Diesel Technology

Fundamentals, Service, Repair

Eighth Edition

by
Andrew Norman

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Preface

Diesel Technology is designed to provide students in the rapidly changing diesel engine field with up-to-date information on the construction, operation, service, and repair of diesel engines. Diesel engines have been the "workhorses of industry" for many years, powering ships, agricultural and construction equipment, generators, pumps, and a host of other applications. They also power the over-the-road tractor-trailers and trucks that carry goods.

In addition to detailing the fundamentals of operation, *Diesel Technology* contains information on the latest developments in the diesel engine field. For many years, the basic design and operation of the diesel engine remained unchanged. Manufacturers concentrated on increasing engine power output and improving reliability. However, the need to meet strict fuel economy and exhaust emissions standards has prompted manufacturers to add complex emissions control devices and electronic control systems to their engines. Today's diesel technician must understand the operation of these components and systems in order to service them properly.

Diesel Technology is written in a clear, logical, and interesting style. It presents complex technical information in an easy-to-understand manner. Each chapter begins with learning objectives and ends with a summary, a list of important terms, review questions, and ASE-type questions. Numerous illustrations are used throughout the text to show and reinforce important concepts. Safety is stressed throughout the text to help ensure safe work practices. Proper hazardous chemical and waste handling and disposal are encouraged throughout the text. A glossary that contains definitions to many of the terms commonly used in the diesel field is located in the back of the text.

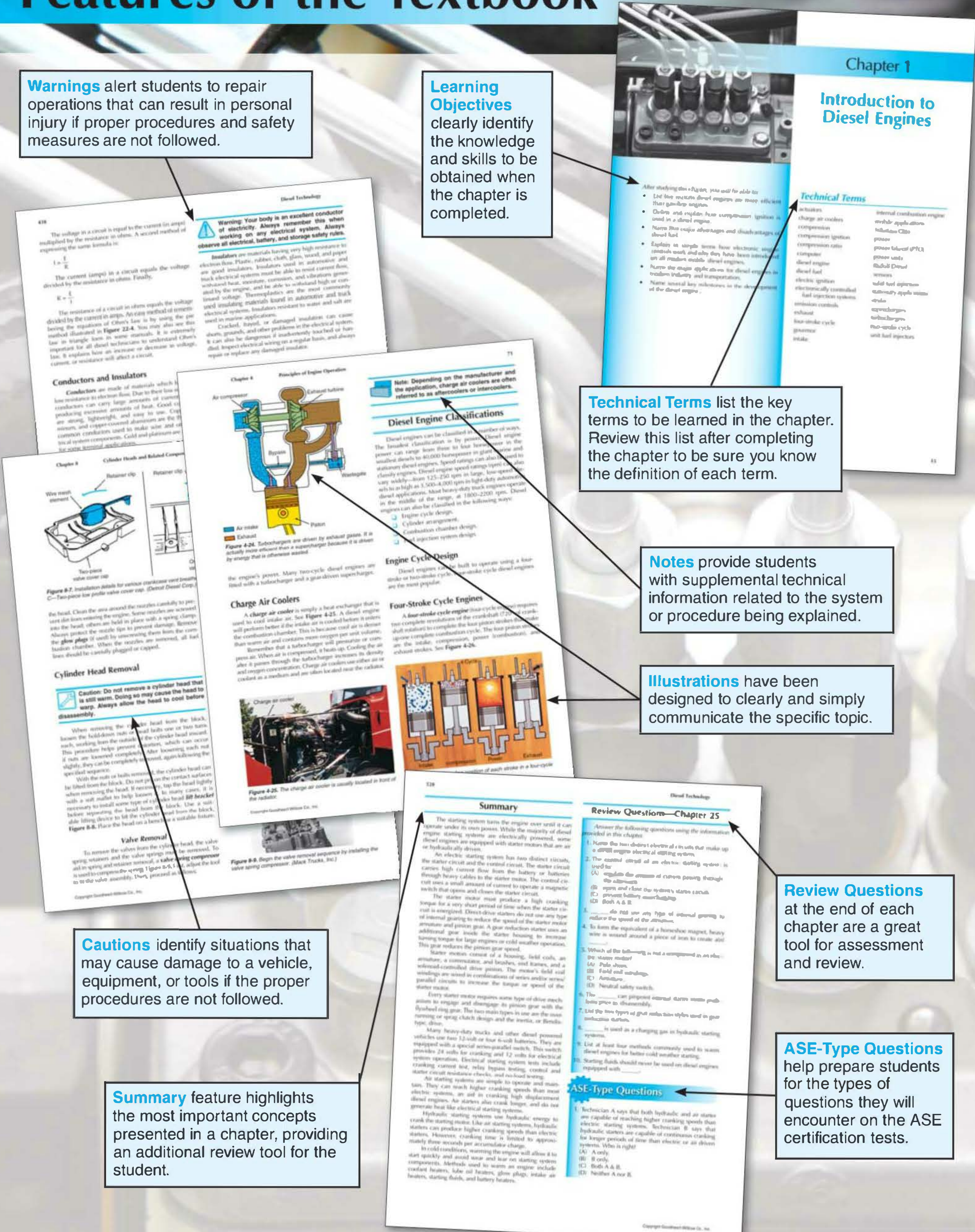
The 2016 edition of *Diesel Technology* has been updated to include the latest advances in the field. Major changes include:

- Updated information on electronic engine controls and fuel injection.
- A new section on emissions that includes coverage of ultra-low sulfur fuels, biodiesel, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR).
- New information on constant geometry turbochargers (CGT), variable geometry (VGT) turbochargers, and variable valve timing.
- An updated Basic Electricity chapter that includes new information on AMG and gel cell batteries, digital battery testing, key off draw testing, and low voltage disconnect systems.
- A new Workplace Employability Skills chapter that outlines the characteristics and proficiencies necessary to obtain and keep a job in the competitive diesel field.

While being an ideal text for the beginning diesel student, *Diesel Technology* is also an invaluable resource for technicians who are currently working in the service and repair of diesel engines. *Diesel Technology* is designed to help students and working technicians prepare to take the ASE Medium/Heavy-Duty Truck Diesel Engines, Electricity and Electronics, and PMI tests.

The diesel service and repair industry offers many challenges and rewards for the well-trained service technician. The U.S. Department of Labor, Bureau of Labor Statistics reports that job opportunities for diesel technicians who have completed formal education and have strong technical skills are projected to grow through 2022. *Diesel Technology* will help you gain the skills necessary to succeed in this dynamic industry.

Features of the Textbook



Warnings alert students to repair operations that can result in personal injury if proper procedures and safety measures are not followed.

Learning Objectives clearly identify the knowledge and skills to be obtained when the chapter is completed.

Technical Terms list the key terms to be learned in the chapter. Review this list after completing the chapter to be sure you know the definition of each term.

Notes provide students with supplemental technical information related to the system or procedure being explained.

Illustrations have been designed to clearly and simply communicate the specific topic.

Cautions identify situations that may cause damage to a vehicle, equipment, or tools if the proper procedures are not followed.

Review Questions at the end of each chapter are a great tool for assessment and review.

ASE-Type Questions help prepare students for the types of questions they will encounter on the ASE certification tests.

Summary feature highlights the most important concepts presented in a chapter, providing an additional review tool for the student.

Student Materials

Workbook

The student workbook contains a variety of practice questions that correlate to the textbook.

Online Textbook

An online version of the printed textbook is available at www.g-wonlinetextbooks.com.

Instructor Materials

ExamView® Assessment Suite

Quickly and easily prepare, print, and administer tests with the ExamView® Assessment Suite. With hundreds of questions in the test bank corresponding to each chapter, you can choose which questions to include in each test, create multiple versions of a single test, and automatically generate answer keys. Existing questions may be modified and new questions may be added.

Instructor's Presentations for PowerPoint®

Help teach and visually reinforce key concepts with prepared lectures. These presentations are designed to allow for customization to meet daily teaching needs. They include objectives and images from the textbook.

Instructor's Resource CD

One resource provides instructors with time-saving preparation tools such as answer keys, lesson plans, correlation charts, and other teaching aids.

Online Instructor Resources

Online Instructor Resources are time-saving teaching materials organized in a convenient, easy-to-use online bookshelf. Lesson plans, answer keys, PowerPoint® presentations, ExamView® Assessment Suite software, and additional teaching aids are available on demand, 24/7. Accessible from home or school, Online Instructor Resources help support busy instructors.

