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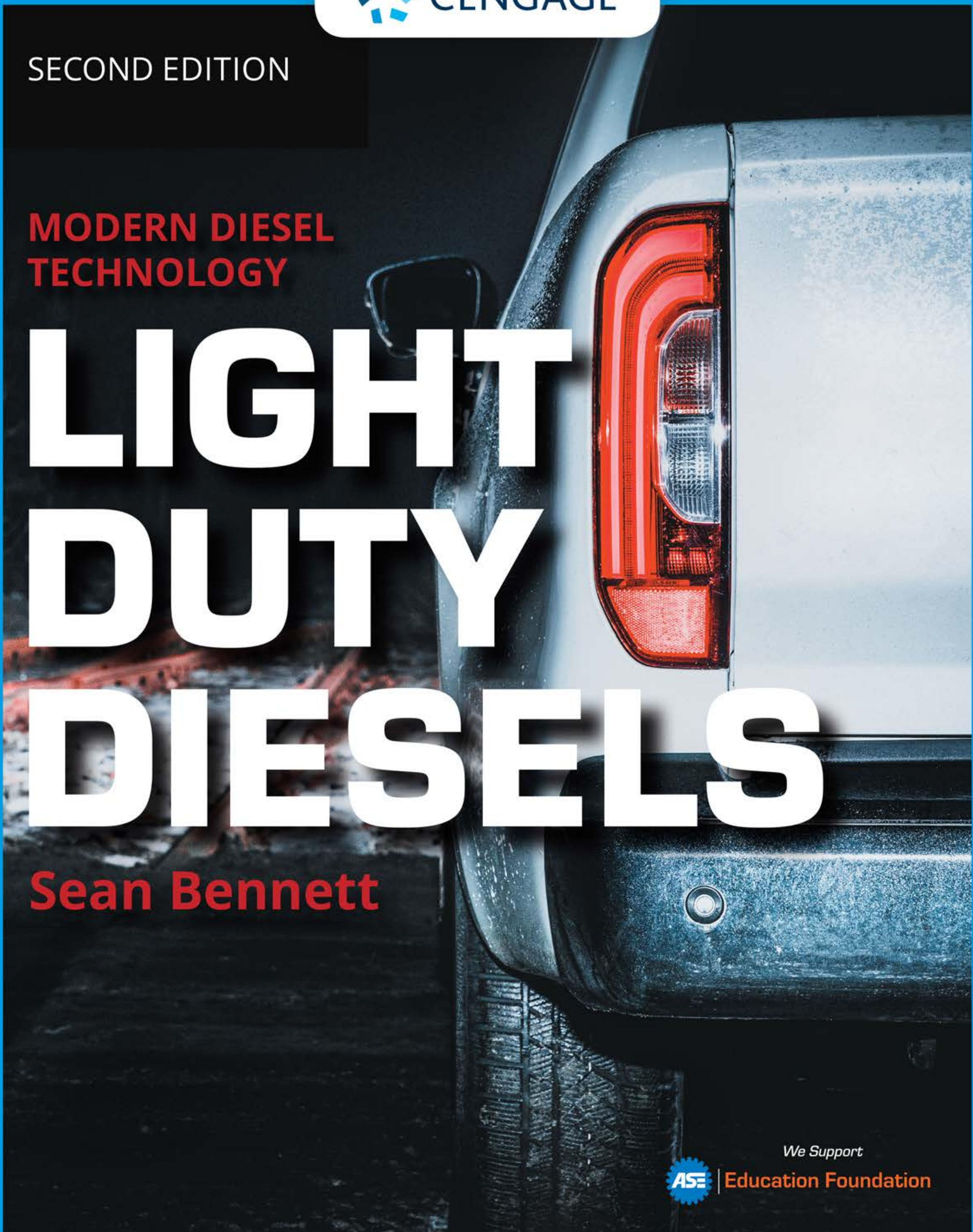
SECOND EDITION

MODERN DIESEL TECHNOLOGY

LIGHT DUTY DIESELS

Sean Bennett



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Sean Bennett

SVP, Higher Education & Skills Product: Erin Joyner

Product Director: Matthew Seeley

Senior Product Manager: Katie McGuire

Senior Product Assistant: Kimberly Klotz

Director, Learning Design: Rebecca von Gillern

Senior Manager, Learning Design: Leigh Hefferon

Learning Designer: Mary Clyne

Marketing Director: Sean Chamberland

Marketing Manager: Andrew Ouimet

Director, Content Creation: Juliet Steiner

Content Creation Manager: Alexis Ferraro

Senior Content Manager: Meaghan Tomaso

Digital Delivery Lead: Amanda Ryan

Art Director: Jack Pendleton

Text Designer: Erin Griffin

Cover Designer: Erin Griffin

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PREFACE

While the sales of automotive diesel-powered automobiles fell to close to zero after the 2015 emissions cheating scandal, this did not impact diesel sales of light-duty trucks which continued to rise at a consistent pace. This pace has recently accelerated since the big three (Ford, GM, and Dodge) leaders in pickup truck sales have all added 3-liter diesel engines to their lineups.

Because the American consumer has traditionally regarded diesels as workhorse powerplants, most diesel engine sales until now were in the vocational pickup truck segment of the highway market. These diesels had a displacement of around 6-liters and were engineered for high torque and tough service. With the introduction of a new generation 3-liter displacement, non-vocational consumers looking for fuel efficiency, engine longevity, and chassis life are being tempted to consider diesel power. The bottom line is that the technology exists to enable a diesel engine to equal or better, the harmful exhaust emissions of gasoline and alternate fueled engines providing current statutory standards are observed.

In off-highway applications, light duty diesel power has always fared well. New generation electronically-controlled diesel out-powered and out-torque their gasoline-fueled rivals while providing greater longevity with lower maintenance. Farmers have the least reason to mistrust the diesel engine because for more than half a century, diesels have powered a large percentage of agricultural equipment. Accordingly, the farmer is the most likely consumer to consider diesel power in the family pickup truck. Light-duty diesel engines have also been used in construction applications for generations for reasons of reliability and extended service life.

Although the sales of diesel engines in automobiles in North American markets were never really significant, this was not the case in Europe and Asia until 2015. In some countries, notably Italy, more than half of automobiles sold were powered by diesels. On that note, it is ironic that the company that best publicized automobile diesels on the world stage (VW Audi diesel powered race cars dominated the grueling 24-hour Le Mans circuit for years) was primarily responsible for its demise in 2015.

New to This Edition

- Hands-on shop tasks are clearly identified by section headings throughout the textbook.
- Expanded coverage of common rail diesel fuel systems, detailed explanations of piezo-electric actuated injectors, and diagnostic testing of electro-hydraulic injectors.
- OSHA-mandatory LOTO compliance procedures are emphasized and outlined in detail.
- Detailed examination of MY2020 diesel exhaust aftertreatment systems including diagnostic and repair strategies.
- Up-to-date coverage of engine electronics including descriptions of PCU-based voltage divider circuits and acoustic sensors.
- Introduction to PicoScope diagnostics and how they are used in electrical and electronic troubleshooting.
- Simple language and clear explanations focus on the competency tasks required by the modern diesel technician targeting A9 certification with no side-tracking into unnecessary engineering detail. Covers ALL the current A9 task competencies ranging from the most recent electronic common rail engines to legacy PLN, EUI, and HEUI managed engines.
- From legacy engines to the latest MY2020 diesels, and electronically guided diagnostics, the text is designed to help students develop the skills required to work effectively with the diesel engines used in highway pickup trucks, school buses, light-duty off highway mobile equipment, reefer powerplants, and small stationary engines.
- Extensive use of color images and schematics that directly connect with the competencies discussed and provides step-by-step, hands-on content
- New photosequences guide learners through common workshop service procedures including the testing of CR injectors.
- Comprehensive glossary and acronyms dictionary that includes all the key terms used in the text, plus clear explanations of the terminology used in the industry.

ASE A9 Certification

While the focus of this book is primarily on the 2020 crop of light-duty, highway diesel engines, some text is devoted to some of the earlier electronic and hydromechanical diesels. This is so for two reasons:

- Diesel engine longevity
- ASE A9 competency certification standards

ASE A9 competency tasks rightly continue to address legacy electronic and hydromechanical diesel engine technologies because they significantly outlast their gasoline-fueled equivalents. The amount of service and repair time increases for vehicles proportionate with age, so diesel technicians are going to see these vehicles in service facilities more often.

Organization of Contents

Special attention is devoted to the Ford 6.7 and 3.0 liter engine families largely because the Ford Motor Company has traditionally been more proactive in supporting educators with teaching support and educational tools. It should be noted that current Ford, GM, and Dodge diesels use common rail (CR) fuel systems manufactured by Bosch. Exhaust gas aftertreatment systems are also highlighted. Today's stringent emissions requirements require an elaborate range of pre-combustion, in-combustion, and post-combustion apparatus to be fitted on engines. These are studied from a technician's perspective because there is a higher incidence of repair orders required for emission control problems than other engine systems on current vehicles.

Multiplexing is a fact of life in any current vehicle and all technicians are required to have a basic understanding of system networking. For this reason, the light-duty generations of CAN technology are included. It is a challenge to make complex electronics technology understandable, so I have adopted a "have-to-know" approach in attempting to make CAN-A, CAN-B, J1850, and CAN-C easier to digest.

Modern Diesel Technology: Light Duty Diesels covers all the task fields required by ASE A9 certification. For this reason, much of the book is dedicated to hands-on competency. Tech tips and highlighted service procedures appear throughout the book with the objective of helping technicians to both understand and undertake service tasks. In addition, to a detailed maintenance and troubleshooting chapter, students are prompted to navigate OEM online service information and diagnostic systems, along with instructions on how to use some of the electronic service tools that are essential in today's shop environments. Throughout the book, the objective is to provide the key theory required to enable sound hands-on shop floor skills, presented in a user-friendly manner.

Sean Bennett, July 2020

About the Series

The Modern Diesel Technology (MDT) series was developed to address a need for system-specific textbooks in the field of diesel engine, truck, and heavy equipment technology. This focused approach gives learning programs more flexibility in designing syllabi that target specific ASE certifications. Because each textbook in the series focuses exclusively on the competencies identified by its title, the series is an ideal review and study vehicle for technicians prepping for certification examinations.

Current titles in the Modern Diesel Technology Series include:

MDT: Electricity and Electronics, by Joe Bell; ISBN: 9781133949800

MDT: Heating, Ventilation, Air Conditioning, and Refrigeration, by John Dixon; ISBN:1401878490

MDT: Electronic Diesel Engine Diagnosis, by Sean Bennett; ISBN: 9781401870799

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MDT: Preventive Maintenance and Inspection, by John Dixon; ISBN: 9781418053918

MDT: Mobile Equipment Hydraulics: A Systems and Troubleshooting Approach, by Ben Watson; ISBN: 9781418080433

MDT: Light Duty Diesels, by Sean Bennett; ISBN: 9781337624978

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CHAPTER 1

Shop and Personal Safety

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Explain the importance of safety awareness for diesel technicians.
- Describe the importance of maintaining a healthy personal lifestyle.
- Identify the PPE required for working in a diesel shop.
- Describe a typical lockout/tagout policy.
- Distinguish between different types of fire.
- Identify the fire extinguishers required to suppress small-scale fires.
- Describe how to use jacks and hoisting equipment safely.
- Explain the importance of using exhaust extraction piping.
- Identify what is required to work safely with chassis electrical systems and shop mains electrical systems.
- Outline the safety procedures required to work with oxyacetylene torches.
- Interpret common workplace safety symbols and emoji.

KEY TERMS

chain hoist
cherry picker
come-alongs
digital multimeter (DMM)
electronic service tool (EST)
green triangle
ground strap
hydraulic boom hoist
lockout tagout (LOTO)
orange omega
Occupational Safety and Health Administration (OSHA)
original equipment manufacturer (OEM)
personal protective equipment (PPE)
single-phase mains
static charge
static discharge
three-phase mains
Underwriter's Laboratories (UL)

Why Read This?

Although employers are mandated to ensure a safe environment, workplace safety is first and foremost a personal responsibility. Keep that thought in mind and your chances of injury will be minimized.

The mechanical repair trades are physical by nature, and those employed as technicians probably have higher-than-average levels of personal fitness. While there are some heavy components on most vehicles, technicians in the modern workplace are never required to lift excessive weights. They are required to understand when and how to use shop jacks and hoisting equipment. Technicians should also make it their business to safely handle materials that can be hazardous. It goes without saying that employers are required to ensure that the shop floor is a safe working environment. Employers who fail to ensure a safe working environment are both breaking the law and endangering their profitability.

Safety Rules

If you look around any service repair shop today, you will notice safety rules and regulations posted on walls and bulletin boards. Although these are posted for maximum exposure, the responsibility to work safely rests with the individual. A large part of safe working practice is common sense. But it is up to the individual to observe these common-sense rules and regulations. It simply does not make sense to take risks when safety is an issue. Those who do, sooner or later get hurt by poor decisions, sometimes fatally.

Experience and Injuries

Most technicians do not want to get hurt in the workplace or anywhere else. But knowing something about potential danger minimizes the risk of injury. A major automotive **original equipment manufacturer (OEM)** monitored accidents in its assembly plants and came up with the following conclusion: line-production employees' risk of serious injury (defined as one that required some time off work) during the first year of employment was equal to that of years 2 through 6 combined. In simple terms, if you can survive your first year injury-free, your risk thereafter diminishes.

Safety Awareness

Teachers of mechanical technology often complain that it is difficult to teach safe work practices to entry-level students. When students enroll in an automotive technology program, they appear to be well motivated to learn the technology but tend to tune out when it comes to learning the health and safety issues that accompany working life. The sad truth is that it is difficult to teach safe work practices to persons who have never been injured. On the other hand, a person who has been injured probably has acquired, along with the injury, a powerful motivation to avoid a repetition.

A Healthy Lifestyle

Repairing vehicles requires more physical strength than working at a desk all day, but it would be a mistake to say it was a healthy occupation. Lifting a 150 lb (70 kg) cylinder head or pulling a high load on a torque wrench requires some muscle power, but you cannot compare this with lifting weights in a gym. In the weight room, the repetitions, conditions, and movements are carefully coordinated to develop muscle power. Jerking on a torque wrench attempting to establish final torque on main caps on an engine job can tear muscle as easily as develop it.

It pays to think about how you use your body and use your surroundings to maximize leverage and minimize wear and tear. Make a practice of using hoists to move heavier components, even if you know you could manually lift the component. You may believe it is macho to lift a cylinder head off a block by hand, but it only takes a slight twist of the back while doing so to sustain an injury that can last a lifetime. There is nothing especially macho about hobbling around with chronic back pain for years.

Physical Fitness

Part of maintaining a healthy lifestyle means eating properly and making physical activity a part of your lifestyle. There are many different ways of achieving this. Team sports are not just for kids and teenagers. Whether your sport is hockey, baseball, basketball, or football, there are plenty of opportunities to compete through all ages and levels. If team sports are not your thing, there are many individual pursuits that you can explore. Working out in a gym, hiking, and canoeing are good for your mind as well as your body, and even golf gets you outside and walking. Because of the physical nature of repair technology, it makes sense to routinely practice some form of weight conditioning, especially as you get older.

Personal Protective Equipment

Personal protective equipment (PPE) refers to anything you wear on your body in the workplace. Some items of personal safety should be worn continually in the workplace. One of these essential items is safety shoes or footwear. Other personal protective equipment such as hearing protection may be worn only when required, for instance when noise levels are high.

Safety Boots

Safety boots or shoes are required footwear in a repair shop. Most jurisdictions require technicians to wear safety footwear. It is an employer responsibility to make sure this happens. Safety footwear is manufactured with steel shanks, steel toes, and UL (Underwriter's Laboratories: www.ul.com) or CSA (Canadian Safety Association) certification. Safety is about you. If you lose a limb in the workplace, your whole life will be affected by the event. Even if

FIGURE 1–1 A safety boot displaying UL and CSA approval insignia.

the law did not require you to wear safety footwear, common sense should tell you that your feet should be protected in a shop environment. Given the choice, safety boots (see **Figure 1–1**) can generally be regarded as a better choice than safety shoes because of the additional support and protection for the ankle area.

