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EFFICIENCY OF GUNS AND MACHINE GUNS FROM THE TECHNICAL POINT OF VIEW*

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From the engineering point of view, a gun or machine gun is a heat engine very similar to a Diesel or petrol engine. It has to do work when operated by a soldier. A fuel is burnt, namely the propellant, and certain power (energy per unit time) is obtained, namely the kinetic energy of the projectile for each interval of rounds fired.

Since the function of a gun or machine gun is in principle that of an engine, it is obvious that for the design of a weapon, like the design of an engine, similar engineering methods and scientific research are to be used. And the course of development of a prototype, either of a gun or a heat engine, will follow similar lines. In the development of a gun the high standard and accuracy of Ballistic measuring apparatus play a very helpful role in the realisation of desired qualities and attainment of higher efficiencies.

This does not mean that we value only the mechanical qualities. We know that the success of a weapon also depends on the troops who handle them and their officers. Therefore it is evident that for the development of a new weapon, besides the technical and economical points of view, the military aspects greatly influence the size and shape.

However, in the following I will restrict myself to the technical points of view and try to form some mathematical terms from which a comparison, not only between two different weapons but also between weapons and the general field of heat engines can be drawn.

The thermodynamic efficiency.

When the projectile leaves the muzzle of a gun it has a kinetic energy $E_1 = \frac{1}{2} m v_o^2 + \frac{1}{2} J \omega_o^2$ expressed, say, in ft lbs. Herein the second term of the energy of rotation is negligibly small compared with the first term of the energy of translation.

This energy is produced by the heat content of the propellant. When C is the charge weight in lbs., H the calorific value in BTU/lb, and 778 the Joule's equivalent in ft lbs/BTU, we have the initial energy $E_2 = C \times H \times 778$ also expressed in ft lbs.

Hence, the ratio E_1 to E_2 gives the degree of utilisation and can be called the " Interior Ballistic Efficiency " of the gun.

$$\eta_{ib} = \frac{\frac{1}{2} m v_o^2}{C \; H \; 778}$$

When we compare this ratio with that normally obtained in the design of combustion engines we find that it includes not only the thermodynamic efficiency η_{th} but also the mechanical efficiency η_m which takes into account the losses due to mechanical friction in the engine gear, so that in our case

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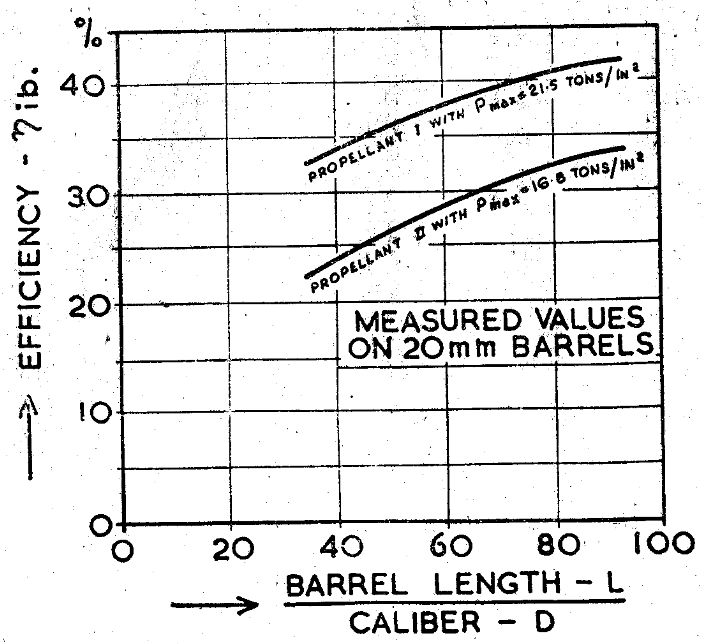

$$\eta_{ib} = \frac{\frac{1}{2}\ m \cdot V_o^2}{C \times H \times 778}$$

Where -

m = Mass of Projectile in $\frac{\text{lbs. wt. Sec}^2}{\text{ft.}}$

V_o = Muzzle Velocity in $\frac{\text{ft.}}{\text{sec.}}$

C = Charge Weight in lbs.

H = Calorific Value of Propellant in B.Th.U./lb.