G-W Online

G-W Online is an easily customizable course management system, which includes all of the student resources. This online solution contains an Online Textbook, workbook questions, e-flash cards, activities, assessments, video clips, and narrated animations for a deeply engaging, interactive learning experience. G-W Online's powerful assessment and course management tools accurately monitor progress and track student learning. The ultimate in convenient and quick grading, G-W Online allows you to spend more time teaching and less time administering.

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Brief Contents

Table of Contents

Chapter 24

Diesel Engine Charging Systems. 495

Chapter 25

Diesel Starting Systems 513

Chapter 26

Engine Reassembly and Installation. . . 531

Chapter 1

Introduction to Diesel Engines

After studying this chapter, you will be able to:

- List five reasons diesel engines are more efficient than gasoline engines.
- Define and explain how compression ignition is used in a diesel engine.
- Name two major advantages and disadvantages of diesel fuel.
- Explain in simple terms how electronic engine controls work and why they have been introduced on all modern mobile diesel engines.
- Name the major applications for diesel engines in modern industry and transportation.
- Name several key milestones in the development of the diesel engine.

Technical Terms

actuators
charge air coolers
compression
compression ignition
compression ratio
computer
diesel engine
diesel fuel
electric ignition
electronically controlled fuel injection systems
emission controls
exhaust
four-stroke cycle
governor
intake
internal combustion engine
mobile applications
Nikolaus Otto
power
power takeoff (PTO)
power units
Rudolf Diesel
sensors
solid fuel injection
stationary applications
stroke
superchargers
turbochargers
two-stroke cycle
unit fuel injectors

This chapter will introduce you to the history behind the diesel engine and the man that invented it, Rudolf Diesel. It also covers the basic operating principles of diesel engines and lays the foundation for the material that will follow in the later chapters. You will also see how the diesel has become the "workhorse" engine of industry.

Diesel versus Gasoline Engines

The ***diesel engine*** is an internal combustion engine that uses the heat of compression to ignite a fuel charge, **Figure 1-1**. Mechanical ignition components used in gasoline engines, such as spark plugs, coils, and distributor assemblies, are not required for ignition. Instead, as the piston in a diesel engine cylinder moves upward on its compression stroke, it compresses the air in the cylinder. The air temperature in the cylinder increases to the point that the diesel fuel ignites as it is injected into the cylinder.

Figure 1-1. Modern diesel engines are available in a wide range of sizes and configurations. All use the heat of compression to ignite internal combustion. (bright/Shutterstock)

Despite the fundamental difference in the way ignition takes place, the major components of a diesel engine are similar to those found in a gasoline engine. Both engines have a cylinder block, crankshaft, valve train, camshaft, pistons, and connecting rods. They both require a lubrication system and a cooling system.

Diesel Engine Stroke Cycle

Diesel and gasoline engines can be designed to operate on a ***four-stroke cycle*** or a ***two-stroke cycle***. Each ***stroke*** in the cycle corresponds to the up or down movement of the piston within the cylinder. Four-cycle gasoline and diesel engines use four piston strokes to complete one operating cycle—one stroke each for ***intake***, ***compression***, ***power***, and ***exhaust***. See **Figure 1-2**. Two-stroke cycle engines accomplish intake, compression, power, and exhaust using only two piston strokes, one upward and one downward.

Virtually all high horsepower gasoline engines are four-cycle engines. Two-cycle gasoline engines are used primarily for power tools, lawn and garden equipment, chain saws, outboard boat motors, and other relatively light-duty applications.

In contrast, both two- and four-cycle diesel engines can be used in high horsepower applications. All modern on-highway diesel engines are now four-cycle engines. Two-cycle diesel engines are popular in marine, power generation, and industrial applications. In a two-cycle diesel engine, intake and compression occur on the upward piston stroke, while power and exhaust occur during the downward piston stroke. See **Figure 1-3**.

Diesel engines are also more efficient than gasoline engines. This is due to several factors, including:

- The method of supplying fuel to the combustion chamber.
- The high compression ratio used in diesel engines.

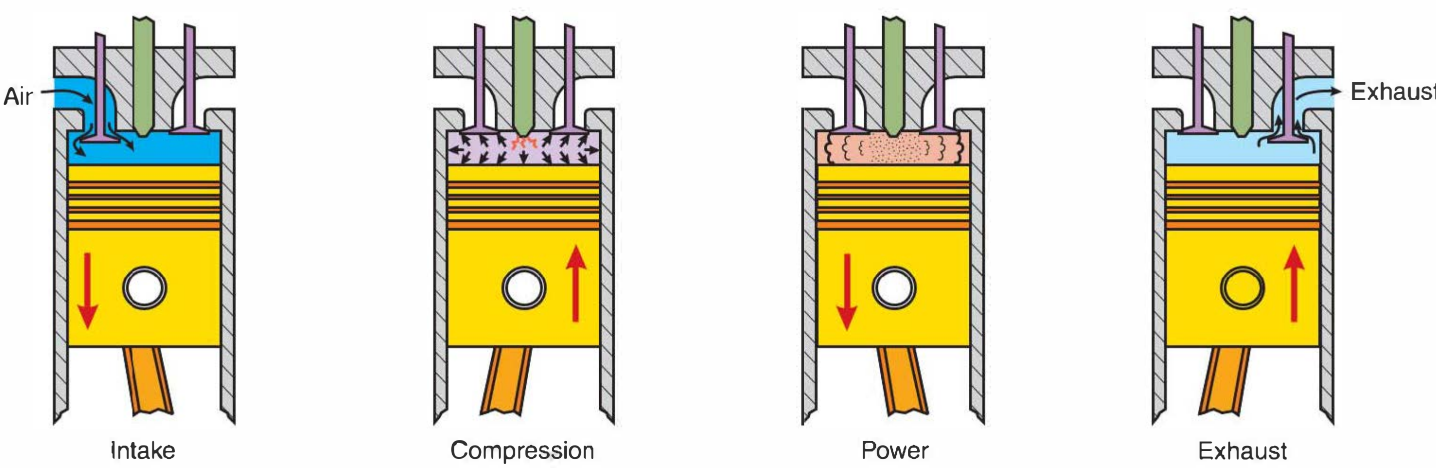


Figure 1-2. The four piston strokes of a four-cycle diesel engine. (Detroit Diesel Corporation)

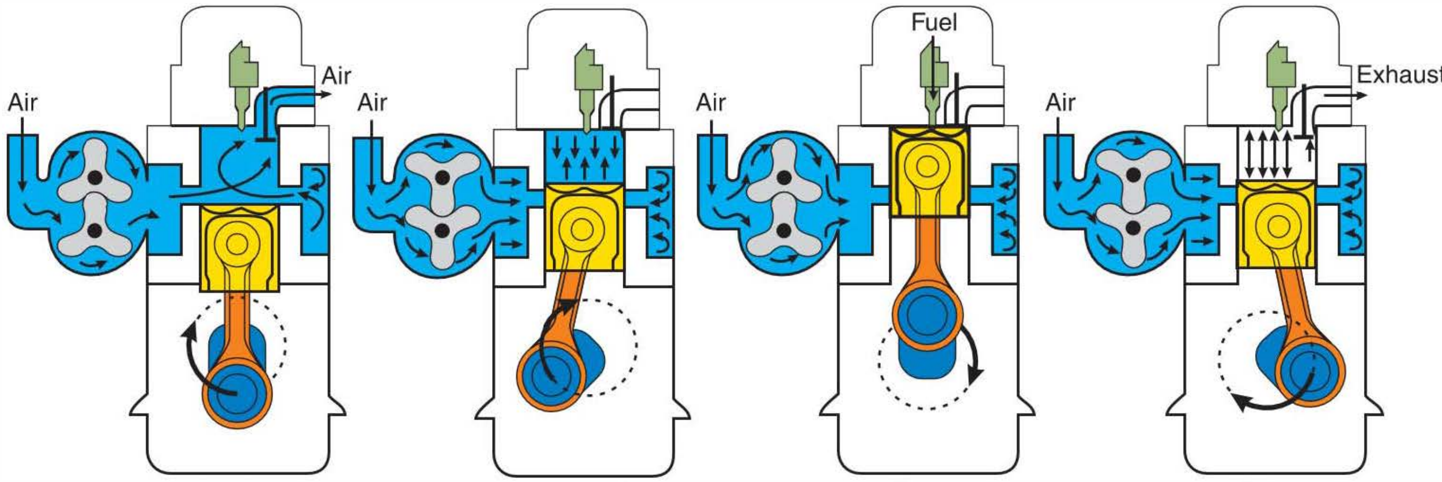


Figure 1-3. *Operating principle of a two-cycle diesel engine. (Detroit Diesel Corporation)*

- The method of igniting the fuel in the combustion chamber.
- The grade and type of fuel used.
- The greater integral strength of diesel engine components.

