9 of reference (10). The volume flow was calculated for the gas-generator engine by taking the arithmetical average of the turbine-inlet and turbine-outlet volume flows. The resultant stage weight was thus determined to be 70 lb. Because a three-stage turbine was assumed, the weight of the turbine was estimated to be 210 lb.

Reduction Gear: The reduction-gear weights were calculated by using 0.143 lb per transmitted horsepower, which was obtained from weight data on a current turbine-propeller engine. The gear weight is based upon the brake horsepower of the gas-generator engine at sea-level altitude. This computation resulted in a propeller reduction-gear weight of 583 lb.

Compressor Drive Gear: The weight of the compressor drive gear was calculated using a specific weight of 0.7 of that of the propeller-reduction gear because a smaller speed ratio is involved. Compressor-power requirements were calculated using the weight flows and pressure ratios at sea-level altitude as the compressor power required was higher there than at 20,000 ft. At sea level the required compressor-drive-gear horsepower is 2606 and results in a weight of 261 lb. The compressor is divided into two parts, necessitating two drive gears; therefore the weight was increased by 30 per cent, which resulted in a drive-gear weight of 339 lb.

Heat Exchangers: Heat-exchanger weights were determined using data from reference (16) which indicated heat-rejection rates of 2500 Btu per min per sq ft per 100 F initial temperature difference for oil coolers and 6000 Btu per min per sq ft per 100 F initial temperature difference for radiators. Wet weights of 48 and 54 lb per sq ft of frontal area, respectively, were used for these two coolers.

In determining the heat rejection of the gas-generator engines, 16 per cent of the heat input of the fuel was assumed to be rejected to the coolant and 2 per cent was assumed to be rejected to the oil. The heat input of the fuel was determined from the power output of the engine and the brake specific fuel consumption by use of a heating value for the fuel of 18,500 Btu per lb. Analysis showed that the sea-level condition was the limiting condition, where the heat-rejection rates for the gas-generator engine were 72,500 Btu per min to the coolant and 9070 Btu per min to the oil.

The radiator weight, which resulted from this calculation, was 343 lb, and the oil-cooler weight was 124 lb.

Miscellaneous Weights: A weight of 200 lb was assumed for accessories and accessory drive gears, and an installation weight of 10 per cent of the sum of the weights so far listed was assumed to take care of such items as engine mounting, oil, coolant, fuel systems, and reinforcements of the inlet and of the exhaust manifolds.

Total Installed Weight: The total installed weight of the gas-generator engine is then given by the sum of the components listed in Table 3. The specific weight for the 20,000-ft altitude, 4000-hp, gas-generator engine was then calculated to be 0.839 lb per hp.

TABLE 3 INSTALLED WEIGHT OF GAS-GENERATOR ENGINE

Component	Weight, lb
Power section	862
Supercharger stage	150
Axial-flow compressor	242
Turbine	210
Heat exchangers	467
Propeller-reduction gear	583
Compressor-drive gear	339
Accessories	200
	3053
Miscellaneous for installation	305
Total installed weight	3358

Discussion

P. H. Schweitzer.[3] This paper raises the question whether the military is not making a mistake by putting all its eggs in the jet basket. For long-range flight with heavy pay load, that means bomb load, the compound engine beats the jet by a tremendous margin.

One hears that the predicted weight of a compound power plant is approximately 0.9 lb per hp. For a 100,000-lb-gross-weight airplane with four 4000-hp engines making a 2000-mile hop, the power plant would weigh approximately 14,000 lb. With 0.32 spec. fuel consumption and 375 mph the fuel would weigh 27,000 lb, which would leave for plane weight and load 59,000 lb. Using jet engines the power plant may weigh not more than 6000 lb but the fuel would weigh not less than 85,000 lb leaving 9000 lb for airframe and load combined. Even if this arithmetic is oversimplified, it illustrates the absurdity of transporting heavy loads to great distances with jet propulsion. The writer would like to see more than just paper research and relatively small-scale experimental work on compound power plants for aircraft.

The paper is a noble effort of a small NACA group in this direction. They deserve utmost encouragement. Although some of the assumptions are on the optimistic side, the calculated performance figures are realistic and are in rough agreement with those of the Schweitzer and Salisbury paper of 1949[4] as well as with the scarce experimental results. For instance, the authors calculated that a 4000-hp gas-generator engine running at 2400 engine rpm would have 1387 cu in. displacement, or 3.05 hp per cu in. The writer has calculated at 1200 rpm 1.485 hp per cu in., which is almost exactly the same.

As mentioned previously, some of the assumptions appear to be somewhat optimistic at present. A turbine-inlet temperature of 2260 R and 85 per cent compressor efficiency seem high. The authors' choice of the constant-volume cycle for their theoretical analysis seems unfortunate because such cycle is neither practicable nor desirable, and it robs the analysis of the flexibility offered by the variation of the point of cutoff in the limited-pressure cycle. By such procedure the inlet-manifold pressure and the compression ratio were fixed automatically for any one altitude. Previous NACA work, like the one cited in reference (12) of the paper, used the limited-pressure cycle; the writer wonders why the authors abandoned it in the present paper.

