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FUNDAMENTALS
OF
DIESEL ENGINES

ALCO-GE DIESEL-ELECTRIC LOCOMOTIVE SCHOOL
INSTRUCTION SERIES
No. 899

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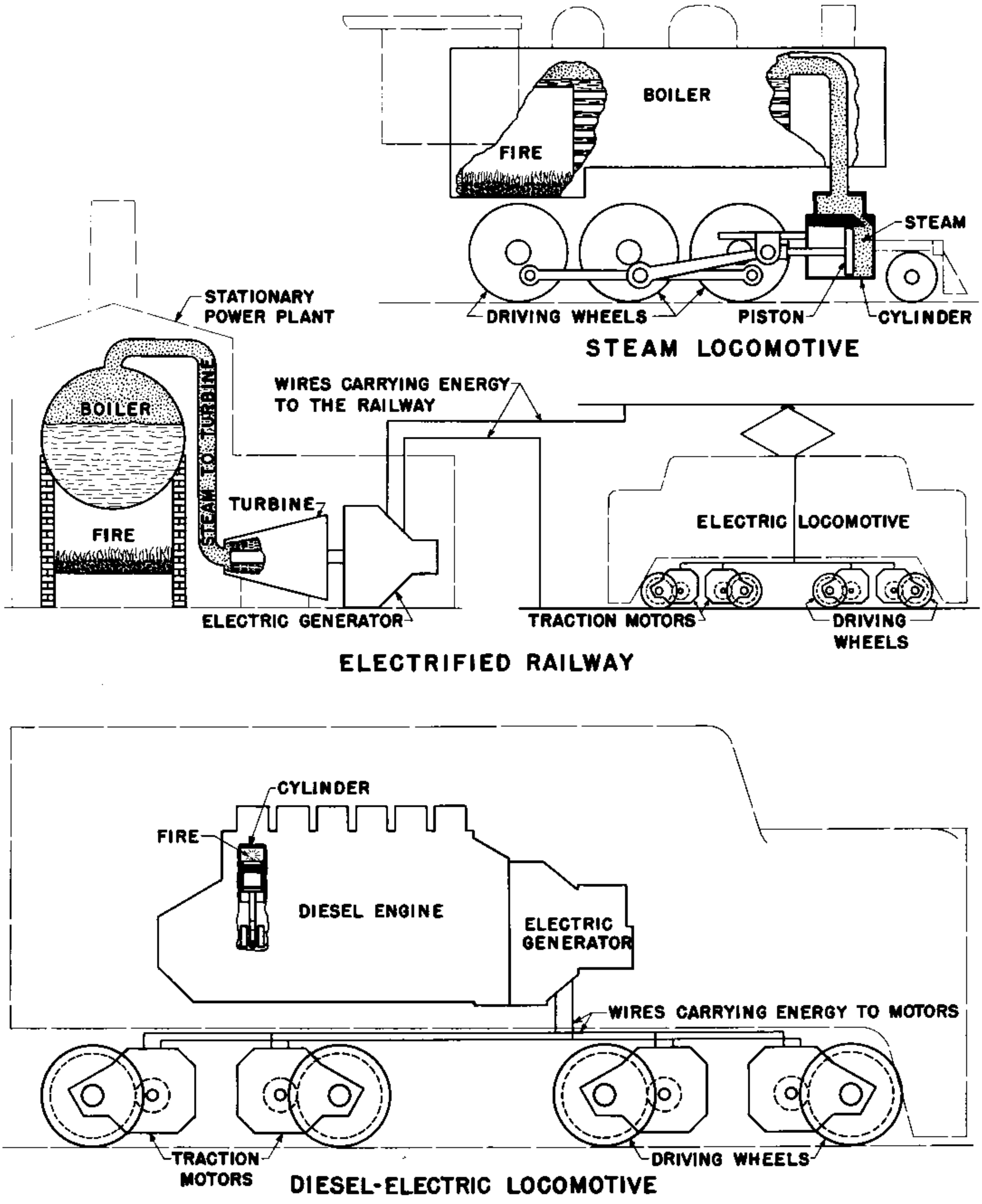
OF
DIESEL ENGINES



STEAM LOCOMOTIVE

ELECTRIFIED RAILWAY

DIESEL-ELECTRIC LOCOMOTIVE

FIG. I

FUNDAMENTALS OF DIESEL ENGINES

Any locomotive requires a source of energy to operate it. With the exception of a few electric locomotives using electricity generated by waterpower or battery, locomotives obtain their energy from the combustion of fuel. Whatever the fuel used, oil, coal, wood or some other fuel, its combustion generates heat energy. This heat energy must then be converted to mechanical energy to propel the locomotive.