Supplying Air and Fuel

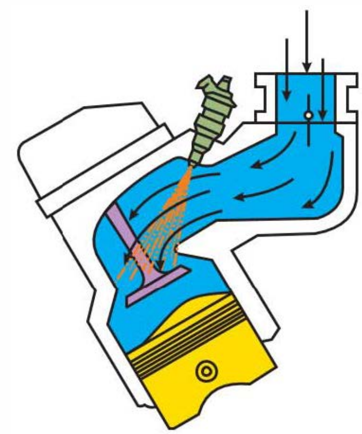
Diesel engines are always fuel injected. Unlike gasoline engines, however, the liquid diesel fuel is not mixed with air before it enters the combustion chamber. Instead, air is drawn into the diesel engine cylinder through the intake manifold and compressed by the piston. As the air is compressed, its temperature increases. An atomized mist of liquid fuel is then sprayed into the cylinder at the top of the piston's compression stroke, **Figure 1-4**. The fuel instantly ignites and burns with the high temperature air in the cylinder, forcing the piston down on its power stroke.

In a carbureted or fuel injected gasoline engine, speed is controlled by regulating the amount of air-fuel mixture that is delivered to the cylinders. However, a diesel engine has no throttling valve in its intake manifold. Air pressure in a diesel engine's intake manifold remains constant at all loads. This results in high efficiency at light loads and idle speeds because there is always an excess of combustion air delivered to the cylinders.

Because diesel engines do not have a throttling valve, another method must be used to control engine speed. Diesel engine speed is controlled by varying the amount of fuel injected into each cylinder. Common ways of controlling the amount of fuel include varying the time solenoid-controlled injection valves stay open, changing the fuel injection pump stroke length, or varying the fuel pressure to the injectors.

A ***governor*** is a device that senses engine speed and load and changes fuel delivery accordingly. Prior to electronic engine controls, all diesel engines used governors that were mechanically, servo-mechanically, hydraulically, or pneumatically controlled. While these designs are still in use in many applications, all on-highway engine manufacturers now incorporate the fuel governing function into the engine's electronic control system.

A



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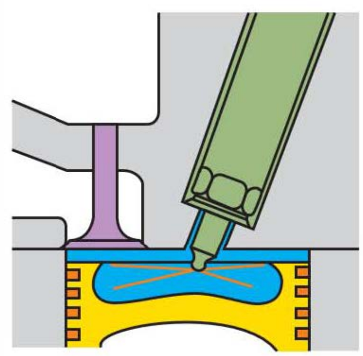

Figure 1-4. *A—In a gasoline engine, air and fuel are mixed and then introduced into the combustion chamber through the intake valve. B—In a diesel engine, air and fuel are not premixed. The fuel is injected directly into the compressed air inside the combustion chamber.*

Compression Ratios

The ***compression ratio*** is a comparison of the volume of air in a cylinder before compression with its volume after compression. A 16:1 compression ratio means that at the top of the compression stroke, the air in the cylinder takes up 1/16 the volume it did when the piston was at the bottom of the compression stroke, **Figure 1-5**.

Diesel engines operate at higher compression ratios than gasoline engines. Typical diesel compression ratios range from 16:1 for stationary engines to 24:1 for passenger vehicles. In contrast, gasoline engines typically use compression ratios ranging from 7.5:1 to 9.5:1.

The higher compression ratios used in diesel engines result in greater thermal expansion of gases in the cylinder following combustion. The end result is a higher percentage of fuel energy being converted into useful power. If the high compression ratios used in diesel engines were used in gasoline engines, preignition or detonation would occur.

Compression Ignition

Because compression raises the air temperature above the fuel's ignition temperature, combustion occurs instantly as the fuel is injected, eliminating the need for a mechanical ignition system. This process is called ***compression ignition***. The elimination of spark plugs, coils, ignition wiring, distributors, and transistorized ignition controls is a major factor in the diesel's simplicity and maintenance economy. It also eliminates systems that are the cause of many performance problems in gasoline engines.

Diesel Fuel

Diesel fuel contains more heat energy (BTUs or joules) than does gasoline. However, diesel is much less volatile than gasoline. The diesel engine's design, including its high compression ratio, is intended to extract the maximum amount of power from its fuel. No gasoline or other internal combustion, reciprocating piston-driven engine can match the diesel engine's ability to get the most power out of its fuel. Fuel efficiency in diesel engines can be as high as 40%. In contrast the gasoline engine, at peak efficiency, converts only about 25% of its fuel energy into usable power. The rest is lost as heat.

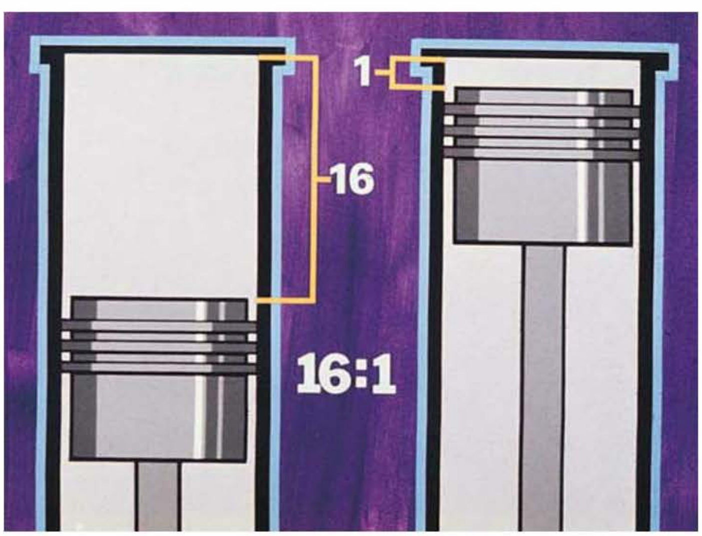

Figure 1-5. *Compression ratios in a diesel engine are high. The compression ratio is determined by comparing the amount of space in the cylinder when the piston is at the top of its travel to the space available when the piston is at its lowest point of travel.*

Durability

Diesel engine cylinder blocks, heads, crankshafts, camshafts, and other major components are designed to withstand operation at high compression ratios and high air temperatures. A typical heavy-duty diesel truck engine will run for 400,000–1,000,000 miles (644,000–1,609,000 km) before it must be rebuilt. Also, the same engine can be successfully rebuilt many times. Gasoline engine components are not as durable as diesel engine components.

Diesel Drawbacks

Despite their many advantages, diesel engines are not perfect. The characteristics that make them more durable than gasoline engines also make them more expensive to build. Diesel fuel injection pumps and injectors must be built to precise tolerances, a requirement that also adds to the initial cost of the engine, **Figure 1-6**.

When compared to a diesel engine, a gasoline engine delivers usable torque through a much wider rpm range. To compensate for this, a heavy-duty truck is equipped with a 10-, 18-, or even 20-speed transmission. Gasoline engines also run quieter and offer faster acceleration than diesel engines.

Diesel fuel attracts water, which can cause bacteria to form in the fuel system. In addition, diesel engines have been subject to escalating emission control standards that have led to changes in engine design and emission control systems. New fuels, engine oils, and coolants must be used properly.

The power output of the diesel engine can also be affected by the temperature of the fuel. At lower temperatures, wax in diesel fuel begins to solidify into crystals that can block fuel flow through filters, lines, and injectors. This

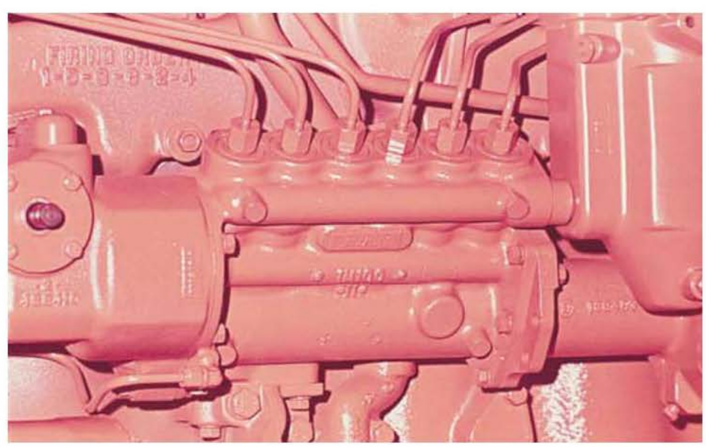

Figure 1-6. *Diesel injection pumps are quite complex and must be built to exacting tolerances. (Caterpillar)*

condition can lead to fuel starvation or no-start conditions. Many diesel engines are equipped with fuel heaters to help prevent this problem. High fuel temperatures above 100°F (38°C) can also thin out the diesel fuel and reduce power output. At temperatures above 150°F (66°C), diesel fuel loses much of its lubricating ability. When this occurs, damage to the injectors and other parts can result.