778 = Mechanical Equivalent of Heat in $\frac{\text{ft. lbs.}}{\text{B.Th.U.}}$.

FIG. 1. EFFICIENCY OF INTERIOR BALLISTICS DEPENDING ON CALIBER LENGTH.

the Interior Ballistic Efficiency equals the product of the thermodynamic and the mechanical efficiencies : $\eta_{ib} = \eta_{th} \times \eta_{m}$

Figure 1 shows the relation between the barrel length and the efficiency η_{ib}. The results are obtained by tests on 20-mm barrels. To simplify comparison with bigger calibers, dimensionless values are given. It is known from the design of combustion engines that a higher peak pressure as well as a longer travel gives better efficiencies. The reason is that a high peak pressure influences the peak temperature and therefore increases the drop of heat available for the thermodynamical process, and that a longer barrel like a longer cylinder (or higher compression ratio) of a heat engine makes the degree of expansion higher.

In this connection it is interesting to consider the corresponding values of efficiency of heat engines. Heavy gas engines run by producer gases can have an efficiency up to 25% when calculated from the heat energy of the fuel consumed to the energy obtained on the wheel, and heavy Diesel engines can reach an efficiency of 30 to 35 per cent, according to the high peak pressure in the cylinders.

We see from figure 1 that the efficiencies of guns are in the same range as stated above for heat engines. That means the utilization of the propellant heat in guns is quite in accordance with the present day standards of general engineering.

When the designer intends to obtain a very high efficiency η_{ib} he is limited by some conditions which he cannot transgress without special arrangements. The magnitude of peak pressure, for instance, is to be kept below certain limits as the yield point of the barrel material has to be taken into consideration.*

On the other hand, the designer cannot raise the barrel length to values higher than 45 to 70 caliber lengths because the weapon would become too

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* For calculation of the tangential stress admissible sometimes Winkler's Formula is used

$$\sigma_{\text{admissible}} = 3 \times \frac{2k^2 + 1}{k^2 - 1} \times P_{max} ,$$

where k is the ratio of outside to inside diameter. For a given peak pressure P_{max}, lower stresses are obtained by this formula than those obtained by the use of the exact equations derived from the theory of elasticity

$$\sigma_t = \frac{k^2 + 1}{k^2 - 1} \times P_{max} ; \quad \sigma_r = -P_{max}$$

in combination with the limiting condition of yielding

$$\sigma_t^2 + \left(\sigma_t - \sigma_r \right)^2 + \sigma_r^2 = 2\sigma^2_{\text{admissible}}.$$

However, gun barrels calculated after Winkler show no deformation. One reason for this behaviour seems to be that the material has a much higher yield point at short dynamical loads (as in guns and machine guns) than in the static material test. Though I cannot give an exact figure about the yield point increase of barrel steel I would like to mention that, after E. Meyer, soft steel has a 50 per cent higher yield point at an elongation rate $f\varepsilon \doteq 100$ sec^{-1}.

Elongation rates of this range are usual at medium calibers.

long and too heavy, and in recoil driven machine guns, the rate of fire would drop too much due to the heavy masses moved.

Just when we take into consideration the weight of the gun and the rate of fire we come to another technical term of quality :

The power per unit weight.

For comparison of different heat engines (petrol or Diesel engines) use is sometimes made of the " power per unit weight ". This value indicates how much energy per second is obtained per pound of the engine weight. As we generally express the power in HP and the weight in lbs we will obtain the specific power in HP/lb.

For instance, the specific power of a common autocar engine is about 0·1 HP/lb and that of highly developed aircraft engine is about 0·8 HP/lb.*

This specific power includes all features and components of design, construction, and materials used. Therefore it is a measure of the technical quality of the engine.

In the field of gun design it is also possible to use the value of the specific power as a measure of quality. We have first to see how we can introduce this specific power into the other data generally used as characteristics of guns.

Since power means energy produced per unit time we have first to consider the energy.

I think the energy which may most conveniently indicate the quality of a gun is the muzzle energy $E_o = \frac{1}{2} m v_o^2$.