There is a range of options when it comes to selecting safety footwear. There is also a wide range of prices. The safety boots shown in Figure 1–1 display a **green triangle** denoting them as a Class 1 shoe with a steel toe and puncture resistant sole. The **orange omega** symbol indicates that the shoe is suitable for environments where there is some danger of high voltage electrical conductivity. Note that better-quality safety footwear lasts longer and tends to be more comfortable.

Safety Glasses

Many shops today require all their employees to wear safety glasses while on the shop floor. This is really just common sense. Eyes are sensitive to dust, metal

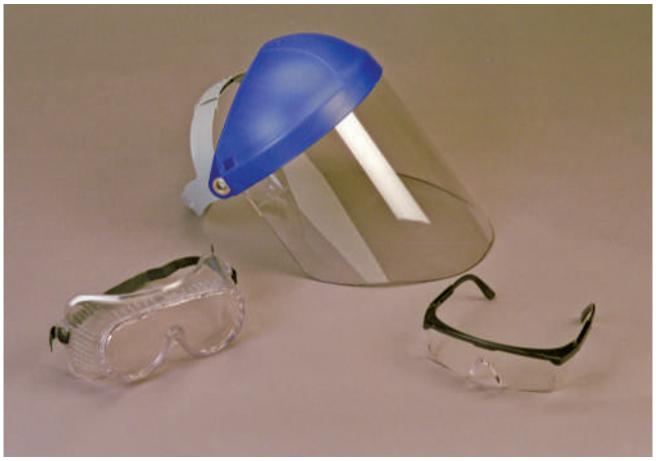


FIGURE 1–2 Safety glasses, splash goggles, and face shields are all approved methods of protecting your eyes.

shavings, grinding and machining particulates, fluids, and fumes. They are also more complex to repair than feet when injured. It also makes sense to wear safety glasses when working with chassis electrical equipment because of the potential danger represented by battery acid and arcing at terminals.

Perhaps the major problem when it comes to making a habit of using safety glasses is the poor quality of most shop-supplied eyewear. Shops supply safety glasses because in many cases they are legally liable if they do not. All too often, this means they provide low-cost, mass-produced, and easily scratched plastic safety glasses. If you have a pair of safety glasses that impairs your vision, you will probably want to wear them as little as possible. A pair of safety glasses in your pocket is not going to protect you from eye injuries.

Don't Be Cheap!

The solution is not to depend on your employer to provide safety glasses. Get out of the mind-set that safety glasses should be provided to you at no cost. As we have said, "free" safety glasses are uncomfortable and may actually impair vision. Buy your own. Spend a little more and purchase a good quality pair of safety glasses. These will be optically sound and scratch proof. Even if you do not normally wear eyeglasses, after a couple of days, you will forget you are wearing them. **Figure 1–2** shows some eye protection options available to technicians.

Hearing Protection

Two types of hearing protection are used in shops. Hearing muffs are connected by a spring-loaded band and enclose the complete outer ear. This type of hearing protection is available in a range of qualities.

FIGURE 1–3 Hearing protection.

Cheaper versions may be almost useless, but good-quality hearing muffs can be very effective when noise levels are extreme. But be careful. Hearing muffs that almost completely suppress sound can be dangerous because they disorientate the wearer.

A cheaper and generally effective alternative to hearing muffs is ear sponges. Each sponge is a soft cylindrical or conical sponge. The sponge can be shaped for insertion into the outer ear cavity. Almost immediately after insertion, the sponge expands to fit the ear cavity. The disadvantage of hearing sponges is that they can be uncomfortable when worn for long periods. Technicians should also consider using other types of soft earplugs, most of which are wax based. **Figure 1–3** shows some types of earmuffs and earplugs.

CAUTION

Damage to hearing is seldom the result of a single exposure to a high level of noise. More often, it results from years of exposure to excessive and repetitive noise levels. Protect your hearing! And note that hearing can be damaged by listening to music at excessive volume as easily as exposure to buck riveting.

Gloves

A wide range of gloves can be used in shop applications to protect the hands from exposure to dangerous or toxic materials and fluids. The following are some examples.

CAUTION

Never wear any type of glove when using a bench-mounted, rotary grinding wheel: there have been cases where a glove has been snagged by the abrasive wheel, dragging the whole hand with it.

Vinyl Disposable

Most shops today make vinyl disposable gloves available to service personnel. These protect the hands from direct exposure to fuel, oils, and grease. The disadvantage of vinyl gloves is that they do not breathe, and some find the sweating hands that result to be uncomfortable. Most shop-use vinyl gloves today are made of thin gossamer that allows some touch sensation.

Cloth and Leather Multipurpose

A typical pair of multipurpose work gloves consists of a rough leather palm and cotton back. They can be used for a variety of tasks ranging from lifting objects to general protection from cold when working outside. You should not use this type of glove after saturation with grease or oil.

Hazardous Materials Gloves

Gloves designed to handle acids or alkalines should be used for these tasks only. Gloves in this category are manufactured from unreactive, synthetic rubber compounds. Care should be taken when washing up after using this type of glove.

CAUTION

Never wear leather gloves to handle refrigerants: leather gloves rapidly absorb refrigerant and can adhere to the skin.

Back Care

Back injuries are said to affect 50 percent of repair technicians at some point in their careers seriously enough for them to have to take time off work. A bad back does not have to be an occupational hazard. Most of us begin our careers in our twenties when we have sufficient upper-body strength to handle plenty of abuse. As we age, this upper-body strength decreases, and bad lifting practices can take their toll.

Observe some simple rules for lifting heavy items:

- Keep your back vertical while lifting (do not bend).
- Keep the weight you are lifting close to your body.
- Bend your legs and lift using the leg muscles.

Figure 1–4 shows how to protect your back when lifting heavy objects: one of the keys is to hold the weight as close to your body as you can get it.

Back Braces

A back brace may help you avoid injuring your back. Wearing a back brace makes it more difficult to bend your back, so it “reminds” you to keep it straight when

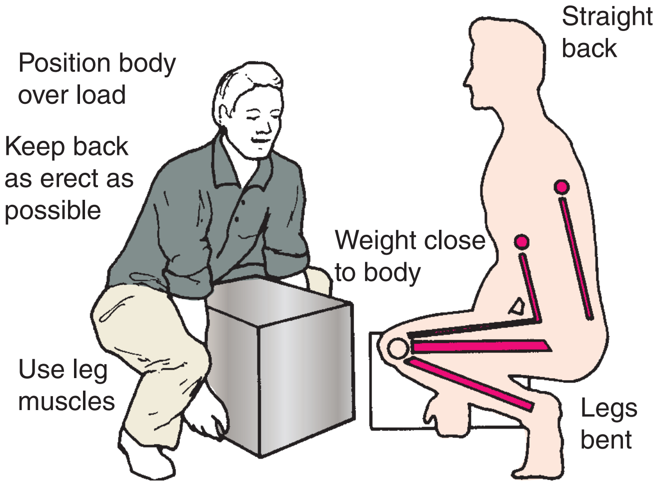


FIGURE 1–4 Use your leg muscles, never your back, when lifting any heavy load.

lifting. You may have noticed that the sales personnel in one national hardware and home goods chain are all required to wear back braces. As an automotive technician, you will be required to use your back for lifting, so you should consider the use of a back brace. Body shape plays a role when it comes to back injuries: if you are either taller than the average height or overweight, you will be more vulnerable to back injuries.

Coveralls and Shop Coats

Many shops today require their service employees to wear a uniform of some kind. This may be work shirts and pants, shop coats, or coveralls. Uniforms have a way of making service personnel look professional. Shop workwear should preferably be made out of cotton for reasons of comfort and safety. When ordering work clothing for personal use, remember to order at least a size larger than your usual nominal size: unless otherwise treated, cotton shrinks when washed. Shop coats can also be used, but because these come pretty close to our definition of loose clothing they are a second-best choice to coveralls.

CAUTION

Avoid wearing any type of loose-fitting clothing when working with machinery. Shop coats, neckties, and not tucking a shirt into pants can all be classified as loose-fitting clothing.

Artificial Fibers

When artificial fibers are used as material for coveralls, they should be treated with fire retardant. Cotton smolders when exposed to fire. That is, it smolders so long as it is not saturated with oil, fuel, or grease. When any material is saturated with petroleum products, it becomes highly flammable. Cleanliness is essential: oily shop clothing not only looks unprofessional, it can be dangerous!

Artificial fibers can be especially dangerous. When not treated with fire retardant, artificial fibers melt when exposed to high temperatures. This can cause them to fuse to the skin. You should note that even when treated with fire retardant, some artificial fibers will burn vigorously when exposed to direct flame for a period of time.

CAUTION

Note that even when treated with fire retardant, some artificial fibers will burn vigorously when exposed to direct flame for a period of time.

Butane Lighters

There are few more dangerous items routinely observed on the shop floor than the butane cigarette lighter. The explosive potential of the butane lighter is immense yet it is often stored in a pocket close to where it can do the most amount of damage. A chip of hot welding slag will almost instantly burn through the plastic fuel cell of a butane lighter. Owners of these devices will often compound the danger they represent by lighting torches with them. If you have to have a lighter on your person while working, purchase a Zippo!

Hair and Jewelry

Long hair and personal jewelry produce some of the same safety concerns as loose-fitting clothing. If it is your style to wear long hair, it should be secured behind the head, and you should consider wearing a cap. Because of the recent trend to wear more body jewelry, you should remove as much as possible of this while at work. Body jewelry is often made of conductive metals (such as gold, platinum, silver, and brass), so you should consider both the possibility of snagging jewelry and of creating some unwanted electrical short circuits.

First Aid and LOTO

Most larger companies provide their mechanical technicians with some basic first aid skills training but it should be understood that first aid is no more than assisting with an injury until a qualified person can take over. Local ambulance and hospital contact information should be posted on the shop bulleting board. Shop LOTO procedure is required by OSHA and this is also explained in this section.

First Aid

Because of the nature of the work in service facilities, it makes sense that all technicians receive first aid training. The training program should educate non-professionals on how to handle minor workplace injuries and when to seek assistance. Because mechanical technicians work with abrasive power tools, impact tools, and corrosive chemicals such as battery acid, a key item of safety equipment is an eyewash station such as that shown in **Figure 1–5**. Technicians should be schooled in how to use an eyewash station from day one on the shop floor.

Lockout/Tagout

Lockout, tagout (LOTO) is a vehicle securement procedure designed to minimize the potential for accidents while a vehicle is being serviced. The **Occupational Safety and Health Administration (OSHA)** describes LOTO as being shop procedures used to control the release of hazardous energy. All shops should display an easy to interpret LOTO procedure that is integrated into workplace policy.

FIGURE 1–5 An eyewash station is a key requirement for any vehicle service facility: all technicians should be trained when and how to use the station from day one in the workplace.

LOTO Coverage

LOTO addresses the unwanted release of uncontrolled energy and it applies to both mobile and stationary equipment in the workplace. It includes:

- Tire repairs (dismount and pressurizing)
- High voltage safety
- Mechanical energy (gravity and potential)
- Fluid power (hydraulic and pneumatic)
- Loss of fluid power
- Thermal energy (fire and explosives)
- Chemical energy (contact with corrosives and toxins)

Because there is some variability of the type of work done in each distinct workplace, there is no universal set of LOTO guidelines. But it is a service shop requirement and it is essential that every employee be trained to understand and use the shop's LOTO regulations. **Figure 1–6** shows a simple lockable clamp that is a basic LOTO device: the technician installing the device would be typically identified by employee number and telephone contact.

FIGURE 1–6 A LOTO lock-clamp with tag for technician ID.

Fire Safety

Service and repair facilities are usually subject to regular inspections by fire departments. This means that obvious fire hazards are identified and neutralized. While it should be stressed that fire fighting is a job for trained professionals, any person working in a service shop environment should be able to appropriately respond to a fire in its early stages. This requires some knowledge of the four types of fire extinguishers in current use.

Fire Extinguishers

Fire extinguishers are classified by the types of fires they are designed to suppress. Using the wrong type of fire extinguisher on certain types of fires can be extremely dangerous and actually worsen the fire you are attempting to control. Every fire extinguisher clearly indicates the types of fires it is designed to extinguish. This is done by using class letters. This means that it is important to identify each of the four types of fires that could occur in the workplace. The role of the technician in suppressing a fire is to estimate the risk required. Intervention should only be considered if there is minimal risk.

Class A — A class A fire is one involving combustible materials such as wood, paper, natural fibers, biodegradable waste, and dry agricultural waste. A class A fire can usually be extinguished with water. Fire extinguishers designed to suppress class A fires use foam or a multipurpose dry chemical, usually sodium bicarbonate.

Class B — Class B fires are those involving fuels, oil, grease, paint, and other volatile liquids, flammable gases, and some petrochemical plastics. Water should not be used on class B fires. Fire extinguishers designed to suppress type B fires work by smothering: they use foam, dry chemicals, or carbon dioxide. Trained fire personnel may use extinguishers such as Purple K (potassium bicarbonate) or halogenated agents to control fuel and oil fires.

Class C — Class C fires are those involving electrical equipment. First intervention with this type of fire should be to attempt to shut off the power supply: assess the risk before handling any switching devices. When a class C fire occurs in a vehicle harness, combustible insulation and conduits can produce highly toxic fumes, so great care is required when making any kind of intervention with electrical fires in vehicle chassis or buildings. Fire extinguishers designed to suppress electrical fires use carbon dioxide, dry chemical powder, and Purple K.

Class D — Class D fires are those involving flammable metals: some metals when heated to their fire point begin to vaporize and combust. These metals include magnesium, aluminum, potassium, sodium, and zirconium. Dry powder extinguishers should be used to suppress class D fires.

Figure 1–7 shows the symbols used to categorize each type of fire and the types of fire suppressant required to put each out.

Shop Equipment

There is an extensive assortment of shop equipment that technicians should become familiar with: some of this can be dangerous if you are not trained to use it. Make a practice of asking for help if you must operate any equipment with which you are not familiar.

Lifting Devices

Many different types of hoists and jacks are used in automotive shops. These can range from simple pulley and chain hoists to hydraulically actuated hoists. Weight-bearing chains on hoists should be routinely inspected (this is usually required by law). Chain links with evidence of wear, bent links, and nicks are reason enough to place the equipment out of service. Hydraulic hoists should be inspected for external leaks before using. Any drop-off observed in hydraulic lifting equipment while in operation should be reason to take the equipment out of service. Never rely on the hydraulic circuit alone when working under equipment on a hoist: after lifting, support the equipment using a mechanical sprag or stands.

CAUTION

Never rely on a hydraulic circuit alone when working underneath raised equipment. Before going under anything raised by hydraulics, make sure it is mechanically supported by stands or a mechanical lock.

Class of Fire	Description of Fire	Typical Fuel Involved	Type of Extinguisher
Class A Fires	**For Ordinary Combustibles** Put out a Class A fire by lowering its temperature or by coating the burning combustibles.	Wood Paper Cloth Rubber Plastics Rubbish Upholstery	Water*[1] Foam* Multipurpose dry chemical[4]
Class B Fires	**For Flammable Liquids** Put out a Class B fire by smothering it. Use an extinguisher that gives a blanketing, flame-interrupting effect; cover whole flaming liquid surface.	Gasoline Oil Grease Paint Lighter fluid	Foam* Carbon dioxide[5] Halogenated agent[6] Standard dry chemical[2] Purple K dry chemical[3] Multipurpose dry chemical[4]
Class C Fires	**For Electrical Equipment** Put out a Class C fire by shutting off power as quickly as possible and by always using a nonconducting extinguishing agent to prevent electric shock.	Motors Appliances Wiring Fuse boxes Switchboards	Carbon dioxide[5] Halogenated agent[6] Standard dry chemical[2] Purple K dry chemical[3] Multipurpose dry chemical[4]
Class D Fires	**For Combustible Metals** Put out a Class D fire of metal chips, turnings, or shavings by smothering or coating with a specially designed extinguishing agent.	Aluminum Magnesium Potassium Sodium Titanium Zirconium	Dry powder extinguishers and agents only

**Cartridge-operated water, foam, and soda-acid types of extinguishers are no longer manufactured. These extinguishers should be removed from service when they become due for their next hydrostatic pressure test.*

Notes:

(1) Freezes in low temperatures unless treated with antifreeze solution, usually weighs over 20 pounds (9 kg), and is heavier than any other extinguisher mentioned.