Diesel Engine History

The steam engine was the driving force behind the Industrial Revolution in the United States and Europe during most of the nineteenth century. Toward the end of the nineteenth century, however, it could no longer meet the needs of all industries, particularly smaller businesses. Steam engines were very large, making them best suited for heavy industry and transportation. They required an external firebox to burn fuel, a boiler to store the steam that drove the piston, and a condenser to turn the steam back into water. Steam engines required constant tending by an operator and were highly inefficient. The average steam engine converted only 6% of its fuel heat into usable power.

Internal combustion engines filled the need for a small, efficient power source. In an ***internal combustion engine***, fuel burns inside the engine itself, rather than in a separate furnace or firebox. Higher working pressures are also possible when air and combustion gases are used instead of steam to propel the piston inside the cylinder.

The gasoline engine and the diesel engine are the two most widely used internal combustion engines in the world. Credit for their invention is historically given to two men—***Nikolaus Otto*** for the gasoline engine and ***Rudolf Diesel*** for the engine that bears his name. However, the triumphs of Otto and Diesel would not have been possible without the theories and experiments of earlier inventors and scholars. The fact that both Diesel and Otto faced challenges to their patents (Otto's patent was eventually broken) proves that many people were working toward the same goal.

Early Theories and Successes

Nicholas Sadi Carnot, a French scientist, formulated theories on the thermodynamics of engine operation that would influence both Otto, and to a greater extent, Diesel. In papers published in 1824, Carnot introduced the idea of a cycle in heat engine operation. The cycle consisted of a series of steps that would both produce power and return the engine to its original position. Carnot theorized that a piston could be driven back and forth in a cylinder by first heating and then cooling a gas trapped inside the cylinder. The controlled expansion of the gas as it is heated and the contraction of the gas as it cooled would drive the piston.

In theory, Carnot's engine was 100% efficient. All heat generated would be turned into useful power. Carnot admitted that a 100% efficient engine was an impossibility, but it was an idea that would intrigue a young Rudolf Diesel over fifty years later. Although Carnot never attempted to build a working model based on his theory, his ideas on engine cycling and the use of an expanding gas to move a piston were major contributions to small engine design.

In 1860, Etienne Lenoir demonstrated a double-acting internal combustion engine fueled with street lamp gas. It used many of the principles found in modern engines. A mixture of air and lamp gas was drawn into one end of a long cylinder that housed a piston connected to a crankshaft. The mixture was ignited by an electric spark. The resulting explosion drove the piston along the cylinder to the end of its stroke. The process was then repeated at the other end of the cylinder with the explosion occurring on the opposite face of the piston. This drove the piston back to its original position. On its return trip, the piston helped clear the cylinder of the waste gases remaining from the previous explosion. The two firings per cycle were timed to occur at 180° of crankshaft rotation apart.

The Silent Otto Engine

Nikolaus Otto, a German traveling salesman, heard of the Lenoir engine during one of his many trips throughout Europe. Although he lacked an engineering background, Otto became interested in building a small engine that could successfully control an explosive fuel. Otto began work on his engine in the 1860s. He received financial backing from the German industrialist Eugen Langen, and by 1876, their company, Deutz Motors, was producing an internal combustion engine that operated at atmospheric pressures. The engine, called the Silent Otto, used a four-stroke combustion cycle. The Silent Otto drew in a mixture of gasoline and air, compressed it in the cylinder to a compression ratio of about 2.5:1, ignited it with a flame, and then expelled the exhaust gases. The thermal efficiency of the Silent Otto was about 14%, more than twice that of the steam engine.

A reliable ignition system was a problem for early gasoline engines. The first solution used a *hot-bulb chamber*, located next to the main combustion chamber. This small chamber was continually heated by the burning fuel and stayed hot enough to ignite each subsequent fuel charge. Because it remained hot all the time, the hot-bulb chamber tended to preignite the air-fuel mixture, especially at low engine speeds when the charge could not be compressed fast enough by the piston. Another problem was initial engine start-up. The hot-bulb chamber had to be preheated with a blow torch before it could successfully fire the first charge.

The introduction of an ***electric ignition*** system that used spark plugs solved many of the gasoline engine's ignition problems. With electric ignition, the widespread acceptance and success of the gasoline engine was assured. Gasoline engines proved to be compact and lightweight for the power they produced. They continue to be the engine of choice in most passenger vehicles and serve in countless light manufacturing and portable power applications.

The Development of the Diesel Engine

The success of the Silent Otto did not stop others from pursuing a better engine design. Otto's 14% fuel efficiency offered plenty of room for improvement and the dangers involved in igniting and containing an explosive charge convinced many engineers that safer, more efficient engines were possible. One of these engineers was Rudolf Diesel, **Figure 1-7**.

Rudolf Diesel was an extremely brilliant man. He was educated in Germany, attending the Commercial School at Augsburg and then the Technical University at Munich. One of Diesel's university instructors was Carl Linde, the founder of the modern refrigeration business. Linde introduced Diesel to the heat engine theories of Carnot and planted the seed of an idea that eventually grew into the diesel engine.

After graduating with the highest test scores in the university's history, Diesel went to work for Linde. He traveled throughout Europe and North Africa repairing refrigeration systems and acting as a company representative. Diesel began his inventive career while working for Linde.

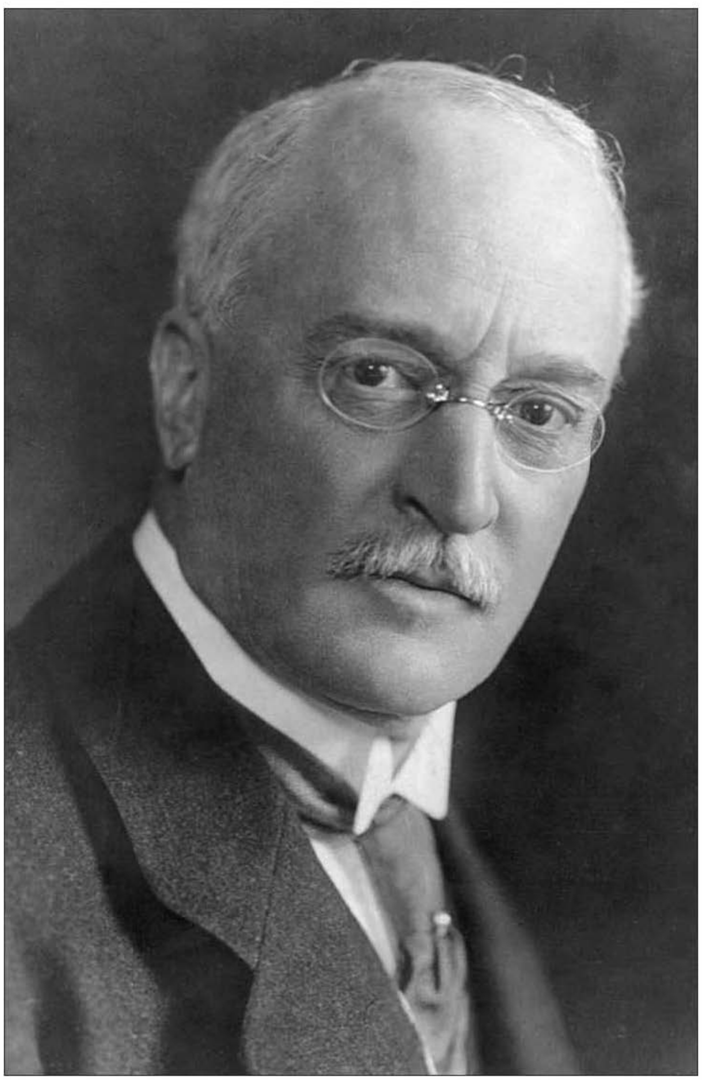

Figure 1-7. *Rudolf Diesel, the father of the diesel engine. (MAN Historical Archives)*

His first invention was a refrigeration system that made clear ice instead of crystalline ice. However, a clause in his employment contract prevented him from marketing the system, and Diesel's interests soon turned to engine design.

