TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 482

IGNITION AND COMBUSTION PHENOMENA IN DIESEL ENGINES

By F. Sass

From Zeitschrift des Vereines deutscher Ingenieure
September 10, 1927

Washington
October, 1928

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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IGNITION AND COMBUSTION PHENOMENA IN DIESEL ENGINES.*

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Evidences were found that neither gasification

nor vaporization of the injected fuel occurs

before ignition; also that the hydrogen coef-

ficient has no significance. However, the

knowledge of the ignition point and of the

"time lag" is important. After ignition, the

combustion proceeds in a series of reactions,

the last of which at least are now known.

It is remarkable that the Diesel engine has existed some

thirty years and has been brought to such a high degree of

technical perfection, without even an approximately correct ex-

planation of what occurs in the combustion space. We were con-

vinced that the fuel (gas oil or tar oil), after its introduc-

tion into the combustion space, had to go through a peculiar

transformation before igniting. It was thought that all the

fuel particles, which are still liquid at the time of injection,

must be converted into the gaseous form before ignition and that

no ignition and combustion was possible before the complete gas-

ification of every individual drop.   Diesel himself held this
opinion.* In 1912 he mentioned, as the second of his "fundamen-
tal ideas" the "gradual introduction of finely divided fuel un-
der combustion of the same in this highly heated and compressed
air under simultaneous action on the outgoing piston" and then
continued:

. "Since a fuel can burn only after it has been gasified, the
immediate result of this second fundamental principle for all
nongaseous fuels is the gradual gasification of the fuel in the
working cylinder, sometimes only in very small quantities for
each stroke of the piston, with the extraction of the heat of
gasification from the working process itself; in other words,
the development of the process of gasification into a part of
the working process in the working cylinder."

Also in many other places, Diesel spoke of the necessary
gasification of the fuel.   In his book (Berlin, 1913, p. 150),
he mentioned, as one of the "fundamental laws of Diesel-engine
construction," the "injection of the fuel with highly compressed,
but cooled and purified air, not only for the production of an
intimate mixture, but also especially for the sake of the gasi-
fication resulting from the fact that numerous fuel particles
in the whole mass of the combustion air first gasify and then
ignite and thus produce the necessary heat for the gasification

*"Die Entstehung des Dieselmotors," Jahrbuch der Schiffbautech-
nischen Gesellschaft, Vol. 14 (1913), p. 262.

of the rest of the fuel, for which the heat of compression alone is insufficient."

It is not certain as to whether this was Diesel's opinion from the first, or whether he was influenced by P. Rieppel's article, which was published in 1907-8.* Rieppel was the first who sought a scientific explanation of the fact that aliphatic gas oils and aromatic coal-tar oils behave quite differently in the Diesel engine. On the basis of observations of a running engine, using gas oils and coal-tar oils and mixtures of the two, and on the basis of experiments with "bombs," he expected to find the explanation in the fact that the usable fuels form oil gases with the addition of only a little heat, while the more difficultly combustible oils require more heat or a longer time for the formation of the oil gases.

According to Rieppel, the hydrogen coefficient of the fuel, i.e., the molecular ratio of hydrogen to carbon, is of decisive importance, because hydrogen is given off by the usable oils at a relatively low temperature and, due to its low ignition point, which Rieppel put too low at 500°C (932°F), starts the self-ignition of the other molecules. Aufhäuser also accepted this valuation of fuels according to the hydrogen coefficient,** and soon afterwards the opinion became general that the liquid fuel in the combustion space must be converted into the gaseous form

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*Versuche über die Verwendung von Teerölen zum Betrieb des Dieselmotors, Forschungsarbeiten, No. 55, Berlin, 1908. See also V.D.I., Vol. 51 (1907), p. 613.
**Die Triebmittel des Dieselmotors mit besonderer Berücksichtigung der Seeschiffahrt," Jahrbuch der Schiffbautechnischen Gesellschaft, Vol. 14 (1913), p. 368.

before ignition could occur. It is strange that no one seems
to have raised the question as to the possibility of the complete
conversion of the fuel into the gaseous form in the extremely
short interval between injection and ignition, which is generally
only a few thousandths of a second.

The Experiments of Wollers and Ehmcke

Even now we are far from the full explanation of the igni-
tion and combustion phenomena. If the right beginning has been
made, this is due chiefly to the researches of Wollers and
Ehmcke,* which were undertaken at the suggestion of the late Dr.
Alt, in order to investigate the possibility of using coal-tar
oils in Diesel engines. These researches furnished convincing
evidence against the possibility of the formation of oil gas in
the engine, which has subsequently been confirmed by further ob-
servations of engines in operation.

Wollers and Ehmcke investigated four fuels characterized
by their different behavior in Diesel engines, namely, light
natural-tar oil, paraffin oil, vertical-furnace tar and coal-
tar oil, in an electrically heated bomb, and analyzed the gaseous
mixtures obtained at four different pressures. It was found that
the experimentally found dependence of the vapor pressures on the
temperature (Fig. 1), and on the time required for vaporization

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*"Der Vergasungsvorgang der Treibmittel, die Oelgasbildung und
das Verhalten der Oeldämpfe bei der Verbrennung im Dieselmotor,"
Kruppsche Monatshefte, Vol. II (1921), p. 1. (See also N.A.C.A.
T.M. No. 281 - "Combustion of Liquid Fuels in Diesel Engine." By
Otto Alt.)

