REPORT No. 7.

PART 1.

REVIEW OF THE DEVELOPMENT OF ENGINES SUITABLE FOR AERONAUTIC SERVICE—ORIGIN, MEANS USED, AND RESULTS.

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Part 1 (a).—SERVICE REQUIREMENTS FOR AERONAUTIC ENGINES—POWER VERSUS WEIGHT, RELIABILITY, AND ADAPTABILITY FACTORS.

Transportation over land and water has been revolutionized by the addition of engine motive power to vehicles and boats to a degree that requires no study to appreciate but the contribution of the portable power plant to aerial navigation is even greater. It is fundamentally creative, for without the aeronautic engine air flight would be quite impossible. Not only does an engine constitute the essential element of the air craft, but the engine must be suitable for the purpose; it must have certain characteristics never before required or produced by engine designers. Success in flight and improvements in flying machines rests absolutely upon the success with which the engine and its accessories that make up the portable power plant can be made to fulfill the new requirements peculiar to the flying machine. Before someone flew, no one could specify just what the aeronautic motor should be able to do, except that, of course, it should be as light as possible and not stop in the air. Nor was there any demand for such an engine that would serve as an inducement to engineers familiar with engine production to build one. In short, while those few experimenters who were engaged in trials of balloons and gliding planes felt they might be helped if they could secure a proper light motor, no one felt sure it would be of service if produced, and of course no one could say how light it should be, or what other characteristics should be incorporated, except that of reliable continuous running during a flight. Formulation of some of these specifications may be said to date from about the years 1901–2, when the Wrights, on the one hand, and Langley, on the other, found that existing engines developed for other classes of service were unsuitable, the nearest approach being the automobile engine, then pretty uncertain in operation and weighing about 15 pounds per horsepower in the lightest forms—a weight that would not serve even if the operator were willing to risk his life on the possibility of engine stoppage in flight. It was apparent at once that redesign for reduced weight per horsepower was necessary, and the Wrights proceeded to rebuild the automobile engine, while Manly boldly departed from any existing practice and built his five fixed radial cylinder engine, both Manly and Wrights retaining the water cooling of the most successful automobile engines. Both succeeded in reducing weight enough to make flight possible, the Wright engine producing a horsepower with about 7 pounds and the Manly with about 2.4 pounds of engine weight, the former with a 12-horsepower, and the latter with a 50-horsepower engine.

Thus was flight initiated with engine redesign for weight reduction, and so has flight improved in range, speed, and safety, with further redesign of engine in the 13 or 14 years that have elapsed since that time, but the end is not yet in sight. The progress that has been made in engine construction, principally in Europe, is truly amazing, in view of the unique character of the problem and the short time that has elapsed; but all this has only served to increase the demand of the aeronautic engineer on the engine designer and manufacturer, so clearly and firmly is the principle established, that progress in flying rests fundamentally on engine improvement. These years of experience, however, have resulted in some data, derived largely from laboratory tests on the characteristics of the engines that are most successful in flight, and in some more or less accepted formulations of the sort of service required of aero engines and their essential parts in addition to weight, speeds, power, and general reliability, that might be classified as adaptability factors.

Any engine, for whatever service, must be suitable, and its design must be based as much on the specifications for suitability involving these adaptability factors, as on the fundamental principles of thermodynamics, stress resistance and the properties of the materials available, and these adaptability factors must be derived from the users or operators of the machines before the engine designer can interpret them, preparatory to the incorporation into the engine proper of those structural elements that will make it suitable. At the present time there are available some conclusions along this line of experience, a few of which will be quoted and summarized before undertaking to analyze the engine structure proper.

After nine years' use of engine-driven aeroplanes the engine structure was summed up in 1912 by Capt. H. B. Wild, Paris, as from his own experience as follows:

> The comparatively crude and unreliable motor that we have at our disposal at the present time is no doubt the cause of many of the fatalities and accidents befalling the aeroplane. If one will look over the accessories attached to the aero engine of to-day, it will be noted that it is stripped clean of everything possible which would add head resistance or weight. The designer of the aero engine is too anxious to eliminate what he deems unnecessary parts in order to reduce the weight of the engine, and in doing so he often takes away the parts which help to strengthen the durability and reliability of the motor.
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> Few engine designers seem to appreciate the importance of eliminating the least tendency toward variation of anglular velocity or in the torque, if the engine is required to drive a propeller. The effect of continually accelerating and retarding a propeller is most detrimental to its efficiency. * * * In front elevation an areo engine should be as compact as possible, so as to reduce head resistance.

Additional specific requirements named include—

> (*a*) oil tank of six hours' capacity with reliable pump for forced feed lubrication, internal oil pipes, (*b*) standardized propeller hub and crank shaft end, (*c*) heater for carburetors and gravity feed of gasoline, (*d*) dual ignition and no loose wires, (*e*) exhaust silencer, (*f*) exhaust valve lifters for stopping and compression release for starting, (*g*) engine speed indicator, (*h*) cool valve seats. * * * Engine builders

generally would also do well to visit aviation grounds more frequently and to take more interest in the engines which have left their hands. * * * though in many cases the aviator does not leave the engine alone when it is working right, but tinkers with the different adjustments until they are all out of harmony with one another and places the blame where it does not belong. * * * The demand for a reliable motor is still prominent.

Writing in 1912, Awsbert Vorreiter, Berlin, gives the principal requirements which aviation engines have to meet, as—

First. Small weight referred to horsepower.

Second. Small consumption of fuel, water, and oil, so as to obtain the maximum possible radius of action with a given quantity.

Third. Absolute reliability since in the case of the dirigible engine hardly any—in the aeroplane engine absolutely no—repairs can be made during a flight.

In the demand for low weight per horsepower the requirement of the low fuel and oil consumption per horsepower-hour are included, since to-day it is no longer a question of getting a machine to fly for a short time only, but to construct flying machines for practical purposes, we have to figure on a running time of several hours. It may easily be shown by calculation that an engine very light compared with output, but requiring an excessive amount of fuel and oil, may weigh more per horsepower when the weight of fuel and oil are included than a heavy engine with low fuel and oil consumption. It is true that the oil consumption cuts less of a figure because the quantity of oil as compared with the fuel is small and in a good engine amounts to not more than one-tenth. As a most favorable value for fuel consumption of an aviation motor we may assume 0.536 pound per horsepower-hour, which value has been repeatedly reached in aeroplane engines. In dirigible engines figures as low as 0.514 pound have been obtained.

Hand in hand with the reliability goes the demand for durability and continuous maintenance of high capacity. It is here that older constructions of aviation engines sometimes fall down very badly. Only the continuous output which the engine is able to give is to be seriously considered in an aviation engine as distinct from the automobile engine. While the latter is only very seldom required to give its maximum output—and then only for a short time—the aviation engine almost always runs under full load.

Additional specific requirements mentioned include—

(*a*) carburetor action and engine performance must be independent of barometer, of temperature, of dust, and of tilting of engine, (*b*) uniform turning movement, (*c*) balance of engine parts, (*d*) high enough energy in rotating parts to produce fly-wheel effect to resist variable propeller resistances and maintain engine speed, (*e*) propellers give best efficiency at speeds lower than are feasible in engines—in some cases as low as half, (*f*) proper cooling of engine to insure lubrication, minimum distortion of metal parts, temporary or permanent, (*g*) locate exhaust discharge away from operator, (*h*) least weight of engine by designing for maximum feasible speed, maximum work per cubic foot of displacement, and least weight of metal of selected kind and cross section.

In a paper read before the institution of automobile engineers (London) in 1912, Mr. A. Graham Clark summarizes the qualities regarded as essential or desirable in an aeronautical engine, as follows:

(1) Reliability: Failure of the engine necessitates the immediate descent of the machine, if of the heavier-than-air type, which, should it occur at an inopportune moment, may be attended with disastrous consequences.

(2) High power weight ratio:
(3) Economy in fuel and oil:
Are desirable because of the increased radius of action.

(4) Low air resistance: The importance of air resistance becomes more marked with increase in the speed, as the power absorbed in this direction varies as the cube of the velocity. It may be remarked in this connection that the horsepower required to propel a flat plate 3 feet in diameter through the air is increased from about 6 to over 16 by increasing the relative velocity of the plate to the air from 50 to 70 miles per hour.

(5) Controllability or flexibility, although there is not the same need for it as with engines employed on automobiles, is none the less a desirable quality since at low

speeds of rotation the propulsive or tractive effort of the propeller is insufficient to move the machine along the ground, and hence the pilot will be able to start up without assistance should circumstances necessitate his so doing. Further, as the engine is not required to develop its full power in horizontal flight and when alighting, the ability to vary the speed during descent is certainly preferable to the crude method of switching the ignition off and on.

(6) Freedom from vibration: The necessity for elimination of vibration as far as possible will be obvious when the slender nature of the supports upon which the engine is carried is realized, especially as vibration of a dangerous character may be set up in the various parts of the machine.

(7) Accessibility: The question of convenience of access is frequently overlooked or, at any rate, disregarded on account of the care and attention which is now given to the class of engine before any extended flight is made. But it must be realized that from commercial considerations alone, apart from the addition to the time during which the machine can be used and which may, under some circumstances, be of value, it would be an advantage to be able to readily examine or dismantle any part, especially when the applications of the aeroplanes are more widely extended.

(8) Silence is desirable in any machine used for pleasure or sporting purposes, but when it is intended for employment on military reconnoissance duties it becomes of increasing importance to be able to maneuver without giving audible warning of approach, especially at night.

(9) Cleanliness is in the nature of a refinement, but it is none the less necessary since a dirty appearance is generally caused either by the oil splashed about during hand oiling or by the exhaust, both of which are objectionable—the former because the part requiring such attention is apt at times to run dry owing to the irregularity of the supply of lubricant, and the latter because it indicates an open exhaust.

Another contribution along similar lines worthy of reproduction is that of Granville E. Bradshaw before the Scottish Aeronautical Society (Glasgow), December, 1913:

There is probably no form of prime mover in existence that is more highly stressed or that has a more strenuous life than the aeroplane and there is undoubtedly no engine that has greater claims on reliability. The aeroplane, manufacturers' cry for the extremely light engine is probably greater to-day than it ever has been in the history of aviation. The demands of the authorities who purchase aeroplanes are such that probably as much as 90 per cent of the factors which determine the most successful machine are governed directly or indirectly by the weight efficiency and fuel efficiency of the engine. By the former is meant, of course, the number of pounds of weight for every horsepower developed. That the engine shall be extremely reliable is of course taken for granted.

Among the essential features of all successful aeroplanes are the following:

(1) It shall climb very quickly. This depends almost entirely on the weight efficiency of the engine. The rate of climb varies directly as the power developed and indirectly as the weight to be lifted. That the aeroplane shall be very efficient in this particular can easily be understood when one remembers that its capabilities of evading destruction from projectiles depend to a great extent on how quickly it can get out of range of such projectiles. It must also be efficient in climbing in order to successfully rise from a small field surrounded by tall trees which may be necessitated by a forced landing during a cross-country flight over a populous district.

(2) It shall have a good gliding angle; or, in other words, that from any given height it shall be able to glide for a great distance, is also governed indirectly by the weight of the machine, and consequently by the weight of the power plant, because a machine with a heavy power plant must be designed with a larger lifting surface and must be stronger in proportion. With the same lifting surface and head resistance the angle of descent of the heavy-engined machine will be steeper[1] than that of the light machine, as higher speed is necessary to support increased weight.

(3) It shall have a combination of fast and slow flying speeds. This is of paramount importance and one that aeroplane constructors are paying probably the greatest amount of attention to. The capabilities of a machine to fly slowly as well as fast depend almost entirely on the adoption of an extremely light and powerful engine. If the machine is designed for very high speed, a slow speed is only possible by the machine, and consequently the power plant, being very light. Note.—The wing characteristics of lift and drift are also very important.

(4) It shall be safe to handle in all winds both with and without the engine in operation. Aeroplanes have been built that will carry as much as 15 to 20 pounds

[1] The heavier machine glides faster, not steeper.

per square foot of supporting surface, but constructors nowadays agree that the lightly loaded machine is the safer to handle and the average loading on the planes is to-day generally in the neighborhood of 4 or 5 pounds per square foot. A heavily loaded machine depends to a great extent on high speed of flight in order to maintain it in the air. Should the speed fall, unconsciously to the pilot, through loss of engine power or from any other cause, the control becomes sluggish and will not answer quickly, the aeroplane, unless the nose is put down very quickly to increase the speed, flounders about like a log in the sea and generally ends in a side slip and one of these terrible nose dives that have deprived us of so many of our best pilots. The life of the pilot of the heavily-loaded machine is more dependent upon the good behavior of the engine than is the life of the pilot of the lightly-loaded machine, and the latter could probably go on flying in search of a good alighting ground with two or three cylinders not firing at all.

(5) It shall be able to remain in the air for long periods. This depends chiefly on the oil and gasoline consumption of the engine and without efficiency in this respect, the extremely light power plane is practically useless, as flights of only a few minutes duration are not likely to be of much use in serious warfare.

All the essentials just enumerated and particularly the last depend of course on the engine being absolutely free from any breakdown, which point has not been dealt with as it is not a debatable one. We are all without doubt of one mind on this matter.

Finally there are reproduced below some extracts from the Notice to Competitors issued by the British Government for 1914 competition for naval and military aeroplane engines, all bearing on the question engine-service requirements:

1. REQUIREMENTS TO BE FULFILLED.

(*a*) Horsepower, 90–200. (*b*) Number of cylinders to be more than 4. (*c*) Gross weight per horsepower, calculated for six hours' run not to exceed 11 pounds. The gross weight includes engine complete with carburetor devices connected up (exclusive of the gasoline tank and pipes), all ignition and oiling appliances, starting handle, all cooling appliances— e. g., fan guarding, air guides, and any water radiator and water connections and any oil left in the engine. It will also include all fuel and oil supplied for six hours' run and all oil containers and pipes therefrom.

The gross weight per horsepower is the total weight of the engine divided by the figure for horsepower, below which the output has not been allowed to fall throughout the six hours' run, with a tolerance of 3 per cent for small variations and inaccuracy of measurements.

(*d*) Shape of engine to be suitable for fitting in an aeroplane.

2. DESIRABLE ATTRIBUTES OF AN AEROPLANE ENGINE.

(*a*) Light total weight. (*b*) Economy of consumption. (*c*) Absence of vibration. (*d*) Smooth running whether in normal or inclined position and whether at full power or throttled down. (*e*) Slow running under light load. (*f*) Workmanship. (*g*) Silence. (*h*) Simplicity of construction. (*i*) Absence of deterioration after test. (*j*) Suitable shape to minimize head resistance. (*k*) Precautions against accidental stoppage—e. g., dual ignition. (*l*) Adaptable for starting otherwise than by propeller swinging. (*m*) Accessibility of parts. (*n*) Freedom from risk of fire. (*o*) Absence of smoke or ejections of oil or gasoline. (*p*) Convenience of fitting in aeroplane. (*q*) Relative invulnerability to small-arm projectiles. (*r*) Economy (in bulk, weight, and number) of minimum spare part equipment. (*s*) Excellence of material. (*t*) Reasonable price. (*u*) Satisfactory running under climate variations of temperature.

In the recently issued specifications issued by the United States Navy Department a number of items appear bearing on engine-service requirements which are abstracted and reproduced below for comparison.

"They shall be well balanced and produce no excessive vibration at any power. To be capable of being throttled down to 20 per cent of the revolutions per minute for full power. The weight of the engine complete, with ignition system, magnetos, carburetors, pumps, radiator, cooling water, and propeller not to exceed 5 pounds per brake horsepower. Engine to be fitted with some type of compression release as a means of stopping it. To be fitted with a practical means of starting from pilot's seat when installed in an aeroplane. All moving parts not lubricated by a splash or forced lubrication system to be readily accessible for inspection, adjustment, and oiling. Ready means shall be provided for checking and making adjustment to the timing of the engine. To have an accurate and positive lubricating system which will insure a uniform consumption of lubricating oil proportional to the speed of the engine. All parts subject to corrosion to be protected from the effects of salt water. To be fitted with an approved attachment for obtaining the revolutions per minute. To be provided with means for preventing fire in case the engine is turned upside down. A hand-throttle lever and connections to carburetor to be provided that can be applied for convenient operation by the pilot. This lever to be designed with a positive means of retaining it at the throttle adjustment desired by the pilot. All bolts and screws without any exception to be provided with an approved positive means for preventing backing out due to vibration. No soft solder to be used in any part of the power plant."

Among the conditions for acceptance tests the following stipulation will be noted: "Motor to be run at full power for one-half hour under conditions approximating operations in the aeroplane in a heavy rainstorm."

At the present time many of the important conditions that an aeronautic engine must fulfill are pretty well settled, at least in kind, if not degree, but every day sees some new attribute announced as desirable, so that while it can hardly be said that aero service requirements for engines are now reducible to rigid specifications, they can be formulated with enough precision to enable an engine designer and manufacturer to undertake production with some prospects of success or acceptance. In so proceeding, however, no designer or manufacturer can afford to ignore past experience in engine construction nor, on the other hand, may old constructions be slavishly reproduced, for what was acceptable yesterday may not be to-day, and certainly will not be to-morrow.

All these service requirements can be classified under three headings for future more or less minute analysis.

POWER-WEIGHT RATIO, RELIABILITY, AND ADAPTABILITY.

If the engine complete with full tank is light enough it can be used—and is most useful when most light, and this weight involves many factors, each of which must be considered—some independent of others but many interrelated. The longer the contemplated flight, the more change there must be in the relation between specific fuel and oil consumption of the engine and the weight of the engine proper; so in any consideration of this item length of flight must be included. Not yet, however, has the engine or flight art reached the point where it is prepared to fix a minimum weight, though each year sees a definite maximum. In fact, one of the problems of the day for the aero engine designer is to discover means for lowering more and more both this maximum permissible weight that many can attain, and the minimum possible attainable by only a few of the best—and with increasing flight lengths this is becoming more and more a matter of raising thermal efficiency, engine speed, and cylinder mean effective pressure, with corresponding reduction of lubricating oil. On the weight question, therefore, it is not the service conditions that specify what is wanted other than that it shall be as low as possible, but rather the engine designer is put on his mettle to say how far it is possible to go with due consideration to the other two elements—reliability and adaptability.

Reliability is demanded always, but how much? Some writers call for absolute reliability and others try to specify in numerical terms a value for one or another of its elements. For example, in the 1913 German tests, any engine that dropped to 85 per cent of its normal speed was rejected, and this stipulation was retained for the 1914 competition. Again, in the British conditions, the only power rating allowed was the least attained at any time in six hours. Now absolute reliability is impossible, for this would mean continuous, uninterrupted operation without variation in any respect, except at the operator's will. No such engine has ever been built nor will it ever be built. Obviously what is wanted is as great a reliability factor as the engine designer and builder can secure consistent with other factors, so here again, as with the unit weight factors, the problem is one for the producer to say how far the reliability can be assured, rather than for the user to specify and reject, especially on laboratory tests. However, rejection on such grounds is far more justifiable than acceptance, for the engine so accepted may fail on its first flight, due to some accident or to faulty operator's adjustment. What is needed here is, first, analysis of the reliability factor into its elements and by cooperation between engine designer and user, an agreement on reasonable values for each, so one will not promise, nor the other expect the impossible, but each understand clearly the limits—and more important, the reason for the limit—that means may be sought to eliminate the disturbing cause.

About the same situation is true with the third factor, adaptability, and its elements—such as shape, vibration, silence, accessibility, uniformity of torque. They may be specified to-day only in the qualitative or comparative way, though some of them are capable of formulation, quantitatively, such for example as torque variations. So far it has not seemed feasible to impose any such limits but to leave the field wide open to the designer with an expression of desire for as high a degree of success as is possible with each.

The reason for this state of affairs in the art is clearly due to its youth and the necessity at present, and for some time to come, for the maximum possible encouragement of invention, design, research, and manufacture, until it becomes clear to all just how far it is possible to go in any direction after engaging all available resources of talent, material, money, and plant. When, after such a period, one or more standard types of engine or engine parts—or even of air craft itself—have been established, then will it be feasible to specify more particularly and numerically all the elements of each of the factors of unit weight, reliability, and adaptability.

In the meantime, the problem is one of review of engines produced and an analysis of their construction and performance as a whole and with it a similar analysis of fundamental possibilities. This must include a more or less standard examination of each of the essential parts of the engines and the relation of form and arrangement to the perfection or imperfection with which the part performs its partial duty or function. Even now, as Soreau, reporting the French tests, points out, the relative importance of low engine weight proper, reliability and life, and consumption of fuel and oil, originally considered in this order, has been reversed, experience indicating that the last is now first and the first last.

Part 1 (b).—MEANS EMPLOYED UP TO THE PRESENT TO PROMOTE AERO-ENGINE DEVELOPMENT, INCLUDING POSSIBLE MEANS NOT EMPLOYED.

Any new art develops as fast as encouragement is offered or as fast as the necessary means are made available and intelligently used, and, of course, inversely as the difficulties involved. It would be hard to find any class of machine among those developed in modern times that had to face the same inherent difficulties incident to the nature of the problem, or one that received, at least for the first few years, so little real encouragement and assistance as this one, the aero engine. The initial step is one of conception, which must be subsequently checked by construction and trial. This must be followed by commercial perfection, which requires endless research by test and computation—not only on the machines as a whole but to a larger degree on each element of the problem that analysis indicates to have separate entity, and on groups of elements that have coordinate functioning. Construction is here again necessary, not only of the complete machine, but also of variants on each part, and of instruments, appliances, models, and apparatus that do not themselves enter into the result but are essential to its attainment. Finally, with commercial perfection, further construction work is necessary to create the means of rapid large scale reproduction within the limits of dimensions needed for interchangeability of parts, i. e., establishment of the manufacturing plant. It must be understood, however, that these three steps that must be undertaken in this order on general principles may not be repeated many times over even when concerned with the same product, such as the aero engine, or that the earlier step ceases when the latter is inaugurated, for this is not true. These three stages or periods of development may, for the want of better terms, be designated as, first, the period of invention; second, the period of design; and, third, the period of manufacture. Design can not be undertaken before invention, whether that invention be of the patentable sort or not. Yet invention undoubtedly proceeds long after design has been firmly established and, of course, while manufacturing may not be undertaken until both invention and design have accomplished a reasonably commercial perfect product, it goes without saying that both invention and design will continue during the whole of the manufacturing period.

With the exception of invention, which needs little encouragement beyond a stimulation of the imagination, the primary factor in successful development is money, for, with sufficient funds, the necessary professional skill, labor, materials, and plant may be secured for carrying out the steps of design and manufacture. Of course, money may be, and usually is, misspent in these developments, especially when the control is in the hands of persons lacking engineering skill and experience, so there should be added the requirement that organization be associated with money.

No better illustration of this situation can be given than that of the steam turbine, whose period of development practically coincides with that of the aero engine, but which has been brought to a state of commercial perfection that the aero engine has not even approached, partly by reason of the better understanding of the service requirements that are not yet fully formulated for the flying machine, but almost entirely because of the differences in the means employed for the development. The steam turbine had its invention stage, and while invention still proceeds it is largely superseded by rational design for manufacture, under skillful guidance, under proper organization, suitably financed and satisfying an ample, well-understood market demand. The aero engine is still largely undeveloped, invention is still more active than design, and the almost microscopic, painstaking research required to establish the data necessary for design is almost wholly lacking, so naturally manufacturing in the true sense of the term is correspondingly nonexistant, though a few individual models of engines are being reproduced in fair numbers.

The millions of dollars needed for rational perfection for manufacture become available to the suitable organization ordinarily only when a permanent market is clearly in sight and when the service requirements of the product are reasonably definite. In the case of the aero engine, this market has been absent or at least very uncertain and the service requirements very hazy—both so much so that under ordinary conditions the aero engine could not have reached even the degree of perfection so far attained, unsatisfactory as it may be, without other incentives or different sorts of encouragement than the ordinary article of commerce receives as, for example, again the steam turbine. This special element in perfecting the aero engine is that of governmental aid based on military necessity, a comparatively recent force in the situation but now a very strong one in Europe, but almost wholly lacking in America. The military establishment can purchase what it needs in the market only when there is a reasonably strong civilian demand for the same article, strong enough to warrant the financial investment necessary for its perfection—and such is the case with the automobile and traction engine. On the other hand, when there is no such demand, however active invention may be, rational design and manufacture will be absent and must be supplied by the Army and Navy through their own organization and plants, or, as an alternative, reasonably steady annual governmental appropriations for purchasing sufficient quantities by the military departments may be made the basis of support for civilian production. Such is the case, for example, with ordnance and to some extent with ships.

For several years after the demonstration that engine-driven air craft could make successful flights the only encouragement offered to development was that of adventurous sport. Men whose incomes were sufficient became purchasers of machines for their own amusement and others bought machines for making exhibition flights before paying audiences for the profit to be derived. Both sorts of operators took chances with the imperfections of the machine in a spirit of adventure or speculation, but practically all made short flights that made no such demand on the engines as is now standard. Men such as Eiffel, and Deutsch de la Meurthe, should be mentioned for their contributions of large sums of money for scientific investigations, not of engines, however, and the national subscription funds of France and Germany, all of which assisted in development. In many cases, even with these short flights, the engine was taken apart, cleaned, repaired, and readjusted before each ascent. Even as late as September, 1912, Mr. Earle L. Ovington, writing in the Scientific American reports:

Usually every 15 hours of running, and at most every 20, my mechanics (skilled men) went through the interesting process of separating every single component part of my motor, one from the other. The valves were reground and retimed, because of valve-gear wear, new valve springs were inserted, the tappet rods were adjusted, and the whole motor was given a rigid inspection. The Gnome, in common with most rotary motors, uses castor oil as a lubricant, hence at each cleaning great quantities of carbon were removed. I claim that any engine requiring such attention may rightly be termed "delicate." How far would you get in an automobile if you had to take the entire engine to pieces and readjust practically every working part of the whole motor every 15 or 20 hours of service?

In an article in the Auto Car of March 28, 1914, we find the following statement:

The Gnome engine requires cleaning out after about 24 hours' continous running if it is to be kept in tune. The French military regulations demand that the Renault be cleaned out after 200 hours' running. Users of other aeroplane engines have told the writer that cleaning carbon out is hardly ever necessary.

With such an uncertain and capricious market perfection of the aero engine could hardly be expected in a whole lifetime, especially as the amount of business in any one country would scarcely suffice to support one producing establishment, and that one unable to bear the expense of the high-salaried engineers competent to supervise the work and when, at the same time, the stimulus to the imagination created by the idea of the mechanical flight produced thousands of inventions and inventors, each seeking and many finding financial support, under the influence of the excitement of the time rather than from any sound business basis. Failures necessarily must be numerous under such conditions, and every failure, whether of mechanism or finances, set back the art and discouraged the rest.

During this period the military organizations of all the nations watched results and purchased a few machines for experimental purposes, out of which grew the conviction now so firmly established and so thoroughly demonstrated in the present European war that, however imperfect the aeroplane, it is a military necessity and must be perfected. Perfection being impossible or too slow without governmental aid, plans were formulated by the European nations, one after the other, and, in addition to creating a corps of flying men with suitable cooperation with the military establishment, competitive tests for aero engines were organized by Germany 1912–14; France 1909, 1911, and 1913 in cooperation with the Ligue Nationale Aérienne and the Automobile Club de France; Italy 1913; and England 1914, in which substantial money prizes were offered for successful machines and in some cases buying orders given to winners in the contest. It was the intention to make each of these contests an annual event so as to not only continue the development of engines under this incentive, but to show clearly the annual progress by comparison of the entries in successive years on the basis of their performance, in relation to their form, materials, and proportions. The contests so far held are summarized in Appendix 1, which also reproduces the conditions and such of best results with some discussions and interpretations as are obtainable from published reports. Unfortunately the European war has interrupted reports of such tests as were completed in 1914 and prevented the carrying out of others, so that the latest information of this class is not now obtainable.

Besides these governmental contests with cash prizes and purchasing orders, which are undoubtedly the biggest single influence so far brought to bear on the rational development of the aero engine, there are some other coordinate factors to be noted, and these are civilian contests conducted by organizations interested professionally in promoting the art or by individuals, reports of which are also given in Appendix 1, with the Government contest reports. Among these private contests are to be noted in France Competition of La Ligue Nationale Aérienne, 1911; Automobile Club of France, 1913; England, Alexander contest, first for British-built engines, 1909, and second for any engine, 1912.

Finally, there must be noted among these influences for good in the rational development of the aero engine the establishment of laboratories for testing engines alone or flying-machine supporting and control elements alone, or both engine and air craft, and reference is made to the paper by Dr. A. F. Zahm, May, 1915, reproduced in Appendix 2, with other laboratory references in addition to those contained in the contest reports of Appendix 1. Some of the results obtained in these laboratories are not published and apparently but little work has been done on engines. It is assumed that most of the laboratory work on engines so far done is such as to be of value only to individuals seeking to perfect their own engine, or, believing it perfected, seeking an independent test report to enlist capital for manufacture or to serve as an advertising inducement to purchasers.

As a consequence, the conclusion must be that the largest single factor in the recent rapid development of the aero engine is governmental, involving the establishment of official organizations to study the problems, the operation of laboratories to determine by test the results attained by designers and producers, especially when large and regular purchasing orders are involved to support civilian development and manufacturing establishments, or in the absence of sufficient orders, and perhaps in addition to them, the distribution of sufficient cash prizes, whether originating in governmental appropriations or private and institutional donations.

Great as has been their influence for good in aero engine development, these contests have not yet been under way long enough to have accomplished more than a small fraction of what may be so attained, nor can this contest means be regarded as either sufficient or without faults. There is an inherent danger that the results of such tests be misinterpreted, and in fact there is even a bare possibility that they may exert a retarding influence on the art. Naturally competitors design engines and enter them to win a prize and the conditions of the contest become the controlling factor in the preparation of an engine for entry. If these conditions place undue weight on factors that are not of primary importance to the engine as it works in place in actual flight, it is easily possible that not only may the best engine from the actual service standpoint be rejected but, worse than that, the bulk of these workers who are engaged in development will be led away from lines that are truly legitimate in order that by following the lines prescribed by the rules they may secure the necessary cash to continue. In view of this possibility too much care can not be exercised in the preparation and regular revision of these contest rules and conditions in order that the result may be what is wanted and what is needed by the whole art, instead of a perfect attainment of a merely hypothetical standard.

Attention is called to these rules in the appendix and especially to the alterations in later German rules as compared with the earlier, all directed toward greater latitude and greater reliance on the judgment of competent engineers and proportionately less on the numerical values of those quantities that are subject to measurement and which require experienced cultivated judgment to interpret into terms of engine goodness which often depends as much on intangible things such as workmanship, ruggedness, simplicity, and the other factors of general adaptability. In this connection there is a most significant, though guarded, statement at the end of the second report of the Deutsche Versuchsanstalt für Luftfahrt by Dr. F. Bendeman, January, 1913, the best document on the subject in existence herewith quoted:

> The further development of the aeroplane and engine construction makes it seem desirable that in a future competition the engine be judged more in its relation to the *operating conditions* of the machine.

Even at best, better than yet arranged, the contest exerts but an indirect effect on engine development, it results in a public statement of a judgment of the machines relatively considered with reference to the rules and to each other. The winner is stated to be that engine that has best fulfilled the prescribed conditions; it is announced as better than others in this respect and that is all. Any test that measures only over-all results, whether of fuel and oil consumption, weight, horsepower, speed, unbalanced forces, torque variation, or similarly measurable quantities is faulty as a factor in direct development of engines to perfection. The only sort of direct contribution that can lead to true scientifically sound advance is that generally termed research which involves the patient analysis of not only over-all performance but more particularly of the performance of each part intended for the execution of every separate function, the accumulation and interpretation of data for the diagnosis not of the faults found but the determination of their causes and discovery of remedies, all of which are to be followed by the application of the promising prospective cures with test checks on their success. This sort of work requires the highest class of training and skill and is to be carried out as much in the computing and drafting room as in the laboratory, but to do most good to a young art struggling blindfolded to advance, every result must be not only convincingly and accurately arrived at but must be given wide publicity. This is the kind of development work that must be done and has not yet been attempted anywhere outside of a few establishments producing engines and in them is only carried on to a small degree because of the heavy expense, and naturally this same expense is sufficient reason for nonpublicity.

Research and publicity of the data of research are far more needed than public contests and their reports. While the latter are in a way an expression of the conclusions of the former, they give no clue to the means found necessary to bring them about no more than the sight of a man cured of an illness by a physician gives the observer any idea of the physician's diagnosis and methods of cure.

The advance of the profession or art is more important than an isolated case of perfection.

