THE COMBUSTION PROCESS IN THE DIESEL ENGINE

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INTRODUCTION

The Diesel engine is characterized by injection of fuel in the combustion chamber and by self-ignition. Both characteristics give rise to typical problems. The former characteristic, i.e., injection of the fuel with subsequent formation of a combustible mixture, is the fundamental one.

This mixture formation immediately preceding combustion and continuing during combustion introduces the element of heterogeneity of the mixture to an extent unknown in gasoline engines. As a matter of fact, one is faced in the Diesel engine with mixture elements varying from pure liquid globulae and deposits to fuel vapors and pure air, the condition of this heterogeneous complex changing with tremendous rapidity, owing to agitation, evaporation, and combustion. As a result, conditions are always elusive; for instance, the strength of the mixture and the temperature of the flame vary continually throughout the charge.

This heterogeneity has its advantage, for it allows one to vary the load down to zero solely by regulating the fuel input, which is the cause of the excellent economy of the Diesel engine under varying load. That, however, is the only advantage. Most drawbacks of the Diesel engine do come from this very heterogeneity of the charge, the most obvious one being the impossibility of burning efficiently a quantity of fuel corresponding to the full amount of oxygen available in the cylinder, so that the power output stays behind that of an efficient gasoline engine. A second drawback, but in practice often the more important one, is the great tendency of the Diesel engine towards incomplete combustion, causing internal troubles as well as dirty and foul-smelling exhaust gases.

Figure 1 represents schematically the charge in a Diesel engine at a phase of its combustion process. Figure 2 represents schematically and comparably the charge in a gasoline engine; the difference in simplicity of conditions as compared with figure 1 is obvious.

This heterogeneity may be put forward as an excuse for the still existing lack of precise knowledge concerning the Diesel process, now that the Diesel engine has reached its fortieth anniversary. Whereas today the knowledge of the combustion process of the gasoline engine has developed to a point where quantitative results of general validity can be foretold, that of the Diesel engine allows only an acceptable qualitative analysis. For the first two decades the process of the Diesel engine was only a confused picture, in which chemical and physical considerations, ignition and combustion phenomena, space and time were all mixed up. A. Riedler (3) was one of the first to try to disentangle the various elements of the problem. He suggested the following picture of the stages of the combustion process: (*1*) introduction of the fuel, (*2*) atomization, (*3*) evaporation, (*4*) mixture formation, (*5*) decomposition, and (*6*) combustion. It is interesting to note that these stages, which Riedler visualized as being subsequent in time, actually do exist but overlap each other considerably.

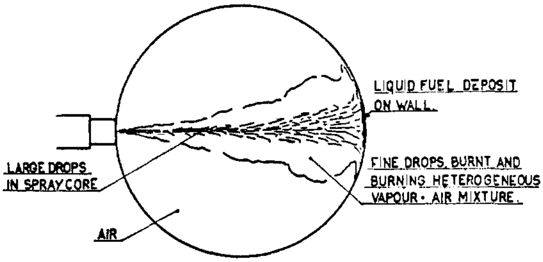


FIG. 1. Diesel engine combustion process schematized

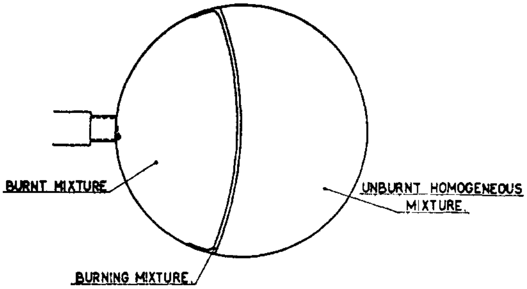


FIG. 2. Gasoline engine combustion process schematized

Before starting to analyze the Diesel process, the authors wish to make two statements: first, that for many reasons (e.g., difficulties due to the heterogeneity mentioned before) the insight available today concerning the Diesel process is due more to mechanical and physical than to chemical research. In this respect it may be useful to state that the authors, as mechanical engineers, have had the full collaboration of physical and chemical scientists; they admit, however, that it is possible that they have stressed the mechanical aspect of the problem rather much. Second, that they intend to give in this exposition only their personal views on the subject with no more than the necessary references to contradictory opinions; a fairly complete reference to the current status of research may be found in their contribution on the same subject in the recently published encyclopaedia *Science of Petroleum.*

ANALYSIS OF THE DIESEL PROCESS

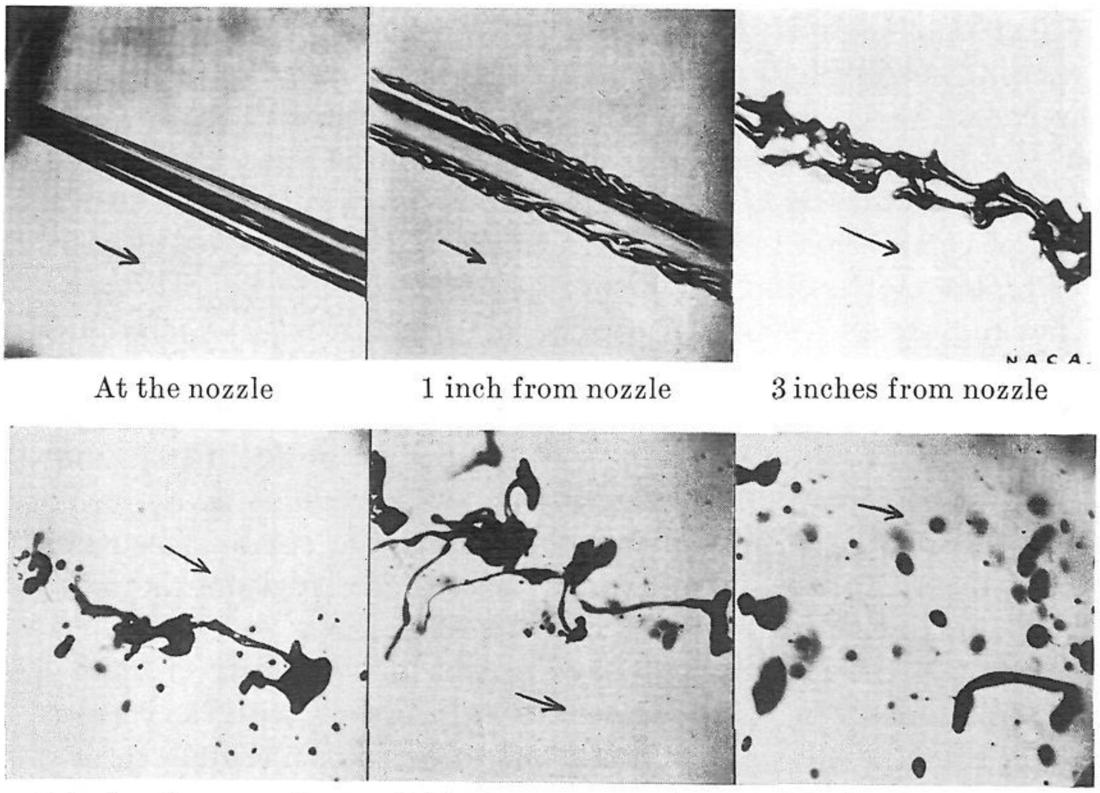
A. Mixture formation

A perfectly combustible mixture is conceivable only with fuel in the vaporized state, the vapors being homogeneously mixed with the air and in such proportion that every bit of fuel and oxygen can be consumed. The fact that the mixture in the Diesel engine is imperfect in all these respects adversely affects, among other things, the progress of combustion. Now combustion, to be most efficient, should occur when the piston is near its top dead center; if part of the fuel burns later, the combustion process will be the less efficient for it. Consequently, the more time in the course of combustion is taken up to correct a certain imperfection of the mixture, the more serious this imperfection is.

The mixture presents two aspects of structure: (*1*) Microstructure, pertaining to the size of the particles of the fuel and to whether these particles are in liquid form or vaporized, all considered locally, without regard to the condition of overall distribution of the fuel throughout the combustion chamber; and (*2*) macrostructure, pertaining to the condition of overall distribution of the fuel throughout the combustion chamber, without regard to the size of the particles of the fuel or whether these particles are in the liquid form or are vaporized.

A good microstructure is obtained by first making drops of small sizes, which then quickly evaporate in contact with the air, with the combustion gases, or with the hot walls. In the early air-injection engines these small drops were actually formed inside the atomizer, where a blast of air of high velocity acted on the surface of the fuel fed into the air stream; only very fine drops entered the combustion chamber. In today's solid-injection engines the droplets are formed not inside the atomizer but almost entirely in the combustion chamber itself, owing to high pressure jets entering at high velocity (over 1000 m. per second) and impinging on the dense air in the chamber. (Here the name "atomizer" for the injector is actually misleading.) The mechanism of this atomization has been adequately dealt with by the National Advisory Committee for Aeronautics, by researchers at the Pennsylvania State College, and by others in very excellent pieces of research work. Figure 3, taken from Report No. 454 of the National Advisory Committee for Aeronautics, illustrates the mechanism of atomization in the clearest way.

