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No. 239

STEAM POWER PLANTS IN AIRCRAFT

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Bureau of Aeronautics, Navy Department

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STEAM POWER PLANTS IN AIRCRAFT.

By E. E. Wilson.

The employment of steam power plants in aircraft has been frequently proposed. Arguments pro and con have appeared in many journals. It is the purpose of this paper to make a brief analysis of the proposal from the broad general viewpoint of aircraft power plants. Any such analysis may be general or detailed. If the approximate analysis shows considerable promise, then an ultimate analysis may be proceeded with.

General Considerations

Power plants for aircraft must meet certain requirements considerably different from those which other power plants are required to meet. A primary requisite of an aircraft power plant is light weight in proportion to the horsepower developed. Compactness is a fundamental requirement not only because compactness is associated with light weight but also because compactness is, of itself, an important factor in design. On this light weight horsepower ratio, aircraft power plants must be unusually reliable and must attain this reliability without attention in the air. They must develop a high percentage of their maximum horsepower at the beginning of a flight, and must sustain a relatively high percentage of their maximum power throughout the flight. They must attain high economy in fuel not only because of the cost involved in operation, but also because the weight of fuel consumed necessarily limits the cruising range and the pay load. Aircraft engines must be extremely flexible in operation; that is, capable of quick acceleration or deceleration from idling speed to full throttle, and vice versa, and of fine adjustment at any crank speed throughout the flying range. Aircraft engines do not attain the long life between major overhauls required by other power plants at present, but long life is likewise of primary importance. To summarize, aircraft power plants must meet the following difficult requirements:

a) Light weight,
b) Reliability,
c) Economy,
d) Durability,
e) Compactness,
f) Flexibility.

Since the controlling factor in aircraft engine design is weight, it is important to consider this requirement. We are accustomed to compare engines on the basis of weight per horsepower. This coefficient in a given engine is capable of reduction, first, by reduction of the weight itself; and, second, by increasing the horsepower. Progress along these lines has been rapid and the limit has not yet been reached.

In our consideration of weights, we must bear in mind that we are not concerned with the bare engine weight alone, but with the whole power plant weight. The necessity for this is apparent at once when we compare conventional water-cooled engines and air-cooled engines. The dry weight per horsepower of these two types of engines is almost the same, but when we take into consideration the weight of the cooling system required by the water-cooled engine, we find a difference in total power plant weight of approximately six-tenths of a pound per horsepower.

In a problem of this kind, it is necessary to carry the weight analysis still further. The modern aircraft power plant, weighing about 3 lb. per horsepower and consuming about 0.5 lb. of fuel per horsepower, will at full throttle consume its own weight of fuel in approximately 6 hours. The fuel consumption of the power plant, then, is of great importance in this weight consideration. This fuel consumption must also be considered on a further basis of miles per gallon, and this consideration involves propeller efficiency. It has been stated as a general proposition that the aircraft propeller should turn, roughly, 10 R.P.M. per mile per hour for best economy. For an airplane flying 100 miles per hour, the best propeller speed will be in the neighborhood of 1000 R.P.M. Airplanes flying at 250 miles per hour on this same basis can be flown with good propeller efficiency at a crank speed of 2500 R.P.M. In the slower aircraft, then, the use of reduction gearing is indicated for crank speeds greatly in excess of 1800 R.P.M. In any consideration of this matter of weight, therefore, we must take into consideration the weight of the power plant, the weight of the fuel consumed, and the propeller limitations.

Our weight-horsepower ratio does not tell the whole story. Even though this may be excellent as measured from every standpoint, we must take into consideration the total weight of the power plant. As the total weight of the power plant increases, the wing area necessary to support it likewise increases and the weight of the structure to support the power plant increases. In other words, the total power plant weight is reflected throughout the whole structure. The size of an airplane is of primary importance and is of particular importance in naval aircraft. The limitations of storage space and handling gear aboard ship establish definite limitations of the sizes of aircraft which can be handled and this may readily require a larger number of small aircraft rather than a smaller number of large aircraft.

In the past, it has been rather widely felt that weight enters more largely into the factor of reliability than is now believed. A heavy power plant is not necessarily a reliable power plant. The weight must be properly placed, preferably in stressed parts, and must be eliminated from unstressed parts. It is hardly fair to compare the reliability of conventional aircraft power plants with that of ground or surface installations. Whereas a surface installation may have duplicate auxiliaries, the weight factor in aircraft engines procludes the use of multiple auxiliaries to a great degree. Thus, the conditions of operation in the air are entirely different from those of normal operation on the ground.

There is a general impression that the present aircraft power plants are comparatively unreliable. A careful analysis of engine failures indicates that a large percentage of them are due to troubles with gasoline, oil, and water lines. It is rather surprising to see the number of failures which are credited to the so-called "plumbing system." In the effort to reduce the total weight of these lines, it is of importance that we do not go too far and introduce the factor of unreliability. This high percentage of plumbing failures will be of interest to us when we come to investigate steam power plants somewhat later in this paper.