Those who are keen on the measure of success achieved in hitting the target may use the kinetic energy on the target $E_t = \frac{1}{2} m v_t^2$ and may add a factor which describes the probability of hitting. They will then have included the quality of the projectile and the influence of the exterior ballistics. Or, those who are more interested in the detonation effect at the target, may use the energy (that is the heat content) of the High Explosives carried with the shell to the target and may also add the factor of probability.

In case we use the muzzle energy there arises the further question of fixing the time during which this energy may be supposed to have been released.

The actual generating time is the travelling time of the projectile along the barrel. This interval is very short and usually measured in milliseconds.

Another time basis may be fixed as the interval between two successive rounds. For machine guns this time interval is obtained from the rate of fire. It is $n = 60/T$ where T is measured in seconds and n in min^{-1} In the case of hand-operated guns, however, the number of rounds per minute would depend to a certain extent on the skill of the soldier. This personal factor may falsify

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* To give an actual example : A 600 HP aircraft engine weighs 730 lbs. Then the specific power is obtained by the ratio 600/730 = 0·822 HP/lb. Each pound of the engine produces 0·822 HP.

any quality term which is meant to refer to the gun alone. We therefore have to eliminate this personal factor and we do so by using an empirical formula which gives us the interval T (in seconds) between two rounds as function of the caliber D (in inches). It is approximately $T \approx 1{\cdot}5 \times D^2$ and differences in values actually obtained on guns are not so important in this connection.*

When we intend to compare the efficiency of guns and machine guns with that of heat engines we have to choose the whole interval between successive rounds as our time basis, and not the actual generating time of the shot travel along the barrel. For, in case of a heat engine we take the entire time of a cycle, for instance the time for all the 4 strokes of a 4-stroke engine, and not merely the time of the working stroke.

Figure 1 (*a*) and 1 (*b*) show tables in which the power of some types of guns and machine guns is stated. They also give the specific power (power per unit weight) in HP/lb. We see that the values of the specific power are much higher for machine guns than for guns, due to the higher rates of fire of machine guns.

FIG 1*a*

Type of Weapon, Country or Manufacturer	Caliber D	Projectile weight W in lbs.	Muzzle velocity Vo in ft/sec	Rate of fire $n = 60/T$ in /min.	Power in HP	Weapon weight in lbs.	Specific power in HP/lb.
I. U. S. SERVICE GUNS							
Antitank Gun	37 mm	(2·62)	2900	$18{\cdot}9 = \frac{60}{3{\cdot}18}$	195	191	1·0
Pack Howitzer ..	75 mm	14·60	1250	$2{\cdot}59 = \frac{60}{13{\cdot}1}$	49·2	341	0·1445
Howitzer	105 mm	33	1550	$2{\cdot}345 = \frac{60}{25{\cdot}6}$	87·5	1080	0·0810
Gun	4·5 inch	54·9	2275	$1{\cdot}975 = \frac{60}{30{\cdot}4}$	264	4200	0·0628
Gun	155 mm	95	2800	$1{\cdot}07 = \frac{60}{56}$	376	9595	0·0392
Howitzer	8 inch	200	1950	$0{\cdot}625 = \frac{60}{96}$	224	10240	0·0218
Gun	8 inch	240·37	2950	$0{\cdot}625 = \frac{60}{96}$	616	29800	0·0206
Howitzer	240 mm	360	2300	$0{\cdot}45 = \frac{60}{133{\cdot}5}$	404	25100	0·0161