In order to obtain small drops the injection pressure and air density should be high, the orifice of the injector small, and fuel viscosity low. As soon as the velocity of the drops relative to the air has decreased appreciably, no further splitting up occurs and the next stages of preparation of the micromixture are provided for by evaporation and dispersion of the vapors in the immediate surroundings. There has been, and probably still exists, considerable divergence of opinion as to how fast droplets of the sizes considered (0.01–0.03 mm.) do evaporate. Our opinion is that this process is exceedingly rapid, especially so once the combustion has set in and gas temperatures have risen from 600° to 800°C. to over 2000°C.



At the nozzle 1 inch from nozzle 3 inches from nozzle

5 inches from nozzle 7.5 inches from nozzle 10 inches from nozzle

FIG. 3. Micrographs showing process of atomization (N. A. C. A.)

Rothrock and Waldron (4) have shown that fuel sprays dissolve in 1 to 2 milliseconds even before ignition; after the flame has started a fraction of that time may be nearer the truth, which corresponds to only a few degrees "crank angle" even at an engine speed as high as 3000 R.P.M. In the flame, therefore, one may consider evaporation as almost instantaneous.

Spreading of the fuel vapors, as they are formed, into the wake of the droplets is effected by indiscriminate turbulence produced by the progress of the droplets through the air, and furthermore by diffusion. Though very little is known about this spreading, it seems that the reach of diffusion is small, but that its function must be important for the final molecular mixing.

In the early stages of the solid-injection engine, it had been found that the microstructure, however important, was not the biggest problem; experiments with extremely fine atomization led to disappointment. The cause of this disappointment was not clear at first, since the success of the air-injection engine had been attributed precisely to its finer atomization. As we will see further on, it was not so much the finer atomization, but the very efficient distribution (macrostructure) in the air-injection engine that caused this success. Now, with solid-injection engines, the finer the atomization, the more difficult it is to get good distribution.

Here we come to the important point of the macrostructure. The macrostructure is performed by injecting the fuel, in one or more sprays, into the air; this results in a structure as shown in figure 1, with great agglomerations of fuel here and pure air there. In order to get quickly a good, that is homogeneous, macrostructure, the relative motion between the heterogeneous portions of the charge must be increased, which explains the importance of turbulence. Turbulence, having done its part for the formation of a homogeneous macrostructure, turns over the job to diffusion again for final microstructure formation.

There exists a great diversity in the ways in which turbulence is applied in practice, for its type, energy, and origin may be vastly different; this diversity corresponds to the large variety of combustion chamber designs on the market.

The various types of air movement in combustion chambers are mainly: (*a*) indiscriminate turbulence, i.e., disorderly eddies with relatively small radii of gyration, which gradually disperse the clouds rich in fuel vapor; and (*b*) air swirl, i.e., orderly movement of the air in large orbits throughout the combustion chamber. This swirl may have two functions: the first one to "scrub" or "winnow" the fuel jets that are sprayed through the moving air, thus removing the vapors and finer drops; the second one, to act as stated above, viz., to carry parts of the charge bodily through the chamber and let indiscriminate turbulence, evaporation, diffusion, etc., finish the work in some other part. The varieties and combinations of these main types are almost endless.

Air swirls are applied, showing speeds varying from case to case, between virtually zero and a hundred or more meters per second, illustrating the range of appreciation that these swirls enjoy among designers. There are good reasons for this difference of appreciation: however useful the swirl may be to attain a good macromixture, at the same time it increases the heat transfer to the cylinder walls, and thereby the heat losses; furthermore, too fast a swirl may throw (or centrifuge) fuel out onto the walls, thus overshooting the target. Some designers, therefore, prefer to aim at good distribution by injection only, sometimes applying a swirl only as strictly required to correct insufficient distribution by the spray. They try to fit the combustion chamber around the (often only alleged) shapes of one or more sprays (cf. figure 4), but since distribution is so heterogeneous in a spray, they have to allow for a relatively large excess of air. Although the power output is thereby restricted, the reduced heat losses may ensure a higher efficiency; thermal stress conditions of engine parts (cylinders, cover, piston) may be excellent. Of course, injection should function excellently for this design.

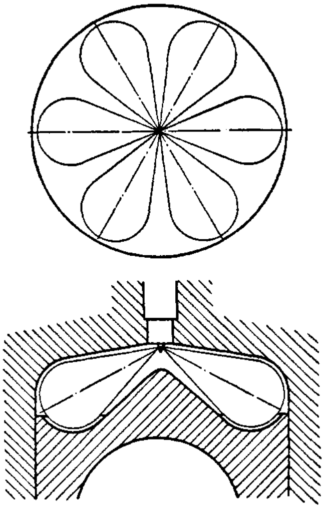


Fig. 4

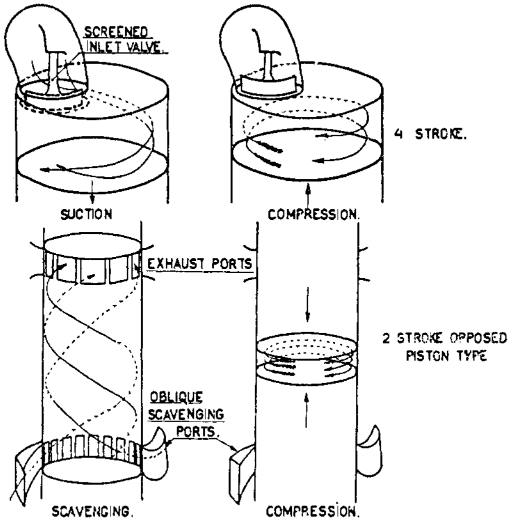


Fig. 5

Fig. 4. Combustion chamber adapted to external shape of sprays
Fig. 5. Induced air movement; four-stroke and two-stroke

Other designers, though, with the idea of simplifying the functions of the injection equipment, prefer to aim at distribution by the air movement only; this solution may result in a somewhat greater reliability, a higher output, and, generally speaking, a better speed flexibility, but it involves a somewhat lower efficiency and a somewhat greater heat stress.

All kinds of compromises between these extremes exist, and usually the respective advocates of each system are most emphatic in their claims.

According to their origin, one may distinguish between induced and forced air movement. Induced air movement is such movement as is caused by the entry of the air in the cylinder. This will always produce indiscriminate turbulence, but by means of special valves or ports orderly swirl may also be set up (see figure 5). Forced air movement is such movement as is caused by the transit of the air from the cylinder to the combustion chamber during compression. This may also be indiscriminate turbulence and/or swirl (cf. figure 6). Combination of both induced and forced air movement also exists (see figure 7). Finally, movement of combustion gases may be caused by the combustion itself.

The allowable velocities of induced air movement are restricted, as too high velocities would hamper the breathing of the engine; that of forced air movement is limited on account of pumping losses, yet forced air movement may be, without objection, much more intense than induced air movement. The use of either movement is limited on account of heat loss and of "fuel-throwing" ("out-centrifuging").

Movement of combustion gases as mentioned may be ensured in particular by starting combustion in a separate chamber, such as a precombustion chamber (cf. figure 8); the combustion in the prechamber causes an increase in pressure by which the gases are blown into the main chamber. Again, the design of the arrangement may be such that either indiscriminate turbulence or orderly swirl is predominant. This combustion gas movement, though very efficient in many instances, is under less direct control than the two first-mentioned air movements, which depend wholly on the design, whereas the combustion gas movement depends also on the behavior of the primary combustion. Here it is the experimental work on the test bench that carries the burden of finishing the design, but it may result in a construction which performs as satisfactorily as that of the air movement type.

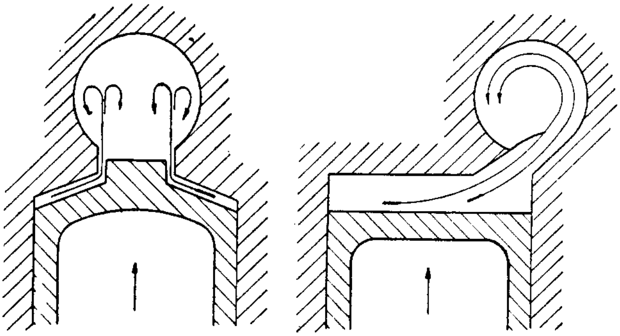


FIG. 6. Forced air movement; turbulence and swirl

The winnowing action of air movement on a spray depends *inter alia* on the structure of the spray and its rate of evaporation. The spray usually consists of a core of rapidly travelling "chunks" of oil which are gradually stripped down to fine drops, and of a mantle consisting of drops so fine as to have lost their velocity. The degree and rate of atomization of the fuel influence the penetration and dispersion of a spray; the finer the droplets, the greater relatively the resistance of the air, that is, the shorter the penetration, but the greater the dispersion will be. Intense atomization makes the spray blunt or "soft," and makes it more susceptible to winnowing.

Low viscosity of the fuel as well as strong evaporation softens the spray and increases the amount of fuel removed by winnowing. The moment of ignition is therefore of great importance, since at that moment the rate of evaporation changes, as we have seen before, affecting spray softness. Therefore special study on the behavior of unignited fuel sprays will not give quantitative results that apply to real engine operating conditions; this of course greatly complicates research and development work.