(Fig. 2) did not differ so much as one would be led to suppose by the behavior of the fuels in a Diesel engine. In Figure 1, for example, the curve of the easily burning paraffin oil nearly coincides with the curve of the difficultly burning vertical-furnace tar and lies halfway between the curves of the light natural-tar oil, generally unsuitable for Diesel engines, and the curve of coal-tar oil. Figure 2 conforms just as poorly with the law, for the curve of the easily usable paraffin oil lies between the light natural-gas oil and coal-tar oil.

In a subsequent series of experiments, the oil vapors were condensed by suddenly cooling the bomb, and the relative spaces occupied by the oil vapors and oil gases were determined by measuring the partial pressure of the remaining oil gases. Here also the results (Table I) disagreed with the previous general opinion that gasification of the fuel was essential to ignition. The difficultly combustible oils, namely, coal-tar oil and vertical-furnace tar, gave for like pressures, a substantially greater oil-gas output than the aliphatic paraffin oil (e.g., 93% and 86% against 69% with paraffin oil), and it was only for the aromatic light oil from natural tar that the gaseous portion of the mixture of gas and vapor was relatively small (54%). The result of the gas analyses was surprising, that the aromatic coal-tar oil furnishes an abundant output of hydrogen, while the aliphatic paraffin oil was quite inferior in this respect. This is the exact opposite of the previous conclusions from the be-

havior of fuels in the Diesel cylinder.

TABLE I.

Separation of fuel oils into gas and vapor according to
Wollers and Ehmcke

		Light oil from natural tar			Paraffin oil		
Saturation pressure	atm.	40	27.5	13	42	35	28
Saturation temperature	°C	419	418	369	459	455	441
Vapor–gas mixture {	Gas %	54	19	8	69	56	54
	Vapor %	46	81	92	31	44	46

		Coal–tar oil			Vertical-furnace tar		
Saturation pressure	atm.	40	34	28	41	28	13
Saturation temperature	°C	495	494	474	464	445	413
Vapor–gas mixture {	Gas %	93	84	75	86	75	12
	Vapor %	7	16	25	14	25	88

The falsity of the former view is still more convincingly
demonstrated by the results of the ignition tests with the oil
gases from the four fuels and then with the liquid fuels them-
selves. The ignition points of the oil gases were determined
in the Dixon furnace, while the ignition points of the liquid
fuels were determined with Moore's ignition-point tester, both
times in an oxygen stream (Table II). The ignition points of
the oil gases are surprisingly higher than those of the liquid

fuels. Moreover, the ignition temperatures of the oil gases
generated in the bomb are all practically alike and show none of
the differences exhibited in the Diesel engine. On the contrary,
the ignition points of the liquid fuels, arranged according to
their magnitude, correspond exactly to their combustibility in
the engine.

TABLE II.

Ignition points of oil gases and liquid fuels according to
Wollers and Ehmcke

	Ignition points in oxygen stream at 1 atm.	
	Oil gases	Liquid fuels
Paraffin oil	614–655°C (1137–1211°F)	240°C (464°F)
Light natural-tar oil	615–651°C (1139–1204°F)	326°C (619°F)
Coal-tar oil	645°C (1193°F)	445°C (833°F)
Vertical-furnace tar	635–661°C (1175–1222°F)	468°C (874°F)

The practical equality of the ignition temperatures of the
oil gases regardless of their source is explained, according to
the gas analyses of Wollers and Ehmcke, by the fact that oil-gas
mixtures all have the same constituents and differ only in the
proportions of these constituents. Therefore, it is extremely im-
probable that, for the ignition of the easily ignitible fuels,
the roundabout way through the much more difficultly ignitible
oil gases is necessary.

Measuring the Ignition Temperature in the Engine

Further proof that no gasification of the fuel can take place in the combustion space before the ignition, is furnished by the measurement of the ignition temperatures in the hot-bulb engine, in which the ignition must naturally take place just the same as in a Diesel engine. The hot-bulb engine is particularly well suited for such observations, because the wall temperature of a portion of the combustion space (namely, of the hot bulb) can be directly measured. The temperatures of the hot bulb given in Table III were measured in a 30 HP. A.E.G. medium-pressure engine of a new type at 15-16 atm. compression pressure and ignition by means of a small hot bulb a (Fig. 3), which was heated by starting with a "cartridge." The hot bulb was drilled at the points 1-3 close to the inner surface, and a platinum platinum-rhodium thermo-electric couple introduced into each hole, which had a diameter of 5 mm (0.197 in.). Holes 1 and 2 were filled with melted tin for better heat conduction. Hole 2 is near the center of the fuel jet of about 30°, while holes 1 and 3 lie nearer its rim. The accuracy of the thermo-electric couple, after calibration, was about $\pm 1\%$.

TABLE III.

Temperatures of hot bulb of 30 HP. A.E.G.
medium-pressure engine under various loads

Time	R.P.M.	Load k W	Temp. of hot bulb			Temp. of exhaust
			Hole 1	Hole 2	Hole 3	
9.30-11.00	400	20.1 = 1/1	365°C	395°C	350°C	281°C
11.05-11.30	405	14.9 = 3/4	290°C	315°C	270°C	211°C
11.35-12.10	410	10.5 = 1/2	320°C	360°C	300°C	177°C
12.15-12.45	415	5.2 = 1/4	440°C	490°C	460°C	159°C
12.50- 1.20	420	Idling speed	400°C	460°C	430°C	125°C
1.25- 2.00	275	Low idling speed	420°C	450°C	415°C	109°C

The lowest temperatures of the hot bulb were obtained at
3/4 load corresponding to the injection period which varied with
the load. They were only 270-315°C (518-599°F) and were there-
fore more than 100°C (180°F) below the ignition temperature of
acetylene which, according to Table IV, has, with 416-440°C(780.8-
824°F) the lowest ignition point of all the constituents of the
oil-gas mixture. If, therefore, the gasification of the fuel be-
fore combustion were indispensable, no ignition could occur in
this engine from full load to about 1/4 load, because the temper-
ature of the ignition source in this load range is below the low-
est ignition temperature of the oil-gas constituents. In reality,
however, the ignitions are uniform and sure at all loads.