Approximate Analysis

With this basis established, we are now ready to make the approximate analysis of the suggestion of the employment of steam power plants in aircraft. Any steam power plant must consist of:

a) The boiler,
b) The engine,
c) The auxiliaries,
d) The condenser.

A condenser is absolutely necessary in aircraft for the reason that no airplane could possibly carry sufficient water to operate noncondensing.

Fortunately, we have as a basis of our analysis, a very thorough investigation undertaken by the Bureau of Engineering of the Navy Department, during the years immediately following the war. This investigation was carried on by a Committee on Experimental Power which included among its members some of the foremost American engineers who have been associated with steam-driven motor cars and gas turbine-driven torpedoes.

The Committee began its report with the following statement: "It is quite manifest that, theoretically, no steam plant can compete with the internal combustion engine in economy and fuel consumption, and in small powers it could not compete in weight of plant per horsepower." The accuracy of this statement is borne out by the fact that whereas aircraft engines are operating on a specific fuel consumption of 0.50 lb. of fuel per brake horsepower per hour, a good average figure for even a large steam power plant is not better than 1 lb. of oil per horsepower hour. Roughly, the specific economy of the steam power plant is about half that of the internal combustion engine as applied to aircraft. This is inherent in the cycles employed and the manner of employing them.

The Bureau of Engineering's report further presented the idea that the development of a practical steam power plant for aircraft propulsion presented three distinct problems:

(1) The production of a steam engine of minimum weight, which shall have the highest possible efficiency and lowest possible fuel consumption, and which shall possess reliability and durability. In the production of an engine possessing these characteristics, the Committee favored the steam turbine.

(2) The production of a suitable steam generator automatic in action. For this purpose, the Committee felt that the flash boiler was the only one which considerations of weight would admit.

(3) The development of a condenser. It was considered that this development presented more difficult problems than that of the engine and that the drag of such a condenser, no matter how well designed, would probably be prohibitive unless some such device as the "wing" radiator could be used.

The Committee considered that the foundation of a complete power plant was the steam generator. The generator finally arrived at, consisted essentially of a system of tubing into one end of which the feed water was forced, while from the other end the steam issued. No storage space for either surplus water or steam was provided. In a generator of this type, where there is no reservoir or stored heat, such as all water-level boilers possess, it was necessary that the exact proper proportions of fuel and water supply should at all times be maintained accurately. Fluctuations in pressure and temperature of steam due to sudden changes in the demand or load could only be prevented by self-acting devices. If controlled by hand, any changes in steaming rate would have been made cautiously. Such operation would not be practicable in ordinary use.

The Committee felt that the task of devising a practical generator was divided into two distinct problems. The first was the development of the generator proper, and the second the production of an efficient and practical system of controlling it when developed.

The particular form which this generator took was largely dictated by the fact that fire brick or other refractory lining for the combustion chamber could not be used on account of its weight. The combustion chamber (Fig. 1) was therefore enclosed within the walls of steel tubing through which the steam generated in the heating coils passed and became super-heated. In order to conserve the heat radiated from these walls, an air jacket surrounded the entire boiler, and air was drawn through this jacket by a fan blower and delivered to the combustion chamber. A light sheet steel casing enclosed the tubing in order to prevent hot gases in the combustion chamber from entering the air jacket, and the latter had an outer wall of thin sheet aluminum between which and the inner wall was a space of four inches through which the air passed. This method of heat insulation proved exceedingly effective and little heat was radiated to the atmosphere.

The ultimate design contemplated the use of fuel oil, but for convenience in experimenting, kerosene was used for fuel. Neither the heating tubes nor the metal casing enclosing them possessed any appreciable structural strength, and to supply this, a light truss made of half-inch tubing was placed within the air jacket. To this, the inside and outside walls were attached. The portion of the truss, together with the inner and outer walls which covered the outer wall of the generator, was made removable so as to give access to the tubing.

In the ultimate design, it was accepted that the fuel pump would be included in the same housing with the water feed pump, and both pumps, together with the fan blower, would be driven by a turbine mounted on the pump housing so that the plant as a whole would be self-contained. For convenience and experimentation, however, the fuel pump was mounted on an independent foundation which was driven by an electric motor by belt, the same motor driving the fan blower to which it was coupled by means of a flexible shaft.

The boiler, in general shape, was a horizontal, multi-circuit flash boiler to which water was fed in sixteen parallel streams. These streams without interruption passed parallel through sixteen flat coils of one-half inch tubing in which complete evaporation took place. The steam issuing from these sixteen circuits was thoroughly mixed in a manifold and then passed in seven parallel streams through 3/4" tubes for superheating. The superheated steam was delivered through a small delivery manifold to the automatic throttle which maintained a constant fixed pressure within the boiler and automatically delivered all the steam generated at this pressure.

The superheating tubes were wound spirally to form an open end box with round corners, the tubes being close pitched so as to lie close together, forming the four sides of the box. The chamber formed by these tubes served as a combustion chamber. The outer surfaces of these tubes were in contact with a light-metal casing which enclosed the entire tube system. The contact of the superheating tubes with the inside of this boiler casing, coupled with the positive air circulation which was maintained over the outside in proportion to the quantity of fuel being burned, prevented the casing from burning and made insulation unnecessary.