In steam locomotives the fuel is burned in a boiler, and the heat energy converts the water to steam. The steam is transmitted through pipes to the cylinders, which are directly connected to the driving wheels through pistons, crossheads, connecting rods and crank pins. The pressure of the steam pushes the pistons in and out of the cylinders to generate mechanical energy to propel the locomotive.

On electrified railroads the fuel is burned in the boilers of stationary power plants to generate steam which is used to turn electric generators. The energy thus derived is transmitted as electric current through wires to the locomotives along the railroad. In the locomotive, traction motors convert this electrical energy to mechanical energy to propel the locomotive.

The Diesel-electric locomotive, like the steam locomotive, obtains its energy from fuel burned within the locomotive. It differs, though, in that it burns the fuel in the engine cylinders instead of in a separate firebox. It is the pressure of the gases heated by the burning fuel, instead of steam, which pushes the pistons to produce the mechanical energy. The intermediate substance, steam, and its attendant apparatus, boiler, firebox and steam pipes, are eliminated.

It is impractical to connect the pistons of the Diesel engine directly to the locomotive driving wheels because the Diesel engine cannot start under load nor operate effectively at extremely low speeds. Therefore, the engine drives a generator which generates electrical energy. This energy turns traction motors that are geared to the driving axles as in the locomotives of electrified railroads. (Fig. 1) Thus the engine may turn at high speeds while the locomotive is running very slowly.

INTERNAL COMBUSTION ENGINES COMPARED

The Diesel engine is one form of internal combustion engine. Another form which may be more familiar to many readers is the gasoline engine. Consequently, an examination of the principal similarities and differences between these engines will prove helpful.

Either a gasoline or Diesel engine must do the following five things in order to produce a power impulse:

1. Fill the cylinder with air
2. Compress the air in the space between the piston and cylinder head
3. Introduce fuel into the cylinder and mix it thoroughly with the air
4. Ignite and burn the fuel
5. Discharge from the cylinder the gases resulting from combustion.

This cycle of operations may be performed in four strokes of the piston (two inward and two outward) or in only two (one in and one out). If four strokes are used to complete the cycle it is known as a four-stroke-cycle. If only two strokes are used it is a two-stroke-cycle. Most gasoline engines and all Alco Diesel engines for locomotive service operate on four-stroke-cycles. Consequently this discussion will be confined to the four-stroke-cycles.

The cycles of operation of gasoline and Diesel engines, even though both use four strokes, differ in respect to:

1. The time at which fuel is introduced into the cylinder
2. The method of ignition
3. The manner in which the fuel burns.

To show these differences clearly it will be convenient to use diagrams, called indicator diagrams or indicator cards, which picture what happens inside a cylinder of an engine. On these diagrams (Figs. 2 and 3) the horizontal dimension represents the volume of space between the cylinder head and the crown of the piston. This may be thought of as being represented by the distance from the cylinder head to the piston. This is exactly true for that part of the diagram representing the stroke of the piston and in most Diesel engines it is approximately true for that part representing the clearance space. The clearance space or clearance volume is the volume remaining between piston and cylinder head when the piston is as close to the head as it gets in its stroke.