(2) Also called ordinary or regular dry chemical (sodium bicarbonate).

(3) Has the greatest initial fire-stopping power of the extinguishers mentioned for Class B fires. Be sure to clean residue immediately after using the extinguisher so sprayed surfaces will not be damaged (potassium bicarbonate).

(4) The only extinguishers that fight A, B, and C classes of fires. However, they should not be used on fires in liquefied fat or oil of appreciable depth. Be sure to clean residue immediately after using the extinguisher so sprayed surfaces will not be damaged (ammonium phosphates).

(5) Use with caution in unventilated, confined spaces.

(6) May cause injury to the operator if the extinguishing agent (a gas) or the gases produced when the agent is applied to a fire is inhaled.

FIGURE 1–7 Guide to fire extinguisher selection.

Jacks

Many types of jacks are used in automotive service facilities. Before using a jack to raise a load, make sure that the weight rating of the jack exceeds the supposed weight of the load. Most jacks used in service repair shops are hydraulic, and most use air-over-hydraulic actuation because this is faster and requires less effort. Bottle jacks are usually hand-actuated and designed to lift loads up to 10 tons (1.02 tonnes): they are so named because they have the appearance of a bottle. Air-over-hydraulic jacks capable of lifting commercial vehicles are also available.

Using hydraulic piston jacks should be straightforward. They are designed for a vertical uplift only. The jack base should be on level floor and the lift piston should be located on a flat surface on the equipment to be lifted. Never place the lift piston on the arc of a leaf spring or the radius of any suspension device on the vehicle. After lifting the equipment, it should be supported mechanically using steel stands. It is acceptable practice to use a hardwood spacer with a shop jack: it should be exactly level and placed under the jack. Whenever using a jack to raise one end of a vehicle, make sure that the vehicle being jacked can roll either forward or backward. After lifting, the parking brakes should be applied and wheel chocks should be used on the axles not being raised.

Hydraulic Boom Hoists

Hydraulic boom hoists also known as **cherry pickers** come in many shapes and sizes. Light duty boom hoists such as that shown in **Figure 1–8** can be used to raise a component such as a cylinder head from an engine, while heavy duty hoists can lift a complete diesel engine out of a chassis. Most boom hoists have extendable booms. As the boom is lengthened, the weight that the device can lift reduces. Take care that the weight you are about to lift can be raised by the cherry picker without toppling.

WARNING

As the boom of a boom hoist is lengthened, the weight it can lift reduces significantly. Make sure that the weight you are about to lift is appropriate for the boom length you have set: failure to do this can cause the cherry picker to topple.

Chain Hoists

These are often called chain falls. **Chain hoists** can be suspended from a fixed rail or a beam that slides on rails, or they can be mounted on any of a number of different types of A-frames. Chain hoists in shops in most jurisdictions are required to be inspected periodically. An inspection on a mechanical chain hoist will include chain link integrity and the ratchet teeth and lock. Electromechanical units will require an inspection of the mechanical and electrical components. Where a chain hoist beam runs on rails, brake operation becomes critical: some caution is required when braking the beam because aggressive braking can cause a pendulum effect on the object being lifted.

Come-Alongs

Come-alongs describe a number of different types of cable and chain-lift devices that are hand-ratchet actuated. They are used both to lift objects and to apply linear force to them. When used as lift devices,

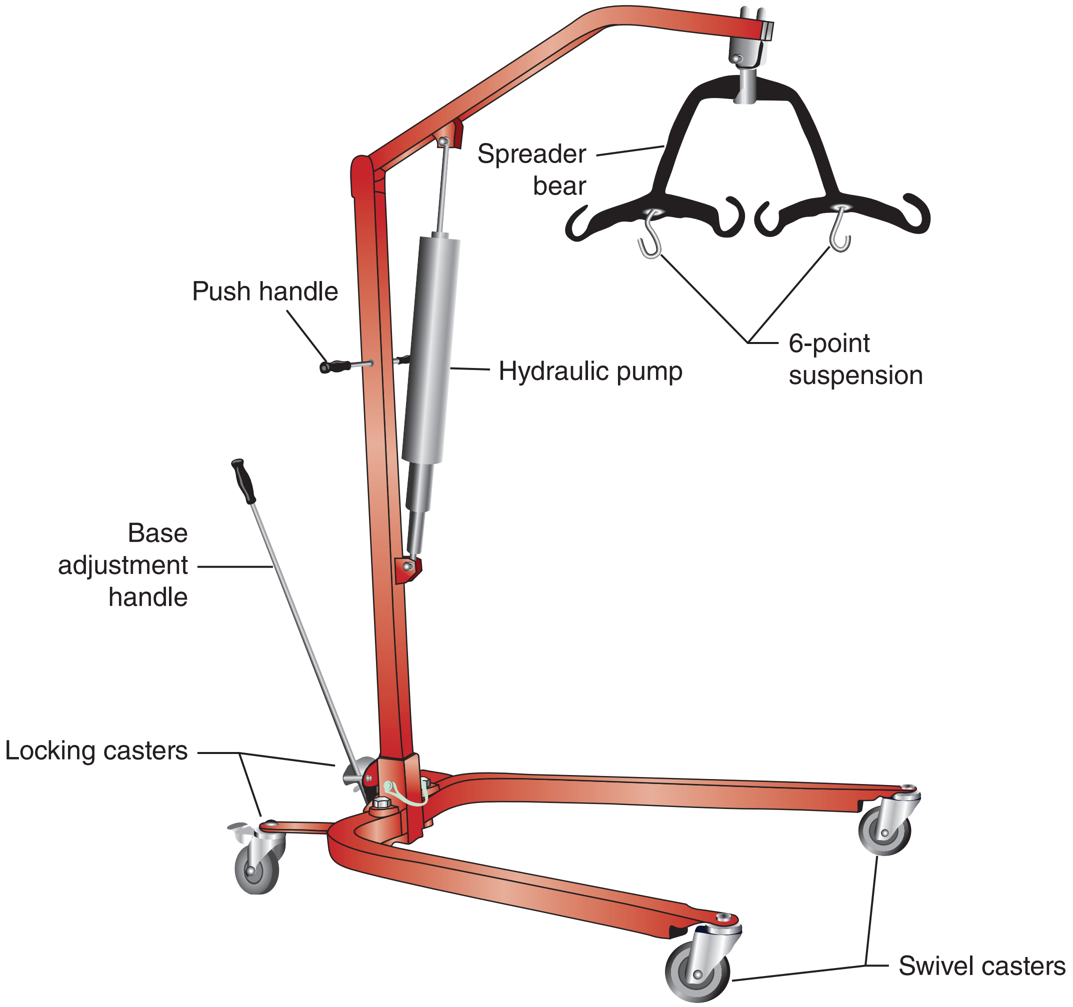


FIGURE 1–8 Light duty hydraulic boom hoist.

come-alongs should be simple to use, providing the weight being lifted is within rated specification. However, come-alongs are more often used in automotive shops to apply straight-line force to a component, usually to separate flanges. Great care should be taken: make sure that the anchor and load are secure and that the linear force does not exceed the weight rating of the device.

WARNING

Diesel exhaust fumes have been proven to cause respiratory problems, cancer, birth defects, and other reproductive harm in humans. Avoid operating diesel engines unless in a well-ventilated area. When starting an engine outside a shop, warm the engine before driving it into the shop to reduce the contaminants emitted directly into the shop while parking the unit.

General Shop Precautions

Every service facility is different and because of that the potential dangers faced in each shop will differ. In this section, we will outline some general rules and safety strategies to be observed in truck and heavy equipment shops.

Exhaust Extraction

Engines should be run in a shop environment using an exhaust extraction system: in most cases, this will be a flexible pipe or pipes that fit over the vehicle exhaust pipes(s). When moving vehicles in and out of service bays, park the unit in the bay and shut the engine off. Avoid running an engine without the extraction pipe(s) fitted to the stack(s). **Figure 1–9** shows the operating principle of an exhaust extraction pipe: both stationary and portable systems may be used.

WARNING

When attempting to fit an exhaust extraction pipe to a vehicle exhaust system, check the temperature of the exhaust gas aftertreatment piping before attempting to handle it: diesel particulate filters can retain heat long after a regeneration cycle and cause severe burns.

Workplace Housekeeping

Sloppy housekeeping can make your workplace dangerous. Clean up oil spills quickly. You can do this by applying absorbent grit: this not only absorbs oil but makes it less likely that a person will slip and fall on an oil slick. Try to organize parts in bins and on benches when you are disassembling components. This not only makes reassembly easier, it makes your work environment a lot safer.

FIGURE 1–9 Shop exhaust fumes removal.

Components Under Tension

Even on light duty commercial vehicles, many components are under tension, sometimes under deadly tensional loads. Never try to disassemble a component that you suspect is under a high-tension load unless you are exactly sure of how to go about it. Refer to service literature and ask more experienced coworkers when you are unsure of a procedure.

Compressed Fluids

Fluids in both liquid and gaseous states can be extremely dangerous when proper safety precautions are not observed. Equipment does not necessarily have to be running to produce high-fluid pressures. Residual pressures in stationary circuits can represent a serious safety hazard. Technicians should also be aware of the potential danger represented by oxygen cylinders due to their high pressure and potential to aid in combustion and explosions. When shops receive fire safety inspections, fire personnel are more concerned about the storage location of compressed oxygen cylinders than compressed fuels such as acetylene and propane.

Pneumatics Safety

Compressed air is used extensively in automotive facilities. It can be dangerous if not handled with respect. Compressed air is used to drive both portable and nonportable shop tools and equipment.

WARNING

Always wear safety glasses when coupling and uncoupling, or when using pneumatic tools.

Some examples of shop equipment that use compressed air:

- pneumatic wrenches
- pneumatic drills
- shop air-over-hydraulic presses
- air-over-hydraulic jacks
- air-over-hydraulic cylinder hoists

Figure 1–10 shows a typical setup for a ½-inch-drive impact gun used every day in diesel and truck repair shops.

Hydraulic System Safety

Vehicle and shop hydraulic systems use extremely high pressures that can be lethal when mishandled. Once again, never forget that idle circuits can hold residual pressures, and many circuits use accumulators. The rule when working with hydraulic circuits is to be absolutely sure about potential dangers before attempting to disassemble a circuit or component.

WARNING

Always wear safety glasses when working close to shop or vehicle hydraulic circuits, and check service literature before attempting a disassembly procedure. Ask someone if you are not sure rather than risk injury.

Some examples of chassis systems that use hydraulic circuits:

- tailgate lift and auxiliary circuits
- high-pressure fuel management circuits
- automatic transmission control circuits
- air-over-hydraulic brake circuits
- clutch control circuits

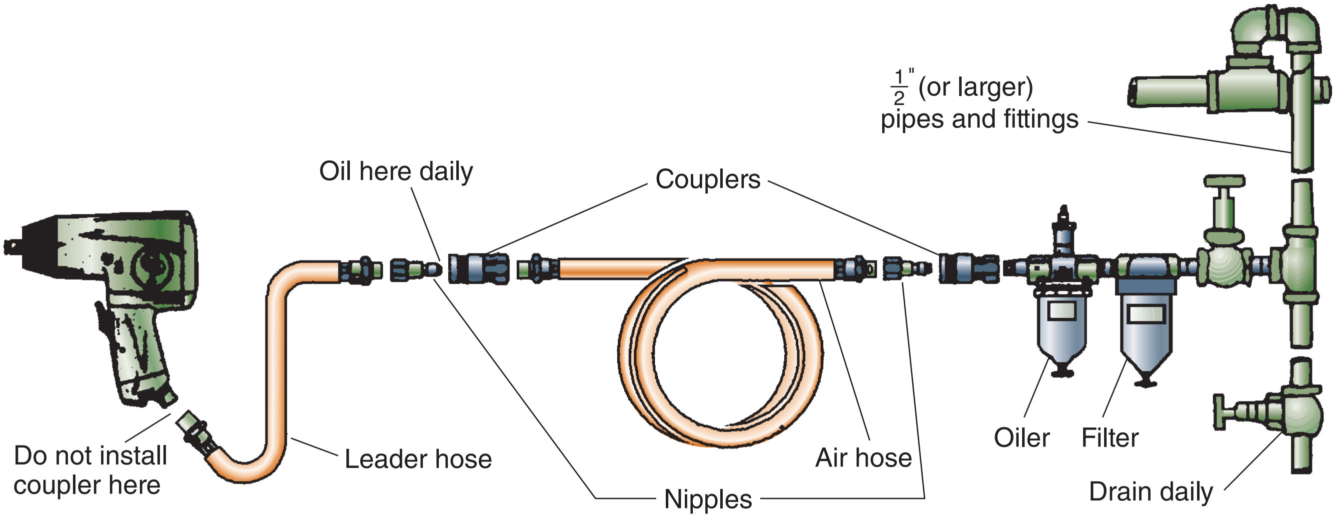


FIGURE 1–10 Typical setup for a ½-inch drive impact gun.

Some examples of shop equipment using hydraulic circuits:

- jacks and hoists
- presses
- bearing and liner pullers
- suspension bushing presses

Chassis and Shop Electrical Safety

Vehicles today use numerous computers. These computers are all networked to a central data backbone using multiplexing technology. The chassis subsystems controlled by computers include:

- engine
- transmission
- brakes
- traction control
- vehicle directional stability
- lights
- dash electronics
- collision warning systems
- infotainment and communications systems

These systems function on low-voltage electrical signals and use thousands of solid-state components. While some of these electronic subcircuits are protected against voltage overload spikes, others are not. An unwanted high-voltage spike caused by static discharge or careless placement of electric welding grounds can cause thousands of dollars worth of damage.

Static Discharge

When you walk across a plush carpet, your shoes “steal” electrons from the floor. This charge of electrons accumulates in your body and when you go to grab a door handle, the excess of stolen electrons discharges itself into the door handle, creating an arc which we see as a spark. You will note that the accumulation of a **static charge** is influenced by factors such as relative humidity and the type of footwear you are wearing. Getting a little zap from the static charge that can accumulate in the human body is seldom going to produce any harmful effects to human health, but it can damage sensitive solid-state circuits.

Static Discharge and Computers

Static charge accumulation in vehicles running down a highway and in the human body can easily damage computer circuits. Because vehicles today use a wide range of computer-controlled circuits it is important for technicians to understand the effects of **static discharge**. The reason that static discharge has not caused more problems than it has in the service repair industry is due to:

- technicians’ footwear of choice, usually rubber-soled boots
- shop floors that tend not to be carpeted

Rubber-soled footwear and concrete floors are not conducive to static charge accumulation. Having said this, technicians should remember that the flooring in vehicles is almost always carpeted. It is, therefore, good practice when troubleshooting requires you to access electronic circuits to use a **ground strap** before separating sealed connectors and before working on any vehicle electronic circuit, even if you are just connecting an **electronic service tool (EST)** to a data link. A ground strap electrically connects you to the device that you are working on, so an unwanted static discharge into a shielded circuit is unlikely. Special care should be taken when working with modules that require you to physically remove and replace solid-state components such as PROM chips from a motherboard.

Chassis Wiring and Connectors

Every year, millions of dollars worth of damage to vehicles is created by truck technicians who ignore OEM precautions about working with chassis wiring systems. Perhaps the most common abuse is puncturing wiring insulation with test lights and **digital multimeter (DMM)** leads. When you puncture the insulation on copper wiring, that wiring is immediately exposed to both oxygen (in the air) and moisture (relative humidity!). The resulting chemical reaction produces copper oxides that then react with moisture to form corrosive cupric acid. The acid begins to eat away the wiring, first creating high resistance, and ultimately consuming the wire. The effect is accelerated when copper-stranded wiring is used because the surface area over which the corrosion can act is so much greater.

WARNING

Never puncture the insulation on chassis wiring. Read the section that immediately precedes this if you want to know why!

The sad thing about this type of abuse is that it is so easily avoided. There are many ways that a vehicle technician can access wiring circuits using the correct tools. Use breakout tees, breakout boxes, and test lead spoons.

FIGURE 1–11 High-voltage three-phase electrical outlet.