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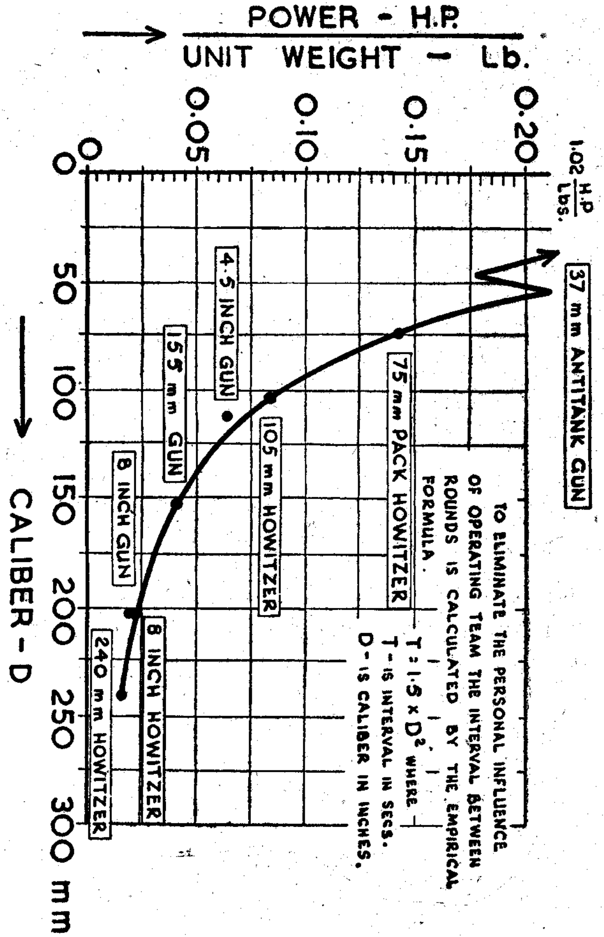
* I have always found values given by military authors like "6 rds/min", or "2 rds/min", or "1 rd/min". But never have I seen a value given as "3·27 rds/min". From this it is evident that generally these intervals are given in round numbers and are not so exact as the other data of a gun.

Fig 1(*b*)

Type of Weapon, Country or Manufacturer	Caliber D	Projectile weight W in lbs,	Muzzle velocity Vo in ft/sec	Rate of fire $n=60/T$ in/min.	power in HP	Weapon weight in lbs.	Specific power in HP/lb.
II. MACHINE GUNS							
Aircraft Machine Gun (1939) Aviation	7·35 mm	0·0207	2775	$1430 = \frac{60}{0\cdot042}$	107·3	18·5	5·8
Aircraft Machine Gun 1928 Rheinmetall	7·9 mm	0·0282	2480	$1100 = \frac{60}{0\cdot0545}$	90	26·6	3·38
Machine Gun M 1919 AG Browning	0·3 in	0·0217	2740	$450 = \frac{60}{0\cdot1333}$	34·5	32·5	1·06
E.M.G. 1934 .. .. Mauser	7·9 mm	0·0282	2480	$850 = \frac{60}{0\cdot0706}$	69·4	(34)	(2·04)
Machine Gun M2 .. Browning	0·5 in	0·100	2810	$510 = \frac{60}{0\cdot1175}$	190	82	2·31
Machine Gun .. .. Solothurn	12·7 mm	0·115	2490	$600 = \frac{60}{0\cdot10}$	201	86	2·34
Aircraft Machine Gun, Type AS. Oerlikon	20 mm	0·295	2950	$300 = \frac{60}{0\cdot20}$	363	92·5	3·92
Anti-Aircraft M.G. .. Madsen	20 mm	0·352	2950	$300 = \frac{60}{0\cdot20}$	436	114·5	3·81
Aircraft Gun .. .. Hispano Suiza	20 mm	0·276	2980	$711 = \frac{60}{0\cdot0985}$	703	99·0	7·1
Anti-Aircraft M.G. .. Bren	30 mm	0·88	3480	$400 = \frac{60}{0\cdot15}$	2010	440	4·57
Aircraft M.G., MK 108 .. Rheinmetall	30 mm	0·88	(1970)	$480 = \frac{60}{0\cdot125}$	(770)	(170)	4·52
Anti-Aircraft M.G. .. Vickers	40 mm	1·9	2460	$200 = \frac{60}{0\cdot30}$	1080	700	1·54
Anti-Aircraft M.G. .. Bofors	40 mm	1·96	2870	$(150 = \frac{60}{0\cdot40})$	(1140)	1051	1·08

Figure 2 shows the same specific powers for U.S. service guns when drawn against the caliber. The figures are taken from the book "Weapons of the World-War II" by G. M. BARNES. Only the figures of the rounds per minute are slightly changed by use of the above mentioned formula to eliminate the personal factor.

FIG. 2. POWER PER UNIT WEIGHT U. S. GUNS.



TO ELIMINATE THE PERSONAL INFLUENCE OF OPERATING TEAM THE INTERVAL BETWEEN ROUNDS IS CALCULATED BY THE EMPIRICAL FORMULA.

