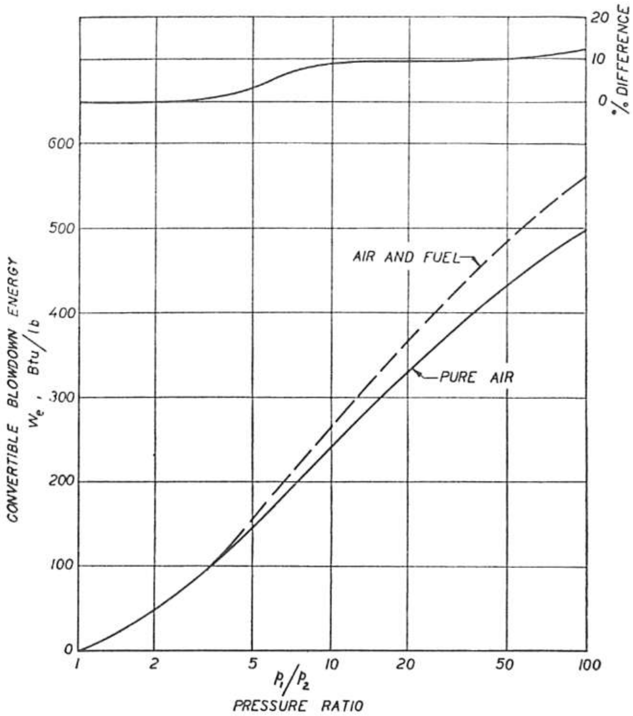

Fig. 4 Effect of Fuel

(Assumptions: T_1 = 4000 R; p_2 = 14.70 psia; fuel = $[CH_{2.25}]_x$; fuel/air = 0.0665.)

correct fuel-air mixture are compared. In the computation for the curve marked "air and fuel," a chart of thermodynamic characteristics prepared by Hershey, Eberhardt, and Hottel was used.

In view of the fact that the exhaust release pressure is seldom more than 6 times atmospheric, the error committed by using the air chart is negligible.

Discussion

Israel Katz.[6] The authors have added materially to the advance of internal-combustion engines and have presented a convincing case favorable to piston-engine compounding. The following remarks are made solely to illustrate how energy in the engine exhaust may perhaps best be employed in aircraft propulsion machinery.

While utilization of exhaust energy affords a ready means for boosting the power output of many engines, it is quite evident that aircraft piston engines have reached a point in development where substantial improvements yield only marginal performance advantages. Turbosuperchargers and coupled gas turbines offer but minor gains in net propulsive effort over the thrust boosts attainable with relatively simple duct-type augmenters or jet stacks (devices which involve little penalty in terms of mechanical complexity, increased weight, operating hazards, costs, and installation difficulties).

However, a 15 per cent power boost for sea-level take-off and moderate altitude cruise (up to 20,000 ft) without loss in fuel economy currently justifies the complexities of turbine compounding, and the leading engine builders have recently announced their contributions to this art. On the whole, such gains are only of temporary importance (long-range heavy bomber propulsion) and involve engine and airframe design changes which already crowd the point of marginal return. Further reduction in the weight/power ratios of existing engines may involve serious losses to reliability or endurance. Higher compression ratios or operation at very high manifold pressures will now yield only minor gains in economy or power output within limits set by incidence of detonation, spark-plug fouling, lead deposition, bromide attack on combustion-space components, increased fuel-octane requirements, and inadequate cylinder cooling. Operation at higher piston speeds will contribute to some power advantages, but also to greater mechanical losses, deleterious vibration, piston scuffing, and abnormal bearing wear.

[6] Associate Professor, Cornell University, Ithaca, N. Y. Jun. ASME.