Besides these considerations there remains the question of liquid fuel being deposited on the walls, either directly by the jet or by the fuel being centrifuged out by air movement. These deposits are a typical imperfection of both micro- and macro-structures. For their combustion they have to be evaporated and then distributed by air movement. In the authors' opinion the liquid deposits form one of the biggest difficulties that have to be overcome in controlling the Diesel process; this difficulty is greatest either when using low-volatility fuels such as residual fuels or with small engines (on account of the small free space for the sprays). A carefully established balance between air movement, combustion gas movement, and wall temperature is necessary to get rid of these deposits. In general, high wall temperatures are extremely useful. In some cases where the air movement is small, it may happen that evaporation is too rapid for the amount of air passing over the spot, resulting in local over-richness. Usually, a large portion of the piston crown forms part of the combustion chamber wall, and so presents a relatively high temperature (up to 600°C.) right at the most important spots where the fuels jets

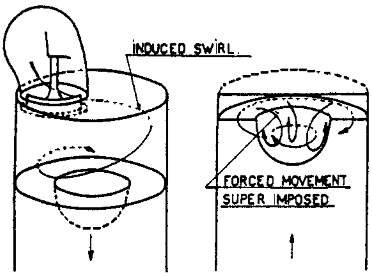


FIG. 7

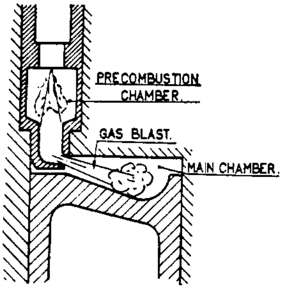


FIG. 8

FIG. 7. Combination of induced and forced air movement
FIG. 8. Precombustion chamber principle

strike. If it be required to maintain such a high temperature in small engines, one has to resort to heat-insulated linings for the combustion chamber. In the absence of these hot walls, specially adapted fuels—without low volatility fractions—would have to be used, particularly in view of good combustion at part loads.

B. Self-ignition

If "ignition" in the technical sense may be described as "causing flame combustion," then "self-ignition" is the process of chemical reactions in the fuel-air mixture leading to flame combustion.

In the authors' opinion the best representation of the self-ignition process in the Diesel engine is as given in a previous paper (1) from which figure 9 is here reproduced. The fuel, whilst being injected and atomized, absorbs heat from the air and evaporates rapidly. The vapors, almost instantaneously attaining the temperature of the surrounding air (which locally may drop appreciably owing to this abstraction of heat, but is still of the order of 500° to 800°C.), enter into chemical reactions with the air, thus leading to locally increased temperatures; finally, in one or more spots where the conditions are most favorable, flame conditions will be reached. From these spots or flame nuclei the flame may spread with great rapidity. Of course a number of flame nuclei may have been born without growing to ripeness; these would-be nuclei are overtaken by the one or two more successful ones which will start the inflammation.

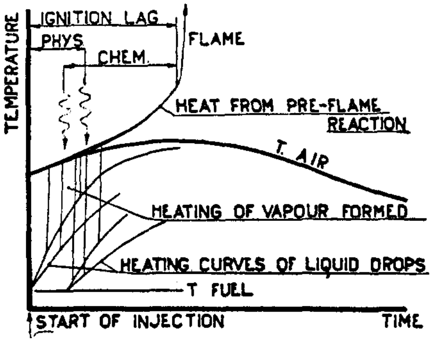


FIG. 9. Temperature during ignition

The evaporation effect has been shown by the afore-mentioned photographs of Rothrock and Waldron (4). Later experiments by Selden and Spencer (5) have shown the pressure drop due to the abstraction of heat. Large-scale pressure diagrams taken on Diesel engines may also show this pressure drop, but it is soon, often even immediately, overcome by the pressure rise due to the preflame reactions (cf. figure 10).

The time which elapses between the beginning of fuel injection and the reaching of flame conditions (or, as others have it, the beginning of rapid pressure rise) represents the ignition delay, which the authors have subdivided into (*1*) "physical delay," this being the period of the development of enough fuel vapor (endothermal part) to initiate the next period, and (*2*) the "chemical delay," this being the period required by the preflame reactions in order to reach flame conditions (exothermal part). The physical and the chemical delays cannot, of course, be entirely separated as to time, since considerable overlapping occurs. Still, physical and chemical delays must be, principally, considered as two separate phenomena; fuels of very low volatility show much longer total delays than could possibly be explained from their chemical character alone. For fuels of normal volatility the physical delay may be very small, probably between 5 and 10 per cent of the total delay; with residual petroleum fuels and also with some vegetable oils, it may amount to some 50 per cent of the total delay, the latter being thereby almost doubled.

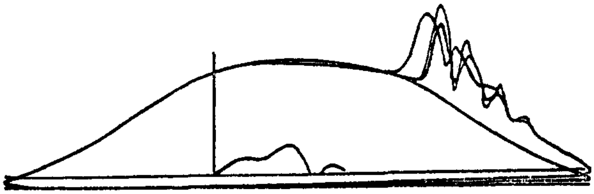


FIG. 10. Pressure drop during first part of delay. Vertical line = beginning of injection

It has been asked just what constitutes the most favorable conditions that lead to the formation of a flame nucleus. The answer is that one can only guess. Some experiments on self-ignition of vapor-air mixtures, by Peletier and Van Hoogstraten in the laboratory with which the authors are affiliated, are very interesting. For a C. F. R. gasoline engine that was being motored—with the ignition cut off—the investigators found that the lowest compression ratio which would cause a vaporized mixture to ignite by compression alone occurred with a mixture strength of 150 per cent of the theoretical value, and they found a similar value to hold for many fuels. This may be an indication that the flame nuclei in the Diesel engine are the spots where vapor-air mixtures of about such a composition exist; it may be assumed that fuel drops do not count in this respect.

During the same experiments (without sparks!) the heat development by preflame reactions could be clearly observed from indicator diagrams taken at a compression ratio just below the critical point (see figure 11);

this heat development by preflame reactions was also proven by the fact that the torque required for motoring the engine would then fall off to *nearly zero. The phenomenon was accompanied by luminescence and* an extremely acrid smell. Approaching the critical point of self-ignition, inflammation followed gradually. Most probably this is what occurs locally and on a smaller scale in the Diesel engine in said would-be nuclei.

Having tried to grasp as far as possible the character of a flame nucleus, the further question that rises is: What is its size? Let us assume that a certain mixture strength does constitute the most favorable conditions for the formation of flame nuclei. Now, minute regions showing this very mixture strength must needs exist around every fuel droplet, since its atmosphere contains all graduations from pure fuel vapor down to pure air. If these minute regions of most favorable mixture strength, or any single one of them, were capable of acting as centers whence flame spreads with great rapidity, then ignition delay would be entirely independent of injection characteristics, turbulence, etc., but it is not. The heat losses of such minute regions may be so great that it is impossible for them to reach flame temperature in so small a space. One is led to conceive of larger and stronger nuclei, characterized by a generation of heat that surpasses the heat losses to their neighborhood. The creation of these circumstances, i.e., nuclei sufficiently potent with respect to their surroundings, depends on many conditions, such as reaction velocity, temperature, and turbu-

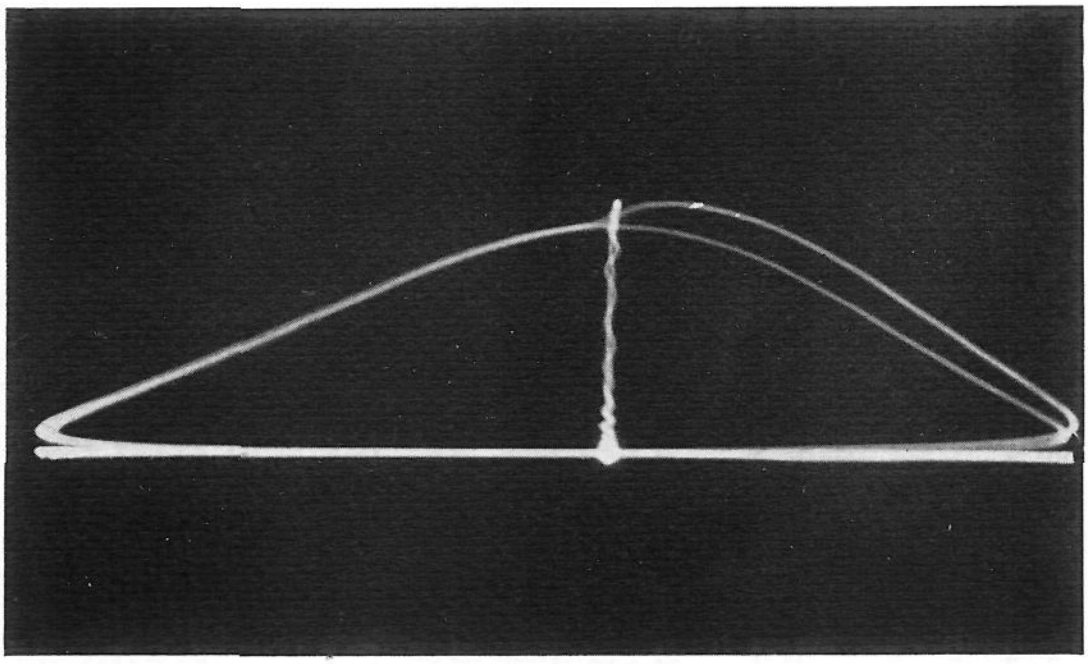


FIG. 11. Pressure developed by flameless reactions. Vertical line = top dead center position of piston

lence. Turbulence in particular may influence the ignition delay; this influence has been the object of many discussions and a few words about it may be of interest.