However sadly lacking are the data of research on aero engines, what literature there is descriptive of engines, of conditions of flight, of experiences, successes, and failures, of contests and over-all performances should be most thoroughly collected and recirculated in the form of collected papers.[1]

Part 1 (c).—GENERAL CHARACTERISTICS OF PRESENT AERO ENGINES: POWER, SPEED—ENGINE, RADIATOR, WATER, GASOLINE AND OIL TANK, WEIGHTS—FUEL AND OIL CONSUMPTION, AGGREGATE POWER-PLANT WEIGHTS WITH FULL TANKS FOR GIVEN LENGTH OF RUN—ENGINE TYPES.

Since the period 1901–1903, with the two engines, Wright of 12 horsepower, a converted four-cylinder, vertical automobile engine weighing for engine alone about 7 pounds per horsepower and the then novel Manly design of radial star fixed cylinder engine of 50 horsepower, weighing for engine alone 2.4 pounds per horsepower, there has been produced in the interval more than a hundred different designs that have survived the stage of first trial. There are now on the market perhaps half this number of different engines being regularly reproduced, each to some extent and several quite extensively (for this art), and of several of these designs engines are available in more than one size.

While most of these engines have capacities of 50 horsepower, more or less, the number that reach or exceed 100 horsepower is steadily increasing, following the demand of the aeroplane and made possible by greater experience in construction of the smaller sizes. It is worthy of note that the 1913 winner of the Gordon-Bennet cup race carried 200 horsepower and the Russian Sikorsky used in his 17-passenger machine 400 horsepower in two engines. The latest Curtiss aeroplanes carry 320 horsepower in two engines, and the English Sunbeam catalogues a single engine of 225 horsepower. While some types of engine construction give trouble in large sizes, there is no reason to believe that the limit of engine capacity has been anywhere nearly reached, for even if a high limit of cylinder diameter be found, which is not the case yet, multiplicity of cylinders can carry up total capacity. Naturally there is no limit to the number of separate smaller capacity engines that may be placed in one air craft except that as the weight per total horsepower of two or more engines is always greater than of one engine of equal aggregate capacity. On the question of total power there is no high limit in sight, though the normal is somewhat about 100 horsepower. Germany in 1914 required for her latest army planes 80 to 120 horsepower and more for hydroaeroplanes, while the United States Navy specifications of 1915 call for 100 to 160 horsepower. It may easily happen that this trend toward larger engine capacities will result in the elimination of some styles of engines which only operate well in smaller units, or what is more likely as the number of different types of air craft increases in the limitation of engine type to flying machine type.

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[1] A more or less complete bibliography of aero engines is offered in Appendix 3 as a nucleus, as full as the limited time available will permit, and to show the character of some of these papers, a selected few are reproduced. To complete this bibliography and republish these papers will be of very great service to the art, especially if there be added a corresponding collection of patents in all countries either in full or in abstract.

Speeds of engines are all in excess of 1,000 revolutions per minute, most engines operating normally between 1,200 and 1,500 revolutions per minute, with a few exceeding 2,000 revolutions per minute, the highest being the Sunbeam engine, rated at 2,500 revolutions per minute. These, of course, are the speeds when carrying normal full load and therefore a reduction of load, such as would follow a change of propeller to one of lesser torque or such as results from a gust of air in the direction of propeller air discharge, will accelerate the speed. This is because the full throttle, mean torque, of these engines is about constant up to speeds considerably in excess of their normal, probably approaching 2,000 revolutions per minute for most of them, though in all mean torque will decrease beyond some critical speed, due to valve and port resistance on the one hand and insufficient speed of combustion on the other. Below this critical speed, which is partly a matter of design of valves and ports, the horsepower is directly proportional to speed, and so speed increase is a natural means of reaching the light weight per horsepower of engine. It does not necessarily follow, however, that, because in a given engine the high speed does not reduce the mean driving torque, the engine will not suffer from the speed. In fact, it is just here that so many of the failures are found, the engines literally shaking themselves apart and pounding or grinding themselves to pieces. With due attention to the forces developed by high speed, and to bearing friction effects of rapid motion over loaded sliding surfaces, and to the suitable arrangement as well as proportions and materials for it, there is no reason why, from the engine operation standpoint, the present normal range of 1,200 to 1,500 revolutions per minute should not be exceeded if the service demands it, though the engine designer's problems are easier, the lower the speed. It must be noted that there seems to be no essential relation between propeller speed and engine speed if the operator has no objection to gearing, which in these days of automobile alloy steel gears can be made probably the most reliable element of the machine. Testing of engines at excess speeds to limits of unbalanced forces, bearing friction wear, and mean torque would seem to be a rational means of assuring that the operating speed itself will not cause trouble however much other causes might enter. Such a practice would be somewhat in accord with the hydrostatic test of 50 per cent excess of working pressure now standard with steam boilers and somewhat similar because each may in emergency reach that excess, in the one case of speed and in the other of pressure which may cause failure.

Engine weights now attained, per horsepower developed, exclusive of tanks, radiators, and supplies of gasoline, oil, or water, by the several classes or types of machines, at their own normal speeds, have not been materially lowered for some time, attention having been rather concentrated on the reliability and adaptability factors with existing weights, instead of on further weight reduction, though this will undoubtedly come in time. There is, however, a rather marked division of unit engine weights according to system of cooling of engine, whether by air or by water, involving besides water weight, that of radiator. For example, the most popular French rotating star cylinder air-cooled Gnome engine weighs just about 3 pounds per horsepower, ranging from 2¼ for 100 horsepower to 3⅓ for 50 horsepower, while the vertical water-cooled automobile style and winner of the last German competition weighs 4.2 pounds per horsepower. (A number of tables and some charts of engine weights are given in the papers in the appendix which are not repeated here, as it would serve no good purpose.) Attention is however called to the fact that the highest weight reported in the German competition (second) is about 6 pounds. This is about the present high limit, while 2.2, the value for the Gnome 100 horsepower, is the low limit, the water-cooled group occupying the upper portion of this range, the air-cooled, its lower portion. It is most interesting to note that the middle range in the neighborhood of 4 pounds is occupied by both types, providing that water-cooled engines can be built as light as some kinds of air-cooled engines, or that air cooling does not necessarily result in the lightest engine.

Whatever influence in this unit weight of engine alone the general arrangement may have is shown by a comparison of figures for some typical differences of arrangement or type. It ordinarily is of the order of a fraction of a pound and may be entirely offset by some other structural feature, not a factor in general arrangement, such as the use of a steel cylinder in one arrangement against a cast-iron cylinder in the other, or a high mean effective pressure in one against a low value in the other due to different weights of active mixture taken in per stroke. It would seem that cylinders set radially about a short single throw crank should yield an engine weight per horsepower less than the same number of cylinders set in line along a long multi crank shaft. Also that a V arrangement of two lines of cylinders should weigh less than a single line because of shaft and frame differences, but it is not clear whether a given output in four cylinders will yield a greater or less weight than in six or eight similarly arranged, nor is it clear just what difference in horsepower, if any, should be expected per unit of displacement per minute in water-cooled as compared with air-cooled cylinders. As pointed out, according to the general figures given, the aggregate of all such differences lie between the limiting weights of about 2½ pounds and 6 pounds per horsepower and therefore cover a range of about 3½ pounds per horsepower for such engines as are now in use and for which test data are available. Just how much of this difference is chargeable to one or another of the factors of arrangement, detail form, proportions, or material, it is not possible at the present time to accurately fix, but as a first attempt the following figures, Table I, are given as derived from available data:

TABLE I.—*Weights of engines in pounds per horsepower versus type construction.*

Cylinders and cooling.	Class construction.	Engine name.	Authority.	Weight. Alone.	Weight. Plant.
				Lbs.	*Lbs.*
Water-cooled fixed cylinder	4 cylinders in line	Benz	Bendemann	3.57	4.20
	6 cylinders in line	Daimler	do	3.75	4.36
	8 cylinders in line	Sturtevant	Maker	3.9	
	12 cylinders U	Sunbeam	do	4.0	
	Radial star	2-cycle laviator	"Flight"	3.02	
Air cooled:					
Fixed cylinder	8 cylinders U	De Dion Bouton	do		5.81
	12 cylinders U	Renault	do		6.38
	Radial star	British Anzani	Maker		4.0 3.4 4.1
	Special	Ashmussen	do	3.3	
Rotating cylinder	1 radial star	B. M. and F. W.	Bendemann	4.72	4.72
	2 radial star	German Gnome	Maker		3.088 2.480 2.701

TABLE I.—*Weights of engines in pounds per horsepower versus type construction*—Contd.

Cylinders and cooling.	Class construction.	Engine name.	Authority.	Weight.	
				Alone.	Plant.
				Lbs.	*Lbs.*
Water-cooled fixed cylinder	4 cylinders in line.	Daimler	Bendemann	4.29	4.92
	6 cylinders in line.	do	do	4.60	5.23
	8 cylinders in line.	Curtiss	Maker	4.0 8.4 4.4	
	12 cylinders U	Rausenberger	do	3.9	
	Radial star	Salmson	Soreau		5.47
Air cooled:					
Fixed cylinder	8 cylinders U	Renault	"Flight"		5.66
	Radial star	British Anzani	Maker		3.6 3.7 3.4
Rotating cylinder	1 radial star	Gyro	Bendemann	4.81	4.81
	2 radial star	Le Rhone	Maker		2.9
Water-cooled fixed cylinder	4 cylinders in line.	Daimler	Bendemann	4.74	5.37
	6 cylinders in line.	Argus	do	4.60	5.23
	8 cylinders in line.	Sunbeam	Maker	4.1	
	Radial star	Salmson	"Flight"	4.15 3.42 3.3	
Air cooled:					
Fixed cylinder	8 cylinders U	Wolseley	"Eng'y"		[1] 4.7
	Radial star	Edelweiss	"Flight"		3.68 2.82
Rotating cylinder	1 radial star	Gnome	Bendermann Lumet.	3.26	3.26
Water-cooled fixed cylinder	4 cylinders in line.	Daimler	Bendemann	4.89	5.52
	6 cylinders in line.	Mulag	do	5.14	5.77
	8 cylinders in line.	Clerget	"Flight"	3.2	
Air cooled:					
Fixed cylinder	Radial star	2-Cycle Laviator	do		3.05
Rotating cylinder	1 radial star	Gnome	Bendemann Lumet.	2.93	2.93
Water-cooled fixed cylinder	4 cylinders in line.	Daimler	Bendemann	5.09	5.72
	6 cylinders in line.	Schröter	do	4.65	5.28
	8 cylinders in line.	Laviator	"Flight"	3.43 3.48	
Air-cooled:					
Rotating cylinder	1 radial star	German Gnome	Maker		3.439 3.197 2.590
Water-cooled fixed cylinder	4 cylinders in line.	N. A. G.	Bendemann	4.33	4.96
	6 cylinders in line.	Hall Scott	Maker	4.32	5.15
	8 cylinders in line.	Panhard Levassor.	"Flight"	4.4	
Air-cooled rotating cylinder.	1 radial star	German gnome	Maker		2,976
Water-cooled fixed cylinder	4 cylinders in line.	N. A. G.	Bendemann	4.36	4.99
	6 cylinders in line.	Austro-Daimler	Maker		4.5
	8 cylinders in line.	Wolseley	"Eng'y"	5.38	
Air-cooled rotating cylinder.	1 radial star	Le Rhone	Maker		3.1
Water-cooled fixed cylinder	4 cylinders in line.	Argus	Bendemann	3.77	4.40
	6 cylinders in line.	Benz	Maker	4.1	
	8 cylinders in line.	E. N. V.	Alexander Prize Report.		6.1
Air-cooled rotating cylinder.	1 radial star	Gyro	Maker		3.25–2.88
Water-cooled fixed cylinder	4 cylinders in line.	Argus	Bendemann	4.38	5.01
	6 cylinders in line.	Wright	Maker	5.1	
Air-cooled rotating cylinder.	1 radial star	Clerget	"Flight"		3.3–2.7

[1] Without flywheel.

TABLE I.—*Weight of engines in pounds per horsepower versus type construction*—Contd.

Cylinders and cooling.	Class construction.	Engine name.	Authority.	Weight.	
				Alone.	Plant.
				Lbs.	*Lbs.*
Water-cooled fixed cylinder	4 cylinders in line.	Sturtevant	Maker	4.0	
	6 cylinders in line.	Green	MacCoult	4.4	
Water-cooled fixed cylinder	4 cylinders in line.	Cheno	"Flight"	3.91	
				2.87	
				3.97	
				2.8	
Water-cooled fixed cylinder	4 cylinders in line.	Clerget	"Flight"	4.23	
				3.96	
Water-cooled fixed cylinder	4 cylinders in line.	Green	Alexander Prize Report.	5.48	6.8

These figures show a consistent weight excess for cylinders in line over radial, but no conclusions can be drawn on the relations between water *vs.* air cooling for either fixed or rotating cylinders. More data and data in greater detail than are now available are necessary before such conclusions are possible. In later tables the figures are analyzed with reference to other units and some desirable conclusions are derived, but always there must be noted the data which one would expect at this date to be quite full and reliable are found to be both meager and uncertain.

To the weight of the engine proper with all the parts that are permanent features built on or into it, such as the magnetos, oil pumps, air fans, and water-circulating pumps, there must be added the weights of other parts to get the weight of the power plant with empty tanks. These additional parts may be called the engine accessories. All such supplies, as fuel, lubricating oil, and water needed for a given length of run, will add more weight, the amount of which depends partly on rate of consumption, partly on the general arrangement, but principally on the length of the run. The fuel weight to be carried per horsepower varies directly with the length of run and inversely as the thermal efficiency of the engine. The oil weight, while varying somewhat with the length of run, probably is not directly in proportion to it and certainly has nothing to do with the thermal efficiency of the engine, but rather depends on such factors as quality of the oil, mode of its application, style of engine, bearing temperature and surface pressure and speed. Water in any properly proportioned jacket and radiator system should not be lost, and its weight may therefore be regarded as a fixed quantity entirely independent of the length of run and additive as is a piece of accessory equipment such as the radiator itself, though its weight value is, of course, a function of the aggregate internal volume of jackets, piping, pump and radiator.

It needs only a superficial examination of these weights of accessories and supplies compared to engine weights to see that for short runs, engine and accessory weights are more important than supply weights, but that for long runs the supply weights, especially those of fuel and lubricating oil, will become the controlling factors in plant weight, and the longer the run, the greater the difference, and the more dependent does plant weight become on thermal efficiency and on efficiency of lubrication. For example, the data of the second German competition showed that the winning 100-horsepower Benz water-cooled engine, weighing 4.2 pounds per horsepower, consumed 0.472 pounds gasoline (thermal efficiency, 29 per cent), and 0.042 pounds oil, or a total of 0.514 pounds of both per horsepower hour. The 70-horsepower Gnome air-cooled engine mentioned in Bendemann's report, and weighing 2.9 pounds per horsepower, consumed 0.805 pounds gasoline and 0.253 pounds oil, or a total of 1.058 pounds of both per horsepower-hour. This being the case, the aggregate weight of the engine and supplies for different lengths of run up to 20 hours compare as follows, neglecting variations in tank weights that should add a little more to the engine of high consumption than to the more economical one. The radiator weight of the Benz engine is included:

Weights of engine, gasoline, and oil.

	For—				
	0 hours.	5 hours.	10 hours.	15 hours.	20 hours.
Benz....pounds..	4.2	6.77	9.34	11.91	14.48
Gnome....do....	2.9	8.19	13.48	18.77	24.06

Such relations as these—(Bendemann report shows the weights equalize in 1½ hours' operation)—lead to that most important conclusion derivable from all the competition test data in existence, viz, engines intended for short runs must be themselves light and need not be especially economical if, by sacrificing economy lightness is promoted. Conversely, engines intended for long runs must be economical at all costs, almost regardless of weight. It may also be added and this seems most significant that reliability is of importance about in direct proportion to the length of run, assuming good condition to be assured before starting in each instance, so that, again on the grounds of reliability, short run engines must be light even if less reliable, measured by period of uninterrupted operation, while to long-run engines considerable weight may be added to gain reliability.

From the design standpoint, a broad principle of practice can be directly derived, to the effect that aeroplane engines being intended for more and more widely varying types of service as to frequency of flights, length of run, and load-carrying capacity, need not be of one design, style, or type, but that different ones are justified and good engineering procedure demands the development and perfection to equal degrees, of as many different types and characteristics as will best serve the varying requirements of flight. From among these, a selection may intelligently be made for general service of undefined nature but with full forehand knowledge of its capabilities and limitations. All this agrees with engineering practice in other fields for there are to-day not only more different steam engines than ever before, but in any one group, such as locomotives, there is greater variety than there ever was; why, therefore, should anyone expect to find a single aeroplane engine or plan the development of one type to the exclusion of others? To do so, is to assume that all flights in all flying machines are the same as far as engines are concerned, which is just about as true as the assumption that a good pleasure motor-boat engine is the right thing for a trans-Atlantic ship, or that the best power plant for a tramp freighter will properly serve a battle cruiser. To be sure there are certain elements of service peculiar to flight, to which all aero engines must be adapted, but this can not be interpreted to mean that all aeroplane engines must conform to one another in arrangement, performance, or even in materials throughout.

Returning to the factors of plant weight, study of which leads to such important conclusions as the preceding, it is worth while to examine more closely the separate influences of the several component factors of accessory and supply weights.

Radiator weights must vary with the amount of sheet metal, cooling surface of given material in kind and thickness. The purpose of this surface is heat dissipation to the air, so the number of square feet and its weight will vary directly as the jacket heat loss of the engine, and directly as the mean temperature difference between water and air, but inversely as the coefficient of heat transmission. The most reliable data on this amount of heat to be dissipated, in fact, the only data are given by Bendemann, who finds that contrary to most internal-combustion engines, including the automobile class, which give up between 30 and 40 per cent of their fuel heat to jacket water, aero engines conform pretty closely to 15 per cent of the heat of combustion given to and carried by the water to the radiator. The difference, 15 to 25 per cent, is either not taken up by the water from the combustion chamber at all, passing out in exhaust gases instead, or, being taken in part by the water, is dissipated directly from jacket and water pipes to the air. In formulating the rules of the German competition, the radiator weights were assumed to conform to automobile practice and taken at 0.13 pound per 1,000 British thermal units per hour, but the experiments indicate that this should have been about 0.4 pound per 1,000 British thermal units per hour. Taking the calorific value of gasoline at the round number of 20,400 British thermal units per pound and the consumption of the more efficient water jacketed engines as one-half pound per hour per horsepower, the heat supplied per hour per horsepower is 10,200 British thermal units, of which 15 per cent, or 1,530 British thermal units per hour must be dissipated by the jackets. This quantity with the constant of 0.4 pound per 1,000 British thermal unit hours would make the radiator weight 0.61 pound, per horsepower of engine. Comparing this with the radiator weight of the 61.6 horsepower Green (British) engine, winner of the Alexander prize competition, which had a total weight of 46.9 pounds, the actual unit weight of radiator and connections becomes 0.76 pound per horsepower of engine, a fairly good check, considering the wide differences of design and circumstances. Winkler puts radiator weight between 0.40 and 0.55 pound per horsepower.

It is perfectly well known how fundamentally dependent on the flow conditions of the air, on the air side, and on the presence of air or steam bubbles, on the water side, is the coefficient of heat transmission for such apparatus as radiators, and yet this subject has scarcely been touched as a research problem, especially when it is considered that the mean temperature difference, another prime variable, is itself subject to considerable control. This will account for such differences in radiator weights as exist and is responsible for the belief that very material reductions may be expected in radiator weights following proper research or arrangements for securing rates of heat transmission and on thin noncorrosive metal inclosures.

Water weights are, of course, directly under control of the designer within certain limits, as the jacket spaces may be long or short, wide or narrow, pipes short and small or long and wide, and the water space in the radiator itself, almost anything. In the same 61.6 horsepower Green engine, winner of the Alexander prize, the whole water weight was 34.1 pounds, or 0.56 pound per engine horsepower less than the radiator weights. Winkler places this between 0.2 and 0.3 pound per horsepower. Other values for different engines are given in Table II to show the order of the magnitude of this factor.

Tanks for gasoline and oil will weigh more for large than for small supplies, but not in proportion to their volumes, as shape, thickness, and kind of material will determine the square feet of metal and weight of the tank per cubic foot of capacity as much as the volume. Other things being equal, that shape of tank will weigh least that has least weight per cubic foot of volume, and cylindrical tanks are most economical of metal weight, needing no stays, so the ratio of length to diameter is an important factor, which, however, also affects wind resistance, but these variations are not of such an order of magnitude to warrant detailed study here. The above-noted Green engine, 61.6 horsepower, and a gasoline tank of 70 gallons weighing 39.7 pounds, and a lubricating-oil tank of 6 gallons weighing 9.2 pounds, so that the net weights are, gasoline tank 0.65 pound and oil tank 0.015 pound per engine horsepower, or 0.57 pound per gallon for 70 gallons and 1.54 pounds per gallon for 6 gallons. Bendemann gives the round number of 0.2 pound tank weight per pound of gasoline or oil, which does not check the above figures. Tanks used in tests, he writes, are frequently too light for actual service, which indicates a necessity for standardizing tank-metal thickness, shape, and to some extent size, as large capacity may be just as well carried in several small tanks as in one large one and with better weight distribution on the frame, as well as affording a measure of safety.

Gasoline consumption for the better water-jacketed engines averages very closely 0.5 pound per hour per brake horsepower (B. H. P.), and for the rotating-cylinder air-cooled engines about 0.8 pound for full load, though, as might be expected, there are quite wide variations with type of engine and its condition as to cleanliness, adjustment, load, and speed. There is practically no data available on the rise of consumption with poor adjustment of carburetor, ignition, leaky valves or pistons, gumming bearings, carbonized combustion chamber, or even at speeds other than normal, or throttle positions other than wide open. It is not possible from test data to even approximate the gasoline consumption of an aero engine in actual flight service, though, judging from data on other classes of gasoline engines, it may easily be double this best value obtained by perfectly tuned new engines in competitive tests. We have many figures on total consumption of gasoline and oil during competition flights, but horsepower of course was not determined, and such figures must be compared with each other to give a true picture of range of possible variation. Even here, however, the operators are skilled and on their mettle, so they may be expected to better ordinary everyday flight consumption. These engine-test figures may be translated into thermal efficiency approximately by taking the average calorific value of American gasoline at 20,400 British thermal units per pound, making the engine heat consumption for the two typical classes 10,200 British thermal units and 16,320 British thermal units per hour per brake horsepower, equivalent to $\frac{2545}{10200}=25$ per cent and $\frac{2545}{16320}=15.6$ per cent thermal efficiency referred to brake horsepower. With the actual consumption of the Benz engine of 0.472 pound, Bendemann reports a thermal efficiency of 29 per cent, which requires that the gasoline used have a calorific value of 18,900 British thermal units per lb., which is the value used by Güldner for European gasolines. Other figures indicate about an equivalent difference between the American and European fuels which could be accounted for by the prevalence of paraffins and olefins, respectively, in each, even if of equal density.

Such a thermal efficiency as this high value is truly remarkable, and under the condition of operation and size of aero engines can hardly be bettered, judging from other experiences and from fundamental conditions to be examined later, but the low value is too low to be tolerated without adequate compensating advantages in engine weights for short flights and in the reliability and adaptability factors. Actual test values for specific engines and tests are reported in the appendix and need not be detailed here, but attention is again called to the practical importance of consumption data on other than these best conditions to show not only how high it may be in service, but also how sensitive it is to each individual adjustment and operating condition that may exert an influence.

Oil consumption is a thing that seems to follow no particular law, however much may be known about contributory circumstances, such as chemical character, viscosity, mode of application, surface speed, pressure and temperature, air evaporation, combustion chamber carbonization and cracking, and exhaust discharges. Beyond the more or less general adoption of castor oil to avoid gasoline absorption in the crank cases of rotating-cylinder aero engines, and the use of most widely different systems of feed and bearing conditions, this is a practically wide-open field of research. In all the competition tests the oil consumption has been made a subject of measurement, but no analysis of causes of consumption has been made, nor are there any data on the relative consumption of different oils or of different oiling systems for a given engine. The figures must be taken for no more than they really represent, viz, what was used, but it can be assumed that they are no guide whatever to the oil that will be consumed in actual service, except when consumption is fixed by a pump plunger displacement. Nor do these figures aid in fixing the least value attainable after proper thorough research on the lubrication of a given engine, which is rather more a matter of reliability and engine life than of oil weight to be carried. In the German tests values were found ranging from 0.009 pound to 0.089

pound per hour per brake horsepower for the water-cooled engines and from 0.145 to 0.253 pound per hour per brake horsepower for the rotating air-cooled cylinder engines. The only conclusions derivable from these figures are that there is a very wide variation—about 25 to 1—proving the need of study, and that on the whole the rotating air-cooled cylinders are much greater oil consumers than the fixed water cooled.

The aggregate weight of all the units of the power plant, engine, engine accessories, and supplies can be represented algebraically or graphically with every element involved in correct relative magnitude. All of these weights are constants for each engine, except the gasoline and oil weights, which are products of consumption per hour and the length of the run. Accordingly, the graphic representation will be a series of straight lines or of the aggregate, a single straight line. Algebraically the equation of that line will contain two constants, each of which is the sum of similar constants, one representing intercepts on the axis of zero time and the other slopes. In order to keep the various elements of the aggregate weight distinct and to bring out clearly the big factors of weight of engine proper and of gasoline weights, it is desirable that the excellent arrangement of a single line for each engine used by Bendemann in the second German report be supplemented by a general equation involving all the constants and a table of values for each as derived from the tests. Such an equation will have the following form:

$$\left.\begin{array}{l}\text{Weight of plant complete with}\\ \text{tanks full for } H \text{ hours' run,}\\ \text{pounds per horsepower.}\end{array}\right\} = \left\{\begin{array}{l}\text{Weight of engine alone per horsepower.}\\ +\text{Weight of gasoline tank per horsepower.}\\ +\text{Weight of oil tank per horsepower.}\\ +\text{Weight of radiator per horsepower.}\\ +\text{Weight of water per horsepower.}\\ +\text{Weight of muffler.}\end{array}\right.$$
$$+\left\{\begin{array}{l}\text{Pounds gasoline per hour per horsepower}\\ \text{Pounds oil per hour per horsepower}\end{array}\right\} H.$$

Symbolically this takes the following form with corresponding meanings from the former equation:

$$W = W_e + W_{gt} + W_{ot} + W_r + W_w + W_m + (G+O)H$$

In the following Table II are given some typical values for these seven constants, derived from the tests and for the total W for 0 and 10 hours. The gasoline and oil weights are added for 15 and 20 hours, but the plant weight can not be so given because of the uncertainty of the tank weights, which naturally are not directly proportional to content weights. It is interesting to note, however, that in 10 hours the plant weight is doubled—that is, the supplies for that time equal the weight of the plant empty for water cooled fixed cylinder engines. The air cooled rotating cylinder engines in the same time of 10 hours more than quadruples the weight.

TABLE II.—*Weights of engine accessories and complete plant weights per horsepower versus type construction.*

Name and authority.	Engine alone.	Gasoline tank.	Oil tank.	Radiator and connections.	Water.	Muffler.	Total engines and accessories.	Gasoline per hour.	Oil per hour.	Gas and oil for 5 hours.	Gas and oil for 10 hours.	Plant and supplies for 10 hours.
Average values, Bendemann	......	(1)	(2)	0.63		......	......	......	......	......	......	......
4-cylinder 100-horsepower Benz, Bendemann	3.57	0.944	0.034	.626		......	5.224	0.472	0.042	2.57	5.14	10.364
6-cylinder 90-horsepower Daimler, Bendemann	3.75	1.02	.076	.626		......	5.472	.510	.038	2.74	5.48	10.952
4-cylinder 70-horsepower Daimler, Bendemann	4.29	1.01	.094	.626		......	6.020	.505	.047	2.76	5.52	11.540
4-cylinder 100-horsepower Daimler, Bendemann	4.29	.988	.080	.626		......	5.984	.494	.040	2.67	5.84	11.324
4-cylinder 70-horsepower Daimler, Bendemann	4.74	1.006	.062	.626		......	6.434	.503	.031	2.67	5.34	11.744
6-cylinder 100-horsepower Daimler, Bendemann	4.60	1.056	.062	.626		......	6.344	.528	.031	2.99	5.99	12.33
4-cylinder 60-horsepower Daimler, Bendemann	4.89	1.002	.058	.626		......	6.576	.501	.029	2.65	5.30	11.876
4-cylinder 65 horsepower Daimler, Bendemann	5.09	.998	.120	.626		......	6.834	.499	.060	2.79	5.59	12.424
4-cylinder 95-horsepower N. A. G., Bendemann	4.33	.970	.070	.626		......	6.002	.485	.038	2.61	5.23	11.232
4-cylinder 55-horsepower N. A. G., Bendemann	4.36	1.038	.018	.626		......	6.042	.519	.009	2.64	5.28	11.322
4-cylinder 95-horsepower Argus, Bendemann	3.77	1.060	.178	.626		......	5.642	.534	.089	3.11	6.23	11.872
4-cylinder 70-horsepower Argus, Bendemann	4.38	1.176	.166	.626		......	6.34	.588	.083	3.35	6.71	13.058
6-cylinder 100-horsepower Argus, Bendemann	4.60	1.172	.134	.626		......	6.532	.586	.067	3.76	6.531	13.064
6-cylinder 100-horsepower Mulag, Bendemann	5.14	1.056	.042	.626		......	6.864	.528	.021	2.74	5.49	12.354
6-cylinder 90-horsepower Schröter, Bendemann	4.65	1.242	.094	.626		......	6.612	.621	.047	3.34	6.68	13.292
6-cylinder 125-horsepower (Hall-Scott makers)	4.32	......	......	.51	.32	......	......	.60	.03	......	......	......
Average of 6, British (Anzani, maker)	3.7	......	......	......	......	......	......	.54	.164	......	......	......
6-cylinder 87-horsepower (Benz, maker)	4.0	......	......	......	.138	.101	......	.557	.022	......	......	......
6-cylinder 60-horsepower (Wright, maker)	5.1	......	......	......	......	......	......	.53	......	......	......	......
Austro-Daimler "Flight"	......	......	......	[3].616 [4].589 [5].474	......	......	......	......	......	......	......	......
Green, Alexander test	5.48	.65	.15	.76	.56	......	7.00	.59	.175	......	7.65	15.25
Gnome, 1913, Lumet	......	......	......	......	......	......	3.366	.849	.255	5.520	11.04	14.41
Gnome, 1911, Lumet	......	......	......	......	......	......	2.88	.805	.253	......	10.58	13.46

[1] 20 per cent of fuel weight
[2] 20 per cent of oil weight.
[3] In 65 horsepower.
[4] In 90 horsepower.
[5] In 130 horsepower.

NOTE.—Plant weights are given without muffler.

Typical arrangements of cylinders, pistons, jackets, frames, crank shafts, valves, valve gear, and typical structural forms of each, have been produced in great variety and in considerable numbers. Of these a fair number have received more or less development work, but the majority of them must be regarded as hardly more than interesting proposals, or experiments in need of development work to definitely reject or retain them for use. Features of detail will be treated later in the course of the analysis of the engine after a review of the types classified by general arrangement.

Most of the engines operate on the four-stroke cycle, though the two-cycle system is represented, both air and water cooling is used, and of the air-cooled class there are representatives of self-cooling by rotation of cylinders, by fan circulation and by propeller blast, or free air currents over fixed cylinders. All engines are multicylinder, four or more, and generally more, and while nearly all use horizontal shafts with direct or spur-gear propeller drive, the vertical shaft with bevel-gear drive of propeller is represented.

These types, classified by cylinder and crank arrangement, are as follows:

1. Automobile type, four or more cylinders in line, each with its own crank, cylinder heads up. Air or water cooled.
2. V type, two rows of cylinders of four or more each, inclined to each other, one crank for each V pair of cylinders. Air or water cooled.
3. Radial star rotating cylinders, with crank shaft fixed, or rotating in the same or opposite direction. Air cooled only.
4. Special arrangement or combinations of the preceding.

Of these classes the first three are the most typical of the aero engine art in point of numbers of representatives, amount of development work done on them, and of standing in the engine-building industries of the firms represented, as will be seen from the following list of names of engines and makers, Table III, arranged under each class heading. This is not to be regarded, however, as a criticism of any of the other classes.

