FD2872,46It5

B.I.O.S. No. U.5.

Lilienthal Gesellschaft Report No. 158, pps.25-36.
28, 29 January, 1943.
O.Lutz.

Basic problems involved in the use of oxygen carriers for raising the performance of aero engines.

Contents.

1. Introduction

The internal combustion engine requires three substances for carrying out its work: a fuel carrier, an oxygen carrier and a ballast carrier.

After being accustomed for decades to a substance with a calorific value of 10,000 heat units as a fuel carrier, and a mixture of oxygen carrier and ballast carrier in the ratio of 1:4, it is difficult to consider different combinations. Previous work showed that the performance of the power unit can be raised if the partial pressures of the usual oxygen and ballast carrier are increased and if, as regards fuel, the use of higher latent heat reduces the thermal loading.

Instead of varying the fuel carrier, there is also the possibility of changing the oxygen carrier. This is important if, for instance, an internal combustion engine is to run under water, thus being completely shut off from the outside air. An attempt must here be made to run the power unit completely without air. Even in the decade before World War One many suggestions were made concerning this. None of them, however, attained any technical importance. This may possibly be due to the fact that the operation of internal combustion engines under water in itself involves difficult technical problems. Specially recommended at that time as oxygen carriers were nitric acid, hydrogen peroxide, liquid oxygen, and tetra-nitro-mephane. Nitrous oxide was not thought likely to produce results, on account of its low oxygen content.

Aero-engines, which always move in the air envelope surrounding our globe, do not in the first instance make such extreme demands as submarine engines. Of late years it has been shown that, especially when flying at great altitudes, a partial addition of oxygen carriers to the already rarified air can bring surprisingly good results, even taking into account the weights which have to be carried. Authorities on power units have already pointed out that, for the future, performances at extreme altitudes are out of the question without the processes lately introduced for supplying oxygen carriers.

It is advisable to exploit the successes gained at high altitudes for rise in low-altitude-flying. But whereas at high altitudes the power unit with added power can only be brought up to a performance below maximum power, the performance close to the ground would greatly exceed the maximum. It is easy to see that special thermal problems would arise here; nevertheless there are good prospects of achieving success in this field also.

I will first deal with certain thermo-dynamic data, which are thus far remarkable, that they show that the absolute oxygen content is not the only factor which determines suitability. In addition, I will deal briefly with the suitability of the oxygen carriers under consideration, and with some problems which arose when the process was introduced.

2. Thermodynamic conditions.

The effect of the supply of oxygen carriers on the performance of an aero-engine may be expressed, subject to certain reservations, in a relatively simple, complete form.

The factors excluded cancel each other out in the oxygen carriers under consideration, so that it is possible to compare the individual substances by this means. For the principal substances under consideration, oxygen and nitrous oxide, the results of more exact calculations are appended.

(Fig.1 - Arrangement diagram)

a) <u>Arrangement</u>: <u>Alteration in indicated power.</u>

Illustration 1 shows a diagram of the arrangements: working cylinder, boost air pipe, blower, intake duct. The oxygen carrier is either blown or injected into the intake duct or the boost air pipe. The introduction of a volume G_x(Kg/s) alters the original charging weight $G_{L.o}$(Kg/s) by ΔG_L (Index o refers to the original state, without additional supply). The alteration in the indicated power results from the alteration in the charge weight due to the injection of the oxygen carrier, and the energy content of the oxygen carrier:-

$$\frac{\Delta N_i}{N_{i.o}} = \frac{\Delta G_L}{G_{L.o}} + \sigma \frac{G_x}{G_{L.o}} \qquad (1)$$

Here the "air value" σ indicates the degree in which the combustion of the oxygen carrier increases the release of heat energy, relative to the combustion of air:

$$\sigma = \frac{O_x}{O_L} - \frac{bw}{698} + x\,\frac{Q + (aw)}{698} \qquad (2)$$

$\frac{O_x}{O_L}$ = relative proportions of oxygen

bw = heat of formation of the liquid substance at 20° in Kcal/Kg

x = proportion vaporised in the boost air pipe.

ζ = internal heat of vaporisation in Kcal/Kg

(aw) = heat to the substance vaporised, relative to 20°

698 = calorific value of a normal mixture of gazoline vapour and air in Kcal/Kg.

b) <u>Alteration in the volume of air.</u>

In general, the performance will only be raised when working at full throttle, as with a smaller load the power unit itself can still have its performance raised. This means that engine speed cannot be raised during the time that the oxygen carrier is being supplied (possibility of using variable pitch air-screw).

Then

$$n = \text{constant} \qquad (3)$$

The volume used by the power unit in unit time must therefore be equal to the original volume:

$$\frac{G_{L.o}T_{L.o}}{M_L P_{L.o}} = \frac{C_L T_L}{M_L P_L} + \frac{x C_x T_x}{M_x P_L} \qquad (4)$$

(M = molecular weight; gas equation for the oxygen carrier considered as approximately valid). Neglecting small values of the second order of magnitude, then:

$$\frac{\Delta G_L}{G_{L.o}} = \frac{\Delta P_L}{P_{L.o}} - \frac{\Delta T_L}{T_{L.o}} - \frac{G_x}{x G_{L.o}} \frac{T_L}{T_{L.o}} \frac{P_{L.o}}{P_L} \frac{M_L}{M_x} \qquad (5)$$

The method of presentation selected has the advantage that the individual expressions after (1) show those constituents of the performance in relation to which they take effect; the last expression shows the displacement of the boost air by the oxygen carrier. The temperature expression $\frac{\Delta T_L}{T_{L.o}}$ can be split up into an (adiabatic) constituent $\frac{\Delta T_L}{T_{L.o}}$ arising from the alteration in the boost pressure, and a second $\frac{\Delta T_x}{T_{L.o}}$ which is brought about by the mixture with the oxygen carrier.

