THE PROSPECTS OF GAS TURBINES IN NAVAL PROPULSION

by

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Hero, the Alexandrian, is credited with first conceiving the principle of the gas turbine in 130 B.C. The first patent was issued to the Englishman, John Barber, in 1791. Despite these very early origins, real progress was not realized until made possible by advances in the metallurgical and aerodynamic sciences early in the twentieth century. By 1930, however, very positive progress was on record, including the turbo-supercharger, developed in this country by Dr. Sanford Moss. That year marked the appearance on the drafting boards of Whittle's first aircraft gas-turbo-jet engine and ushered in the really modern era of extremely rapid development. A full chronology of gas-turbine development during the long period so briefly referred to may be found in the works of R. T. Sawyer and S. A. Moss.

During the 1930's important advances were made by the Swiss firms of Brown-Boveri, Escher Wyss, and Sulzer in their programmes of locomotive and land power-station gas-turbine development. These events were comprehensively reported to the Navy Department's Bureau of Engineering by Lieutenant Commander Warren Noble, U.S.N.R., in 1938. His estimate of the situation was so startlingly enthusiastic that the Department almost immediately requested an investigation by a committee of the National Academy of Sciences into the feasibility of harnessing this " new " work horse for naval propulsion. This committee, after almost two years of study, recommended the establishment of a naval gas-turbine programme including the construction and exhaustive laboratory testing of a gas turbine capable of sustained operation at 1,500 degrees F. With the adoption of this recommendation and the appointment of Dr. R. B. Kleinschmidt as the technical director of the programme, the Navy embarked upon a long voyage during which it encountered lots of rough weather. However, in spite of metallurgical hurricanes, aerodynamic typhoons, and mechanical siroccos, subsequent events have established the wisdom of this basic undertaking.

To initiate the original programme, a contract was negotiated in December, 1940, with the Allis-Chalmers Company for the design and construction of a 3,500-horsepower unit suitable, not for installation in a ship, but for laboratory investigation of those components which most logically might be used in a prototype shipboard plant. This step was followed, a year later, by the setting up of a programme of high-temperature materials research at both the United States Naval Engineering Experiment Station and the Massachusetts Institute of Technology.

Twelve months later, in 1942, two other laboratory models were placed on order. One of these, the Elliott 2,500-horsepower unit, utilizing Lysholm compressors, has been capably reported upon by several of the participating designers. The other, a 750-horsepower unit, to be manufactured by the

DeLaval Company, is to utilize a Birmann mixed-flow compressor, thereby providing a logical complement to the axial-flow and Lysholm machines already on order. The year 1943 saw the Bureau of Ships extend its programme to include two free-piston gas-generator projects and a study of pressure-fired boilers, thereby completing the set-up for a six-pronged assault on the propulsion-gas-turbine problem.

Those six projects have formed a framework or foundation structure for the work which has followed. An outgrowth of the original Elliott 2,500-horsepower laboratory plant has been the authorization for the construction of a similar 3,000-horsepower propulsion plant intended for installation in a vessel. Literally hundreds of interlocking and dovetailing projects have been undertaken ranging all the way from paper studies accomplished by one engineer in a week to the design, construction, and test of hardware, involving a great many technicians for a great many months.

PRESENT ACTIVITIES OF BUREAU OF SHIPS

Cycle Studies

The wealth of literature available on the subject of the selection of the optimum cycle for a given application attests the magnitude of the task of arriving at any one answer which, regardless of how intelligent it may appear at the time of design conception, will continue to appear intelligent throughout the three to five years which normally is required to bring that conception through the successive stages of detail design, component construction and testing, component alteration, and final plant assembly and testing. Such rapid progress is being made in the development of information concerning all the many factors which affect, both individually and in combination, the final result that the whole thing is worse than trying to buy a suit which will be a perfect fit, five years hence, for your growing boy, who is now ten years old.