TABLE III.—*Aero engines by classes.*

Class No.																				
I.			II.						III.			IV.								
Cylinder crank arrangement.																				
Fixed in line.			Fixed V, 2 cylinders per crank.						Rotary.			Fixed star.						Miscellaneous.		
Cooling.																				
Water.			Air.			Water.			Air.			Air.			Water.			Air.		
Engine or maker.																				
Benz.			De Dion Bouton.			Curtiss.			B. M. & F. W.			Anzani.			Two-cycle laviator.			Ashmusen.		
Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.
1,013	4	1,288	80	8	1,800	75 100 160	8 8 8	1,100 1,250 1,100	37.5	7	1,031	25 30 40	3 3 6	1,250	80	6	1,300	105	12	1,800
Daimler.			Renault.			Sturtevant.			Gyro.			Anzani.			Salmson.					
88.9	6	1,387	70	8	1,800	140	8	2,000	38.8	7	954	50 60 70	6 10 10	1,250	90 135 200	7 9 14	1,250	....	....	....

TABLE III.—*Aero engines by classes*—Continued.

Class No.																				
I.			II.						III.			IV.								
Cylinder crank arrangement.																				
Fixed in line.			Fixed V, 2 cylinders per crank.						Rotary.			Fixed star.						Miscellaneous.		
Cooling.																				
Water.			Air.			Water.			Air.			Air.			Water.			Air.		
Engine or maker.																				
Daimler.			Wolseley.			Sunbeam.			Old Gnome.			Anzani.			Salmson.					
Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.
71.3	4	1,412	82	8	1,650	225	2	2,000	49	7	1,194	{ 80 100 125	10 10 10 }	1,250	{ 150 300	9 9	1,250 1,200 }	....	....	....
Daimler.						Sunbeam.			Old Gnome.			Anzani.								
99.2	4	1,373	....	....	....	150	8	2,000	62.9	7	1,156	200	20	1,250	....	....	....	....	....	....
Daimler.						Rausenberg.			Gnome.			2-cycle laviator.								
70.4	4	1,343	....	....	....	150	8	1,200	{ 50 60 80	.... 7	.... 120 .... }	50	6	1,200	....	....	....	....	....	....

Daimler.						Clerget.			Gnome.			Edelweiss.								
103.1	6	1,315	......	......	......	200	8	1,300	100 100 160	9 14 14	1,200	75 125	6 10	1,350 1,350	......	......	......	......	......	......
Daimler.						Laviator.			Gnome.											
60	4	1,396	......	......	......	80 120	8 8	1,200 1,200	200 80 100	18 7 9	1,200	......	......	......	......	......	......	......	......	......
Daimler.						Panhard-Levassor.			D'Hénain.											
66.5	4	1,391	......	......	......	100	8	1,500	50	7	......	......	......	......	......	......	......	......	......	......
N. A. G.						Wolseley.			Clerget.											
95.7	4	1,344	......	......	......	130	8	1,200	50 80	7 7	1,180 1,180	......	......	......	......	......	......	......	......	......
N. A. G.									Demont.											
55.8	4	1,408	......	......	......	......	......	......	300	6	2,000	......	......	......	......	......	......	......	......	......
Argus.									E. J. C.											
96.7	4	1,368	......	......	......	......	......	......	60	6	2,000	......	......	......	......	......	......	......	......	......
Argus.									Esselbé.											
71.0	4	1,342	......	......	......	......	......	......	65	7	1,250	......	......	......	......	......	......	......	......	......

TABLE III.—*Aero engines by classes*—Continued.

Class No.																				
I.			II.						III.			IV.								
Cylinder crank arrangement.																				
Fixed in line.			Fixed V, 2 cylinders per crank.						Rotary.			Fixed star.						Miscellaneous.		
Cooling.																				
Water.			Air.			Water.			Air.			Air.			Water.			Air.		
Engine or maker.																				
Argus.									S. H. K.											
Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.	Horse-power.	Number of cylinders.	Revolutions per minute.
102.1	6	1,370	......	......	......	......	......	......	{ 70 90	7 7 }	......	......	......	......	......	......	......	......	......	......
Mulag.									S. H. K.											
101.6	6	1,396	......	......	......	......	......	......	{ 140 180	14 14 }	......	......	......	......	......	......	......	......	......	......
Schröter.																				
88.9	6	1,252	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......

Hall-Scott.																				
125	6	1,300																		
Austro-Daimler.																				
90 120	6	1,300 1,200																		
Wright.																				
60	6	1,400																		
Sturtevant.																				
100	4	2,000																		
Green.																				
100	6	1,250																		
Clerget.																				
50 100	4 4	1,450 1,300																		
Chenu.																				
65 90 100 250	4 4 6 6	1,800 2,300 1,600 1,500																		

CLASS 1.—*Automobile class.*

Water cooled:
- American—
  - Hall-Scott.
  - Sturtevant.
  - Wright.
- German and Austrian—
  - Mercedes (Daimler).
  - Austro Daimler.
  - Benz.
  - N. A. G.
  - Argus.
  - Mulag.
  - Schroeter.
  - Basse & Selve.
  - Flugwerke Deutschland.
- French—
  - Clerget.
  - Chenu.
- British—
  - Argyll.
  - Green.

CLASS 2 V.

Water cooled:
- American—
  - Curtiss.
  - Sturtevant.
  - Ransenberger.
  - Maximotor.
- French—
  - Panhard-Levassor.
  - Clerget.
  - Laviator.
- British—
  - Sunbeam-Coatalen.
  - Wolseley.

Air cooled:
- French—
  - Renault.
  - De Dion-Bouton.
- British—Wolseley.

CLASS 3.—*Radial start rotating air cooled.*

American: Frederickson.

German:
- Kruk.
- Hirch.
- R. E. P.
- B. M. & F. W.

French:
- Gnome.
- Clerget.
- Canda.
- Burlat.
- Helium star.
- Demont.
- D'Henain.
- E. J. C.
- Esselle.
- S. H. K.

CLASS 4.—*Specials.*

Radial star-fixed cylinders:
- French—
  - Salmson, water cooled.
  - Laviator, two cycle.

Opposed fixed cylinders:
- American—Ashmusen.

Squirrel-cage cylinders:
- French—Edelweiss.

Radial fan:
- French—Anzani.

Inverted automobile:
- German—Daimler.

Many engines appearing in older lists are omitted, because of the belief that they are now superseded or abandoned, and likewise, some new engines now in existence are not mentioned because of lack of general acceptance as commercial. It may be, and is quite likely, that errors have been committed in these insertions and omissions, but this is inevitable without personal visits to the engine shops, which, in the present instance, were quite impossible.

REPORT No. 7.

PART 2.

AERO ENGINES ANALYZED WITH REFERENCE TO ELEMENTS OF PROCESS OR FUNCTION, ARRANGEMENT, FORM, PROPORTION AND MATERIALS, AND THEIR BEARING ON THE POWER-WEIGHT RATIO, RELIABILITY AND ADAPTABILITY FACTORS.

By Charles E. Lucke.

Part 2 (a).—AERO ENGINE PROCESSES AND FUNCTIONS OF PARTS VERSUS POWER-WEIGHT RATIO, RELIABILITY, AND ADAPTABILITY FACTORS.

In any machine the process is of superior importance to the mechanism as the latter is but one of many possible means for the execution of the former, and however necessary it may be to have the mechanism adapted in form, proportion, arrangement, and materials, to its objective process, success of the machine is fundamentally dependent on the process itself. Most machine processes are really combinations of a series of separate individual process steps working together, just as the mechanism parts themselves coact, and these processes are commonly said to be similar when they consist of the same partial steps executed in the same order as a series, and machines executing them are regarded as belonging to the same class, or as similar machines. There are, however, very great differences to be found in these similar machines which, therefore, may be vastly dissimilar from other standpoints. In the first place the process steps may differ widely in degree though being identical in kind, and this difference in degree may be in turn responsible for very considerable differences in mechanism. No better illustration is available than the common piston steam engine in which one basic step is expansion of steam after admission and before exhaust, yet experience has developed a whole succession of valves and valve gears, some adapted to moderate and others to high expansion ratios, while expansion to pressures below atmosphere immediately calls for the condenser with its elaborate series of auxiliary appliances and pumps. Differences in mechanism may be almost infinite even though the same process is executed, and to the same degree, and the steam engine will again serve as an illustration. Such differences may be significant or not. They must be regarded as significant when some good purpose is served whether the differences are those of detail parts form such as the shape of a piston; of arrangement of the same typical parts, such as the locomotive engine as compared with that of the steamship; of proportion of parts, as diameter of cylinder or thickness of wall; or of material. Such differences as are now accepted and well understood in the steam-engine field can all be analyzed into significant or indifferent from the standpoint of service requirements. These service requirements require years of experience to be appreciated to a degree that permits of a reduction to standards of practice in arrangement, form, proportions, and materials of the mechanism and its parts. Even after the establishment of such experience standards of practice for machines performing a definite fixed service there will always remain very considerable differences of the indifferent or nonessential order.

Aero engines, while belonging to the now large and established class of internal-combustion engines, and to the smaller fairly well-developed subclass of the gasoline carburetor internal-combustion engine, in which the farm, automobile, and boat types are most fully developed, are themselves still struggling through the development stage, due to the youth of the special service to be performed, and in spite of all that might be borrowed from the older most similar arts. In fact there is some evidence that these older arts have exerted a distinct retarding influence even where assistance might be expected, because borrowing is the easiest mode of acquisition. It is not unnatural to find automobile practice being adopted for aero engines, when it is not yet clear that there is anything required of the aero engine sufficiently different from what the automobile or boat engine can supply, to make the latter unsuitable for the service of the former. At the same time there is equally strong evidence that in some respect the differences in service requirements have been exaggerated or misinterpreted with the result that totally different engines were produced unlike anything before built, and yet just as unsuitable as the borrowed auto or boat engine.

In proportion as service requirements on the one hand become better understood, and as engine capabilities or limitations, on the other hand, are recognized and utilized, so will the aero engine as a type come into full growth. Review of the engines so far proposed, built, and tried out, indicates a strong trend in some directions, but just as surely proves that in most essentials the period of blind grasping at every possibility whether rationally defensible or not, has not yet come to an end. The most hopeful sign of progress is the now general recognition that no older type of engine can be borrowed bodily for aero service, and following this, the large number of suggestions for modification that have been and are now being made, some rational, derived through reasoning from fact data, but often without any recommendation other than mere purposeless difference.

Most of the rational development so far accomplished has been devoted to forms of the type parts, to their grouping or general arrangement, and to special materials for their construction, rather than to the processes that are fundamental to the gasoline carburetor type of internal combustion engine. Aero-engine designers being so intensely absorbed in the problems of arrangement of parts, adaptation of form of parts, reduction of metal thickness and application of materials of high elastic limit or low specific gravity, have in some instances, though fortunately not all, been diverted from thought of the process steps to be executed, in kind and degree. This becomes clear by comparisons, first of aero engines with each other and second of any one engine with the absolute standards of thermodynamics.

It is clear that if at the same speed and using the same fuel one engine gives a materially higher mean effective pressure than another, or a lower specific fuel consumption, then some elements of the thermodynamic process have been violated by the mechanism of the inferior machine. It is also true that if the thermal efficiency obtained is a smaller fraction of the thermodynamic limit of possibility than in an auto engine, for example, then again something has been incorporated in the aero-engine structure inferior to its counterpart of the auto engine structure. To a lesser degree similarly, if aero-engine stoppages not due to seizure of bearings or breakage of parts are more frequent than in auto engines, or even if they stop at all under these conditions, then the process requirements are in some way being violated by unsuitable mechanism, for if they were not the engine would continue to run, and without change. As a matter of fact, the whole question of reliability is one of maintenance or continuity of the process in every stage, assuming, of course, an absence of the pure mechanism troubles of breakages or bearing failures. Likewise, some of the elements of the adaptability factor, as well as those of reliability or of high power and fuel efficiency, are concerned with the process, for, should excessive tilting of the engine interfere with the carburetor action and result in poor mixtures, or should passage through a cloud or fog obstruct the intake with frost or ice, or should flights at excessive altitudes change the mixture, then the engine becomes inoperative by reason of process interference due to lack of adaptability of the mechanism to the maintenance of the process when subjected to the ordinary interference of actual use peculiar to air flight.

Proper execution of the processes by mechanism that insures its continuity in kind, and the constancy of every step, in degree, regardless of any interfering conditions incident to normal or even extraordinary aerial use, is a necessary prerequisite to the high mean effective pressure and high thermal efficiency that together make for low power plant weight per horsepower for any length of flight. It is just as essential to the continuity of operation and output that constitutes reliability, entirely independent of whatever contribution may be obtained to the same end, from variation of general arrangement, and detail design of parts as to form or thickness or from the selection of special materials.

The processes are comparatively simple and easy to state, though a thorough analysis of the relative or absolute perfection of execution that various designers have accomplished through their mechanism would require far more space than is available here. Such an analysis must moreover be based on far more test data than have even been made available anywhere. Judging from the literature of the subject and from some familiarity with general practices not so recorded, it can be stated that practically no work has been done except by a few large engine building concerns who keep their results secret, and comparatively speaking, no data obtained bearing directly on the execution of the process steps, and the effect of design on process, for aero engines, though some interpretation can be based on the few overall results of engine tests. While the details of design versus process are beyond the scope of this report, it is possible even from a statement of the processes and their fulfillment conditions, to derive some general specifications for the parts of the apparatus that, taken together, make up the power generating part of the engine, as distinguished from those parts that merely transmit or support.

As the working medium is primarily an explosive mixture of air and the vapor of gasoline, the first broad process step is mixture making, preparatory to introduction into the cylinder unless it be made directly therein. This must be followed by the second step of suitable treatment of the mixture in the cylinder, including expulsion of burnt products. Finally, as combustion develops heat in contact with metal walls, continuity of operation or the maintenance of a steady state in all respects requires heat abstraction and dissipation to a degree and at a rate equal to that of heat reception, so the third broad process step is cooling.

Each of these three broad divisions of the general power generating process, mixture-making, cylinder treatment of mixture, and combustion chamber cooling is itself a process, and is in turn subdivisible into more detailed or subprocesses, each definable to some extent as to degree or range that it is desirable to maintain.

The mixture-making process starts at the point of supply of gasoline and air and ends at the intake port of each cylinder. The one exception to this used in a few engines is the making of mixture directly in the cylinder by pump injection of gasoline, a method so wholly unsuited to the small cylinder high-speed engine, with such volatile fuel as gasoline, as to be rejected without further discussion not only on rational grounds but on actual comparative experience with the now standard system of mixture making. This standard practice that has taken many years to establish recognizes mixture-making as a distinct function to be carried out external to the cylinders, so as to permit of some control of this independent function without the interference that must result when it is combined with others in a single apparatus part.

Applying the common but more or less inaccurate name of carburetion, to this mixture-making function because the principal structural element of the process is the carburetor mechanism, the process divides itself into (*a*) fuel supply; (*b*) air supply; (*c*) carburetion proper, which includes proportioning, mixing, and vaporizing, and (*d*) mixture distribution to cylinders. Each of these steps must be carried out without variation in spite of anything that might happen beyond extraordinary accidents, and the apparatus, mechanism, or equipment must be so constructed as to insure the results desired. This is by no means easy, as will appear from even a superficial analysis of conditions and possibilities. Air must be taken from the atmosphere through which the machine is moving at a high, though not constant speed, a speed so high that the air pressure equivalent to the velocity, or velocity head of the air, is quite appreciable. With the air intake opening pointing in the direction of travel the velocity head is added to the static pressure of the air and air flow necessarily varies with flight speed, though it should not. This might be avoided by suitably shaped entrance orifice, the plane of which is in the direction of flight, but this is no safeguard when turning or in side gusts. The first requirement of air intake must, therefore, be independence of flow of air with reference to direction and speed of motion. Atmospheric air varies in absolute pressure with altitude and likewise varies in temperature, in water vaporized, and suspended water such as fog or rain. Each of these things exerts separately and together an influence on carburetion. Temperature, pressure, and moisture affect air density and hence the flow through the air orifice under a given pressure drop. Temperature affects the vapor pressure of the gasoline. (Absolute pressure affects air flow itself independent of the density change.) Vaporized moisture affects the accumulation of water in the mixture passages due to reduction of temperature incident to gasoline vaporization, and both vaporized and suspended moisture affect the accumulation of ice in the mixture passages, unless heat be added in sufficient degree. These things need hardly be stated to be accepted as fundamentally important and as necessary elements for incorporation directly or indirectly into specifications for the air supply to the carburetor. The carburetor action should be made quite independent of these variables and it must be sufficiently independent to prevent changes of mixture quality beyond the allowable working range. Therefore, however great a variation may be encountered during actual flight, in direction and velocity of flight or wind, in barometric pressure, in atmospheric temperature, in atmospheric moisture vaporized or suspended as well, the mixture quality must be kept within the two limits to be determined as necessary to continued engine performance.

Gasoline must be carried in a closed tank and must be fed to the carburetor through a pipe, and the supply to the carburetor should be quite independent of the direction and angle of inclination of the whole structure. It positively must be unaffected by such changes of relative position of tank and carburetor, as may be due to not only ordinary but even extraordinary or emergency turning, gliding, climbing, or temporary falling movements of the whole machine. If the machine should completely fall and upset, the gasoline should be prevented from running out on the hot exhaust pipe as this is likely to cause a fire. Gravity feed from tank to carburetor is affected, as to head, by every variation in angle and direction of inclination of the frame. Gravity feed tanks must have an air vent and so if overturned the vent becomes a spill hole unless a special check feature be added. In stationary plants gravity feed from supply tanks is forbidden by the fire underwriters' regulations because of the possibility of drainage of the whole tank due to a leak in any part of the pipe system. Air or gas derivable from fire-charged bottles, from pumps, from combustion chamber relief valves, or from exhaust back pressure acting on the liquid surface in depressed gasoline tanks will feed the gasoline from any relative position of tank and carburetor. If reasonably high pressures are used in comparison with the normal static gasoline head, the delivery pressure will be substantially constant at all inclination angles and spilling will be confined to the small carburetor float chamber as the main tank is closed. This system is in quite general use in auto practice. Pump feed from a main depressed tank with air vent to a small auxiliary gravity tank with overflow return directly above the carburetor, is the standard stationary system. Recently automobile practice has adapted this to its service requirements, replacing the pump and overflow return by a vacuum lift system operated from the suction header beyond the throttle, but retaining the depressed main tank with air vent and the small auxiliary gravity tank without air vent, which being so close to the carburetor can supply it at all times at substantially constant head. These two systems of pump and suction header lift may be operated with a closed main tank if slightly modified and in the event of a leaky pipe no loss or fire can occur because instead of gasoline escaping air flows in, doing no harm if the leak is small, but stopping the supply without loss if the leak is large.

The extraordinary changes of motion in direction and speed, both horizontally and vertically, peculiar to the aeroplane introduce liquid inertia and centrifugal pressures which may accelerate or retard gasoline flow by raising or lowering the pressure at the point of delivery to the carburetor. This is a peculiarity of the aero-engine service conditions which requires special attention. To cover all these influences an additional specification may be added for the carburation system; the fuel tank, piping, and supply system must deliver fuel to the carburetor at pressures that do not vary enough to cause the mixture quality to vary beyond the limits required for the proper steady operation of the engine regardless of angularity of the machine or of changes of its motion as to direction or velocity, and they must be such as to prevent fuel loss from small leaks and to minimize any spilling when overturned, preventing whatever spills touching hot parts or reaching electric sparks. References to the literature are made for actual tank arrangements which require no comment here except the approval of the practice of using more than one tank and especially of installing a small emergency reserve tank holding enough to insure a safe landing after main tanks are empty.

When supplied with atmospheric air and with fuel under pressure or static head, the carburetor mechanism is supposed to make a proper explosive mixture and through intake header and branches to deliver to each of the several inlet valves identical charges of that mixture equal in quality and quantity. This is supposed to happen regardless of the total quantity of mixture required by the engine load or speed and regardless of any variation in air temperature, pressure, moisture, direction, and velocity of flight or fuel delivery pressure. The possibilities of success in attaining this mixture-making ideal must, of course, depend on the definition of proper mixture, for in this is to be found the allowable range of variation from absolute constancy of quality.

Mixtures that enter the cylinder with too much gasoline for the air to support in combustion will not be explosive if the vaporized fuel excess is large enough and with such mixtures the engine is inoperative. Long before such a great fuel excess as this is reached the engine may be operative yet operate badly. It is clear that any excess vaporized gasoline in the mixture can not burn, so it will decompose or carbonize, depositing carbon all over the combustion chamber, including spark plugs and piston head, and show in exhaust as smoke. Such a mixture will be operative for a time, such time as it takes for the carbon to accumulate in layers thick enough to glow on hot spots, such as piston heads, causing back fires or preignition and possibly short circuits and miss fires from collections on spark plugs if they are so designed as not to be self-cleaning. Carbon deposits will also cause piston rings to stick and leak and impair lubrication when it collects on cylinder walls and between rings. To be sure, a certain amount of just such carbonization can be traced to lubricating oil that works past pistons, but this is an independent matter to be separately treated by oil selection and supply system. Excess fuel in the liquid state may be present when the vaporized part and the air make a proper mixture, and such excess will partly decompose as above, but part will be dissolved by the lubricating oil and defeat lubrication besides being a dead loss.

Excess vaporized gasoline in the mixture should be prevented, first, to prevent carbonization, but also to avoid the slow combustion that results when the excess is too great. A small excess gives the highest rate of combustion and high rates of combustion are necessary in aero engines to permit of attaining the highest initial cylinder pressures with the very high mean piston speeds in use, none of which are below 1,000 and some in excess of 2,000 feet per minute. By use of properly high compression and more than a single point of ignition a sufficiently high rate of combustion appears to be obtainable without resorting to such overrich mixtures with their carbonizing evils and direct waste of fuel. It may therefore be set down as a requirement that mixtures preferably should not contain any excess fuel at any speed and load, and positively must not contain enough to cause carbon accumulation, measurable fuel waste, or interfere with lubrication.

It goes almost without saying that mixtures of air and fuel must be homogeneous and uniform throughout; that is, the constituents must really be mixed. On reaching the cylinder at least, no liquid should remain unvaporized, or, to use a short word, the mixture should be dry. A correct overall ratio of gasoline to air by weight as required for combustion reaction will not serve the purpose if the gasoline is in liquid form, or even if it is vaporized, but all concentrated in one corner of the combustion chamber with pure air in some other corner, such as is sure to happen with direct injection or with more unvaporized liquid admitted past the inlet valve than can be vaporized while entering. Such nonhomogeneous and wet mixtures will both carbonize and cut lubrication even if total weights are correctly related, so the second and third requirements of mixture must be homogeneity, and dryness at least after admission.

Other things being equal, a cool mixture carries more heat per cubic foot and hence more work capacity than a hot mixture of the same fuel and air. But with liquid fuel, mixtures that are too cold are no mixtures at all, any more than a brook running through the country can be said to be mixed with the atmosphere, though rain by a stretch of the imagination might be, and a fog really is, though not so intimate a mixture as vaporized moisture. Any gasoline-air, kerosene-air, benzol-air, or alcohol-air mixture, in combining proportions may be dried if the temperature be high enough and the temperature required will be least for the fuels of greatest vapor pressure of their heaviest constituent if they are solutions of heavy and light parts, as is the case with the petroleum distillates. For any one fuel the required drying temperature is least the more intimately the air and fuel are mingled or stirred, so that any fuel particle will be required to exert only the partial pressure of the vapor in the final mixture, instead of the full mixture pressure of one atmosphere that is necessary without true mixing. Mixtures should, therefore, be as cool as possible consistent with dryness and the maximum permissible moisture is that which will vaporize on entrance. The higher the mixture pressure the greater the work capacity of the charge, so that everything that contributes to such must be promoted as much as the preparation of cool and otherwise proper mixtures. This means in effect that the pressure drop between the air and the cylinder must be a minimum, but this is entirely a question of proportions of passages.

Finally with reference to mixture quality there can not be much excess air, preferably none. Of course, excess air can not cause carbonization or lubrication trouble; in fact, it exerts a beneficial influence tending to burn accumulated hot carbon or lubricating oil vapor, and it permits of a somewhat higher compression which improves economy. But all the explosive mixtures of hydrocarbon vapors and air become nonexplosive in ratios very close to the combining proportions on the excess-air side, and with even a slight air excess the rate of combustion becomes prohibitively low. Summarizing mixture-quality requirements, a mixture is proper when it has the least and preferably no excess of either air or fuel, when it is homogeneous, when it is dry after entrance and as cool as possibly consistent with homogeneity and dryness, and when it is supplied at the maximum absolute pressure. To produce such mixtures is the function of the carburetor.

Carburetor mechanisms capable of making mixtures of such specified quality under the previously noted conditions of air and fuel supply are practically nonexistent at present, and improvement can hardly be expected so long as carburetor production remains a separate business, and purchasers buy on name instead of on performance, as is the practice, selling on name only, at present in the motor-car and motor-boat industries. Not until the aero-engine producer develops carburetor specifications in terms of mixtures produced and testing appliances to prove fulfillment and to locate causes of nonfulfillment of each separate requirement can the needed mixture-making carburetor be obtained. Under these conditions it matters very little whether the aero-engine builder makes his own, or buys on guaranty of performance, independent of engine operation.

Very great progress has been made in recent years in carburetor design for automobile and marine engines, but the end has not been reached, because all data point to a failure to maintain the quality of mixture in all the specified respects. In some respects the problem is less difficult with the aero engine than with the auto, as the former is not subjected to as wide a range of flow rates nor to such sudden and frequent changes in flow rates as are the latter, due to automobile driving in dense traffic or over country roads with constant changes of grade, curves, and rough spots requiring continuous opening and closing of the throttle. This fact is responsible for the general practice among aero engine builders of buying stock automobile carburetors on the theory that, the service being less severe, they should work better on aero service; yet such a conclusion is not warranted. While it is true that flow rate fluctuations will not be so great and so cause less variation in proportions, it is also true that the normal condition of flying with feed throttle wide open or nearly so produces a more intensive temperature drop, reducing vapor pressure and decreasing the degree of gasoline vaporization or increasing mixture wetness and condensing or freezing more water. It is also true that far stronger variations of fuel and air supply conditions must be encountered in air flight than in road driving. What is still more significant, however, is the fact that the aviator has no such opportunity to make hand adjustments as has the chauffeur, nor are the consequences of auto-engine stoppage due to bad mixture hardly more than annoyance, while such a stoppage of an aero engine may mean a complete wreck. It can not be too strongly stated that acceptance for use of standard carburetors on their names, or even reputation, is not a satisfactory practice for aero engines. They should be designed or purchased to specifications of maintenance of mixture quality under all variations of working conditions within possible ranges to be met with in service.

There seems to be no doubt after the years of experience in carburetor construction for automobiles and boats that the gasoline float chamber apparatus, with simultaneous vacuum flow of gasoline and of atmospheric air, is permanently established and must be retained. Adhering to this principle of construction as the basis of proportioning and of the first step in mixing, does not prevent the addition of other elements to correct the faults inherent in the simple combination. Mixture proportioning correctors in the form of compensators to reduce the natural tendency for gasoline to flow in excess at high rates of vacuum when the ratio is correct for low, are now available in considerable variety and some are fairly good, though even in the best there is considerable room for improvement. These compensators constitute the principal differences between modern carburetors.

It is in control of mixture quality in other respects than proportioning that carburetors now available are lacking; for example, to render the mixture quality independent of atmospheric changes, fuel supply, pressure fluctuations, and above all independent of their own cooling action. This self-cooling is due to vaporization of gasoline, the latent heat for which lowers the temperature of the mixture below that of the entering air. Heat must be supplied if liquids are to be vaporized, and no amount of human ingenuity can overcome this law of physics. If the latent heat of vaporization be supplied from waste heat sources for so much of the gasoline as can vaporize in its air supplied at atmospheric temperature, then the resulting mixture will have the same temperature as the atmosphere and there will be neither vapor condensation nor water freezing on the intakes. Such mixtures especially when the air is cool are not sufficiently dry and certainly are variably dry, dryness varying with atmospheric temperature. To produce even this much effect requires a considerable amount of heat from either hot jacket water or exhaust gases. To get this amount of heat into the entering air or the mixture it is necessary to observe the laws of heat transmission and provide sufficient heating surface of suitable form. To simply surround the body of the carburetor with a water jacket or to take the air from a short exhaust-pipe jacket, which are the only means now in general use, is entirely inadequate, as can be proved by simply taking the mixture temperature by a thermometer in the intake pipe or by observing the flow through experimental glass headers and branches. Of course such wall heaters will prevent any adhering frost, but they can not prevent its formation as free snow to be drawn into the cylinders. This problem of mixture making by carburetors is one of the most important of all the elements of the aero engine structure and the carburetor proper its most important apparatus, on which much work has been done, but more remains, especially of the adaptation order.

(In this connection the paper by Dr. Karl Buchner on carburetion, which is one of the best, is reproduced in full in the appendix.)

Distribution of the mixture from the carburetor to the cylinder inlet valves without change of quality in transit, and in such a way as to insure a supply of mixture of equal quality to each cylinder, is a problem of equal importance to that of correct mixture making and is intimately associated with it. If the carburetor should yield correctly proportioned mixed and completely dry mixtures, this distribution header problem disappears, and any form of branch pipe will serve the purpose in place of the long elaborately curved headers now in use. Such mixtures are too warm to develop the maximum possible mean effective pressure. To get the greatest power output per cubic foot of piston displacement per minute requires a temperature lower than corresponds to complete dryness, probably corresponding to just such quantity of moisture as can be evaporated during entrance through the inlet valve and, therefore, the aero engine header may be expected to carry some moisture.

Such mixtures have a tendency to separate the liquid, which resists division equally among the branches, and where vertical flow must take place there is a tendency for the liquid, which always flows along the walls to drop back by gravity, to accumulate, and then suddenly carry over as a wave, causing a miss, especially at low-engine capacity. To prevent lagging of liquid, vertical pipes must be made so small as to produce skin friction forces superior to gravity at the lowest flow rates. If this is done then, at high flow rates, a considerable drop in pressure with consequent loss of power will result, unless, as is often the case, the carburetor is located at the highest point and the liquid allowed to drain downhill with the mixture current in large pipes. On reaching a bend the liquid flowing along the side walls always collects on the inside as the air stream impinges on the outside, while at a Y or branch the liquid may choose almost any path and is quite beyond control, for wherever the mixture velocity is locally least then the liquid concentrates and this point is constantly changing. The best that can be done is to use long-radius bends and flow paths to each cylinder of approximately equal length and curvature, but this gives no assurance of equal distribution of liquid. The frequent use of two carburetors on six cylinders in line and eight cylinders V engines is evidence of an effort to reduce this trouble.

The only absolutely reliable way to avoid these special headers and the irregular engine action that results in two cylinders never doing quite the same work or remaining equally clean, is to completely dry the mixture by raising its temperature, accepting the higher temperature and lowered mean effective pressure in the interests of cleanly, steady, operation, securing shorter simplified headers and possibly making up lost output by a small increase in cylinder diameter or by raising the mixture pressure by blowers. There really seems to be considerable reason for the use of blower-supplied air for carburetors other than to compensate for loss of density when mixtures are warmed to dryness, which heating incidentally renders the engine more independent of variations of fuel quality than it now is. By suitable regulators the air blast can be controlled so as to give always the same absolute pressure at the carburetor intake, regardless of barometer or flight speed and direction. With such an auxiliary blower and pressure regulator, the friction effect of intake ports and small-diameter low-lift valves, while remaining a direct engine resistance, will have no effect whatever on the weight of charge per stroke and the mean effective pressures. Other things being equal, an initial pressure in the cylinder of 16, as compared with 14 pounds per square inch absolute, an increase of 2 pounds should increase the mean effective pressure and power one-seventh, over 14 per cent, while adding only 2 per cent additional load (if the mean effective pressure were 100 pounds), a net power gain of over 12 per cent if the blower be efficient. The use of such blowers is not unknown in two-cycle engines, though four-cycle engines have not employed them as yet, and the N. E. C. (New Engine Co.) two-cycle engine is so equipped, the blower in this case taking the place of a piston as a precompressor to prepare the charge for entrance into the motor cylinder when the port uncovers.