Turbulence enhances mixing and heat transfer. These combined influences affect the ignition process in different ways: first of all, they may shorten the delay, owing either to an increase of the rate of heating of the droplets, thus shortening the physical delay, or to the compensation of a locally too large heat abstraction from the air, thus shortening the chemical delay. Therefore, in its first aspect, turbulence acts beneficially on the delay. In its second aspect, however, the combined influences of turbulence tend to lengthen the delay: as soon as the local mixture temperatures exceed the temperature of the surroundings the greater heat transfer tends to cool the would-be nuclei. The mixing influence, moreover, tends to decrease the local vapor–air ratio, which at first has no effect at all, as long as there still remain regions very rich in vapor; but as soon as these have been dispersed, the mixture becomes diluted below the composition

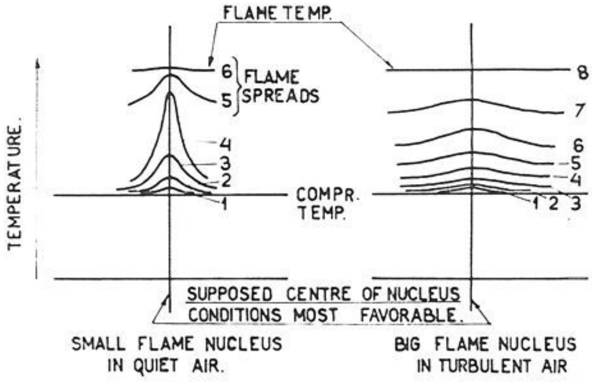


FIG. 12. Nucleus formation in quiescent and in turbulent air schematized

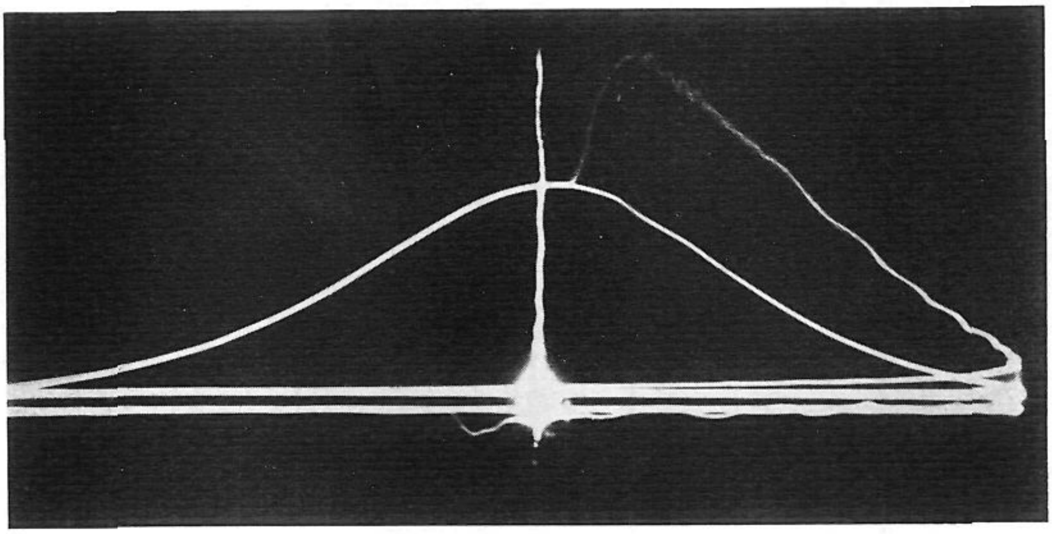


FIG. 13. Diagram of combustion starting from a small nucleus (moderate turbulence). Vertical line = top dead center position of piston.

most favorable for self-ignition. Thus with strong turbulence both the increased heat transfer from the nuclei and this dilution of regions rich in vapor may lead to increased delays. Schematically these favorable and unfavorable influences may be illustrated by figure 12. Under favorable influences a nucleus may be, so to speak, of the size of a mere pinhead; the pressure diagram will deviate only very little from a straight compression diagram, up to the moment where pressure begins to rise rapidly (cf. figure 13), owing to combustion; under unfavorable influences there may be formed a nucleus of much larger dimensions (cf. figure 12); a gradual extra pressure rise of several atmospheres may have been produced

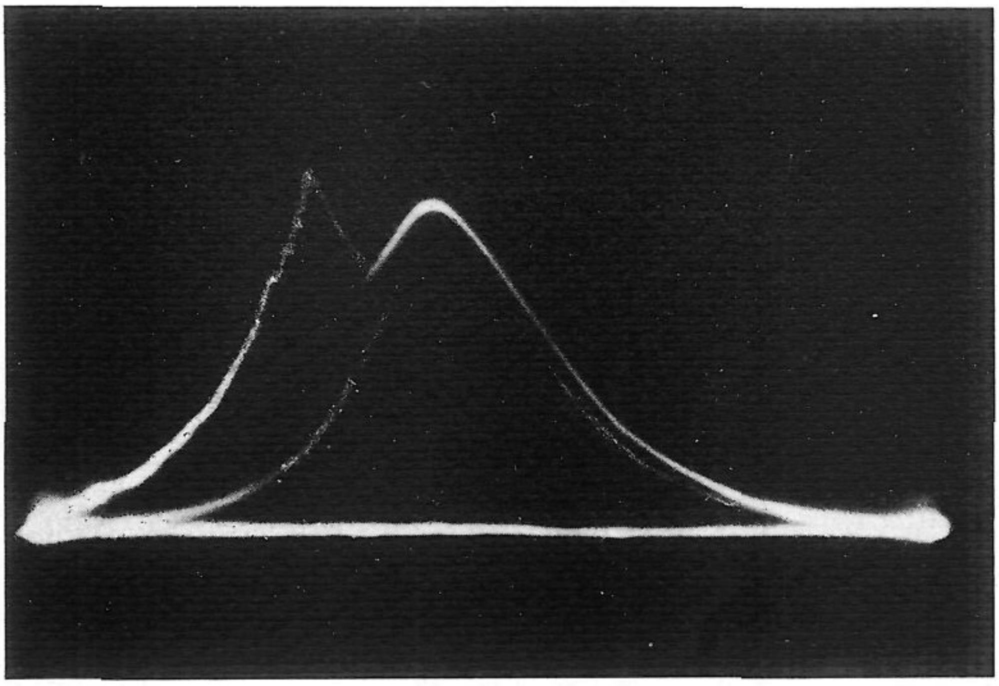


FIG. 14. Diagram of combustion starting from a big nucleus (high turbulence), reading from right to left

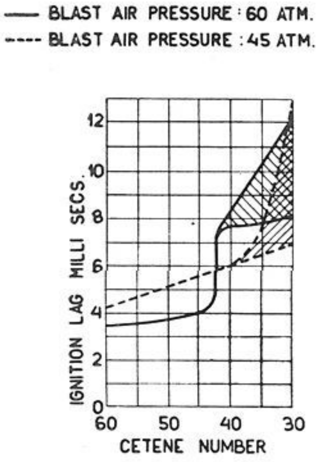


FIG. 15. Delays in air-injection engine

by preflame reactions in a large portion of the charge, before, finally, combustion proceeds rapidly (cf. figure 14). (The two diagrams shown on figures 13 and 14 are taken on a low-turbulence and a high-turbulence type of engine, respectively.) The following experiments on an air-injection engine appear to show both favorable and unfavorable influences of turbulence (figure 15), low blast air pressure (45 atm.) giving low turbulence, and higher blast air pressure (60 atm.) giving higher turbulence. For cètene numbers from 60 to 42, the higher turbulence gives shorter delays than the lower turbulence; between 42 and 30, however, the influence is just the reverse. (The cross-hatched area in the figure is due to unstable ignition conditions.)