Mains Electrical Equipment

Mains electrical circuits, unlike standard vehicle electrical circuits, operate at pressures that can be lethal, so you have to be careful when working around any electrical equipment. Electrical pressures may be **single-phase mains** operating at pressure values between 110 and 120 volts or **three-phase mains**, operating at pressures between 400 and 600 volts. In most jurisdictions, repairs to mains electrical equipment and circuits must be undertaken by qualified personnel. If you undertake the repair of electrical equipment, make sure you know what you are doing! **Figure 1–11** shows a three-phase outlet of the type commonly used in truck shops to power compressors, machine shop equipment, and arc welding stations. Learn how to identify these outlets with high electrical potential that can kill if mishandled.

Take extra care when using electrically powered equipment when the area in which you are working is wet. And remember that a discharge of AC voltage driven through a chassis data bus can knock out all the electronic equipment networked to it. Electrical equipment can also be dangerous around vehicles because of its potential to arc and initiate a fire or explosion.

CAUTION

Do not undertake the repair of mains electrical circuit and equipment problems unless you are qualified to do so.

Some examples of shop equipment using single-phase mains electricity:

- electric hand tools
- portable electric lights
- computer stations
- drill presses
- burnishing and broaching tools

CAUTION

Take care when using trouble lights with incandescent bulbs around volatile liquids and flammable gases: these are capable of creating sufficient heat to ignite flammables. Many jurisdictions have banned the use of this type of trouble light, and they should never be used in garages in which gasoline, propane, and natural gas-fueled vehicles are present. Best bet: use an LED trouble light encased in rubber-insulated housing!

Welding Safety

Every mechanical technician should have an understanding of how to use gas and electric arc welding equipment. This section addresses the basics of this equipment.

Oxyacetylene Equipment

Technicians use oxyacetylene for heating and cutting on an almost daily basis. Less commonly this equipment is used for braising and welding. Some basic instruction in the techniques of oxyacetylene equipment safety and handling is required. The following information should be understood by anyone working with oxyacetylene equipment.

Acetylene Cylinders

Acetylene regulators and hose couplings use a left-hand thread. Left-hand threads tighten counterclockwise (CCW). An acetylene regulator gauge working pressure should *never* be set at a value exceeding 15 psi (100 kPa). At pressures higher than this, acetylene becomes dangerously unstable. An acetylene cylinder should always be used in the upright position. Using an acetylene cylinder in a horizontal position will result in the liquid acetone stablizer draining into the hoses.

The quantity of acetylene in a cylinder cannot be accurately determined by the pressure gauge reading because it is in a dissolved condition. The only really accurate way of determining the quantity of gas in the cylinder is to weigh it and subtract this from the weight of the full cylinder, often stamped on the side of the cylinder.

WARNING

It is a common malpractice to set acetylene pressure at high values. Check a welder's manual for the correct pressure values to set for the equipment and procedure you are using.

CAUTION

Never operate an acetylene cylinder in anything but an upright position. Using acetylene when the cylinder is horizontal results in acetone exiting with the acetylene, which can destabilize the remaining contents of the cylinder.

Oxygen Cylinders

Oxygen cylinders present more problems than acetylene when exposed to fire. For this reason they should be stored upright and in the same location in a service shop when not in use. This location should be identified to the fire department during an inspection. They should never be left randomly on the shop floor.

Oxygen regulator and hose fittings use a right-hand thread. A right-hand thread tightens clockwise (CW). An oxygen cylinder pressure gauge accurately indicates the oxygen quantity in the cylinder, meaning that the volume of oxygen in the cylinder is approximately proportional to the pressure.

Oxygen is stored in the cylinders at a pressure of 2,200 psi (15 MPa), and the handwheel-actuated valve forward-seats to close the flow from the cylinder and back-seats when the cylinder is opened. It is important to ensure that the valve is fully opened when in use. If the valve is only partially opened, oxygen will leak past the valve threads. **Figure 1–12** shows a typical oxyacetylene setup for a cutting torch procedure.

CAUTION

Never use oxygen as a substitute for compressed air when cleaning components in a shop environment. Oxygen can combine with solvents, oils, and grease, resulting in an explosion.

Regulators and Gauges

A regulator is a device used to reduce the pressure at which gas is delivered. It sets the working pressure of the oxygen or fuel. Both oxygen and fuel regulators function similarly. They increase the working pressure when turned clockwise and close off the pressure when backed out counterclockwise.

Pressure regulator assemblies are usually equipped with two gauges. The cylinder pressure gauge indicates the actual pressure in the cylinder. The working pressure gauge indicates the working pressure, and this should be trimmed using the regulator valve to the required value while under flow.

Hoses and Fittings

The hoses used with oxyacetylene equipment are usually color-coded. Green is used to identify the oxygen hose and red identifies the fuel hose. Each hose connects the cylinder regulator assembly with the torch. Hoses may be single or paired (Siamese). Hoses should be routinely inspected and replaced when defective. A leaking hose should never be repaired by wrapping it with tape. In fact, it is generally bad practice to consider repairing welding gas hoses by any method. They should be replaced when they fail.

Fittings couple the hoses to the regulators and the torch. Each fitting consists of a nut and gland. Oxygen fittings use a right-hand thread and fuel fittings use a left-hand thread. The fittings are machined out of brass that has a self-lubricating characteristic. Never lubricate the threads on oxyacetylene fittings.

Torches and Tips

Torches should be ignited using the following sequence:

- Open the cylinder flow valve.
- Set the working pressure using the regulator valve for both gases under flow, then close.

- Next, open the fuel valve only and ignite the torch using a flint spark lighter.
- Set the acetylene flame to a clean burn (no soot) condition.
- Now open the oxygen valve to set the appropriate flame. When setting a cutting torch, set the cutting oxygen last.
- To extinguish a torch, close the fuel valve first, then the oxygen.
- Finally, the cylinders should be shut down using the main flow valve and the hoses purged.

Welding, cutting, and heating tips may be used with oxyacetylene equipment. Refer to a welder's manual to identify the specified working pressures for each type of tip. There is a tendency to set gas working pressure high. Even when using a large heating tip often described as a rosebud, the working pressure of both the acetylene and the oxygen is typically set at 7 psi (50 kPa). **Figure 1–13** shows a typical oxyacetylene cutting torch.

Backfire

Backfire is a condition where the fuel ignites within the nozzle of the torch, producing a popping or squealing noise: it often occurs when the torch nozzle overheats. Extinguish the torch and clean the nozzle with tip cleaners. Torches may be cooled by immersing in water briefly with the oxygen valve open.

FIGURE 1–13 Oxyacetylene cutting torch.

Flashback

Flashback is a much more severe condition than backfire: it takes place when the flame travels backward into the torch to the gas-mixing chamber and beyond. Causes of flashback are inappropriate pressure settings (especially low-pressure settings) and leaking hoses/fittings. When a backfire or flashback condition is suspected, close the cylinder valves immediately, beginning with the fuel valve. Flashback arresters are usually fitted to the torch and will limit the extent of damage when a flashback occurs.

Eye Protection

Safety requires that a number 4- to number 6-grade filter be used when using an oxyacetylene torch. The flame radiates ultraviolet light that can damage eyesight. Sunglasses, even when UV rated, are not

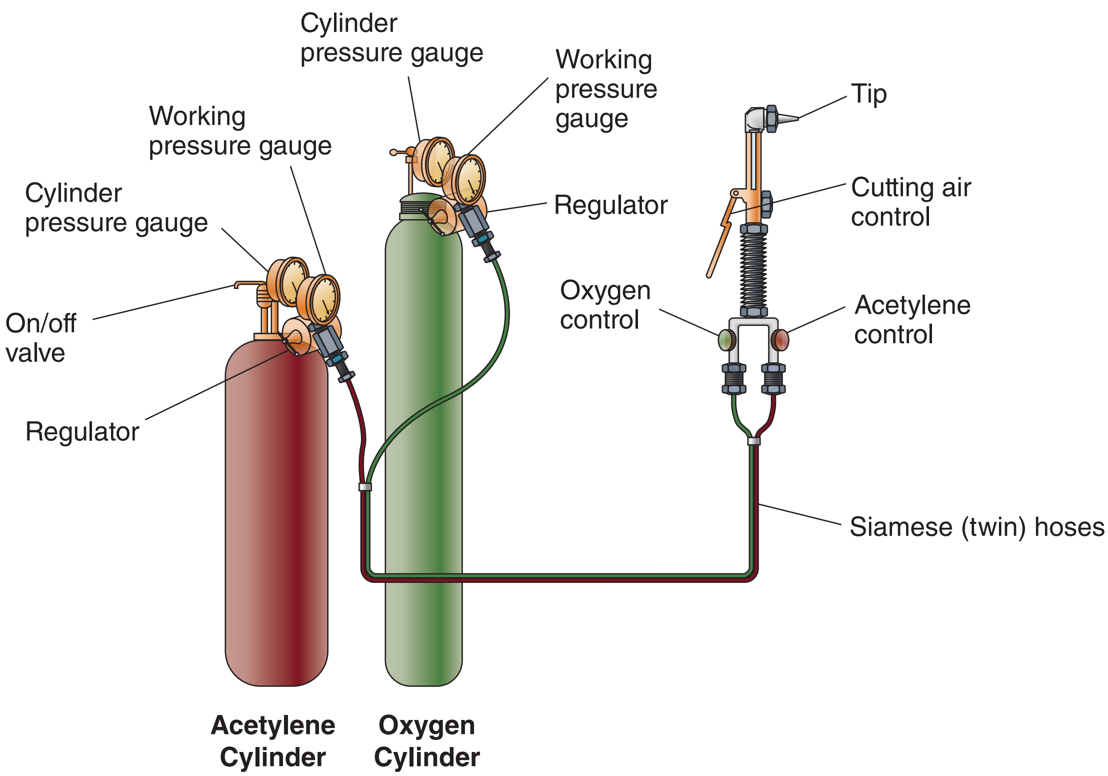


FIGURE 1–12 Oxyacetylene station setup with a cutting torch.

sufficient protection and can result in damage to eyesight with short exposure to an oxyacetylene flame.

Oxyacetylene Precautions

Things to do and not to do:

- Store oxygen and acetylene upright in a well-ventilated, fireproof room.
- Protect cylinders from snow, ice, and direct sunshine.
- Remember that oil and grease can spontaneously ignite in the presence of oxygen.
- Never use oxygen in place of compressed air.
- Avoid bumping and dropping cylinders.
- Keep cylinders away from electrical equipment where there is a danger of arcing.
- Never lubricate the regulator, gauge, cylinder, and hose fittings with oil or grease.
- Blow out cylinder fittings before connecting regulators: make sure the gas jet is directed away from equipment and other people.
- Use soapy water to check for leaks: *never* use a flame to check for leaks.
- Thaw frozen spindle valves with warm water; *never* use a flame.

Adjustment of the Oxyacetylene Flame

To adjust an oxyacetylene flame, the torch acetylene valve is first turned on and the gas ignited. At the point of ignition, the flame will be yellow and producing black smoke. The acetylene pressure should then be increased using the torch fuel valve. This increases the brightness of the flame and reduces the smoking. At the point at which the smoking disappears, the acetylene working pressure can be assumed to be correct for the nozzle jet size used. Next, the torch oxygen valve is turned on. This will cause the flame to become generally less luminous (bright) and an inner blue luminous cone surrounded by a white-colored plume should form at the tip of the nozzle. The white-colored plume indicates excess acetylene. As more oxygen is supplied, this plume reduces until there is a clearly defined blue cone with no white plume visible. This indicates the *neutral* flame used for most welding and cutting operations.

Electric Arc Welding

Electric arc welding and cutting processes are used extensively in truck and heavy equipment service garages. Arc welding stations work on one of two principles:

- Transformer: This receives a high-voltage feed (mains electrical) then reduces it to a lower-voltage, high-current circuit.

FIGURE 1–14 Arc welding electrode holder.

- Generator: This generates a high-voltage charge, then conditions it to lower-voltage, high-current circuits.

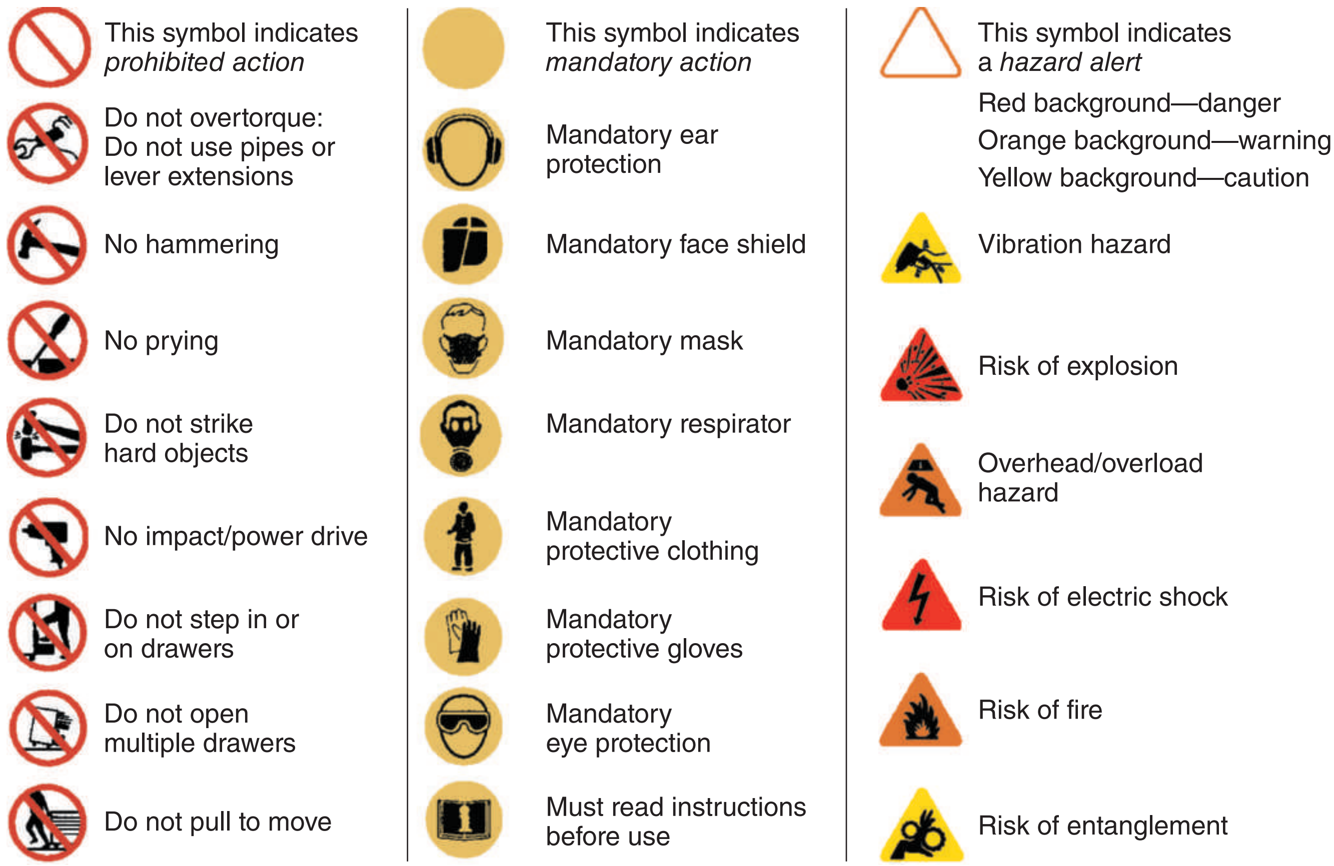
Just as with oxyacetylene welding, before attempting to use any type of arc welding equipment, make sure you receive some basic instruction and training. Typical open-circuit voltages in industrial welding stations are usually around 70 volts while closed-circuit voltages are typically a little over 20 volts. The following types of welding stations are nonspecialized in application and are found in many truck shops:

- Arc welding station: This uses a flux-coated, consumable electrode. Arc welding is often known as *stick welding*.
- MIG (metal inert gas): This uses a continuous reel of wire, which acts as the electrode around which inert gas is fed to shield the weld from air and ambient moisture. Closely related to MIG welding is flux-shielded reel welding.
- TIG (tungsten inert gas): This uses a non-consumable tungsten electrode surrounded by inert gas, and filler rods are dipped into the welding puddle created.
- Carbon-arc cutting: An arc is ignited using carbon electrodes to melt base metal while a jet of compressed air blows through the puddle to make the cut.