4) Alteration in boost pressure: influence of blower.

There is a connection between the alteration in the volume of air taken in by the blower and the change in boost pressure, which is expressed by the characteristic curve of the blower. Assume, for the sake of simplicity, that the oxygen carrier is introduced after the blower: then the alteration in the volume delivered by the blower is equal to the alteration in the weight delivered $\frac{\Delta G_L}{G_{L.o}}$. As the blower speed is unaltered, we may put for the characteristic curve (cf. figure 2):

$$\frac{\Delta H}{H_o} = -c\,\frac{\Delta G_L}{G_{L.o}} \tag{6}$$

(H = output of the blower in Kcal/Kg or mkg kg).

Now, the expression for the output is

$$H_o = c_{pL}\,(T_{L.o} - T_a),$$

and so for the alteration in the boost air temperature ΔT_L:

$$\frac{\Delta T_L}{T_{L.o}-T_a} = -c\,\frac{\Delta G_L}{G_L}$$

and as alteration in temperature and pressure are connected

(since $\frac{\Delta T_L}{T_{L.o}} = \frac{x-1}{x}\,\frac{\Delta p_L}{p_{L.o}}$),

then for the expressions $\frac{\Delta p_L}{p_{L.o}} - \frac{\Delta T_L}{T_{L.o}}$:

$$\frac{\Delta p_L}{p_{L.o}} - \frac{\Delta T_L}{T_{L.o}} = -\frac{c}{x-1}\left(1-\frac{T_a}{T_{L.o}}\right)\frac{\Delta G_L}{G_{L.o}}$$

For the alteration in the weight of the air, we have left:

$$\frac{\Delta G_L}{G_{L.o}}\left(1+\frac{c}{x-1}\left(1-\frac{T_a}{T_{L.o}}\right)\right) = -\frac{\Delta T_x}{T_{L.o}} - \frac{G_x}{G_{L.o}}\,\frac{T_L}{T_{L.o}}\,\frac{p_{L.o}}{p_L}\,\frac{M_L}{M_x} \tag{7}$$

The factor which indicates the influence of the blower:

$$1 + \frac{c}{x-1}\left(1 - \frac{T_a}{T_{L.o}}\right)$$

is shown in figure 3

(Figs. 2 and 3 - Alteration in volume of air. Influence of the blower)

Thus, the amount of alteration in the volume of air is inversely proportional to the steepness of the blower characteristic and the external temperature.

As will be shown later, all the oxygen carriers under consideration effect a positive alteration $\frac{\Delta G_L}{G_{L.o}}$; so that the specific increase in output rises somewhat with altitude.

β) Alteration in boost air temperature: influence of the mixture.

The boost air temperature is lowered owing to the vaporisation of the injected oxygen carrier: ignoring the slight change in temperature of the part of the fluid which does not become vaporised, we may proceed from the following assumption:-

$$G_L c_{pL} T_L + x(G_x c_{px} T_x - G_x r)$$

$$= (G_L c_{pL} + x G_x c_{px})(T_L + \Delta T_x)$$

(c_p = specific heats,
ΔT_x = alteration in temperature in the boost air pipe due to mixing);

with the approximates $G_L \sim G_{L.o}$ and $T_L \approx T_{L.o}$.

$$\text{we have } \frac{\Delta T_x}{T_{L.o}}\left(1 + x\frac{G_x c_{px}}{G_{L.o} c_{pL}}\right) \approx -x\frac{G_x}{G_{L.o}} \cdot \frac{c_{px}(T_{L.o} - T_x) + r}{c_{pL} T_{L.o}} \qquad (8)$$

For the required change in the volume of air, we have thus:

$$\frac{\Delta G_L}{G_{L.o}}\left(1 + \frac{c}{x-1}\left(1 - \frac{T_a}{T_{L.o}}\right)\right) \approx x\frac{G_x}{G_{L.o}} \cdot \frac{c_{px}(T_{L.o} - T_x) + r}{c_{pL} T_{L.o}} \qquad (9)$$

$$\text{(simplified: } 1 + \frac{1}{x}\frac{\Delta p_L}{p_{L.o}} \approx 1,$$

$$1 + x\frac{G_x}{G_{L.o}}\frac{c_{px}}{c_{pL}} \approx 1 + x\frac{G_x}{G_{L.o}}\frac{M_L}{M_x}$$

only strictly fulfilled in the case of diatomic gases in the above range of temperature.

The expression in brackets on the right side is a criterion for the vaporisation process in the boost air pipe; those oxygen carriers in which it is positive should be vaporised in the boost air pipe $\left(\frac{G_L}{G_{L.o}}\right.$ positive;$\left.\right)$ those in which it is negative, in the cylinder.

c) Alteration in brake horse power: specific increase in output.