TABLE IV.

Ignition temperatures of the constituents of an oil-gas mixture
according to Wollers and Ehmcke

	In oxygen at 1 atm.	
Hydrogen H_2	580-590°C	(1076-1094°F)
Methane $C H_4$	556-700°C	(1033-1292°F)
Ethane $C_2 H_6$	520-630°C	(968-1166°F)
Propane $C_3 H_8$	490-570°C	(914-1058°F)
Ethylene $C_2 H_4$	500-519°C	(932- 966°F)
Acetylene $C_2 H_2$	416-440°C	(781- 824°F)
Carbon monoxide CO	637-658°C	(1179-1216°F)

Vaporization before Ignition

The often contested question as to whether vaporization of
the injected fuel is necessary before ignition can take place,
has likewise been clarified by recent researches. Alt* rightly
calls attention to the fact that the mean boiling points of many
difficultly combustible aromatic fuel oils are lower than the
corresponding temperatures of gas oil and paraffin oil, and that,
on the other hand, the mean boiling points of the aliphatic fuel
oils are higher than their ignition points. From this fact Alt
concludes that vaporization cannot be especially important for
ignition, since otherwise the higher the ignition point above the
boiling point, the more favorable it would be for the ignition.

*"Flussige Brennstoffe und ihre Verbrennung in der Dieselmaschine,"
V.D.I., Vol. 67 (1923), p. 586, and the special number "Diesel-
maschinen," 1923. (For translation, see N.A.C.A. Technical Mem-
orandum No. 281).

Neumann* has recently investigated the vaporization process mathematically and found that, due to lack of time, no appreciable vaporization of the fuel drops can occur before ignition (Fig. 4). Only the time lag is available for the vaporization, i.e., the time between the beginning of the injection and the beginning of the combustion. This interval is even shorter than assumed by Neumann, who calls it the interval between the beginning of the delivery stroke of the pump and the visible pressure increase in the indicator diagram. In reality, a considerable portion of this time (generally more than half) is consumed by the "injection lag," that is, the interval between the beginning of the pump stroke and the beginning of the injection, which is used for the compression of the fuel oil and the expansion of the delivery tube. According to our own measurements, the time lag is only 1/400 to 1/300 or, at most, 1/100 second. In this short time, according to Figure 4, the volume of the drops can have diminished hardly 0.1%. It may therefore be said that practically no vaporization of the injected fuel occurs before ignition.

Hydrogen Coefficient

Table V gives the results of the analysis of six aliphatic fuel oils in the chemical laboratory of the A.E.G. (Allgemeine Elektrizitäts-Gesellschaft) turbine factory.** Of these the

*"Untersuchungen über die Selbstzündung flüssiger Brennstoffe," V.D.I., Vol. 70, (1926) p. 1071.
**Thus far the laboratory has chemically tested over 80 fuel samples from various sources, the majority of them in the running engine.

Mexican gas oil II has a hydrogen coefficient of

$7.54 \div (84.99 \div 12) = 1.066;$ South-African gas oil,

$8.56 \div (86.44 \div 12) = 1.19.$ Both these values are very low in

comparison with the maximum of about 2, and nevertheless both

these fuels are quite usable and have very good heat values.

The Mexican gas oil I, on the contrary, is useless, due to its

hard-asphalt content of 0.975%, notwithstanding its greater hy-

drogen content of 11.5% and its favorable hydrogen coefficient

of 1.63.   In starting the ignition, the hydrogen does not play

the part which has hitherto been ascribed to it. It does not

first split off and thereby introduce the ignition, of which it

is incapable,* due to its high ignition temperature of 580-590°C

(1076-1094°F), Table IV, but burns only after the beginning of

the combustion, simultaneously with the carbon, in a roundabout

way through a series of intermediate substances which character-

ize the combustion reactions of the fuel oil.

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*In aromatic fuel oils, e.g. coal-tar oil, which give off hydro-
gen on being heated, the hydrogen can introduce the ignition.

TABLE V

Elementary analyses and index values of several fuel oils

Source of Oil				1 German paraffin oil	2 No. Amer- ican gas oil	3 Mexican gas oil I
Elementary analyses	{	C H O+N S	% " " "	86.74 10.65 1.64 0.97	84.36 11.75 3.59 0.30	84.61 11.50 1.66 2.23
Ash Water Hard asphalt			% " "	0.027 0.00 0.11	0.00 0.00 0.00	0.00 0.00 0.975
Flash point Burning point Solidifying point			°C " "	77 108 3	91 104 Below −15	67 131 −5.5
Sp. G. at 20°C				0.875	0.863	0.875
Heat value	Upper kcal/kg Lower "			10738 10162	11500 10866	10856 10253
Viscosity in Engler degrees	At 12°C " 20 " " 30 " " 50 "			2.13 at 10°C 1.68 -- 1.23	1.67 1.41 -- --	2.69 -- 1.76 1.44

Table V (Cont.)