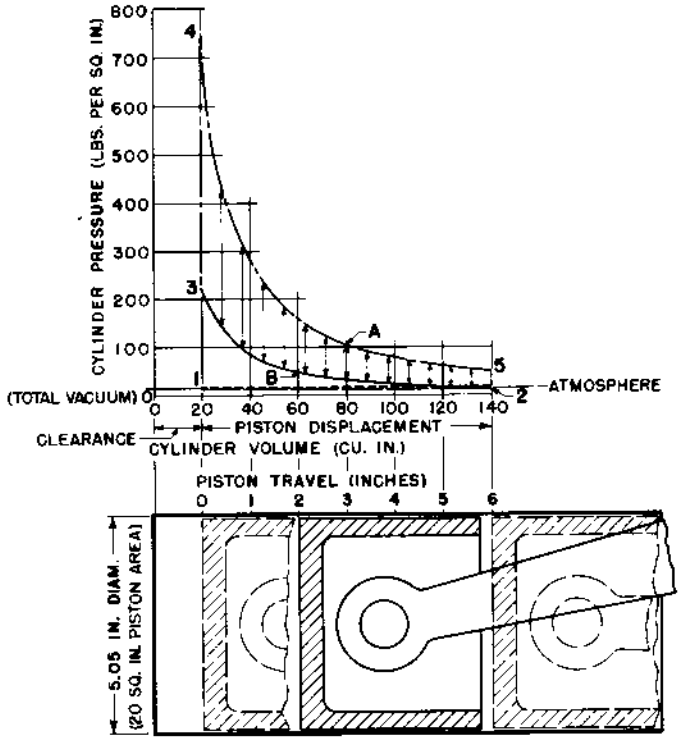
The vertical dimension represents the pressure of air and combustion gases in the cylinder. Thus on Fig. 2 at point "A" we find that when the piston is 3 inches from the top dead center on one of its strokes the pressure in the cylinder is slightly over 100 pounds per square inch. At "B" we find that when it is 2 inches from top dead center on another stroke the pressure is 50 pounds per square inch. Similarly any other point on the diagram represents a particular position of the piston on a particular stroke and the corresponding pressure existing in the cylinder.

THE OTTO CYCLE

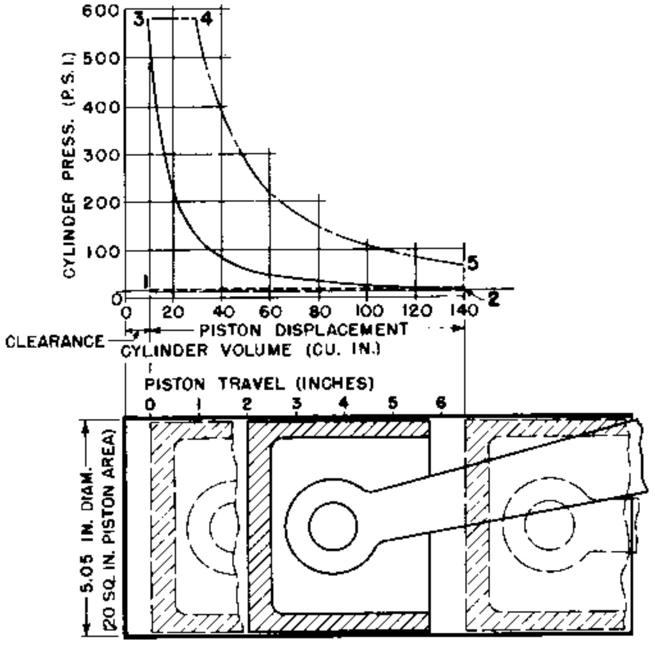
The theoretical cycle of operation of the common gasoline engine, named the Otto cycle after the maker of the first engine to operate on this cycle, is pictured in Fig. 2. The pressure scale at the left of the diagram shows pressures in pounds per square inch absolute, i.e. above the pressure of an absolute vacuum. The pressure of the atmosphere outside the cylinder is represented by the thin horizontal line at

14.7 psi (pounds per square inch) on the scale.

The line from point 1 to point 2, drawn like this — — — — —, represents the suction or intake stroke of the piston. The piston is moving outward drawing in a mixture of air and fuel. Theoretically the pressure in the cylinder during this stroke would be that of the atmosphere outside, and should be thus shown on a theoretical diagram. This is also true of the exhaust stroke. But if the lines representing both of these strokes are shown at atmospheric pressure they appear as one. Actually there is some resistance to the flow of the air or exhaust gases through the valves, so the pressure within the cylinder is lower than that of the atmosphere during the intake stroke and higher during the exhaust stroke. In order to show the two strokes distinctly this actual difference in pressure has been shown on Figs. 2 and 3, although the remainder of these diagrams represent theoretical conditions only.



OTTO CYCLE
FIG. 2



DIESEL CYCLE
FIG. 3

The solid line from point 2 to point 3 represents the compression stroke, during which the piston moves inward and compresses the air-fuel mixture in the cylinder.

At about the time the piston reaches the end of the compression stroke the fuel is ignited by an electric spark, and it burns almost instantaneously. The fuel in this cycle burns so rapidly that the piston moves very little during the period of combustion. It is said to burn at constant volume.