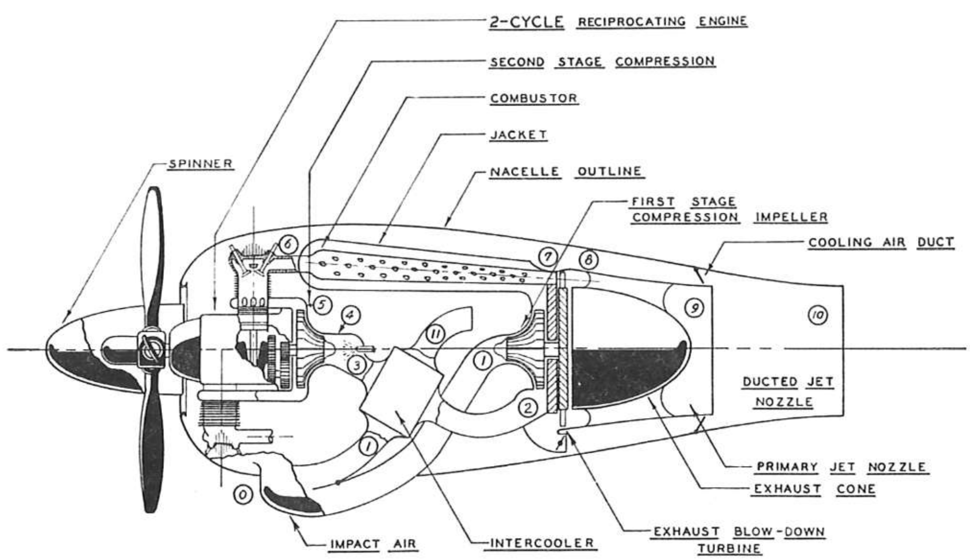

Fig. 5 Turbo Topping Power-Plant Installation Composed of a Mechanically Supercharged Two-Stroke-Cycle "Topping" Engine, Several Combustors, a Turbosupercharger and Ducted Jet Nozzle

(Air passing through first-stage compressor supplies engine and combustors. Engine exhaust gases 6, combine with air from the first-stage compressor 2, expand through the turbine 7, and primary jet nozzle 9, and finally merge with cooling air to provide substantial thrust boost 10. Drawing by Lieut. Col. E. E. Ambrose, U.S.A.F., working on this development under direction of discusser at Cornell Aircraft Power Plants Laboratory.)

Perhaps a novel approach to this seemingly exhausted endeavor may expose a new field for further developments. Highly refined engines surely merit the attention that a new viewpoint can bring to bear.

A recent classroom study, at the Sibley School of Mechanical Engineering, devoted to significant changes in aircraft-engine design and compounding possibilities, tentatively discloses that power-plant performance may be substantially improved if piston engines were used as "topping units" in combination with turbo-power-plant components. The power-plant installation evolved from this study (Fig. 5 of this discussion) may have some very promising features, such as:

1 High power output at moderate crankshaft speeds to be achieved through two-stroke-cycle operation, substantial supercharge, and uniflow scavenging during extended valve overlap. The use of very rich fuel-air mixtures should permit operation at high charge densities with low-octane fuels and afford a measure of internal cooling during the scavenge period.

2 Unusual over-all fuel economy (for the installation weight/power ratio) to be made possible by afterburning prior to turbine expansion (consistent with maximum allowable turbine-blade temperatures), in addition to the use of exhaust energy for supercharger operation and thrust augmentation in a ducted jet nozzle (where combustion products are to merge with heated cooling air).

3 Low weight/maximum-power ratio to be attained through two-stroke-cycle engine simplicity and the use of relatively light auxiliary components.

4 Low cost/power ratio to be achieved through use of existing highly developed piston engine, turbosupercharger and gas-turbine components.

5 Good installation versatility and maintenance ease.

Design details cannot be discussed, but the following information will illustrate other anticipated installation properties:

1	Displacement (piston engine), cu in	2000
2	Installation weight, lb	2900
3	Sea-level take-off power, bhp	3600
4	Static jet thrust (take-off), lb	800
5	Take-off bsfc (installation), lb per bhp-hr	0.56
6	Take-off crankshaft speed, rpm	3000
7	Take-off bte, per cent	21.6
8	Manifold air pressure (TO), in. Hg abs	80
9	Release pressure (TO), in. Hg abs	60
10	Combustor pressure (TO), in. Hg abs	49
11	Combustor temperature (TO), deg F	1400
12	Cruise power at 10,000 ft and 400 mph, bhp	1800
13	Cruise jet-thrust at 10,000 ft and 400 mph, lb	600
14	Cruise bsfc (installation), lb per bhp-hr	0.43
15	Cruise power bte, per cent	28.2