Diesel's First Engine

Diesel's first engine was an *external combustion engine* that used ammonia vapors instead of steam to drive the piston. The low boiling point of ammonia meant that less heat was required for vaporization. Diesel also devised a system in which glycerin absorbed the ammonia vapor as it was expelled from the cylinder. The glycerin held the vapor's heat so that it could be recycled to heat more ammonia. The goal was a super-efficient engine that could run for hours after a short initial warm-up period. Although his model worked, problems with heat exchange, leaks, and power output led Diesel to abandon the design in April of 1889.

Diesel's experiments led him to two important conclusions. The first was that the difference between the pressure of the compressed gas at the start of the power stroke and the pressure of the expanded gas at the end of the power stroke should be as great as possible. This would provide an equally wide heat range difference, with the maximum amount of heat being converted to usable power. To accomplish this, Diesel estimated that pressures of fifty to sixty atmospheres would be needed inside the cylinder.

Diesel's second conclusion was that both ammonia vapor and steam were too difficult to handle at such high pressures. The best gas for the job was simply air. In the ammonia vapor engine, both the ammonia and glycerin had to be heated and cooled from external sources. For a short time, Diesel approached his high compression air engine in the same way, considering the use of an external source to heat the air.

The Beginning of the First Diesel Engine

Diesel was driven in his work by Carnot's vision of a perfectly efficient heat engine. He had not set out to build an internal combustion engine. Finally, in his own words, Diesel formulated "the idea of using air not only as a working medium, but also as a chemical medium for combustion." He considered his work of the previous five years, "a long detour to an idea that has been used for a long time in gas and hot air engines: combustion in the cylinder itself."

Diesel also realized that igniting the air-fuel charge using a hot bulb or external spark would not be practical at the high temperatures and pressures his engine would generate. Instead, Diesel decided on "undertaking combustion in the highly compressed air itself." In other words, the high heat of the compressed air would be used to ignite the fuel.

The ideas of internal combustion air as a working medium, and compression ignition were not new. The first two were being successfully used in the Silent Otto engine and many other engines that were produced before 1892.

The principles of compression ignition were well documented by several scholars. Diesel's originality came in the way he proposed to control combustion in the cylinder.

Refining the Engine

Diesel believed the gasoline engine operated on a poor working principle. Since an almost equal mixture of gasoline and air was used, ignition inside the combustion chamber resembled more of an explosion than a controlled burning of fuel. The result was a major increase in temperature. Much of the fuel heat was lost through the cylinder walls or in the exhaust gases.

To correct this inefficiency, Diesel proposed drawing in about nine times more air than was actually needed to burn the fuel. The air would be compressed until it reached a temperature that was much higher than the temperature at which the fuel burned. At the point of maximum air compression, a small amount of fuel would be introduced into the cylinder. The high heat of the compressed air would immediately ignite the fuel. As the fuel burned, its expanding combustion gases would drive the piston down on its power stroke. In Diesel's engine, these expanding combustion gases would theoretically perform another equally important job. They would absorb the heat generated by the burning fuel so the temperature inside the cylinder would remain constant.

With little or no excess heat generated, Diesel calculated that his engine would be 72% efficient. In his 1892 patent draft, Diesel proposed coal dust as the engine's probable fuel. Diesel imagined a system in which coal dust would be stored in hoppers and gravity fed into the cylinders through rotating disks. In theory, the job of introducing fuel into the cylinder appeared rather simple. In practice, the task would prove much more difficult.

Early Engine Models

Diesel made a mistake by filing his patent before building a working model of his new engine. This would eventually cause him numerous problems, because the engine he would ultimately produce differed significantly from the one he proposed, **Figure 1-8A**. Diesel pursued thermal efficiency and the Carnot cycle at the expense of mechanical efficiency. It was soon clear that the power needed to compress the air inside the cylinder could not be generated using the amount of fuel Diesel proposed. Simply put, Diesel's engine would not run.

Diesel corrected this problem by decreasing compression levels inside the cylinder dramatically and increasing the amount of fuel used by a factor of eight. Both steps decreased operating efficiency. Diesel's engine now had to be liquid cooled to remove excess heat. He also abandoned the theory of constant temperature operation in favor of constant pressure operation. In other words, enough fuel would now be introduced into the cylinder so that expanding combustion gases could maintain a constant pushing pressure on the piston through its entire power stroke. These changes brought Diesel's engine closer to other engine designs of the day, **Figure 1-8B**.

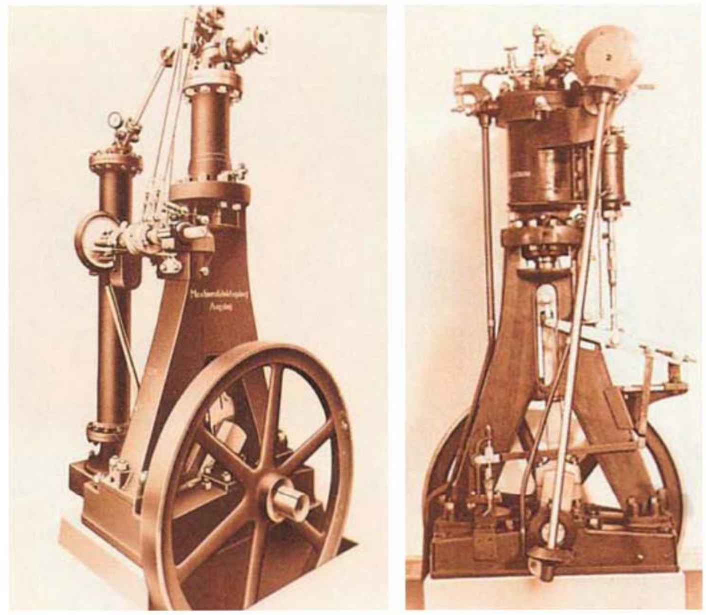

Figure 1-8. *A—Diesel's first experimental engine was built in 1893. B—Modified diesel engine. Following modification, including enlargement of the piston bore, the first power tests were performed on the diesel engine in 1895. The tests showed that the new engine had an efficiency of 26.2%.*
(Diesel & Gas Turbine Publications)

With the exception of compression ignition, Diesel's engine now closely resembled an engine proposed by Otto Kohler five years earlier. Diesel steadfastly insisted that his ideas were not influenced by others. His cold dismissal of such charges was viewed by many peers as a sign of his guilt. Rather than refile a patent that reflected the changes in his design, Diesel foolishly attempted to defend his 1892 patent. Much of Diesel's later life was spent defending his early ideas rather than formulating new ones.

The years between 1892 and 1897 were Diesel's most productive. During this period, he supervised the building of the first diesel engines at the Augsburg Engine Works. However, all did not go smoothly. Leaking valves and gaskets made reaching the high air pressures needed to start combustion nearly impossible. When these problems were solved, the engine exploded violently when the first fuel charge was injected into the cylinder. Numerous liquid fuels were tried, with kerosene producing the best results.

Vaporizing the fuel proved especially troublesome. An air-blast system using an air compressor from a refrigerator was the first workable solution to this problem. Vaporization was later refined with the development of a sieve-type atomizer. The piston was also enlarged and the combustion chamber redesigned. A better fuel pump was installed and a crude fuel distributor was devised. By February of 1897, after almost five years of extensive trial-and-error testing, Diesel's engine was ready for sale to business and industry. Although a far cry from Carnot's perfect heat engine, the diesel engine offered a thermal efficiency of over 30%. Fuel consumption was only one-half that of the gasoline engine.

The First Diesel Engines in Industry

The first commercial installation of a diesel engine was a two-cylinder, 60 horsepower engine installed in a Bavarian match factory. At an exhibition for engines and driven machines in Munich in 1898, the diesel engine was officially presented to the public for the first time, **Figure 1-9**. Interest in the diesel engine was high, and Diesel quickly sold licensing rights to build the engine to companies in France, England, Germany, Russia, and the United States. Diesel was now a rich man and was riding a wave of success.

Nevertheless, production was slow and problems persisted. The sheer size and weight of the diesel engine limited its use. The bulky air compressors, air tanks, valves, and lines needed to run the fuel injection system prevented mobile applications, and the fledgling automobile industry quickly adopted the gasoline engine as its power source. By 1902, only 350 diesel engines were in operation. Problems with fuel vaporization and distribution, fuel quality, and air compression were common in the early diesel engines.

Diesel's attempt at operating his own production plant was a failure. Also, personal clashes with his industrial backers resulted in Diesel having little input in the technical improvements made to his original design after 1900.