When a fuel burns and heats the surrounding gases they must either expand or undergo a rise in pressure. Since in the Otto cycle there is no opportunity for the gases to expand during combustion their pressure increases greatly as shown by the line (——-——-——-—) from 3 to 4. By the time combustion is completed the piston starts on its second outward stroke, now under the high pressure of the heated gases. This is the power stroke. As the gases expand, their pressure decreases so that the mean, or average, pressure acting on the piston through its stroke is much less than the maximum pressure resulting from combustion at the stroke's beginning. The end of this stroke is at 5. The sudden drop in pressure here is due to the opening of the exhaust valve and consequent passage of the gases from the cylinder to the atmosphere.

The total pressure acting against the crown of the piston is not all effective in producing power. Some must be used to store energy in the flywheel to force the piston back and forth on the other three strokes. On those strokes movement of the piston is opposed by the differences between the pressures existing in the cylinder and atmospheric pressure. The difference between the average pressure pushing the piston outward on the power stroke and the sum of those opposing its movement on the other three strokes is called the mean effective pressure, abbreviated m.e.p. Since the pressures opposing piston movement on the exhaust and intake strokes are very small, the m.e.p. is only slightly less than the average difference between the pressures on the power and compression strokes, shown by the double-ended arrows on Fig. 2

The exhaust stroke is represented by the line(--------------------)from 5 to 1. At 1 the cycle begins again with another intake stroke.

THE THEORETICAL DIESEL CYCLE

The true theoretical Diesel cycle, named for Dr. Rudolph Diesel, its inventor, is shown in Fig. 3. The various operations in this cycle are represented by the same numbers and line symbols used in Fig. 2 for the corresponding operations in the Otto cycle. The pressures shown in these diagrams are typical of the cycles represented, but do not represent any particular engines.

As air is compressed its temperature tends to rise. This accounts for the heating of the cylinder of the hand tire pump when one pumps up a tire by the roadside. The principle of heating air by compression was used by some aboriginal tribes to light fires. They placed a bit of tinder in the bottom of a hollow tube and then drove a closely fitting plunger into the tube by a sharp blow of the hand. The air which was trapped and compressed by the plunger was heated. The temperature inside the tube rose so high that the tinder was ignited.

Similar action takes place inside the internal combustion engine cylinder. As air is compressed by the piston its temperature rises. This fact limits the allowable compression pressures in Otto cycle engines. The fuel is already present in the cylinder during compression and would be ignited before the piston reached dead center if compression raised the temperature high enough.

The Diesel engine does not introduce fuel into the cylinder until compression is completed, or nearly so. Consequently, it is practicable to compress the air so highly that its temperature rises above that required to ignite the fuel. In fact, that is the best-known characteristic of the Diesel engine. It ignites fuel by the heat of compression without a spark or other external source of heat. The Otto cycle engine requires an electric spark for ignition.

The difference in typical compression pressures is clearly shown by comparison of the positions of point 3 on Figs. 2 and 3.

Fuel is always burned in the Otto cycle very rapidly while the piston is virtually stationary at the end of its stroke, so the cylinder volume does not change during combustion and the pressure rises tremendously (Fig. 2). In the true Diesel cycle the fuel is injected at a controlled rate so that it burns more slowly. The piston moves outward, increasing cylinder volume, during combustion. If the time combustion started and its rate were properly controlled, the expansion of the gases behind the piston would just compensate for the rise in temperature and the pressure would neither rise nor fall during combustion. Fig. 3 shows constant pressure combustion between points 3 and 4.

COMPRESSION RATIO

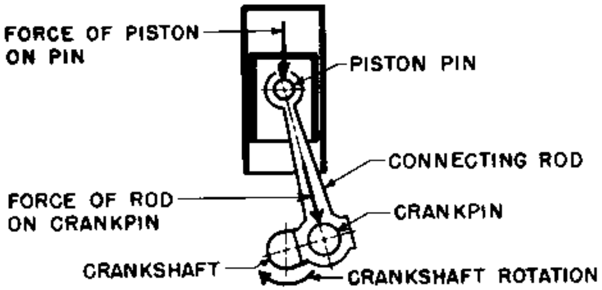
One of the early types of internal combustion engines sucked air and fuel into the cylinder during the first part of the outward stroke of the piston and then ignited and burned the fuel at about midstroke. There was no compression of air before ignition. This engine was so inefficient that it was not used long. Both theory and practical experience show that high compression ratios contribute to high efficiency. The compression ratio is the displacement volume (area of piston x stroke) plus the clearance volume (volume remaining between piston and cylinder head at the inmost end of the stroke) divided by the clearance volume. If we represent the displacement volume by the symbol V and the clearance volume by v, the compression ratio= $\frac{V+v}{v}$.