Work along this line is further complicated by the several special requirements of a naval plant, with which the designers of merchant-marine, aeronautical, locomotive, or stationary gas turbines do not particularly have to worry. These special requirements are :—

(*a*) Excellent cruising, or light-load, fuel economy, *plus* good fuel economy at the higher loads as well.

(*b*) Manoeuvrability, that is, ability to accommodate rapid changes from low power (or dead-plant conditions) to high power to stop to back and, again, to high power ahead, etc., in any sequence, and with great frequency.

(*c*) Air economy. The requirements for air must be reduced to the minimum in order that the size, and the weight, of intake and exhaust ducting will not become prohibitive.

(*d*) Resistance to severe shock or other battle damage.

(*e*) Economy of strategic materials. It would be foolishly shortsighted to develop, at great expense in time and money, prototype machinery which could not be reproduced in wartime in the required quantities because of the unavailability of metals or materials essential to its satisfactory performance.

All of the above special requirements are combined in a naval plant with the several non-special requirements common to one or more of the other applications, as :—

(*a*) Reliability. Certainly this requirement is common to all applications, but it is particularly important to aeronautical, merchant-marine, and naval plants.

(*b*) Minimum weight. This requirement is almost paramount for aircraft applications but it is only a little less important in naval installations, because every pound which is spent on main engines means one pound less which is available for vital ammunition, guns, armour, or fuel oil. It is also important, in lessening degrees, to locomotive and merchant-marine plants.

(*c*) Minimum space. Aeronautical, naval, and locomotive applications have this requirement in common, although " frontal area " is probably the prime factor for aircraft engines, whereas all dimensions are important to locomotives and naval craft.

(*d*) Accessibility or ease of maintenance. This requirement, which is seemingly incompatible with the weight and space limitations mentioned in the foregoing, is probably more important in naval installations than in any others because of the necessity of operating for weeks and months away from shore-based repair facilities. However, it is an important consideration in all prime-mover designs, regardless of application.

To utilize fully the versatility of the gas turbine in meeting the maximum number of the foregoing general and special requirements, we have devoted much time and manpower to the study of those variables which have a profound effect upon the character and performance of the resultant plant. Proper cycle selection is the framework upon which the elements of aerodynamics, metallurgy, and other engineering sciences are added to achieve the desired result. Studies have been made, and are constantly being revised, of all the various cycles, mechanical arrangements, and different types of components known to the Navy. Here, again, it must be pointed out that the effort devoted to these studies has varied from a few engineer man-days to many hundreds of man-days, including, in some cases, laboratory substantiation of predicted results.

Component Studies

A re-examination of the initial programme, described at the beginning of this paper, will recall to mind that many different types of components were included in the six original projects. Those original projects, therefore, afforded opportunity for the thorough exploration of the performance characteristics and construction techniques involved with axial-flow, Lysholm, Birmann, free-piston, and controlled-piston compressors, and axial-flow reaction, axial-flow impulse-reaction, and Birmann mixed-flow turbines. The information generated by these investigations has been supplemented continuously by concurrent, or subsequent, studies of centrifugal, mixed-flow, and radial-inflow compressors, and of axial, radial-inflow, and radial-outflow types of turbines.

In addition to investigations of the many types of compressors and turbines indicated above, the heading *Component studies* must also include investigations such as those on extended-surface regenerators, various types of dynamic or " strong-wave " machines, the acoustic combustion chamber, various control devices, and control instrumentation.

Materials Studies

The materials investigation programmes at the Naval Engineering Experiment Station and the Massachusetts Institute of Technology, mentioned early in this paper, have concentrated primarily upon the development and application of suitable high-temperature blade materials and, as in all other phases of the overall programme, these efforts have been co-ordinated carefully with those of the dozens of other investigations dealing with the same problem. Those two projects have been concerned, primarily, with the conventional super-alloys of the chrome-nickel-cobalt type, but very considerable additional amounts of Bureau time and contract money has been spent on ceramics, powder metallurgy, casting techniques (including grain-size control), welding techniques, and material-inspection methods.