The evaporation tubes were wound to form sixteen independent flat coils which stood on end in the vertical plane just behind the combustion chamber. The gases leaving the combustion chamber passed through the spaces between the flat coils. These coils themselves tapered toward the rear and were arranged so that the spaces between them also gradually contracted. By tapering the coils and contracting the spaces between the coils, the area through which the gases flowed was gradually reduced to compensate for the reduction in gas volume. The gases having passed between the layers of flat evaporating coils, passed up the stack which was located in the cover at the extreme rear end. Thus the combustion took place at the front of the boiler and the gases flowed directly rearward. The water was put into the rear end and the steam flowed forward. This made the boiler strictly counter-flow and maintained a maximum temperature difference between the fluid and the gases at all times.

This boiler proved to be a very efficient and flexible steam generator. It was designed to evaporate 9000 pounds of water per hour at 300 to 500 pounds' pressure, and at a temperature of 800 to 900 degrees Fahrenheit. It proved to be capable of evaporating much more water than this and to maintain an efficiency of 80% under these full load conditions. On one test with a throttle pressure of 325 pounds gauge and a throttle temperature of 772 degrees Fahrenheit, burning 1.2 pounds of oil per square foot of heating surface, it evaporated 9450 pounds of water per hour with an 80% efficiency. The capacity of the water pump was reached at this flow and this prevented ascertaining the maximum capacity for evaporation of the boiler.

In practical operation, trouble has been experienced with generators of the flash type, having no surplus water and steam space, due to the fact that a sudden change in the throttle opening of the hand-operated valve caused wide fluctuations in steam pressure, and with a sudden closing of the throttle, an amount of water might be lost through the system through the safety valve which, for the purpose for which this generator is designed, would be serious. In order to eliminate these drawbacks, a radical change from the ordinary mode of operating the generator was made. Both the hand-operated pressure valve and the safety valve were dispensed with. In lieu thereof, a type of throttle was adopted which was so arranged that whatever might be the rate of steam produced up to full capacity, the throttle allowed its outflow to the engine but at the same time maintained the predetermined pressure within the generator. Manual regulation was furnished to permit control of the amount of fuel and water at will. In other words, manual control was to be over only the stuff going into the system instead of the stuff going out of the system. This system not only insured a constant steam pressure under all rates of steaming, but also dispensed with the necessity of a blow-off safety valve.

Considerable experimental work was done in the effort to give adequate control for the generator, and this was finally effected through the development of some rather intricate accessories. While these were made to function quite satisfactorily in the experimental installation, the Board pointed out that intricate devices of this kind are difficult to maintain in service, particularly in the rather rough service to which aircraft are subjected in landing and taking off in rough fields or on rough water.

For the tests kerosene was used as a fuel and there is, of course, a wide difference, as the report pointed out, between the use of a volatile fuel and that of a fuel which has to be sprayed under pressure, and to which air must be supplied under forced draft from a blower. Resort in general was had under these conditions to utilizing multiple burners and by lighting a greater or less number of burners for any desired rate of steaming. An ingenious arrangement for taking care of this problem with kerosene was developed, but in this case as well as in the case of control of the rate of steam generated, a device was used which might involve difficulties in service operation.

As a result of all these experiments, a generator was developed from which it was estimated that the finished weight of the generator, including pumps, fans, and all other auxiliaries, can be reduced below 2000 pounds which would give a generator weight of less than 2 pounds per horsepower. It was felt that a generator had been developed with high thermal efficiency as compared with other boilers, which could if further developed have a capacity for producing steam at any desired rate of superheat; which had large steaming capacity per unit of weight and space occupied; which had adequate steadiness of steaming rate under fixed conditions; which had adequate heat insulation without the use of fire brick or refractory lining; which was safe from disastrous explosions without the use of a blow-off safety valve; which gave excellent automatic distribution of water through the heating coils, thus preventing overheating of any coil; which had an efficient automatic throttle system maintaining constant pressure without regard to sudden changes in the demand for steam with the engine; which had an efficient and easy method of controlling manually the rate of combustion and corresponding water supply; which was capable of raising steam quickly from cold water, and which would be free from scaling or cracking.

It was felt that there had not been developed adequate control of steam temperature upon sudden manual changes in the steaming rate, nor was it felt that the problem of outside rusting of steel tubing had been solved. It was felt that the generator had a number of favorable points as a whole, with special reference to aircraft propulsion, as follows:

1. Reliability and probably durability as compared with internal combustion engines.
2. The use of fuel oil in place of gasoline.
3. Adaptability for large powers without increase in complexity and with reduced weight per unit of power.
4. Retention of or possible increase in efficiency at high altitudes.
5. Ease of operation and control.

The designers felt that the system had certain unfavorable points as follows:

(1) Low thermal efficiency as compared with internal combustion engines.

(2) Greater weight per horsepower than internal combustion engines, except possibly for large powers.

(3) Large condensing surface required unless wing surfaces could be used.