The alteration of the indicated power can be determined, as the initial equation (1) shows, from the alteration in the weight of air used and the "air value" σ according to (2), which can be ascertained from the properties of the oxygen carrier. From it, conclusions can be drawn as to the alteration in brake horse power, if we take into account that the engine speed remains constant during the process, and that therefore the friction horse power N_R can be assumed to be constant.

If the characteristic curve factor C of the blower can be assumed to be equal to 1, then the blower horse power N_L remains constant, otherwise there is a slight dependance on the alteration in the weight of air delivered. If, for the sake of simplicity, we assume that $C = 1$, it follows that $N_L = 0$. i.e.:-

$$\Delta N_e = \Delta N_i$$

and so

$$\frac{\Delta N_e}{N_{i.o}} = \zeta \frac{G_x}{G_{L.o}}$$

or

$$\frac{\Delta N_e}{G_x} = \zeta \frac{N_{i.o}}{G_{L.o}} \qquad (10)$$

ζ being the value later shown in figure 7.

Then for a four-stroke engine with external ignition, we may write:

$$\frac{N_{i.o}}{G_{L.o}} = 1.40 \frac{PS_x}{g} \qquad (11)$$

and for the specific increase in output:

$$\varphi = \frac{N_e}{G_x} = 1.40 \zeta \qquad (12)$$

From figure 7 it appears that the values of φ fluctuate between 2.5 and 4.5 $\frac{PS_s}{g}$, so that from a four-stroke engine with external ignition we may expect outputs of from 3.5 to 6.3 $\frac{PS_s}{g}$

In the case of an engine with self-ignition, which normally operates with a surplus of air, caution is necessary in determining the "air value". It must be taken into account that the oxygen carrier may possible burn with a different fuel deficiency than the consumed air. As the calorific value of the mixture is less than in an engine with external ignition, heat of formation and heat of vaporisation play a more important part.

If injection occurs into the blower or before the blower, the relationship becomes more complicated, as the intake temperature comes in as another variable (influence of the mixture). Before going into this, the results obtained up to the present from comparing various oxygen carriers must be introduced.

3. Some oxygen carriers compared

a) The oxygen carriers in question

The choice of oxygen carriers was limited to those which could be considered in view of the supply position as regards related spheres of application. Such are:-

80% Hydrogen peroxide, nitric acid, oxygen, nitrous oxide, tetra-nitro-methane.

The material data are set out in Table 1.

(Fig.4 - available oxygen content)

(Fig.5 - alteration in weight of air charge)

b) <u>The oxygen carriers compared</u>

Figure 4 shows the available oxygen content in relation to air. At the head, of course, stands oxygen, followed by nitric acid and tetra-nitro-methane. It will be shown that this picture is not a true indication of the suitability of the substances for engines.

The first alteration is brought about by the effect of the supply of oxygen carrier on the weight of the air charge. In accordance with (9):

$$\frac{G_L}{G_{L.o}} = r\frac{G_x}{G_{L.o}} = 0.59\left(\frac{c_{px}(T_{L.o} - T_x) + r}{c_{pL}T_{L.o}} - \frac{M_L}{M_x}\right) \quad (9a)$$

where the blower characteristic factor $C = 1$, external temperature $T_a = 233^o$, and the boost air temperature $T_{L.o} = 323^o$.

These values were compiled for the substances selected in figure 5, and were included in Table 1. The best result by a long way was that for hydrogen peroxide, while nitric acid, liquid nitrous oxide, and tetra-nitro-methane were about equal. N_2O already shows no further effect at 20°, while gaseous O_2 causes the volume of air to fall sharply. Reference has already been made to the fact that substances with positive values are better vaporised in the boost air pipe.

The "air value" also depends on the proportion which is vaporised, as will be gathered from (2). Figure 6 shows the air value, divided into that part which is dependent on x, and that part which is independent of x. In spite of their oxygen content, hydrogen peroxide and nitrous oxide showed the greatest improvement, while nitric acid was inferior (on account of its positive heat of formation). Tetra-nitro-methane is already better than nitric acid, while hydrogen peroxide has risen to 95% and nitrous oxide to 85%.

Finally, figure 7 shows the alteration in the indicated power. For x - 1 hydrogen peroxide is ahead, even outstripping oxygen. This high value is largely due to the great heat of vaporisation, which causes the boost air to cool considerably, so that the volume of air delivered by the blower rose considerably (fig.5); this will be discussed later.

Complete vaporisation in the boost air pipe - except with oxygen and nitrous oxide is a matter of some difficulty, especially with tetra-nitro-methane (setting point +12°). But nitric acid and tetra-nitro-methane are only superior to pressureless liquid nitrous oxide in the case of complete vaporisation in the boost air pipe, nitric acid by about 10%, tetra-nitro-methane by about 25%. If vaporisation fails, there is practically no difference between nitrous oxide and tetra-nitro-methane, while nitric acid is inferior by about 10%.