All two-cycle engines and all rotating cylinder four-cycle engines with inlet valves in pistons have mixture quality and supply conditions somewhat different from those of the four-cycle fixed-cylinder engines, and among the latter the air-cooled differs somewhat from the water-cooled group. The cylinder heads of four-cycle air-cooled engines are normally hotter than those that are water cooled, so that the mixture entering will receive more heat and may, therefore, be more wet as supplied, provided distribution from the carbureter is not a disturbing element, as, for example, if each cylinder had its own separate carbureter. If cylinders are not too large and the air cooling is vigorous it is possible to get the walls of the air-cooled cylinder quite as cool as the water-cooled one but only with excessive power consumption for air circulation, the Renault, for example, taking 8 per cent of its output for only such cooling as is normally provided. Most of the rotating-cylinder four-cycle engines with inlet valves in the pistons, including the Gnome, for example, take their mixtures into the crank case at the shaft center. In this crank-case chamber, which is rapidly whirling, with pistons churning up and down at the same time, a most vigorous stirring and heating action takes place. It would be hard to conceive of a better mixture conditioning apparatus than this Gnome crank case, provided there were some means of control of the temperature of the mixture, which in this case undoubtedly gets too warm, though dryness and homogeneity are practically perfect. Finally, two-cycle engines take the mixture from the carbureter into an auxiliary chamber for precompression, located in the crank case as the most favorable arrangement, or in a trunk enlargement of the main piston and cylinder preferably, as, for example, in the Laviator engine. While, of course, this precompression mixture has the evil effect of imposing negative work, equivalent to engine friction, it is highly beneficial as to mixture quality when the precompression chamber is so located, as is usually the case, as to get and stay warm, because in this case the chamber is at once a mixture stirrer and heating dryer, heating partly by wall contact and partly by compression.

Mixture treatment in the cylinder after it has been made and delivered to the intake port, begins with actual entrance and proceeds along different lines in the two and four cycle engine, in some respects. Nearly all aero engines are four-cycle engines, and these take the mixture in through a suction valve under the influence of the lowered cylinder pressure maintained by the piston outstroke. This admission should be accomplished with the least possible loss of pressure and rise of temperature. Loss of pressure imposes direct negative fluid friction work, the extent of which is measured by the velocity of flow through the valve, and the shape of the opening, but even with small valves and badly shaped openings or ports, this loss may be, but not often is, very serious. Two pounds per square inch would be large and with mean pressures approaching 100 pounds it would be equivalent to a little over 2 per cent. However small it may be, it can be controlled by valve and port dimensions and these, because of the high speed of aero engines, must be given far more attention than in any other class. It is the terminal pressure at the end of the suction that is one of the determining factors in the weight of the charge, each pound per square inch accounting for about 7 per cent loss of power. Since inertia of the incoming stream tends to build up the terminal pressure over the mean suction pressure, if valve closure is delayed the right amount, the value is so great that care must be exercised to secure it, and Winkler recommends a closure 40° after dead center. This delayed inlet valve closure can be secured only by mechanical inlet valves which also give best control over the mean suction resistance, so that under no consideration should automatic inlet valves be employed, as they have been, to save valve gear weight, because more power is lost than would compensate for this weight. Charge density at the end of suction is just as much a matter of temperature as of pressure, a rise of about 500° F. on entrance accounting of itself for about a 50 per cent reduction of charge weight and hence of power output, or approximately 1 per cent for every 10° rise, with the probability that the rise averages in well-cooled engines somewhere about 200°, or 20 per cent, and in the less well-cooled ones over 300°, or 30 per cent, in general round numbers.

Reduction of suction heating is partly a question of arrangement and partly of wall cooling but to some extent depends on the temperature of the hot gases left in the clearance after the previous explosion. As to arrangement, head valves discharging mixture directly into the cylinder seem to be more rational than side-pocket valves, though no data are available to prove that the former results in less suction heating than the latter. It also seems likely that air-cooled heads and valve chambers unless vigorously air blasted and of small chamber should heat the mixture more than water-cooled ones, but no one has ever determined how small a diameter can be equally well cooled by air and water nor how much air is needed. Nor can it be said how much of the total suction heating is due to exhaust gas mixture in the clearance with the fresh incoming charge. It is interesting to note that the air-cooled radial fixed cylinder Anzani gave in the tests 99½ pounds square inch effective pressure referred to brake horsepower, as much as most of the water-cooled engines.

Not only is it important that the charge in the cylinder be as cool as possible for the maximum charge density required for high mean pressures, consistent, of course, with complete vaporization, for which 120° F. is enough with gasoline if the mixture is well stirred, but it is perhaps even more important as the controlling factor in the permissible compression. This degree of compression of the charge before ignition is the prime variable in fuel consumption per horsepower hour and thermal efficiency, as has been demonstrated conclusively both by thermodynamic analysis and experimental data on all classes of internal-combustion engines. The highest compression possible must be obtained at all costs, and since it is the ignition temperature of the mixture that imposes a limit the objective of the engine designer must be to so treat the mixture as to get the maximum compression volume ratio and final pressure before the mixture being compressed reaches the ignition temperature which is a physical constant of the mixture, never accurately determined but probably very close to 935° F. This compression for the best water-cooled engine has been found to be about 5 to 1 volumes and less for cylinder not so well cooled. Of course, self-ignition before compression is complete will occur if any metal part, such as the exhaust valve or piston head, or a carbon deposit, is overheated, because this will produce a local overheating of the charge in contact with the hot spot before the whole mass has reached the ignition temperature. Prevention of this is a matter of engine cooling and of the internal cleanliness that comes with proper lubrication and carburetion. Assuming such to be properly cared for, the compression permissible with gasoline mixtures is fixed by the initial temperature of the charge. The final temperature varies with the initial in a geometric ratio, as is indicated by the standard equation for adiabatic compression, so a few degrees rise initially results in several times as great a terminal rise.

Charge weight per cubic foot of suction must be a maximum, and so also must the compression, if the mean effective pressure and thermal efficiency are to have the highest possible value, as they should in aero engines. All efforts in this direction may be entirely defeated, however, if there is any material leakage of the charge during compression through valve seats or past the piston. It is of no value to secure maximum charge weights during suction if appreciable amounts are afterwards lost before the charge has a chance to do any work. Tightness of piston depends on the piston rings, on the oil film between piston and cylinder, and on the maintenance of shape of cylinder and piston, neither of which may warp in any direction. Valve leakage likewise is minimized by providing nonwarping valve disks and seats with strong spring loads to keep the valve tightly against its seat during the first period of compression; at other times the gas pressure itself will suffice. These are questions of form and materials and will be taken up later, but they are mentioned here because a failure means defeat of the results of an otherwise well-executed suction process.

Four-cycle engines, after the suction periods, have their charges directly in the cylinder ready for compression and subsequent ignition. Two-cycle engines must put the charge through the preliminary compression process in a precompression chamber where the mean pressure of precompression must be added to that of suction, the sum of the two subtracted from the mean effective pressure of the compression and expansion strokes to get the net available. Therefore, assuming equal performance of the compression and expansion strokes, the two-cycle engine is charged with more negative work than the four-cycle by the amount of the precompression stroke, assuming equal negative work of suction in each. Suction heating effects on the two-cycle are bound to be less than in the four, because the precompression cylinder is sure to be cooler than the working cylinder into which the four-cycle charge enters directly, and so also is clearance gas with which the fresh charge mixes, as in the two-cycle case; this is reexpanded fresh charge remaining after discharge, while in the four-cycle it is hot burnt gases. All this two-cycle pump chamber charge will not enter the working cylinder nor remain there, for some will remain in the precompression chamber by reexpansion or failure of the pressure to drop during the open-port charging period to atmosphere. Some will escape through the exhaust port with the exhaust gases during the end of the transfer period when both transfer and exhaust are open, regardless of piston baffles of or special relative positions of inlet and exhaust ports designed for the purpose. During transfer the fresh charge bodily displaces the hot burnt gas that fills the motor cylinder and its clearance, and it is inconceivable that a considerable amount of mingling should not occur with corresponding heating and expansion effects. These mixture-heating effects are added to those of wall-contact heating, which walls in the two-cycle engines are always much hotter than in the four. The net effect is inevitably a discharge of some of the fresh charge with the burnt gases unless special arrangements are made to prevent this, and then each of these introduces its own evil.

Two methods of preventing this fresh charge heating on transfer in two-cycle engines and consequent loss of charge are in use, one is to intentionally reduce the charge transferred to so small a quantity as will not escape, and the other to expel burnt gases by a blast of fresh air, and then to expel this scavenging air which, of course, is cooler than the burnt gas, by the fresh charge. The former means intentionally reduced charge while the latter more than doubles the negative work of precompression which in effect is equivalent. Some part of the compression stroke in any two-cycle engine, so much as is required to cover the exhaust port, must result in further expulsion of charge. Naturally as in four-cycle engines, the charge weight can be built up in two-cycle engines to any value, by sufficient precompression, but to accomplish this the charge must continue to enter after the exhaust port is closed, which requires an admission or transfer valve mechanically operated and suitably timed, an extra complication. This is not common practice and no data are available on it, so for the present it must be regarded as merely an interesting possibility.

In the two cycle engines the net effect of all heat exchanges and pressure changes, incident to charging the main cylinder, is undoubtedly a lower mean effective pressure and thermal efficiency than in four-cycle engines, and for equally good design and construction in each class the two cycle is unable to carry compressions as high as the four, proving higher temperatures before compression. Any engine taking its charge into the crank case, as do most of the rotating cylinder four-cycle machines, or into a chamber connecting with the main piston, as the two-cycle Laviator, is subject to mixture quality impairment and equivalent charge loss, whenever the main piston leaks under its high explosion pressures, by the displacement of the fresh by the burnt gases.

While dealing with charge weights and volumetric efficiency of cylinders, the exhaust stroke of the four-cycle cylinder and the reexpansion stroke of the two-cycle precompression chamber must be considered as controlling by their terminal conditions of pressure the point of the return or suction stroke at which charging will actually begin. No flow can be started from the intake header until the clyinder pressure is lower. At the end of the four-cycle exhaust stroke the cylinder pressure is higher than atmosphere, and still higher than the mixture-header pressure by the amount of the suction-header vacuum. Suction can not begin until the cylinder clearance volume of gases has expanded enough to lower the cylinder pressure (terminal exhaust value) to below that of the mixture header. An appreciable part of the suction stroke is therefore useless for actual charging, the loss increasing with higher terminal exhaust pressures and lower suction-header pressures. A similar condition exists in the two-cycle precompression chamber; for there the pressure at the time the transfer to the working cylinder is complete must be something higher than atmosphere, and the higher the speed the more excess there must be, because of the limited time for pressure equalization. This mixture must expand not only to atmosphere, but as much below as the suction header or carbureter vacuum, even with a mechanically operated valve, and still more with the more common spring closed automatic check valve, by the amount of spring tension and valve inertia, before real suction can begin. The clearance in such precompression chambers is large, to limit the maximum precompression pressure to something less than 10 pounds per square inch, and, therefore, the reexpansion line will be very flat, cutting off a considerable part of the stroke as useless before the pressure has dropped sufficiently for suction to start. Many times the loss occurs here, as in four-cycle cylinders with their smaller clearances and steeper reexpansion lines, even with equal pressures at the start.

No separate data are obtainable for aero engines on any one of these quantities concerned with charge weight and the corresponding pressure and temperature changes, nor is there any indication that such information has even been sought. Even the over-all effects, as measured by volumetric efficiency, have apparently not been investigated, though all that is required is a measurement of air and gasoline or exhaust gas and a comparison with the piston displacement, the ratio of volumes constituting the true volumetric efficiency. Other things being equal, the horsepower per cubic foot of displacement per minute should be directly proportional to this volumetric efficiency, so it is a little surprising that the aero interests, which must have the most powerful engine per pound of metal, should have neglected to separately study each of the prime variables. As already noted, more designers seem to have been concerned with reduction of metal volume than with process perfection, though without proper execution of basic processes metal reduction may not only fail to give a light engine, but may even defeat the ultimate object by making the engine as structurally weak as it is weak in mean effective pressure or thermal efficiency. It must not be understood that no good performance results based on proper execution of the processes have been obtained; in fact, there are some most remarkable successes; but, on the other hand, these stand out so strongly as to prove that the procedure that has resulted so successfully is not the rule in the art, and may even in the case of the successful engine be as much a matter of good luck as patient, systematic investigation.

Assuming a good charge weight in the cylinder, or a high volumetric efficiency, the cylinder has at least the capacity for a high mean effective pressure and thermal efficiency, provided the subsequent treatment is proper. This treatment consists in compression with ignition before it is completed; combustion as rapid as possible consistent with absence of shocks; and expansion ending before the end of the stroke, by early opening of the four-cycle engine exhaust valve to drop the pressure to as near atmosphere as possible, at the end, and by uncovering the exhaust port of the two-cycle engine to get the same drop low enough before the end of stroke to allow the fresh charge to enter. It can be shown that both the mean effective pressure and the thermal efficiency will be highest for a given cylinder charge when the combustion starts as late as possible on the compression stroke and is completed as soon as possible on expansion stroke, or, referring to the shape of the indicator card, when the explosive combustion line is practically vertical, leaning, if at all, toward the expansion line than oppositely. Such a condition of affairs results in the Otto gas cycle, the efficiency of which is a function of compression only and the mean effective pressure of which is a function, partly of the compression, but also partly of the height of the vertical explosion line, which in turn depends on the weight of the charge or the volumetric efficiency. Should the combustion line be not of this shape, results are bound to be inferior, as can be demonstrated thermodynamically, and yet the maintenance of such explosion lines in service operation so fundamentally related to results, is now as much a matter of hand adjustment as of design. This is a strong reason for caution in applying special test results obtained by skilled enginemen, to conclusions of aero engine possibilities in actual service, where engine skill is likely to be less than in the shop or laboratory and where, even if it were not, the problems of flight control are so absorbing as to minimize the attention that can be given to engine adjustment. Recognition of this condition also suggests the great desirability of exerting sufficient effort in design, to reduce to a minimum or eliminate entirely the dependence of the operating result on such adjustments as affect the shape and position of the combustion line. Such explosion lines as are desired and needed for maximum power and thermal efficiency will result, if the combustion period is confined to within a sufficiently small crank angle at the inner dead center when the piston is substantially at rest, and it is common to take this angle as about 30° half before and after dead center. At a rotative speed of 1,200 revolutions per minute about the minimum for the good aero engines, or 20 revolutions per second, each revolution is completed in 0.05 second, and an angle of 30° being one-twelfth of a revolution combustion will be completed in about 0.004 second. The higher speed engines of 2,400 revolutions per minute must accomplish the result in half the time or 0.002 second. In this short time the mixture must be ignited, and the flame communicated from particle to particle, till all the mixture has been burned, even the part most distant from the ignitor. Assuming a uniform linear rate of flame propagation or flame speed and a 6-inch diameter cylinder about as large a one as any aero engine carries, the flame must travel half a foot in 0.004 to 0.002 second, which requires a linear velocity of 500 to 1,000 feet per second, or 30,000 to 60,000 feet per minute if a single igniter is used on one side.

While no direct data on the possibility of attaining such rates by normal propagation are available it is likely that from interpretation of indirect data, they are probably not reached, so the rates are abnormal or maximum pressures not attained. At any rate conditions that could in any way improve this situation must be grasped and utilized. The first of these is concerned with mixture proportions which exert so strong an influence on the rate of propagation in explosive combustion. This is another argument for perfection of carburetion, and for the continuous maintenance of the exact proportions found best, because even a slight change of proportions, such as would never be noticed in an automobile, may exert a powerful influence under the steady high speeds of the aero engine. Next in order comes the flame path itself which if cut in half reduces the necessary combustion rate to half and this is partly a question of shape of combustion chamber and partly one of number and location of igniter plugs. It certainly should take less time to inflame the charge in an engine with valves in the head than in a tee-head form, for example, if each had one plug, so the former shape is preferable on this score. It would seem as if one plug located in the center of the head would ignite the whole charge in the time required for the flame to travel a distance equal to the radius and, therefore, that such a location whould halve the time required by one plug located at the side, yet no such degree of difference has been established. Moreover, it would seem that two plugs simultaneously sparking, and located at opposite ends of one diameter would require more time to accomplish ignition than one in the center as each separate flame would have to travel more than a radius to burn all the mixture, and yet two such plugs seem to give a quicker combustion than the one in the center, instead of slower. This question of combustion rate versus spark plug location and number is still pretty well open, though clearly of considerable importance in securing proper combustion lines for most effective working. Reliability should also be served as there is a better chance of avoiding failure with two independent magnetos and two sets of spark plugs than one, and this much has been established as good practice, but accurate simultaneous sparking of both plugs is absolutely necessary.

There are two considerations that bear on the question, both of which require definite investigation. In the first place it is the volumetric rate of combustion that is of primary importance, not the linear rate. It is clear that a greater volume of mixture will be burnt with a fixed linear rate, if the ignition is at the center of a complete sphere of flame as the sphere has a greater volume for its radius than any other geometric body. This would seem to favor central ignition, but as the normal aero engine combustion chamber with head valves is a short cylinder in which the axis is short compared with the diameter, ignition at the center will burn in the first half of the total time a mixture volume proportional to the area of a circle of half the bore, while during the second half the circular ring between this circle and the cylinder wall will burn and this ring has three times the area and volume of the center cylinder. Therefore, with central ignition, the volumetric rate is low at first, and high at the end, averaging three to one in the second as compared to the first half, and it is the second half that is most important because here expansion is beginning and tending to lower pressures which it is the function of combustion to raise. If the situation be reversed so that the higher rates occur in the early part of the period available, then there will be less to burn after expansion has started and this will be accomplished by two plugs. The second consideration is that of non-uniform rate of propagation or accelerated combustion, and recognizes that mixtures which are agitated, burn much faster than those that are quiet. The advancing combustion wave started at any ignition point agitates the mixture beyond, somewhat like a compression wave, and two ignitors may be expected to increase this agitation and so accelerate combustion, compared with single point.

Whatever the rate of combustion, it is necessary to start combustion before the end of compression, and the slower the combustion rate, or the higher the piston speed, the more advance must be allowed. This advance, needed to limit the combustion completion time must be as small as possible because pressure rise during compression is just as detrimental as excessive friction, and is accepted at all only as the lesser of two evils. It would seem as if, with sufficiently high volumetric rates of combustion, and a sufficiently large number of ignition points, spark advance would be minimized. Manual advance might even be eliminated entirely as an operator's adjustment, if the magnetos and distributors used had proper electrical characteristics with speed increases to give earlier sparks passage at higher speed. With widely varying throttle openings and engine speeds, such as are typical of auto engines, chances of success are more remote than with aero engines where speed and throttle positions are changed so seldom.

While it is possible to experimentally determine the degree to which each process step important to the power weight ratio has been executed in an aero engine, and to measure the precise amount of disturbing effect of each interfering influence to be encountered in practice and, therefore, experimentally study processes with reference to reliability and adaptability as well, no such work appears to have been undertaken or, if it has, the results have not been recorded. All that has been published with respect to the judging of process fulfillment has been concerned with a few simple over-all measurements of horsepower, speed, and fuel consumption from which some conclusions are derivable, but not of such significant value to designers and operators of engines as would be the case with true investigation work of the analytical character that accounts separately for each factor that enters into the result. As has already been pointed out, these results are subject to some interpretation by comparison, one with the other, and each with thermodynamic standards. All the facts necessary for the latter are not available, and must be assumed in part, so the conclusions will be correspondingly approximate and subject to caution in use.

From the measured brake horsepower and speed, the speed can be eliminated by division and a quantity obtained which measures the effectiveness with which those processes that are concerned with output have been executed, and this is the mean effective pressure referred to brake horsepower. This quantity, of course, includes all negative work of gas friction through carburetor header ports, valves, and exhaust muffler, all mechanical friction, all fan, pump, and magneto work; all negative work of precompression in two-cycle engines and the windage of rotating cylinder engines. For the most satisfactory conclusions these included items of loss should be separately determined and certainly the motor cylinder work done behind its piston should be isolated from the rest, but up to the present the only separate factor thus embraced is the windage of the rotating cylinder engines in the German tests. Comparison of these over-all competition test results giving the mean effective pressure referred to brake horsepower with each other is possible from Table IV.

TABLE IV.—*Mean effective pressures referred to brake horsepower versus engine classes.*

Class No.													
I.		II.				III.		IV.					
Cylinder-crank arrangement.													
Fixed in line.		Fixed V, 2 cylinders per crank.				Rotating.		Fixed star.				Miscellaneous.	
Cooling.													
Water.		Air.		Water.		Air.		Air.		Water.		Air.	
Engine or maker.													
Benz.		De Dion-Bouton.		Curtiss.		B. M. & F. W.		Anzani.		Laviator, 2 cycle.		Ashmusen.	
M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.
106.9	Bendman.....	67.3	"Flight".....	107.7 111.7 104.7	Maker.........	66.6	B.............	76.5 78.5 76.9	Maker.........	65	"Flight"......	77.5	Maker.
Daimler.		Renault.		Sturtevant.		Gyro.		Anzani.		Salmson.			
114.4	B.............	64.1 60.2	"Flight".....	100	Maker.........	76.9	B.............	83.2 80.1 86.8	Maker.........	83.5 92.8	"Flight"......	....	
Daimler.		Wolseley water-cooled exhaust box.		Sunbeam.		Gnome.		Edelweiss.					
103.5	B.............	79	"Eng'g"......	127	Maker.........	75.0	B.............	97	"Flight".....	....	....	....	

Daimler.				Rausenberger.		Gnome.		Laviator, 2 cycle.					
102.0	B			103	Marker	71.3	B	57.2	"Flight"				
Daimler.				Clerget.		German Gnome.		1911 Anzani.					
107.1	B			101.5	"Flight"	67.9 / 67.2	Maker	99.56	Lumet				
Daimler.				Laviator.		German Gnome.		1911 Nieuport.					
107.0	B			106 / 92.5	"Flight"	78.7 / 65.2	Maker	88.76	Lumet				
Daimler.				Panhard Levassor.		Le Rhone.							
104.8	B			82	"Flight"	85.6 / 89.2	Maker						
Daimler.				Wolseley.		Clerget.							
98.0	B			77	"Eng'g"	57.6 / 72.8	"Flight"						
N. A. G.													
106.0	B												
N. A. G.													
94.9	B												

TABLE IV.—*Mean effective pressures referred to brake horsepower versus engine classes*—Continued.

Class No.													
I.		II.				III.		IV.					
Cylinder-crank arrangement.													
Fixed in line.		Fixed V, 2 cylinders per crank.				Rotating.		Fixed star.				Miscellaneous.	
Cooling.													
Water.		Air.		Water.		Air.		Air.		Water.		Air.	
Engine or maker.													
Argus.													
M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.
106.5	B												
Argus.													
107.5	B												
Argus.													
101.1	B												

Mulag.													
101.3	B												
Schröter.													
79.2	B												
Hall-Scott.													
92.75	Maker												
Austro-Daimler.													
93	Austrian Army official.												
Wright.													
83.7	Maker												
Sturtevant.													
103.8	Maker												
Chenu.													
96 .04 110 102	"Flight"												

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TABLE IV.—*Mean effective pressures referred to brake horsepower versus engine classes*—Continued.

Class No.													
I.		II.				III.		IV.					
Cylinder-crank arrangement.													
Fixed in line.		Fixed V, 2 cylinders per crank.				Rotating.		Fixed star.				Miscellaneous.	
Cooling.													
Water.		Air.		Water.		Air.		Air.		Water.		Air.	
Engine or maker.													
Clerget.													
M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.	M.E.P.	Authority.
98.3 101.5	"Flight"												
Green.													
74	McCoull												
1911 Labor-aviation.													
102.4	Lumet												

1911 Aviatic.													
118	Lumet												
1911 Chenu.													
98.33	Lumet												

Values of mean effective pressure exceeding 114 pounds per square inch, referred to brake horsepower, reported for one engine, and in many instances in excess of 100 pounds per square inch for water-cooled fixed-cylinder engines, warrant the conclusion that little betterment is possible in view of the prevailing lower figures in engines of other classes. These attained values are truly remarkable and can hardly be exceeded unless the initial pressures are raised above atmosphere by blowers. That some engines do not attain these values is proof of their inferiority of design, but there is some question as to capacity for maintenance of the high value after long periods that can be settled only after very long trial runs. The contest figures are reliable and acceptable for the conditions imposed, and if such values can be maintained in flight, little more can be expected. Such a high value as 127 pounds reported by one maker can hardly be credited, nor can so low a value of 74 pounds be regarded as good enough to be acceptable. Air-cooled cylinder values are consistently lower even for fixed cylinders and much more so for rotating cylinders, which indicates a fundamental inferiority.

There is some question of the validity of a comparison of mean effective pressures for different engines at unequal speeds, especially as rotating cylinder engines are never run over 1,500 revolutions per minute while fixed cylinder engines are operated over 2,000 revolutions per minute. To eliminate such an objection and at the same time permit of a judgment of the best speed at which to run an engine of given design, the horsepower-speed curve should be determined, or its equivalent curve of mean torque speed, or of mean effective pressure referred to speed. It is evident that, if with an increase of speed the mean effective pressure remains constant, then the horsepower will be proportional to speed, and the best speed to use for aero engines will be the highest at which the inertia or centrifugal forces are not excessive, assuming proper bearing conditions to be provided. This best maximum speed for fixed cylinder engines is undoubtedly the speed at which the inertia force of the reciprocating parts at the beginning of the outstroke is equal to the normal maximum gas-pressure force acting on the piston. For these conditions the force transmitted to the crank pin at the moment of explosion will be zero, gradually rising through the stroke and will be maintained high until near the end of the outstroke during the last half of which the increasing inertia forces are additive to the lessening gas pressure forces. During the idle stroke of suction the inertia force acting alone imposes just the same crank-pin forces as would the explosion when starting. Any less inertia while reducing the transmitted crank-pin forces for idle strokes increases them at the beginning of the working stroke. As the normal or most used speed is less than the maximum and the maximum gas pressures likewise, this normal condition and not that of maximum should be made the basis of selection of operating speed for minimum weight of engine, coupled with general serviceability. The speed at which normal maximum gas pressures will be balanced against reciprocating inertia, which is a function of the square of the speed and of the weight of parts directly, will, of course, depend on these weights. Heavy reciprocating parts may be best operated at lower speed than light reciprocating parts which include piston, wrist pin, and part of the connecting rod.

For a water-cooled engine of the automobile type Winkler gives 350 pounds per square inch as the maximum explosion pressure. Accordingly from the equation, reciprocating inertia pounds per square inch of piston $= 0.00034 \frac{W}{a} N^2r$, and taking $\frac{W}{a} = 0.5$, calculated from the weight distribution figures given by Winkler, the speed at which this would become equal to 350 pounds per square inch is 2,640 revolutions per minute. (NOTE.—$\frac{W}{a}$ = pounds reciprocating weight per square inch piston, N = revolution per minute, r = radius of crank in feet.) The rotating cylinder engine introduces a different condition, for here the reciprocating parts always exert a centrifugal force varying from a maximum at out center to a minimum at inner center and such as will keep the connecting rods always in tension if speed and reciprocating weights are large enough to develop centrifugal forces higher than the gas pressure, the maximum for which is found at 250 pounds per square inch normal.

From this standpoint the operating speed or high limit is fixed by the weight of reciprocating parts, and the normal maximum gas pressures, and this is the controlling factor so long as mean effective pressures do not fall off materially with speed. Examination of any horsepower-speed curve will show it to have a straight line form up to some critical value which is easily determined by test, though no authentic curves are available for aero engines. Of course, this critical speed must be beyond the operating range and is a second high limit to be considered in conjunction with that imposed by inertia. The best procedure is undoubtedly the selection of such proportion of gas passages, carburetor, and ignition conditions on the one hand, and reciprocating parts weights on the other, as will bring the critical speed equal to the inertia speed limit. Curvature of the horsepower-speed curve is due partly to increased losses of charge at the higher speeds, and partly to insufficient rate of combustion. Which of these two is in any instance the controlling factor must be discovered before any plan of improvement can be undertaken and this is most directly done by plotting the volumetric efficiency-speed curve beside the horsepower-speed curve. If the latter departs from the straight line before the former, it is clearly not due to insufficient charge. In such a case enlargement of valves or ports, or reduction of carburetor vacuum will not improve matters at all, as it is a low rate of combustion that is responsible for the result, to cure which attention must be devoted to mixture quality and ignition.

Fuel consumption per horsepower hour, or the equivalent thermal efficiency, is also an indication of the overall effectiveness of the process execution, and comparison of engines on this basis can be made from the data of Table V, selected from the test reports. These would tell more if divisible into the factors as indicated in considering the mean effective pressure.

TABLE V.—*Fuel consumption (pounds per brake horsepower-hour) and thermal efficiency versus engine classes.*

Class No.									
I.		II.		III.		IV.			
Cylinder-crank arrangement.									
Fixed in line, 1 cylinder per crank.		Fixed V, 2 cylinder per crank.		Rotating.		Fixed star.			
Cooling.									
Water.		Water.		Air.		Air.		Water.	
Engine or maker.									
Benz.		Curtiss.		B. M. & F. W.		Anzami.		Solmson.	
Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.
0.472	0.29	0.560 .504 .525	0.22 .25 .24	0.845	0.16	0.58 .57 .57	0.23 .24 .24	0.53	0.25
Authority.									
B.		Maker.		B.		Maker.		Lumet.	
Daimler.		Sturtevant.		Gyro.		Anzani.			
0.510	0.27	0.511	0.24	0.785	0.17	0.49 .53 .51	0.27 .25 .26	....	....
B.		Maker.		B.		Maker.			
Daimler.		Sunbeam.		1911 Gnome.		1911 Nieuport.			
0.505	0.27	0.5	0.25	0.787	0.17	0.805	0.17	....	....
B.		Maker.		Lumet.		Lumet.			
Daimler.				1911 Gnome.		1911 Anzani.			
0.494	0.28	....	....	0.805	0.17	0.668	0.20	....	....
B.				Lumet.		Lumet.			
Daimler.				German Gnome.		1913 Anzani.			
0.503	0.27	....	....	0.6614	0.20	0.711	0.19	....	....
B.				Maker.		Lumet.			

TABLE V.—*Fuel consumption (pounds per brake horsepower-hour) and thermal efficiency versus engine classes*—Continued.

Class No.									
I.		II.		III.		IV.			
Cylinder-crank arrangement.									
Fixed in line, 1 cylinder per crank.		Fixed V, 2 cylinder per crank.		Rotating.		Fixed star.			
Cooling.									
Water.		Water.		Air.		Air.		Water.	
Engine or maker.									
Daimler.				Gnome, average of six 45-horsepower engines.					
Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.
0.528 .501 .499	0.26 .27 .27	....	....	0.7108	0.19	....	....	....	....
B.				Lumet.					
Benz.				Gnome, average of twelve 63-horsepower engines.					
0.537	0.25	....	....	0.7354	0.18	....	....	....	....
Maker.				Lumet.					
Wright.				1913 Gnome.					
0.53	0.23	....	....	0.849	0.16	....	....	....	....
Maker.				Lumet.					
N. R. G.									
0.485	0.28	....	....	....	....	....	....	....	....
B.									
N. R. G.									
0.519	0.26	....	....	....	....	....	....	....	....
B.									

TABLE V.—*Fuel consumption (pounds per brake horsepower-hour) and thermal efficiency versus engine classes*—Continued.

Class No.									
I.		II.		III.		IV.			
Cylinder-crank arrangement.									
Fixed in line, 1 cylinder per crank.		Fixed V, 2 cylinder per crank.		Rotating.		Fixed star.			
Cooling.									
Water.		Water.		Air.		Air.		Water.	
Engine or maker.									
Argus.									
Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.
0.534	0.26	....	....	....	....	....	....	....	....
B.									
Argus.									
0.583	0.23	....	....	....	....	....	....	....	....
B.									
Argus.									
0.586	0.23	....	....	....	....	....	....	....	....
B.									
Mulag.									
0.528	0.26	....	....	....	....	....	....	....	....
B.									
Schröter.									
0.621	0.22	....	....	....	....	....	....	....	....
B.									

TABLE V.—*Fuel consumption (pounds per brake horsepower-hour) and thermal efficiency versus engine classes*—Continued.

Class No.									
I.		II.		III.		IV.			
Cylinder-crank arrangement.									
Fixed in line, 1 cylinder per crank.		Fixed V, 2 cylinder per crank.		Rotating.		Fixed star.			
Cooling.									
Water.		Water.		Air.		Air.		Water.	
Engine or maker.									
Hall-Scott.									
Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.	Fuel.	Efficiency.
0.6	0.21	....	....	....	....	....	....	....	....
Maker.									
Austro-Daimler.									
0.52	0.26	....	....	....	....	....	....	....	....
Government Acceptance Test.									
1911 Labor-Aviation.									
0.617	0.22	....	....	....	....	....	....	....	....
Lumet.									
1911 Aviatic.									
0.595	0.23	....	....	....	....	....	....	....	....
Lumet.									

NOTE.—For Continental engines a calorific value of 18,900 British thermal units per pound has been assumed, for American and British engines 20,400 British thermal units per pound.