Figure 1–14 shows a typical arc welding electrode holder used with an arc welding station.

Safety Symbols and Emoji

Safety symbols and emoji are commonly used on placards, decals, shop signage, and vehicles. Although they are supposed to be intuitive, this is not always the case. **Figure 1–15** shows examples of typical generic safety symbols used in service facilities.



Courtesy of snap-on tools company

FIGURE 1–15 Generic safety symbols.

SUMMARY

- While all service shops play a role in ensuring a safe working environment, technicians should think of safety as a personal responsibility.
- Personal protective equipment (PPE) such as safety footwear, eye protection, coveralls, hearing protection, and different types of gloves are required when working in a service garage.
- Lockout tagout (LOTO) relates to vehicle securement during service procedures. Technicians must be familiar with the workplace LOTO policy prior to working on vehicles or equipment.
- Technicians should learn to distinguish between the four different types of fires and identify the fire extinguishers required to suppress them.
- Jacks and hoists are used extensively in service facilities and should be used properly and inspected routinely.
- The danger of inhaling engine exhaust emissions should be recognized, and when engines are run inside a garage, exhaust extraction piping must be fitted to the exhaust stacks.
- It is important to identify what is required to work safely with chassis electrical systems because of the costly damage made by simple errors.
- Shop mains electrical systems are used in portable power and stationary equipment and can be lethal if not handled properly.
- Oxyacetylene equipment is used for heating, cutting, and welding. Technicians should be taught how to work safely with oxyacetylene torches.
- Arc welding and cutting processes are also used in service facilities. This type of high-voltage equipment can be safely operated with some basic training.
- Technicians should be familiar with the symbols and emoji used on workplace signage, placards, and equipment.

REVIEW QUESTIONS

1. When is a worker more likely to be injured?
   A. First day on the job
   B. During the first year of employment
   C. During the second to fourth years of employment
   D. During the year before retirement
2. When lifting a heavy object, which of the following should be true?
   A. Keep your back straight while lifting.
   B. Keep the weight you are lifting close to your body.
   C. Bend your legs and lift using the leg muscles.
   D. All of the above.
3. Which of the following best describes the purposes of LOTO?
   A. A workplace lottery
   B. Vehicle and equipment securement during servicing
   C. Certification standards for PPE
   D. CVSA safety standards
4. Which of the following is usually a requirement of a safety shoe or boot?
   A. UL certification
   B. Steel sole shank
   C. Steel toe
   D. All of the above
5. What type of gloves should never be worn when working with refrigerant?
   A. Synthetic rubber
   B. Vinyl disposable
   C. Leather welding gloves
   D. Latex rubber gloves
6. Which of the following is under the most pressure?
   A. Oxygen cylinders
   B. Acetylene cylinders
   C. Diesel fuel tanks
   D. Gasoline fuel tanks
7. Which type of fire can usually be safely extinguished with water?
   A. Class A
   B. Class B
   C. Class C
   D. Class D
8. When attempting to suppress a Class C fire in a chassis, which of the following is good practice?
   A. Disconnect the batteries.
   B. Use a carbon dioxide fire extinguisher.
   C. Avoid inhaling the fumes produced by burning conduit.
   D. All of the above.
9. What color is used to indicate the fuel hose in an oxyacetylene station?
   A. Green
   B. Red
   C. Yellow
   D. Blue
10. In which direction do you tighten an oxygen cylinder fitting?
    A. CW
    B. CCW
    C. Depends on the manufacturer

CHAPTER 2

Introduction to Diesel Engines

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Identify contemporary on-highway and off-highway light duty diesel engines.
- Interpret diesel engine terminology.
- Describe the differences between *naturally aspirated* and *manifold-boosted* engines.
- Explain how volumetric efficiency affects cylinder breathing.
- Detail the events of the four-stroke diesel cycle.
- Identify the subsystems that make up a diesel engine.
- Interpret the term *cetane number* and relate it to ignition temperature.
- Calculate engine displacement.
- Define *rejected heat* and explain thermal efficiency in diesel engines.
- Define the term *mean effective pressure*.
- Outline how the relationship between crank throw angle and cylinder pressure is used to manage output in modern diesel engines.

KEY TERMS

after top dead center (ATDC)
before top dead center (BTDC)
bore
bottom dead center (BDC)
clearance volume
combustion pressure
compression ignition (CI)
compression ratio
cylinder volume
diesel cycle
direct injection (DI)
engine displacement
fire point
friction
heat energy
ignition lag
indirect injection (IDI)
inertia
manifold-boost
mean effective pressure (MEP)
naturally aspirated (NA)
oversquare engine
ratio
rejected heat
spark ignited (SI)
square engine
stroke
swept volume
thermal efficiency
top dead center (TDC)
torque
undersquare engine
vocational automotive diesels
volumetric efficiency

Why Read This?

For purposes of study, light duty diesel engines are those with displacements of eight liters or less. Unlike the Europeans, the American consumer never truly embraced diesel engine power in passenger vehicles and following the Volkswagen emission scandal in 2015, sales of diesel engines in cars barely register today. However, diesel engines suit pickup truck applications, especially when the truck is used as a work tool rather than a family vehicle. In model year (MY) 2019 pickup truck sales, 12 percent were diesel powered (Diesel Technology Forum), and this percentage is projected to increase by 168 percent by 2024. The term that we will use to describe this family of engines is **vocational automotive diesels**.

Diesel power has always been a popular option in off-highway light duty applications. A combination of low emissions, fuel economy, and significant longevity has driven a surge in sales of small diesel engines. These engines are used in industrial, agricultural, construction, and stationary applications.

Vocational Automotive Diesels

It should be noted here that diesel engines specified for pickup truck applications are engineered as work engines. When these engines are actually used in a work environment, they tend to produce much improved fuel economy and greater longevity over their gasoline-fueled counterparts. However, the pickup truck has always been more than merely a work vehicle, and the owner who specs diesel power for a family vehicle is probably going to be disappointed with the supposed fuel economy advantage.

The following lists some of the more common light duty, vocational automotive diesel engines:

- Ford Power Stroke 6.7 liter V-8
- Ford Power Stroke 3.0 liter V-6
- Cummins ISB 6.7 liter I-6 (Dodge)
- Fiat EcoDiesel 3.0 liter V-6 (Dodge)
- GM Duramax 6600 (6.6 liter) V-8
- GM Duramax 3000 (3.0 liter) V-6
- Jaguar Land Rover 3.0 V-6
- Mazda 2.2 liter I-4
- Sprinter MB 3.0 liter V-6
- Sprinter MB 2.0 liter I-4
- Detroit DD5 5.1 liter I-4

Although diesel engine sales in passenger automobiles have been nearly flat since 2015, Jaguar-Land Rover (JLR) and Mazda continue to provide diesel engine options in some of their vehicles. Auto companies caught up in the emissions cheating scandal have ceased to sell diesel power in North America and the EPA's closer scrutiny of diesel engines has motivated those companies that were compliant in 2015 to phase out or reduce their diesel options.

Vocational automotive diesel engines must meet U.S. EPA (Environmental Protection Agency) on-highway emissions standards with the result that all current engines are computer controlled with a full spectrum of exhaust aftertreatment devices. Today, hydromechanically managed diesel engines continue to be manufactured, but most are rated at 70 horsepower (52 kilowatt) or less.

Off-Highway Light Duty Diesels

The diesel engine has always fared better in light duty applications that are not intended for highway operations. This category of engines powers turf equipment, recreational marine equipment, farm equipment, mobile refrigeration (reefers), and stationary applications such as generators and pumps. Manufacturers servicing this sector of the industry include Caterpillar, Deutz, Hatz, Isuzu, John Deere, Kohler, Kubota, Lister Petter, Mitsubishi, Perkins, and Yanmar. It should be noted that this class of small-bore engines (some may be single cylinder) is now regulated by U.S. EPA emissions standards. However, this is a recent development, so older versions of these engines still use hydromechanical (no computer) fuel management and no exhaust gas treatment. Some examples of recent versions of offhighway light duty diesel engines are:

- Caterpillar C1.5 liter, three-cylinder
- Cummins QSB 4.5 liter, four-cylinder
- Deere 4024T 2.4 liter, four-cylinder
- Deere PowerTech PSX 6.8 liter, six-cylinder
- Deutz TCD 2.9 liter, four-cylinder
- Isuzu C-Series 1.5 liter, three-cylinder
- JCB Ecomax 4.4 liter, four-cylinder
- Kohler 1.0 liter three-cylinder
- Kubota 1.12 liter, three-cylinder
- Lister Petter TR1, 0.773 liter, one-cylinder
- Lister Petter TR2, 1.55 liter, two-cylinder
- Yanmar 4JH 2.2 liter, four-cylinder

Many off-highway light duty diesel engines are subjected to less rigorous duty cycles than their on-highway counterparts. This means that the percentage of legacy (older) engines is much higher. Many of these older engines use hydromechanical management. Observe the equipment used on farms today and you're likely to see the most modern machinery working alongside fifty-year-old equipment.

Diesel Engine Terms

Before you can properly understand how any engine functions you have to become familiar with some of the language we use to describe its operation. You will find that the basic engine terminology and principles introduced in this chapter are used repeatedly throughout the textbook. As you progress through it, make sure that you use the glossary to check the definitions of any words you are unfamiliar with. Mostly, we will use the technically correct term in this textbook, but remember that the terminology used on the shop floor might differ. When you reference manufacturer's service literature, you will be expected to have a basic understanding of the key terms introduced in this chapter. If you have studied spark-ignited (SI) gasoline-fueled engines, you may find you are familiar with many of these definitions, in which case you can just skip over them. **Figure 2–1** shows a Ford 6.7 liter engine that powers many pickup trucks.

Compression Ignition

A diesel engine is defined by the fact that it uses **compression ignition (CI)**. The key difference between what we know as a **spark-ignited (SI)**, gasoline-fueled engine and a diesel engine is in the way each ignites the fuel charge. In the SI engine, ignition of the fuel charge takes place when a spark is delivered to the engine cylinder. The CI engine relies on the heat of compression to ignite the fuel charge. For this reason, more heat must be generated in the engine cylinder of a CI engine, at least enough to ignite the fuel charge.

Engine Definitions

You probably are already familiar with some of the terms introduced in this section. Even if you are, read through them because the definitions here may differ in small ways from those you are familiar with.

Diesel Engine

A diesel engine is a type of internal combustion engine in which the fuel/air charge is ignited by the heat of compression. While some diesel engines are equipped with glow plugs, these are start-assist devices that do not play a role during normal engine operation.

Air

Air is a gaseous mixture of nitrogen and oxygen. We breathe this mixture we call air and so does a diesel engine. Air is composed of a little under 80 percent nitrogen and a little over 20 percent oxygen. The oxygen available in air is used as the reactant to combustion for the fuel in most internal combustion engines.

Fuel

The fuels we use in diesel engines are hydrocarbons (HCs). The source of most diesel fuel used today is petroleum. However, other hydrocarbon-based fuels (such as

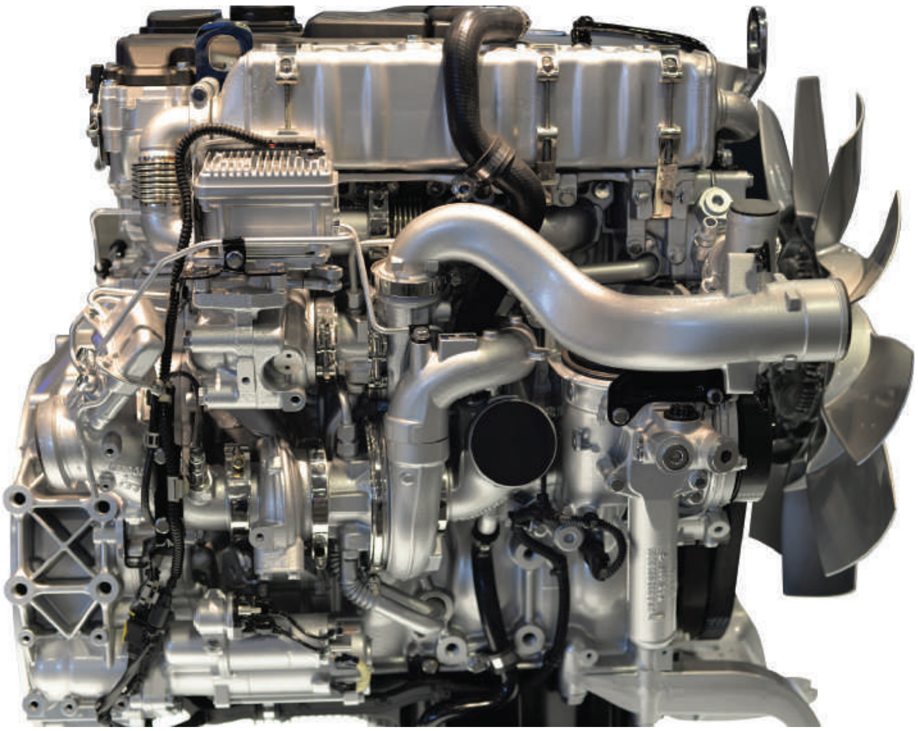


FIGURE 2–1 2019 Detroit DD5 (5.1 liter) engine.

soy base, biodiesels) are used and under some conditions can work as efficiently as petroleum-based fuels.

Heat Energy

Heat energy is a rating of the available energy in any given fuel. As the heat energy of a fuel increases, so does the potential for converting this heat energy into useful energy at the flywheel. For instance, gasoline contains less heat energy by weight than a diesel fuel. Because of this, the power potential of diesel fuel per unit of fuel used is usually greater than that for an equivalent gasoline-fueled engine.

Naturally Aspirated (NA)

The term **naturally aspirated** is used to describe an engine in which air (or air/ fuel mixture) is induced into its cylinders by low cylinder pressure created by the downstroke of the piston. Naturally aspirated diesel engines today tend to be in nonmobile applications.

Turbo-Boost

Most diesel engines today are turbo-boosted like the example shown in **Figure 2–1**. Another way of saying turbo-boost is **manifold-boost**. Manifold-boosted describes any engine whose cylinders are charged at pressures above atmospheric pressure. The diesel engines manufactured for applications such as Ford, General Motors, and Dodge pickup trucks and commercial vans are all turbo-boosted. The same is true of the diesel engine options in most Japanese and European import automobiles.

Volumetric Efficiency

Volumetric efficiency is defined as the measure of an engine's breathing efficiency. The best way to think of it is as the ratio between the volume of fresh air taken into the engine cylinder before the intake valve(s) close versus the cylinder swept volume. Volumetric efficiency is usually expressed as a percentage. In turbocharged engines, volumetric efficiency can often greatly exceed 100 percent. The best way of defining the term is to say that it is the amount of air charged to the engine cylinder in an actual cycle versus the amount it would contain if it were at atmospheric pressure.

These first few definitions should be sufficient to allow us to understand the operation of the diesel cycle, which we will introduce next. Toward the end of the chapter, we are going to introduce another group of terms to give us some of the building blocks required to understand the diesel engine.

The Diesel Cycle

A cycle is a sequence of events. The **diesel cycle** is best introduced by outlining the four strokes of the pistons made as an engine is turned through two revolutions. A full cycle of a diesel engine requires two complete rotations. Each rotation requires turning the engine through 360 degrees, so that a complete diesel cycle translates into 720 crankshaft degrees.

Each of the four strokes that make up the cycle involves moving a piston either from the top of its travel to its lowest point of travel or vice versa; each stroke of the cycle therefore translates into 180 crankshaft degrees. The four strokes that comprise the four-stroke cycle are:

- Intake
- Compression
- Power
- Exhaust

The four strokes of the diesel cycle are shown in **Figure 2–2**.

