	.25	3.90
Rubberized, varnish 1875	7.63	7.37	8.20	.26	3.53	.57	7.73	7.62	7.36	11.51	7.04	.26	3.53	4.47	63.5	.32	4.34
Rubberized, varnish 1875 and spar varnish	8.80	8.44	9.49	.36	4.27	.69	8.18	8.82	8.56	11.54	8.28	.26	3.03	3.26	39.4	.28	3.27
Rubberized, varnish 1876	7.85	7.63	8.50	.22	2.89	.65	8.53	7.89	7.69	10.72	7.43	.20	2.61	3.29	44.3	.26	3.38
Rubberized, varnish 1876 and spar varnish	9.13	8.89	10.08	.24	2.70	.95	10.69	8.82	8.51	11.49	8.27	.31	3.64	3.22	38.9	.24	2.82
Rubberized, varnish 1877	7.83	7.57	8.46	.26	3.43	.63	8.32	7.81	7.60	11.10	7.15	.21	2.76	3.95	55.3	.45	5.92
Rubberized, varnish 1877 and spar varnish	9.23	8.94	9.77	.29	3.25	.54	6.04	9.19	8.85	11.69	8.14	.34	3.84	3.28	39.0	.44	5.23
Cotton (light weight):																	
Varnish 1875	3.74	3.45	3.75	.29	8.40	.30	8.70	3.89	3.58	4.70	3.55	.31	8.67	1.15	32.4	.03	.84
Varnish 1875 and spar varnish	4.86	4.62	4.91	.24	5.19	.29	6.27	4.20	3.99	5.74	3.96	.21	5.27	1.78	45.0	.03	.75
Varnish 1876	3.60	3.43	3.65	.17	4.96	.22	6.42	3.36	3.20	4.40	3.19	.16	5.00	1.21	37.9	.01	.31
Varnish 1876 and spar varnish	4.28	4.07	4.30	.21	5.16	.23	5.66	3.98	3.79	5.05	3.76	.19	5.02	1.29	34.3	.03	.79
Varnish 1877	3.46	3.24	3.50	.22	6.80	.26	8.03	3.35	3.13	4.34	3.10	.22	7.03	1.24	40.0	.03	.96
Varnish 1877 and spar varnish	4.47	4.18	4.49	.29	6.94	.31	7.41	4.59	4.29	6.01	4.23	.30	7.00	1.78	42.1	.03	.71
Balloon fabric, cloth outside (1½-ounce double bias), No. 3	11.35	10.98	11.62	.37	3.37	.64	5.83	11.35	10.68	14.52	....	.37	3.37	3.54	32.3	....	....
Balloon fabric No. 3 and balloon fabric No. 3 spot proof	11.60	11.30	11.76	.30	2.68	.46	4.07	11.38	11.05	13.92	....	.33	3.00	2.87	24.8	....	....
Balloon fabric No. 3, proof No. 123	12.37	11.95	13.20	.42	3.52	1.25	10.50	12.28	11.89	15.20	....	.39	3.28	3.31	27.8	....	....

REPORT No. 6.

PART 2.

SKIN FRICTION OF VARIOUS SURFACES IN AIR.

By Willis A. Gibbons.

INTRODUCTION.

The relation of skin friction or surface friction, to the relative velocity of a surface and the surrounding medium, and the variation of this relation with the nature of the surface is of growing importance to the science of aeronautics. Owing to the greater speeds now developed in air craft of all kinds, it was decided to investigate these relations with particular reference to the sort of surfaces which would be used in aeronautic work.

W. Froude[1] measured the resistance for various surfaces of various lengths in a water channel, and the results of his experiments lead to the following conclusions:

1. The force tangential to the plane due to skin friction, ordinarily varies according to the 1.85–2 power of the velocity for smooth surfaces. For rougher surfaces, it varies practically as the square of the velocity.
2. The length of the plane has a decided effect on the average resistance per unit area, the resistance decreasing as the length increases.
3. Smooth surfaces do not necessarily increase according to a lower power of the velocity than *rougher* surfaces, although the numerical value of the resistance per unit area is less.
4. The index decreases as the length increases for smooth surfaces.