TABLE 1.

showing the substances and the values calculated for them

	ψ_x	M_x kg/Mol	γ_x kg/l	$Q_{x\,o}$	$\vartheta_{st\,o}$	$V\,Q_{wdm\,r}$ Kcal/kg	p Kcal/kg.	c_{px} Kcal/kg.	bw_{fl} 20°	O_x	x = o	x = 1	$\frac{\Delta G_L}{G_{L.o}} \times \frac{G_x}{G_{L.o}}$	$\vartheta = \frac{AN}{N_L}$ x = o	$\frac{G_x}{G_{L.o}}$ x = 1
H_2O_2 80%	+20	28.85	1.346	151.4 1)	-29.02 2)	108.2 4)	376 7)	0.281 7)	-187.8	0.376	1.884	2.409	4.36	1.884	1.974
HNO_3 100%	+20	63	1.522	86	-42.3	115 5)	103.5 7)	0.160	+203.5	0.635	2.434	2.582	0.69	2.434	2.989
gaseous O_2	+20	32	-	-	-	-	-	0.218	0.0	1.00	4.290	4.290	-0.822	4.290	3.805
liquid O_2	-183	32	1.146	-183	-218.5	50.9 6)	46.4	0.216	+84.8	1.00	4.169	4.299	0.40	4.169	2.535
N_2O liquefied (under pressure)	-20	44	1.013	-	-90.83 3)	66.9 6)	55.8	0.205	-380.0	0.364	2.104	2.196	0.39	2.104	2.426
N_2O liquefied (under pressure)	±0	44	0.925	-	-90.83	60.5 6)	50.9	0.205	-390.5	0.364	2.119	2.198	0.255	2.119	2.348
N_2O liquefied (under pressure)	+20	44	0.793	-	-90.83	43.7 6)	37.4	0.205	-411.3	0.364	2.150	2.203	-0.014	2.150	2.195
N_2O liquefied (without pressure)	-88.5	44	1.225	-88.5	-90.83	90.0 6)	85 5)	0.201	-343.2 8)	0.364	2.052	2.207	0.86	2.052	2.214
$C(NO_2)_4$	+20	196	1.650	126	+13	80.0 7)	72 7)	0.050 7)	-457	0.490	2.759	2.863	0.90	2.759	3.393

1) 100% H_2O_2
2) H_2O_2 begins to separate out; eutectic (56.2%) congealed at -48°.
3) triple point, p = 658.95 mm Hg.
4) at 10°
5) at 86°
6) at ϑ_x
7) estimated
8) at -88.5°

(Fig. 6 - air valve)

(Fig. 7 - alteration in Indicated Power)

(Fig. 8 - alteration in Indicated Power (O_2 ÷ N_2O))

(Fig. 9 - Temperatures in the Boost Air System)

The physical properties of nitrous oxide which make it suitable for engines may be seen in the fact that, whereas the oxygen content is only 36.4%, the gaining output is 59.8% compared to liquid, and 71.4% compared to gaseous oxygen.

The differences are still further reduced if injection takes place before the blower. The results of complete calculations may be seen in figure 8 . Here nitrous oxide reaches 75.5% of liquid oxygen, and actually 88.7% of liquid oxygen vaporised before the blower. Also included in this diagram are the results for various blower characteristics - indicated for different values of the factor C. These influences are not of great importance.

In figure 9 a practical example is given of the course of the temperature in the boost air pipe. If we assume an external temperature of -50°, and if injection takes place before the blower, then with nitrous oxide the temperature falls to -87.8°, with oxygen to -75.9°; after the blower the original temperature falls from 63.5° to 21.6° with nitrous oxide, and to 33.0° with oxygen. A necessary condition is that complete vaporisation occurs before the blower.

If injection takes place after the blower, the corresponding boost air temperatures, again with 50% gain in performance, are -19.5° for nitrous oxide, +18.5 for oxygen, that is, considerably lower than when injection takes place before the blower. In the first case the boost pressure is increased in comparison with the initial condition, in the second case it falls slightly.

The diagram also includes those temperatures which would occur if hydrogen peroxide, injected after the blower, were made to vaporise completely. According to figure 7, as already shown, the gain in output should be very satisfactory here. But it appears that for a 50% gain in performance the fall in temperature (-75°) would be so great, that the process could no longer be controlled by the existing means, quite apart from the fact that at such low temperatures hydrogen peroxide becomes solid. If only that proportion is vaporised which would cause as much cooling as does the complete vaporisation of nitrous oxide, then the usable outputs will be almost exactly equal.

4. Thermal load on the power unit

a) Deduction from the equations

It is difficult to establish a definite thermo-dynamic factor for the thermal load on the power unit. Besides the absolute value of the combustion temperatures, the peak pressures (spitzendrücke) which occur also determine thermal loading of the piston, and these again depend, not only on the maximum temperature, but also on the rate of combustion.

The tendency to knocking which is an important factor in the thermal load on the piston is also affected by alteration in the rate of combustion. The temperature of the exhaust gases is important for the exhaust valves. As alterations in exhaust temperature and maximum temperature during combustion are practically in direct relationship and as in some engine types the thermal load on the exhaust valves is of special importance, we shall here go into the alterations in exhaust temperature T_{ab}.