Elementary analyses and index values of several fuel oils

Source of Oil		4 Mexican gas oil II	5 Argentine gas oil	6 So. African gas oil
Elementary analyses	C % H " O+N " S "	84.99 7.54 5.02 2.45	84.65 13.54 1.63 0.18	86.44 8.56 5.00 0.00
Ash % Water " Hard asphalt "		0.01 0.00 0.00	Traces 0.00 0.00	0.02 Traces 1.167
Flash point °C Burning point " Solidifying point "		112 141 -5.0	210 255	111 133 Below -15
Sp. G. at 20°C		0.870	0.865	0.921
Heat value	Upper kcal/kg Lower "	10919 10512	10843 10193	10759 10297
Viscosity in Engler degrees	At 12°C " 20 " " 30 " " 50 "	1.83 -- 1.57 1.44	45.18 29.25 16.96 5.46	13.22 7.03 4.58 1.95

Explanation of the Ignition According to Tausz

If neither gasification nor appreciable vaporization of the fuel occurs before the ignition, the fuel drops must ignite directly from the liquid state, for which reason they must first be heated to a certain temperature. The ignition point, which must not be confused with the flash point or burning point, is the lowest temperature at which a substance can ignite spontane-

ously. It is determined with the ignition-point tester, which is described by Harold Moore in The Automobile Engineer (1920, p. 200), and which has been improved by the Friedrich Krupp Company. The determination can be made either in air or oxygen at atmospheric pressure. It is more accurate to find the ignition point in compressed air at the pressure reached at the end of the compression in the Diesel engine, as did Tausz and Schulte.*

The three cases give quite different values for the ignition point (Table VI).

TABLE VI.

Ignition points of a few aliphatic fuels in air and in oxygen at
  1 atm. and in compressed air, according to Tausz and Schulte

	Ignition points – atmospheric pressure		Ignition points in compressed air	
	In Air	In Oxygen		Pressure atmospheres
Gas oil	336°C 637°F	270°C 518°F	205°C 401°F	27
Kerosene	290 to 435°C 554 " 815°F	250 to 265°C 482 " 509°F	200°C 392°F	26
Shale oil	354 " 435°C 669 " 815°F	272 " 290°C 522 " 554°F	200°C 392°F	23
Paraffin	388 " 414°C 730 " 777°F	243 " 258°C 469 " 496°F	228°C 442°F	11.5

*"Ueber Zündpunkte und Verbrennungsvorgange im Dieselmotor" Halle, 1924; V.D.I., Vol. 68, May 31, 1924, pp. 574-578. (For translation, see N.A.C.A. Technical Memorandum No. 299 – "Determination of Ignition Points of Liquid Fuels Under Pressure," by J. Tausz and F. Schulte, 1925.

The ignition point is generally lower in oxygen than in air and still lower in compressed air of the usual pressure in Diesel engines. For a few substances (such as ethyl benzene, allyl alcohol, trinitrophenol, etc.) the ignition temperature is higher in oxygen than in air. This fact caused Tausz to give an interesting explanation of the ignition, according to which the substances absorb oxygen before ignition, forming superoxides (peroxides), i.e. supersaturated oxygen compounds which are stable only in a transitory pressure and temperature range, beyond which they suddenly decompose. This decomposition produces much heat and the substance ignites.

With substances whose ignition point is higher in oxygen than in air, the superoxide, before it decomposes (i.e. ignites) can absorb more oxygen, thus forming a substance with a higher ignition point. The oxygen absorption needs to take place only in a relatively small portion of the molecules in the fuel drops, because the heat freed by the decomposition of the superoxide suffices to decompose the remaining molecules in the fuel drop, i.e., to start the combustion. Only in so far as the oxygen absorption signifies decomposition of the fuel to a very slight degree, are we justified in claiming that the injected fuel decomposes before ignition.

Ignition Points in Compressed Air

The experiments of Tausz and Schulte also showed that the ignition point is generally lowered by increased pressure for a few substances not used as engine fuel, but can also be raised to a certain degree. Mixtures behave differently from the original substances. A few of the ignition curves are shown in Figure 5. The gas oil mostly used in Diesel engines ignites, at the customary compression pressure of about 30 atm., somewhat above $200^{\circ}C$ ($392^{\circ}F$). Kerosene behaves similarly. The ignition point of gasoline is higher and that of benzol considerably higher. Nevertheless, both these oils burn well in Diesel engines, though the compression must be considerably higher, especially for benzol. Since these produce high stresses in the working parts and since they cost considerably more than gas oil, they do not come under consideration for Diesel engines.

Neumann expresses the opinion that it is more correct to attribute the lowering of the ignition point to the increasing density, rather than to the pressure of the air, since the fuel drops are heated by conduction, which depends on the air density. By plotting the ignition points found by Tausz and Schulte against the air density γ, Neumann obtains the curve (Fig. 6) of the absolute ignition temperatures T_s, which follows the law $T_s = C\gamma^{-m}$, in which $C \sim 709$ and $m = 0.16$ for aliphatic oils. We can follow Neumann in so far as the air density and not

the air pressure determines the ignition point.   The formula for
the mean ignition temperature of different fuel oils is of no
practical importance, however, because the ignition points of var-
ious fuels exhibit differences which must be considered in de-
termining the compression, although they do not appear in the
formula.