According to the assumptions, about 60 per cent of the air is short-circuited in the two-stroke-cycle engine, and the resultant 0.054 cylinder fuel-air ratio is considered adequate to permit good combustion efficiency. For an injection-type engine is such a fuel-air ratio not too rich to permit smokeless exhaust?

Was blowdown recovery ignored in the power analysis and if not, which was the method used to calculate it? In reference (12) of the paper, the turbine-inlet temperature was calculated by treating the reciprocating engine as a steady-flow machine. But, unless it has an infinitely large exhaust receiver, the reciprocating engine is not a steady-flow machine. If it has, no blowdown recovery is possible.

Referring to the experimental part of the paper, it is unfortunate that most of the tests were conducted with insufficient exhaust lead. Perhaps that could have been avoided if the observation that, with adequate exhaust lead, the pressure drop is insensitive to the fuel-air ratio, had been made earlier. This observation is identical with the statement that the Kadenacy effect increases with the engine load.

The writer disagrees with the authors in attributing the smooth

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[4] "Compound Powerplants," by P. H. Schweitzer and J. K. Salisbury, Quarterly SAE Transactions, vol. 3, 1949, pp. 656–669.

running of the gas-generator engine to the low compression ratio, and the increase of compression pressure with engine speed to better ring-seal or inertia effects.

The most gratifying result of the experimental work is the observation that conventionally designed two-stroke-cycle engines operated with such extreme manifold pressures (50–135 psia) and temperatures (300–600 F) can run for hundreds of hours without mechanical troubles and distress and without excessive ring and cylinder wear.

M. J. Tauschek.[5] While the gas-generator engine is proposed primarily for aircraft use, some consideration should be given to this power plant for railroad and marine propulsion. For that matter, it may even find application in heavy military equipment. The advantages of the gas-generator engine in these applications are incurred through its high specific output. For example, such an engine at 1800 rpm would deliver 2.2 hp per cu in. displacement, as contrasted to approximately 0.3 hp per cu in. for a conventional supercharged four-stroke Diesel engine. With these high outputs, it is possible to build a prime mover of substantial power within the space limitations imposed on propulsion machinery. At the same time the desirable fuel consumption of the conventional Diesel engine is not sacrificed.

A number of other advantages accompany the application of this power plant to surface transportation. The complication of controlling the engine with variation in altitude is no longer present, and the rather involved control schemes outlined in the subject paper are unnecessary. Again, the feature of the engine whereby losses in the compressor or Diesel engine are recovered partially by the turbine permits design compromises to be made which ordinarily would impair the performance of a conventional Diesel engine. For example, the fuel-injection system need not be critical. As a final point, a supply of hot gas at elevating pressure is readily available for heating and for powering auxiliary equipment.

Authors' Closure

The authors wish to thank Dr. Schweitzer and Mr. Tauschek for their interest in this paper and their kind comments thereon. While the NACA's interest in the gas-generator engine was primarily concerned with its possible use as an aircraft power plant, the paper was given to the ASME with the thought in mind that the information to be presented might be helpful in designing a power plant for applications other than in the aircraft field. Mr. Tauschek, who did much of the early NACA analytical work on the gas-generator engine, mentions some of these additional fields. It might also be pointed out that the gas generator in a ground vehicle, together with one or two turbines and suitable gearing to provide the torque conversion required, represents, in effect, a variable-speed transmission and, in addition, the need for a clutch is eliminated. By-pass valves (waste gates) for the turbines are required for such an installation.

In answer to Dr. Schweitzer's comments, a turbine-inlet temperature of 2260 deg R (1800 deg F), and a compressor efficiency of 85 per cent may seem high, but in the light of possible future developments of the art, these values serve as probable limitations to the ultimate performance of the gas-generator engine. In any event, curves are shown in the paper which allow conversion of the performance to other values of turbine-inlet temperature and compressor efficiency. Constant-volume combustion was assumed because such combustion is easiest to obtain in a high-speed compression-ignition engine and, because in a pressure-limited cycle, results obtained using an Otto cycle are more conservative than those obtained using a Diesel cycle.

The cylinder fuel-air ratio of 0.054 used in the analysis is probably near the clear exhaust limit. Whether this will affect the turbine blading is beyond our knowledge at this time.

No blowdown recovery was assumed in the analysis; preliminary work indicated that the results obtainable under the cycle used would not be worth the complication of providing suitable ducting to a blowdown turbine.

With regard to the operation with insufficient exhaust lead, it was known, after preliminary tests, that the lead was insufficient; however, the length of time required to machine another cylinder with suitable lead made it imperative to operate in the meantime with the old cylinder.

The authors still feel that the smooth combustion obtained with the gas-generator engine was due to the fact that a low compression ratio and heated inlet air resulted in a higher mean temperature and pressure during injection than obtainable with a high-compression engine with unheated inlet air.

[5] Thompson Products, Inc., Cleveland, Ohio.