We may deduce from the energy balance, without addition:

$$G_{L.o}c_{pL}T_a + 698G_{L.o} - N_{i.o} = G_{L.o}c_{pab}T_{ab.o}$$

$$\left(\frac{1}{\eta} - 1\right)N_{i.o} = G_{L.o}(c_{pab}T_{ab.o} - c_{pL}T_a)$$

with addition

$$\left(\frac{1}{\eta} - 1\right)N_{i.o} = (G_L + G_x)c_{pab}T_{ab}$$
$$-G_L c_{pL}T_a - G_x c_{px}T_x + xG_x r$$

If we simplify this by putting $c_{pab} \sim c_{pL}$, then

$$\frac{N_i}{N_{i.o}} \quad \frac{(G_L + G_x)}{G_{L.o}} \quad \frac{(T_{ab} - T_a)}{(T_{ab.o} - T_a)}$$

$$+ \frac{G}{G_{L.o}} \quad \frac{c_{pL}T_a - c_{px}T_x + xr}{c_{pL}(T_{ab.o} - T_a)}$$

or - suppressing the small expressions of the second order:-

$$\frac{\Delta N_i}{N_{i.o}} \approx \frac{\Delta T_{ab}}{T_{ab.o} - T_a} + \frac{\Delta G_L + G_x}{G_{L.o}} + \frac{G_x}{G_{L.o}} \quad \frac{c_{pL}T_a - c_{px}T_x + xr}{c_{pL}(T_{ab.o} - T_a)}$$

Using equations (1) and (2), we get:

$$\frac{\Delta T_{ab}}{T_{ab.o} - T_a} \approx \frac{G_x}{G_{L.o}} \left(\sigma - 1 - \frac{xr - c_{px}T_x + c_{pL}T_a}{c_{pL}(T_{ab.o} - T_a)}\right)$$

b) <u>The oxygen carriers compared</u>

In figure 10, the expression y stands for $T_a = 233^0$ and $c_{pL}(T_{ab.o} - T_a) = 270$ Kcal/kg of formula (13). It appears that - if vaporisation occurs in the boost air pipe - hydrogen peroxide causes no increase in the temperature of the exhaust; next in order is nitrous oxide, followed by nitric acid and tetra-nitromethane.

(Fig.10 - alteration in Exhaust Gas Temperature)

(Fig.11 - relation between increase in power and rise in exhaust gas temperature)

A criterion for the suitability of the oxygen carriers for engines is the relationship between increase in performance and increase in exhaust temperature; as limits must be set to the increase in exhaust temperature, this value gives an indication of how much individual substances will increase the performance. Hydrogen peroxide would be particularly outstanding (figure 11) if vaporisation in the boost air pipe occurred. If one considers, however, that only nitrous oxide and oxygen are certain to vaporise, then liquid nitrous oxide is clearly superior to all other substances (for instance, more than 100% better than oxygen). It will be clear from what has already been said that this superiority will be even greater if injection takes place before the blower.

5. Suitability of the oxygen carriers from the point of view of the engine and its operation.

a) Corrosion behaviour.

As a basis for the employment of oxygen carriers, it is considered essential that the power unit is unaltered; it is impossible for the present at least to adapt the power unit to the oxygen carriers. Therefore the oxygen carriers must not be such as to corrode the material of which the aero-engine is constructed. Matters are made simpler by the fact that the substances when in contact with the power unit are only in a rarefied condition, and that the times during which they are supplied are short compared with the total operating period.

The corrosive effect of hydrogen peroxide on iron is difficult to investigate, as there is a catalytic effect which causes the oxygen carrier to disintegrate; rust is certain to form. Light metal alloys are not heavily attacked, but inter-crystalline corrosion may occur. Bronzes are attacked.

Nitric acid attacks iron, but light metal alloys free of magnesium behave well. All magnesium alloys, like H_y7 and H_y9, are heavily attacked. Bronzes also are unsuitable.

Oxygen has practically no effect, but in the case of the aluminium-magnesium alloy H_y9 corrosion was observed after a lapse of weeks. But with nitrous oxide liquefied under pressure we observed no corrosion at all, and even the ubiquitous water corrosion is somewhat reduced.

With the short supply period, oxygen and nitrous oxide should cause no difficulty, hydrogen peroxide very little, and tetra-nitro-methane again none. On the other hand, nitric acid cannot be supplied to modern aero-engines without danger.

b) Knocking behaviour.

The performance of a modern four-stroke aero-engine with external ignition is limited by the resistance offered to knocking by the fuel and the shape of the combustion space. Since at high altitudes gains in performance of up to 100% compared with the initial performance are demanded, the behaviour of the oxygen carrier as regards knocking is of crucial importance.

So far, the only data about knocking are those for oxygen and nitrous oxide. With nitrous oxide the rate of combustion increases, which implies a greater resistance to knocking. From experiments carried out in many quarters, it appears that, when knock-free maximum performance is obtained without addition, then there is certain not to be any knocking with addition of oxygen carriers. It should be mentioned here that the performance has already been raised by more than 100%, and that we have already achieved freedom from knocking at performances at which knocking occurred when there was no oxygen addition.

Oxygen can also be used in modern aero-engines without causing difficulties. Here it is important to achieve complete vaporisation in the boost air pipe, if we are to exploit to the full the possibility of reducing thermal loading. DVL have had considerable success through installing a special vaporiser after the blower. Of course, with oxygen the absolute gain in performance must be lower than with nitrous oxide, otherwise thermal overloading of the engine will occur.

It was found impossible to run a DB-601 on a supply of hydrogen peroxide. Even when a small volume was supplied running became unsteady, and there were clear indication of delayed combustion. The experiments in question were only of an exploratory nature, the oxygen carrier being supplied in the same simple manner as nitrous oxide or oxygen. It is possible that with special precautions improvement could be made.

Nitric acid also causes increased knocking, as appeared from experiments made by BMW.