The greatest area of promise for the diesel engine appeared to be marine applications. The first diesel-powered, ocean-going ship was the 7000 ton *Seelandia*, a Danish vessel powered by two 1000 horsepower, eight-cylinder, four-stroke engines. Its maiden voyage to Bangkok in 1912 sparked a great deal of interest. As Europe and the world moved steadily toward war, interest in diesel-powered warships and submarines increased.

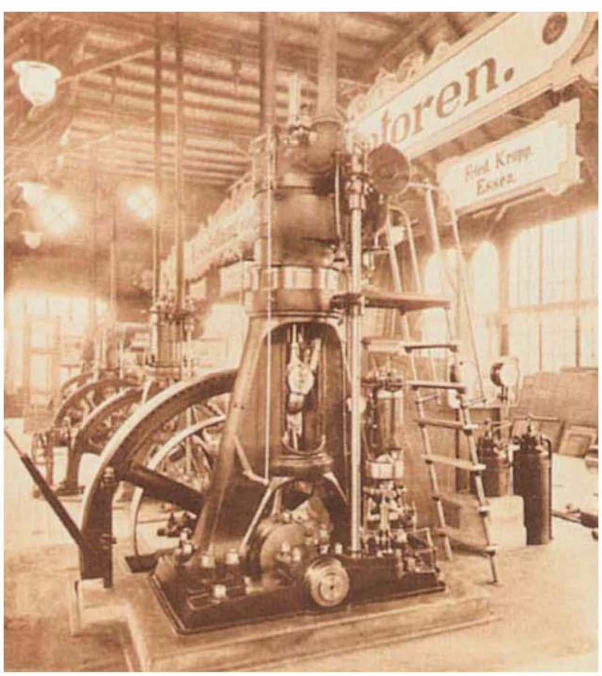

Figure 1-9. *At an exhibition in 1898, Diesel's engine was officially shown to the public for the first time.*
(Diesel & Gas Turbine Publications)

The Demise of Rudolf Diesel

Despite the increasing application of his engine design, Rudolf Diesel faced impending bankruptcy by the autumn of 1913. He complained of poor health and was beset by critics eager to discredit his work and challenge his patents. In late September, Diesel boarded the steamship *Dresden* for a trip to England. He planned to attend the groundbreaking for the British Diesel Company's new production plant. Diesel would never arrive for the groundbreaking. Sometime during the night of September 30th, Diesel disappeared from the ship. In early October, a Dutch pilot boat recovered a body from the sea. As was the custom, the captain of the pilot boat removed certain personal effects from the body and then returned it to the sea. These personal effects were later identified as Diesel's.

The exact circumstances of Diesel's death were never fully determined. Many factors point toward suicide, but some suspect Diesel possibly met an untimely death at the hands of German military agents, anxious to keep diesel engine technology from the British.

Had Diesel lived, he would have seen a rapid succession of technological advances that finally unleashed the diesel engine's full potential. After World War I, marine diesels were rapidly refined. The 1920s also saw the perfection of ***solid fuel injection***, which allowed diesel fuel to be injected directly into the combustion chamber without using an air compressor.

Another major milestone occurred when the Robert Bosch firm of Stuttgart, Germany developed a compact, reliable fuel injection pump. These advances opened the door for smaller, lighter, faster diesel engines that could power trucks and automobiles. The Daimler-Benz Company introduced the first production model diesel automobile in 1936.

Continued Development of the Diesel Engine

In America, interest in the diesel engine was spearheaded by such men as Clessie Cummins, owner of the Cummins Engine Company in Columbus, Indiana. In 1930, Cummins outfitted a Packard automobile with a modified diesel marine engine and drove it from Indianapolis to New York City—over 800 miles at a cost of $1.38. Cummins also drove the only diesel-powered vehicle ever entered in the Indianapolis 500, completing the race without a fuel stop.

Several companies, including General Motors (Detroit Diesel), Caterpillar, Allis-Chalmers, and Worthington were building and marketing diesel engines by the late 1930s. The diesel proved its worth in World War II so well that Detroit Diesel's Gray Marine earned the nickname "the engine that won the war of the seas." Land-based diesels proved their reliability in thousands of installations.

Diesel-Electric locomotives rapidly replaced less efficient steam engines in railroad applications, **Figure 1-10**. By 1941, almost 1400 diesel locomotives were operating on American rail systems, and by the 1950s, the transition to diesel locomotives was complete.

Figure 1-10. *By the 1950s, diesel locomotives replaced all of the inefficient steam engines on railroads. (Albert Pego/Shutterstock.com)*

By the 1950s, diesel engines had also become dominant in heavy-duty trucks and construction equipment. The development of the compact Roosa Master fuel distributor paved the way for diesel-powered farm tractors and agricultural equipment. Buses and other public transportation vehicles were converted to fuel-efficient, durable diesel engines. Electric power generation, mining, and irrigation are all areas that came to rely heavily on diesel power.

The Age of Diesel Electronics

For many years, the basic design and operation of diesel engines remained unchanged. Manufacturers concentrated on increasing engine power output and overall reliability. However, concerns over exhaust emissions and the need to conform to strict emissions standards have led diesel manufacturers to design ***electronically controlled fuel injection systems*** and ***emission controls***. The electronic controls are similar to those that have been adopted by the automotive industry for gasoline engines. They use ***sensors*** to monitor operating conditions, a ***computer*** to calculate the ideal fuel and engine settings for these conditions, and electromagnetic ***actuators*** to make the necessary adjustments. Diesel engine technicians must understand how these electronic controls operate in order to service them properly. Mastering new troubleshooting techniques and test equipment is essential for success.

One of the best examples of the benefits of electronically controlled fuel injection systems is the high-pressure common rail diesel injection system that has made high-performance, fuel-efficient diesel engines a reality. The numerous benefits of this modern fuel system have made it the most common fuel system found on today's heavy-duty truck applications.

The common rail fuel system is also having a distinct impact on the automotive diesel market. In Europe, nearly 50% of new passenger cars are diesel powered. With the introduction of tighter emissions standards and ultra-low sulfur diesel fuel, lightweight, responsive diesel-powered cars and light trucks will become more common on American highways. Currently in the U.S., only 3% of the passenger cars are powered by diesel engines. The number is expected to increase significantly, with projections of 8% to 10% of passenger cars on the road being diesel powered in five years.

Modern Diesel Applications

The many applications of the modern diesel engine can be grouped into two broad categories:

- Mobile applications.
- Stationary applications.

Mobile Applications

In ***mobile applications***, the engine propels the vehicle or machine upon which it is mounted from one location to another. In most cases, the diesel engine pushes or pulls a load while also driving external accessories. For example, the engine may propel its machine via the powertrain to the wheels, while another train of gears from the engine drives a power takeoff. A ***power takeoff (PTO)*** is essentially a supplemental drive. The PTO may drive another machine that is pulled behind the first one. A good example of this is a farm tractor pulling and powering a hay baler. All mobile applications require a powertrain to convert engine speed to the desired machine speed. Examples of mobile diesel engine applications include:

- Cars, trucks, and buses, **Figure 1-11**.
- Ships and boats, **Figure 1-12**.
- Locomotives.

A **B**

Figure 1-11. *Various applications of mobile diesel engines. A—Cars and light trucks. B—Medium and heavy-duty trucks and buses. (Daimler AG, Blue Bird)*

Figure 1-12. *Applications of marine diesel engines vary from tankers to cutters to tugboats to yachts. (Hellen Sergeyeva/Shutterstock.com)*

- Railcars.
- Construction equipment, **Figure 1-13**.
- Forestry equipment.
- Harvesting and farm equipment.
- Wheel and crawler tractors.

Stationary Applications

Diesel engines used in ***stationary applications*** produce power from a fixed location for industrial use, **Figure 1-14**. They are often called ***power units*** and are mounted on a stand, transmitting their power to the load through a coupler or driveline. Because no mechanism is needed to propel the engine and machinery, the distribution of power is simplified. Modern stationary applications for diesel engines include:

- Electric power generators (gen-sets), **Figure 1-15**.
- Industrial PTO units.
- Motorized pumps.
- Cranes and power shovels.
- Diesel starting units.

Figure 1-13. *As the workhorses of industry, diesel engines power off-highway and construction equipment as well as over-the-road medium and heavy-duty trucks. (Courtesy of Deere & Company)*

Figure 1-14. *One typical application of stationary diesel engines. While these engines are permanently fixed, smaller diesel engines are transportable to any place where a powerful, efficient engine is needed.*

Figure 1-15. *Typical gen-set. Diesel power is used to generate electricity, pump fluids, and hundreds of other industrial applications.*

Continued Advances in Diesel Engine Efficiency

The diesel engines of today have changed drastically from that first model created by Rudolf Diesel over 100 years ago. New materials and advances in technology are consistently being incorporated into the design of diesel engines to further improve efficiency and decrease any negative environmental impact. Some of the technological developments made in the past 20 years include:

- Enhanced use of ***turbochargers*** and ***superchargers*** to increase power output and improve efficiency.
- Changes in combustion chamber, piston, and valve designs to increase fuel burning efficiency and power output.
- Advanced materials used to construct pistons, connecting rods, and other engine components.