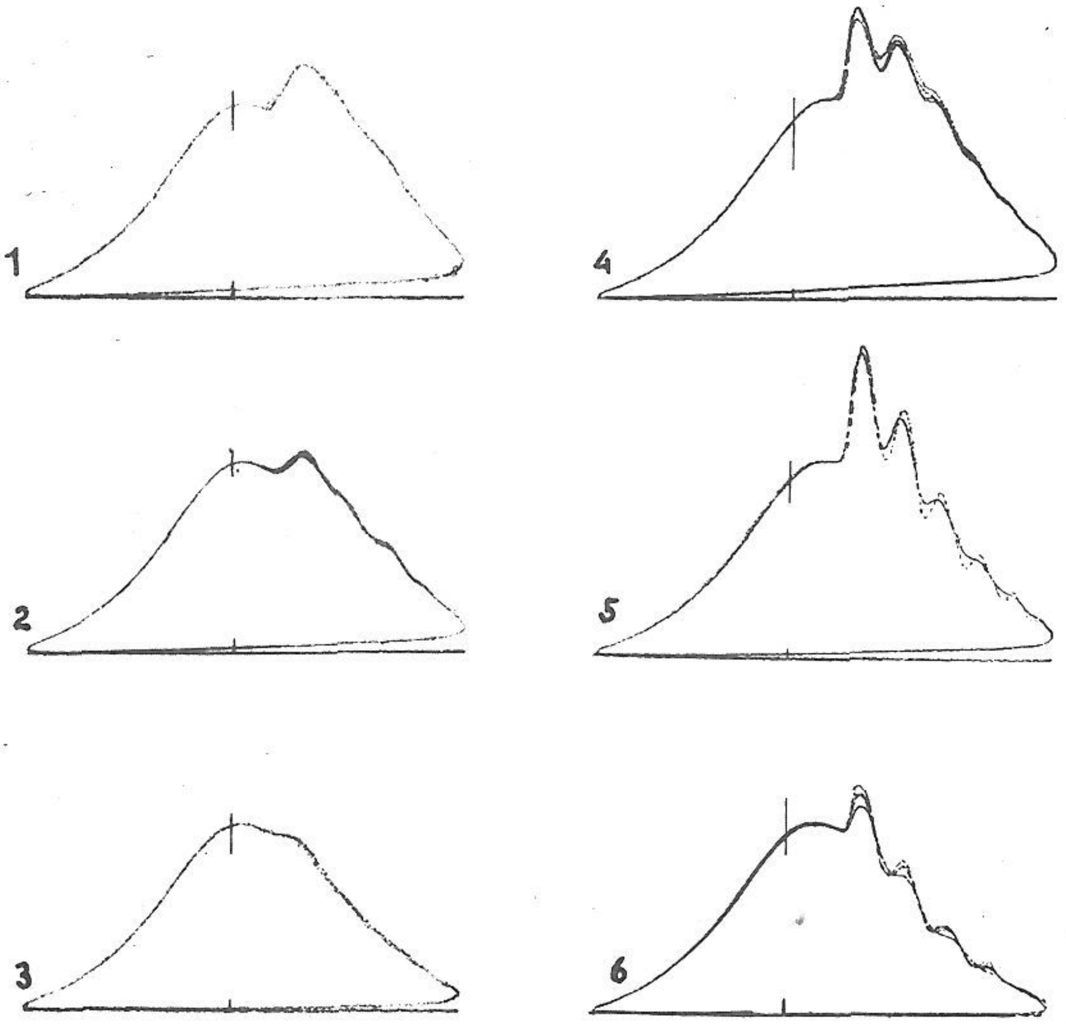


FIG. 16. Diagrams showing decrease in combustion velocity with decreasing load in air-injection engine (1, 2, 3) and high combustion velocities in solid-injection engine (4, 5, 6). The short vertical lines show the beginning of injection.

After having shown the influence of turbulence in dispersing regions rich in fuel vapor and the possible effects therefrom on ignition delay, we shall now briefly discuss some further effects on the rate of burning. Figure 16 shows how turbulence affects, through the rate of burning, the shape of the pressure diagram of a given engine (which was equipped for either air injection or solid injection) for different loads, that is, for different fuel–air ratios. It will be seen that when using air injection the rate of burning drops appreciably with the load, which is due to increasing leanness of the mixture. When using solid injection, on the other hand, and for about the same delay values, the rate of burning is better maintained when the load is decreased, which is due to the more localized fuel distribution through the charge. Of course, in the solid-injection engine also the rate of burning may eventually become insufficient, owing to the delay becoming extremely long, as shown in figure 17. One must keep in mind the hypothetical character of the above-mentioned considerations; the ways and means of direct observation, which would give better evidence, fail at present.

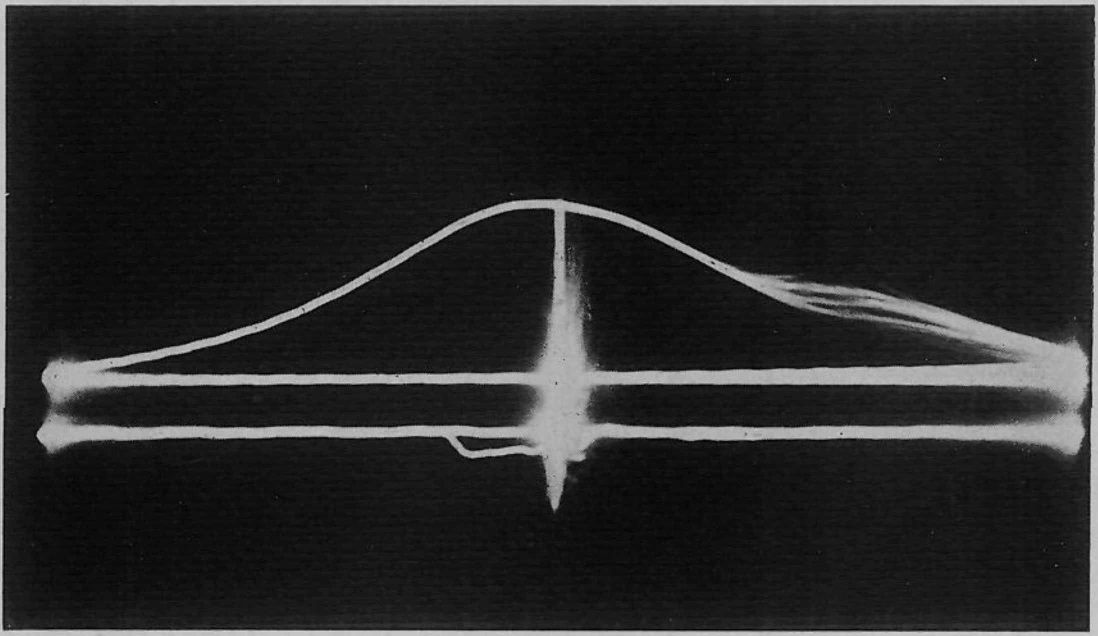


FIG. 17. Effect of extremely long delay in solid-injection engine

Such is also the case when it comes to an investigation of the chemical side of ignition. The ignition process is short (0.001 to 0.005 sec.), and as most chemical hypotheses have been derived from experiments made under conditions entirely different from the actual process, it always has to be proved over again that the conclusions hold good. The three main hypotheses are the following: (*1*) fuel molecules combine with oxygen directly (oxidation theory); (*2*) fuel molecules form unstable peroxides which decompose exothermally (peroxide theory); (*3*) fuel molecules tend to crack and become thereby abnormally sensitive to oxygen; or they do crack and oxygen reacts with the free radicals *in statu nascendi* (thermal stability theory).

Regarding the oxidation theory, there is no definite proof that fuel and oxygen do not react directly with each other, perhaps following some kind of chain reactions. True, in an oxidation test the affinity of the fuel for oxygen is smaller than the actual delay period would indicate; however, conditions in an oxidation test are entirely different from those in the actual engine process, and the former cannot be considered, therefore, to furnish definite proof of what happens in the latter. For instance, by extraction with sulfur dioxide those fractions of a lubricating oil are removed which, in the crankcase, are most prone to oxidation; yet the original oil, being lower in cetene number than the raffinate, is less prone to ignition in the combustion chamber. Here again, conditions obviously are vastly different. A further example is the fact that, although carbon disulfide is known to combine eagerly with oxygen at temperatures materially lower than prevail in the combustion chamber, yet this very carbon disulfide, when blended with a fuel, will lower its cetene number, that is, its eagerness to combine with oxygen.

As to the peroxide theory, initiated by Tausz and Schulte (6), the presence of peroxides has repeatedly been proved during flameless reaction experiments; yet exothermal decomposition of these peroxides does not seem to occur, since, as we have seen, the development of the flame in the engine hardly has the character of a phenomenon initiated by an explosive exothermal reaction such as Tausz and Schulte supposed, but is a gradual building up of a heat center. Peroxides are known as ignition inducers; the authors have experimented with organic peroxide dopes in the fuels and also with ozonides formed in various fuels by ozone treatment. These experiments have rather led to the conclusion that both peroxides and ozonides may act as carriers of active oxygen, enriching the air in the engine with small quantities of such active oxygen; this has an effect similar to either an increased temperature or an increased oxygen content, both shortening the delay. One might imagine that the tendency of a fuel to form peroxides, ozonides, or other unstable oxygen compounds would concur with its cetene number. Such a concurrence has not been confirmed by the following experimental facts: As for peroxides, tetrahydronaphthalene does develop at temperatures up to 100°C. a peroxide which is a powerful dope, yet tetrahydronaphthalene without peroxide has an extremely low cetene number. As for ozonides, experiments with fuels subjected to ozone treatment before being used in the engine showed that, without any connection with the cetene number of the original fuel, some fuels did increase in cetene number, while others did not (see table 1).