Fuel consumption of less than half a pound per brake horsepower-hour, reported for fixed water-cooled cylinders on reliable authority, with corresponding thermal efficiencies approaching 30 per cent, are nothing short of wonderful for such high-speed engines, and judging by the performance of other classes of engines and by the thermodynamics of limiting possibilities, little more can be expected. What must be sought for here is, therefore, not an improvement of the best, but a general raising of the poorer ones to level of the best, and the maintenance of the high test value in actual-service flight. In this prime factor, as in that of mean effective pressure, the fixed water-cooled cylinder has a demonstrated superiority, while the least favorable is the rotating air-cooled. The difference between the best and worst is very large indeed.

Comparison of engine results with each other, especially when it is not possible to divide overall results into contributing factors, can give no information as to how far it may be possible to further improve engines. It merely indicates which is the better, and may throw some light on type availability, as, for example, the fuel consumption of two-cycle engines must always be greater than four-cycle, if each is equally well designed; or again, air-cooled engines may or may not have as high a mean effective pressure as water-cooled.

Thermodynamic standards of comparison do indicate goodness more absolutely, and these are now in general use in engineering practice. Accounting for and eliminating operative conditions, such absolute standards illuminate the goodness of the machine with reference to the execution of its basic process. Such, for example, is the case with steam turbines, the performance of which is compared with that of the Rankine cycle as a standard, for equal initial and terminal conditions of pressure, temperature, and steam quality. It is also the case with internal-combustion engines of the classes that have really been subjected to any reasonable degree of investigation which are judged by the Otto and Diesel gas cycles. But the aero engine has not as yet been so studied. According to this method equations are derived from a study of the ideal Otto gas cycle for thermal efficiency and mean effective pressure. Thermal efficiency, for example, referred to indicated horsepower is found to be a function of the amount of compression only, and given by the following equation, in which the subscript (*b*) refers to the condition after, and (*a*) to that before, compression:

$$E=1-\left(\frac{V_b}{V_a}\right)^{\gamma-1}=1-\left(\frac{P_a}{P_b}\right)^{\frac{\gamma-1}{\gamma}}=1-\frac{T_a}{T_b}$$

Comparing this with the thermal efficiency of an engine of known compression results in an efficiency ratio, and in Table VI are given some values for aero engines, computed with what data are available and certain assumptions noted. As the fuel consumption per brake horsepower-hour is the only experimental quantity beside the compression, the factor includes all losses, both mechanical and thermal, which former should really be separated out.

Similarly, mean effective pressure can be shown thermodynamically to be not only a function of compression, as is efficiency, but also of the calorific value of the mixture, the negative work and suction heating or volumetric efficiency. As these effects are not separately known, and as all aero engines work on gasoline, although benzol is also used in Germany, and are capable of making and using the same calorific power mixtures measured at 32°, and one atmosphere, this factor disappears as a variable, and becomes a constant 103 British thermal units. The equation then takes the following form:

$$(m.\ e.\ p.) = 5.4 \times 103 \times \left[1 - \left(\frac{P_a}{P_b}\right)^{\frac{\gamma-1}{\gamma}}\right] = 556.2 \times E$$

Comparison of this computed result with that measured by test gives the diagram factors of Table VI, including all losses due to every cause. Comparison of the diagram factor with the efficiency factor for each engine indicates whether or not the interferences affecting one are greater than those that affect the other. For example, two engines might have identical efficiency factors and yet one may heat the charge much more than the other with a lower volumetric efficiency. This one will have a very much lower diagram factor than the other, or otherwise the ratio of efficiency factor to diagram factor will be different, and such is the case in general, comparing air-cooled with water-cooled engines, especially if the former are of the rotating cylinder heated crank case sort.

TABLE VI.—*Diagram factors and efficiency ratios.*

Class No.											
I.		II.				III.		IV.			
Cylinder crank arrangement.											
Fixed in line of 1 cylinder.		Fixed V?, 2-cylinder crank.				Rotating.		Fixed star.			
Cooling.											
Water.		Air.		Water.		Air.		Air.		Water.	
Engine or maker.											
Benz.						B. M. & F. W.		Nieuport.		Salmson.	
P.	E.	P.	E.	P.	E.	P.	E.	P.	E.	P.	E.
Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.
106.9 .353	0.29 .630	....	....	....	....	66.6 .222	0.16 .348	....	0.17 .370	78.2 .260	0.224 .487
Daimler.						Gyro.		1911 Anzani.			
103.5 102.0 .345 .340	0.27 .28 .587 .608	....	....	....	....	76.9 .256	0.17 .370	79.6 .332	0.20	....	....
Daimler.						1911 Gnome.					
107.1 107.1 .357 .357	0.27 .26 .587 .565	....	....	....	....	66.9 65.4 .223 .215	0.17 .370	....	....	....	....

TABLE VI.—*Diagram factors and efficiency ratios*—Continued.

Class No.											
I.		II.				III.		IV.			
Cylinder crank arrangement.											
Fixed in line of 1 cylinder.		Fixed V?, 2-cylinder crank.				Rotating.		Fixed star.			
Cooling.											
Water.		Air.		Water.		Air.		Air.		Water.	
Engine or maker.											
N. A. G.											
P.	*E.*	*P.*	*E.*	*P.*	*E.*	*P.*	*E.*	*P.*	*E.*	*P.*	*E.*
Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.	Diag. fact.	Efficiency ratio.
101.0	0.28										
94.0	.26										
.337	.608										
.316	.565										
Angus.											
106.5	0.26										
107.0	.23										
.355	.565										
.337	.500										
Austro Daimler.											
94.0	0.26										
.31	.565										
Cheno.											
103.6	0.229										
106.5	.253										
Wright.											
80.2	0.182										
.267	.417										
Green.											
77.0	5.23										
.258	.504										

NOTE.—*E.* is thermal efficiency referred to brake horsepower and *P.* is mean effective pressure pounds per square inch referred to brake horsepower.

On account of lack of sufficient data for individual engines, a compression ratio of *1:4.5* has been assumed for all engines, equivalent to an air card efficiency of *48.0* per cent and theoretical *M.E.P.*=*300*.

These figures, which should throw so much light on performance, are, as a matter of fact, of but little value because of the absence of accurate data, especially on compression and engine friction, both mechanical and fluid. They are, however, given to illustrate the method of judging by thermodynamic standards rather than by simple comparison of engines one with the other, in the hope that in future tests such data will be obtained as to make possible the determination of both diagram factors and thermal efficiency ratios.

Continuity of the operation of mixture treatment in the cylinder is dependent on the maintenance of a steady state as to temperature of the metal parts, and this is possible only by a cooling system of considerable complexity from the thermal standpoint, however simple the apparatus may seem, superficially examined. Cooling for the maintenance of a steady state of temperature in the metal parts is not of itself sufficient, as the parts must be held to a low limit of temperature, which requires a definite heat conducting and dissipating capacity in proportion to the heat receiving capacity of the part. This limit of allowable temperature is imposed not only by the requirements of the charging and compression functions but is necessary for other reasons. If metal parts become too hot oxidation sets in, stiffness is reduced, and deformation, both the temporary sort resulting from expansion and the permanent sort due to molecular rearrangements, becomes troublesome. Cylinder lubrication is also dependent on the temperature of the metal surfaces, of piston barrel exterior and cylinder interior, which, if too high, prevents any oil remaining without destructive distillation or carbonization, or impairs its lubricating value by excessive reduction of viscosity.

Heat is received by all metal parts in contact with the hot gases and these parts include the cylinder head, inlet and exhaust valves, the walls of any valve pockets, the igniter plug, the piston head, and the whole interior of the cylinder wall exposed at the end of the outstroke. The heat received by the cylinder proper is greatest for the part exposed during the first part of expansion just following explosion, and extremely hot gases are in contact with the whole interior of the clearance space. In addition, heat is given up by burnt gases escaping through the exhaust valve and ports to the valve and its stem to the stem guides, port walls, and connecting parts of the cylinder head or the side pocket that carries the exhaust valve.

Heat received from hot gases must be conducted through the metal by more or less devious and rarely straight paths to the external surfaces of the metal walls from which heat may be abstracted. The first means of abstraction from the exterior faces of the walls is air in motion, induced or driven by a fan which may be separate, or the propeller itself. In some cases the free air moving past with the velocity of flight is relied upon, but the most unique arrangement is that of the rotating cylinder cooperating with the free air movement. The second means of abstraction is water or oil, or in general a liquid circulated by a pump, first over the heat receiving walls and then through the radiator where the free air again takes it up with or without the assistance of a fan. A third method, as yet used in very few aero engines, though frequently used elsewhere, is the boiling water jacket, noncirculatting, with an air cooled steam condenser and condensate return. In any case the ultimate disposition of the heat is to the free air, and when liquids are interposed as carriers it is with the idea that some good results will follow what appears to be at first an indirect method. The only sort of good result that would be worth while is a better abstraction from heated walls in steadiness and degree, and that such is the case is unquestionable, not only on rational grounds, but by experimental demonstrations.

Whenever heat is to pass between a fluid and a body of metal, it has been established that a layer of fluid adhering to the metal as a film acts on the heat flow as an insulating layer. The thickness of this dead fluid film, and therefore its thermal resistance, depends on the condition of fluid motion, or, as it has been termed, on the scrubbing action. High velocities always reduce the film thickness and the thermal resistance. The thermal resistance (reciprocal of the conductivity) of gases and, therefore, of gaseous films of given thickness, is of the order of magnitude of 1,000 times that of metals and 10 times that of liquids and the thermal resistance of liquids 100 times that of metals.

Heat flowing from hot cylinder gases to the air directly must, therefore, pass through a complex path of at least three parts, a dead gas film on the inside walls of the cylinder, the metal wall and a second dead gas film on the outside. When a circulating liquid is introduced the path is more complex, consisting of a dead gas film on inside cylinder walls, the metal walls, a liquid film outside the walls, a second liquid film on the inside of the radiator, jacket, or water pipe walls, and finally a second gas film on the outside of radiator jacket or pipe. Each of these elements of the heat path exerts a thermal resistance to heat flow, and the resistance of the whole path is the sum of the separate resistances.

Heat flows according to a law similar to Ohm's law for electricity, inasmuch as the flow varies directly with the difference of potential or temperature, and inversely as the resistance. Therefore, over any complex path, consisting of several parts each of different resistance series as the same quantity of heat is passing through all, the whole temperature drop is divisible into partial temperature drops in the proportion of the partial resistance to the whole resistance. The resistance of any one part of the path is inversely proportional to the conductivity of the substance, is directly proportional to the length of path in the direction of heat flow, and is inversely as the cross section of path at right angle to the heat flow. Accordingly the temperature drop through a gas film is almost a thousand times as great as through a metal wall of equal thickness, and the drop through a liquid film also of the same thickness would be about ten times that through the metal. Gas film thicknesses and thermal resistances on the interior of the combustion chamber, because of lack of circulation there, must be fairly thick and so highly resistant. These interior gas film resistances must be much greater than the air films on the exterior where air is blasted over surfaces and very much more in turn than the resistance of films of liquids circulating over those exterior surfaces. Of all the temperature drops, by all odds the least is that through the thin cylinder walls when the flow is direct.

The object of the design of the cooling system is to keep the interior metal walls as cool as possible, and these walls will be cool in proportion as the thermal resistance of the heat flow path is greatest on the side of heat reception and in proportion as the resistance on the outside is small and the heat flow path through the metal short, or in the event of this being impossible then of equivalently larger cross section.

By reason of the fact that they normally work at or nearly at full power and at such high speeds, aero engines develop more heat per square inch of wall interior than any other class of internal-combustion engines of the same bore, and it is an open question whether cylinder bore has much, if anything, to do with this quantity. Cooling must, therefore, be more effectively provided than in any other similar engine, so that careful study of heat flow conditions should be well repaid in improved results, both as to maintenance of high power and reliability. While considerable advance has been made in this direction it is more concerned with general system than with details. The literature, for example, is full of controversial matter on air cooling versus water cooling, on the relative merits of air blasted fixed versus rotating cylinders, and such matters of general arrangement, but there is a general lack of attention to the rational thermal analysis or design of the heat flow path for control of its resistances and temperature gradients.

Cooling of cylinder-barrel walls is perfectly easy by either air or water, but to get air cooling as effective as water the air must circulate many times faster than the water, which is quite effective, whether it has any material velocity or not. Extension of exterior surface is, of course, a direct and rational means of reducing the necessary air velocity to secure a rate of heat abstraction that will keep the temperature of the metal walls much nearer to that of the circulating air than to the interior hot gases. Such ribbing is quite unnecessary with water or oil in jackets as the rate of abstraction by this medium of higher conductivity is so high that no more abstraction surface is required than that receiving heat to keep the metal at a temperature very close to that of the liquid.

Difficulties of cooling begin only on the irregular parts and increase with their irregularity or thermal isolation from heat dissipators. The first irregular element met is the cylinder head or side valve pocket. This receives heat over the whole interior, including the valve faces, and also from the walls of the exhaust port. It can not be of uniform metal thickness, and by reason of valve seats and ports the metal heat flow path can never be of uniform length, so it is to be expected that however uniform in temperature the interior of the smooth cylinder barrel may be no such condition can apply to heads or valve pockets. The intake port and valve, with its stem and stem bearing, are coolers and need no other cooling than is available from the incoming charge, especially when the mixture carries some liquid still to be vaporized. It is this inlet self-cooling that is responsible in part for lowered volumetric efficiencies, so the heat exchange here that helps in one direction is harmful in the other.

Exhaust ports, whether cast in or welded to sheet metal or screwed into machined seats, can not be too well cooled, because they start at the exhaust valve seat, at which point heat is received on both the port side and combustion chamber side. Exhaust ports also carry the stem bearing of the exhaust valve, which is the only means of disposing of the heat received by the valve itself on either side. For the amount of heat received and to be disposed of, without undue localized rise of temperature at the exhaust valve seat, these exhaust ports of cylinder heads or valve pockets are normally not cooled sufficiently. Increased metal cross section and metal extensions to jacket or air blast spaces would naturally assist. Still worse in many engines is the condition of the exhaust valve receiving heat on both sides and with no source of dissipation except its stem and the stem bearing. These stems should have a large metal cross section, and the metal should be of as high conductivity as possible, while the joint from valve stem to disk should be of long curve and the disk of increasing thickness toward the center to further promote conducting capacity. The stem bearing can hardly be too big or long nor too well cooled by sufficient metal and heat dissipating surface, but heat transfer from the stem to the guide bearing can hardly be expected without an adequate oil film, because a dry stem means a gas film of so much greater thermal resistance than oil as to render useless the large metal cross section and surface. To hold oil in such a stem bearing without an elementary stuffing box is, of course, almost impossible, but though such a device is not used, it should be added to replace the present two diameter stems now in use for this purpose. It requires only a casual survey of the illustrations of aero engines to see how different is the means for head cooling and expecially that of the exhaust valve, its seat, stem and port walls, and how easily, therefore, distortion of the metal parts may occur, due to unequal expansion, resulting possibly in breakages but certainly, when valves and seats are involved, in serious leaks which, once started, especially at exhaust valves, rapidly increase by the high erosion influences.

Probably the worst cooled part, aside from the exhaust valve, is the piston head, which receives heat over its whole top surface, equal to the area of the cylinder bore circle at least, and more if arched upward or dished down, as may properly be done, especially the former to give it some stiffness and elasticity in thermal expansion. This heat, while imparted in small part to the crank case air, must largely and almost wholly be disposed of to the cylinder walls by a radially outward conduction across the head, followed by conduct down the piston barrel, thence across an oil film to the cylinder walls. By increasing the metal thickness of the piston head regularly from the center outward in proportion to the square of the radius, its heat carrying capacity could be made proportional to the receiving surface above. Then by suitably thickening the upper barrel the axial heat carrying capacity can be made great enough to take what is delivered by the outer ring of the head and conduct it down for the oil film to be taken up and transferred to cylinder walls. This last transfer is most effective the longer the piston and the better the oil film, and as it is thus disposed of the thickness of barrel may be reduced. Such additional piston metal to secure an adequate heat carrying path will be least the greater its thermal conductivity, and there is no reason why suitable carrying capacities should not result without undue weight. Examination of the illustrations will indicate that apparently the idea of most of the designers has been to use as thin, and uniformly thin, metal as possible with no thought of heat conductivity whatever, though a few give evidence of some grasp of the problem. An exception to the overheated piston is found in the rotating cylinder engine that carries its inlet valve in the piston, which in this case is adequately cooled, but at the expense of volumetric efficiency. There is no reason, should thick metal pistons prove objectionable, why air blasts should not be introduced directly under the pistons except the consequent evaporation of lubricating oil.

Piston heads that are very unequally heated or very highly heated are subject to a considerable expansion and to oxidation as well, besides being responsible for decreased volumetric efficiency and preignition or lowered compression. Excessive and variable expansion of the head besides resulting in permanent deformation or cracks will cause the piston to bind on the cylinder unless cut away or given extra cylinder clearance. If sufficiently cut away to give relief, leakage is promoted, which defeats lubrication, and the oil film, which is an essential part of the thermal path from piston to cylinder, is destroyed and overheating accelerated. Some little clearance, and more at the top than along the barrel, is necessary, but the less the better, and the better the cooling of the piston head whether by conduction across it and down the barrel or through separate conduction bars, directly from head center to barrel and to oil film, the less clearance will be necessary. A photograph is given in a German report of a piston that failed from overheating, and such failures seem to be frequent. There is also shown a burned spark plug, which should be cooled just as well as other parts to prevent excessive temperature rise, though its end must be warm to promote cleanliness, but not so warm as to make an incandescent spot, or to cause destruction.

Cracked cylinders are also more or less common from unequal cooling, and in both the German and the British Alexander tests such cases are reported. In the latter the fact that the cylinder ran 11 hours before failing proves the crack to be not due to any gas-pressure stress. This unequal cooling or heating may be due to uneven thicknesses of metal or to unequal heat abstraction, as would occur in water jackets with steam or air pockets, or to the impact of the air blast from the propeller on the front side of a forward cylinder. Rotating air-cooled cylinders and, in fact, even fixed air-blasted cylinders can not be equally cooled because it is quite impossible to force equally cool fresh air at equal velocity around the whole cylinder, no matter how many baffles or guides are used, and this inequality must promote distortion. One compensating element used, that of eccentric ribs giving more surface for heat abstraction on the side of least air activity, is ingenious, probably more so than effective. There seems to be no hope whatever of air cooling ever being made as uniform as with water, and therefore more distortion effects are certain in air-cooled engines even though, by the use of excessive quantities of air and fan or windage power, the walls could undoubtedly be kept as cool as with water, it could not be a uniform cooling, and hence not as desirable. In the German test report the windage of the Gnome rotating cylinder engine is given as 8 per cent of the output, which checks exactly the value given by Winkler for the Renault fixed-cylinder engine fan power.

Water gives control of temperature in degree as well as uniformity, for with sufficient radiator capacity the water temperature entering jackets can be kept only a few degrees above that of the free air. By sufficient circulating-pump capacity the delivery temperature from the engine jackets can be kept as near the inlet temperature as may be desired. On the other hand, should the engine be found to work better with warmer water, or if radiator size is to be minimized, and the advantage be regarded as greater than a warmer engine, this can be accomplished by reducing radiator size with corresponding rise of temperature of water inlet to engine without in any way affecting the uniformity of heat abstraction from the engine metal. The limit of this occurs when the jacket water is allowed to boil, as in the Antoinette, in which case the radiator becomes an air condenser and very small because of high temperature difference between steam (212° F.) and the free air. Higher temperatures than this can be secured by the use of oil in jackets, as is done in some farm tractors to further reduce radiator size, and such oil has the advantage of not freezing.

Piston-cooling effectiveness is more or less measured by the limiting diameter that is operative, and the tendency to use multiple cylinders of small diameter, especially in the rotating air-cooled engine, which go as high as 20 cylinders per engine, and to keep their cylinder diameters less than 5 inches, can be traced directly to this. Even with water-cooled engines a limit is reached, dependent entirely on this piston-cooling factor, and larger cylinders than are now used require better cooling of the piston by the methods indicated.

Temperature expansion stresses added to those imposed by gas pressures and mass motion forces have never yet been successfully attacked by the stress analyst, but even if they could be treated mathematically it would help but little when the temperature in the various parts of the metal structure are unknown. No class of machine except the large internal-combustion engine suffers so severely from these temperature conditions as aero engines, and in none is the consequence of failure likely to be so serious. This new and difficult problem must be attacked patiently and systematically by experimental research if any but accidental or haphazard results are to be attained. Pending such needed fact data on temperatures and temperature gradients and on the effects of mean temperature or temperature differences on volumetric efficiency, on limiting compressions, on metal expansion, on permanent distortion, or on corrosion, the best that can be done is to use that method of attack that promises best results in uniformity of cooling and in low mean temperature. This undoubtedly involves the use of liquids as heat receivers from the metal walls, but just as surely demands proper arrangement of metal parts for promotion of heat transmission as uniformly as possible through the several parts.

Lubrication as a process is of considerably greater importance and significance in the aero engine than in any other, for while it has but little direct relation to the power weight ratio, it has an indirect one and, of course, bears directly on reliability, constituting probably the most important element of this factor. The indirect relation of lubrication to the power weight ratio results from the use of unusual metals at bearing surfaces, especially cylinder versus piston, adopted for reduction of metal volume, and bringing cast iron and bronze against steel, and even steel against steel. Lubrication is also as pointed out previously, a factor in cooling when the heat dissipation path includes an oil film surface, maintenance of which reduces heat resistance to a proper value, but loss of which results in overheating of the parts that are thus thermally isolated. Not only is the lubrication of the aero engine peculiar in these two respects of unusually difficult metals to be lubricated, and heat conductivity function in addition to that of lubrication, but in other respects as well. Maximum compactness in the interests of low weight leads to the use of small bearings and as high bearing pressures as may be feasible for the very high speeds in use. In the case of rotating cylinder engines any change in angular velocity produces piston side thrust loads, not found in any other machine and these may be extremely high, so high as to even bend the cylinders as cantilever beams if the acceleration, positive or negative, is large. All aero engines have closed crank cases and these must necessarily get very warm, largely from heat received from the underside of pistons, but also from the whole side of the piston barrel and the exposed cylinder wall. The cylinder wall is hot by reason of the heat being conducted through, so that the viscosity of the oil on it is reduced just about to the limit. In the hottest region near piston heads, and even in some cases in other parts as well, the cylinder oil suffers decomposition changes, due to the heat, as is proved by the progressive loss of lubricating value of oil in circulating return systems. Not only is the oil subjected to variable and high temperatures, but it must be of such character as will not leave excessive carbon residues in the combustion chamber when it works past pistons, but must vaporize on the hot surface with least carbonization. Coupled with these high interior temperatures of the aero engine are possible excessively low temperatures of the surrounding air, freezing temperatures in high altitudes being rather the rule than the exception, and yet immediately before or after, the machine may be close to the earth where the temperature in summer may exceed 100 degrees.

It is clear that aero engine lubrication is not only more important as a process than in other classes of engine with reference to need and consequences, but is very much more difficult on account of the excessive heating, even when the engine is built of the standard materials of internal combustion engine practice, i. e., cast-iron piston on cast-iron cylinders, but is doubly difficult when steel is substituted to reduce metal volume, so it is natural to find new elements of practice introduced.

Crank shaft and crank pin bearings of aero engines offer no more difficulty on aero engines than on others, provided the bearing pressures imposed by the designer in an effort to cut down material are not excessive and provided the surrounding atmosphere is not hotter. The necessity for crank cases imposed by the presence of dust in the air at landing and starting points, does make the atmosphere surrounding these bearings abnormally hot, especially when the pistons are inadequately cooled as is more often the case than not. This hot atmosphere created by hot pistons and conserved by the closed crank case naturally raises main and crank pin bearing temperatures to some value higher than the crank case air, fixed by the heat generated in them by friction, and so reduces oil viscosity correspondingly. This would seem to be sufficient reason for using lower bearing pressures or larger surfaces than in auto engines, for example, and this conclusion is reenforced by the fact that the bearing surface speed is so very high and continuously so. Instead of larger main and crank pin bearings, the aero engines so far developed usually have equal or smaller ones than automobile or boat engines. No matter how elaborate the oil-feeding system nor how carefully the grade of oil may be selected, this practice can not be accepted until it has been more fully demonstrated than has yet been done, that it is necessary.

Piston and wrist pin lubrication present still greater difficulties, and no new methods of lubrication are available beyond the supply of excessive quantities of oil to these surfaces. As already pointed out, aero-engine pistons are hotter than those of other engines because of the higher speed and consequent greater heat quantity per minute taken up by the pistons, and also because these are of thinner metal and so can not dispose of their heat so readily to the cylinder walls. This is further aggravated by the shortness of the pistons, which in some cases are hardly more than two-thirds of a diameter in length, though Winkler recommends 1.1 diameter, while stationary-engine pistons are regarded as requiring a length of two diameters. Such short pistons reduce the heat dissipating cylinder contact surface, but also increase the side-thrust pressures. They tend to cock sidewise, especially when made loose to relieve expansion, and so concentrate side thrust at the ends instead of distributing it over the already too small surface. In the rotating cylinder engines additional side thrust of almost any amount may result from variations of angular velocity if sudden. Under such high temperatures and high side pressures, perhaps badly distributed, the viscosity and lubricating value of most oils falls very low and the decomposition conditions are approached with production of light constituents that evaporate and of tar or carbon constituents that stick. Yet in spite of this the speed of the rubbing surfaces is so very high as to require lower surface pressures and temperatures rather than higher. Mean piston speeds are never under 1,000 feet per minute, a high limit for good stationary-engine practice, and even exceed 2,000 feet per minute.

To still further aggravate this piston-lubrication condition, steel pistons have been introduced against cast-iron cylinders, steel cylinders with cast-iron pistons, and steel pistons against steel cylinders, again in the interest of reduction of metal volume, though nowhere in engineering practice has there been any success in lubricating such surfaces, especially when very hot.

The fact remains, however, that these aero engines do run, but the absence of sufficient reliable data extending over years of experience, commensurate with that on which present standards of internal combustion engine practice rests, makes it a source of wonder whether the lubrication of aero engines at present is wrong and bad, or whether on the other hand they have taught old practice something new. About all that can be said at present, however, is that many aero-engine failures traced to lack of lubrication are recorded; that the oil comsumption of these engines is very high, in some cases reaching half the weight of fuel; and finally that the greatest caution should be observed in following present methods. At the same time, the construction of engines to operate cooler at lower bearing surface pressures and with parts of successively different materials should be undertaken for test data. Each new combination should, be experimentally tested to destruction with decreasing quantities of selected but different oils to definitely settle this question in the laboratory.

As to details of method of application of oil, there seems to have been developed some more or less general practices. All rotating cylinders are lubricated by crank-case sprays, which in the case of those taking the charge through the crank-case involves the carrying of appreciable quantities of oil into the combustion chamber where it burns, at least in part. This is practically equivalent to the splash system for fixed cylinders, which for auto engines has proved only moderately successful and for aero engines is quite unsuited. All fixed-cylinder engines use forced lubrication for main and crank-pin bearings, through hollow or drilled shafts and cranks, the pressure being developed by pumps, many of which have failed even during competition tests. Normally these fixed-cylinder engines have crank-case oil tanks at the lowest points, often, though not always, carrying here all the oil supply for a full length run of 10 hours or more, as a means of preventing solidification of oil under low-air temperatures, and with all or most of the distribution pipes inside the crank case for the same reason, sometimes substituting cored or drilled passages in the casting for pipes. These pump-forced feeds are so far all of the central system, one pressure supply, sometimes with a duplicate in reserve, being provided with multiple outlets, which has an element of danger, because tight bearings needing most oil receive least in proportion to the loose bearings which, offering less resistance to oil escape, tend to take it all. There are three typical pump systems: First, complete circulation of the whole supply to bearings with gravity return to sump and pump; second, direct feed of fresh oil from pump with no return; and third, combinations of this with two pumps, one for fresh and one for circulating oil, discharging into common bearing tubes or into separate ones. Any circulating oil system requires a cooler, and the exposed crank-case sump surface is sometimes relied on, sometimes supplemented by air-circulation tubes or by carrying the oil supply to exterior cooling surfaces, and as a rule this oil cooling is made complementary to carburetor mixture or air warming, by passing one in thermal contact with the other. As a rule cylinders and wrist pins are lubricated by the oil escaping from main and crank-pin bearings, but considerable modification of details is found, and reference is made to the papers and reports reproduced in the appendix. Among these that of Benderman, reporting on the second German ocmpetition, is so good that it is worth quoting.

Lubrication.—The amount of lubricating oil required is affected by the system of lubrication and the circulation of the lubricant. The lubricant of an aeroplane engine should not only reduce the friction between the parts which are in sliding contact, and not only remove the frictional heat, which is considerable, due to high bearing pressure, but in many cases it also has to cool the piston heads. The oil is largely lost without doing any work. It works past the piston into the combustion chamber and there fouls spark plugs and valves. This, of course, can not be avoided altogether, but it may be minimized by guards at the cylinder ends and by positively feeding the oil to the wrist pins. Much oil escapes in the form of vapor and fog through the ventilating funnels (breathers), which equalize pressure or vacuum in the crank case without allowing the oil to squirt out or dirt to enter. If these breathers are made long and exposed to the air blast the oil vapor will condense in them and distant places, such as the cam shaft above the cylinders, may thereby be lubricated in place of the hand lubrication.

The loss of oil by leaks in the casing depends on the number and kind of the joints. Especially the guides of the valve tappet rods throw out a great deal of oil. It will, therefore, be well to keep their diameters at the place where they emerge, small. In one motor the tappets are nearly surrounded by the ventilating pipes (breathers), which direct the oil coming back to the crank case.

The lubricating qualities of the oil decrease with increasing temperature. Therefore rapid circulation of the oil in the bearings subjected to high pressures is required; also sufficient cooling in a spacious oil pan, preferably with cooling tubes. At high temperatures as tables 5 shows, castor oil is considerably more viscous and effective than good mineral oil. It, therefore, so far can not be done without in air-cooled engines. For water-cooled engines one of the two mineral oils mentioned was always satisfactory during the competition.

The most simple system of oil distribution is the so-called splash system (very imperfect). The fresh oil supplied from outside or the storage oil collecting in the crank case is whirled around by the rotating and reciprocating parts and is thus intended to get to the proper places. This means that considerable excess of oil is required; the losses are considerable. Engines lubricated in this way usually have a smoky exhaust.

More advantageously the oil is positively conducted by a distributing line to the fixed bearings, and from there as far as possible without loss conducted to the connecting rod ends and to the rubbing surface of the piston. This is best effected by full oil throw rings on the crank and a pipe connection between the ends of each connecting rod. In some cases the oil throw rings are only partially executed and are partially replaced by turned grooves in the side of the crank. These catch the oil, which, after leaving the bearings, runs along the side of the crank.

In other cases the oil conducted to the crank bearing is forced into the interior of the crank shaft and from there under the influence of centrifugal force runs to the connecting rod ends. On the way into the shaft it has to overcome centrifugal force. That requires very neat bearings and at times high oil pressures. Piston force pumps in this case are to be preferred to gear pumps. The positive supply to the wrist pins permits the most complete utilization of the oil. The lubricating oil consumption is reduced and a supply for several hours may be provided in the moderately enlarged crank case. If the crank case should be too small, a pump for fresh oil has to replenish the supply from without. The fresh-oil pump may either discharge into the circulation line or may feed a special distribution net, separated from the closed-circuit line. This, however, is hardly advantageous, since the required small make-up of fresh oil, should the closed circuit fail, does not suffice to keep the engine running for any length of time. Special attention must be given to the fact that the oil in cold weather becomes so thick in exposed pipes that a dangerous lack of oil will be the result and the bearings will melt.

The circulating oil becomes polluted by metal dust and deposits of combustion. Small particles, however, do not matter; larger ones may be kept away from the pump by brass screens. In the engines tested these screens were not always well accessible. From the fine carbon particles which the circulating oil carries with it after a certain length of time, the bearing metal receives a grayish look, but its durability is thereby increased.

The oil pump is connected by a short suction line with a point of the case located so low that in all inclined positions of the engine it is covered by oil. The lubricating oil, which is very thick at low temperatures, renders the design of the oil pump very important. All automatically operated parts, such as valves with springs, and such, easily fail, and therefore are to be avoided.

Part 2 (b).—GENERAL ARRANGEMENT, FORM, PROPORTIONS, AND MATERIALS OF AERO PARTS—POWER-WEIGHT RATIO, RELIABILITY, AND ADAPTABILITY.