Zahm[2] measured the resistance due to surface friction of planes in a current of air, and found that all smooth surfaces showed an increase in resistance according to the 1.85 power of the velocity. Buckram with 16 threads per inch gave a high resistance and an index of 2.05, practically 2.

He measured the resistance of planes of various lengths and obtained the following equation connecting the length of a plane with its velocity and surface friction:

$$P \propto L^{-.07} V^{1.35} \qquad (1)$$

When V = Velocity in feet per second.
L = Length of planes.
p = Tangential force per square foot.

[1] British Assoc. Report, 1872, 118; 1874, 249.
[2] Phil. Mag., VIII, 58-66 (1904).

Lanchester[1] shows that to express the resistance of a plane bringing into account the linear size and kinematic viscosity, we have the relation—

$$R \propto v^q L^1 V^r \qquad (2)$$

When $q+r=2$
v = Kinematic viscosity.
L = Linear size.
V = Velocity.

The kinematic viscosity[2] $v=\frac{\mu}{\rho}$

When μ = Coefficient of viscosity.
ρ = Density.

The kinematic resistance, $R=\frac{F}{\rho}$, i. e., it is the resistance per unit density.

Lanchester points out that in terms of R, Zahm's equation (1) becomes

$$R \propto L^{1.93} V^{1.85} \qquad (3)$$

whereas according to (2) L and V should have the same index. He adopts the following for a smooth surface.

$$R \propto v^{.1} L^{1.9} V^{1.9} \qquad (4)$$

Assuming, what we have found to be the case, that the exponent varies with the nature of the surface, we may put this in the form

$$R \propto v^{2-n} L^n V^n \qquad (5)$$

whence

$$F = \kappa \rho v^{2-n} L^n V^n \qquad (6)$$

For any one surface it is convenient to neglect the length, and embody this and the ρ and v values in one constant, so we have.

$$F = K V^n \qquad (7)$$

The value of K depends of course on the units.—throughout this paper F will be in lbs. per square feet, and V in miles per hour. The value of .1 for air is 1.3 times that for water, so this and the relative densities give a means of calculating from one medium to the other.

The values of n and K vary with the surface even for so-called smooth surfaces, and as will be shown, seem in such cases to bear a more or less definite relation to each other.

[1] Tech. Rept. Adv. Com. for Aeronautics, 1909-10, p. 34. [2] Lanchester's Aerodynamics, p. 36.

EXPERIMENTAL.

Through the kindness of the Bureau of Construction and Repair of the Navy Department the excellent facilities afforded by the wind-tunnel of the Washington Navy Yard became available for experiments on the frictional resistance of various surfaces. These experiments were made for the purpose of looking into the matter of surface friction with particular reference to surfaces of the sort which would be of most interest from the standpoint of aeronautics.

A glass plate about 9½ feet long and 34 inches wide was suspended vertically, with its surface tangent to the direction of the wind, by two wires fastened to the upper edge of the plate. The ends of the plate were enclosed in slots in faired struts, which were fixed rigid to the floor and ceiling of the tunnel, and stayed to prevent vibration. Smooth steel rollers attached to each side of the slots, at the upper and lower ends, prevented side movement of the plate. They did not ordinarily touch the latter, being set to allow a clearance of 0.01 inch. Thus the plate was free to move within limits only in the line of the air current.

The trailing edge of the plate was connected by a steel rod to the balance, allowing the horizontal force to be measured.

CORRECTIONS.

It was found by experiment that the ends of the plate, although protected by the struts, were affected by the air current. Tubes were set in the slots and connected with a hook gauge manometer. From the pressure at each end, the force on the plate was measured for different velocities, and by a faired curve, a set of corrections at different velocities was obtained. Both of these corrections are to be added since the air rushing past the slot in which the leading edge fits causes a diminution in pressure, and in the other slot, an increased pressure. Both of these changes in pressure would give a thrust against the wind.