E. C. Magdeburger.[7] The paper presents a simple and quick way of estimating the heat content or potential energy of the exhaust gases of an internal-combustion engine for any possible pressure and temperature of these gases and for any pressure or altitude of the ambient air. "To measure is to economize," is the sage observation attributed to Pascal. Hence this new knowledge of the amount of energy wasted in the exhaust will keep on pointing its accusing finger at the engineer and challenge him to find ways and means of preventing this waste in a world which is becoming more and more sensitive to the status of its rapidly dwindling petroleum reserves.

However, it is not enough, for instance, to know with reasonable certainty just how much petroleum is stored in the vast deposits of oil-soaked shales in Colorado. The question is how are we going to make that oil practically available.

[7] Head Engineer, Bureau of Ships, Navy Department, Washington, D. C. Mem. ASME.

It would seem, therefore, that the value of the paper would be enhanced by the presentation of one possible method which was found in the huge mass of "unfinished business" created by the German surrender. Apparently, only preliminary tests were completed, the purpose of the research having been the development of a "back-pressure" engine suitable for jet propulsion. Unless this idea is found to possess attractive economic possibilities on this side of the ocean, it will stay buried in the mountains

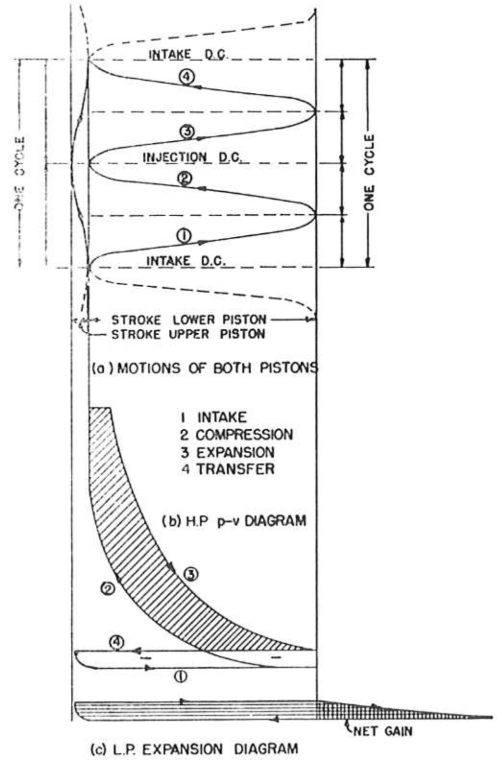

Fig. 6 Diagrams of German Back-Pressure Engine

of rubble and desolation by a people more concerned about physical survival than about contributions to the more efficient use of fuel resources of the world.

The concept of the new engine rests upon two opposing pistons, the lower connected to a crankshaft in a normal manner, the upper made of larger diameter and driven at one half the crankshaft speeds as from the customary camshaft of the four-cycle engine. The engine operates on a cycle requiring four strokes of the lower piston and two strokes of the upper piston. The accompanying diagram, Fig. 6, of piston motions illustrates most effectively the resultant operation. It is obvious that the pistons in the "intake" inner dead center must be separated by only the minimum possible physical clearance, and at the "injection" dead center by the required combustion space. Thus only cool and undiluted air will fill the cylinder at the end of the intake stroke, the cylinder volume in the lower dead center being in excess of piston displacement by one half of the combustion-space volume. It will then be compressed in the normal manner on the upstroke of the two pistons, the fuel will be injected at or near the dead center, followed by the expansion or power stroke down to the bottom dead center of the lower piston. As in every normal four-cycle engine, the exhaust valve is then opened and the gases of combustion are to be "transferred" by displacement. In a normal engine exhausting into the atmosphere, their energy content would be lost and wasted. Furthermore, the gases filling the clearance space normally remain in the cylinder and thus not only is their heat energy wasted but they also dilute and reduce the incoming air charge by heating it. By "transfer" to the low-pressure turbine of a turbocharger, for instance, all of this energy can be recovered in the form of compressed charging air.