Time Lag of Injection

The gas oil almost exclusively used for Diesel engines
ignites, according to Tausz and Schulte, at about 200°C (392°F),
with the customary compression in Diesel engines.   The fuel drops
injected into the combustion space must be heated to at least
this temperature.   It is known, however, that, in order to guar-
antee the starting of the engine from the cold condition, at
least 27 to 28 atmospheres pressure is required for airless in-
jection engines and about 30 atm. for air-injection engines, be-
cause of the cooling caused by the expanding injection air.   If
we assume 28 atm., we find (according to the gas-entropy diagram
of Schule*) 500°C (932°F), as the final temperature corresponding
to an initial temperature of 27°C (80.6°F), and 550°C (1022°F)
for an initial temperature of 50°C (122°F), i.e. temperatures of
about $300-350^\circ$C ($540-630^\circ$F) above the ignition point.

This is clearly shown by Figure 7.   The intersection points
of the ignition curve for gas oil with the curves of the com-

*"Die thermischen Eigenschaften der einfachen Gase und der tech-
nischen Feuergase zwischen 0° und 3000°C," V.D.I., Vol. 60
(1916), p. 630.

pression pressures for 27°C (80.6°F) and 50°C (122°F) initial temperature show the same compression pressures at which the ignition point was obtained in the cold and in the hot engine. The points are surprisingly low, at only 6.1 and 7.3 atm. That the compression pressure must, nevertheless, be much greater, is due to the fact that the fuel drops require some time for heating to their ignition point. This heating must be effected, however, by the time the crank shaft has moved $3-5^\circ$.

The time between the beginning of the injection and the ignition is called "time lag" by C. J. Hawkes,* who first investigated this phenomenon. Figure 8 shows it for Scotch shale oil (Sp. G. 0.86) in air under 14 atm. of pressure, as plotted against the temperature. At 500°C (932°F) it is about 0.007 sec. This value seems too large, which may be due to inadequacy of the experimental apparatus. The compressibility of the oil was disregarded, and there might have been air pockets in the horizontal fuel valve. Fundamentally, the knowledge of the significance of the time lag indicates great progress since, in connection with the dependence of the ignition point on the pressure, it enables the choice of the compression.

Further measurements of the time lag would be valuable, since the location of the time point in relation to the dead center, in which the ignition occurs, determines the maximum pressure and hence the working stress, the shape of the indi-

*"Fuel Oil in Diesel Engines," Engineering, Vol. CX, Dec. 10, 1920, p. 786.

cator diagram, the combustion and the fuel consumption. The
time lag cannot, however, be put equal to the time between the
beginning of the fuel-pump stroke and the pressure rise in the
offset indicator diagram. We must, on the contrary, subtract
from this time the injection lag, which must be determined sepa-
rately, as explained by Hesselman.*

Combustion of Hydrocarbons

The question as to how the injected fuel burns after igni-
tion in the Diesel engine has not yet been fully answered. We
do not know accurately the composition of the fuel oils, but
only that they are very complex mixtures of/hydrocarbons, when
                                          aliphatic
of petroleum or lignite tar origin, predominantly of the compo-
sition $C_n H_{2n+2}$ (paraffins) and $C_n H_{3n}$ (olefins or naph-
thenes) in chain compounds, and of aromatic hydrocarbons for
coal-tar, belonging to the naphthalene, fluorene, phenanthrene
and anthracene groups of ring compounds.

Disregarding the ever-present impurities, the combustion
products of both series of hydrocarbons contain CO_2 and H_2O.
It is true, however, that the fuel oils, in burning, do not
first separate into C and H which then simply combine with
the the oxygen in the compressed air. The combustion of the fuel
oils consists, rather, in passing through a whole series of in-

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*"Hochdrucköhlmotor mit Einspritzung des Brennstoffes ohne Druck-
luft," V.D.I., Vol. 67 (July, 1923) pp. 658-662. (For translation
see N.A.C.A. T.M. No. 312 - "Hesselman Heavy-Oil High-Compression
Engine," by K. J. E. Hesselman.)

termediate compounds, which are different for the gas oils as compared with those for the aromatic hydrocarbons.

Franz Fischer* takes xylene $(C_8 H_{10})$ as an example. Its molecule, when heated, splits up into toluene, benzene, ethylene, methane, etc. Thereupon the molecule again enlarges and, with the liberation of hydrogen, forms diphenyl $(C_{12} H_{10})$. With the continued loss of hydrogen, ever-larger molecules are formed, which are finally comparable only to a great carbon skeleton.

The aliphatic gas oils, which are generally used in Diesel engines, behave differently. They decompose, on heating, into smaller molecules, especially ethylene $(C_2 H_4)$. Apparently this decomposition leads through methane $(C H_4)$, since all hydrocarbons show a tendency to decompose into $C H_4$ and C.** The combustion process of ethylene and methane is now well known.