The higher the compression ratio of the cylinder, the more the pressure will be raised during the compression stroke. Note that the clearance space in the Diesel engine (Fig. 3) is much smaller than that of the Otto engine (Fig. 2) having a cylinder of the same size. It is for this reason that the compression pressure (Point 3) is so much higher in the Diesel engine than it is in the Otto engine. It is this high compression ratio, which may only be used when the fuel is not present during compression, that gives the Diesel engine its high efficiency.

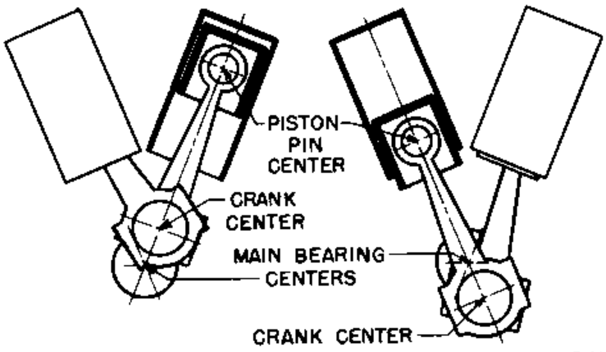
ACTUAL CYCLE OF DIESEL ENGINES

Before discussing the cycle actually used in nearly all modern Diesel engines, two more terms will be explained. Up to this point the piston has been referred to as moving inward and outward in the piston. Most Diesel engines, however, have their cylinders set more or less vertically with the open ends down. Consequently the outward strokes of their pistons are downward and the inward strokes are upward. Through the rest of this discussion the directions up or down instead of in or out will therefore be used. When top of the cylinders is mentioned it will mean the closed end.

In order to convert the reciprocating motion of the piston to rotating motion to turn generators and other machinery the pistons are connected by rods to the cranks of a crankshaft (Fig. 4, a). When the center of the crank to which a given piston is connected lies exactly in line with the crankshaft bearing centers and the piston pin centers as seen from the end of the engine (Fig. 4, b and c) no amount of thrust on the piston will turn the shaft. Consequently the piston is said to be on dead center at these positions.



(a) CONVERSION OF PISTON MOTION TO ROTATION OF CRANKSHAFT



(b) RIGHT PISTON ON TOP DEAD CENTER (c) LEFT PISTON ON BOTTOM DEAD CENTER

FIG. 4

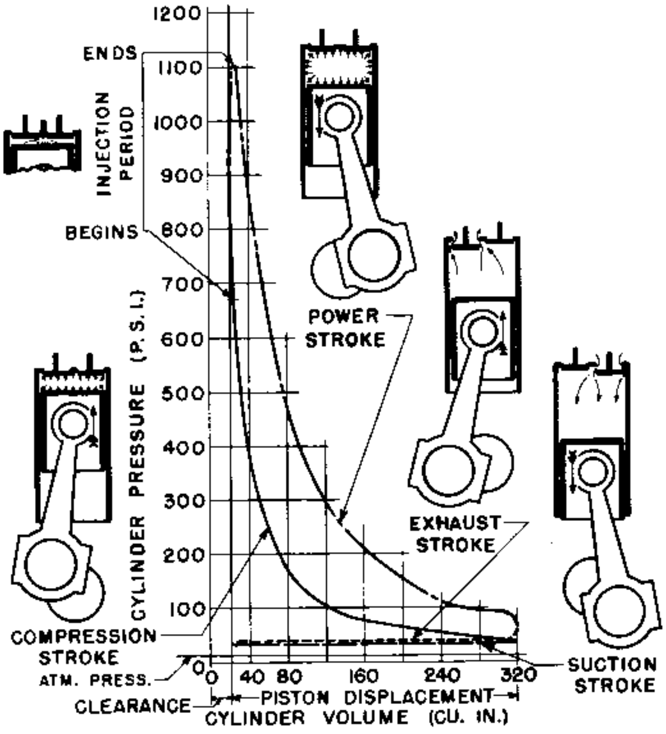
As the piston approaches dead center its motion slows to a stop and at the moment the crank passes the dead center position the piston is stationary. Then, as the crank continues its rotation, the piston begins its stroke in the opposite direction.