The new engine differs from others by this ability to displace all of the gases of combustion out of the cylinder. Furthermore, by properly designing the turbine nozzles and the exhaust duct between the cylinder and the turbine, the pressure of exhausting gases can be maintained and a very much greater part of the heat energy of these gases can be converted into mechanical energy of the turbine shaft, thereby raising the weight and the density or pressure of the air charge, with consequent increase in net output and improvement in thermal efficiency or fuel consumption.

This is one way of materializing the energy now going to waste in the exhaust gases of internal-combustion engines. Is it practically attractive? Or is there a better way?

E. F. Obert.[8] The authors have emphasized that either an ideal turbine or an ideal complete-expansion engine will deliver the same ideal amount of work when the working fluid is the exhaust gas from a reciprocating piston engine. The authors show that their first equation, for the complete expansion engine, gives the same answer as their fourth equation, for the ideal exhaust turbine. This proof (and the necessity for such a proof is debatable because the end result appears to be self-evident) is not too satisfying because their fourth equation must be solved by graphical integration. A more elegant solution is available by defining a slightly different thermodynamic system. Consider that their fourth equation arises from analysis of a nonsteady flow system, which consists of a turbine with flow from the cylinder into the turbine and from the turbine into the atmosphere. Applying the "first law" to each element of fluid which flows reversibly through the adiabatic turbine (which is the system)

$$\underset{s=C}{W_{\text{rev}}} = \int_{G_0}^{1} (h_x - h_0)dG = \int_{G_0}^{1} h_x dG - h_0(1 - G_0)$$

and this is the fourth equation of the paper. Suppose now that the system is defined as the "cylinder" at the time of exhaust blowdown. For this system the decrease in internal energy is

$$\Delta U = G_0 u_0 - u \qquad [1]$$

Now examine the fluid leaving this system, say, through a reversible nozzle

$$\begin{aligned} \underset{\text{rev}}{E_{\text{flow}}} &= \underset{s=C}{\Sigma} G\left(u_0 + p_0 v_0 + \frac{1}{2g_c} V^2\right) \\ &= \int_{G_0}^{1} h_0 dG + \int_{G_0}^{1} \frac{V^2}{2g_c} dG \\ &= (1 - G_0)h_0 + KE_{\text{rev}} \qquad [2] \end{aligned}$$

The change in energy indicated by Equation [1] herewith, for an adiabatic and reversible expansion must be equal to that of Equation [2] but of opposite sign

$$(1 - G_0)h_0 + KE_{\text{rev}} = u - G_0 u_0$$

Since the work to be obtained from this flow must come from conversion of the kinetic energy

$$W_{\text{rev}} = [u - G_0 u_0 - (1 - G_0)h_0]_{s=C} \qquad [3]$$

Equation [3], unlike the author's fourth equation, is quite easily solved (and of course Equation [3] reduces directly to the author's first equation, because $G_0 = v/v_0$).

It is well to remark that the foregoing equations (and most of the author's equations) are not limited to perfect gases and lend themselves to more exact solutions when using combustion charts such as the Hottel charts.

[8] Associate Professor, Mechanical Engineering, Northwestern Technological Institute, Evanston, Ill. Mem. ASME.

A. R. Rogowski.[9] The authors of this paper have introduced a valuable concept. The fact that an ideal blowdown turbine will convert into work the same amount of energy that the ideal engine would, if both expansions were carried to ambient pressure, gives the engineer a most useful criterion for comparison of actual exhaust-turbine performance.

Since the authors are considering ideal cases, and since, in fact, the authors' expression for w_e is strictly true only if $v = v_1$, it is suggested that the exhaust release be assumed to take place at bottom center. Then the ideal efficiency of the blowdown process will be

$$\frac{w_e}{(u - u_1)(1 - G_0)}$$

From a practical standpoint, early exhaust release will result in loss of reciprocating-engine work which is chargeable against the turbine. The values of T and p may be calculated easily for the theoretical engine cycle, but are much more difficult to estimate for an actual engine. This is another argument for using the foregoing concept, mainly as a simple criterion for comparison of actual turbine performance.