$T = 1.5 \times D^2$ WHERE

T- IS INTERVAL IN SECS.

D- IS CALIBER IN INCHES.

Fig 2

It is astonishing how the points obtained fall into a single curve though different types of guns and howitzers are considered simultaneously.*

One fact is remarkable. For heat engines, normally, the specific power increases when the power itself increases, and bigger engines usually have higher efficiencies and higher specific power. In the case of guns, however, the specific power decreases sharply with the increase of caliber.

Before we discuss the cause for this behaviour of bigger guns we should remember the following two facts :

(1) The magnitude of the gun power is enormous when related to the generating time. The American 240-mm gun, for instance, has a generating time of 21·4 milliseconds and, related to this time, a power of 2·5 Million HP. This amount can never be approached by any type of heat engine. (It is understood that the installed capacity of all the hydro-electric power stations combined was 670000 HP in India, in 1948 ; that is about one fourth of the power of this gun.)

(2) The ratio of the actual generating time to the cyclic period is lower with guns than with heat engines. If we assume a ratio of 1 : 4 for the mean power of a 4-stroke engine, the corresponding value of the 240-mm gun will be about 1 : 6000, the generating time being 21·4 milliseconds while the cyclic interval is about 133·5 seconds. The factor of time utilisation is constant with heat engines but decreases with bigger caliber of guns.

Now we shall see how the specific power varies in respect of caliber D. The specific power

$$P_s = \frac{\frac{1}{2}\, m\, v_o^2}{T}\, \frac{1}{W_g}, \qquad \text{where :}$$

m = mass of shell varies as the cube of D ....$c_1 D^3$

v_o = Muzzle velocity does not depend on caliber ....$c_2 D^0$

T = whole interval as given by the empirical formula, varies as square of caliber ....$c_3 D^2$

W_g = weight of the gun. This may be assumed as proportional to the barrel weight.

$W_b = 1.\ \pi/4\ (D_o^2 - D^2) \cdot 8$

with

$1 = c_4 \cdot D$ (c_4 = caliber length) ....$c_6 D^3$

$D_o = k \cdot D$

$k = f\left(\frac{P\ \max}{\sigma\ \text{admiss.}}\right) = c_5$

We obtain

$$Ps = \frac{c_7}{D^2}$$

As can be expected from the above relation, the curve $P_s = f(D)$ computed from actual figures is of hyperbolic character (see Fig. 2).

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* I am very sorry that I cannot show the corresponding values of Indian and British guns due to lack of time for obtaining exact data.

Figure 3 shows the specific power of some machine guns also drawn against the caliber. Apparently the graph looks confusing, but becomes clear when the year of design is mentioned and other details are given.