Turbine-cooling Studies

Periodic analysis of the aforementioned work on cycle selection, component development, and materials research has led to an increase of emphasis (in terms of percentage of available manpower and money) on the development of suitable methods of cooling hot turbine parts in order to make higher top-cycle temperatures usable and to reduce the strategic-material content required for satisfactory turbine life. The extremely encouraging results achieved in this respect at the National Advisory Committee for Aeronautics laboratories, as reported by O. W. Schey and H. H. Ellerbrock, and the predictions of W. R. Hawthorne, have given us a good deal of faith in the authors' calculations. It would be hard to overstate the confidence which the authors have in the premise that some form of liquid cooling will be utilized on all naval and marine gas turbines in use ten years from the present. It appears that the future of air cooling for the hot turbine parts may not be spectacularly bright, but we believe that the field of liquid cooling offers a greater opportunity for clear-cut performance gains than any other one single line of exploration. Liquid cooling probably will be advantageous for all types of turbines regardless of application, with the possible single exception of airborne units.

Other Current Bureau of Ships Activities

Security considerations prevent the further discussion of present Bureau activities along gas-turbine lines. It can be stated, however, as an index to this activity, that several top-flight gas-turbine manufacturers presently are engaged in construction contracts for the Bureau. These projects will be described publicly as soon as circumstances will permit.

PROSPECTS FOR THE FUTURE

What this country needs is not more rosy predictions of a bright future for the gas turbine, but more down-to-earth certified performance records. This "glamour girl," this "pin-up of the power profession," as the gas turbine was so aptly described by Dr. Lester Goldsmith four years ago, has been all but murdered in her golden teens by exaggerated publicity, extravagant predictions, and over-zealous enthusiasm. The rude shock incident to a realistic inventory-taking process has soured many individuals on the whole subject, and has caused many capable, open-minded engineers to develop a "show-me" type of sales resistance to any favourable statement made concerning the gas turbine.

This feeling is particularly difficult to combat in the field of locomotive, marine, and naval propulsion. It cannot be said, as it can of the aeronautical gas turbine, that a marine, locomotive or naval gas turbine is a vital necessity. The existing machinery available for those three applications is far from being unsuitable, outmoded, or insufficient for the task assigned. In those fields, the gas turbine must show a positively advantageous balance against its competition in order to receive the high-level favour necessary for the release of the very considerable investment funds involved in the development of even a moderate size of gas-turbine installation. The task is made more difficult, also by the fact that the short, 500-hour life which is suitable for aeronautical uses has not, heretofore, been acceptable in the other applications, regardless of how many other attractive features the arrangement may possess.