From the above general statement, it will be seen that a very conscientious endeavor was made to solve the problem of a steam generator and that excellent progress was made in the work. The general details of the procedure have been outlined with a view to indicating on what basis the total weight per horsepower of this particular generator was arrived at. From the outline of the unfavorable points listed by the inventors, it is apparent that while the mechanical difficulties of the problem were well taken care of, some of the major objections to the use of steam power plants still persisted.

We are now prepared to continue in our analysis of the problem, taking in turn the engine, the auxiliaries, and the condenser. It is well within the realm of possibility that a steam turbine, with all its auxiliaries, can be built for 1 pound per horsepower. Such a turbine will of necessity incorporate reduction gears if the high shaft speeds necessary for turbine efficiency with light weight are to be coupled with low propeller speeds which are likewise necessary for over-all efficiency. Taking the weight of the boiler as 2 pounds per horsepower and assuming an engine weight of 1 pound per horsepower, we arrive at a weight of 3 pounds per horsepower. We have, then, already reached the power plant weight of the Liberty engine as ordinarily installed in landplanes. More modern engines have a power plant weight of 2 pounds per horsepower. Since we have assumed that the other auxiliaries may be incorporated in the total weight of the engine, we are now prepared to pass on to the condenser.

In this analysis, we have at hand some experience in the use of the wing type radiator for internal combustion engines. In an airplane having approximately 850 square feet of total wing area, 370 square feet of wing type radiator was required to cool the circulating water of a 600 HP. engine. If now we use wing radiators on both the upper and lower airfoils, we will have a total of 1700 square feet of wing type radiator available, or approximately 4.6 times as much surface as is required for the internal combustion engine. All of this surface is, of course, not available because of structural interferences, and it is safe to say that four times as much area is available as is required for the internal combustion engine.

The rate of heat dissipated from the cooling water of an internal combustion engine must now be compared with that of the rate of heat dissipation from the condensate of the steam power plant. If we assume 10 pounds of steam required per horsepower hour in an engine, and assume 1000 B.t.u. per pound of steam to be dissipated, we have 10,000 divided by 60, or 167 B.t.u. per minute, to be dissipated. The average aircraft engine dissipates about 25 B.t.u. per minute per horsepower to the cooling water, so that 6.7 times as much area is required for the steam power plant as for the internal combustion engine plant, assuming that the rate of heat dissipation from water to air and from steam to air are equal. Since we have but four times as much area available in an airplane as is required for cooling an internal combustion engine, it is obvious that the area available is insufficient.

The above figures were based on the assumption that the rate of heat transfer for steam condensing in the radiator is approximately equal to that of circulating water cooling in the same radiator. This, however, is not the case, and an example will illustrate this: A 600 HP. internal combustion engine in an airplane flying at a speed of 60 miles per hour requires 12 square feet of frontal area of radiator with a 4-inch core, or about 520 square feet of surface. This is equivalent to .87 square feet of area per brake horsepower of the engine. For a steam power plant, referring to Fig. 3, for an air speed of 60 M.P.H., we see that approximately 60 square feet of area will condense 1 pound of steam per minute, or 60 pounds of steam per hour, which is equivalent to 1 square foot of cooling surface condensing 1 pound of steam per hour. Since now a steam power plant requires, roughly, 10 pounds of water per horsepower hour, we will require 10 square feet of area per horsepower to condense the steam of such a power plant. The ratio, then, is 10 to .87 or 11.5, from which it is seen that $11\frac{1}{2}$ times as much cooling area is required per horsepower hour to condense the steam as is required to cool the circulating water of an internal combustion engine.

We see, too, that only 4 times the area required is available if we use both surfaces of an airplane, whereas $11\frac{1}{2}$ times as much area is required. The wing type radiator is therefore eliminated from our consideration because of insufficient wing area available.

Fig. 2 has been calculated from the best information available. The data are quite limited and, like most data for condensing apparatus, disclose rather wide discrepancies. In developing the curve, an effort has been made to arrive at a reasonable basis of comparison. For the purpose of this approximate analysis, Fig. 2 is sufficiently accurate.

It will be noted that the curve is calculated for steam at 212° and air at 100° Fahrenheit. This steam pressure corresponds, of course, to 14.7 pounds absolute pressure. Any steam turbine to attain any reasonable efficiency must of necessity operate at a much lower back pressure than this. A good turbine should operate at about 1/2 pound back pressure provided the exit area is sufficient to take care of the steam at this volume. Now the temperature corresponding to 1/2 pound absolute is approximately 100°, at which temperature with an outside air temperature of 100°, which is frequently encountered in operation, there is no temperature difference and therefore no possibility of condensing the steam. Obviously, we would have to choose some other back pressure at which we could attain all the economy consistent with maintaining sufficient temperature difference between the steam and the outside air to condense the steam. Manifestly, any temperature lower than 212° would result in a corresponding increase in the condensing surface required. In other words, we could not hope to get economy any where near approaching that of steam power plants on shore without a condenser whose area and weight will be greatly in excess of what already constitutes an impossible condenser for aircraft engines.