The correction for the wires was found by adding 4 more supporting wires, making 6 in all and measuring the force on the plate with these additional supports, then removing the original wires and measuring the resistance of the plate at different velocities with four wires. Subtraction gave the effect of the two wires, which were used as supports in all regular tests. This correction is of course to be deducted from the observed force. To avoid masking, small wedges were used to hold the added wires away from the glass, the added wire passing around under the lower edge of the plate in each case.

SURFACES.

Plate glass was used as a standard, or ideal surface, since it is probably as smooth as any surface, and can be easily duplicated. The various fabrics were attached to this by a nitrocellulose varnish, by which, with a little practice, we were able to obtain a surface practically smooth, so far as unevennesses from wrinkles, etc., were concerned. The amount of varnish needed was so small and its colloidal nature such that it was possible to attach an uncoated linen to the glass without affecting the outer surface of the fabric appreciably. The linen surface could then be tested, and treated further as desired.

When more than two coats of varnish were applied, the surface was sand-papered between each coat.

Where fabrics were singed between tests, the singeing was done with a blow-torch.

The surfaces tested may be grouped as follows:

1. Plate glass.
2. Fabric surfaces with nap.
3. Fabric surfaces without nap (linen and cotton).
4. Varnished fabrics (cotton and linen).
5. Rubber coated linen (plain and aluminum surface).

The experiments were made at velocities of 30, 40, 50, 60, and 70 miles per hour. Owing to the large size of the plate (area about 50 square feet) the forces were large enough to enable considerable accuracy to be obtained. For example in the case of plate glass, the gross uncorrected force is about 0.27 pound at 30 miles per hour. On this account and also on account of the greater range of velocities we were able to detect variations in apparently smooth surfaces which were not noticeable in earlier experiments at low velocities.

The values of F (pound per square feet) the relative value of F compared with that for glass called for want of a better term, the resistance factor (*R. F.*) and the values of n and K are given in Table I.

TABLE I.—*Results of experiments on surface friction, in air, of various surfaces.*

[Tests were made in wind-tunnel, Washington, D. C.]

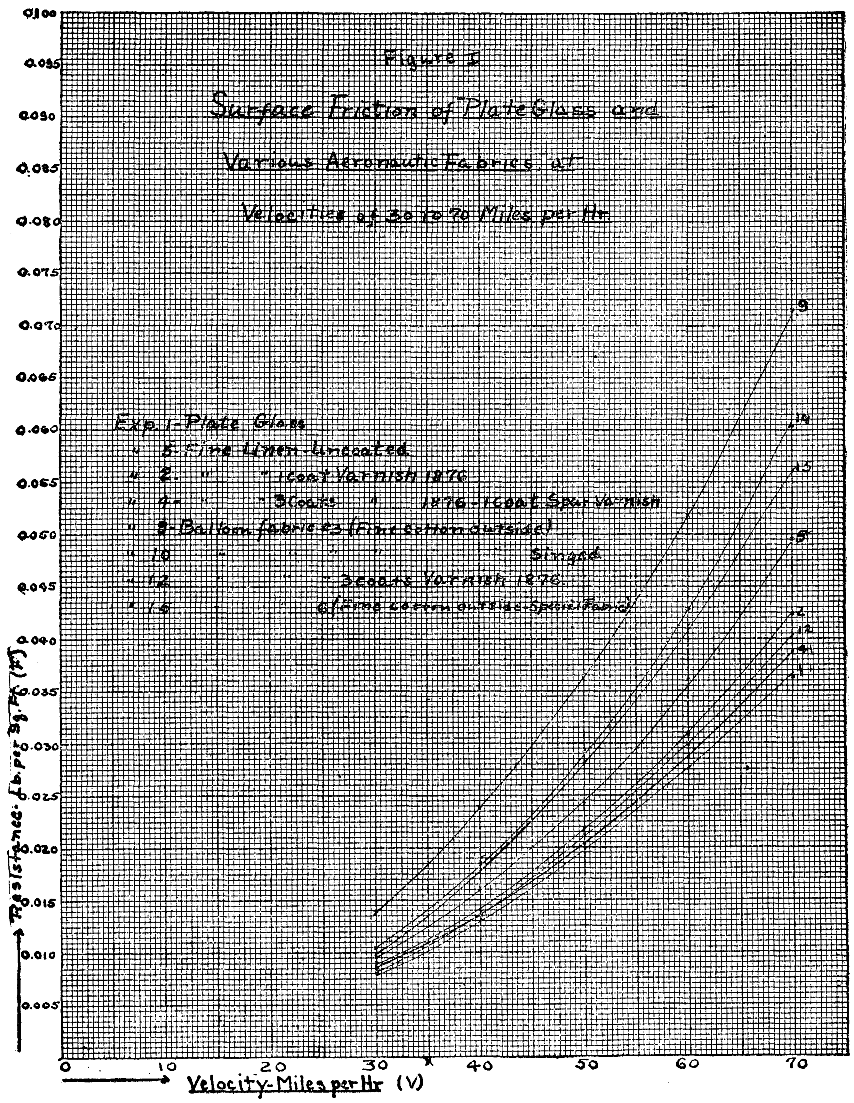
NOTE.—n, k, and F are values in equation $F=KV^n$. F=lb./sq. ft.
V=miles per hour.
R. F.=Resistance factor=F observed/F glass.