If in every cylinder the same mean effective pressure were obtained, and if all cylinders weighed the same number of pounds per cubic foot of displacement per stroke, including their attached valves, rods, pistons, wrist pins, and connecting rods, then the weight per horsepower of engine at the same engine speed would depend on the frame and shaft weights per cylinder which is a result of the general arrangement. If at the same time the thermal efficiency of all engines were the same, the added weight of fuel and tanks per horsepower would be the same for all. Differences in weight per horsepower of engine proper and of engine, oil, fuel, radiator, and tanks taken together are considerable, the heaviest being more than twice the weight of the lightest even for short runs, and the excess is more than this for the longer runs. The basic causes for such differences can be reached only by analysis along these lines, and such analysis will indicate that as many of the elements of actual difference are accidental or incidental as are essential or inherent in arrangement, form, proportions, or material.

The influence of arrangement to be first examined is in some cases quite clear and in others complex. Where, for example, arrangement of cylinders in number and position has no effect on the limiting speed, on the mean effective pressure, on thermal efficiency, or on the weight of cylinders complete per cubic foot of displacement per stroke, then the effects of arrangement are clear, qualitatively. The contrary is the case when a given arrangement that gives reduced frame and shaft weight per cylinder as compared with another also requires heavier cylinders, or is limited to a lower speed, or is incapable of any but a low mean effective pressure, for here the result depends on the degree to which one factor compensates another.

Differences in arrangement are more bold and numerous in aero engines than in any other class, and some of them are quite unique, yet with these truly remarkable differences that are quickly grasped by a reference to the illustrations in the appendix, the surprising thing is not that the weight per horsepower varies considerably with arrangement but that it does not vary even more. This is an indirect proof of the existence of these compensating factors, and shows that arrangement has not as great an effect on weight per horsepower as might at first be expected. Air cooling versus water cooling is a fair illustration of this, for elimination of jacket, radiator, and pipe metal and of water reduces weight, of course, but the result is usually a lower mean effective pressure and thermal efficiency. Again, the rotating cylinder air cooled as compared with the fixed cylinder, while eliminating fans and rib casings, adds a windage power requirement, must have steel cylinders to avoid the uncertainty of casting soundness in resisting the great centrifugal forces, and so must use excessive quantities of oil, which has to be carried.

Ignoring for the present those compensating differences and concentrating attention on the effects of arrangement alone, it is clear that two similar cylinders set side by side, each developing the same power and of equal thermal efficiency, will not require shaft and frame weights twice as great as one. Adding a third is equivalent to placing between the frame and shaft ends an intermediate piece without ends, and hence of less weight, but each cylinder added, beginning with the fourth, adds exactly the same frame and shaft weight as the third, and therefore has very little influence on weight per horsepower, unless other modifications are introduced, such as casting two cylinders en bloc, removing main bearings between alternate cranks, and thickening of frame and crank shaft to meet the stresses introduced by increased lengths. Therefore multiplication of similar cylinders along one line reduces weight per horsepower fast at first, and beginning with four rapidly less, and beyond a certain number of cylinders the weight reduction is more or less equalized or overbalanced by the necessity for greater metal cross-sections per foot of length in shaft and frame. To illustrate the point, a given style of boat engine having the same cylinder on engines of one, two, three, four, and six cylinders in line is selected, as no other class of engine covers such a wide range of number of identical cylinders. For one size of cylinder the single-cylinder engine weighs 472 pounds, and the two-cylinder engine 626 pounds, the second cylinder having added 154 pounds, or 33 per cent. The third three-cylinder engine weighs 716 pounds, so that the third cylinder has added 90 pounds, and each additional cylinder also adds the same 90 pounds up to six, the weight of which is therefore that of the two-cylinder engine, 626 pounds, as these are retained for ends, together with the weight of four cylinders of 90 pounds each between, or $360+626=986$ pounds. The corresponding weights per horsepower have the following relation, taking that for one-cylinder engine as unity, the numbers representing 1, 2, 3, 4, and 6, respectively, are 1, 0.52, 0.40, 0.335, 0.274. The fact that each intermediate cylinder has added exactly the same weight in this engine indicates that shaft and frame weights per foot have also remained constant, but in some cases, and properly, these are made heavier in passing, for example, from four to six cylinders, so that the small reduction in weight per horsepower above 5 per cent of the weight of the single-cylinder engine is lost entirely, and the six-cylinder would be no lighter than the four per horsepower.

Further weight reduction by arrangement alone is available with multiplication of similar cylinders, not in line axially in a plane passing through and including the shaft, but radially about the shaft in a plane at right angles to it. Two cylinders with axes in line and with connecting rods working on one crank pin, constituting the two-cylinder opposed engine, or two cylinders with axes at right angles also working on one crank constituting the right-angled V engine, add no frame weight for the second cylinder over what the first requires. It really reduces it by the metal required to cover the bore hole, except for some thickening at the joints. Nothing at all is added to the shaft weight except when the crank pin is made longer, as is rarely the case. This arrangement gives a greater gain in weight per horsepower than two cylinders in line, but when the second cylinder is added radially in another plane and has its own crank it should result in a weight exactly the same as for two in line, because the difference is merely one of rotating one cylinder with reference to the other, retaining the same metal throughout.

These are the two fundamental arrangements of multicylindering for the standard piston-connecting rod-crank engine, and so long as the cylinders remain fixed there is no reason why each cylinder in any combination should not weigh the same and give the same mean effective pressure or thermal efficiency as any other. In this case the weight per horsepower of engine and plant is less the more the cylinders are multiplied and the more the multiplication takes place radially around one crank rather than with separate cranks, up to the point where the shaft and frame thickening must be so great as to compensate for reductions, which begins to be appreciable at four cranks and is very marked at six, except as other details may modify the result.

Fixed-cylinder multiplication radially about one crank presents no objectionable features until the cylinders become inclined differently to the normal horizontal plane, when there enter lubrication difficulties on cylinder-piston surfaces, especially when cylinder heads are lower than the crank shaft. The tendency for oil to work past the piston into the combustion chamber, fouling spark plugs or carbonizing the interior and requiring more oil to keep the surface properly wetted, is strong enough when the head is directly above the shaft, but is stronger when it is lower, and doubly so when the head is directly below. This has prevented the general adoption of any radial arrangement about one crank beyond the horizontal opposed and the 90° to 45° V, set with equal angles to the horizontal. Any more than two radial cylinders compose unequal angles and involve different tendencies to oil flow toward heads in each, so while multiplication in this direction promises greater weight reduction than in line with a crank to each cylinder, the latter has been carried farther in point of general adoption.

The four and six cylinders, each with its own crank, are standard, and doubling the rows of cylinder axes in line without changing the cranks gives the 8 and 12 cylinder opposed, the former used a little, the latter not at all. It also gives, when axes are inclined, the 8-cylinder V, a much used standard, and the 12-cylinder V, but little used so far, but possessing advantages that are promising.

Radial disposition of fixed cylinders which should give the greatest possible weight reduction in frame and shaft has a few representations, notably the air-cooled Anzani, which uses three or five cylinders in one plane on one crank and then duplicates on successive cranks until the 200-horsepower engine is reached, which has 20 cylinders in four planes of five stars each, and five cranks. It is the operation of this and similar engines and of the bold departure of the German Daimler inverted cylinders (Bendeman report), with heads directly under cranks, which makes it doubtful that the old conclusion that such arrangements must lead to fouling is really valid. This latter engine did not foul in the competition, and it will be worth watching in service to see if it continues to keep as clean as do cylinders with heads above cranks, and not to require excessive amounts of oil to make up for gravitational cylinder wall drainage. If this should work at all right, this arrangement offers further opportunities for weight reduction over the now standard multicrank form.

Even here, however, there is a limit to the number of cylinders that can be radially placed about one crank, a limit imposed by their intersections, and while the rotating Gnome uses a maximum of nine and a minimum of five, the fixed Anzani uses three or five. The Anzani figures for two sets of three are 50 horsepower and 200 pounds, or 4 pounds per horsepower, and for two sets of five 100 horsepower and 330 pounds, or 3.3 pounds per horsepower, the reduction of 0.7 pounds per horsepower, or 17½ per cent, being the effect of using five instead of three per star, all cylinders being of same size. Similarly the effect of doubling the number of rows is shown by comparing the 10-cylinder 100-horsepower with the 20-cylinder 200-horsepower, both having sets of five, the former two sets and the latter four sets. The former weighs 363 pounds, and the latter 682 pounds, the difference of 310 pounds being the weight added to the first 10 cylinders, which themselves weigh 363 pounds, and showing nearly proportionate addition of weight per crank added, the actual addition being 88 per cent. The gain is of course greater in passing from a one crank star to a two than from two to four cranks, as might be expected from the study of cylinders in line. This is shown by the figures for the 3-cylinder, 30-horsepower, 121 pounds, compared to 6 cylinders (two sets of 3 50–55 horsepower, 200 pounds), the second row adding 79 pounds to the first 121 pounds, which is only 65 per cent, as compared with 88 per cent when two rows are added to two to make four.

Increase of cylinders radially about a crank always reduces weight, but the weight reduction is most when the frame and shaft weight is large in proportion to cylinder weight, and least otherwise. Ideally the weight reduction by multiplication of cylinders would be zero if the shaft and frame weighed nothing. This is clearly shown by the figures given by Winkler in Table VII for the proportionate weight of the various parts of fixed auto type and rotating radial cylinder engines. To these figures are added some pound values for the parts computed from Winkler's fractional weights and assumed typical total weights.

TABLE VII.

[NOTE.—The table is based on Winkler's figures for weight distribution in different types of engines. The first three engines are of the fixed cylinder in line type; the last is an ordinary Gnome engine. The total weights have been assumed.]

	100 horsepower 4-cylinder engine.		55–60 horsepower 4-cylinder engine.		150 horsepower 6-cylinder engine.	
	Per cent.	*Pounds.*	*Per cent.*	*Pounds.*	*Per cent.*	*Pounds.*
Crank case, complete	23.75	95.00	19.00	49.40	23.00	126.50
Cylinders	26.00	104.00	30.00	78.00	28.50	156.80
Pistons	5.75	23.00	8.50	22.10	7.00	38.50
Connecting rods	6.50	26.00	5.00	13.00	9.00	49.50
Crank shaft	15.00	60.00	14.50	37.70	13.00	71.50
Cam shaft	3.25	13.00	2.00	5.20	2.00	11.00
Valve rods, etc	5.50	22.00	4.50	11.70	4.50	24.75
Valves, springs, etc	3.25	13.00	2.00	5.20	3.50	19.25
Pump, including connections	1.50	6.00	2.75	7.15	1.50	8.25
Carbureter, throttle, etc	.50	2.00	1.50	3.90	.50	2.75
Magneto, etc	7.50	30.00	7.00	18.20	6.50	35.75
Oiling system	.50	2.00	1.25	3.25	....	....
Rest	1.00	4.00	2.00	5.20	1.00	5.50
Total	100.00	400.00	100.00	260.00	100.00	550.00

TABLE VII—Continued.

	Rotating-cylinder engine.	
	7 cylinders.	50 horsepower.
	Per cent.	*Pounds.*
Crank case	20.00	30.00
Cylinders	27.50	41.25
Pistons	7.00	10.50
Connecting rods	6.00	9.00
Crank shaft	8.00	12.00
Cam shaft and drive	2.00	3.00
Cam-shaft casings	3.75	5.625
Tappets and rods	4.00	6.00
Magneto	7.50	11.25
Oiling mechanism	2.50	3.75
Carburetor, including throttle	1.25	1.875
Frame	9.50	14.25
Rest	1.00	1.50
Total	100.00	150.00

These figures are most interesting, but must be used with considerable caution, as the Winkler fractions are general averages and when applied to a given engine may give pound values that are somewhat in error. One instance of this appears in the value obtained for the magneto in pounds by applying the general average fraction to a given overall engine weight and which works out in the table as 35 pounds for one and 18 for another. While of course there really may be this difference, it is not fundamental nor is there any acceptance of its accuracy. The really valuable parts of the table are those items for the principal parts, such as cylinders. crank case, pistons, and shafts.

Radial disposition of cylinders does not suffer from inequality of oil flow to combustion chambers only when cylinders and frames are rotated about the crank shaft, but here the tendency toward head-flow is increased by the centrifugal force on the oil, which is far greater than pure gravitation and which apparently is at least a contributing factor to very high oil consumption of these engines and their quick carbonization. It may be that this is more an effect of the use of steel and of high wall temperatures than of centrifugal flow, as such engines are always air cooled by reason of the difficulty of making moving water joints and of controlling water flow with the centrifugal forces acting in jackets and pipes, but everything points the other way. Inverted cylinders having head flow tendencies between these rotating cylinder engines and the normal vertical must be accepted with great caution at present, though there is at present no data that warrant a conclusion. Complete radial star disposition of rotating cylinders gives the smallest possible frame and crank weight per cylinder, but it is not possible to use some of the cylinder constructions and materials that are perfectly feasible in fixed cylinders. Centrifugal forces put cylinders and connecting rods under a tension stress that is pretty large at the high speeds used, and angular velocity changes impose cylinder-bending stresses, due not only to their own overhang but also to the pistons, and these stresses are additional to those imposed by explosion pressures. To reduce these special centrifugal stresses to a minimum, the weights of the parts must be the very least possible, and this is to be accomplished by the use of an assuredly sound and high-tension metal, such as one of the steels. These engines, then, have adopted steel as a cylinder material not so much from choice as of necessity, and the fact that the surfaces could be lubricated at all has acted as an incentive to its substitution for the old standard cylinder material, cast iron, in the fixed cylinder engines, with corresponding weight reduction per cylinder in that class. The effect of this weight reduction must not be exaggerated. Steel pistons, for instance, are only 12 to 15 per cent lighter than cast-iron ones, since bottom must not be too thin on account of the danger of burning through. Furthermore, pistons weigh only about 7 per cent of the total engine weight. Greater effects are possible when steel cylinders and sheet jackets are substituted for cast iron, yet even here the gain is rather less than might be expected, because of the heads, and the substitution is warranted more on grounds of assumed soundness of forged rolled or drawn steel compared with cast-iron, which may have hidden defects such as blow holes, cold shorts, or bad shrinkage stresses.

In this brief review of the effects of general arrangement of cylinders and cranks on the weight per horsepower, it was assumed that other factors remained fixed, such, for example, as the weight of cylinders per cubic foot of displacement per stroke. Variations in details of construction of the cylinder complete with valves and valve drives, pistons, and connecting rods, such as might affect this unit weight, are not only pretty numerous and cover a considerable range, but taken in conjunction with the corresponding variations of material, the resulting unit weights of the complete cylinders follow no simple law. A type construction of few parts that would tend to lightness may employ a heavier material that equalizes the weight. A somewhat more complicated or essentially heavier construction will often be found associated with a lighter material, producing the same result and unit weight. The combination of lighter construction and material together, cooperating to produce low unit weight, is also found, but unfortunately this is usually offset by lower mean effective pressure and efficiency or by a less favorable general arrangement.

The object sought is the lightest combination of form and material for cylinders, pistons, and their accessories consistent with proper values of the other factors that contribute in the same direction to a higher horsepower per pound of total weight.

It seems pretty clear that designers and inventors of aero engines have started with some favorite general arrangements of cylinders, cranks, and frames and then have selected detail part forms and such material for cylinders and pistons as was either essential, as in the rotating cylinder engines, or as would bring the net result into successful competition with previous engines. To put it otherwise, there is no combination of the various factors that contribute to a low weight per horsepower ratio involving the most favorable value of each factor. This would require the largest number of cylinders that could be disposed radially about one crank, followed by further extension in line on other cranks, as to general cylinders-frame-crank arrangement. It would also require the use of the simplest piston, cylinder, valve, and connecting rod construction, all of steel, operating at the highest speed, and processes, and producing the highest mean effective pressure and the lowest fuel and lubricating oil consumption. Such a combination has so far been impossible and is mentioned here to accentuate the position of the factor at present under consideration, that of weight per cubic foot of displacement per stroke of cylinders, including all attached parts.

Lightness of metal parts may be secured by the use of large volume of low density material of low stress resistance such as aluminum or by a small volume of metal having high stress resistance but of greater density, such as steel, or some compromise, such as cast iron. If the material were required to perform the stress resistance function alone, the modern steels which can be counted on for upward of 175,000 pounds per square inch elastic limit and some 15 per cent elongation with an ultimate tensile strength approaching 200,000 pounds per square inch, are so superior that nothing else could be considered. That other materials are used at all is due to the fact that the material of some parts must have other properties, each contributing to a different function than that of stress resistance. Piston and cylinder material must have good conductivity, especially the former. Pistons and exhaust valves especially, but to some extent the whole combustion chamber, must resist oxidation under high temperatures and water jackets must resist hot water corrosion. All heated parts should have the lowest possible coefficient of expansion to minimize the thermal stresses of unequal heating, and the expansion characteristics of cylinder material with reference to that of the piston should be such as to oppose seizing on heating. The piston must heat more than the cylinder, so cylinder material should have a higher thermal coefficient of expansion than piston material, though in small cylinders with proper clearance the same material will serve but never should piston metal have a higher coefficient than cylinder metal. Permanent distortion of metals under the heating conditions of operation is not permissible in cylinders, heads, valve seats, valves, and pistons, so some commercial alloys, including some steels, are barred on this account. Finally the metal of these two parts, cylinder and piston, should have such a molecular structure as will lubricate well, cast iron on cast iron is the best, cast iron on steel next best, and steel on steel the worst combination, neglecting the nonferrous alloys which may be serviceable though they are as yet unknown quantities. This is not an absolute necessity except where excessive oil consumption is more important than metal weights. Engines intended for short flights, an hour or so, might very properly have piston-cylinder materials that ignore this, compensation being secured by large oil consumption which adds little weight. But long flights will add enough oil weight to more than offset the weight reduction obtained by making both parts of steel, as compared with both cast iron, or one of each.

About every combination of standard ferrous materials forged, cast, drawn, and rolled for the heated parts that could be produced has been tried, and is even now in use, so it can be definitely stated that practice in ferrous materials is not yet established, which means that there are insufficient data at hand on the differences in their behavior and practically none on the nonferrous. Here is a field for investigation that is of most fundamental importance practically untouched metallurgically, and solution of which requires scientific research under the combined efforts of enginemen familiar with the requirements, of metallurgists familiar with alloy production and properties, and of shopmen familiar with the processes of forming and fitting.

No metal equal to cast iron on cast iron has ever been found for the pistons and cylinders of internal-combustion engines in all the desired properties except one, that of metal weights for a given size. Casting, as a process however, is most uncertain; the known defectives amount to almost 50 per cent while the unknown possibilities and hidden defects are responsible for large factors of safety and the use of excess metal. This excess is quite prohibitive and fruitless in rotating cylinders with the enormous centrifugal stresses that come from speeds exceeding 1,200 revolutions per minute, because each pound excess metal adds its own equivalent centrifugal stress and so fails to add to the certainty of safety as in fixed cylinders. Excess thickness adds to the resistance to heat escape through cylinder walls. It was in these rotating cylinders that the first departure from the older internal-combustion engine practice took place, from sheer stress resistance requirements regardless of other properties. The steel cylinder machined from a forged-steel billet was developed by the French rotating cylinder engine builders, and with cast-iron pistons it operates successfully.

Some builders of fixed cylinder engines encouraged by this demonstration adopted steel for cylinders with cast-iron pistons. Even steel pistons, were tried and in some cases adopted for use in both steel and cast-iron cylinders, apparently without gain, in the former case because of increased lubrication requirements and in the latter from reversed expansion coefficients or permanent distortion. Some of these steel fixed cylinders are cast with heads in one piece and machined all over to disclose defects, but in other cases rolled or forged steel cylinders are combined with cast-iron heads in which ports are most readily formed. The most radical of all these steps is undoubtedly that undertaken by the German Daimler Co. in constructing cylinders, heads, ports, valve seats, and jackets, all of sheet steel welded together by the modern oxygen flame method. Only experience can tell how successful this may prove in practice, though in the competition tests the engine gave a most remarkable performance.

At the present time the only data bearing on the question are those of oil consumption, Table VIII, with respect to materials. This is not a basic figure anyway, and is complicated by variations in oil and in oil application methods, so it is inconclusive though interesting.

TABLE VIII.—*Oil consumption versus engine type and cylinder piston materials.*

Cylinders and cooling.	Class construction.	Materials.		Engine name.	Authority.	Oil per HP.-H.
		Cylinder.	Piston.			
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	100-horsepower Benz.	Bendemann	0.042
	6 cylinders in line	do	do	100-horsepower Daimler.		.031
	8-cylinder V	Steel	do	90-horsepower Daimler.	Bendemann	.038
			Steel	Austro-Daimler	Maker	.027
		Cast iron	Cast iron	140-horsepower Sturtevant.	do	.045
		do	Steel	150-horsepower Sunbeam.	do	
	12-cylinder V	do	do	225-horsepower Sunbeam.	do	.03
	Radial Star	do	do	Salmson	Walker, 1912	.054
Air-cooled fixed cylinder.	8-cylinder V	do	Cast iron	Renault	do	.045
	Radial Star	do	do	British Anzani	Maker, Av. of 6.	.164
Air-cooled rotating cylinder.	1 Radial Star	Steel	Steel	8-horsepower German Gnome.	Maker	.167
	2 Radial Star	do	do	160-horsepower German Gnome.	do	.167
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	71-horsepower Daimler.	B	.047
	6 cylinders in line	do	do	100-horsepower Argus.		.067
	8-cylinder V	do	do	Curtiss	Maker	.045
			Steel	Wolseley	Walker, 1912	.041
Air-cooled fixed cylinder.	Radial star	do	Cast iron	Anzani	Lumet	.255
Air-cooled rotating cylinder.	1 Radial Star	Steel	do	100-horsepower German Gnome.	Maker	.171
	2 Radial Star	do	do	200-horsepower German Gnome.	do	.171
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	100-horsepower Daimler.	B	.040
	6 cylinders in line	do	do	100-horsepower Mulag.		.021
	8 cylinder V	do	do	Hall-Scott	Clark, 1912	.106
Air-cooled rotating cylinder.	1 Radial Star	Steel	Steel	1911-Gnome	Lumet	.212
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	70-horsepower Daimler.	B	.031
	6 cylinders in line	do	do	90-horsepower Schroeder.		.047
Air-cooled rotating cylinder.	1 Radial Star	Steel	Steel	1911 Gnome	Lumet	.253
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	60-horsepower Daimler.	B	.029
	6 cylinders in line	do	do	125-horsepower Hall-Scott.	Maker	.030
Air-cooled rotating cylinder.	1 Radial Star	Steel	Steel	1913 Gnome	Lumet	.255
Water-cooled fixed cylinder.	4 cylinders in line	Cast iron	Cast iron	66-horsepower	B	.060
	6 cylinders in line	do	do	87-horsepower Benz.	Maker	.022
Air-cooled rotating cylinder.	1 Radial Star	Steel	Steel	Gyro, 1911	Clark	.017

TABLE VIII.—*Oil consumption versus engine type and cylinder piston materials*—Continued.

Cylinders and cooling.	Class construction.	Materials.		Engine name.	Authority.	Oil per HP.-H.
		Cylinder.	Piston.			
Water-cooled fixed cylinder.	4 cylinders in line..	Cast-iron..	Cast iron..	100-horsepower N. A. G.	B............	0.038
	6 cylinders in line..	...do......	...do......	100-horsepower Cheno.	Clark........	.005
Water-cooled fixed cylinder.	4 cylinders in line..	...do......	...do......	95-horsepower N. A. G.	B............	.009
Water-cooled fixed cylinder.	4 cylinders in line..	...do......	...do......	96-horsepower Argus.	B............	.089
Water-cooled fixed cylinder.	8-cylinder V.......	Cast iron..	Steel......	1911 Labor-Aviation.	Lumet........	.073
	12-cylinder V......	...do......	...do......	1911 Aviatic......	.....do........	.054
	Radial Star........	...do......	...do......	Green............	Clark........	.11

There appears to be some relation between oil consumption and cylinder arrangement, but not so with reference to piston versus cylinder materials. For example, radial cylinders seem to require much more oil than vertical cylinders, but there is no conclusive evidence that air-cooled cylinders require more than those that are water cooled. Again, comparing the three Daimler engines as to oil versus materials, it appears that there is no appreciable difference between cast iron and steel cylinders, cast iron and steel pistons, though such a serious conclusion should not finally rest upon a single instance like this.

An effort to retain the low metal weight characteristics of steel and to meet lubrication requirements, that is worthy of note, involves the use of liners for cylinders and of sleeves, or even a separate barrel for pistons, made of a material such as cast iron or bronze having a good lubricating surface. This is not only objectionable as complicating the thermal and total stresses, increasing thermal resistance of cylinders, and adding something to weight removed but it now seems to be unnecessary.

At present the standard material for fixed cylinders is unquestionably cast iron with heads in one piece, and with cast-iron pistons. There is, however, a growing tendency to use tube steel for cylinders. This steel cylinder involves a head complication in shop practice, solution of which is now in course of development. Heads must have irregular forms due to ports and valve stem guides, which are most easily and satisfactorily cast. Such a cast head requires a joint to connect it to a drawn-steel cylinder. As alternatives the following are used, cast-steel cylinders with heads in one piece and cylinder and head machined from a forged billet or finally the complete sheet metal welded Daimler construction.

Steel is the adopted standard material for connecting rods and crank shafts and always is a very high tension alloy such as nickel or chrome nickel, which permits these parts to be very small and light while amply strong and stiff. Crank case or frame material is still unsettled, ranging from the forged steel cage of the rotating cylinder engine through cast steel, cast iron, and aluminum, with the last prevailing in fixed cylinder engines. No successful attempt is yet on record, to use welded or riveted sheets and standard structural steel shapes in the long frames and crank cases of fixed cylinder multicrank engines, where frame weight per cylinder is a matter of considerable importance. It would seem as if stiffness or its equivalent uniformity of distortion can better be served with less weight by such structural steel construction than by the soft aluminum casting. To give a general survey of the practice in materials, Table IX is added.

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TABLE IX.—*Materials*

Engine or makers' name.	Cylinder and crank arrangement rotating part.	Cooling medium and system.	Horse-power.	Number of cylinders.	R. p. m.
Benz	Vertical fixed separate	Water, C. P.	88 103 150	6	1,250 1,250 1,250
Hall-Scott	do	do	125	6	1,300
Frederickson, 2-cycle	Cylinders, rotating shaft, stationary.	Air		5 10	
Sturtevant	V-type, L head, cast in pairs	Water; C. P.	140	8	2,000
Sunbeam	V-type, L head, en bloc	do	150 225	8 12	2,000
Austro-Daimler	Vertical fixed separate	do	90 120	6 6	1,300 1,200
Le Rhone	Rotating cylinders, shaft stationary.	Air	80 160	9 18	1,200 1,150
British Anzani	Fixed star	do	25–200	3–20	1,250
Ransenzerger	V-type, separate cylinders, valves in head.	Water	150	12	1,200
Argyll	Vertical fixed, sleeve valves, separate cylinders.	do	120	6	
Wright	Vertical fixed, separate cylinders, heads screwed in.	Water, C. P.	60	6	1,400
Sturtevant	Vertical fixed cylinders en bloc, T head, 4 valves per cylinder.	Water	100	4	2,000
Curtiss	V-type, separate cylinders, L head, 4 valves per cylinder.	do	200	8	1,500
Chenu	Vertical fixed cylinders in pairs, T head.	do	65 90 100 850	4 4 6 6	1,800 2,300 1,600 1,500
Clerget	V or vertical fixed separate cylinders, valves in head.	do	50 100 200	4 4 8	1,450 1,300 1,300
Do	Rotary cylinders, valves in head, mechanically operated.	Air	50 80	7 7	1,180 1,180
De Dion Bouton	V-type, separate cylinders, L head	do	80	8	1,800
Edelweiss	Radial star, fixed pistons, reciprocating cylinders.	do	75 125	6 10	1,350 1,350
Laviator	V-type, separate cylinders, valves in head.	Water	80 120	8 8	1,200 1,700
Panhard-Levassor	V-type, cylinders en bloc, L head	do	100	8	1,500
Salmson	Fixed star, valves in head	do	90 135 200 300	7 9 14 9	1,250 1,250 1,250 1,200
Wolseley	V-type separate cylinders, valves in head.	Combination water.	82 130	8 8	1,650 1,200
Green	Vertical fixed, separate cylinders, valves in head.	Water	100	6	

NOTE.—I=integral head; C. P.=centrifugal pump.

for engine parts.

Materials for—									
Cylinder.	Cylinder heads.	Cylinder jackets.	Head jackets.	Pistons.	Valves.	Connecting rods.	Crank shafts.	Frames or crank case. Upper.	Lower.
Cast iron	I	Sheet steel, welded.	Sheet steel, welded.						
do	I	I	I	Cast iron.	Tungsten steel.	I-section chrome nickel steel.	Chrome vanadium steel.	Aluminum alloy	Aluminum alloy.
do	I			do	Cast iron, rotary rocking.	Nickel steel.	Nickel steel.	Cast iron with nickel-steel rings shrunk over.	
do	Cast iron	I		Semisteel.	Tungsten	H-section chrome nickel steel.	Chrome nickel steel.	Aluminum alloy.	
do	I	I	I	Steel		H-section high tensile steel.	High tensile steel.	Do.	
do	I	Copper electrol dep.	Copper electrol dep.	Pressed steel.					
Steel with cast-iron liner.	I			Steel					
Cast iron	I			Cast iron.	Nickel steel.	I-section nickel steel.	Nickel chrome steel.	Do.	
do	I	Spun copper pressed on and locked by steel rings.		do		H-section nickel steel.	Chrome vanadium steel.	Do.	
Forged steel.		Sheet steel, welded.							
Cast iron	Cast iron	I	I	Cast iron.	Valve heads, cast iron.	H-section chrome nickel steel.	Chrome nickel steel.	Do.	
do	I	I	I	Semisteel.					
do	I	Monel metal, welded.	Monel metal, welded.		Tungsten steel.	I-section.	Krupp steel.	Do.	
do	I	I	I					Do.	
Steel	I	Copper electrol deposited.							
Forged steel.								Steel.	
Steel				Steel				Aluminum alloy.	
High tensile steel.				Cast iron.				Special aluminum frame.	
Steel	Air cooled.				Concentric valves, nickel steel.				
Cast iron	I	I	I						
Forged steel.	I	Spun copper, corrugated, brazed.		Cast iron.		H-section.		Aluminum alloy.	
do	I	Copper	Steel exhaust-valve boxes.	Forged steel and phosphor-bronze bearing rings.		Tubular		Do.	
Cast steel		Spun copper.	I	Cast iron.	Nickel chrome steel.	Nickel chrome steel.	Chrome vanadium steel.	Do.	

Form of cylinder proper including head is a direct contributing factor in the cylinder weight per horsepower, as is also to some extent the proportions. For a given bore and stroke, and made of the same material, all cylinders would weigh the same if they were similar in form, and as they are not similar the differences in form must account in some measure for total weight differences. That form that gives the least metal volumes evidently should be lightest. On this basis air-cooled cylinders with their radiating heat dissipating ribs, casings and baffles are heavier than water-cooled cylinders of the same bore, stroke, material, and similar valves. This excess weight of the air over the water-cooled cylinder added to its fan weight, when subtracted from the weight of radiator, pipes, pumps, and water, measures the excess weight of the water-cooled cylinder with its accessories. With radiators especially designed for lightness and for a minimum supply of water rapidly circulating, there is no essential reason why the air-cooled cylinder engine complete should weigh materially less than the water cooled. As a matter of fact, the actual difference itself is small, even when all contributing factors in each case are not equally well selected, as appears from the comparison of the weights of some well-known eight-cylinder V engines given in Table X.

TABLE X.—*Comparative weights per cubic foot displacement of air and water cooled 8-cylinder V engines.*

Engine or makers' name.	B. H. P.	R. P. M.	Bore (inches).	Stroke (inches).	Displacement (cubic foot per stroke).	Total weight, engine complete.	Engine weight per cubic foot per stroke.	Remarks.
Curtiss	75	1,100	4.00	5.00	0.2912	300	1,030	Water cooled. Water-cooled engines give weights without radiator water.
	100	1,250	4.25	5.00	.3260	340	1,034	
	160	1,100	5.00	7.00	.6370	700	1,100	
Sturtevant	140	2,000	4.00	5.5	.321	550	1,715	
Sunbeam	150	2,000	3.54	5.91	.271	610	2,245	
	225				.407	905	2,245	
Rausenberger	150	1,200	4.125	6.0	.557	590	1,060	
Clerget	200	1,300	5.512	6.299	.695	640	921	
Laviator	80	1,200	3.937	5.118	.289	275	952	
	120	1,200	4.488	6.299	.465	418	900	
Panhard-Levassor	100	1,500	4.331	5.512	.372	440	1,183	
Wolseley	130	1,200	5.0	7.0	.637	700	1,100	
De Dion-Bouton	80	1,800	4.173	4.724	.303	465	1,535	Air cooled. Weight given includes 2 exhaust connectors; also fan.
Renault	70	1,800	3.780	4.724	.233	396	1,700	Do.
Wolseley	82	1,650	3.750	5.500	.281	[1] 385	1,370	Cylinder barrels. Air cooled. Exhaust valves. Water cooled.