The above calculations are based on the assumption that the wing type radiators could be kept reasonably free from water and that the steam could be kept in reasonable contact with the cooling surfaces. As a matter of fact, those surfaces on the lower side of the wings will probably contain a dead water film of considerable thickness and thus considerably reduce the effectiveness of this cooling surface. The calculations are therefore based on assumptions which are considerably more favorable to the problem than would actually be encountered in service.

So far, we have not considered the drag of a radiator for steam power plants. If we utilize all the wing area available and then resort to the core type radiator for the remainder, we still have twice as much drag area in the steam power plant as in the internal combustion engine. The resistance of the cooling surface due to the air flow varies approximately as the square of the speed of advance, and the power required varies as the cube of the speed of advance. An increase of 100% in the area of cooling surface required will, at high speeds, become a serious factor, and it is obvious that since fuel is required to produce power, the economy of the steam power plant over that of an internal combustion engine will again be impaired.

So far we have not considered the weight of such a radiator. The average weight for an aircraft radiator is about .3 pound per square foot, dry. With .87 square foot of cooling area required per horsepower, a 1000 HP. internal combustion engine would require approximately 261 pounds of radiator weight. Since it requires 11½ times as much cooling surface for the steam power plant, we would reach a total of 3000 pounds for a 1000 HP. engine, or 3 pounds per horsepower. In other words, the weight of the radiator of the steam power plant is as great as that of a combined boiler and engine estimated above, and the total weight of such an installation, exclusive of the engine and condenser auxiliaries, would be 6 pounds per horsepower. This is just about twice as great as the average weight of the modern aircraft power plant, and on a weight basis alone, neglecting the resistance factor, our steam power plant would weigh twice as much as our internal combustion engine and would require about twice as much fuel. In other words, if a steam power plant is to compete with an internal combustion engine on the all-important basis of pounds per horsepower per mile flown, it will have to show an improvement in both economy and weight of at least 100%.

Steam power plant economics of the order of 1/2 pound of fuel per horsepower hour are, theoretically, within the realm of possibility. Their attainment will require higher pressures and higher degrees of superheat than are customary on the shore. Certain special installations are already working under these conditions, although not yet approaching the theoretically possible economy. These economies can only be obtained with the development of suitable materials. It is a matter of common knowledge that improvement in steam power plant economy has been sufficiently rapid to challenge that of Diesel installations.

In considering this matter, we must keep in mind the all-important factor of reliability in aircraft and the fact that aircraft installations are subjected to severe shocks of landing and take-off from rough ground or water which will make the maintenance of high pressure joints somewhat difficult. There is further to be considered the crash hazard to the crews of aircraft using a steam power plant in which high pressures and high temperatures prevail. There is the further danger of fire resulting from such a crash since the fuel lines will be in close proximity to a hot furnace. It is now commonly recognized that in a crash, fire is much more likely to result from burning of the lubricating oil than from the gasoline alone. Gasoline sprayed on hot surfaces evaporates so rapidly that it is less likely to ignite on contact with hot surfaces than is the heavy lubricating oil with its low rate of evaporation. The hazard resulting from the utilization of high pressure steam in aircraft power plants must be given due consideration.

Now, there are only three major reasons why the use of a steam power plant might at first appear attractive:

(1) The possibility of an increase in the reliability and life of the power plant.

(2) The possibility of utilizing a cheap, heavy fuel and of reducing the fire hazard.

(3) The possibility of attaining higher powers than are possible with the present type of internal combustion engine.

Taking first this possibility of increase in reliability and life between overhauls, it is desirable to review the reliability and life between overhauls of the present engines. The modern aircraft engine is not such an unreliable piece of machinery as it appears to be. We have on record, tests of aircraft engines which have run over 300 hours at full throttle, non-stop. Approximated into miles at the rate of 100 miles per hour, this means a distance of 30,000 miles at full speed. Compared with the automobile engine, this is a commendable performance even when we remember that the automobile engine weighs approximately 15 pounds per horsepower. Compared with the steam power plant of a battleship, which will weigh roughly 135 pounds per horsepower, this performance is also commendable. Most battleships would encounter considerable difficulty in steaming 30,000 miles at full speed even when attended by a full crew which can closely supervise the engine operation at all times. The modern aircraft engine is not, then, so unreliable as it appears, especially when we remember that a major portion of the failures is due to piping and not to the engine itself.

Now since our steam power plant will have a very much larger proportion of piping, we can by the same token expect a considerable number of similar failures, particularly when we reduce the weight of this piping to the point which weight limitations will require. In other words, by the time we have reduced the weight of the steam power plant to the minimum, as we have done in the aircraft power plant, and by the time we have added to it the necessary automatic appliances and complications necessary to meet the requirements of aircraft, we will have so far reduced its possible reliability as to make it look extremely unfavorable in comparison with the internal combustion engine. This stands to reason because the internal combustion engine is a self-contained unit, whereas the steam power plant must divide itself into four separate units and must incorporate more accessories and appliances than the aircraft engine can ever require.