A simple proof that the exhaust energy recovered by an ideal blowdown turbine is equal to

$$w_e = (h - h_0) - A\ (p - p_0)v$$

may be obtained by considering the engine cylinder and turbine as an "open system."

Starting with the energy present per pound of gas in the cylinder at point (4) as u, then during the blowdown process the system will lose $(1 - G_0)$ pounds which leaves the system, carrying with it $(1 - G_0)u_0$ Btu of internal energy. The flow work required to force it out of the system will be

$$Ap_0\ (1 - G_0)v_0$$

The system will lose turbine work w_t, and will gain piston work during the exhaust stroke of

$$Ap_0\ (v_1 - v_2)$$

At the end of blowdown, there will remain G_0 lb in the cylinder, the thermodynamic condition of which will be the same as the turbine exhaust, since all the gases have expanded isentropically from p to p_0. The energy left in the cylinder will be $G_0 u_0$.

Noting that $G_0 = v_2/v_0$ and $v = v_1$, we may write

$$u - w_t - (1 - G_0)u_0 - Ap_0\,(1 - G_0)v_0 + Ap_0(v_1 - G_0 v_0) = G_0 u_0$$

From which, combining terms

$$w_t = u + Apv - Apv + Ap_0 v_1 - (1 - G_0)h_0 - G_0 A p_0 v_0 - G_0 u_0$$

or

[9] Associate Professor of Aeronautical Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

$$w_t = h - Av(p - p_0) - (1 - G_0)h_0 - G_0h_0$$

Therefore

$$w_t = h - h_0 - A(p - p_0)v = w_e$$

QED.

A similar analysis may be made for the case of an internal-combustion engine discharging its exhaust gas into a receiver held continuously at p_4 pressure. From the receiver, the exhaust gases flow through the turbine, expanding to p_0 pressure. In this case

$$h_{rec} = h$$

Flow through the turbine = $(1 - G_0)$ lb per lb of gas in the engine cycle

$\therefore$ turbine work per lb gas in cycle = $(1 - G_0)(h - h_0)$

The extra pumping work required of the engine to force the gas into the receiver is

$$A(v - v_2)(p - p_1)$$

In this case

$$G_0 = \frac{v_2}{v} = \frac{1}{r} \text{ and } p_1 = p_0$$

$$\text{Pumping work} = A(v - G_0v)(p - p_0)$$

$$= A(1 - G_0)(p - p_0)v$$

The net turbine work per lb of gas in the engine cycle will thus be

$$(1 - G_0)[(h - h_0) - A(p - p_0)v]$$

or

$$\frac{r-1}{r}[(h - h_0) - A(p - p_0)v] = \frac{r-1}{r}w_e$$

Henry Schreck.[10] When presenting this paper, the authors seemed to limit their work to a blowdown process of a mass of gas out of a container through a nozzle down to atmosphere. The example used in the paper is for the exhaust of a gasoline engine, but reference is also made to the exhaust of Diesel engines which, therefore, are included in this treatise. Now then, in the case of a gasoline engine, say, an aircraft engine, there is an abundance of heat left in the outgoing exhaust, which is not true in the case of the Diesel engine, for which an actual example and its solution might be in place in the authors' closure.

A few years ago one of our leading locomotive builders entered into a contract with a well-known builder of supercharger exhaust turbines for airplane engines. The contract came about on the basis of an outstanding success of the latter in developing the same system for a new supercharged high-speed locomotive Diesel, using a liberal-sized exhaust manifold and the blowdown method as the authors call it. On the Diesel engine this system turned out to be a miserable failure because the turbine did not have sufficient output to meet the requirements for the desired supercharging. The condition was turned into success by substituting the larger exhaust manifold with small individual pipes from each cylinder, thereby utilizing the heat mass plus the kinetic energy of the gases as they leave the cylinders.

It would be interesting to have somebody, maybe the authors, work out the actual conditions with which the engineer is confronted when determining the exhaust-power utilization of an actual Diesel engine.

[10] Retired, Jackson Heights, New York. Mem. ASME.