Whereas these considerations do not show that these particular peroxides or unstable oxygen compounds have a part in the process unless administered beforehand to the fuel, of course other peroxides may be generated, under engine conditions, that do influence the process. The thermal stability theory, advanced by Prof. Dr. W. J. D. van Dijck and the authors, suggests that the tendency to ignite is mainly the result of the thermal unrest of the fuel molecules. One of the starting points for this hypothesis was the high degree of agreement between two formulas, one evolved by us for the evaluation of ignition quality in the engine, the other by A. Holmes for the evaluation of gas-making properties of a gas oil. Experiments on the initial rate of cracking appeared to sustain the hypothesis that a higher ignition quality corresponds to a high initial rate of cracking. Isoöctane was an exception in this respect, in that it showed a very high initial rate of cracking notwithstanding its low ignition quality; this could be explained by means of Rice's observation on the relative inactivity of the isobutyl group, which would be the radical split off by isoöctane. Later experiments in the authors' laboratory with compression of hydrocarbon–nitrogen mixtures in an engine (with the exclusion of oxygen, in order to prevent oxidation) have shown, however, that at temperatures corresponding to those in the engine, little or no decomposition takes place, unless some oxygen is present. This seems to strengthen that part of the hypothesis mentioned above which states that "fuel molecules tend to crack and become therefore abnormally sensitive to oxygen."

TABLE 1

Effect of ozonization upon the cetene number of a fuel

FUEL	CETENE NUMBERS	
	Before ozonizing	After ozonizing
A	51	70
B	49	52
C	44	70
D	44	44
E	40	46
F	40	40

So far no more information has been obtained, and the problem of the chemistry of self-ignition in the Diesel engine is still unsolved. Coöperation with the investigators of gasoline detonation appears to be indicated. Of such coöperation the compression experiments mentioned above are an example; the close relationship between cetene and octane numbers is also well known.

C. Combustion stages

In principle, four combustion stages may be distinguished, as seen from figure 18, which shows, by means of a schematic pressure diagram, the following combustion stages: (*1*) delay; (*2*) inflammation of the fuel present at that moment; (*3*) injection-controlled combustion;—burning of fuel injected into the flame; and (*4*) after-burning of all the fuel that has not yet found its oxygen or of which the burning rate had been too low (weak mixture, chilling).

Comparison with the ideal diagram, also given in figure 18, where every bit of fuel would be burned immediately as it enters the combustion chamber, reveals that there are mainly two independent causes for combustion lagging behind: namely, the delay and the after-burning, the former being caused through deficiency of reaction velocity, the latter mainly through deficiency of mixing. All variations on the schematic diagram are met with in practice.

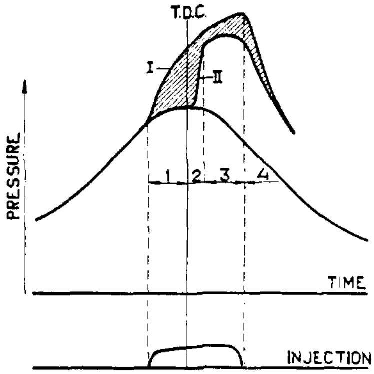


FIG. 18. Actual and ideal pressure diagrams

D. Physical and chemical aspects of combustion

1. Physical aspects

The purpose of combustion in the engine is the development of pressure, and the characteristics of the pressure diagram form the principal physical aspect of combustion. Two requirements should be taken into account: (*1*) The development of pressure should occur as near the top dead center position of the piston as possible, having due regard to a reasonable maximum pressure. (*2*) The shape of the combustion pressure curve should be as smooth as possible, so as not to cause vibrations of the engine parts ("Diesel knock"). The control of the development of pressure would be entirely in the hands of the designer if the ideal diagram of figure 18 could be realized, the maximum pressure being controlled by suitable timing of the injection. Actually this is still the method of controlling the maximum pressure, but as the course of combustion depends *inter alia* on the type of fuel (viscosity, ignition quality, volatility) the maximum pressure may also vary with the fuel used, e.g., to the extent of one to five atmospheres.

In order to develop the pressure as near as possible to the top dead center, after-burning must be reduced to a minimum. It may be said that wherever fuel and air have been mixed in a proper ratio so that a high flame temperature is reached, the reaction velocity is high enough to satisfy the requirements as to restriction of after-burning for the highest engine speeds. The causes of after-burning, which have been mentioned above, may be summed up as follows:

(*1*) *Inefficient mixing, in particular overrichness of parts of the charge.* This tends of course to become the worse the greater the quantity of fuel, but it depends fundamentally on engine design. The influence of fuel quantity (load, brake mean effective pressure) is seen in figure 19, showing how combustion becomes more and more prolonged with greater loads. Consequently, the specific fuel consumption increases with the load. This is clearly shown by curves of fuel consumption per indicated horsepower-hour, i.e., per unit of work done in the cylinder. (The consumption per brake horsepower-hour increases also for lower loads, but this is due to the decreasing mechanical efficiency (cf. figure 20) and not so much to after-burning.)

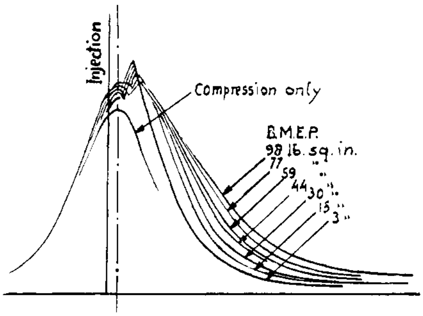


FIG. 19

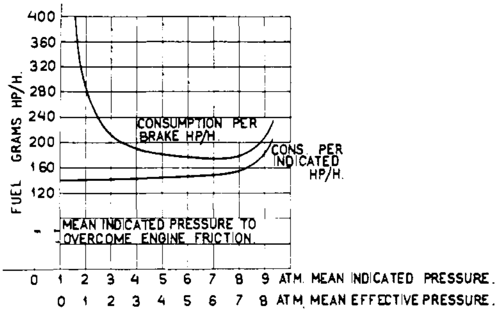


FIG. 20

FIG. 19. Diagram showing increased after-burning with increased load (Dicksee)
FIG. 20. Typical fuel consumption curves

(*2*) *Deposits of liquid fuel on the walls of the combustion chamber.* This phenomenon is illustrated very well in figure 21, showing a photograph from N. A. C. A. report No. 545 by Rothrock and Waldron (4). At the spots where the fuel jets strike the walls, flames are seen to linger after the main combustion is finished. This happened especially in the low load

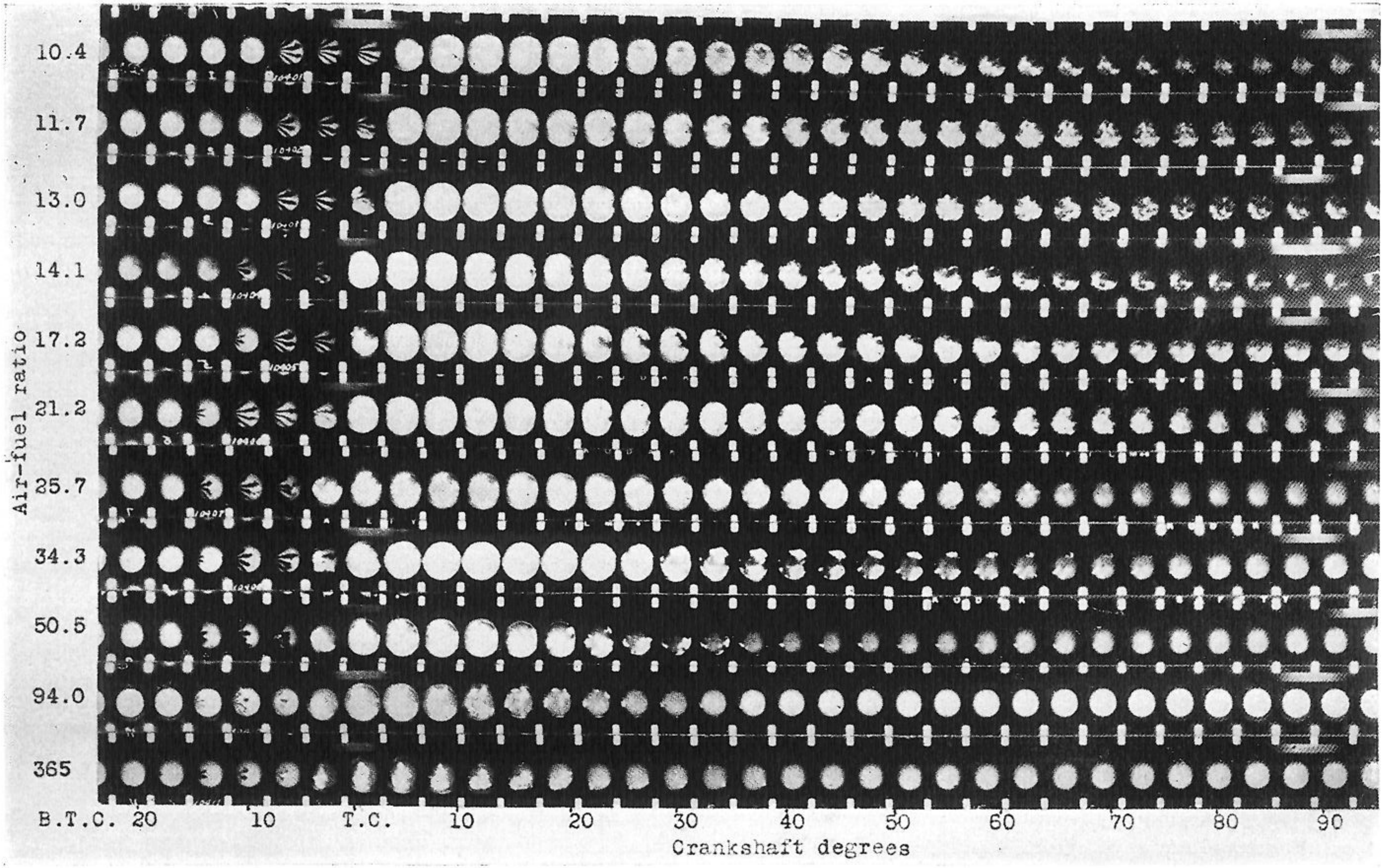


FIG. 21. Photographs showing after-burning due to fuel deposits on combustion chamber walls at air–fuel ratio between 94.0 and 25.7 (N. A. C. A.).