The possibility of utilizing a cheap heavy fuel and thus reducing the fire hazard is an attractive one. To date, the possibility of using such a heavy fuel in aircraft has not been demonstrated by burning it under boilers. It would appear that the proper course of procedure is to burn this fuel in an internal combustion engine, and this problem is well on the way to solution. Even were it possible to burn a cheap heavy fuel, the total quantity of fuel required for the most economical steam power plant we can expect to design would be so great as to wipe out a good deal of the margin of economy.

The possibility of attaining higher powers than are possible with the present type of internal combustion engine is not so attractive for the reason that even with the internal combustion engine, the necessity for very large aircraft is not apparent. It can be shown that there is a definite point in size beyond which it is uneconomical to go even for weight-carrying airplanes. In any event, it is possible to utilize internal combustions in multiple-cylinder installations which have the added attraction, provided the airplane is so designed as to fly on any one of the multiple engines, of increased dependability. This possibility, then, does not look particularly well in heavier than aircraft.

In lighter-than-air craft, it would seem that steam power plants might have some better applications. However, the element of economy is of relatively greater importance in these aircraft because they are designed for long range. A central generating plant with propellers driven by electric motors is offered as one possibility, but the total weight of a combined turbo-electric system even with the central plant can be shown to be prohibitive.

So far we have discussed the more conventional types of steam power plant. An analysis of the possibilities of an unconventional development, based on the mercury boiler indicates that a nearer approach to the requirements of aircraft can be made with this plant. If the economy of such a plant can be improved to the point of equality with the internal combustion engine, then the total weight per horsepower of such a plant is not of such pressing importance in an airship where the weight of the fuel carried is a much greater proportion of the gross weight of the airship than is the weight of the power plant itself. It is only by some such development that steam power plants can ever be applied to aircraft and the first application, if any, would seem to be in airships. Even under the best conditions, steam power plants in heavier-than-air craft appear so unattractive as to be entirely eliminated.

Summary

From the above approximate analysis it will be seen that on the basis of the weight of the power plant alone, steam power plants for aircraft are precluded. On the basis of economy alone, they are again precluded. On the basis of the resistance of the cooling surface required alone, they are precluded. On the basis of the sum of these three considerations, they are absolutely impossible. It would therefore appear that the ultimate analysis mentioned in the beginning of this paper is no longer necessary as no promise whatever results from the approximate analysis.

The foregoing approximate analysis is manifestly based on practical considerations. The same results are indicated, however, in the theoretical analysis. The starting point of any theoretical analysis is a comparison of the cyclic efficiencies of different processes. By comparing possible efficiencies based on computations for cycles which approach the actual cycles employed in the mechanism, we may arrive at an approximation of the promises held forth by each cycle. The Rankine cycle is the only steam cycle that reasonably approximates in representation the action of steam in cylinders and nozzles for which efficiency can be read off charts. The Otto cycle is the cycle ordinarily employed in internal combustion engines, and charts are available for this cycle.

Assuming an initial pressure of 200 lb. gauge for dry saturated steam, and 0.25 lb. per square inch absolute back pressure, the thermal efficiency of the Rankine cycle is about 34%. For the Otto cycle with a compression pressure in atmospheres of 10, which approximates the compression pressure for modern aircraft engines, we find a thermal efficiency of 48% for the cycle. From this we see that the steam cycle is at a disadvantage from the viewpoint of thermal efficiency with respect to the Otto cycle in the ratio of 34 to 48. This, of course, accounts for the low economies of steam power plants.

This whole problem may be viewed from another angle. In the modern aircraft engine, we may assume that about 1/3 of the total heat of the fuel is converted into useful work; about 1/3 is rejected to the atmosphere in the exhaust gases, and the remaining third is rejected to the atmosphere through the jackets either indirectly in water-cooled, or directly in air-cooled engines. Since the heat converted into useful work is likewise dissipated into atmosphere by the propeller, the modern aircraft engine may be said to dissipate all its heat directly to the atmosphere.

In the steam cycle, the heat must first be transferred to the working fluid, which is water in the ordinary steam cycle, and to water and mercury in the so-called mercury boiler system. Both of these liquids must be retained in the system and recirculated in aircraft engines. For an overall efficiency of 25%, if we convert 25% of the heat into useful work and dissipate it to the atmosphere, and if in the boiler we attain an efficiency of 80% and reject 20% directly to the atmosphere, then only 45% of the total energy is rejected to the atmosphere directly. The remaining heat must be transferred indirectly to the atmosphere through the cooling system. Manifestly, any such indirect system which is required to transfer 55% of the total heat available to the atmosphere through some intermediate heat transfer apparatus will require an apparatus which is heavy and offers far more drag than does the ordinary aircraft radiator. Thus, on theoretical grounds, we can substantiate the foregoing conclusion based on practical grounds.

When we compare such a system requiring heavy and cumbersome apparatus to reject the heat by indirect methods with a system of the modern air-cooled engine, which rejects all of the heat directly to the atmosphere without such intermediate apparatus, our steam system is shown to be at even worse disadvantage. From the practical as well as the theoretical standpoint, it must appear that the steam power plant cannot compete with the internal combustion engine in aircraft.