- Use of ***charge air coolers*** resulting in a 3%-5% improvement in fuel mileage and a reduced exhaust emissions.
- Improvements to ***unit fuel injectors*** and common rail injection systems, which are both capable of attaining higher injection pressures than earlier fuel injection systems.
- Matched intake and exhaust flow systems.
- Low-flow cooling systems and extended life coolants.
- Computerized fuel management systems and variable injection timing.
- Introduction of ultra-low sulfur diesel fuel and improved engine oil formulations to decrease emissions and improve efficiency.
- Incorporation of emission control technologies, such as exhaust gas recirculation systems, oxidation catalysts, particulate trap filters, and selective catalytic reduction systems—all designed to lower emissions and meet current environmental regulations.

The new generation of diesel engines operates on the basic principles set forth by Rudolf Diesel over a century ago, but they offer today's diesel service technician many challenges and opportunities to learn new skills.

Summary

Diesel engines are internal combustion engines that use compression for ignition. Air and fuel are not premixed before entering the combustion chamber. Liquid diesel fuel is injected into the highly compressed, high-temperature air inside the cylinder, where it ignites and burns.

Since there is always an excess of combustion air in the cylinder, engine speed is controlled by metering the amount of fuel injected into the cylinder. Electronic controls have increased the precision and speed at which this can be done.

When compared to gasoline engines, diesel engines operate at high compression ratios. Diesels are more durable than gasoline engines, but are more expensive to manufacture. With proper care, diesel engines can be rebuilt several times and will provide many years of service.

The diesel engine was invented by Rudolf Diesel, an engineer who never lived to see his engine fully appreciated or used to its potential.

Robert Bosch developed the first compact, reliable fuel injection pump during the late 1920s. It opened the door for smaller, faster diesel engines in trucks, farm equipment, boats, and other mobile applications.

Modern diesel engines are used in many mobile and stationary applications, such as trucking, construction, mining, agriculture, rail, marine, and power generation. The diesel engines of today have changed drastically from that first model created by Rudolf Diesel. New materials and advances in technology are consistently being incorporated into the design of diesel engines to improve efficiency and decrease any negative environmental impact.

Review Questions–Chapter 1

Answer the following questions using the information provided in this chapter.

1. What is a diesel engine?
2. List at least four reasons why diesel engines are more efficient than gasoline engines.
3. In a diesel engine, the ______ is not mixed with air prior to entering the combustion chamber.
4. In a diesel engine, speed is controlled by regulating the amount of ______ delivered to the cylinders.
5. There is always a(n) ______ of combustion air in a diesel engine.
6. What is the function of the governor in a diesel engine?
7. Diesel fuel contains more ______ than gasoline.
8. What problems are associated with diesel fuel at both low temperatures and at very high temperatures?
9. Who was the first engineer to develop a compact, reliable diesel fuel injection pump?
   (A) Nikolaus Otto.
   (B) Rudolf Diesel.
   (C) Robert Bosch.
   (D) Clessie Cummins.
10. Define the terms *mobile* and *stationary* as they pertain to diesel engine applications.

ASE-Type Questions

1. Typical compression ratios used in diesel engines range between _____.
   (A) 8.5 and 10:1
   (B) 10 and 15:1
   (C) 16 and 24:1
   (D) 19.5 and 27:1
2. Technician A says that when compared to a diesel, a gasoline engine delivers usable torque through a much wider rpm range. Technician B says gasoline engines also run quieter and offer faster acceleration. Who is correct?
   (A) A only.
   (B) B only.
   (C) Both A & B.
   (D) Neither A nor B.

3. Technician A says unit fuel injectors are being used on diesel engines because they are capable of attaining higher injection pressures than inline pump fuel injection systems. Technician B says that inline injection pumps are capable of attaining higher injection pressures than unit fuel injectors. Who is correct?
   (A) A only.
   (B) B only.
   (C) Both A & B.
   (D) Neither A nor B.
4. Technician A says that electronically controlled fuel injection systems have improved the efficiency of diesel engines. Technician B says that the most common fuel system found on modern diesel engines in the high-pressure common rail fuel injection system.
   (A) A only.
   (B) B only.
   (C) Both A & B.
   (D) Neither A nor B.
5. Technician A states that both four-stroke and two-stroke diesel engines are used for high-horsepower diesel engines. Technician B states that only four-cycle engines are used for high-horsepower diesels. Who is correct?
   (A) A only.
   (B) B only.
   (C) Both A & B.
   (D) Neither A nor B.
6. All of the following are characteristics of diesel engines, EXCEPT:
   (A) they are more durable than gasoline engines.
   (B) diesel engines operate at lower compression ratios than gasoline engines.
   (C) all diesel engines are fuel injected.
   (D) diesel engines convert a higher percentage of fuel into useful power.
7. All of the following are drawbacks to the diesel engine, EXCEPT:
   (A) does not produce usable torque through a wide rpm range.
   (B) power output can be affected by the temperature of the diesel fuel.
   (C) they offer faster acceleration than gasoline engines.
   (D) they are more expensive to build.
8. Technician A states that solidified wax can lead to fuel starvation or a no-start condition. Technician B states that high temperatures can thin out diesel fuel and increase wear. Who is correct?
   (A) A only.
   (B) B only.
   (C) Both A & B.
   (D) Neither A nor B.
9. All of the following are changes or systems designed in the last 10 years to improve the efficiency of diesel engines, EXCEPT:
   (A) inline fuel injection pumps.
   (B) computer-controlled fuel management systems.
   (C) high-efficiency charge air coolers.
   (D) redesigned intake and exhaust valves.
10. Stationary applications for diesel engines include:
   (A) motorized pumps.
   (B) starting units.
   (C) industrial power takeoff units.
   (D) All of the above.

Chapter 2

Shop Safety

After studying this chapter, you will be able to:

- Explain the importance of shop safety in a repair shop.
- Describe the personal safety precautions that a technician must follow.
- Outline the general shop housekeeping procedures that must be maintained.
- Explain the safety rules that must be practiced when working with fuel injectors.
- Describe the three basic types of fires.
- Describe the proper use of the different types of fire extinguishers.
- Know your rights under the right-to-know laws.

Technical Terms

asbestos
carbon monoxide
caution
evacuation routes
eyewash station
fire extinguishers
note
right-to-know laws
safety data sheets (SDS)
warning

The most important consideration in any shop should be accident prevention and safety. Safety is everybody's business. Most accidents result from one or more broken safety rules. The injured person learns to respect safety rules the hard way—by experiencing a painful injury. You must learn to respect safety rules by studying and following the rules in this book and in manufacturers' service manuals.

Safety Notices

The chapters in this text contain special notes labeled ***note, caution,*** and ***warning.*** Notes contain information that can help you complete a particular task or make a job easier. Cautions are placed to warn you not to make a mistake that could damage the engine or vehicle. Warnings are a reminder of those areas that could cause personal injury or death. An example of a typical notice is shown in **Figure 2-1.**

In addition, most manufacturers' service manuals also contain safety symbols that provide an additional signal for the need to use caution. Always pay attention to these symbols. Personal safety is always the *number one* consideration when working with diesel engines. Safety is not based simply on do's and don'ts—it is a matter of understanding the job at hand and using common sense.

Personal Safety

The following are general guidelines for personal safety, as well as accident prevention. Knowing and following these safety rules is very important. Keep yourself neat and clean. This means a clean, pressed uniform—not clothing that has oil or grease stains and keeping yourself well groomed. Not only does this promote health and safety, it shows professionalism.

You should dress comfortably, but safely. Avoid wearing dangerous clothing, such as ties, open jackets, sweaters, or long sleeve shirts. Remove any rings, watches, or other jewelry. Never wear jewelry or any other item that can become caught in moving machinery. Loose clothing or jewelry can become caught in the moving parts of an engine or a rotating shaft, pulling you in with it. If your job position requires you to wear a tie, tuck it inside your shirt when around engines or other machinery. If you wear your hair long, it should be tied up or kept under a hat.

Warning: Do not create sparks or flames around diesel fuel. While diesel fuel is not as volatile as gasoline, it will flash and burn if exposed to a heat source.