zone (air–fuel ratio 25.7 to 94). Under higher loads the phenomenon became less clear, since then there were more causes provoking after-burning; with extremely small fuel quantities the sprays did not reach far enough to touch the walls. In practice, similar zones of joint load condition and after-burning due to fuel deposits may exist; it depends on numerous circumstances whether the trouble will be bad at all and if so, at which load. It usually will be more pronounced at the lower end of the load range, owing to poorer heat conditions and to longer delays, and especially owing to the low rate of evaporation. It is, however, certain that with heavy residual fuels it persists often over the entire load range and results then in a higher overall fuel consumption and a lower maximum power.

(*3*) *Long delays during which the fuel mixture has become lean throughout, resulting in low flame temperatures* (cf. figure 17).

Further there are still a few chemical causes:

(*4*) *Dissociation of the flame gases, especially at high loads, reducing the maximum flame temperature.* The degree to which this phenomenon participates in causing after-burning may be estimated as small in comparison with the phenomena mentioned above.

(*5*) *Chilling of the flame near cool walls.* This will mostly accompany the second and third causes mentioned and would probably be quantitatively far less serious, but for the secondary phenomenon,—that of leaving partially burnt products, which may accumulate in the engine.

Of course, on first inspection of an engine and of its diagrams, it is not obvious which cause of after-burning prevails. Often experiments with fuels of different types may throw more light on the matter.

From the foregoing it is evident that a fuel of low viscosity, high volatility, and high ignition quality will ignite easily but will tend to form localized overrich mixtures. High viscosity, low volatility, and low ignition quality will, on the other hand, cause a fuel to aggravate wall deposits and to form well-distributed mixtures, which may, owing to this good distribution, become too weak for rapid burning. The effect of a change of fuel on the efficiency of combustion may thus give some indication as to the most obvious cause for after-burning. Quite often, though, the various causes are so nicely balanced that the change of fuel has little effect; this does not imply at all that the engine is perfect. An analysis of the composition of the partially burnt products may then be useful.

The shape of the pressure diagram is evidently greatly influenced by the delay. The delay, followed by the subsequent inflammation, tends to give rise to one or two kinks in the pressure rise, where the rate of the pressure rise may change so abruptly as to cause vibration (audible as Diesel knock) and increased stresses in engine parts. In a given engine the knock will usually increase with the delay, then decrease again (cf. figure 22).

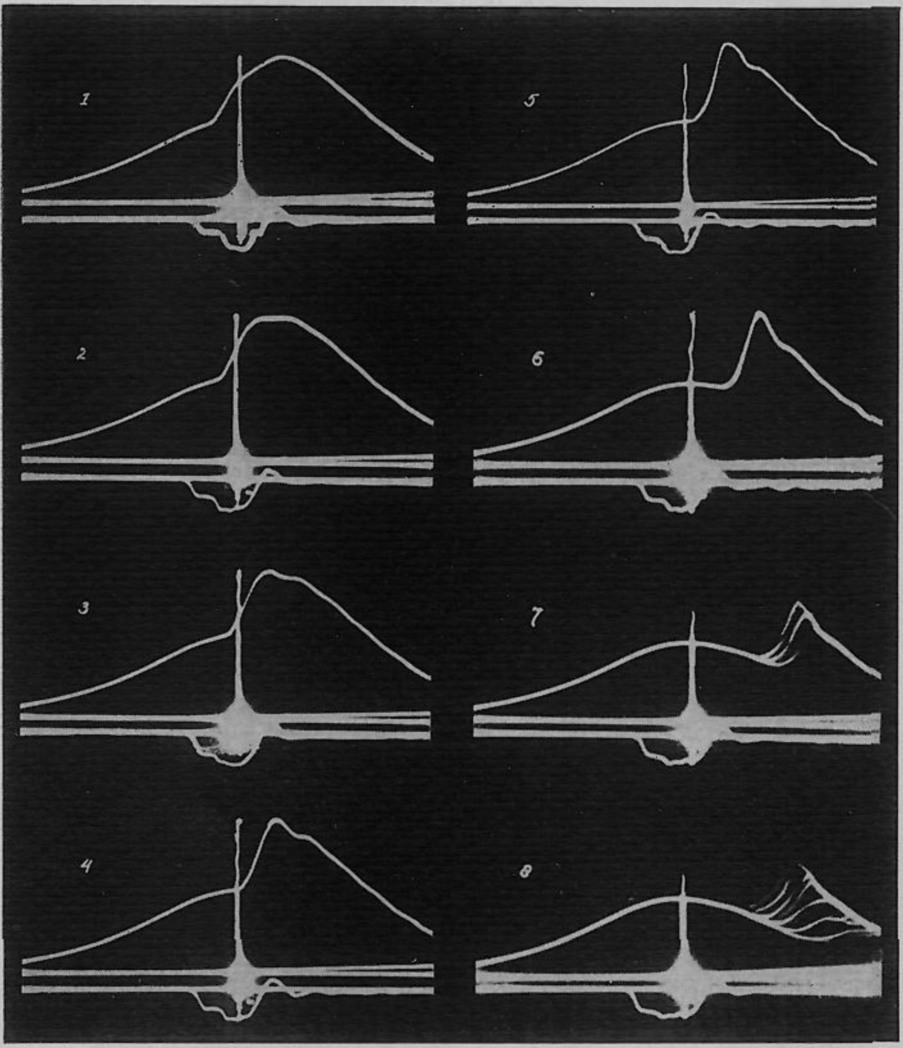


FIG. 22. Series of diagrams with increasing delays (1 to 8)

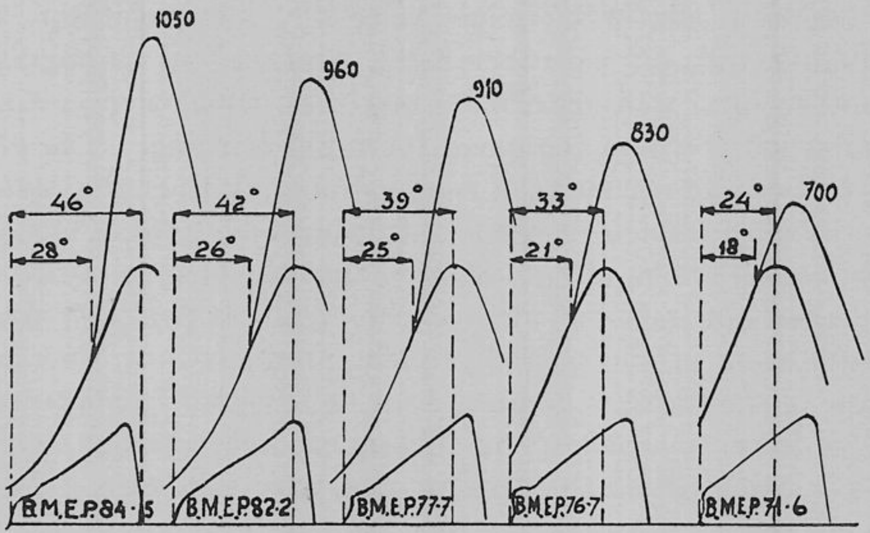


FIG. 23. Smooth pressure rise notwithstanding long delays

The increase is due to the increase of the fuel quantities liable to explode with the delay and to the steadily improving distribution of the mixture; the decrease is due partly to the final weakening of the mixture which always occurs, and partly to the rapidly increasing volume of the combustion space. The state of turbulence during the inflammation period appears to have much to do with the rate of pressure rise, but whether this is due to improved mixing or to more rapid flame propagation cannot be made out. What the rate of pressure rise will be for a certain delay depends entirely on engine type, load, and speed (cf. figure 16). Thus some engines may have either short or long delays and yet remain smooth (cf. figure 23), whereas others will have a much more pronounced tendency to knock (cf. figures 13, 14). Therefore, although generally speaking a fuel of high ignition quality may decrease objectionable knocking in many engines in comparison to a fuel of low ignition quality, in other cases the effect may be less pronounced, and in still others neither of them will knock in an objectionable way.