No.	Nature of surface exposed.	n.	$K10^7$.	30 miles/hr.		40 miles/hr.		50 miles/hr.		60 miles/hr.		70 miles/hr.	
				F.	*R. F.*	*F.*	*R. F.*	*F.*	*R. F.*	*F.*	*R. F.*	*F.*	*R. F.*
1	Plate glass	1.81	166	.0079	1.000	0.0133	1.000	0.0199	1.000	0.0276	1.000	0.0364	1.000
2	Fine linen: 1 coat aero varnish, 1876	1.84	163	.0085	1.081	.0141	1.080	.0218	1.098	.0309	1.118	.0424	1.162
3	3 coats aero varnish, 1876	1.89	129	.00822	1.042	.0138	1.060	.0208	1.048	.0295	1.067	.0403	1.108
4	3 coats aero varnish, 1876, 1 coat spar varnish	1.84	153	.0081	1.031	.0135	1.034	.0204	1.028	.0287	1.038	.0387	1.061
5	Uncoated	1.94	128	.0095	1.205	.0161	1.234	.0249	1.254	.0361	1.305	.0496	1.362
6	1 coat varnish, 1877	1.85	149	.0082	1.034	.0136	1.040	.0206	1.039	.0292	1.056	.0395	1.085
7	3 coats varnish, 1877	1.85	149	.0082	1.044	.0137	1.040	.0204	1.028	.0288	1.041	.0394	1.081
8	3 coats varnish, 1877, 2 coats spar varnish	1.84	157	.0082	1.044	.0134	1.026	.0204	1.028	.0286	1.033	.0392	1.078
9	Balloon fabric: No. 3, double parallel, cotton surface	1.90	219	.0139	1.766	.0238	1.822	.0365	1.838	.0518	1.873	.0715	1.965
10	No. 3, double parallel, singed	2.05	96.5	.0103	1.311	.0184	1.408	.0292	1.470	.0426	1.539	.0603	1.654
11	No. 3, double parallel, 1 coat varnish, 1876	1.95	123	.0094	1.190	.0164	1.253	.0251	1.264	.0362	1.309	.0490	1.345
12	No. 3, double parallel, 3 coats varnish, 1876	1.85	153	.0083	1.056	.0139	1.063	.0213	1.072	.0300	1.082	.0403	1.107
13	No. 3, bias, cotton surface	1.95	207	.0133	1.691	.0227	1.739	.0343	1.728	.0494	1.782	.0694	1.902
15	No. 6, bias, special, cotton surface	2.03	99.7	.0099	1.252	.0180	1.378	.0281	1.414	.0412	1.490	.0556	1.528
16	No. 6 bias, special, cotton, singed	2.05	82.5	.0088	1.127	.0157	1.202	.0247	1.243	.0368	1.331	.0500	1.372
21	Aeroplane fabric: Rubber surface	1.83	165	.0084	1.070	.0142	1.082	.0215	1.083	.0299	1.081	.0393	1.079
22	Rubber aluminum surface	1.83	166	.0085	1.078	.0142	1.083	.0213	1.073	.0299	1.081	.0401	1 101

RESULTS.