Only in engines which inject the fuel oil into the cylinder with a blast of highly compressed air can the true Diesel cycle, with its combustion at constant pressure, be approximately carried out. As such engines, known as air injection engines, have been constructed up to the present, they can operate at low speeds only and are necessarily large and heavy. In order to obtain the necessary power in the available space for a locomotive Diesel, the engine must run at higher speed. In such engines the fuel must be injected alone, without an air blast. This is known as solid injection.

Solid injection engines actually operate on a mixed cycle in which most of the combustion takes place at constant volume, as in the Otto cycle, and only a small portion of the combustion takes place at constant pressure. The actual cycle of operations of a typical four-stroke-cycle, solid injection engine is shown in Fig. 5.

It will be noticed that in Fig. 5 the sharp corners and points of the previous diagrams have disappeared. These were shown in the previous diagrams because they pictured theoretical conditions. The physical limitations of actual engines produce more gradual changes from one operation to another, so that on the diagram the sharp demarcations between operations are not present. The time required for valves to open and shut, for combustion to get under way and for air and gases to start or stop motion are among the physical limitations causing the rounding of these corners.

Fig. 5 represents a much larger cylinder than those represented by Figs. 2 & 3, and the horizontal dimension (cylinder volume) is drawn to a different scale. However, the pressures are shown on the same scale in all three diagrams. Notice that the sharp rise in pressure during combustion which was characteristic of the Otto cycle is here added to the high compression pressure which was characteristic of the true Diesel cycle. The result is a much higher firing pressure in the mixed cycle than was found in either of the others.



ACTUAL CYCLE
SOLID INJECTION ENGINE
FIG. 5

FUEL INJECTION

As the piston approaches top dead center on the compression stroke, fuel oil must be forced into the highly compressed air in the cylinder. In the engine whose operation is pictured in Fig. 5 injection begins when the piston is about 0.1" from the end of its compression stroke. Injection ends at about the same point on the power stroke. While the piston only moves a total of 0.2", or about one one-hundredth of its total travel for a revolution, during this injection period, the time consumed is about 1/8 of the time for a revolution of the crankshaft.

Since combustion is dependent on the uniting of air with the fuel, the fuel must be broken up into a very fine mist and thoroughly mixed with the air. This is accomplished by forcing the oil through tiny holes in a nozzle which projects slightly through the cylinder head into the clearance space above the piston.

The pressure with which the oil is forced through the tiny holes of the nozzle must be much higher than that within the cylinder.

The duration of the combustion period is controlled by the rate at which oil is injected into the cylinder. It burns as it enters.

The force with which the piston is pushed down, and hence the speed and power of the engine, is determined by the amount of fuel injected for each power stroke. The fuel injection pump meters the fuel as it pumps it, injecting just the amount called for by the governor.

If, when the cycle pictured in Fig. 5 was performed, less fuel had been injected and burned, the pressure would not have been raised so high. Consequently, the space between the compression and expansion lines (m.e.p., approximately) would have been less. If the speed of the engine had not changed, the power developed would therefore have been less. The relationship between speed, m.e.p., cylinder dimensions and power output is simple. The speed of the engine, the mean effective pressure on the piston, the length of the piston stroke, and the area of the piston all increase the power output of the cylinder as they increase. If the m.e.p. in pounds per square inch, the length of the stroke in feet, the piston area in square inches, and the number of power strokes per minute (counting all cylinders in the engine) are multiplied together and the product divided by 33000, the result is the power developed in the engine. The actual output is reduced somewhat by friction in the moving parts. Mathematically this is expressed in the easily remembered formula, $HP = \frac{PLAN}{33000}$

From the above it may be seen that when the bore and stroke of an engine cylinder have been fixed there are still two ways in which its power output may be varied. One is to vary the amount of fuel burned per stroke (change m.e.p.). The other is to vary its speed. If the load on the engine is increased without a corresponding increase in the fuel injected per stroke, the engine speed will be decreased. If load is decreased the speed will increase. It is the function of the governor to regulate the fuel supply to maintain constant speed as the load varies.

SUPERCHARGING

It is well known that air is required to support combustion. For each pound of fuel oil burned in a four-stroke-cycle solid injection Diesel engine about 25 pounds of air is necessary. At atmospheric pressure this air occupies about 324 cubic feet of space. If the pressure on this air is doubled (raised to 14.7 psi above atmospheric pressure), without changing its temperature, twice as many pounds of air will be contained in the same volume. In other words, when compressed to 14.7 psi gauge pressure, a given volume of air will support the combustion of twice as much fuel as will the same volume of air at the pressure of the natural atmosphere.