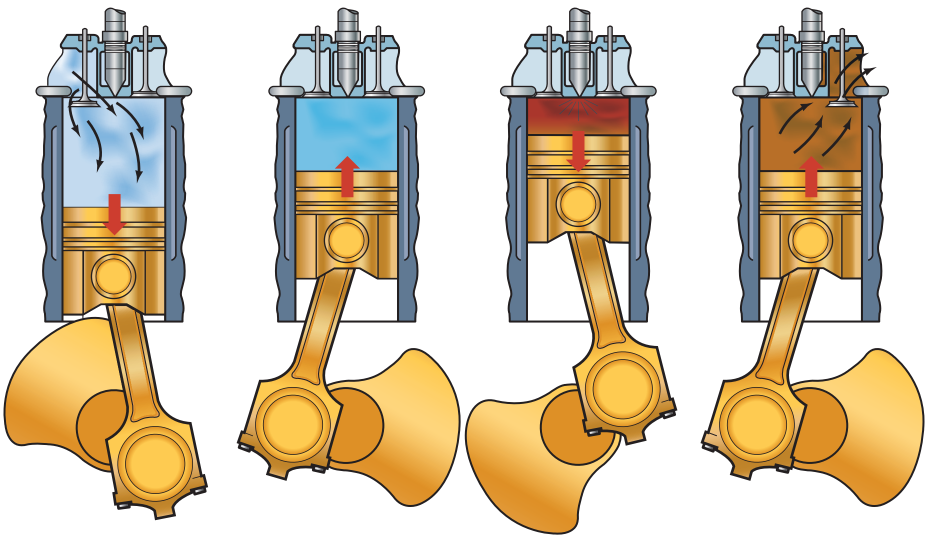


FIGURE 2–2 The four-stroke diesel cycle.

Direct Injection, Compression Ignition Engine

We can now take a closer look at what happens during the four-stroke diesel cycle. Make sure you refer **Figure 2–2** to help you understand the description provided here. In this description, we are going to describe what happens in a turbocharged diesel engine.

Intake Stroke

The piston is connected to the crankshaft throw by means of a wrist pin and connecting rod. The throw is an offset journal on the crankshaft. Therefore, as the crankshaft rotates, the piston is drawn from top dead center (TDC) to bottom dead center (BDC): while the piston moves through its downstroke, the cylinder head intake valve(s) are held open. As the intake valves open, turbo-boosted air is forced into the engine cylinder as the piston travels downward. This means that at the completion of the intake stroke when the intake valves close, the cylinder will be filled with a charge of filtered air. The actual quantity of air in the cylinder will depend on the extent of turbo-boost. Turbo-boost varies with how the engine is being operated.

The *air* that is taken into the cylinder is a mixture of approximately four-fifths nitrogen and one-fifth oxygen. The oxygen is required to combust the fuel. Note that no fuel is introduced into the engine cylinder during the intake stroke. When the air charged to the engine cylinder is pressurized using a turbocharger, more oxygen can be forced into the cylinder. All diesel engines are designed for lean burn operation; that is, the cylinder will be charged with much more air than that required to combust the fuel. Volumetric efficiency in most phases of engine operation will usually exceed 100 percent in turbocharged engines.

Compression Stroke

At the completion of the intake stroke, the intake valves close, sealing the engine cylinder. The piston is now driven upward from BDC to TDC with both the intake and exhaust valves closed. The quantity of air in the cylinder does not change, but compressing the charge of air in the cylinder gives it much less space and in doing so, heats it up considerably. Compression pressures in modern diesel engines vary from 400 psi (2750 kPa) to 700 psi (4822 kPa).

The actual amount of heat generated from these compression pressures also varies, but it usually substantially exceeds the minimum ignition temperature values of the fuel. Compression ratios used to achieve the compression pressure required of diesel engines generally vary from a low of 14:1 to a high of 25:1. However, in modern turbocharged, highway diesel engines, compression ratios are typically around 16:1 to 17:1. The MY 2020 Mazda diesel has a compression ratio of 14:1 but to achieve this, they use twin series turbocharging to help pressurize the intake air.

Power Stroke

Shortly before the completion of the compression stroke, atomized fuel is introduced directly into the engine cylinder by a multi-orifice (multiple hole) nozzle assembly. The fuel exits the nozzle orifices at very high pressures and in a liquid state. The liquid droplets emitted by the injector must be appropriately sized for ignition and combustion. These fuel droplets, once exposed to the heated air charge in the cylinder, are first vaporized (their state changes from that of a liquid to a gas), then ignited. The ignition point of the fuel is usually designed to occur just before the piston is positioned at TDC: you can compare the ignition point of diesel fuel in the cylinder with spark timing in a gasoline-fueled engine. However, in the diesel engine the cylinder pressures that result from combusting fuel in the cylinder can be managed with more precision than in indirect-injected gasoline engines. This is because fuel can be injected at high pressures into the cylinder during combustion.

During the power stroke, cylinder pressure resulting from the combusting of fuel acts on the piston, driving it downward through its downstroke. The piston moves linearly, that is, in a straight line. It is connected to the crankshaft throw, which rotates. In this way, cylinder pressures are converted into a twisting force we know as **torque**. Because the crank throw is offset from the crankshaft centerline it acts as a lever. For this reason, in managing the power stroke it is desirable to have little pressure acting on the piston at TDC because it has zero leverage at this location. As the piston moves downward, the leverage will increase incrementally until the angle between the crank throw and connecting rod is 90 degrees (maximum leverage). By getting cylinder pressure (managed by the fuel system) and throw leverage (a hard value dependent on the rotational position of the engine) to work together, it is possible to deliver relatively constant torque from around 15 degrees after top dead center (ATDC) to 90 degrees ATDC. This relationship between pressure and throw leverage helps to transmit the energy produced in the engine cylinder as smoothly as possible to the flywheel. All current diesel engines use computers to precisely manage the relationship between cylinder pressure and crank throw angle. **Figure 2–3** shows the key events of the compression and power strokes.

Exhaust Stroke

Somewhere after 90 degrees ATDC during the expansion stroke, most of the heat energy that can be converted to useful mechanical energy has been converted, and the exhaust valve(s) open. The products of cylinder combustion are known as end gas. The

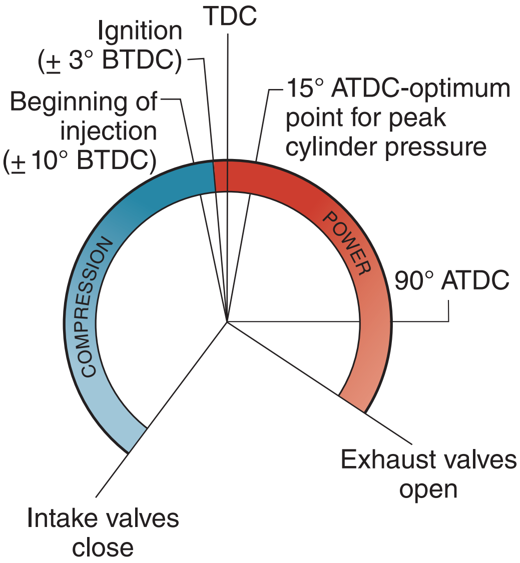


FIGURE 2–3 Events of the compression and power strokes.

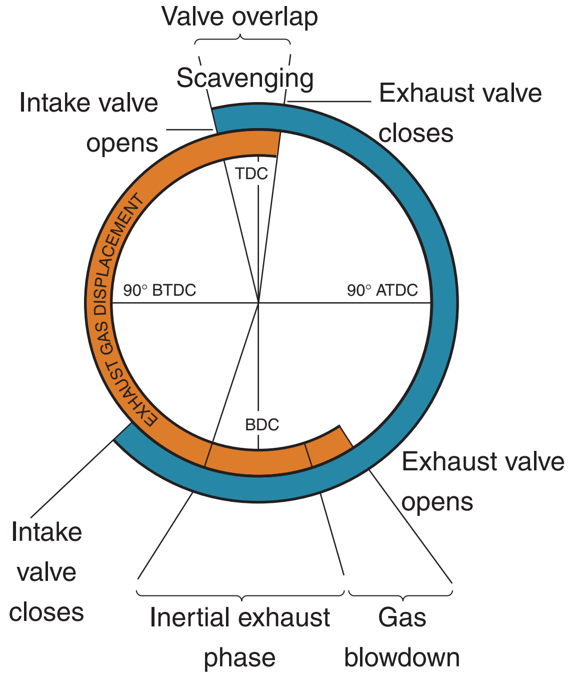


FIGURE 2–4 Key valve open and close events through the four-stroke diesel cycle.

exhausting of combustion end gases occurs in four distinct phases, and the process begins toward the end of the power stroke as the piston is traveling downward:

1. Pressure differential—At the moment the exhaust valves open during the latter portion of the power stroke, pressure is higher in the cylinder than in the exhaust manifold. High-pressure end gas in the cylinder will therefore flow to the lower pressure in the exhaust manifold. This phase is sometimes known as gas blowdown.
2. Inertial—Next the piston comes to a standstill at BDC at the completion of the power stroke. However, gas inertia established during the pressure differential phase will result in the end gases continuing to flow from the cylinder to the exhaust manifold while the piston is in a stationary and near-stationary state of motion.
3. Displacement—As the piston is forced upward through its stroke, it forces out (positively displaces) combustion end gases above it.
4. Scavenging—Toward the end of the exhaust stroke, as the exhaust valve(s) begin to close, the intake valve(s) begin to open with the piston near TDC. The scavenging phase takes place during valve overlap and can be highly effective in expelling end gases and providing some piston crown cooling. The efficiency of the scavenging process is greatest with turbocharged engines and because it is executed with air only, may be prolonged over a wide range of crank angle degrees.

Figure 2–4 diagrams the key valve open and close events through the four strokes of the cycle. Study it carefully.

Engine Systems and Circuits

Many of the components in the diesel (compression ignition or CI) engine are identical to those in the SI engine. For study purposes, the engine components are divided as follows:

1. Engine housing components—the cylinder block, cylinder head(s), oil pan, rocker covers, timing gear covers, manifolds, and flywheel housing.
2. Engine power train—the components directly responsible for power delivery to the drivetrain, including the piston assemblies, connecting rods, crankshaft assembly, vibration damper, and flywheel.
3. Engine feedback assembly—the engine's self-management components also known as the valve train assembly. This term is used to describe the diesel engine timing gear train, camshaft, valve trains, valves, fueling apparatus, and accessory drive components.
4. Engine lubrication circuit—the oil pump, relief valve, lubrication circuitry, full flow filter(s), bypass filters, and heat exchangers.
5. Engine cooling circuit—the coolant pump, thermostat(s), water jacket, coolant manifold, filter, shutters, fan assembly, radiator, and other heat exchangers.
6. Engine breathing system—the engine intake and exhaust system components, including precleaners,

air cleaners, ducting, turbocharger, charge air heat exchangers, intake and exhaust manifolds, pyrometers, exhaust gas recirculation (EGR) system, diesel particulate filter (DPF), exhaust piping, engine silencer, catalytic converter, and selective catalytic reduction (SCR) emission control apparatus.

7. Engine fuel management system—the fuel storage, pumping, metering, and quantity control apparatus, including a management computer, sensors and actuators, hydraulic injectors, electronic unit injectors (EUIs), hydraulically actuated electronic unit injectors (HEUIs), common rail (CR) injection, hydromechanical injection pumps, fuel tanks, filters, and transfer pumps.

Diesel Fuel

It helps to know a little bit about the diesel fuel used to fuel compression-ignited engines. The fuel used in modern diesel engines on North American highways is composed of roughly 85 percent carbon and 12 to 15 percent hydrogen, not too much different from the chemical composition of gasoline. Unlike gasoline, diesel fuel does not vaporize easily at ambient temperatures, so it is less likely to form combustible mixtures of fuel and air. The heat required to ignite the fuel oil is defined by the most volatile fractions of the fuel: this is determined by the fuel's cetane number (CN). The ignition temperature of highway diesel fuel is usually around 250°C (482°F): this is equivalent to a CN of around 45. The ignition temperature would be higher, around 290°C (550°F), using fuel with the poorest ignition quality (rated with a CN of 40) that can be legally sold for use on North American highways.

Using diesel fuel oils with a fire point of around 250°C (482°F) means that at least this temperature must be achieved in the engine cylinder during the compression stroke of the piston if the fuel is to be ignited. In fact, actual cylinder temperatures generated on the compression stroke tend to be considerably higher than the minimum required to ignite the fuel. The greater the difference between these two temperature values, the shorter the ignition lag. **Ignition lag** is the time between the entry of the first droplets of fuel into the engine cylinder and actual ignition that begins combustion.

More Engine Terms

Now that you have an understanding of some basic engine terms and know how the different engine cycles function, you should be ready for some more definitions. We have already used some of these terms in describing the engine cycles, so the objective here is to reinforce them. Refer to **Figure 2–5** as you read through the following definitions to make sure you understand each.

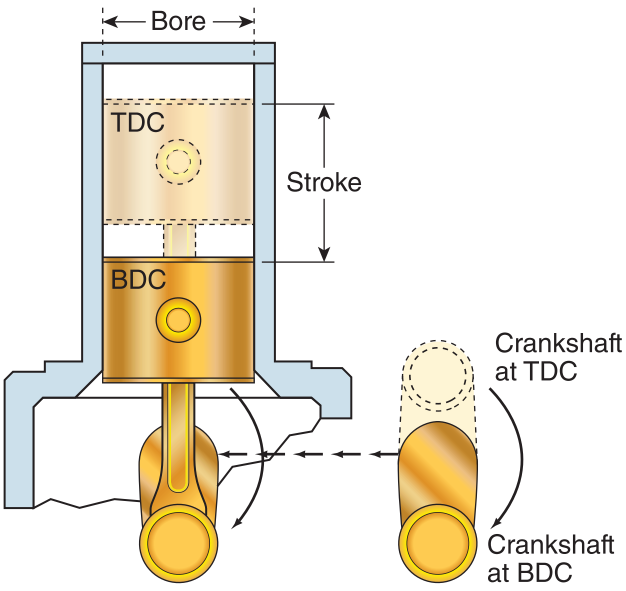


FIGURE 2–5 Bore and stroke, TDC and BDC.

Top dead center (TDC): the highest point of piston travel in an engine cylinder.

Bottom dead center (BDC): the lowest point of piston travel in an engine cylinder.

Before top dead center (BTDC): a point of piston travel through its upstroke.

After top dead center (ATDC): a point of piston travel through its downstroke.

Bore: cylinder diameter. Bore is how we express piston sectional area over which cylinder pressures act. **Figure 2–5** illustrates the bore dimension in a sectioned engine. To calculate the area of a circle we use the formula: $\pi \times$ R2. Because π is not a mathematical constant we do not use this when calculating *engine displacement* described later in this section.

Stroke: the distance through which a piston travels from BDC to TDC. Stroke is established by the crank throw offset; that is, the distance from the crankshaft centerline to the throw centerline multiplied by 2 equals the stroke dimension. **Figure 2–5** illustrates the bore dimension in a sectioned engine.

Swept volume: the volume displaced by the piston in the cylinder as it moves from BDC to TDC. It can be calculated if both stroke and bore are known.

Clearance volume: the remaining volume in an engine cylinder when the piston is at the top of its travel or TDC. The clearance volume on older indirect-injection (IDI) diesel engines was considerable, but it is much less on today's direct-injected (DI) engines.

Cylinder volume: the total volume in the cylinder when the piston is at BDC: You can total calculate cylinder volume by adding cylinder swept volume to the cylinder clearance volume.

Engine displacement: the *swept volume* of all the engine cylinders expressed in cubic inches or cubic centimeters/liters. It is one way of expressing engine size. To calculate engine displacement you do the following:

D = bore × 2 × stroke × 0.7854 × # cylinders

In the preceding formula, 0.7854 represents $\pi/4$. We've simplified the calculation by rounding π to 3.1416. When 3.1416 is divided by 4, the mathematical constant 0.7854 that can be used in formulas is produced.

Example

Ford 6.7 liter Power Stroke engine displacement calculation data:

8-cylinder engine, bore 99 mm, stroke 108 mm
= 99 × 99 × 108 × 0.7854 × 8
= 6,650,817.47 cubic millimeters
= 6.7 liters (rounded)

Note that 1-liter is equivalent to 1,000,000 cubic milliliters.

TECH TIP

To convert liters to cubic inches or cubic inches to liters, use the following simple formula in which 61 is either multiplied or divided into the value to be converted:

6.7 liters × 61 = 408.7 cubic inches or rounded to 409 cubic inches

To change cubic inches into liters, you do the opposite:

408.7 cubic inches ÷ 61 = 6.7 liters

Square engine: an engine in which the cylinder bore diameter is exactly equal to the piston stroke dimension. For instance, an engine with a 4-inch piston diameter and a 4-inch stroke is classified as *square*. When bore and stroke values are expressed, bore always appears before stroke.