Tetra-nitro-methane has the unfavourable property of neutralising the lead content of fuels containing lead by means of oxydation. Even small volumes of it reduce the octane number.

c) Storage

The storage of oxygen carriers is very important in practice, for large volumes must be carried. In addition to the weight which is taken up, the space occupied is an important factor when they have to be carried in aircraft.

Figure 12 shows the densities of the oxygen carriers (for nitrous oxide liquefied under pressure the officially laid down value 0.75 Kg/l is given). Tetra-nitro-methane is the most favourable, while nitrous oxide liquefied under pressure is unfavourable.

The case is reversed as regards the setting point, which is important when operating at great altitudes, that is, at temperatures of -50°C and under. It will appear from figure 13, that tetra-nitro-methane can hardly be used, and that hydrogen peroxide will cause difficulty, while nitric acid is at the fringe, and oxygen and nitrous oxide are suitable.

In addition to storage in aircraft, the possibility of storage for delivery requires attention. Here those substances which are only liquid in a super-cooled state are unsuitable, as special steps have to be taken to maintain this temperature. The problems which arise here are already solved; nitrous oxide has a decisive advantage in tactical use, as the vaporisation is 3 to 3.5 times less than that of liquid oxygen.

(Fig. 12 - Densities of oxygen carriers)

(Fig. 13 - Setting points)

d) Handling

Convenient and safe handling of the substances is of merely secondary importance as regards engines, but is discussed here for the sake of completeness, as any special measures undertaken for the instruction and protection of ground personnel depend on it. It would be a hindrance to the general use of the process if only special personnel could be allowed to deal with it.

Hydrogen peroxide is sensitive to impurities of a metallic or organic nature, as these can cause disintegration of the oxygen carrier. Burns caused by contact with the substance are harmless, if it is washed away at once; longer exposure is dangerous.

Nitric acid is relatively insensitive to impurities; only a certain group of organic substances can cause disintegration. On the other hand, the physiological effects are extremely disagreeable. The vapour is very poisonous, and contact causes severe corrosion to the tissue of the skin and bones (see note at end of this paper).

Oxygen is insensitive to impurities, burns only result from long exposure.

Nitrous oxide is likewise insensitive to impurities and is less active towards organic substances than oxygen. Despite the less extreme temperature, burns appear more quickly than with oxygen, as nitrous oxide moistens the skin more quickly. Physiological effects ("laughing gas") only reach an unpleasant intensity with strong concentrations, and are therefore unimportant in practice.

Tetra-nitro-methane is not highly sensitive to impurities. The vapour is very poisonous; it appears to have no harmful effect on the skin.

Therefore, no special precautions are necessary in handling oxygen and nitrous oxide; with hydrogen peroxide, limited safety measures are necessary, while only instructed personnel can be allowed to deal with tetra-nitro-methane and nitric acid.

6. Conclusions as to the choice of oxygen carriers.

To sum up our findings:-

1). Output in the engine depends, not on the oxygen content alone, but also on the heat of vaporisation and the extent to which vaporisation takes place in the intake pipe.

2). Hydrogen peroxide would be the most suitable substance, if vaporisation in the intake were complete. But the boost air would cool to such a degree that only slight gains in performance would be possible.

3). Nitrous oxide has the most suitable thermal properties, as it vaporises well, and the heat of vaporisation is such that gains in performance of 100% are possible; the output attains that of nitric acid, and moreover nitrous oxide permits the greatest gain in performance of all the substances used (apart from completely vaporisable hydrogen peroxide).

4). The corrosion factor makes nitric acid and tetra-nitro-methane unsuitable for prolonged operation.

5). The knocking factor limits the possible substances for engines with external ignition to oxygen and nitrous oxide.

6). On the other hand, nitrous oxide only reaches 60 to 75% of the specific output gain which is available from oxygen, so that under two headings the choice is limitless; for short period use to achieve large gains, in performance nitrous oxide is best, while for smaller gains in performance over longer periods oxygen is best.

7. Results of experiments

The appended results have been repeatedly checked by industrial undertakings and research workers. The following account contains details about them. The object is here to arrive at a conclusion as to the so-called specific gain in output which can be obtained from nitrous oxide.

According to formule (10) and figure 7 the mean value:

$$\varphi = \frac{N_i}{N_{i.o}} : \frac{G_x}{G_{L.o}}$$

for nitrous oxide with complete vaporisation in the boost air pipe ($x = 1$) given:-

super-cooled pressureless material	2.714
material (at 20°) liquefied under pressure	2.195

Taking into account also that ξ and ξ are in the relationship $\varphi = 1.40\, \xi$, we get the values given in figure 14.

(Fig. 14 - Specified gain in output)

In this figure the maximum value is still that for pressureless substance injected before the blower. In this case the performance of the blower is not constant, as the weight of air delivered falls as the temperature before the blower falls. φ here becomes:

$$\varphi = 1.40 \left(\quad - \frac{N_L}{N_{L.o}} \; \frac{G_{L.o}}{G_x} \right)$$

the alteration in the performance of the blower being more considerable than when injection takes place after the blower because of the greater gain in the weight of air. In practice the injection point is always very close to the blower, on account of the short intake pipe; therefore complete vaporisation before the blower is unattainable. Also, the centrifugal effect of the rapidly rotating impeller, with nitrous oxide prevents the formation of snow (which in theory should occur at pressures below 0.9 ats), and with oxygen prevents the formation of Leyden frost.