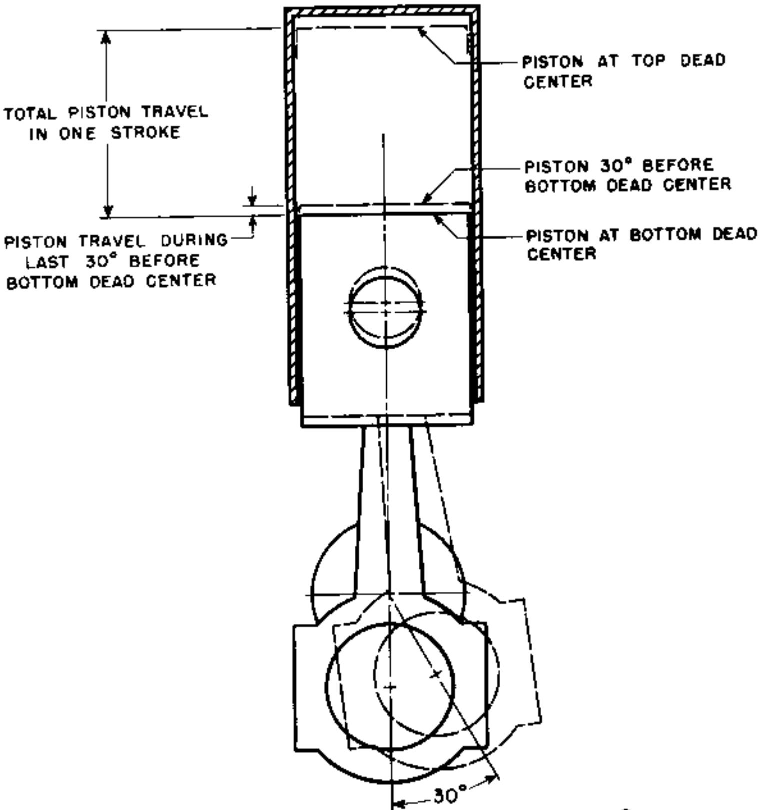
By raising the pressure of the air flowing into the cylinders (supercharging) more air is packed in on each intake stroke. This permits the burning of more fuel on each power stroke. The result is more power per cylinder from a supercharged engine than from a non-supercharged engine (a naturally aspirated engine) of the same piston stroke, cylinder bore and speed.

The cycle of operation illustrated in Fig. 5 is that of a supercharged engine. For this reason the cylinder pressure during the intake stroke is approximately 20 psi above that of the atmosphere, as is shown by examination of the diagram.

VALVES

Poppet valves in the head of the cylinder are opened by rocker arms actuated from the camshaft through push rods. These valves admit air and let out exhaust gases at the proper times. Since large volumes of gases must be handled quickly, two valves are provided for air and two for exhaust in each cylinder.

The piston moves but little and could not produce much power during the last few degrees of revolution of the crankshaft at the end of the power stroke (Fig. 6). Consequently, the exhaust valve is opened slightly before the end of this stroke (Fig. 5) to allow more time for combustion products to be completely cleared out before the cylinder is again filled with air. To further insure complete removal of combustion gases the air valve is opened somewhat before and the exhaust valve left open a few moments after the beginning of the intake stroke. Thus the incoming air is able to push out exhaust gases remaining in the clearance space. The removal of exhaust gases from the cylinder is known as scavenging, and the exhaust stroke is sometimes called the scavenging stroke.



PISTON TRAVEL DURING BOTTOM 30° OF STROKE
FIG. 6

Again at the end of the intake stroke and beginning of the compression stroke the crankshaft rotates several degrees with little movement of the piston. In order to take advantage of this time for the admission of air to the cylinder the air valves remain open until the crankshaft has rotated a few degrees beyond dead center and the piston has started on the compression stroke. (See Fig. 5.)

Since a slight period of time elapses between the beginning of fuel injection and the actual ignition of the first particles of fuel, injection is started slightly before the piston reaches the end of the compression stroke. This causes ignition to begin at the desired point in the cycle. The rate at which fuel is injected is regulated so that it is burning during an appreciable length of time while the piston is passing the end of its stroke and commencing the power stroke. The result is that most of the combustion takes place at constant volume while the piston is practically stationary at the end of its stroke. During this portion of the combustion period pressure rises rapidly. The remainder of the combustion period occurs with the piston moving downward, increasing the volume occupied by the gases. This increasing volume allows the gases to expand as they are heated by the burning fuel and the rate of combustion is so controlled that the pressure remains approximately constant during this period. After combustion ceases the gases expand as the piston moves outward and the pressure consequently decreases, since no heat is now being furnished to maintain the pressure.