H. W. Welsh.[11] In view of the current widespread interest in compound reciprocating engines, this paper is timely indeed. Theoretical studies of this nature are frequently quite valuable in analyzing the potentialities of various proposed designs. The chart presented in Fig. 3 of the paper is quite general since it can be applied to theoretical Diesel and Otto-cycle engines equally well.

However, the fact that Fig. 3 is based on the temperature and pressure at the time of release makes it extremely difficult to use

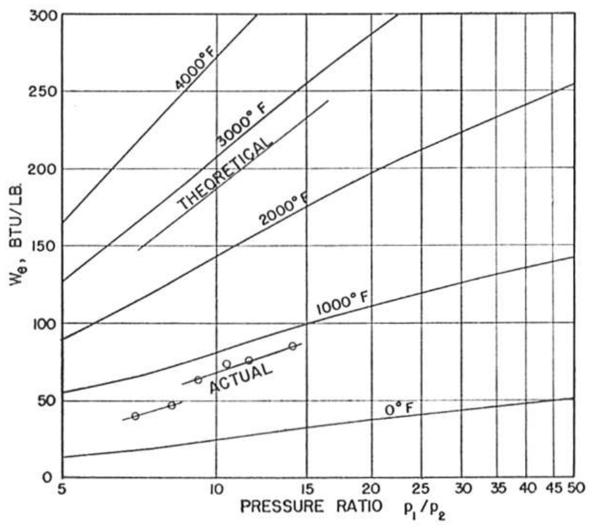

Fig. 7 Convertible Blowdown Energy C9HC Single-Cylinder Test Data

(Data taken at sea level; 2500 rpm; 0.080 F/A; 4.552 in.² nozzle.)

for practical applications. Also, since the exhaust energy came from another cycle, the writer cannot help but wonder what is the relation between the work of the basic cycle and the convertible energy of the exhaust.

Unfortunately, the authors have not presented test data showing the degree of correlation between theory and actual performance. For that reason, the writer takes the liberty of presenting some data obtained by his company. The tests were run to determine the actual convertible energy in the blowdown from cylinder to exhaust pressure.

The data, expressed as a function of theoretical cycle release to exhaust pressure ratio, are compared to the authors' calculations in Fig. 7 herewith. Although there is considerable agreement with regard to the slope of the curve, the recovery is only about 35 per cent of that predicted from Fig. 3. The large difference is indicative of the losses inherent in exhaust power-recovery systems. The losses cover almost every conceivable form, including shock, friction, and heat transfer.

Owing to the magnitude of the losses, it is apparent that actual test data must be used for all power-recovery applications and, while the chart in Fig. 3 is very interesting from the theoretical standpoint, it should not be considered a short cut to evaluating

[11] Assistant Project Engineer, Wright Aeronautical Corporation, Wood Ridge, N. J. Jun. ASME.

the energy actually available. The reader is referred to three papers which discuss the amount of available energy in the exhaust.[12]

In terms of engine performance, test data show that the blowdown energy (convertible energy in this paper) varies from 30 to more than 50 per cent of the brake output of typical aircraft engines. When this energy is converted to useful work in a turbine, geared to the engine, the engine power output can be increased to 15 to 25 per cent at no increase in fuel consumption. Although performance data are restricted, it may be of interest to note that the writer's company is now producing a true compound engine utilizing the blowdown energy. Pictures of the engine appeared in newspapers and trade magazines a few months ago.

Authors' Closure

The authors wish to express their sincere appreciation for the enthusiasm and co-operation of those who participated in the discussion, which is rather thought-provoking and adds much value to the paper.

Prof. Israel Katz described an interesting compound power plant for aircraft propulsion in which a two-stroke cycle engine is used as a "topping unit." The compounding of two-stroke cycle engines has been a relatively neglected subject in this country, but it does seem to present interesting possibilities.

Mr. E. C. Magdeburger described an intriguing engine which, it is understood, was to be used to create direct thrust on the water (jet effect) when the exhaust is discharged through a submerged nozzle. To this end the engine is to make use of three unusual features, i.e., (1) pushing out the residual gas from the clearance volume, (2) recovering blowdown energy, and (3) creating a back pressure in the exhaust at the expense of the piston work, utilizing that, too, to increase the thrust.