Figure 2-1. *This a typical warning used in this textbook. Cautions and notes are styled in a similar manner.*

Footwear is the most important part of the diesel technician's attire. Proper footwear for the shop is a pair of steel toe safety shoes with slip-resistant soles, as they can protect against flying sparks, heavy falling objects, and chemicals. Most safety shoes are constructed using materials that will give the shoe a long life expectancy in a harsh shop environment. These shoes also have additional support for standing on the concrete floors in most shops. Protective head covering such as a hard hat is advised when working in a pit or under an overhead hoist.

Personal Protective Equipment

Personal protection is vital when performing many jobs in the shop. Failure to wear the proper eye, respiratory, skin, or hearing protection can result in a permanent injury. In some cases, the damage does not appear until it is too late to correct, often occurring slowly over a period of months or years.

Wear eye protection at all times. When you enter a shop, you are entering an area that at any time, may result in a situation where dirt, metal, or liquid is splashed in your face. You should wear special safety glasses, goggles, or a face shield whenever a particular job requires it, such as welding, chiseling, or grinding, **Figure 2-2.**

If you accidentally get debris or chemicals in your eyes, flush your eyes using an ***eyewash station.*** You should know where the eyewash station in your work area is located and know how to use it before you need it. Refer to the user's manual provided by the eyewash station manufacturer for instructions on proper use.

Respiratory protection, such as face masks, should be worn whenever you are working on systems that can produce dust and dirt. While most dust is not potentially harmful, some dust may contain ***asbestos***, which is a known carcinogen (can cause cancer). Respiratory protection is also a good idea when working around any equipment that gives off fumes, such as a hot tank or steam cleaner.

Figure 2-2. *Various types of eye protection. You should always wear some sort of eye protection whenever you are in the shop.*

Protective gloves are necessary whenever you are working with chemicals such as parts cleaning solvents. If you spill oil, diesel fuel, cleaning solvents, or any other substance on your skin, clean it off immediately. Prolonged exposure to even mild substances may cause severe rashes or chemical burns.

Hearing protection is important when working around noisy engines and machinery. Largely ignored for many years by technicians, shops are beginning to supply ear plugs and other hearing protection, **Figure 2-3.** It is important to wear hearing protection when working in a noisy area or when using certain tools, such as pneumatic impact wrenches and chisels.

Shop Safety Rules

It is not only important to dress safely, but you must also work safely as well. These general shop rules should also be kept in mind while you are working. Following them can prevent a painful injury or death. Horseplay is never permitted in the shop area. Report all accidents promptly so that proper first aid or medical assistance can be provided. Always lift heavy objects by bending down and using your leg muscles so as not to strain your back, **Figure 2-4.**

Some areas in the automotive repair shop are more dangerous than others. Areas where dangerous equipment is used or toxic chemicals are stored are often identified by brightly colored floor markings or signs to alert employees to the potential hazards. When working in these marked safety areas, take extra precautions to prevent injury.

Drawings showing evacuation routes should be posted in prominent areas throughout the shop. ***Evacuation routes*** are designated exit pathways that will allow you to quickly exit the building in case of an emergency. Always study the evacuation routes and be aware of your location in relation to these routes whenever you are working in the shop. Being able to quickly exit the building during an emergency could save your life.

Figure 2-3. *Hearing protection is an often overlooked safety device. However, it is a very important one.*

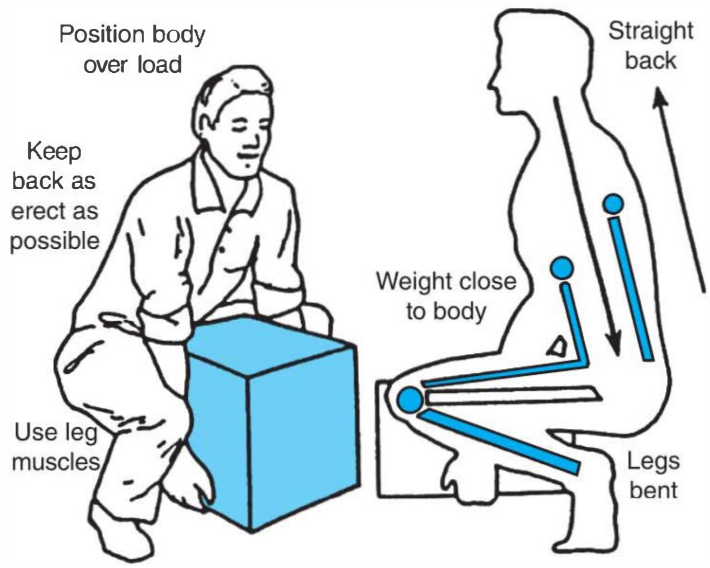

Figure 2-4. *Using the correct lifting technique will prevent a painful back injury. Never lift more than you are capable of handling safely.*

Shop Cleanliness

Keep all workbenches clean. This reduces the chance of tools or parts falling from the bench, where they could be lost, damaged, or cause injury. A clean workbench also reduces the possibility that critical parts will be lost in the clutter. It also reduces the chance of a fire from oily debris. Do not allow oily rags to accumulate. Place them in a secure, self-closing fireproof safety container. Place all trash, defective parts, and paper debris in a waste can. Recyclable core parts should be kept in a location away from the primary work areas.

Return all tools and equipment to their proper storage places. This saves time in the long run, as well as reducing the chance of accidents, damage, and theft. Do not leave any pieces of equipment where others could trip on them. If tools are dirty or oily, clean them before you put them away. This will not only extend the life of the tool, but is also a courtesy to others who use them. Never use a damaged tool or piece of equipment—report any damaged shop equipment immediately. Remove creepers from the floor area when not in use. Always be aware of and follow all safety rules when using any piece of equipment. If you do not know how to use a piece of equipment, read the manufacturer's instruction manual before use. Use all tools properly; more accidents are caused by the improper use of hand tools than the improper use of power tools.

Clean up any spilled oil, grease, diesel fuel, coolant, or other fluids from the floor immediately. Many people are injured when they slip on floors coated with oil, fuel, antifreeze, or water. Do not leave open containers of any chemical in the shop or outside.

Vehicle Safety Rules

Move vehicles very slowly (about 2 mph) in and out of the shop, checking to see that no one is in the way.

Get someone to help you guide the vehicle in and out of the shop. Do not step in the path of a moving vehicle. Do not work beneath a vehicle that does not have properly installed jack stands, **Figure 2-5.** Do not stand under a rack or lift unless safety pins are in place. When lifting the hood of a heavy-duty truck, be sure that it is in a locked position and is well supported, **Figure 2-6.**

When lifting an engine from a vehicle, be sure that the lift or crane has the proper lift capability to do the job, **Figure 2-7**. Be certain all throttle linkage connections are intact and all fuel lines are connected before cranking the engine. When running an engine in the shop, it must have an exhaust hose connected to the outside for proper ventilation, **Figure 2-8.** If the shop is not properly ventilated, ***carbon monoxide*** will quickly build up, possibly causing death. Never leave a running vehicle unattended.

Some vehicle systems operate on voltage and current levels that are high enough to cause severe injury or electrocution. For example, the electronic injection systems on some engines operate on as many as 150 volts and 10 amps. Similarly, the startup voltage of HID lighting systems may exceed 20,000 volts. When working on these systems, take all the precautions recommended by the vehicle manufacturer. Make sure battery voltage has been disconnected from the system and that any residual voltage in the system has been discharged. Hybrid diesel-electric vehicles operate on extremely high voltages. Before servicing these vehicles, be sure to disable their high-voltage systems. Follow all the manufacturers recommended safety and service procedures. Always wear insulated lineman's gloves rated at 1000 volts when working on or near live high-voltage circuits on a hybrid vehicle.

To prevent accidental air bag deployment, use caution when working on vehicles equipped with supplemental restraint systems (SRS). Follow the manufacturer's instructions for disabling the SRS before attempting to work on or near

Figure 2-5. *Jack stands should be used whenever you must work under a vehicle. Be sure to locate them under the vehicle's frame, not under a drivetrain or suspension part. (Snap-On Tools)*

Figure 2-6. *When working on an engine, be sure that the hood is in the locked position and is well supported. (Daimler AG)*

Figure 2-7. *When removing an engine, use a lift that is rated to do the job. This lift is sometimes referred to as a "cherry picker." (Snap-On Tools)*

Figure 2-8. *Carbon monoxide can quickly build up in a shop, causing asphyxiation and possibly death. Always use exhaust hoses to vent these gases, even if the engine will be running for only a few seconds. (Nederman, Inc.)*