TURBOSUPERCHARGER

The exhaust gases leaving the cylinder still contain heat energy which cannot be extracted in the cylinder. Some of this is used to further expand the gases in a gas turbine which forms part of the turbosupercharger. The turbine consists of a number of vanes which direct the hot gases against blades mounted on the outer edge of a disk. These vanes are so shaped that the gases expanding through them gain very high velocities. When they hit the rotor blades at these high velocities they push against them, causing them to turn. The impeller of a centrifugal air compressor is mounted on the other end of the shaft on which the turbine rotor is mounted. As it turns, this impeller draws air in from the atmosphere and forces it into an air manifold under pressure. From the manifold the air rushes into each cylinder as its air valves are opened.

The exhaust stroke is found in Fig. 5 at slightly more than 20 psi above atmospheric pressure. This is due to the resistance of the supercharger turbine to the passage of the exhaust gases from the cylinder. The power taken from the cylinder by this back pressure represents but a small portion of the total required to drive the supercharger. The remainder is obtained from heat in the exhaust gases which would otherwise be lost.

CAMSHAFTS

In order to make the 12 and 16 cylinder engines compact and to avoid extremely long crankshafts the cylinders are arranged in two banks in the form of a 45° "vee". The air and exhaust valves and fuel injection pumps of each bank are operated by a camshaft. Each opening of a valve or stroke of a fuel injection pump occurs only once in four strokes of the piston. Each piston makes two strokes (one up and one down) in each revolution of the crankshaft. Consequently the camshaft must make exactly one revolution for every two made by the crankshaft. This relationship is accomplished by gearing the camshaft to the crankshaft with twice as many teeth on each camshaft gear as on the crankshaft gear. Since the distance from crankshaft to camshaft would necessitate unduly large gears for direct meshing, an idler gear is inserted between each camshaft gear and the crankshaft gear. These idler gears have no effect on the gear ratio.

The camshaft rotation and, hence, the valve and fuel pump operation are rigidly associated with the rotation of the crankshaft. In fact the crankshaft is a major link connecting valve and injection pump operation to piston position. Consequently the crankshaft position is used as a measurement of the time when each valve or pump operation (known as an event) should occur. The timing of valve and injector events is always determined in degrees of crankshaft rotation from top or bottom dead center position of the associated piston.

COOLING

Since a great deal of heat is generated in the cylinders by the burning of the fuel they would become overheated and would soon be destroyed if some arrangement were not made for cooling them. They are cooled by circulating large amounts of water through space surrounding the cylinder walls and through passages in the cylinder heads. This water is circulated by a centrifugal pump geared to the crankshaft. The water is cooled by circulation through air cooled radiators.

LUBRICATION

All moving parts must be protected from friction by a film of oil. In order to insure this protection, lubricating oil is pumped to all bearings by a circulating pump which is also geared to the crankshaft. This oil carries away heat from the bearings, cylinder walls, and particularly from the pistons, as well as lubricating them.

It is very important to exclude dirt from the closely fitted parts and small orifices of the Diesel engine. Consequently, air, fuel and lubricating oil are filtered before entering the engine.

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The end of the engine connected to the generator is called the generator end. The opposite end is called the free end. The free end is considered the front of the engine, even though it may be placed to the rear in a locomotive. The right side of the engine is the side of the engine on the right as one stands at the generator end and faces toward the free end. The opposite side is, of course, the left side. Cylinders are numbered from the free end.

Since the construction of the first commercially practical Diesel engine in 1897, the economy of Diesel engines has led engineers to strive to adapt them to more and more applications. The early Diesels were too heavy and bulky to be used in other than stationary and marine applications. However, the advent of improved materials made possible the construction of engines of less weight able to withstand the high pressures inherent in Diesel operation, and the development of equipment for solid injection of the fuel made high speed Diesel engines possible. These high speed engines of relatively light weight are capable of high power output in limited space, which makes them suitable for locomotives, trucks, busses, tractors, construction machinery, and other portable-power applications. Today the Diesel engine, with such wide applicability, with rugged construction, and with the capacity to burn low cost fuel with high efficiency, reigns supreme in the field of compact, heavy-duty power plants.

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