For an ordinary engine an elevated back pressure has a very detrimental effect upon its volumetric efficiency. If a "back-pressure engine," such as described by Mr. Magdeburger, were used, then the volumetric efficiency would be almost independent of the exhaust pressure. Such an engine, although requiring unusual valve arrangement, may be attractive for certain applications.

Profs. E. F. Obert and A. R. Rogowski offered proofs of the equation for convertible blowdown energy. The former's proof applies to two-stroke cycle engines, and the latter's to four-stroke cycle engines. The final result is the same in both cases.

The authors had obtained similar proofs but for brevity they were not included in the paper. However, the authors are glad that their omission has been ably filled by Professors Obert and Rogowski.

[12] "Design of Nozzles for the Individual Cylinder Exhaust Jet Propulsion System," by B. Pinkel, L. R. Turner, and F. Voss, NACA ACR April, 1941 (Wartime Report E-83).

"Performance of an Exhaust-Gas 'Blowdown' Turbine on a Nine Cylinder Radial Engine," by L. R. Turner and L. G. Desmon, NACA ACR E4K30 December, 1944 (Wartime Report E-30).

"Engine Compounding for Power and Efficiency," by E. F. Price and H. W. Welsh, SAE Transactions, vol. 2, April, 1948, pp. 316–328 and 344.

The authors agree with Professor Obert that most of the equations in the paper are not limited to perfect gases. They can be used for solutions involving combustion products such as was done in obtaining Fig. 4.

Professor Rogowski introduced an expression for the "ideal efficiency of the blowdown process." His expression is not clear to the authors. The efficiency of a "process" is difficult to define. For practical purposes, Professor Rogowski's u and u_1 are at least as difficult to evaluate as the authors' T and p for an actual engine.

Professor Rogowski presented an interesting scheme in which an engine exhausts into a receiver where the pressure is kept constant at p_4. This scheme is theoretically very attractive but also involves certain limitations. Primarily, it is applicable only to four-stroke cycle engines where one piston stroke is available for pushing the exhaust gases out of the cylinder against p_4 pressure. Then, owing to the necessity of maintaining the exhaust back pressure at p_4, which is much higher than the intake pressure p_1, any low or medium compression-rate engine is out of the question. Unless a high-compression-ratio engine or some special engine, such as described by Mr. E. C. Magdeburger is used, the volumetric efficiency will be intolerably poor.

Assuming an ideal Diesel cycle with a compression ratio of 20:1, a fuel/air ratio of 0.045, and initial conditions of 14.7 psia and 560 R, the air-cycle efficiency is 54.6 per cent, and the theoretical mean effective pressure is 188 psi. Based upon Professor Rogowski's scheme, the efficiency is raised to 61.7 per cent, and the mean effective pressure to 212 psi (referred to engine displacement). This shows a theoretical net gain of 13 per cent in power and economy. This is paid for by the addition of a turbine and its controls.

In reply to Mr. Henry Schreck, it may be pointed out that Fig. 3 of the paper is equally applicable to gasoline engines and Diesel engines. A typical Diesel blowdown with 60 per cent excess air involves 50 psia release pressure and 1000 F release temperature, which results in a convertible blowdown energy of 32 Btu. One pound of cylinder gas contained 19,000/23.2 = 820 Btu. The recovered energy is therefore approximately 4 per cent. Mr. Schreck also touched upon the question of exhaust manifolding. Although the authors are carrying on a very promising experimental research on this subject, the test results are not yet released for publication.

Mr. H. W. Welsh's information is a welcome addition to the paper. While the authors agree with Mr. Welsh that actual tests must be resorted to for exhaust-energy recovery applications, the fact that the actual recovery is only 35 per cent of that predicted from Fig. 3 indicates that the art of designing exhaust-blowdown turbines is still in its infancy. As Mr. Welsh correctly points out, the losses in a blowdown turbine cover almost every conceivable form, such as shock, friction, and heat loss. A blowdown turbine also has to negotiate widely varying blade-to-jet speed ratios. It is hoped that concerted research will improve substantially the efficiency of present-day exhaust-blowdown turbines.