In order that the steam power plant may compete, it is necessary to eliminate much or all of this intermediate apparatus. In the mercury boiler in which the heat of condensation of the steam is transferred to the mercury which, in turn, is utilized in a turbine, this elimination takes place to a certain degree. There still remains, however, the necessity of transferring the heat of condensation of the mercury to the atmosphere. It is possible that the apparatus required will not be in excess of that now used with water-cooled aircraft engines. It seems well within the realm of possibility that a complete mercury outfit in comparatively small sizes can be built for about 5 pounds per horsepower, and such an apparatus would compare favorably, on the basis of economy, with internal combustion engines, as well as eliminating much of the cooling surface required. It would, however, still be complex when compared with an internal combustion engine which is, after all, one of the simplest of engines.

Water-cooled engines are rapidly passing out of general use in aircraft, only for smaller sizes.. With modern engines, a power plant weight of 2.3 lb. per horsepower is common. The mercury installation would then weigh over twice as much per horsepower as the air-cooled engine installation in general use. Even this system does not offer great promise for aircraft. For steam to be considered as a propulsive means for aircraft, it is necessary to devise some means of application which will completely eliminate the cooling system, which will permit power plant weights of not to exceed 2 lb. per horsepower, which will permit economies of better than .50 lb. of fuel per horsepower per hour, and which will be as simple, as easily maintained and operated, as rugged, and as dependable as the modern aircraft engine. From our present knowledge, this is a rather large order.

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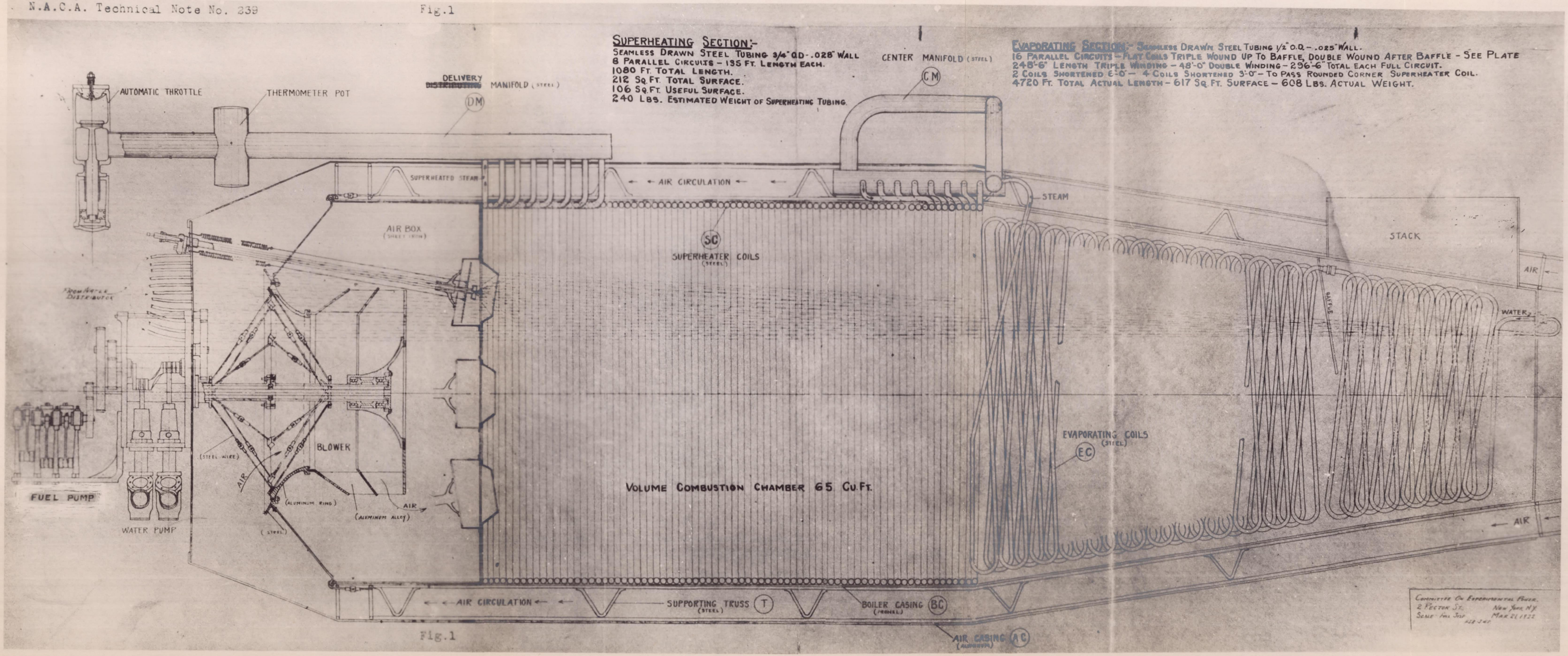

SUPERHEATING SECTION:-
SEAMLESS DRAWN STEEL TUBING 3/4" O.D - .028" WALL
8 PARALLEL CIRCUITS - 135 FT. LENGTH EACH.
1080 FT. TOTAL LENGTH.
212 SQ. FT. TOTAL SURFACE.
106 SQ. FT. USEFUL SURFACE.
240 LBS. ESTIMATED WEIGHT OF SUPERHEATING TUBING.