Nevertheless, the authors still believe that a strong case can be made for the

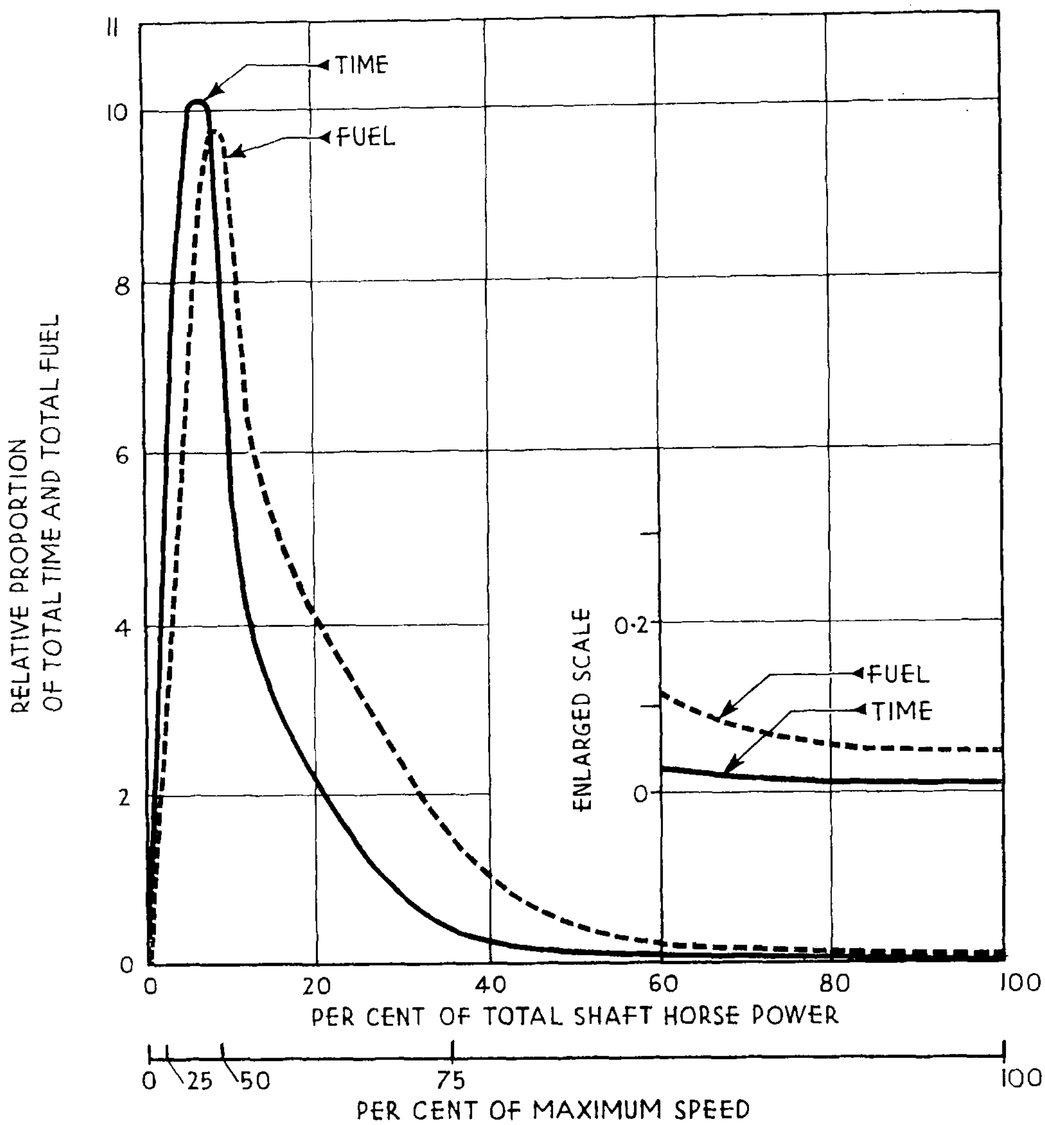

FIG. 1

gas turbine in naval applications, if sound judgement and foresight are compounded with skill, energy, and perseverance in the administration of each project. They believe that the next large-scale project to be undertaken should, in the interest of economy of time, as well as of money, be composed of elements which are available in fully developed form at present.

A characteristic of a propulsion power plant for naval combatant service, which is unique in the general marine picture, is the very widely varying power requirement. If we consider, for example, a destroyer of recent years, statistical studies, during both peace and war, have shown that such a vessel operates for an overwhelming proportion of its total operating life at a very low proportion of the installed power. Fig. 1 shows the statistical average operating history of a large number of vessels over an extended period of wartime operation. An integration of the curves of Fig. 1 indicates that the upper 80 per cent. of the installed horsepower is used for less than 4 per cent. of the operating life of the vessel ; 70 per cent. for less than 1 per cent. ; and 60 per cent for less than 0.3 per cent. A representative figure for those machinery weights which are uniquely associated with the steam propulsion plant of the vessels studied is 16 pounds per horsepower, including propulsion turbines, condensers and air ejectors, boilers, steam piping, blowers, feedwater service pumps, tanks, heaters and heater-drain pumps, and circulating pumps. For a 60,000-horsepower, twin-screw vessel (two identical 30,000-horsepower units), this means that for 99 per cent. of the operating life of the vessel (during which 97 per cent. of the total fuel is burned), 300 tons of propulsion machinery are carried about as a reserve against the sudden requirement for more than 30 per cent. of the available power. The practicability of replacing this top 70 per cent of installed power, which is required to operate for only 1 per cent of the life of the vessel, with a relatively short-lived gas-turbine plant weighing between ½ and 2 pounds per shaft horsepower is attractive, and *appears feasible within the presently existing state of the art.* One of the several potential arrangements for accomplishing this desirable result is, in the authors' opinion, especially worthy of description. This arrangement was first proposed, as far as the authors know, by Mr. S. A. Kane, then of the Bureau of Ships, in 1946.