Oversquare engine: is the term used to describe an engine in which the cylinder bore diameter is larger than the stroke dimension. Most indirect-injected, gasoline-fueled, spark-ignited engines are oversquare.

Undersquare engine: the term used to describe an engine in which the cylinder bore diameter is smaller than the stroke dimension. Most high-compression diesel engines such as the one we based the earlier calculations on are undersquare.

Compression: when a gas is squeezed by driving a piston into a sealed cylinder, heat is created. For instance, when you use a hand-actuated bicycle pump to inflate tires, the pump cylinder heats up.

Compression ignition (CI): a high-compression engine in which the heat required to ignite the fuel in its cylinders is sourced from compression. More commonly known as a *diesel engine*. CI is an acronym commonly used to describe a diesel engine.

Spark ignited (SI): an engine in which the fuel/air charge is ignited by a timed electrical spark.

Direct injection (DI): either a CI or SI engine in which the fuel charge is injected directly into the engine cylinder rather than to a precombustion chamber or part of the intake manifold.

Indirect injection (IDI): a CI or SI engine in which the fuel charge is introduced outside of the engine cylinder to a precombustion chamber, cylinder head intake tract, or intake manifold. IDI engines are rare today, although they were common in light duty diesels a generation ago.

Ratio: the relationship between two values expressed by the number of times one contains the other. We use the term in automotive technology to describe the drive/driven relationships of two meshed gears, the mechanical advantage of levers, and cylinder compression ratio.

Compression ratio: a measure of the cylinder volume when the piston is at BDC versus cylinder volume when the piston is at TDC. Theoretically, compression ratios in diesel engines range between 14:1 and 24:1. In reality, most modern diesel engines have compression ratios typically between 16:1 and 17:1.

Compression pressure: the actual cylinder pressure developed on the compression stroke. Actual compression pressures in diesel engines range from 350 psi (2.40 MPa) to 700 psi (4.80 MPa) in CI engines. The higher the compression pressure, the more heat developed in the cylinder. Modern diesel engines typically produce compression pressures of ± 600 psi.

Combustion pressure: the highest pressure developed in an engine cylinder during the power stroke. In today's efficient, electronically controlled diesel engines, combustion pressures may peak at up to five times the compression pressure.

Fire point: the temperature at which a flammable liquid gives off sufficient vapor for continuous combustion to take place. Also known as **ignition temperature**. The fire point or ignition temperature of a diesel fuel is specified by cetane number (CN).

Friction: force is required to move an object over the surface of another. **Friction** is the resistance to motion between two objects in contact with each other. Smooth surfaces produce less friction than rough surfaces. Lubricants coat and separate two surfaces from each other and reduce friction.

Inertia: describes the tendency of an object in motion to stay in motion or conversely, the tendency for an object at rest to remain that way. For example, an engine piston moving in one direction must be stopped at its travel limit and its kinetic inertia must be absorbed by the crankshaft and connecting rod. The inertia principle is used by the engine harmonic balancer and the flywheel—the inertial mass (i.e., weight) represented by the flywheel has to be greatest in a single-cylinder, four-stroke cycle engine. As the number of cylinders increases, the flywheel weight can be reduced due to the greater mass of rotating components and the higher frequency of power strokes.

Thermal efficiency: a measure of the combustion efficiency of an engine calculated by comparing the heat energy potential of a fuel (calorific value) with the amount of usable mechanical work produced. Electronically controlled CI engines can have thermal efficiency values exceeding 40 percent. A typical gasoline-fueled car engine has a thermal efficiency of just over 30 percent. A rocket engine produces thermal efficiencies of over 60 percent.

Rejected heat: that percentage of the heat potential of the fuel (see the thermal efficiency definition) that is not converted into useful work by an engine. If a CI engine operating at optimum efficiency can be said to have a thermal efficiency of 40 percent, then 60 percent of the heat energy of the fuel has to be dissipated as *rejected heat*. Half of the rejected heat is typically transferred to the engine hardware to be dissipated to the atmosphere by the engine cooling system, and the other half exits in the exhaust gas. A turbocharger makes use of rejected heat by compressing the intake air forced into the engine cylinders, thereby increasing the thermal efficiency of the engine. **Figure 2–6** shows how the potential heat energy of fuel is released when combusted in a diesel engine.

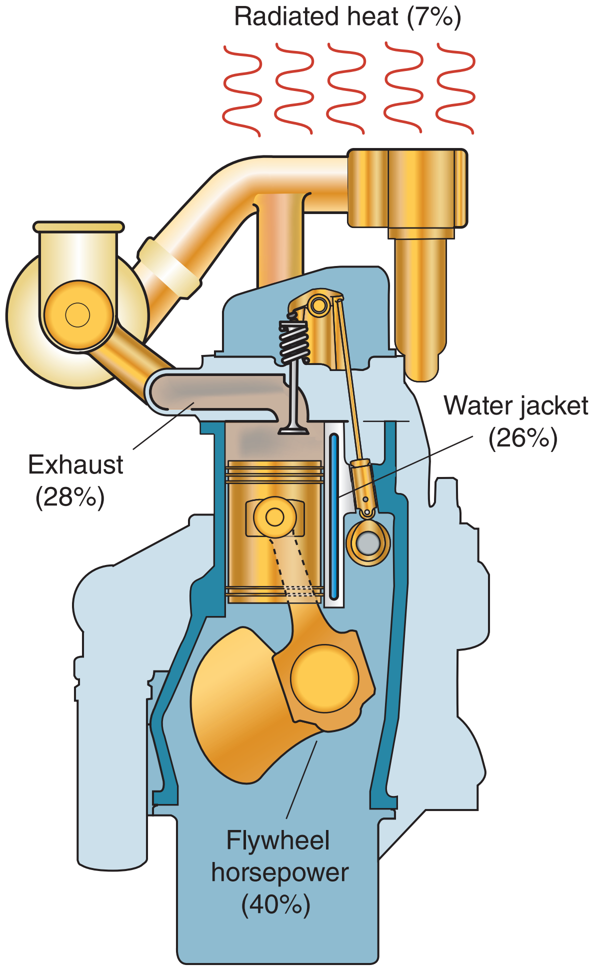


FIGURE 2–6 How the potential energy of diesel fuel is released in a diesel engine.

Two Key Principles

Next we will take a look at a couple of principles that are key to understanding the operation of any engine.

Mean Effective Pressure (MEP)

Mean effective pressure (MEP) is a way of describing the engine cylinder pressure that can actually be converted into useable torque. Simply, it is peak combustion pressure (produced during the power stroke) minus peak compression pressure (produced during the compression stroke). MEP describes the relationship between the *work performed* by the piston (in compressing the air charge) and the *work received* by the piston (through its downstroke on the power stroke). If the engine is going to continue to rotate, there has to be a net gain in terms of work. MEP is an important definition.

Modern, computer-controlled diesel engines can manipulate MEP by varying valve opening and closing. For instance, diesel engines using an internal compression brake open the exhaust valve(s) under engine braking just as the compression stoke is being completed. This means that when the engine brake is actuated, the piston is required to do its normal amount of work in compressing the air in the cylinder during the compression stoke, but just at the point that the power stroke would normally begin, the exhaust valves open, and the cylinder charge is dumped. The result is that the piston does its normal work on its upstroke, but is denied receiving any work during the power stroke. The role of the engine is therefore reversed. It becomes a power-absorbing pump rather than a power-receiving pump.

Another way of managing the MEP is to use variable valve timing. In diesel engines, this is used for power optimization and as an emission control strategy. The closure of the intake valves can be delayed by the computer managing the engine under some running conditions to make it perform like a smaller engine. In other words, the MEP equation becomes a *soft* value managed by the engine controller computer.

Cylinder Pressure and Throw Leverage

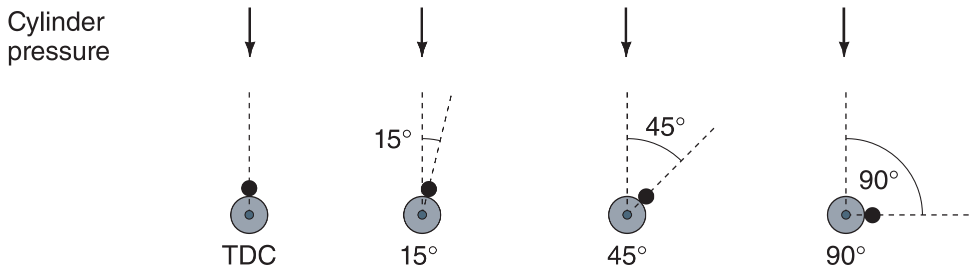
The objective of any engine is to transfer the power developed in its cylinders as smoothly and evenly as possible to the power takeoff mechanism, usually a flywheel. The relationship between the crankshaft throw (to which the piston assembly is connected) and the crankshaft centerline is that of a lever. A lever is a device that provides a mechanical advantage. The amount of leverage (mechanical advantage) depends on the rotational position of the throw, which ranges from zero or no leverage when the throw is positioned at TDC to maximum leverage when the throw is positioned at a 90-degree angle with the connecting rod after TDC. This makes the relationship between cylinder pressure (gas pressure acting on the piston) and throw leverage (the position of the piston) critical in meeting the objective of smooth/even transfer of power from engine cylinders to drivetrain.

Let us take a look at this principle in operation. When the piston is at TDC beginning a power stroke, it is desirable to have minimum cylinder pressure, because in this position throw leverage is zero; therefore, no power transfer is possible. A properly set up fuel system attempts to manage cylinder pressure so that in any given performance mode it peaks somewhere between 10 degrees and 20 degrees ATDC when there is some but nevertheless a small amount of throw leverage. As the piston is forced down through the power stroke, gas pressure acting on the piston diminishes, but as it does so, throw leverage increases. Ideally, this relationship between cylinder pressure and crank throw leverage should be managed in a way that results in consistent torque delivery from an engine cylinder through the power stroke until the throw forms a 90-degree angle with the connecting rod; this occurs a little before true 90 degrees ATDC.

Crank throw leverage changes in accordance with the exact engine rotational position. In a modern computer controlled diesel engine, cylinder pressure is managed by the fuel injection system. Precise management of cylinder pressure is critical for smooth engine operation. This principle is demonstrated in **Figure 2–7**.

Modern Diesel Engines

All highway diesel engines sold in the United States and Canada today are computer controlled. Computer controls are required to meet stringent EPA emissions standards. Every engine system is monitored and managed by computer. In addition, the engine management



The image depicts the angle between the crank throw and piston travel plane:
This should not be confused with crank angle degrees ATDC which will be slightly different.

Throw vector angle	0°	15°	45°	90°
Leverage	Zero	Minimal	Increasing	Maximum
Ideal cylinder pressure	Zero	Maximum	Decreasing	Decreasing

Crankshaft axis

Crank throw

FIGURE 2–7 Relationship between cylinder pressure and crank throw leverage.

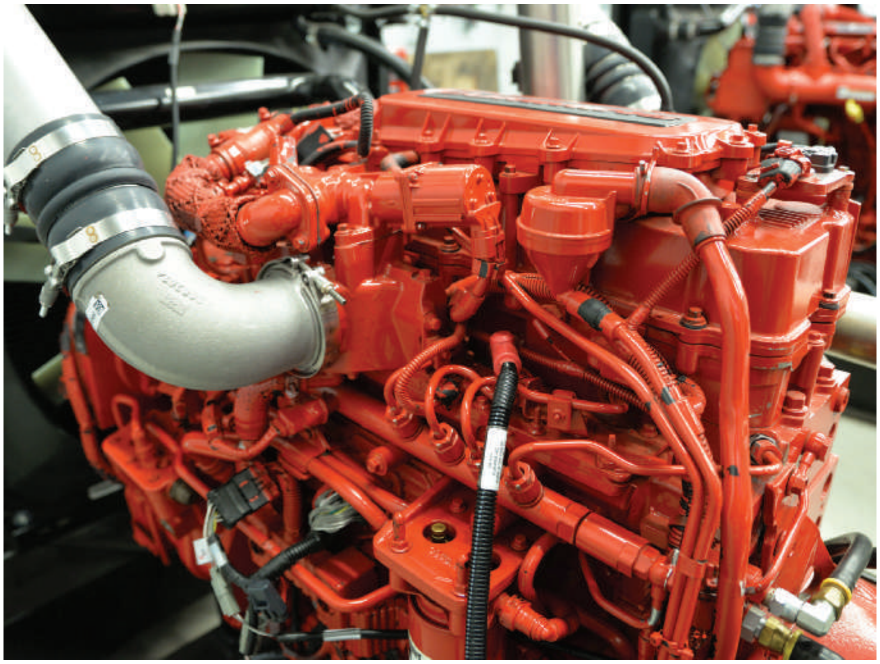


FIGURE 2–8 Cummins ISB engine used as optional power in Dodge pickup trucks.

computer is networked to other chassis computers to optimize:

- engine power
- fuel economy
- emissions
- vehicle longevity

The clean looks of the diesels of a generation past have been replaced by engines that are cluttered with external emission control apparatus and complex exhaust aftertreatment hardware. **Figure 2–8** shows a side view of a Cummins ISB engine used as optional power in Dodge pickup trucks.

Because of the need to monitor the performance of every engine condition and adapt to every consequence, in addition to the emissions hardware, dozens of sensors and actuators are arranged over the engine. Sometimes it can be difficult to identify engine hardware beneath all the wiring harnesses. Working on the electronically controlled engines of today requires manufacturer training. Attempting to service and repair engines without the appropriate training can result in costly damage.

SUMMARY

- Light-duty diesel engines are used in on-highway and off-highway vehicles and machinery. Most on-highway diesel engines are electronically controlled but many off-highway engines use hydromechanical management.
- Light-duty, on-highway, diesel engines are used in older passenger cars and workhorse pickup trucks. Off-highway applications for light-duty diesels include agricultural, marine, construction, generators, reefers, and stationary pumps.
- Almost every mobile highway diesel engine is manifold-boosted and managed electronically. Many off-highway light duty diesels are naturally aspirated and managed hydromechanically.
- The diesel cycle is a four-stroke cycle consisting of four separate strokes of the piston occurring over two revolutions; a complete engine cycle is therefore extended over 720 degrees.
- Diesel engine subsystems can be grouped as the engine housing components, the power train, and feedback assembly. These components are supported by lube, cooling, breathing and fuel delivery circuits.
- Diesel engines are managed by the fuel delivery system: this can be either electronic or hydromechanical.
- Engine displacement is calculated by multiplying (bore × 2) × stroke × the number of cylinders.
- MEP is the average pressure acting on the piston through the four strokes of the cycle. Usually, the intake and exhaust strokes are discounted, so MEP is equal to the average pressure acting on the piston through the compression stroke subtracted from the

average pressure acting on the piston through the power stroke.

- Diesel engines are usually classified as *undersquare* because they rely the heat generated through the compression stroke to ignite the fuel charge.
- An engine attempts to convert the potential heat energy of a fuel into useful kinetic energy: the degree to which it succeeds is rated as its thermal efficiency.
- That portion of the heat energy of a fuel not converted to kinetic energy is known as *rejected heat*. Rejected heat must be dissipated to the atmosphere by means of the engine cooling and exhaust systems.
- Ideally, engine fueling should be managed to produce peak cylinder pressures at somewhere around 10 to 20 degrees ATDC when the relative mechanical advantage provided by the crank throw position is low. This means that as cylinder pressure diminishes through the power stroke, throw mechanical advantage increases, peaking when the throw angle is 90 degrees ATDC, providing a smooth unloading of force to the engine flywheel.