In the illustration the results of experiments at various places are shown (injection before the blower); we are aware that the outputs achieved in practice are less than the theoretical values, for the reasons given. For the future, we must attempt to make improvements by controlling developments.

It will be understood that the theoretical output can only be attained if there is sufficient fuel for the combustion of the additional oxygen. Power units which run on rich mixtures and in which only slight gains in performance are required do not require any special handling; but in cases where extremely large gains in performance are required, it will be necessary, besides supplying the oxygen carrier, to make adjustments to the injection pump.

It is noteworthy that the outputs here given are in part the result of experiments in which the ratio of fuel to air was variable. The gain in output is thus the increase compared with the most favourable performance on air. If we took as our basis the performance on air with the governor at the same setting throughout, the gain in output would be greater.

8. <u>The attainable flight performance</u>

The attainable flying performance is presented in figures 15 and 16. The aircraft in question is a modern type, the powers being calculated for identical **conditions**, with and without additives, and thus forming a basis for comparison. It is recognised that it is difficult to calculate the absolute powers unless you are yourself the manufacturer; therefore the type is not named, and the comparative values, not the absolute values, are stressed.

Figure 15 shows on the left the engine powers, with the gain in performance permitted during the past year and that which it is hoped to achieve in future; the latter has already been surpassed on a test-stand, as BMW will report in more detail later on. At a height of 12 Km. the increase which was permitted at the Front was 50%, which in future will be almost doubled. On the right are entered the horizontal flying speeds; the gain at main operational height is considerable; a favourable circumstance is, that with the gain in performance there is a better ratio between co-efficient of buoyency and co-efficient of resistance.

Figure 16 shows improvements in the rate of climb;

(Fig. 15 - Flight performance of a twin-engined aircraft)

(Fig. 16 - Flight performance of a twin-engined aircraft)

It is understandable that at higher altitudes the speed of climb will increase substantially, so that altogether the tactical success was remarkable. Also the illustrations show that at 10 to 11 Km. the twin-engined aircraft was at least as fast as a single-engined fighter without additive.

It appears to me specially important to establish a comparison with thrust aids. This is not the place to go into details, but it should be stated that in reconnaissance flights over England there was a thrust consumption of 0.6 - 0.7g/Kgs. - data taken from flight performance. This figure, which is so to speak net, the resistance of the thrust aid having already been deducted, has not been attained by any of the aids known to-day.

9. <u>Construction of the equipment</u>

The equipment originally used to achieve gains in performance was of simple construction; the nitrous oxide was blown into the intake pipe under its own vapour pressure. But difficulties soon appeared in practice; e.g. the reduction in pressure as the substance was used up, and cooling from outside, resulting in reduced gain in performance, also the boiler-like behaviour of the containers when fired on. Although special developments to the containers made it possible to achieve adequate safety against enemy attack, provided certain geometrical relationships were observed, nevertheless the advantages of the pressureless fluid as regards gain in output and space-weight ratio were so pronounced that the equipment is nowadays largely constructed for the pressureless liquid. Figures 17 and 18 show the way in which the equipment was constructed for an aircraft type Junkers 88, which can carry 360 Kg. of special substance corresponding to a working capacity of 21,000 Hp/minutes. The containers are ordinary aluminium containers with comparatively moderate insulation, so calculated that the vapour loss is about 1% per hour on the ground, and about 0.6% per hour at the operational height.

(Fig.17 - Power boosting equipment)

(Fig.18 - Power boosting equipment)

The equipment can also be used for liquid oxygen, but the vapour loss would be 3.2 times as great on the ground and about 5 times as great at altitude, so that the stored working capacity, what with the length of time during which it must be stored in practical operations, is not noticeably greater than for nitrous oxide. Attempts are being made to improve the insulation, so that in cases where only a slight gain is required, liquid oxygen can also by used in the equipment.

(Fig.19 - Method of operation of special equipment)

The technical construction of the equipment can be gathered from the diagram, fig.19, which makes it clear that tasks simple in themselves become more difficult if push-button control, selective supply etc. are required. The scope of this report prevents our going into details about the equipment. The surprising nature of the task of development may be realised from the fact that when the equipment was first set to work there was no effect for four or five minutes. This is the time necessary to fill the leads to the power unit with liquid. In practice, such a lapse of time is, of course, intolerable. Insulating the pipe or further cooling its walls by means of prolonged vaporisation provided no final remedy. The solution was last found in the shape of a large supplementary outlet which is actuated when the equipment is switched on and is closed by thermal effect when the liquid arrives at this point.

10. Conclusions

To sum up: The oxygen content is not the only factor which contributes to a gain in output in a boosted engine. Above all, the heat of vaporisation and the negative or positive heat of formation of the oxygen carrier are important. This leads to the conclusion that the theoretical output from nitrous oxide is equal to that of nitric acid. As regards possibilities of application to power units of modern aircraft, the corrosion factor and above all the knocking effect are the major considerations.

These requirements reduce the possible oxygen carriers, in view of the supply situation, to oxygen and nitrous oxide, at least for power units with external ignition. Nitrous oxide is thus far superior to oxygen, that it puts less thermal load on the power unit, and so allows an absolute gain in performance of 60% - 80% compared to oxygen. Also it is more easily handled because of the less extreme temperatures. The specific gain in output with the additive supplied after the blower is as 0.60 : 1; with the additive supplied before the blower it is 0.73:1: the vapour loss for nitrous oxide is 3-3.5 times less on the ground, and about 5 times less at altitude.