[1] Without flywheel.

NOTE.—Engine weights taken from Table I, where sources of information are given.

There is a somewhat surprising range of weights here and one that bears close study as directly related to design, form, and material quite independent of speeds and mean effective pressures. The lowest value is 900 and the highest 2,245 pounds per cubic foot of suction stroke. There seems to be no doubt of the superiority of head-valve construction over side-pocket valves in weight reduction, and there is no marked difference between an air and a water cooled construction. This last conclusion is most important in view of the consistent inferiority of air cooling with reference to mean effective pressure and fuel consumption. Next to general arrangement, weights per cubic-foot displacement are fundamentally related to materials and wall thickness.

Cylinder metal volumes are least in any cylinder, other things being equal, when the valves are placed in the head instead of in side pockets, so in the interest of cylinder lightness this arrangement must be adopted unless it appears that the compensating factors, which will be referred to later, overbalance the extra pocket metal, but this is not the case. There are, however, several successful aero engines that follow the standard automobile practice of locating valves in side pockets mostly of the L-head form. One arrangement has the valves side by side, both stems pointing toward the crank case, both seating down in a wide pocket. The other locates the two valves axially in line, one stem pointing up, while the other points down, and seating on opposite sides of a narrow pocket.

The compensating weight elements referred to in connection with the head valve as compared with the side-pocket valve arrangement are those of valve gear. Two side by side valves in one wide pocket are ordinarily driven by a pair of push rods. Placing one valve above the other in a narrow pocket reduces the width and hence the metal of the pocket, but adds a rocker arm with bracket and pin and some additional rod length. Placing both valves in the head removes the pocket metal entirely, but adds a second rocker and push-rod extension ordinarily. It is the weight of these two rockers and push-rods extension that is to be balanced against the metal of the pocket. Such side pockets with ports, being irregular in shape and necessarily jacketed, can be formed, as in the case with cylinder heads that carry valves, only by casting (except when welded of sheet metal as in the Daimler experiment). The added cast iron due to pockets in combustion chamber and jacket wall will weigh more than the steel rocker arm and the push-rod extension. The weight difference in favor of the head-valve arrangement is greater still when a single rod alternately works in tension and compression on one rocker actuating both vlaves, as in the Austro Daimler, but in this case two different cams should be used, one to lift and the other to depress. Further reduction is possible in standard four and six cylinder engines by placing the cam shaft directly on the heads as in the German Daimler, for here the combined weight of all push rods is removed and the weight of a pair of gears and a vertical shaft introduced instead. This is no advantage, however, in V engines, because with the push-rod drive one cam shaft can serve both rods, and this is one of the advantages of V arrangement. Removal of one push rod and cam entirely becomes possible when the inlet valve is made automatic as it is in several engines, but the loss of volumetric efficiency resulting cuts more from the power than removal of push rod even with rocker does from the weight. For this reason automatic valves are not to be recommended, though there is another reason also strong enough alone, that of unrestrained seat impact.

Water-jacket metal in all cast cylinders will normally weigh more than the metal of the cylinder proper inclosed by it, in spite of the fact that it might be made thinner, due to lack of pressure loading in one case and in the very high internal pressures in the other. The area of the jacket metal is considerably greater than that of the cylinder, especially when the water space is large, and the foundry can not make a sound jacket casting as thin as lack of stress would warrant. Accordingly, while the cast jacket is retained in many aero engines in accordance with automobile practice, this can hardly be accepted as the best aero engine practice, which seeks weight reduction by legitimate removal. Sheet metal of copper, brass, aluminum, or steel in sheets, in drawn tubes, spun and die pressed shapes is so peculiarly adapted to the purpose that its lack of immediate general adoption requires explanation. This is to be found first in the joint difficulty originally encountered in automobile practice, where such a mechanical discouragement was sufficient to cause rejection in view of the slight importance of the weight relation to automobiles, especially as the cast jacket is cheaper. With aero engines the case is different because the need of saving every ounce is vastly greater, and the cast jacket is a larger fraction of the total weight when all the other economics have been practiced, so the per cent gain by sheet metal substitution is great enough to warrant efforts to find suitable joints. This has been accomplished in a variety of ways, one of them being especially noteworthy, viz, electrolytic deposition of the whole jacket metal or electrolytic deposition of the joint. Added to this is the now generally available method of the oxygen flame weld, beside the usual screw-cover and press-fit joint which has always been available. Experience with these sheet-metal jackets has indicated the necessity for expansion provisions to avoid overstressing of the joint when the cylinder expands, exactly as in big gas engines. This conclusion is itself a measure of the distortional stresses set up in one-piece castings and an additional reason for their abandonment. To these advantages of weight reduction and relief of cylinder metal from jacket stress, the sheet metal jacket gives additional assurance of safety when jacket water freezes, and especially with cast heads or cylinders permits complete assurance of the external soundness of the cast metal that is to resist explosion pressures and of the reality of water spaces, which when cored may be filled with metal in corners where the designer intended water to be, so adding to expansion stresses and preignition tendencies that result from the consequential overheating.

At least three openings to the combustion chamber through the jacket space are necessary for insertion of inlet valves, exhaust valve, and igniter. The outer ends of these passages must be joined at the jacket wall by the jacket itself and the use of sheet-metal jackets calls for joints at these points. These offer no difficulty if welded autogenously or accomplished by electrolytic deposition, though considerable pressure joints are apt to be troublesome. Expansion is provided in three separate ways, (*a*) the slip joint, packed by a rubber ring as in Green (British), (*b*) corrugated bellows, (*c*) the elongation of a thin jacket of suitable metal provided the joint is welded as in the Benz (German) which seems quite satisfactory.

Jacket water spaces are usually made narrower on aero engines than others but the width may properly be even further reduced to hardly more than a water film as the corresponding high water velocity is beneficial to heat abstraction around the barrel. On the heads greater width is usually necessary to avoid the formation of pockets where air or steam may collect next to the irregular port walls, and the outlet for water must be at the highest point to promote expulsion of any bubbles. Jacket lengths on the cylinder barrel are usually short, normally extending little if any below the lowest position of the piston head. This is not as satisfactory as a longer jacket even if the space be narrow, especially as the cylinder walls are so thin as to have a minimum of heat-conducting capacity longitudinally. The piston barrel will give heat to every part of the cylinder wall with which it comes in contact and if at some low part there is no water, then the heat must be dissipated to the air directly or conducted up to where the jacket starts.

Provisions for valve insertion and removal, to facilitate inspection and regrinding, are used in the very best large internal-combustion engine practice but would add weight to the aero engine if adopted. Inlet valves are carried in cages, which, with their fastening and the necessary additional guide walls, add several times the weight of the valve. Through the opening of the removed inlet cage the exhaust valve, which must seat on water-cooled metal, becomes accessible. This accessibility of valves is the primary recommendation for the side pocket, which permits of the use of the above construction when both stems are opposed in line as in the Mulag. In the parallel construction it is accomplished by two covers, one over each valve, as in Sturtevant. It is also attained in the head valve arrangement without cages by the separate or removable head which in aero engines is objectionable for many reasons. This problem has been boldly met by the designers of many of the best aero engines by simply providing a joint between cylinder and frame that is easy to loosen and by using valve gear and pipe connections that are quickly detachable, so the entire cylinder, which even in the largest sizes is not heavy, can be bodily removed by hand with ease and the valves reached through the bore. In this way the number of parts is kept to a minimum and a material contribution to low cylinder weight is secured.

Low valve weight would demand the thinnest disk and stem and the shortest possible stem, but process considerations are in opposition to this conclusion, especially in exhaust valves where heat dissipation is opposed thereby. Practice oscillates between these two extremes, but the heavy construction of exhaust valves must be favored while the light is permissible on self-cooling inlets, unless it be regarded, as in marine and automobile practice, unwise to use two different valves in the interest of reduction of spares. It is otherwise perfectly feasible to make inlet valve disks thin with short stems of small diameter, and exhaust valves thick with large diameter stems, perhaps taper bored from the end toward the disk, and long enough in the guides to dispose of the heat. If a metal of high conductivity could be found otherwise suitable, then exhaust-valve thickness might be reduced. Keeping the weights now used for both valves, the excess desired in exhaust valves can be secured by reducing the inlets, though many good engines are amply well cared for in this respect. Valve material is invariably steel, forged to meet the requirements of inertia and impact shock at high speeds and of corrosion, especially in exhaust valves, and alloy steels seem better adapted than carbon steels for this purpose. Shock troubles of broken stems, battered push rods, and worn seats would all disappear if some form of good rotary valve could be evolved, and this is a most attractive possibility with as yet no realization in sight, though the case is by no means hopeless.

A general comparison of water cooled cylinder weights with various constructions of jackets, valve location, and drives, per cubic foot of displacement per stroke, is given in Table 11 to show limiting effects of various structural details, but unfortunately in an inconclusive way for cylinders alone, as shafts and frames are included.

Table XI.—*Weights of engines per cubic foot displacement (per stroke) versus type construction of parts.*

Cylinders and cooling.	Class construction.	Cylinder material.	Valve location.	Suction valve, A. or M.	Name.	Bore.	Stroke.	Revolutions per minute.	Weight per cubic foot.
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Benz	5.180	7.087	1,288	1,075
			Pocket	M	Sturtevant	4.5	6.0	2,000	778
	6 cylinders in line	do	Head	M	Daimler	4.724	5.512	1,315	1,418
			Pocket	M	Mulag	4.331	6.693	1,346	1,536
		Steel	Head	M	Daimler	4.134	5.512	1,387	1,301
	8 cylinders, V	Cast iron	do	M	Curtiss	4.00	5.0	1,100	1,030
			Pocket	M	Sturtevant	4.00	5.50	2,000	1,718
		Steel	Head	M	Laviator	3.937	5.118	1,200	952
	12 cylinders, V	Cast iron	Pocket	M	Sunbeam	3.54	5.91	2,000	2,225
		Steel	Head						
	Radial star	Cast iron	Pocket	A	Laviator	3.937	5.118	1,300	1,115
		Steel	Head	M	Salmson	4.724	5.512	1,250	947
Air cooled:									
Fixed cylinders	8 cylinders, V	do	do	M	Wolseley	3,750	5.500	1,650	[1] 1,370
			Pocket	M	De Dion Bouton	4.173	4.724	1,800	1,535
	12 cylinders, V	Cast iron	do	M	Renault	3.780	5.512	1,800	1,511
	Radial star	do	Head	A	Anzain	3.54 3.54 4.13	4.72 5.12 4.92	1,250	837 806 865
	Horizontal opposed cylinder		Pocket	M	Ashmusen	3.75	4.5	1,800	1,000
Rotating cylinders	1 radial star	Steel	Head	A	B. M. & F. W.	4.331	4.724	1,031	625
	2 radial star	do	do	A	German Gnome	4.33 4.72	4.72 4.72	1,200 1,200	536 436
Water-cooled fixed cylinders:	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,412	1,375
			Pocket	M	Chenu	4.331	5.118	1,800	1,468
	6 cylinders in line	do	Head	M	Argus	4.921	5.118	1,370	1,394
			Pocket	M	Chenu	4.331	5.118	1,609	1,527
		Steel	Head	M	Green	5.512	5.981	1,250	885
	8 cylinders, V	Cast iron	do	M	Curtiss	4.25	5.00	1,250	1,034
			Pocket	M	Sunbeam	3.54	5.91	2,000	2,245
		Steel	Head	M	Laviator	4.888	6.299	1,200	900
	12 cylinders, V	Cast iron	Pocket	M	Rausenberger	4.125	6.00	1,200	1,060

[1] With flywheel removed.

Note.—Engine weights taken from Table I where source of information is given.

TABLE XI.—*Weights of engines per cubic foot displacement (per stroke) versus type construction of parts*—Continued.

Cylinders and cooling.	Class construction.	Cylinder material.	Valve location.	Suction valve, A. or M.	Name.	Bore.	Stroke.	Revolutions per minute.	Weight per cubic foot.
Air cooled:									
Fixed cylinders	8 cylinders, V	Steel	Pocket	M	Renault	3.780	4.724	1,800	1,700
	Radial star	Cast iron	Head	A	Anzain	4.13	5.71	1,250	825
						4.53	6.10		811
						4.13	5.52		801
Rotating cylinders	1 radial star	Steel	do	A	Gyro	4.299	4.748	.....	.....
	2 radial star	do	do	A	German Gnome	4.88	5.51	1,200	511
						4.88	5.91		461
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	5.512	5.906	1,373	1,310
			Pocket	M	Chenu	4.331	5.118	2,300	1,491
	6 cylinders in line	do	Head	M	Schroler	4.882	6.299	1,252	1,010
			Pocket	M	Chenu	5.906	7.874	1,500	1,270
	8 cylinders, V	do	Head	M	Curtiss	5.00	7.00	1,100	1,100
			Pocket	M	Panhard Levasson	4.331	5.512	1,500	1,183
		Steel	Head	M	Wolseley	5.0	7.0	1,200	1,100
Air cooled:									
Fixed cylinders	Radial star	Cast iron	do	M	Edelweiss	4.528	4.724	1,350	1,052
						4.522	4.724	1,350	863
Rotating cylinders	1 radial star	Steel	do	A	Gnome	4.33	4.724	1,194	569
	2 radial star	do	do	M	Le Rhone	4.13	5.51	1,150	646
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,343	1,500
	6 cylinders in line	do	do	M	Hall-Scott	5.	7.	1,300	1,132
Air cooled:									
Fixed cylinders	Radial star	do	do	2-cycle A.	Laviator	3.937	5.118	1,200	912
Rotating cylinders	1 radial star	Steel	do	A	Gnome	5.118	4.724	1.156	467
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.331	5.512	1,396	1,564
	6 cylinders in line	do	do	M	Austro Daimler	4.72	5.51	1,300	1,060
Air-cooled rotating cylinders	1 radial star	Steel	do	A	German Gnome	4.33	4.72	1,200	613
						4.72	4.72		563
						4.80	5.51		534

Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,391	1,518
	6 cylinders in line	do	do	M	Austro Daimler	5.12	6.89	1,200	975
Air-cooled rotating cylinders	1 radial star	Steel	do	A	German Gnome	4.88	5.91	1,200	507
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	N. A. G	5.315	6.294	1,344	1,265
	6 cylinders in line	do	do	M	Benz	4.17	5.91	1,250	1,251
Air-cooled rotating cylinders	1 radial star	Steel	do	A	Frederickson	4.50	4.75		680
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	N. A. G	4.724	4.724	1,408	1,272
	6 cylinders in line	do	do	M	Wright	4.375	4.5	1,400	1,300
Air-cooled rotating cylinders	1 radial star	Steel	do	M	Le Rhone	4.13	5.51	1,200	691
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Argus	5.512	5.512	1,368	1,205
Air-cooled rotating cylinders	1 radial star	Steel	do	M	Clerget	4.724	4.724	1,180	588
						4.724	5.906	1,180	513
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Argus	4.921	5.118	1,342	1,385

Here, again, the superiority of the head over the pocket valve arrangement, and the indifference of air versus water cooling, are demonstrated, but in addition the steel cylinder is shown to be superior to the cast iron. As to arrangement of cylinders with reference to crank shaft, comparing the four and six in line, the 8 and 12 cylinder V, there is nothing conclusive demonstrated, though for the latter there are insufficient figures available. Radial star arrangements are consistently lighter than the above, not as much as might be expected for fixed cylinders, but quite markedly so for the rotating, which in round numbers weigh only half as much as the line arrangements. It is the consistent use of steel for cylinders in the rotating against the cast iron in the fixed star arrangements that is responsible for the weight differences reported rather than rotation versus fixity.

Cylinder weight must have some relation to the ratio of bore to stroke for equal displacements, and the variation of stroke per unit of displacement must affect as well the shaft and frame weights. The thickness of the cylinder walls should vary directly with the diameter for explosion pressure stress resistance, while displacement varies directly as the square of the diameter, and directly as stroke. The actual ratios of stroke to bore will be between one and two, the former giving a very short and the latter a very long stroke engine according to practice. The short-stroke cylinder will require a thicker wall than the long for stress resistance, but the difference is so small in view of shop limits and the small diameters that it can be neglected. Even allowing extra thickness, the short-stroke engine will be lighter than the long as to cylinder weight and doubly so when the increased thickness of crank and larger crank case necessary are included. More effect on weight reduction is possible by offsetting cylinders than by working to extremes of stroke bore ratio, as this reduces the height of engine, especially when the connecting rod is shortened as it may be at the same time to equalize the side thrust friction on the two sides of the cylinder wall. This offsetting is quite generally practiced, though it is by no means universal, and weight reduction possible by this means is small.

Cylinders when cast are cast sometimes singly, sometimes two, three, or even four together, to make up multicylinder engines, and this is a factor in weight reduction. Casting a single cylinder complete with head and cast jacket is the old standard practice for small stationary engines, and the method first adopted for auto engines. Such cylinders simplify and cheapen the construction of multicylinder engines of different numbers of cylinders to give different horsepower units, as the only change required to get a new capacity engine is in frame, cam shaft, and crank shaft. When automobile engines became standardized to the four cylinders in line, four crank form, it became evident that weight would be saved and compactness promoted by casting two cylinders in one piece, the jacket consisting of two semicylindrical and two tangent flat plate elements for the barrel, and two semicircular and one flat plate nearly square, connecting member for the top instead of two circles. This produced a stiff structure which permitted a reduction of frame or crank case stiffness, and it shortened the frame and shaft, but required the elimination of one main bearing between the cylinders, for which with this arrangement there is not sufficient room. As a partial offset there is required a somewhat thicker crank and shaft to compensate for the increased bending moment that follows the spreading of main bearings as supports. This practice of casting two cylinders enbloc for four-cylinder engines is equally adapted for six, and is quite commonly adopted, though not universally. Aero-engine practice followed in part this auto and marine practice for cast cylinders of making two enbloc, so that the four-crank engine has three and the six-crank engine four main bearings.

Cylinder removal is facilitated by separate cylinder castings, because there are less parts to be detached, and the weight to be lifted is the least. Separately cast cylinders are better adapted to sheet-metal jackets, so aero engines departed from automobile two enbloc practice in casting such cylinders separately and leaving a bearing between each crank. The four crank engine then has five, the six crank, seven bearings, and the whole engine is symmetrical. This is perfectly sound and good practice, for there are no more important members than the crank shaft and the frame. By this construction the maximum stiffness and best distribution of main-bearing surface is secured, with least deflection at crank pins, and the extra shaft and frame length is worth the small cost in weight, for the weight increase is very small. Steel cylinders are always separate and can be substituted for the cast cylinders with sheet-metal jackets on this type of frame and shaft without any alteration whatever, as may also air-cooled cylinders, which by the very nature of the problem of air cooling can not be cast in pairs at all.

Frame form, for connecting cylinders and main bearings, has a very large influence on the weight per cylinder in multicylinder multicrank engines, because the more direct the stress resistance, the less the metal required. As evolved from old stationary and marine steam engine practice, the main bearings support the shaft from below, the caps being removable upward, which requires a two-part frame. The lower frame member consists of a cross web to carry each main bearing, and these are tied together by a longitudinal web just out of reach of the crank throw, so for a multicrank engine this lower frame member becomes essentially a semicylindrical box with a semicircular cross partition for each main bearing. The upper frame member ties the cylinders to this box by another box, or by the A form of double column. The latter receives a cylinder at its upper ring end, and its legs seat on the lower frame in the plane of the crank path. Thus the stress which is alternately tension and compression in standard steam engines, is communicated from cylinders to main bearings in a decidedly roundabout way. The same is true of the second or box form of upper frame member as to indirectness of stress transmission, for here the upward cylinder thrust is received by a flat plate with holes in it, one for each cylinder, and this horizontal flat plate transmits it down two inclined semi-vertical plates to the edges of the cylindrical box of the lower frame member, which carries the vertical main-bearing cross webs.

Single-acting internal-combustion engines are subjected to a frame stress from explosion-gas pressures; that is, a pure tension between cylinders and main bearings, although inertia of reciprocating parts at high speeds on idle strokes may introduce a compression equivalent to the double-acting steam engine. Aero engines are necessarily light and their parts also, so that there is no real necessity for bottom gravitational support of the crank shaft, nor for keeping the old scheme of removal through end holes in box frames or sidewise through removable columns. Aero-engine crank shafts can perfectly well be supported below by bearing caps, removal of which permits the shaft to drop free. This greatly simplifies the frame which need not be more than a short cross web hanging between cylinders under a horizontal flat plate with holes for each cylinder. This cross web, if cast of aluminum, can be formed for compression resistance as a column, and steel tension rods inserted to relieve it entirely for the tension stress it can not resist. The substitution of steel shapes welded or riveted for the aluminum casting is perfectly feasible in such form as to equally well serve as struts and ties. Resistance of longitudinal bending of crank shaft due to the relative forces at two different cylinders or cranks, is easily resisted by side plates in the cast form, or by diagonal latticed braces in the structural form. This means the elimination of the old lower frame member entirely and the substitution for purposes of inclosure of a mere shell subjected to no stress whatever, but formed solely in the interest of an unstressed oil-tight inclosure.

Aero-engine frames have not all developed along these lines, practically all being of cast aluminum and only a few introducing the steel tension rod, Green for example, while a great many retain the bottom web, leaving a hole where the more serviceable upper direct web should be. There are no structural-steel frames. Reference is made to the illustration in the appendix to frame constructions which should be judged in this light. Modifications of frames along these lines will materially improve the stiffness and life of main bearings, which should reduce lubrication difficulties as well, for the same frame and shaft weights now used, or result in an equivalent weight reduction.

Main bearings are almost universally of the plain type lined with so-called antifriction or white metal, though in a few cases ball bearings, which seem ill adapted, have been employed. The thrust bearing, which is peculiar to aero as compared to auto engines, because the useful effect of all power developed lies in propeller thrust against the frame, must be suitably supported by the frame. As the loads are not severe, and the thrust not irregular as in main bearings, but reasonably steady and always in one direction, this offers no difficulty. The longitudinal side plates connecting the main bearing webs, to make the frame stiff as a beam, are equally serviceable in making it serve as a column loaded by propeller thrust, if the end plate be suitably stiffened. This end-plate stiffening is all the frame modification required to receive the thrust bearing.

Aero-engine pistons follow almost universally the practice in auto engines as to use of cast iron as a material, but vary in practically every other respect. They are invariably shorter and thinner, being machined all over as nearly as pin bosses permit, in an effort to reduce weight, which in many cases has been carried entirely too far. Unless normal speeds are made higher than at present, say 1,500 revolutions per minute, the piston weight can be considerably greater without developing inertia forces equal to explosion pressures. With present piston weights this equality between explosion pressure and inertia forces is reached about 2,500 revolutions per minute. In any case metal sufficient for heat conduction must be available, and reduction on this basis becomes legitimate only when better thermal conductors than cast iron, such as aluminum, copper, or the bronzes, are substituted for it. Complete substitution is difficult, in view of their expansion coefficients and low stress resistances, but these materials can be used as supplementary conductors to stiff cast-iron piston frames. As piston-weights of any one design increase per square inch of piston, the use of a large number of small pistons results in legitimate piston weight reduction over a smaller number of larger ones of equal area. With the exception of the brass L section single top ring of the Gnome engine, aero-engine piston rings differ not at all from the cast-iron ring of auto engines. Usually the thin lower end of aero-engine pistons is stiffened by an internally projecting web, which is an excellent feature and should be retained, however heads and upper barrel are increased. Flat heads, being structurally weak and inflexible, should be definitely abandoned, as is also the case with any cast ribs on the under side of the head, especially as these are useless in tension and involve shrinkage stresses in the making. Downward curving or concave heads being in tension, must likewise yield to the convex upward or domed pistons such as the Daimler, which, without ribs, is the best possible form, but these would be much improved by thickening at the edges. Wrist-pin bosses, while in a few cases separately attached, are normally cast integral, a practice that leads to least metal for strength, though the deformation tendency on expansion is unfavorable.

As a partial compensation for the increased unit side thrust due to shortening of pistons and use of short connecting rods, there is a marked tendency to offset the cylinders an amount recommended by Vorreiter as one-eighth the stroke. This is of no assistance whatever when inertia forces are as high as they should be, as on the suction stroke a side thrust equal to that developed by gas pressure alone is imposed on the other side, so that the symmetrical cylinder setting in line with crank shaft should not be abandoned for this reason. The principal value of offsetting is reduction of engine height.

Wrist pins are properly made hollow in some cases to reduce weight, while leaving enough metal to resist undue stressing and securing the maximum bearing area for the rod end. They should always be hollow. The old bad practice of tapering pin ends is often retained, though in view of its natural tendency to work the pin toward the big end, to loosen and to score the cylinder, which tendency is only opposed by excessive locking requirements, should have been long ago abandoned. Plain cylindrical-ended pins, of two diameters but slightly different, is the best practice, and the next best is a straight pin or tube locked in the bosses. Bearings in the bosses with pins fixed in rod ends have never proved satisfactory in other engines, and there is no difference in aero engines that warrants a different conclusion.

Connecting rods follow the usual auto practice in having the wrist-pin end solid forged, bored, and bushed, with the old split-marine form of crank-pin end, lined with soft metal, and forged of steel. They are, however, universally of high tension alloy steel of sometimes tubular, but almost universally, I section. The special rod forms are confined to the rotating cylinder engines with many rods per crank, where each engine is characterized by some arrangement peculiar to itself, all involving, however, a single bearing embracing the crank pin, to which the other rods are movably attached to allow the small relative oscillation of each with reference to this bearing. This system, which for the want of a better name, may be called the master-and-shoe rod-end construction, even though the name applies to only one form, is adapted to the double rod per crank construction of the V engine as a substitute for the separate embracement of the crank pin by each rod, either of similar rod ends side by side or one straight and the other forked, as the master and shoe results in lower mean pressures and less friction than the double direct.

Weight of engine proper per horsepower is, as pointed out, not to be secured by reducing engine metal alone or by raising speed alone, but may follow a raising of mean effective pressures without any change in metal or speed. It may also be secured with the same metal by maintaining mean effective pressures with increasing speed, or even by lessening mean effective pressures at increasing speeds, provided the latter increases faster than the former decreases. It is therefore important to return to the question of mean effective pressure and examine it in the light of such arrangements of engine as may affect the weight of cylinder complete per cubic foot of displacement and the weight of shaft and frame per cylinder. Mean effective pressure indicated is entirely a question of port and valve size and of port, valve, and combustion chamber temperatures. The former affects the weight of charge by pressure drop and the latter by suction-temperature rise, but the latter also limits the compression, which is the other factor in mean effective pressure. Mean effective pressures referred to brake horsepower are the same, except for mechanical friction and in the case of two-cycle engines for pump work. Any alternative arrangements or detail form that do not inherently increase the suction-pressure drop or the suction-temperature rise or do not produce hotter internal combustion-chamber walls may be made to yield equally high mean effective pressures by the use of suitable proportions and dimensions of passages and chambers. Forms or arrangements of this sort that reduce engine weight per cubic foot also directly contribute to the desired result of reduction of weight per horsepower.

According to this, a given number of fixed water-cooled cylinders of the same size should yield the same indicated mean effective pressures, no matter how they are arranged, whether, for example, four are radial or in line, six in the radial groups of three each or all in line, eight in line or in two fours V connected. Any differences actually found must be charged to proportions, to carburation, or to ignition, and can not be regarded as inherently characteristic of the grouping, though, of course, mean effective pressures referred to brake horsepower will differ by the difference in mechanical friction, which is least for the least product of bearing surface and mean bearing pressure. The same is not true for fixed air-cooled cylinders because their form and arrangement does, to an appreciable extent, affect their temperatures, though the suction-pressure-drop effects can be made the same for all. Therefore, more differences may be justifiably expected among fixed air-cooled than among fixed water-cooled cylinders.

The fixed air-cooled cylinders are likely to run hotter than the water-cooled cylinders so their mean pressures would be lower, as much so as the cooling is ineffective.

Rotating air-cooled cylinders taking their charge through the pistons, probably suffer the greatest of all suction heating effects and must be expected to have the lowest mean effective pressures, indicated and brake, more so because the windage is added to mechanical friction.

Automatic suction valves whether used in fixed cylinders or in the pistons of rotating cylinders, must always oppose suction by greater pressure drops than mechanical valves, each suitably designed, so such engines should have lower mean effective pressures.

Thick-walled cylinders and thin-walled pistons should run hotter than thin cylinders and thick pistons, so differences in mean effective pressure may be expected in these directions, always subject to proper selection of proportions in other directions.

Speed limits should inherently be the same for all fixed cylinder engines, no matter how disposed, so that with proper proportions there is no reason why any arrangement should suffer a greater falling off in mean effective pressure with speed increase than any other, however much the constant high value for one may differ from that of another. Rotating cylinder engines are, however, subject to lower speed limits than are fixed cylinder machines, on account of centrifugal forces, though there is no reason why one kind of rotating cylinder engine should not run as fast as another, nor why all should not suffer the same rate of decrease in mean effective pressures with speed increase, as do fixed cylinder engines except as windage may cause greater losses, referred to brake horsepower.

Any one type of cylinder and piston will run hotter the larger its diameter, so a given piston area in a large number of cylinders should result in higher mean effective pressures from the reduction of suction heating and the increased compression made possible by the cooler interiors. Therefore an eight-cylinder V should be better than four or six cylinders in line of equal displacement, and the rotating cylinder engine of several rows and cranks should be better than equal displacement in one row and one crank.

Similarly a large stroke bore ratio, favoring smaller piston diameters for equal displacements, should yield higher mean effective pressures than a small ratio but this difference is necessarily small, as reduction of cylinder diameter from 6 to 5½ inches, for example, can not greatly affect interior temperatures.

These principles should all be checked by experimental data and can be so checked, but such data have never yet been obtained, largely, because such tests as have been made were directed toward a comparative judging of engines in competition, and were not conducted for discovery of principles of construction. Such results as are available are compared in Table 12 with reference to the variables discussed. In the same table are incorporated the figures for thermal efficiency which controls the weight of fuel to be carried. This, while slightly affected by valve resistances as is mean effective pressure, is dependent primarily on compression for indicated efficiency, and on engine friction and negative work for brake efficiency. It therefore is most affected by temperatures of the charge before compression starts and by interior temperatures, as these affect the maximum compression. As might be expected therefore the differences between the thermal efficiencies are less than those between mean effective pressures.