QUALITATIVE.

The great resistance offered by fabrics with nap on the surface will be noted. The effect of the weave is shown by comparison of experi-



ments 9 and 15. Both fabrics are high-grade cotton, but probably that used in experiment 15 is closer woven and made of longer staple. Biasing seems to increase the index, but the effect would probably not be noted except at very high speeds.

Cotton shows a higher resistance than linen, although the cotton surfaces were finer weave than the linen. The linen yarn, while of more varying thickness, is smoother than cotton yarn, due to the nature of the ultimate fiber and its greater length. The linen yarn is more like a wire.

The effect of varnishing is very apparent, although no conclusion can be drawn as to the relative merits of various aeronautic varnishes. Probably it is more a matter of workmanship in applying and finishing the coat than any particular merit in the varnish itself. The use of a finishing coat of spar varnish gives some improvement.

The use of a varnish seems particularly advantageous in the case of cotton fabrics. This explains the good results obtained in Europe by varnishing the gas bags of dirigibles with cellulose acetate varnish, which both improves the gas-holding properties of the bag and decreases the frictional resistance. In a well-designed balloon most of the resistance offered by the air to the motion of the balloon is due to friction.

QUANTITATIVE.

If we plot the logarithms of the velocity (V) and frictional resistance in pounds per square foot (F) we obtain practically straight lines. From their slope we find the index n. Figure II shows the logarithmic plots for the most interesting cases. It will be noted that in many cases the value for 70 miles per hour seems to lie above the line, possibly indicating an increase in the index as velocity increases, due to greater turbulence. This has been predicted.

Using the slope obtained by logarithmic plots and F=pounds per square foot, V=miles per hour, we may obtain the constant K, as given in Table I.

From these results it will be noted that the smooth surfaces do not necessarily have lower indices. When this was first noted it seemed so anomalous that it was thought at first that there might be some experimental error. However, we note that Froude found a similar result (Table III) in the case of tin foil, varnish, and paraffin.

The high resistance of fabrics having nap on the surface is noteworthy.

Froude's results obtained with an 8-foot plane in a water channel were reduced to the same units, and to air conditions. The values are given in Table II. Considering the differences in conditions the agreement for smooth surfaces is close. The resistance of calico was somewhat higher than the cloth resistance found in our tests. from the photograph accompanying Froude's paper[1] the fabric used by him probably had about 80 threads per inch. Those used by us had about 120 threads per inch, and on this account presumably a smoother surface.