The German Air Force has built up an organisation for maintaining the supply of nitrous oxide which is equal to every demand made upon it.

Finally attention should be drawn to the possibility of combining the above described process for supplying a special oxygen carrier to engines with the system evolved by Stieglitz and Triebnigg of varying the ratios of fuel carrier to ballast carrier. Initial experiments on these lines were already being successfully conducted in the Luftfahrtforschungsanstalt Hermann Göring, 1½ years ago. This suggests the possibility of a combined process on the following lines:-

1). The introduction of an oxygen carrier before the blower in such a way that by partial vaporisation the temperature before the blower can be brought down by 30-50° (even more on the ground).

2). The introduction of a fuel-ballast mixture after the blower in such a way that by partial vaporisation the temperature in the boost-air pipe can be brought down to about 0°.

3). The fuel-ballast mixture to be so adjusted to the oxygen carrier that it is hardly necessary to regulate it at all.

4). The free vaporised ballast in the cylinder must be sufficient for effective internal cooling and for the reduction of pressure peaks.

At the present stage, it seems that this object will be achieved in the near future. In this way, the normal power unit of to-day could become capable of peak performances of a tactical value which would have been undreamed of a short while ago; what before only seemed attainable with take-off and thrust aids will be done with less trouble, and will have a far wider application. In my opinion, the reciprocating engine can now compete in fields which were the exclusive domain of other types of propulsion; taking into account that the power units in question have been tested by years of operational activity, these indications should be taken seriously from the point of view of other types of propulsion.

(Note): while the above was being printed, the firm of BMW Flugmotorenbau GmbH, Berlin-Spandau, very kindly informed me of the following experiences with Nitric acid:

The chief danger resulting from the use of nitric acid is through skin burns. These can, however, be reduced to a minimum in the laboratory by careful handling, and on a large scale by using sealed tanks. Even if some of the liquid gets into the eyes, it will do no harm if it is at once washed away with plenty of water.

As nitric gases can only develop a high degree of concentration if nitric acid is caused to decompose, and as this will practically never occur to nitric acid stored in the open, there is no question of injury arising from the gases or vapours of nitric acid. If it is in close storage, or closed tanks, injury by the gases is impossible.

In three years of experiments, thanks to the observations of proper precautions, no injuries have occurred.

DISCUSSION - F.A.F. Schmidt.

The experiments in the use of liquid oxygen to induce short-period gains in performance were extended recently to include direct injection into the intake pipe before the blower (experiments by P. Kornacker). The specific gain in output can be seen in Fig. 1.

(Fig. 1 - Specific increase in power in H.P./g./sec. for liquid oxygen and liquid GM-1 in terms of the increase in power)

It is almost double that which was obtained by using GM-1. Also, compared with the results reported by O. Lutz in his thesis and in discussion, which were obtained with a different engine, and showed gains in output when using GM-1 of 3.5 to 4.5 HP sec/g., we may expect double this output with liquid oxygen. Experiments with this injection of oxygen were carried out on engine-types DB-601 and DB-605. At first, the maximum permissible gain in performance using liquid oxygen was so chosen that the thermal load was the same as for maximum performance at maximum pressure. It was assumed that when liquid oxygen was used the plug temperature and exhaust temperature ought not to be higher than at maximum power. Under these conditions, we recorded gains of the order of 320-350 HP. at heights of from 10-12 Km.

The next experiments were concerned with obtaining comparisons between the combustion temperatures of an engine working normally, working with liquid oxygen, and with GM-1. The theoretical end temperatures of combustion using liquid oxygen were on an average about 150°C higher than if working with GM-1. Owing to the change in the conditions of heat transfer the actual difference in temperature is less than that which was theoretically calculated. There is furthermore the possibility of influencing maximum pressure and maximum combustion temperatures in the direction of reducing the thermal loading by means of enriching the mixture and adjusting the ignition.

The method of regulation was not in steps, as in the experiments with GM-1 described by O. Lutz, but in such a way that every increase in altitude above maximum pressure altitude was accompanied by an increase in the volume of oxygen injected. This arrangement was made possible by the use of an adjustable injection valve, so that at each height the greatest possible gain in performance could be realised. The quantity of oxygen added was controlled either by means of a pressure capsule, using the absolute pressure, or by the difference in pressure compared to maximum pressure. By a special arrangement of the injector nozzle, which is directly connected with the regulating valve, we were able to reduce the time of response until there was no noticeable time lag between injection and gain in performance.

To sum up, the use of liquid oxygen, thanks to the increased gain in output, gives a flying time almost double that reached on GM-1, the improvements in performance being less than that with GM-1, but still quite adequate for present requirements. Therefore in cases where the gain in power is to be maintained for a longish period, liquid oxygen is superior to GM-1.

In connection with the tests with oxygen, experiments are envisaged involving the simultaneous use of methanol in order to achieve extremely high gains in performance. The cooling effect of methanol relative to weight, is much better than that of inert nitrogen, since the reduction in temperature, when nitrogen is used is due to the heat absorption of nitrogen; while the cooling effect when using alcohol mainly comes about through the great heat of vaporisation. Consequently, the maximum performance possible on liquid oxygen with an addition of methanol is likely to be well above the figure reached so far. In addition, consumption is still more favourable than with GM-1.

Typed: JHM

11th March 1946.