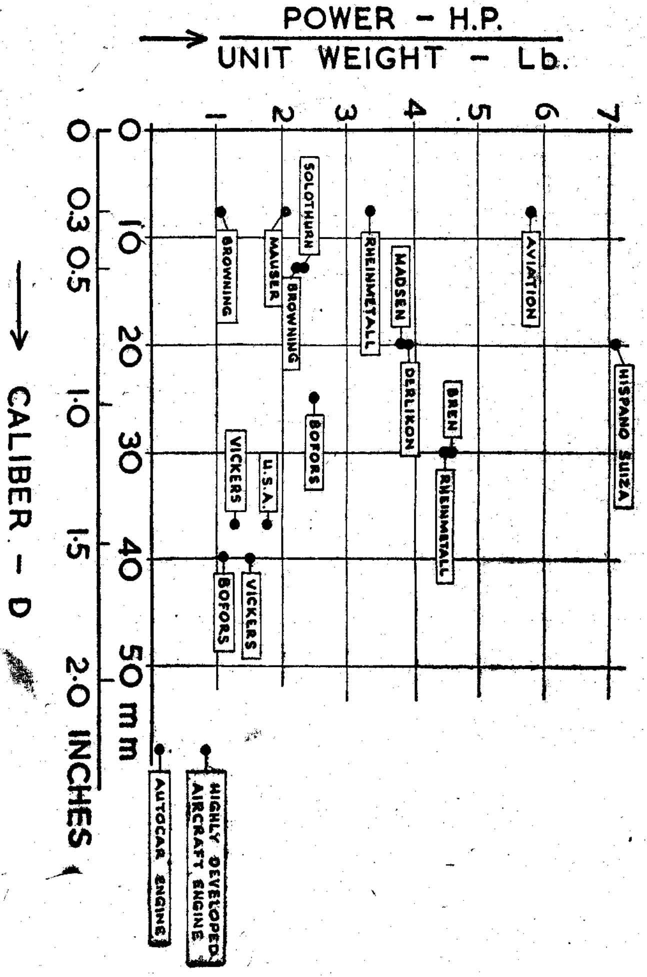

FIG. 3. POWER PER UNIT WEIGHT MACHINE GUNS.

To begin with, we have here two Infantry machine guns of the last war, the American Browning, model 1919 (but still in service) and the German E.M.G. 1934, partly designed by Mauser. The differences of the specific power are chiefly due to differences in rate of fire. We know that the Army is not greatly interested in a very high rate of fire. May be the consumption of ammunition is feared to be too high. A foreign specification, for instance, relating to the design of an Infantry machine gun actually prescribed " to get a rate of fire lower than 500 per min without any mechanical retardation device ".

The Air Force, however, is interested in a rate of fire as high as possible. The fight in the air is very short and the firing time lasts only for 0·5 to 3 seconds according to circumstances. During this short interval as many projectiles as possible have to be shot against the enemy plane. Referring to the graph, consider the values for the Rheinmetall Aircraft M.G., model 1928, having a rate of fire of 1100 per minute and the French Aviation M.G., designed about 1938, having a rate of fire of 1400 rounds/min.

At the 20-mm caliber only a few examples are given. The older Oerlikon M.G., Type AS and the Danish Madsen M.G. were of contemporary design and have correspondingly same values of specific power.

The Hispanc Suiza M.G. is rather an exception, and its very high specific power ($\approx$ 7 HP/lb) may be attributed to its very superior design compared to other machine guns of like caliber. In the last World War this excellent M. G. was in service in U.S.A., in Britain, in France, in Germany, and—as I am informed—is also in service in India.

For the ground-to-air and air-to-air fight two 30-mm weapons were designed in Germany during the last war. The Bren M.G., Type MK 303, had a very high muzzle velocity and was meant for protection of submarines against aircraft. The other MK 108, designed by Rheinmetall, had a high rate of fire but a comparatively low muzzle velocity to which, of course, the velocity of its carrier fighting plane was to be added. Though different in details, both weapons have approximately the same specific power.

At the 40-mm caliber, the specific power of the Vickers M.G. and the well known Bofors M.G. are shown. Though the latter has proved very reliable in function its lower specific power may be attributed to its older design (in the beginning of the thirties).

For comparison with heat engines, values of specific power of a highly developed aircraft engine and a common autocar engine are also shown in the figure. There is no doubt about that in the field of machine gun design we obtain much more power per unit weight than in the field of heat engines. The measure of quality is up to 10 times higher and a designer of weapons can be proud of this fact.

The above comparison, however, is only a restricted one, and hardly holds good when, for instance, we come to the question of wearing time or useful life. An aircraft engine has to run 150 to 300 hours between overhauls and replacement of spare parts in the maintenance shop. A modern aircraft machine gun, howerver, can work only a few minutes. The barrel wears rapidly and must be replaced after 4000 to 8000 shots. When the rate of fire is assumed in the range of 400 to 800 rounds per minute the total working time of a machine gun is restricted to 10 minutes approximately. But this time will do and is sufficient for the shortness of an air fight which lasts only a few seconds.

In the end I have to confess that some more view points exist regarding efficiency of a weapon. One already mentioned refers to the probability of hitting the target. Still others come up from considerations of the effect on the target, for instance, penetration of an armour plate.

Although in my paper I have restricted myself to view points of Internal Ballistic Efficiency and specific power, I hope it has been made clear that the subject of weapon design, as it is to-day, is not merely a matter of mechanical skill of the weapon-smith as in the past, but is one of exact calculation and scientific research like in the neighbouring field of heat engines, and that it has not only achieved a common ground with the subject of heat engines but has even surpassed it in many respects.