TABLE XII.—*Mean effective pressure and thermal efficiencies versus type construction of parts.*

Cylinders and cooling.	Class construction.	Cylinder material.	Valve location.	Suction valve A. M.	Name.	Bore.	Stroke.	Revolutions per minute.	Mean effective pressure.	Efficiency.
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Benz	5.180	7.087	1,288	100.0	0.20
	6 cylinders in line	do	do	M	Daimler	4.724	5.512	1,315	107	.26
			Pocket	M	Mulag	4.331	6.693	1,346	101.3	.26
		Steel	Head	M	Daimler	4.134	5.512	1,387	114.4	.27
	8 cylinders, V	Cast iron	do	M	Curtiss	4	5	1,100	107.7	.22
			Pocket	M	Sturtevant	4	5.5	2,000	100.3	.24
	12 cylinders, V	do	do	M	Sunbeam	3.54	5.91	2,000	126.8	.25
Air cooled:										
Fixed cylinders	Radial star	do	Head	A	Anzani	3.54	4.72	1,250	76.2	.23
						3.54	5.12		78.5	.24
						4.13	4.92		76.9	.24
Rotating cylinders	1 radial star	Steel	do	A	B. M. & F. W.	4.331	4.724	1,031	66.6	.16
	2 radial star	do	do	A	German Gnome	4.33	4.72	1,200	67.0	.21
						4.72	4.72		67.2	
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,412	103.5	0.27
	6 cylinders in line	do	do	M	Argus	4.021	5.118	1,370	101.1	.23
	8 cylinders, V	do	do	M	Curtiss	4.25	5	1,250	111.7	.25
			Pocket	M	Sunbeam	3.54	5.91	2,000	126.5	.25
Air cooled:										
Fixed cylinders	Radial star	do	Head	A	Anzani	4.13	5.71	1,250	83.2	.27
						4.53	6.10		80.1	.25
						4.13	5.52		86.2	.26
Rotating cylinders	1 radial star	Steel	do				4.748	954	76.9	.17
	2 radial star	do	do				5.51	1,200	78.7	.21
							5.91		65.2	
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	5.512	5.906	1,373	102	0.28
	6 cylinders in line	do	do	M	Schröber	4.882	6.299	1,252	79.2	.22
	8 cylinders, V	do	do	M	Curtiss	5	7	1,100	104.7	.24
Air cooled rotating cylinders	1 radial star	Steel	do	A	Gnome	4.331	4.724	1,194	75	.17

Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,343	107.1	0.27
	6 cylinders in line	do	do	M	Hall Scott	5	7	1,300	92.75	.21
Air-cooled rotating cylinders	1 radial star	Steel	do	A	Gnome	5.118	4.724	1,156	71.3	.17
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.331	5.512	1,396	102.8	0.27
	6 cylinders in line	do	do	M	Austro-Daimler	4.72	5.51	1,300	94	.26
Air-cooled rotating cylinders	1 radial star	Steel	do	A	German Gnome	4.33	4.72	1,200	67.9	.21
						4.72	4.72	1,200	67.2	
						4.88	5.51	1,200	78.7	
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Daimler	4.724	5.512	1,394	93	0.27
	6 cylinders in line	do	do	M	Austro-Daimler	5.12	6.89	1,200	93	.26
Air-cooled rotating cylinders	1 radial star	Steel	do	A	German Gnome	4.88	5.91	1,200	65.2	.21
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	N. A. G.	5.315	6.299	1,344	101	0.28
	6 cylinders in line	do	do	M	Benz	4.17	5.91	1,250	113.5	....
Air-cooled rotating cylinders	1 radial star	Steel	do	M	L. O. Rhone	4.13	5.51	1,200	85.6	....
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	N. A. G.	4.724	4.724	1,408	94.9	0.26
	6 cylinders in line	do	do	M	Wright	4.375	4.5	1,400	83.7	.23
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Argus	5.512	5.512	1,368	106.5	0.26
Water-cooled fixed cylinders	4 cylinders in line	Cast iron	Head	M	Argus	4.931	5.118	1,342	107	0.23

NOTE.—Values for mean effective pressure taken from Table IV, where source of information is given. Efficiencies calculated from fuel consumption values in Table V, where authorities will be found.

There appears to be no consistent difference between the performance characteristics of steel compared with cast iron, as combustion chamber materials, when measured in terms of mean effective pressures or thermal efficiencies. The same is true, as might be expected, for fixed cylinder-crank shaft arrangements of four or six in line compared with 8 or 12 cylinder V, or star, though the figures for the latter do fall off a little. As indicated before, the fundamental difference is in air versus water cooling, and fixed versus rotating, or crank case versus direct admission of charge. Fixed cylinders are always superior to rotating, other things being equal, direct charge admission to crank case admission, and water cooling to air cooling.

Reliability of the engine as affected by arrangement, form, proportions, and materials is partly a process question and partly one of endurance of structure. So long as the mixture is made regularly and properly received into the cylinders, and then treated always the same, which includes ignition and cooling, then the mean effective pressure and thermal efficiency should remain the same, and the engine continue to run indefinitely. This is the process part of reliability. It is equally necessary, however, that no part shall break or fastenings loosen, and that bearings shall neither seize nor wear too fast or unevenly. Breakage means immediate involuntary stoppage, and loosening or bearing trouble a more or less fast approach to a stoppage, which, if anticipated, may be voluntary, or if not, a stoppage essentially the same in immediate effects as a breakage.

There is no excuse to-day for any greater number of breakages of aero engine parts than of similar parts of other engines, provided the same amount of skill and foresight in design and construction are exercised. The fact that the consequences of breakage are so much more serious in the case of the aero engine than in any other is sufficient reason why the breakages should be even less than on any other, and should not exceed those that could be called pure accidents beyond the utmost skill and care. It is, however, undoubtedly a fact that stress analysis, skill, and material data, for operating conditions, are far less generally applied to aero engine design than to other important classes of machinery. This is partly because the youth of the art has kept the inventor in the foreground and the computer behind, but largely through lack of rigidity of requirements by purchasers and lack of financial support of the business. If the business of aero engine production were large and regular, or Government supported, it could not only afford to pay experienced stress analysts, metallurgists, and material investigators, but would be forced to do so.

Breakage prevention is therefore almost entirely a question of money, and of realization that design is not purely invention. It is, however, somewhat a question of arrangement and form, for, as has been mentioned, from time to time some arrangements or forms lend themselves better to design for assurance against breakage than do others, or some promote a reduction of seriousness of the consequences of breakage, if it does occur, through pure accident. An illustration of this latter point is the case of the rotating cylinder arrangement versus the fixed. Breakage of a cylinder fastening means a throwing off of the mass under the influence, not merely of the gas pressure but of centrifugal force as well, and with a good possibility of much more serious consequences for the former. Even the breakage of one of the radial valve tappet rods will cause a loose end to fly out and whip through the supporting structure. Such is believed to have been the cause of wrecking a British machine in flight and causing the death of the two passengers. Partial ruptures such as cracks in piston and cylinder are preventable by proper cooling, but the substitution of steel for cylinders directly contributes to this result, as does arching of pistons, the former a contribution of materials and the latter one of form to structural permanence. Complete ruptures are probably more common in valve stems and other small parts than in the main elements of frame, shaft, cylinder, piston, and rods, indicating lack of care or insufficient experience.

All such things are to be eliminated by organization, supplemented by time and by long periods of operation of experimental engines, run under specified unfavorable conditions to complete destruction of any one part under investigation, such as a valve and stem, or of the whole structure. Testing to destruction is the very best way to accelerate experience without danger to anyone. As in the case of the other illustration cited, however, form can contribute something to the reduction of consequences of breakage, and in the case of the stem of the head valve, this has been attempted by placing the edge of the valve seat slightly over one side of the cylinder bore in an offset, or complete enlargement of diameter at the clearance and with the valve circle tangent to the bore. Should a stem break, the valve will drop to the cylinder shoulder instead of on top of the piston, which smashes it or itself, provided the break is high enough upon the stem so the stem does not emerge from the guide. Otherwise the result is quite the same as if the shoulder were not present, except that a larger diameter of valve is possible than without such extension of the bore. This valve trouble is supposed to be quite prevented by side-pocket location of valves, but is not, because should the valve drop into the pocket there is every chance of it sliding over on the piston under the influence of a suction stroke, especially if the flat bridge inclines downhill, as it usually does in single cam shaft V engines, for example, though placing the valve on the opposite or downhill side would prevent it, but would require two cam shafts.

Prevention of undue wear on shaft and pin bearing surfaces is entirely a question of bearing pressures and lubrication. These bearing pressures are all subject to pretty accurate determination by computation, so the design of an engine with excessively high bearing pressures, judged by general machinery bearing experience, is a pure technical mistake, not to be excused by the addition of elaborate forced systems of pump oil supply. Bearings should be large enough to not need elaborate special oils or oil-application systems, but these should be added to make assurance doubly sure, in short; as safety attachments, not as essential elements. Weight reduction secured by cutting down main and pin bearings is too dearly bought to be worth the price. Cylinder and piston bearing wear, while involving the same elements as main bearings, have to endure the additional difficulty of high temperature, but this is not serious if due attention is paid to the principles of heat abstraction. Violation of these principles, coupled with a rise of side thrusts, aggravated by side cocking that follows undue shortening of pistons, is another case of pure neglect. Pistons should be as long and as thick at the top as is consistent with weight-speed limits, and where observance of these limits fails to reduce the pressures and temperatures to values known to run properly in other engines, then definite special remedies can be suggested, only one of which is excessive use of lubricating oil and the last to be adopted instead of the first.

Seizing of running parts at bearing surfaces is entirely a question of relative size or of clearances, and its prevention a question of maintenance of the cold clearances after the parts become heated, which, of course, is least necessary, the better the provision for abstracting and dissipating the heat derived from combustion or developed by friction. Next to cooling, which in main and crank pin bearings is not attempted, though it might well be, and which in cylinders and pistons is their big problem, material selection is most important. Some materials have low relative frictional coefficients for their lubricated surface and are properly related as to thermal expansion. Nothing better than the soft-metal lined or bronze can be found for steel shafts and pins, especially as these expand more per degree rise than the steel, so heating tends to loosen and oppose seizing by assisting lubrication, which by lowered oil viscosity tends to become less effective. The boxes must, however, be stiff enough to really distribute stress. Piston and cylinder bearing surfaces are somewhat more difficult, as the outer part, the cylinder, is normally much cooler than the inner part, the piston. The temperature difference is greater the thinner the pistons, and the difference is much greater than in the case of the standard box on the pin or shaft. It is, therefore, more necessary to care for these clearances. This is done when the materials are the same, cast iron on cast iron, by making the initial clearance high, far higher than would be feasible on shafts. This tends to promote side knocks and leaks at part load. For equally good cooling the steel cylinder with cast-iron piston gives about the same expansion relations as do the bronze box and steel shaft, but not such good antifriction qualities. Steel selection and heat treatment will undoubtedly lead to improved antifrictional results, perhaps even equal or superior to cast iron, after proper research. This seems to be a rational and promising line of development, especially if the cylinders are kept symmetrical, as they can be with head valves.

Reliability so far as carburation, ignition, mixture distribution, and cylinder treatment processes are concerned, has already been discussed. Any derangement whatever here leads to impaired power output or increased and perhaps very much increased fuel consumption. Serious derangement of these processes means stoppage even though the whole engine structure be perfect. Most operating troubles are directly traceable to these process derangements, which if sufficient in degree, mean stoppage, and even if slight, constant tinkering and anxiety.

Adaptability of an internal-combustion engine to aeronautic service is promoted by certain features of the engine that play no part in metal reduction, in mean effective pressure and efficiency increases or in its reliability, though of course low weight of engine and of fuel per horsepower are themselves adaptability factors, as is also any element of reliability.

General external shape and position of points of attachment are subject to a far wider range in aero than in auto engines. In one respect aero adaptability imposes a direct requirement, that of end shape for least head resistance. Engines directly exposed to the air or their casings when covered have a relative movement always approaching, and sometimes exceeding, 100 miles per hour. This must always impose a resistance which is larger, the larger the end area facing the direction of flight and the less smooth the exposed surfaces are. In this respect the rotating-cylinder engines are by far the worst and the single line of cylinders of the auto type of multi-crank engine is best, nearly twice as good as the V engine for example. Air-cooled engines if similarly arranged to water cooled offer more head resistance except for the radiator of the latter which may be very highly resistant but is not necessarily so. But apparently the requirements of low head resistance is losing in importance, at least for war machines, since in these the fuselage is roomy enough generally to accommodate any type of engine.

Ease of starting and a control of speed are also required of aero as of automobile and boat engines, but with some elements of difference. Electric self-starters with generator-motor and storage batteries are prohibited by weight limits, for even if the craft could carry them their weight would be much better disposed in the engine by adding either more horsepower of the same unit weight, more fuel for the same engine to make longer flights, or for equal flights and engine power by using a heavier built and therefore less sensitive engine of longer life. When starting from the ground a starting crank on the shaft end often would be inaccessible and even if it were within reach, engines of large power could not be hand rotated against their normal compression. It has been a general practice to start these engines by hand turning of the propeller blades, a practice that is most dangerous, does the blades no good and certainly requires an extra man because at the moment of starting the operator must be in his seat. All hand-starting difficulties are removed if the compression is relieved and the accessibility of a starting crank can be met with equal ease by a chain and sprocket having a self-releasing ratchet and hand crank on a short auxiliary shaft, near the operator's seat. It may therefore be regarded as necessary that aero engines, certainly the larger ones, and this means most of all if not all of those to be built in the near future, be provided with compression-release cams, equivalent to those so long used on hand-started stationary engines and lever operated from the seat. This same compression release gear will serve as a speed control, should speed variation be necessary, by permitting escape of part of the charge though, of course, with waste of gasoline. It serves as a supplement to the throttle valve of the carbureta, and which is not so wasteful of fuel. Speed reduction by spark retardation should not be practiced on aero engines, though a starting retard is necessary, automatic or manual, because of the serious overheating effects that follow, and aero engines at best are hard enough to keep cool at their high speeds.

Muffling may be regarded as a necessity, however much free exhausts have been used in the past, and whatever unfavorable weight and power effects are imposed must be regarded as warranted. Noise from the exhausts of so many cylinders operating at high speeds becomes a loud roar. There are at 1,200 revolutions per minute from the 20 cylinders of the Le Rhone engine, for example, $600 \times 20 = 12{,}000$ air impacts per minute, and at 2,400 revolutions per minute the eight cylinders of the Sunbeam engine give $1{,}200 \times 8 = 9{,}600$ impacts. With such a disturbance close to him no operator can be expected to keep his head as clear for the serious business of flying as if the noise were absent. To detect engine defects by the noise changes in the machine before they become serious is absolutely impossible, though this is the main reliance in operating any other kind of machine. Free exhausts must be classed, therefore, not as annoyances but as preventers of engine-trouble detection, no matter what the type of machine, and for military machines they are the finest kind of approach signal to the enemy, being audible long before the machine is visible.

Mufflers can be made, due to automobile development, that are quite effective with no more than 2 pounds per square inch back pressure, and possibly less. This will reduce engine output 2 per cent if the mean effective pressure is 100 pounds per square inch, as it is in aero engines, less than 2 per cent for higher, and more for lower mean pressures. The weight increase is almost negligible, being between one-tenth and two-tenths of a pound per horsepower.

Just as soon, however, as mufflers are demanded as a necessity the rotating cylinder engine must be changed or abandoned, as normally the exhaust valve is placed in the center of the head, usually held in place by an open cage screwed to the cylinder, discharging directly into the air. To attach a muffler will require a change of the cage to a closed form with pipe attachment and additional cooling to keep the now inclosed valve as cool as the open one. The muffler would have to be disposed symmetrically about the shaft and inwardly radial pipes held against centrifugal force at the muffler, fitted to the exhaust cage by slip joints. These pipes must, moreover, be circumferentially supported to prevent distortion by variable angular velocities, and they will impose additional windage resistance. The net effect will be a greater reduction of power and a greater increase in weight than muffler attachment imposes on fixed cylinder engines.

It goes without saying that no aero engine with tanks and connections complete is adapted to its purpose if tilting even to very considerable degrees interferes with its operation, and if it stops on tilting to any angle that is remotely possible in real flying it certainly must be rejected as failing in adaptability. There is considerable uncertainty as to the angle and direction of tilt that aero-engine adaptability requires, but the 15° required in the German and British contests seems to be a very modest requirement. No one will deny that the greater the angle of tilt and the more independent of direction, the better the adaptability factor. The conditions when tilting in flight may be quite different from those existing in a tilted engine at rest, especially when the motion is in curves developing centrifugal forces in all masses as well as in the lubricating oil and fuel feed system. Therefore, in considering engine independence of tilting, rapid change of motion as to speed and direction, but especially direction, must be included.

Any changes of direction of motion that the planes could withstand can have no appreciable effect on the motion or friction of the moving masses, but the effects on lubricating oil in the crank case or separate tank or pipes and on the gasoline in the carburetor float chamber, tank, and pipes may easily be as great as in extreme tilting. It is quite possible to imagine a resistance to flow, for example, purely gravitational or purely centrifugal, or both, great enough to cause engine trouble, in the one case from failure of the carburetor and in the other from overheating of bearings robbed of oil, or from flooding of combustion chambers whose pistons get an excess. It is likewise possible that the water-circulation system be similarly deranged by opposition to circulation, causing steam to generate in a jacket, expelling all water, and causing an overheating, with a possibility of a crack, or by a drainage of water from the radiator vent. If an engine could so be designed that it could work on end, lying on its side, or even upside down for a short time, but preferably indefinitely, this would be the ideal. No such possibility is in sight, though engines are now operating in machines moving in curves and circles in horizontal planes, turning the engine on its side, but centrifugal force replaces gravity and no flows are disturbed. Similarly, looping or circle flying in a vertical plane turns the engine so that it operates first on end and then upside down, but, as before, the centrifugal force replaces gravity. Such is not the case, however, in a steep climb or descent nor in the uptilting of one end of the plane due to wind gusts. Here gravity flows are disturbed by the amount of side and end angle. Crank shafts and pin bearings must receive new and end thrusts which are not difficult to handle if they all are properly journaled.

Crank-shaft torque that is most uniform is best adapted to propeller drives, as these propellers being made of wood for lightness may be broken by sudden torque changes. Such changes also reduce the average propeller efficiency and produce reverse rocking forces in the machine frame. Any engine with insufficiently steady torque for propeller safety and for maintenance of high average efficiency may be adapted by addition of sufficient fly-wheel effect between engine and propeller. The same fly-wheel effect increases the crank-shaft torsional distortion and crank deflection and adds to engine weight. Engines that can give sufficiently uniform torque for the purpose without fly-wheels must displace others, and while the four cylinders in line engine seems to serve, it is true that the effort falls to zero on dead center. Anything less than four cylinders is out of the question, because the gas-pressure effort is entirely absent for a part or a whole stroke or more. Increase of number of cylinders over four makes the actual effort or resultant tangential force due to combined gas pressure and reciprocating inertia forces depart less and less from the constant mean effort and minimizes the angular velocity variations of the propeller without any other fly wheel than itself. From this standpoint the more cylinders the better, though from others discussed this is not the case.

Arrangement of a given number of cylinders radially about one crank produces the same torque curve as the same cylinders in line, provided their cranks in the latter case are separated by the same angles as their cylinder axes in the former. When, however, these cylinders in line have cranks parallel in pairs, as in the four and six crank arrangements, the torque will not be as uniform as when these are radially disposed about one crank. It appears, however, that the 6 cylinder in line, 6-crank arrangement, in which the torque never drops to zero, is quite uniform enough for practical work, and the 8 and 12 cylinder V arrangements are progressively better. There is no reason for adopting the radial arrangement if, as is the case, other objectionable elements are introduced, because the above is good enough and anything better not worth another disadvantage. Comparison of turning efforts for any arrangement of cylinders and cranks is easy if they be plotted to a crank angle or crank path base by the usual standard methods. Many of these curves have already been worked out and may be found in the literature, including the inertia as well as gas-pressure force effects, and for such reference is made to the bibliography in the appendix. In no case may a fly wheel be introduced in aero engines to dampen torque variations because of weight limitations.

Balance of reciprocating parts in view of the light and flexible character of the engine supports which are part of the flying-machine structure, is probably the most important of the adaptability factors, because lack of balance means free shaking forces or moments on the whole system, and these being regular and periodic may periodically synchronize with the natural periods of wires, struts, and beams, and so cause displacements of such increasing amplitude as may be responsible for rupture. In no other engine, including the automobile, motor boat, and even the light shell of the racing boat, which comes nearest, is the support so frail and of such small mass capacity for absorbing vibration forces. Therefore, all unbalanced forces or couples and the full displacements or vibration of the engine as a unit are communicated directly to the flying-machine structure practically without any modification. Moreover, aero engine weight being so small in comparison with other engines, its own mass resists displacement by its free unbalanced forces and couples less than any other. For these reasons good balance is essential to aero engines, but absolutely perfect balance is not.

Shaking forces and moments in engines are due to both reciprocating and rotating masses, and vibration or rocking is the result of a failure to balance these forces and moments. Shaking forces due to rotating masses can be balanced perfectly by other rotating masses disposed on opposite sides of the shaft center with proper numerical relation between centers of gravity, radii, and weights. If the plane of rotation of the original rotating mass is not the same as that of its balance weight or weights, then there will be an unbalanced couple even if the centrifugal forces are in balance, unless balancing masses be disposed properly in separate planes, themselves properly related. Due observation of these simple and well-known relations make it a perfectly easy and simple matter to balance rotating parts of an engine by adding suitably disposed extra rotating balance masses. Such dead balance weights are, however, prohibited by the service requirements of least weight per horsepower, so the actual rotating working parts must themselves be so disposed as to balance each other. These parts include the cranks, crank pins, and rod ends principally, but also such small parts as the cams. If cranks, pins, and rod ends are balanced, other minor rotating parts may be neglected, though they set up inevitably some small shaking forces, especially as the speeds are so high, and these forces vary with the square of the speed.

Accordingly, to balance centrifugal forces and couples, due to cranks and their attached rotating masses, of fixed cylinder engines similar cranks must be suitably disposed with reference to the first. To avoid unbalanced couples with balanced forces more than two such cranks are necessary and in different planes. Two similar cranks at 180°, three at 120°, or any number equally spaced will result in force balance, because each introduces an equal force vector, and, the sum of the vector angles being 360°, these vectors will form a closed equilateral force polygon, which means, of course, a zero resultant. Each set of such equally spaced cranks is characterized by a free couple, to balance which a similar and opposite couple must be introduced by adding a similar set of cranks with equal but reversed angular spacing.

Applying this reasoning to fixed cylinder engines, it appears that the least number of cranks that can give couple and force balance is four, set at 0°, 180°, 180°, and 0°, and the next smallest number, six, set at 0°, 120°, 240°, 240°, 120°, and 0°. Of course any multiples of these four and six crank arrangements will also yield such balance. This indicates a condition of inferiority of the fixed cylinders star engine with many cylinders circumferentially disposed about each crank, compared to the single-row and double-row V engines of equal number of cylinders. These star arrangements must have as many multicylinder stars, each working on its own crank, as the single and double rows of parallel arrangement has cylinders, in order to secure equally good rotating mass balance. This would impose on such fixed star cylinder engines an excessive number of cylinders, unless crank counterbalance weights were introduced, with consequent loss of the weight advantage otherwise due to the star arrangement.

Rotating cylinder star engines are peculiar, because with fixed cranks all parts of the engine are rotating—cylinders and frames in purely circular paths, pistons and wrist-pin ends of rods in a sort of oval path, while crank-pin ends of rods are fixed. According to this the cylinder and frame are in force balance when axis angles are equal, and all being in one plane there is no unbalanced moment. The centrifugal force due to the rotation of the piston is a maximum and radially outward when the piston is at outcenter, and a minimum at the incenter position with regular symmetrical gradations between. The net effect is a resultant force constant in amount and direction acting radially outward along the crank and exerting a lifting action if the crank points up, but not producing any vibration so long as the speed is constant. From the balance standpoint, therefore, the rotating star is superior to the fixed star arrangements, but is no better than the four and six cranks and their multiples with parallel rows of cylinders.

Reciprocating masses of fixed cylinder engines, such as pistons, wrist pins, and an appropriate part of the connecting rod, develop inertia forces for uniform rotary motion of the crank that can be expressed by an equation of the form of Fourier's infinite series, each successive term being proportional to a trigonometric function of a multiple of the angle of rotation from inner dead center and to increasing powers of the ratio of crank to connecting rod length. The reciprocating inertia force of one set of reciprocating parts is therefore the sum of an infinite number of forces of different periods or frequency, the first being largest and its period that of an engine speed, each successive one being smaller and of longer period. These reciprocating forces and the couples due to them must be balanced perfectly if possible; and if not, as well as possible. The forces due to valve and valve-gear reciprocation with accelerations determined by cam form may be neglected, though of course if these could be balanced in a simple way it would be desirable.

Balance of main reciprocating forces is possible only by opposing equal and opposite masses of equal simultaneous acceleration, or by arranging reciprocating masses in groups, so that the vector sums of their inertia forces become zero. There is, however, a partial balance possible by the use of crank counterweights or otherwise disposed rotating masses frequently used on stationary and locomotive engines, but normally prohibited on aero engines, on the principle of exclusion of all dead weights, even for balance purposes. A rotating crank counterweight exerts a radial centrifugal force which may be resolved into an axial and a right-angle component. This axial component may be made equal to the first-period inertia force, and, being, of course, opposite, it serves to balance this force. The right-angle component is, however, left and of equal intensity, and so, of course, are all higher period inertia forces. Such counterweights are therefore quite useless alone for flexibly supported engines, though when used with one particular combination of pistons and cylinders they become serviceable without very great weight increases. This special case is that of two cylinders set V at 90°, for here there are two first-period inertia forces at right angles, which are in balance with one counterweight, of mass equivalent to one of them for first-period forces, though higher period forces are still free.

As first-period inertia forces are similar to the axial components of rotating centrifugal forces, a similar grouping of multiples serves to produce balance effects. Such, for example, is the case with the four parallel cylinder four-crank arrangements in which, without balance masses, the first-period inertia forces are balanced, and, of course, also in the 8-cylinder V, which is a duplication of similar parts.

All combinations of arrangements of reciprocating parts for parallel, fixed star, and rotating star cylinders can be examined mathematically or graphically, and most of the proposed arrangements have been so studied and are reported in papers and books noted in the bibliography of the appendix. Of these perhaps the most elaborate is that of Kolsch in his book published in 1911, where conclusions are reproduced on mass balance of both rotating and reciprocating parts. Engines that are in complete mass balance without introduction of balance weights include the fixed cylinders 6, 8, 12, and 16 in a row each with its own crank, the 12 and 16 in two rows V with two cylinders per crank, the two cylinders opposed axes in line with two cranks and its multiple, and all rotating star cylinder arrangements having four or more cylinders per star. Those that are balanced for rotating masses and for the first period reciprocating mass forces but not higher ones, without balance weights, include the fixed cylinder engines of the four parallel cylinder four-crank arrangement and its twin or 8-cylinder V.

Introduction of balance masses gives complete balance to fixed cylinder star engines of four or more cylinders and a balance of first-period reciprocating inertia forces but not of higher ones to the 2 and 4 cylinder V and the 3-cylinder fixed star radial. This fundamental need of balance weights for fixed radial cylinders is also mathematically demonstrated by Milner, who says: "The engine will be completely balanced for primary and secondary forces by a mass $\frac{n}{2}$ times that one of the pistons ("n=number of cylinders") and diametrically opposite and same radius as the crank.

Of course this is in addition to the mass required to balance the rotating parts of the engine. The rotating cylinder engine ordinarily has one connecting rod heavier than the others which itself makes perfect balance impossible.

More cylinders and cranks than are necessary to give the required torque constancy, or the required balance, or the total power within the cylinder diameter limit can not be accepted. Each additional individual cylinder carries with it sources of additional trouble and increases the chances of unreliability, however much the consequences of failure may be reduced. The least allowable number on this basis appears to be 4 fixed cylinders in line or radial fixed or rotating. The maximum should be 6-cylinder 6-crank in line for balance or 8-cylinder V for torque, both advantages being equal in the 12-cylinder V, or twin 6. Of course the rotating cylinder engine of equal number of cylinders and symmetrical parts is just as good in torque and balance, and even a lesser number down to four equal in balance, though deficient in torque, but these rotating cylinders are in no way superior to the above arrangement. Stars fixed cylinders of equal number are equal in torque to the same number rotating if similarly disposed, but inferior in balance unless rotating counterweights are introduced, in which case equality results.

CONCLUSIONS AND RECOMMENDATIONS.

In the following brief statement of recommendations and conclusions, which are presented in the form of a list, no effort is made to develop arguments in support of each because it is believed that the text and appendices of the report themselves serve as sufficient support. No specific type of engine, form of part, material, or design constant is recommended, because it is believed that attention at this time must be directed mainly to methods of procedure that will lead to improvement. Naturally specific recommendations on design could be made, and these will be available at such time in the future as they may be desired.

1. The art has developed several typical arrangements of engine and several different designs of each type that may be regarded as of proven acceptability as to weight per horsepower of engine and thermal efficiency, but which require considerable work to perfect and standardize in detail and material without any further inventive work than properly constitutes part of the normal routine of research and designing engineers. These types are the 4 and 6 cylinders in line, each with its own crank, the 8 and 12 cylinder V with two cylinders per crank, all fixed cylinders and operating with both air and water cooling, preferably the latter, for long flights, and finally the radial star rotating air-cooled cylinder form for short flights.

2. There have also been developed a very large number of special designs of engine, which in some instances have been built and used but in others remain mere suggestions. Each one of these is practically an invention in itself, the precise practical value of which remains more or less in doubt. To properly develop the good points of these and other inventions to come, and to reject or eliminate unfavorable elements that are always present in new machines that have not yet stood the test of time, much work must still be done, quite independent of the research work so necessary for final perfec-

tion and standardization of the now acceptable and more or less largely used types noted above.

3. Direct governmental aid is an absolute necessity to the art, both for the perfection and standardization of accepted types and for encouragement of further invention. Private contributions should also be encouraged, whether for use in connection with the governmental establishment or independently.

4. There should be a regular buying program providing for the purchase of a fixed minimum number of aero engines yearly, to encourage existing engine builders to spend the money necessary to produce what is wanted to meet aviation specifications, because the best shops will not enter the field without some definite assurance of a fixed amount of business, for which they are, however, quite willing to compete.

5. The aviation engineers should standardize service specifications for engines, limiting the specifications strictly to those items that bear directly on service, so designers and builders may know definitely what conditions must be fulfilled without being hampered with purposeless limitations as to the means to be used by them.

6. The Government should conduct regular annual test competitions of engines on rules to be prepared and widely published at least 10 months in advance, and revised yearly immediately following the closing of the previous contest. For those engines that make the best records, substantial rewards must be provided in the form of cash prizes, or buying orders, or both. These cash prizes may be provided by Government appropriation, by private contribution, or both together.

7. There should be established a standardization research laboratory with a permanent staff of engineers selected for efficiency. This staff should conduct the competition tests, over not more than two months of the year, including the reports, and during the rest of the time should carry on tests for design and performance data of every engine of the accepted class noted in No. 1, but of no others. Other engines are to be admitted only on the recommendation of a second laboratory staff devoted to development of invention noted in No. 8.

8. There should be established a laboratory for development of inventions submitted by anyone, when those inventions seem promising. This staff must be quite independent of that of the standardization research laboratory noted in No. 7, and should preferably be located in quite a different place. Its engineers should be, in ability and temperament, quite different as well. When in this laboratory an engine, engine part, or accessory not in the accepted class, has been brought to a condition where its performance is equal or superior to what is in the accepted class, then it may be recommended to the standardization research laboratory for further study and perfection.

9. In at least one of the Government shops, possibly located in one of the navy yards, actual construction of engines of the accepted classes should be undertaken on about the same basis as is now followed for ships, the military shop competing with civilian shop in price and performance. Safeguards must be introduced to prevent any discouragement of private enterprises or charges of unfairness in this competition.

10. Officers and enlisted men who may be charged with the care of aero engines in service should be assigned to duty, first, in the Government aero engine shops, then in both the standardization

research and the invention development laboratories, and finally in the engineering office noted in No. 11, for instruction.

11. There should be established a staff of supervising and designing engineers for internal combustion engines. This staff should prepare all purchasing specifications, prepare engine test competition rules, receive and use all standardization data from the laboratory, exercise general direction over both the laboratories, and prepare detailed drawings for the shops.

12. There should be established the closest possible relation between aero-engine development and that for other classes of internal combustion engines in which the military now has or may in the future have an interest. Among these are included submarine engines, ship and launch engines, automobiles and auto trucks, gun and transport traction engines, and stationary electric generation sets for wireless, mine firing, searchlights or general service. The same designing staff, laboratories, and shops that should be established for aero engines can also advantageously undertake similar work for these other internal combustion engines, as most of the fundamental training, knowledge, data, methods, and skill required for the one is also of equal service to the others. Similarly, officers and enlisted men of those other branches of the service can be given adequate instruction by temporary assignments to the shop, laboratories, and engineering office.

13. Publicity of data should be promoted by governmental publication of reports to keep alive the general interest in the needs of the Military Establishment in the internal combustion engine field, because the greater the interest the greater the contributions of the profession. This publication may also take the form of papers prepared by engineers of any of the various staffs and presented to the national engineering societies. Not only should domestic results be thus given publicity, but all foreign papers and official reports of value should be translated and republished. Whenever data is regarded as being strictly military in value and where publication is therefore deemed inadvisable, such material can, of course, be withheld, but it is believed that in general both Army and Navy have more to gain than to lose by publicity of engineering data on engines.

14. It is regarded as of the utmost importance that advantage be taken by the Government of the service of such civilian engineers as have given special attention to the study, commercial development, and use of internal combustion engines of all classes, and more particularly those not engaged in manufacturing, though not excluding those of high professional standing that may be so engaged. The special knowledge, skill, and experience that these men can bring immediately to the service of the Military Establishment should prove as invaluable here as it has abroad, in Germany, for example, first in organizing the various working staffs recommended above, and later in working with them. Advantages may also be taken of the laboratories of such of the engineering schools as have specialists of the above type on their faculties, or as may be located in large centers where such men not associated with engineering schools may have their regular offices.

15. No recommendation is made on the details of the organization of these various staffs and their coordination with the existing Army and Navy Departments and bureaus except as to necessity.

NOTE.—Part 3 omitted. See note on Preface, page 187.

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