The Steam Cruising-gas Booster Propulsion Plant

Considering the aforementioned 30,000-horsepower propulsion *unit*, this arrangement would involve 9,000 shaft horsepower of steam machinery and 21,000 shaft horsepower of lightweight, compact, gas-turbine machinery.

It is possible to design the steam plant especially for economical operation at the speeds for which it *alone* would be employed. Studies indicate that the Navy could utilize reduction gears of overall size similar to those presently installed and have both the steam-turbine and the gas-turbine torque delivered to the gears. If we conceive of the gas-turbine power being delivered by four to eight separate gas-turbine engines, they could be separated from the gear train by clutches when not in use. The backing requirements, which, for the ship under consideration, would be of the order of 8,000 shaft horsepower (4,000 horsepower per shaft) might be provided by astern wheels built into the steam-turbine casings in the conventional manner.

Fig. 2 shows a possible arrangement of this sort. Calculations indicate that such a plant may be built (within the framework of existing knowledge) to be competitive, from a fuel-economy standpoint, at all loads, and still produce a net saving of about 260 tons (representing a 28 per cent. reduction) in the ship's propulsion equipment, even if a conservative figure of 2 pounds per horsepower is used for the gas-turbine elements. The length of the overall machinery space would be reduced, relative to the former steam plant, by more than 10 feet.

The steam component included in this arrangement would consist of a cross-compound turbine with a single-flow low-pressure element having the astern wheels in its exhaust casing. This turbine could be designed to give the maximum possible economy at the 20-knot point without undue sacrifice either at 9,000 shaft horsepower per shaft (which is the maximum power at which it would operate without gas turbines), or at 30,000 shaft horsepower per shaft when operating in combination with the gas-turbines.

Only one boiler per shaft would need to be provided, since, in the event of a boiler derangement, the two steam plant could be cross-connected, or the gas turbines operated alone, if at least one of the five units per shaft were provided with a starting motor. Overheating of the steam-turbine during operation with the gas turbines alone could be avoided by maintaining a vacuum in the condenser.

The boilers, turbines, condensers, and auxiliaries are visualized as being conventional, non-experimental in nature, and having normal design factors.