EVAPORATING SECTION:- SEAMLESS DRAWN STEEL TUBING 1/2" O.D. - .025" WALL.
16 PARALLEL CIRCUITS - FLAT COILS TRIPLE WOUND UP TO BAFFLE, DOUBLE WOUND AFTER BAFFLE - SEE PLATE
248'-6" LENGTH TRIPLE WINDING - 48'-0" DOUBLE WINDING - 296'-6" TOTAL EACH FULL CIRCUIT.
2 COILS SHORTENED 6'-0" - 4 COILS SHORTENED 3'-0" - TO PASS ROUNDED CORNER SUPERHEATER COIL.
4720 FT. TOTAL ACTUAL LENGTH - 617 SQ. FT. SURFACE - 608 LBS. ACTUAL WEIGHT.

COMMITTEE ON EXPERIMENTAL POWER.
2 RECTOR ST. NEW YORK N.Y.
SCALE: FULL SIZE MAR 21 1922

Fig.1

32-A 32-B 32-C

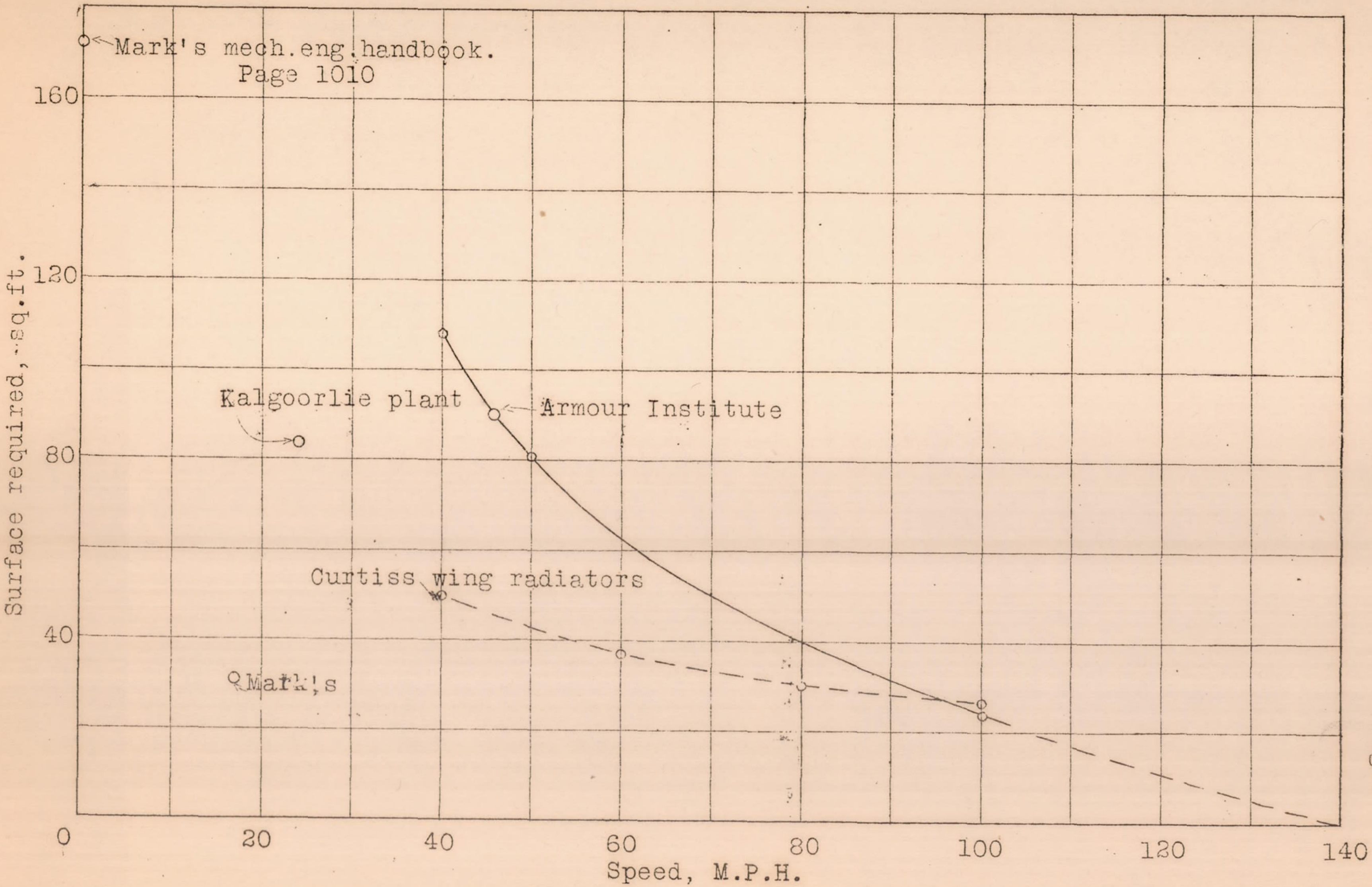

Fig.2 Surface required to condense one pound of steam per minute. Temp. of steam = 212°F
Temp. of air = 100°F