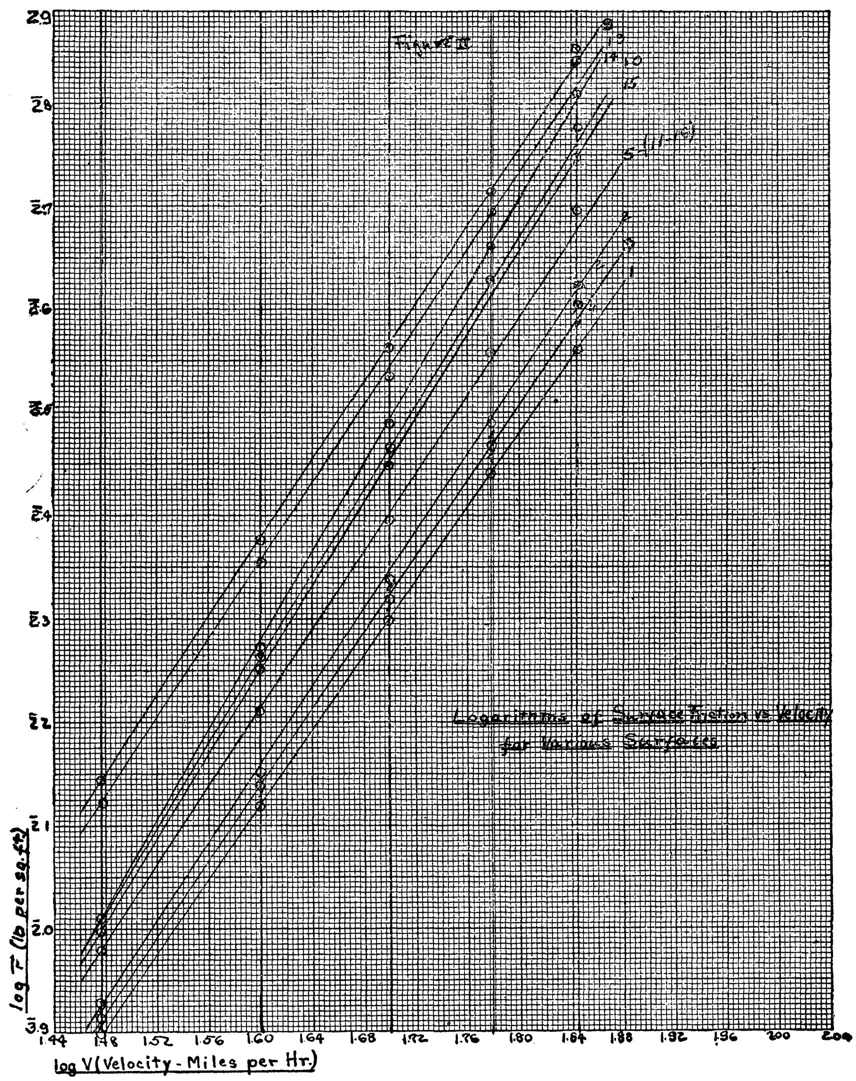
VALUES OF K AND N.

As already noted, smooth surfaces may show a higher index than rougher ones, while the coefficients K vary in the opposite direction. To obtain an idea as to the relative values of these two quantities, we plotted the values of K and N as shown in Figure III. It will be

[1] Brit. Assoc. Report, 1874, p. 249.

noted that the results of our experiments seem to show two distinct types of surface:

1. Those having nap on the surface have high indices and high exponents. They act somewhat similarly to calico and sand-coated surfaces investigated by Froude, and may be classed as rough,