In 1884 Dixon*** found that a perfectly dry mixture of carbon monoxide and oxygen could not be exploded by the electric spark, while the addition of very small quantities of water vapor caused the mixture to explode immediately.**** While Dixon

*"Die neuesten Anschauungen über die Vorgänge bei der Verbrennung und der Oxidation der Kohlen," Gesammelte Abhandlungen zur Kenntnis der Kohle, Vol. IV (1920), p. 448.
** H. Von Wartenberg, "Verbrennungsvorgänge im Dieselmotor," V.D.I., Vol. 68 (1924), p. 153.
***"Conditions of Chemical Change in Gases: Hydrogen, Carbonic Oxide and Oxygen," Phil. Trans. Roy. Soc., London, Vol. 175 (1885), p. 617.
****According to Manchot (Chemiker Zeitschrift, Vol. 47, 1923, p. 781), dry carbon monoxide is not nonignitible but only difficultly ignitible.

concluded that CO oxidized to CO_2 according to the formulas $CO + H_2O = CO_2 + H_2$ and $2H_2 + O_2 = 2H_2O$, Wieland* demonstrated that it must also include formic acid (HCOOH):

$$CO + H_2O = HCOOH$$

$$HCOOH = CO_2 + H_2$$

$$H_2 + O = H_2O$$
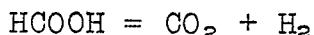
Even this explanation of the combustion is incorrect, for Von Wartenberg and Sieg** have shown that hydrogen peroxide (H_2O_2), which had previously been found in the combustion of CO, is also a necessary intermediate compound in the combustion of CO:

$$CO + H_2O = HCOOH \quad (1)$$

$$HCOOH = C\,O_2 + H_2 \quad (2)$$

$$H_2 + O_2 = H_2\,O_2 \quad (3)$$

$$H_2O_2 = H_2\,O + O \quad (4)$$
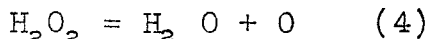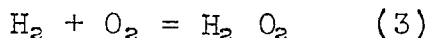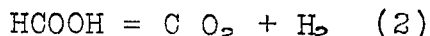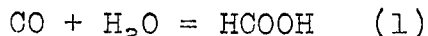
CO occurs again as the last term in the combustion formulas for methane and ethylene, i.e. the same substances into which the gas molecules decompose during combustion. According to Bone and Wheeler*** the combustion of methane takes place as follows:

$$CH_4 + O_2 = CH_2O + H_2O \quad (5)$$
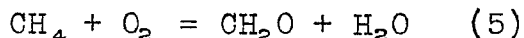
in which the formaldehyde is simultaneously oxidized, according

*"Zur Verbrennung des Kohlenoxyds," Berichte der Deutschen Chemischen Gesellschaft, Vol. 45 (1912), p. 679.
**"Ueber den Mechanismus einiger Verbrennungen," Ber. d. Deutschen Chem. Gesellschaft, Vol. 53 (1921), p. 2192.
***"The slow oxidation of methane at low temperatures," Proceedings of the Chemical Society, Vol. 19 (1903), p. 191.

to the formulas

$$CH_2O + O_2 = CO_2 + H_2O \qquad (6)$$

and
$$2CH_2O + O_2 = 2CO + 2H_2O, \qquad (7)$$
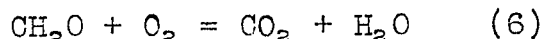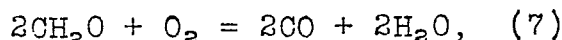
to CO_2 and CO. The latter is then further oxidized, through HCOOH, H_2 and H_2O_2, to CO_2 and H_2O. If formulas (5) to (7) are combined with formulas (1) to (4), we find that methane must burn according to the following reactions:

$$CH_4 + O_2 = CH_2O + H_2O$$
$$CH_2O + O_2 = CO_2 + H_2O$$
$$2CH_2O + O_2 = 2CO + 2H_2O$$
$$CO + H_2O = HCOOH$$
$$HCOOH = CO_2 + H_2$$
$$H_2 + O_2 = H_2O_2$$
$$H_2O_2 = H_2O + O$$
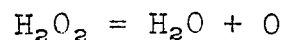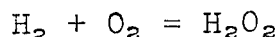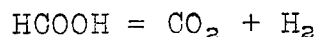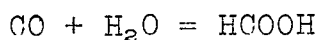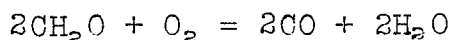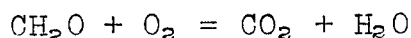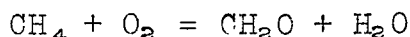
Thus there are not less than five intermediate products, namely, formaldehyde, carbon monoxide, formic acid, hydrogen and hydrogen peroxide which, however, immediately disappear so that only CO_2 and H_2O remain.

The reactions are similar for ethylene, which burns to carbon monoxide and hydrogen (Bone and Wheeler, Jour. Chem. Soc., Vol. 81, 1902, p. 535) according to the formula

$$C_2H_4 + O_2 = 2CO + 2H_2$$

thus involving the following reactions.

$$C_2 H_4 + O_2 = 2CO + 2H_2$$
$$H_2 + O_2 = H_2 O_2$$
$$H_2 O_2 = H_2 O$$
$$CO + H_2 O = HCOOH$$
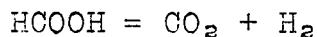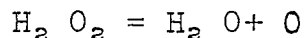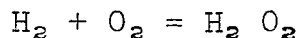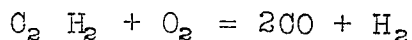$$HCOOH = CO_2 + H_2$$
$$H_2 + O_2 = H_2 O_2$$
$$H_2 O_2 = H_2 O + O$$
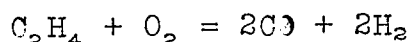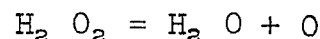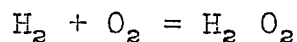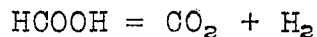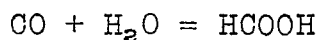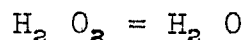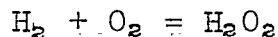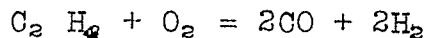
The number of intermediate products is one less than for methane.