2. Chemical aspects

The chemistry of the complex combustion occurring in a Diesel engine is far from being entirely known. The following material, which includes much of a paper presented last year (1), may be advanced as a crude outline of the general situation. Combustion of hydrocarbons may be, in principle, a direct oxidation (for instance, hydroxylation according to Bone and Wheeler) or a decomposition followed by oxidation of the destruction products (Aufhäuser's theory of destructive combustion). Haslam and Russell (2) came to the practical conclusion that generally both types of processes will occur side by side. When the fuel has been vaporized and well mixed with air before burning, the first type of reaction is most likely to develop, but when fuel vapor is suddenly exposed to high temperatures before mixing, the second type of reaction prevails. The conditions for the first type of reaction are met with in dry mixtures in gasoline engines, but in the Diesel engines there appears to be no doubt as to the conditions being more favorable for destructive combustion; the liquid fuel drops surrounded by flames form as many centers of vapor development, whereas the mixing process comes only afterwards. The characteristics of the direct oxidation process in mixtures of normal air–fuel ratio are as follows: blue flame (carbon dioxide and carbon monoxide radiation), no tendency to soot either from overrichness or from chilling, but production of carbon monoxide, aldehydes, and acids under chilling conditions. Characteristics of the destructive combustion process are as follows: radiant yellow-white flame ($C{=}C$ or black body radiation), and tendency to soot when locally overrich and when chilled. Under overrich conditions carbon monoxide and hydrogen are formed by either process.

The evidence given by photographs of the flames, by exhaust color on overload, and by contamination of lubrication oil by soot, all point to destructive combustion as being predominant. Acrid exhaust odors, formation of carbon monoxide at low loads (see figure 24), and varnish-like deposits on pistons and in lubricating oil point to direct oxidation as part of the process, and are most noticeable under light loads and with long delays. This proves without further detail that actually both processes go on side by side.

Chilling, due to cool walls, and dissociation (mainly of carbon dioxide) at high temperatures have been briefly mentioned as chemical causes of after-burning. When it is considered that a severe degree of contamination may be caused by incomplete combustion, due to chilling, of only a very small percentage of the fuel, it is obvious that the incomplete combustion of so little fuel will not materially affect the efficiency of the cycle.

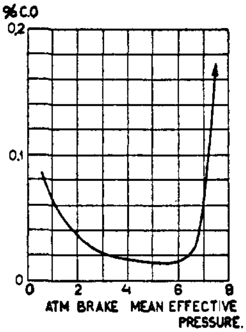


FIG. 24. Carbon monoxide content of exhaust gases

From the foregoing it is seen that analysis of the products of incomplete combustion may be a guide towards a better understanding of the Diesel process. From a practical point of view these products hold one of the biggest problems in Diesel engine development.

Acrid smell and blue fumes from unburnt fuel are intolerable in road vehicles. It has been shown in a practical way that engine design may overcome them by allowing no fuel in the liquid state to come into contact with cool walls. Carbon monoxide is still more intolerable, but as the carbon monoxide content in Diesel exhaust gases is much lower than in gasoline exhaust gases, and as the latter generally are unobjectionable from a hygienic point of view, this is still more true in the case of the Diesel engine. A further effect of liquid fuel deposits may be carbonization, especially with residual fuels, leading to piston and valve troubles. Varnish-like deposits in quantities that will cause sticking of the piston rings within a short time are seldom encountered, but their influence at continuous operation may be severe enough, even if this influence be only the forming of binding material in crankcase sludge.

Stationary and marine engines usually have to be rated, on account of heat stresses, to low outputs, so that their exhausts may always be clear. In the case of vehicle engines, maximum output being required, the formation of soot limits the output, not only with regard to atmospheric conditions in the streets, but also because of the blotting paper action of the soot in drying up the cylinder walls, thus leading to piston troubles. Soot, furthermore, constitutes the greater part of the lubricating oil contamination.

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DISCUSSION[1]

A. M. Rothrock: Mr. Boerlage and Mr. Broeze are to be congratulated on their comprehensive survey of the combustion process in the Diesel engine. They have presented a clear analysis of their own and other researches. Papers presenting such an analysis are particularly valuable in that they permit general conclusions to be drawn from a mass of research and so prevent us from drawing erroneous conclusions from single researches.

In the third paragraph of the paper the authors state that the heterogeneity of the mixture in the engine permits the load to be varied down to zero solely by regulating the fuel input. Although we know, as shown by figure 21, that stratification of the charge does occur at low loads, we cannot be sure that in the Diesel engine such stratification is necessary. Gaseous combustion tests have shown that as the temperature of the gas is increased the limits of inflammability are also increased. With the ambient air at a temperature sufficient to cause the fuel to ignite in 0.001 sec. or less the number of ignition sources is infinite, so that each fuel droplet on vaporizing may act entirely independently of the surrounding

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[1] Received September 19, 1937.

droplets in the case of extremely lean but uniform mixtures. I also question that the excellent economy of the Diesel engine at part loads is caused by the fact that the fuel only is regulated; rather the economy at light loads is the economy inherent in the high compression ratio used with the Diesel, and at full load the good economy is really poor economy if based on what the cycle is capable of delivering providing all the fuel is burned early in the expansion stroke.

Our inability so far to provide means for efficiently burning a quantity of fuel corresponding to the full amount of oxygen available in the cylinder prevents us from obtaining the economy inherent in the high compression ratio of the Diesel engine, but recent researches show that the power output may very closely, if not actually, equal the power output of a spark-ignition engine. With a normally aspirated engine, as shown in figure 14 of the paper presented by Dr. Selden and myself, an indicated mean effective pressure of 163 lb. per square inch was obtained. This value corresponds to that obtained at a compression ratio of between 7.5 and 8.5 on a spark-ignition engine.

The authors' remarks on the slowness of fuel vapor diffusion are particularly important. It seems to me that this physical fact presents the chief obstacle to be overcome in the development of the high-speed Diesel. Also I agree with them fully in their statement that increased atomization will not necessarily improve engine performance. Their discussion on microstructure and macrostructure is particularly worth while. However, I would sooner use the terms "atomization" and "vaporization" than "microstructure," and the term "distribution" rather than "macrostructure."

In the photographic researches on combustion conducted by the National Advisory Committee for Aeronautics we have never obtained any evidence of the high air velocities centrifuging the fuel to the outside of the chamber. Our researches indicate that it is extremely difficult to obtain a good mixture either by air flow alone or by nozzle design alone, but that the two means must supplement each other if the best performance is to be obtained. I also question the statement that greater flexibility is obtained with the use of air flow. We have idled an engine with a quiescent combustion chamber at 200 R.P.M. Our tests indicate that the difficulty in idling an engine without air flow can be overcome through the correct design of the injection system. Air flow definitely permits greater power output and lower fuel consumption to be obtained, particularly at high speeds.

In connection with the authors' statement that forced air movement may be much more intense than induced air movement, I would like to add that in our tests on the N. A. C. A. combustion apparatus we have found that the induced air movement obtained unintentionally may be such as almost to destroy the forced air movement. Consequently particular care must be taken in the engine design so that the induced air movement will not oppose the forced air movement.

Our tests indicate that the penetration of the spray is probably less dependent on the atomization than on the closeness of the drops in the atomized jet. As was shown by Kuehn (Atomization of Liquid Fuels, Natl. Advisory Comm. Aeronaut. Tech. Mem. No. 331 (1935); translated from *Der Motorwagen*, December 10, 1934, January 20, 1935, Feb. 10, 1935), even the largest drops would not penetrate through the air in the combustion chamber more than a fraction of an inch unless they were sufficiently close to entrain the air within the spray.

It is questionable whether or not we should place so much emphasis on flame. Whether or not a flame nucleus is formed depends on our definition of flame. Webster's dictionary defines flame as "a body of burning gas or vapor." In their paper I presume that Mr. Boerlage and Mr. Broeze are referring to a luminous flame nucleus. If heat is being generated through the chemical reaction in the combustion chamber, the mixture is burning and we have combustion, even though we do not necessarily have luminous flame. In any case the luminosity is simply an indication of the temperature and constituents of the gas at the instant under consideration and has no direct relationship to the rate of pressure rise in the combustion chamber. In our own tests (A. M. Rothrock and C. D. Waldron: Natl. Advisory Comm. Aeronaut. Tech. Rept. No. 525 (1935)) we have recorded appreciable pressure rise before recording luminescence. But it must be further remembered that flame which is visible to the eye may or may not be recorded on the photographic film used in the tests, and that certain photographic films will record radiations that are not visible to the eye. Along this same line of discussion, the recent researches of Wilson and Rose (S. A. E. Journal **41,** 343–8 (1937)) offer additional information on the relationship between the start of radiation from the combustible mixture and the start of combustion pressure rise. When the motion pictures obtained by Rothrock and Waldron (see reference above) are projected they show various luminous combustion nuclei appearing and disappearing when the start of injection was 60° before top center. With the later injection starts, all the visible nucleii spread or merged into large combustion areas. I think a too detailed discussion of the process by which these nucleii are formed should wait until we have more information than is available at present.

The authors' statement that a mixture strength of 160 per cent of the theoretical autoignited at the lowest compression ratio is particularly interesting. This fact may have a direct bearing on the long after-burning period in the Diesel engine by requiring an overrich mixture in parts of the combustion chamber to initiate combustion.