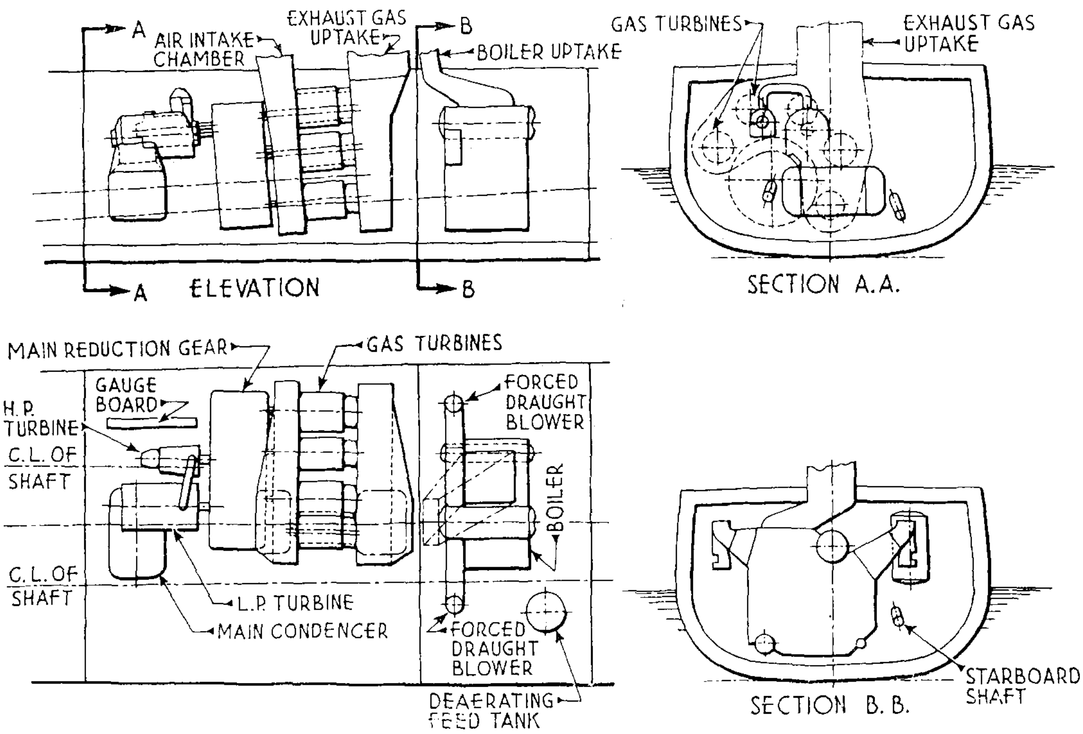

FIG. 2

The reduction gears likewise would follow conventional design practice, except as to arrangement. Each gear would have five single-helical first-reduction pinions and gears and five double-helical second-reduction pinions spaced at 45 degrees around the 130-inch bull gear. Two of the high-speed pinions would transmit power from a gas turbine as well as from one element of the steam turbine. The other three pinions would transmit power only from gas turbines. A friction clutch of the Fawick " Airflex " type could be incorporated in each first-reduction gear in the gas-turbine power train.

The five gas turbine elements on each shaft would be interchangeable. They would be adaptations of the now familiar 500-hour open-cycle 2-shaft aircraft turbo-propeller engine. The compressors probably would be of the axial-flow type and have a 70-to-1 pressure ratio. Combustion is accomplished in the familiar can-type chambers clustered about the central axis. The turbine-inlet temperature would be 1,900 degrees F, giving a design fuel rate of 0·6 pounds per horsepower-hour at full power. The gas turbines should burn the same fuel oil as that used in the steam boiler.

The fuel economy of this combination steam-and-gas arrangement would be at least equal to that of comparable steam machinery at all speeds, and, at the most important points, that is, between 20 and 25 knots, it would be from 10 to 13 per cent. better.

The question may arise as to why, in a gas-turbine discussion, the authors have chosen, for the base-load or manoeuvring plant, a steam turbine rather than some configuration of gas turbines. Rather than that a lack of faith in the abilities of the gas turbine be inferred, it will here be noted that certain practical considerations have indicated the choice of the steam base-load plant. Sufficient emphasis must be given to fuel economy for the base-load or manoeuvring plant (which will consume 97 per cent. of the total fuel burned) to require that the base-load gas turbine plant, if one be installed, attain efficiencies, at all speeds, comparable to the steam plant. At the present state of the development, this can only be achieved at the expense of increasing plant weight and volume by the addition of intercoolers and regenerators. The gas turbine plant then weighs nearly as much as the steam plant. In addition, meeting the reversing requirements involves the use of either a controllable-and-reversible-pitch propeller or a reversing transmission between turbines and high-speed reduction-gear pinions. Either alternative will arouse a very vocal group of antagonists. While the authors favour the development of the base-load gas-turbine plant as a definitely worthwhile project which certainly will receive future attention, economy may dictate that its further development be postponed for the moment. There are, furthermore, certain advantages, primarily of a philosophical nature, which accrue from the retention of the steam plant. First, it is thoroughly developed, proven, and tested, and operating personnel are thoroughly familiar with its use. It also permits retention of certain steam-driven auxiliary machinery, primarily in connection with the ship's " hotel " load. Furthermore, its life is long and its reliability, which is a prime requisite, is excellent. Although it may be a source of amazement to many individuals, the question is occasionally asked, in all sincerity, " Will the gas turbine work ? ", and to these sceptics, the presence of the steam machinery may be a reassurance.