The formula for the combustion of acetylene is

$$C_2 H_2 + O_2 = 2 CO + H_2$$

involving the following reactions.

$$C_2 H_2 + O_2 = 2CO + H_2$$
$$H_2 + O_2 = H_2 O_2$$
$$H_2 O_2 = H_2 O + O$$
$$CO + H_2 O = HCOOH$$
$$HCOOH = CO_2 + H_2$$
$$H_2 + O_2 = H_2 O_2$$
$$H_2 O_2 = H_2 O + O$$
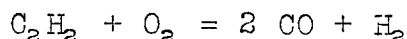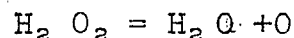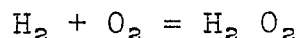
Among the combustion products of ethane from the paraffin series, Evans ("The Chemistry of Combustion," The Chemical Age, Vol. V, 1921, p. 36) found formaldehyde and formic acid, showing that its combustion is similar to that of methane.

Since it is thus demonstrated that the gas oils, in burning, decompose into smaller molecules, chiefly ethylene and methane,

it is extremely probable that, along with the above-mentioned
products, the final combustion products of the gas oils are also
present.   In truth these are only the last reactions.   We do not
know how many preceding reactions there are.   Their number may
be very large and it is to be hoped that chemical research will
yield further information and lead to the complete explanation
of the combustion of hydrocarbons in Diesel engines.

If ignition and combustion of the fuel oil in Diesel engines
take place as stated above, the question may be raised as to how
the combustion reactions can be controlled so that the final
combustion products will be only CO_2 and H_2O.   It is known that
other products are also formed.   We only need to remember the
often smoky exhaust.   If the exhaust gases are not clear, they
must contain particles of soot, which are not pure carbon but
contain molecularly complex hydrocarbons.*   In such a case, the
combustion has taken an undesirable course.

In order to avoid this, there must be no overheated parts
in the combustion space above a certain temperature limit, which
is about 600°C (1112°F) for aliphatic fuel oils.   Liquid fuel
drops must not come in contact with such hot parts, since a sort
of "cracking" would occur, the result of which is a sooty exhaust.

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*K. A. Hofmann and W. Freyer, "Wasserlösliche Kolloide aus
kunstlichen Kohlen," Ber. d. Deutschen Chem. Gesellschaft, Vol.
53 (1920), p. 2078.

Moreover, the question of the control of the combustion re-
actions in the Diesel engine leads to the important matter of
mixture formation, which is a mechanical problem to a much
greater degree than has hitherto been assumed.

Translation by Dwight M. Miner,
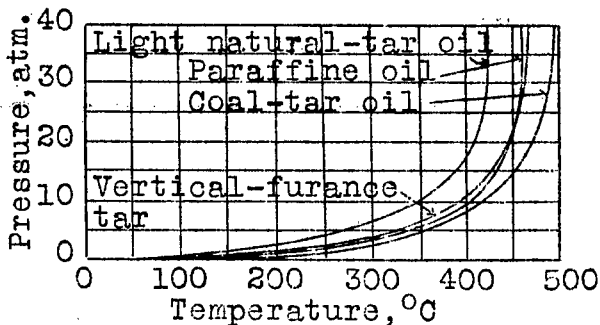National Advisory Committee
for Aeronautics.

Fig.1 Pressure-temperature
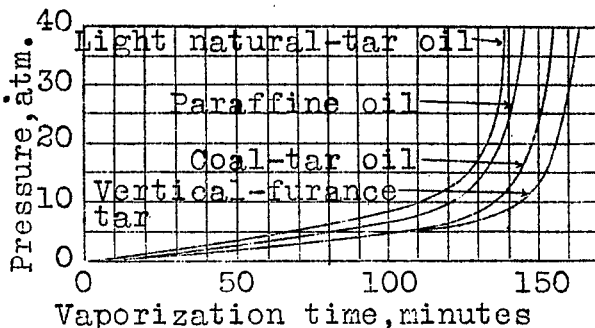curves of fuels
according to Wollers and Ehmcke.

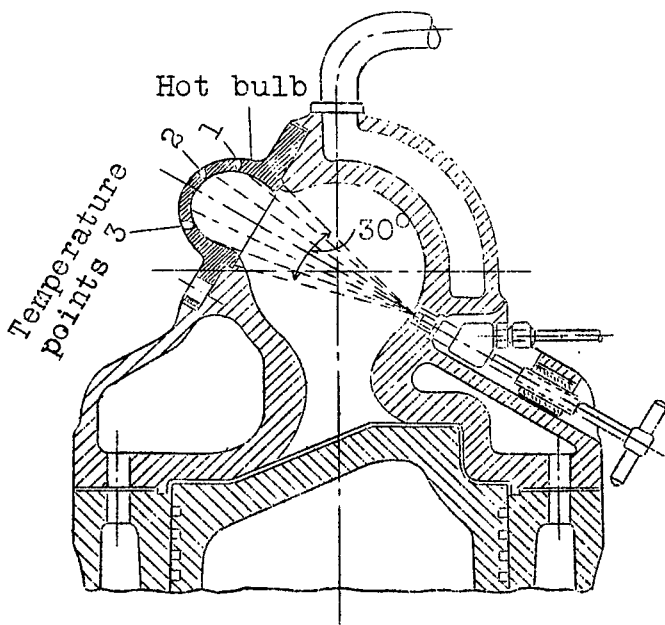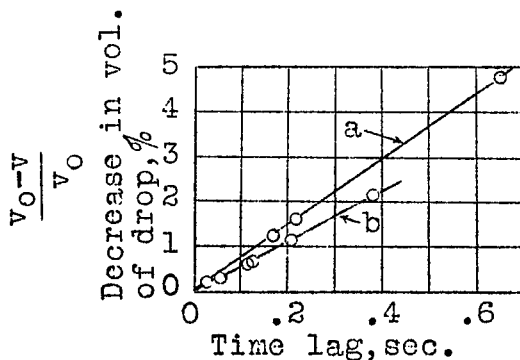Fig.2 Pressure-time curves
of fuels according to
Wollers and Ehmcke.