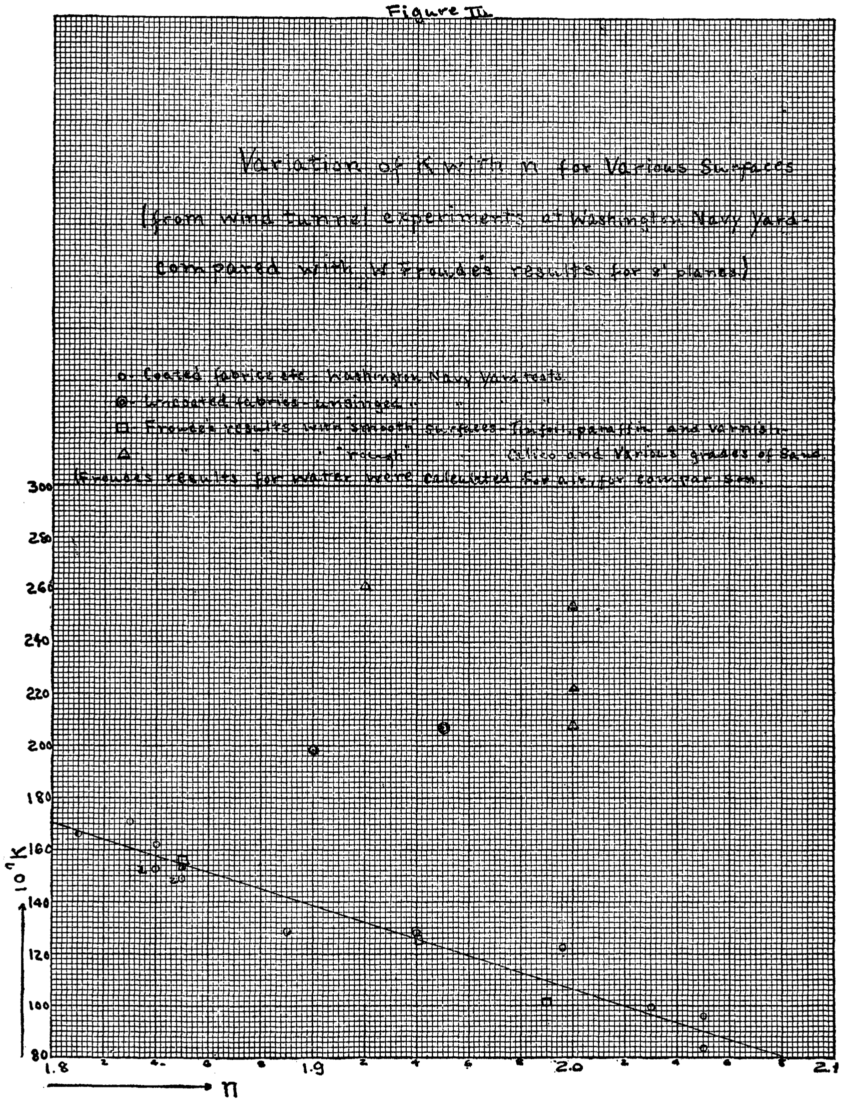


relatively. The index is 1.9 to 2, usually nearer 2, and the coefficient *K*, 0.00002 or more. (*V* in miles per hour.)

2. Surfaces which are free from nap, and more or less continuous and even. Fabric surfaces of fine threads closely woven and free from nap (due to singeing or natural great length of fiber, as linen)

are the roughest of this class. At the other extreme we have coated and varnished fabrics, which may approach glass in smoothness under good conditions.

Considering the nature of the quantities n and K, the points for smooth surfaces lie remarkably close to a straight line, the deviation



amounting to not more than 6 to 8 per cent, except in two cases, and these fall on opposite sides of the line (Fig. III).

The values found by Froude for varnishes, tin foil and paraffin for an 8-foot plane in water are also shown (Table II), and fall close to the line. On the other hand, "rough" surfaces, calico and roughened sand, do not come near the line.

TABLE II.—*Results of Froude's experiments, calculated to air.*

[8-foot plane (600 feet per minute) K in terms of miles per hour.

Surface.	n.	$K.10^7$.
Varnish	1.85	156
Paraffin	1.94	126
Tin foil	1.99	101
Calico	1.92	261
Fine sand	2.00	209
Medium sand	2.00	223
Coarse sand	2.00	255

From these figures we may express the relation of n and K for "smooth" surfaces by the empirical equation—

$$K = .0000746 - .000032n \quad (8)$$

whence

$$F = (.0000746 - .000032n)\, V^n \quad (9)$$

F being in pounds per square foot and V in miles per hour. While this expression is purely empirical, in view of our results it would seem as if it might be possible, within limits, to evaluate the complete equation for a smooth plane of fixed size, from the results of one experiment. To apply this rigidly would of course mean that the curves for smooth surfaces must not cross, i. e., that one given value of F and V applies to one curve only. While our results do not adhere strictly to this the deviations occur generally in the case of curves which are so close together as to almost overlap, and are probably due to experimental error. The value of K depends on L, but this can be figured as already shown.

On the other hand, Froude's results indicate that in the case of water, there is a fall in the index as the length of the plane increases. This change seems to be in the opposite sense to what would be expected. The equation

$$R \propto v^9\, L^r V^r \quad (2)$$

shows that L and V vary according to the same power in every case. We should expect from this the same change in r, whether due to change in L or V. It is known, and our own experiments indicate that increase in V tends to increase r; in other words, at high speeds, the resistance would vary according to a higher power of length and velocity. It seems logical to assume that this interchangeability of V and L would give a similar result as L increases, namely, that r would also increase, for both L and V. These changes in index would probably be so small for ordinary experimental differences as to be negligible.