Other Naval Applications

There are many other naval applications, of a special nature, to which the versatile gas turbine lends itself admirably by virtue of some one, or more, of its uniquely advantageous features. There are, for example, applications, such as motive power for emergency equipment with a very short operating life, and peak-load power for boats and vehicles, where the requirement of light weight subordinates all others save reliability. Applications exist where fuels with the volatility of gasoline are not acceptable, and where, at the same time, powers are sufficiently high or weight limitations sufficiently low to preclude the Diesel. There are many applications where the total life of a prime mover is short but appreciable, and where economy is an important, but not overriding, consideration ; for these, compromise designs, achieving acceptable efficiency with still-acceptable weight, are possible. Other requirements exist for machinery of moderate weight but high power, which are capable of almost instantaneous starting.

For all the foregoing, some form of gas turbine will precisely fill the bill. For example, currently under development for the Bureau of Ships is a 400-horsepower gas turbine for emergency-generator drive with a weight of 600 pounds and a designed life of 5,000 hours (including 500 hours at full power). This prime mover supplants a Diesel engine weighing 8,900 pounds, thereby saving 8,300 pounds (93 per cent. of original weight) at no sacrifice, since fuel economy, in this application, is unimportant.

A gas-turbine prime mover for a portable fire pump shows promise of achieving a specific weight of 1·2 pounds per horsepower for a 50-horsepower output, as compared with 3·7 pounds per horsepower for its gasoline-piston-engine predecessor. It has the added advantage of burning a non-volatile, non-explosive fuel, which is, for fire-fighting equipment, definitely desirable.

Long-range Development Programme

In looking into the less immediate future, with an attempt to predict the direction in which further development should take place, consideration should be given to all of the naval plant requirements described hereinbefore. It appears certain, therefore, that very great effort must be exerted toward the attainment of satisfactory performance of units operating at the very high temperatures above 2,500 degrees F. To the authors, this means concentration upon the liquid-cooling principle with the personnel and money necessary to achieve the same high degree of development which has been achieved by the automotive and aeronautical piston-engine fields. These efforts must be expedited because successful attack upon the problems will depend, to a very great degree, upon laboratory experimentation with working models, a process which is extremely time consuming to say the least.

Likewise, in order to make the most advantage of these high temperatures, after successful methods of handling them have been developed, the satisfactory and efficient production of much higher pressure ratios than those now in general use will be required. This calls, therefore, for continued concentration upon the development of compact, lightweight, highly efficient compressors and, probably, the more effective utilization of intercoolers or wet compression. As an interim future step, we recognize the potential merit of an all-gas-turbine propulsion plant of 30,000-horsepower comparable to the combined steam-and-gas plant described in the foregoing, wherein the cruising element is composed of a free-piston gas generator-gas turbine arrangement and the booster or high-power plant is composed of straight-through units with a 25-to-1 pressure ratio (achieved by suitable intercooling or water-injection methods) and operating at an initial turbine temperature of 2,500 degrees F, or higher, through the use of suitable liquid cooling of the hot turbine parts.

The problem of compressor fouling may well increase to such a degree as to make it desirable to give much greater emphasis to the development of the completely closed cycle than that which now exists. Reports being received from abroad on this subject indicate that our best efforts along the lines of development of the open-cycle units may be nullified by this matter of compressor fouling. It seems wise therefore, in planning a long-range programme to maintain a degree of flexibility which will permit the ultimate utilization of the closed cycle, both for realization of its own inherent advantages and for the contingency that the open-cycle compressor-fouling problem achieves dominating proportions. The closed cycle is so dependent upon the efficiency of its heat-transfer elements that the programme for the future must include continued study directed toward the improvement of their performance and reduction of their size.