Fig.3 Temperature measurements
on a 30 HP AEG medium-
pressure engine.

a, With turbulence
b, Without   "

Fig.4 Decrease in volume
of drop from vapori
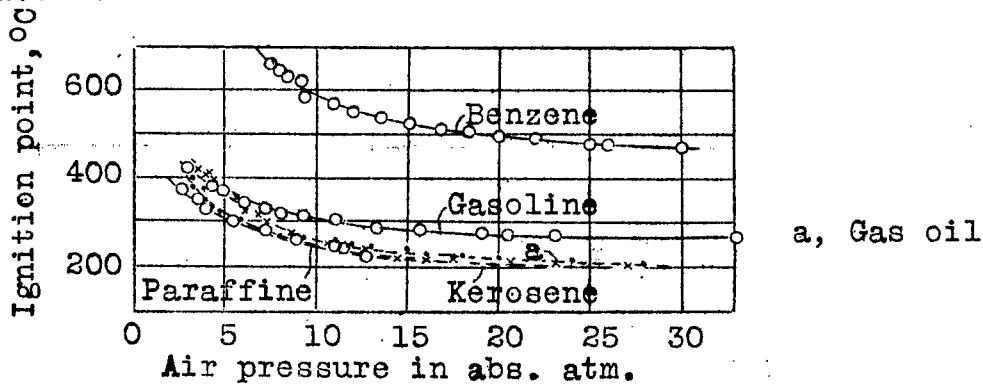zation plotted against time
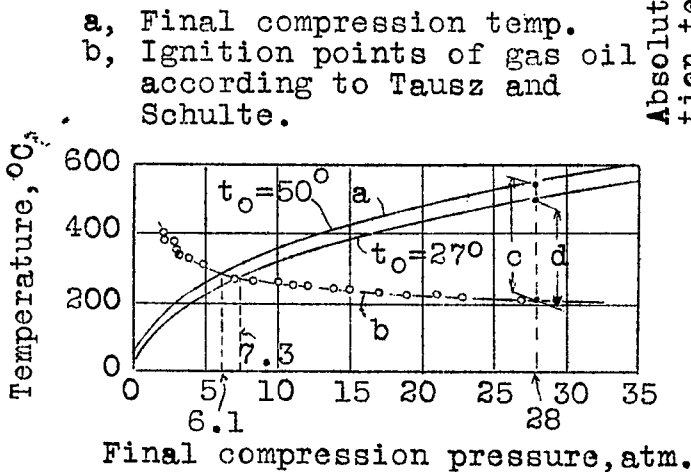lag according to Neumann.

Fig.5   Lowering of ignition point of fuel oils
          with increasing air pressure according to
Tausz and Schulte.

a, Final compression temp.
b, Ignition points of gas oil
   according to Tausz and
   Schulte.

Fig.6   Ignition point plotted
          against air density
according to Neumann.

Final compression pressure,atm.

c, $\Delta t_{50^o} = 340^o$
d, $\Delta t_{27^o} = 293^o$

Fig.7   Final compression tem-
          peratures and ignition
points for gas oil.

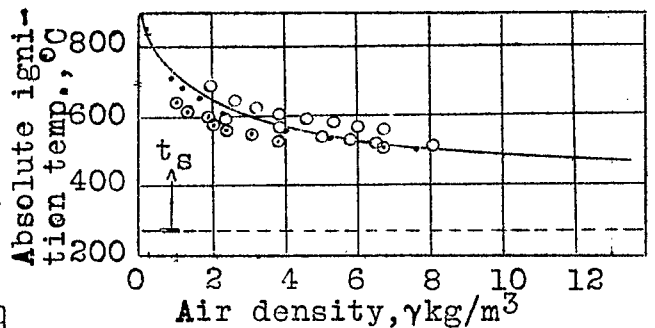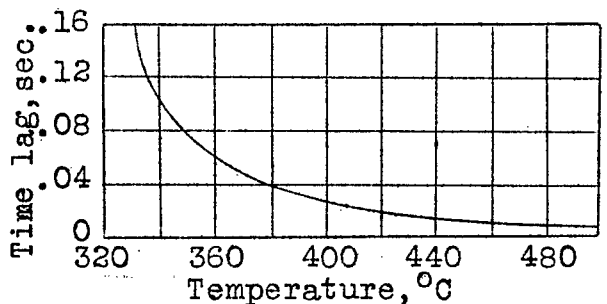Fig.8   Time lag of shale oil
          in compressed air at
14 atm. according to Hawkes.