REVIEW QUESTIONS

1. An 8-cylinder diesel engine has a bore of 80 mm and a stroke of 100 mm. Which of the following correctly describes the engine?
   A. 80 inch displacement
   B. 10 liter displacement
   C. Oversquare
   D. Undersquare
2. Which of the following best describes the term *engine displacement*?
   A. Total piston swept volume
   B. Mean effective pressure
   C. Peak horsepower
   D. Peak torque
3. Convert the displacement of a Cummins 6.7 liter engine into cubic inches.
   A. 350 cubic inches
   B. 409 cubic inches
   C. 440 cubic inches
   D. 500 cubic inches
4. Which of the following engine subsystems plays the larger role in managing engine output?
   A. Air induction system
   B. Throttle body circuit
   C. Fuel system
   D. Lubrication circuit
5. What percentage of the potential heat energy of the fuel does the modern diesel engine convert to useful mechanical energy when it is operating at its best efficiency?
   A. 20 percent
   B. 40 percent
   C. 60 percent
   D. 80 percent
6. Where does scavenging take place on a four-stroke cycle, diesel engine?
   A. BDC after the power stroke
   B. TDC after the compression stroke
   C. Valve overlap
   D. 10 to 20 degrees ATDC on the power stroke
7. Ideally, where should peak cylinder pressure occur during the power stroke?
   A. TDC
   B. 10 to 20 degrees ATDC
   C. 90 degrees ATDC
   D. At gas blowdown
8. Technician A says that all current light-duty highway diesel engines are hydromechanically managed. Technician B says that the popularity of private automobile diesel engines has been increasing since 2017. Who is correct?
   A. Technician A only
   B. Technician B only
   C. Both A and B
   D. Neither A nor B
9. Which of the following best describes MEP during engine operation?
   A. Combustion pressure acting on a piston
   B. Compression pressure produced by a piston
   C. Combustion pressure minus compression pressure acting on a piston.
   D. Intake pressure minus exhaust pressure in a cylinder
10. What term is used to specify the ignition temperature of a diesel fuel?
    A. Cetane number (CN)
    B. Flash point
    C. 700 degrees Celsius
    D. Vaporization temperature

CHAPTER 3

PREREQUISITE: CHAPTER 2

Cylinder Block Assemblies

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Identify the different types of pistons used in small-bore diesel engines.
- Explain the function of piston rings.
- Assess piston assemblies for reuse and outline the procedure required to remove and replace them.
- Describe the role of connecting rod assemblies and outline the procedure required to inspect and install them.
- Describe the role of the crankshaft and outline the forces it is subjected to under normal operation.
- Define the term *hydrodynamic suspension.*
- Inspect and identify typical crankshaft failures and their causes.
- Inspect and outline the procedure required to remove and replace friction bearings.
- Outline the function and failure modes of vibration dampers and flywheels.
- Replace a flywheel ring gear.
- Identify types of cylinder blocks and outline the required inspection procedure.
- Describe the function of the oil pan in the engine.
- Remove, inspect, and replace a diesel engine oil pan.

KEY TERMS

antithrust side
bearing shell
big end
cam ground
compacted graphite iron
compression ring
compressional load
connecting rod
cracked rods
crankcase
crown
cylinder block
direct injection (DI)
forged steel trunk-type pistons
fractured rods
friction bearing
headland volume
hone
hydrodynamic suspension
indirect injection (IDI)
keystone ring
keystone rod
lands
liners
lugging
major thrust side
Mexican hat piston crown
minor thrust side
Monosteel™ pistons (Federal Mogul)
Monotherm™ pistons (Mahle)
Ni-Resist™ insert
oil pan
parent bore
pin boss
piston pin
Plastigage™
powertrain
ring belt

ring groove	sump	torque-to-yield (TTY)
rod eye	template torque (TT)	torsion
scraper ring	thrust bearing	torsional stress
short block	thrust face	trunk-type piston
sleeves	thrust washers	wrist pin
small end	torque	

Why Read This?

In an internal combustion engine, the burning of fuel in an engine cylinder produces cylinder gas pressure. This pressure then has to be converted into useful mechanical energy. This chapter addresses the engine components responsible for converting the gas pressures developed in engine cylinders to torque at the flywheel. We call this group of components the engine **powertrain**. The engine powertrain includes:

- pistons
- piston rings
- wrist pins
- connecting rods
- crankshafts
- friction bearings
- flywheels
- vibration dampers

Function of the Powertrain

The powertrain is driven by cylinder gas pressure. Cylinder pressure acts on a piston and drives it through its stroke. A piston moves straight up or down in the engine cylinder. This linear movement has to be converted into **torque** or twisting force. This is accomplished by connecting the piston assembly to an offset throw on the crankshaft. In this way, the linear force produced by the piston is converted to rotary force known as torque. As pistons travel up and down in the cylinder bore, the crankshaft rotates. Connecting rods pivot on both the piston and crankshaft throw. Torque from the crankshaft is transferred to a flywheel bolted to the crankshaft. The flywheel acts as a coupling to transfer engine torque to the vehicle drivetrain.

Bicycle Powertrain

You can compare what is happening in a typical engine with another type of engine, a bicycle. A bicycle is an engine driven by muscle power. The powertrain of a bicycle consists of a pair of offset throws (we call them pedals), a crankshaft, and a bull gear: cogs on the bull gear allow torque to be transferred to a driven gear and wheel assembly. When a bicycle is ridden, linear force is applied to the pedals by the rider's legs. In just the same way as with a diesel engine, the crankshaft converts the linear force applied to the pedals into torque so that we can power the bicycle down a road.

Cylinder Block and Crankcase

The engine powertrain components are housed in a cylinder block assembly. All the other engine components are attached either directly or indirectly to the cylinder block. In a typically configured engine, an oil pan is bolted below the cylinder block. This lower region of the engine is known as the **crankcase**. The oil pan contains the lubricating oil. Lube oil is required to lubricate and help cool the powertrain components of the engine.

Short Block Assembly

The components of the powertrain and the cylinder block are often known as a **short block**. Although this might be considered a slang term, it is commonly used and is one means of partially reconditioning an engine. When a short block overhaul is undertaken, a fully reconditioned powertrain and cylinder block assembly is mated up to the existing engine's cylinder head(s) and peripheral components. In this chapter, we will begin with a study of the powertrain components in sequence and finish with a look at cylinder blocks.

Piston Assemblies

A piston is a circular plug that seals the engine cylinder bore. It is connected to the crankshaft by means of a connecting rod and moves up and down in the cylinder bore. The role of the piston in the cylinder bore is to:

- Deliver force: It does this when traveling upward on its compression stroke.
- Receive force: It receives force when combustion pressures act on it during the power stroke.

A piston assembly consists of the piston, piston rings, a wrist pin, and connecting rods. Piston rings seal the cylinder and lubricate the cylinder walls. The wrist pin is installed through a boss in the piston; it connects the piston to the connecting rod.

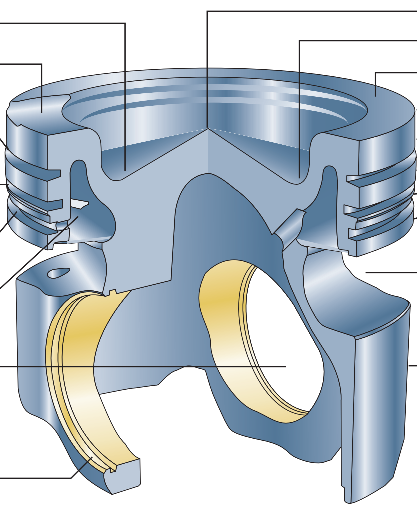


FIGURE 3–1 Piston terminology.

Piston Terminology

A diesel engine piston is shown in **Figure 3–1** along with the terminology we use to describe it. The type of piston shown is a forged steel trunk piston used in a wide range of current highway engines. In light duty diesel engine applications, pistons can be constructed from:

- forged steel
- cast aluminum alloys
- cast composites

If you follow the callouts in **Figure 3–1**, you should be able to make sense of the descriptions that follow in this section.

Piston Crown Geometry

In a diesel engine, the fuel is mixed with the air charge inside the engine cylinder. This means that the shape of the piston plays a role in determining how efficiently the fuel is mixed with the air. The upper face of the piston is called the **crown**. The crown or top of the piston is exposed directly to the cylinder chamber and therefore the effects of combustion. Because of this, a piston should be capable of rapidly transferring the combustion heat it is exposed to. This ability to transfer heat is especially important when aluminum pistons are used. Aluminum has a much lower melting point than alloy steels. Many pistons have cooling jets that spray lubricating oil on the underside of the piston. This helps remove heat and keep piston crown temperatures lower.

Mexican Hat Crown

The shape of the piston crown is important. This shape determines how swirl and squish are generated in an engine cylinder. Swirl and squish determine how injected fuel mixes with the air in the cylinder. The **Mexican hat piston crown** features a recessed circular crater centered by a peaked crown. This crater may be concentrically located in the crown as shown in **Figure 3–1** or offset, meaning that the circular recess is eccentric to the piston circumference. The Mexican hat design is commonly used on current diesel engines because it promotes good fuel/air mixing efficiency. The upper edge of the piston around the crown is known as its leading edge. Most modern diesel engines have low cylinder clearance volumes. This means that at top dead center (TDC), the piston rises in the cylinder bore until it almost contacts it. Shown in **Figure 3–2** is a cutaway of a Detroit Diesel DD5 engine cylinder with a piston featuring a Mexican hat crown.

FIGURE 3–2 A Detroit Diesel DD5 piston shown with the cylinder cutaway: note the aggressive Mexican hat piston crown geometry used in this 5-liter engine.

Trunk-Type Pistons

While larger diesel engines may use two-piece piston assemblies, most light duty diesels tend to use single-piece pistons. Single-piece pistons are known as **trunk-type pistons**. Trunk pistons used in diesel engines can be divided into three categories based on what material they are made of:

- aluminum alloy
- forged steel
- composites

Until recently, small-bore diesel engines used aluminum pistons almost exclusively. However, in late model, low-emission diesel engines, forged steel pistons have increased in popularity. As with many automotive innovations, forged steel pistons were first adopted by factory racing diesels before migrating to aftermarket racing applications and more recently to manufacturer original equipment.

Aluminum Trunk-Type Pistons

Aluminum alloy pistons are lightweight and transfer heat easily. However, because of a lower melting temperature and lack of toughness when compared with forged steels or cast irons, many aluminum trunk pistons use a ring groove insert for at least the top compression ring groove. The insert is usually a **Ni-Resist™ insert**. Ni-Resist has a much higher melting temperature than aluminum, and in addition, it expands and contracts in the same way. **Figure 3–3** is an image of an aluminum trunk-type piston with callouts indicating many of the key terms used in this chapter; note the location of the Ni-Resist insert.

Ceramic Fiber Alumina

Another method of increasing the toughness and high-temperature performance of an aluminum trunk-type piston is to reinforce it with ceramic fiber alumina (CFA). This can also be known as a composite insert. The CFA

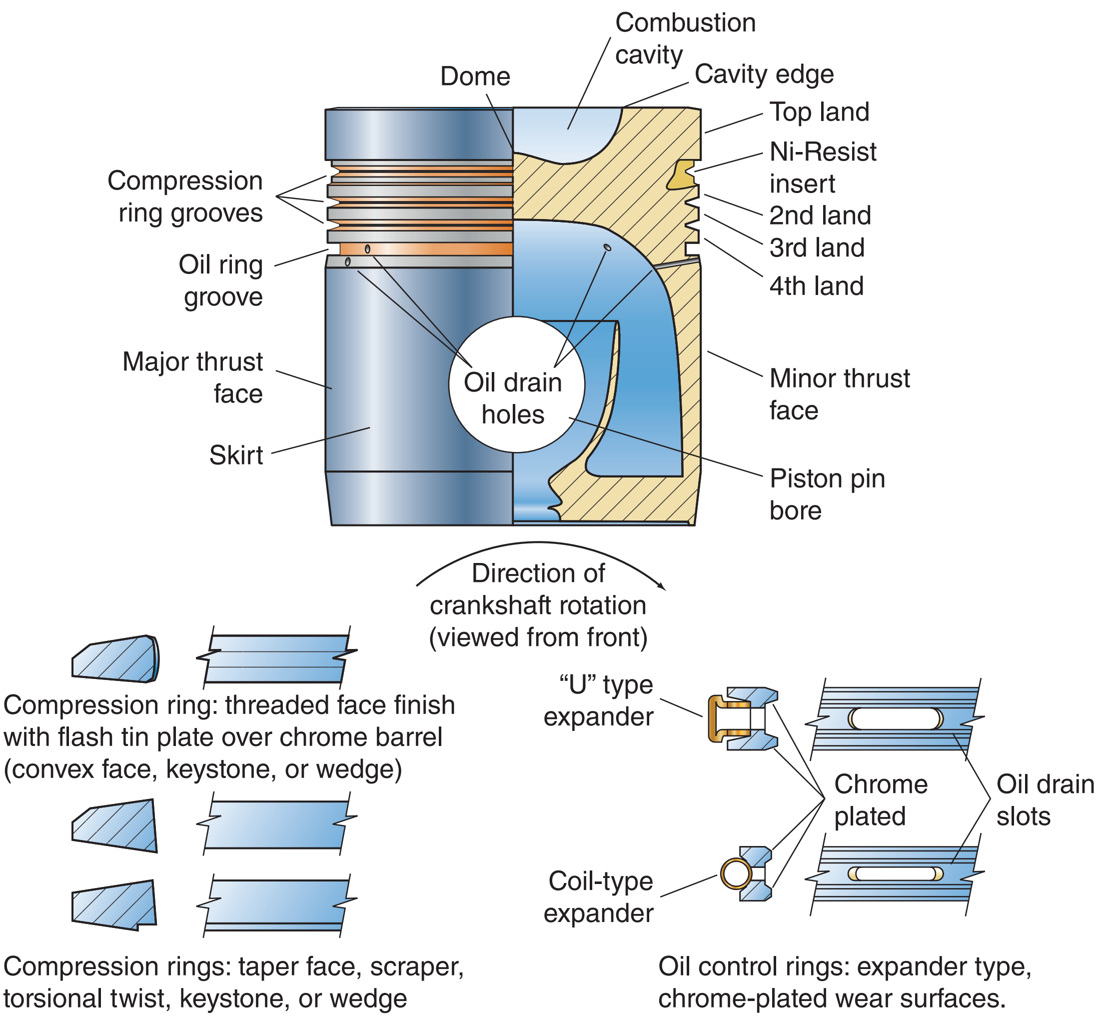


FIGURE 3–3 Aluminum trunk piston and ring terminology.

process eliminates the requirement for a Ni-Resist insert because it reinforces the piston at the top of the ring belt extending up into the top of the crown. This allows placement of the top compression ring close to the leading edge and reduces **headland volume** (see **Figure 3–1**). High location of the top compression ring is a requirement for today's low-emission, highway-compliant diesels because it reduces the dead gas zone between the upper compression ring and the piston leading edge. Another fiber reinforcement manufacturing practice known as squeeze cast, fiber reinforced (SCFR) is used by some manufacturers to toughen the crown area of the piston. This is also an alumina fiber manufacturing process.

Cam-Ground Pistons

Aluminum pistons are lightweight and transfer heat efficiently, but they also expand and contract much more than steels. This means that they have to be designed with much higher clearance in the cylinder bore when cold. It also means that they have to be **cam ground**. A cam-ground piston is slightly oval in shape when cold. As the piston warms up, the area around the **pin boss** expands relatively more than the thinner skirt area between the pin bosses. The idea behind a cam-ground piston is that at running temperatures, the piston should expand to an exactly circular shape with minimal bore clearance.

A big disadvantage of cam-ground pistons is that they should be warmed to operating temperature before being subjected to high cylinder pressures. Failing to warm up a cam-ground piston before loading an engine can overstress the piston rings and lands. Aluminum trunk pistons are shaped to beef up the piston where it is at its weakest. So, in addition to having reinforcement at the pin boss, they also have increased material around the crown, as you can see in **Figure 3–3**.

Weight is always a factor of piston design, so aluminum alloy trunk pistons are more common in light duty applications. Most of the previous generation of automobile engines used aluminum alloy trunk pistons, and this is the piston used in Ford's recently introduced Power Stroke 3.0 liter engine shown in **Figure 3–4**.

Wrist Pins and Ring Belt

Piston wrist pins when not full floating are usually press fit to the piston boss and float on the rod eye. Heating the piston to 95°C (200°F) in boiling water facilitates pin assembly. Because of their higher clearance when cold, aluminum trunk pistons are prone to piston slap during engine warm-up. Piston slap is the tilting action of the piston when the piston is thrust loaded by cylinder combustion pressure. It can be minimized by tapering the piston so that the outside diameter at the lower

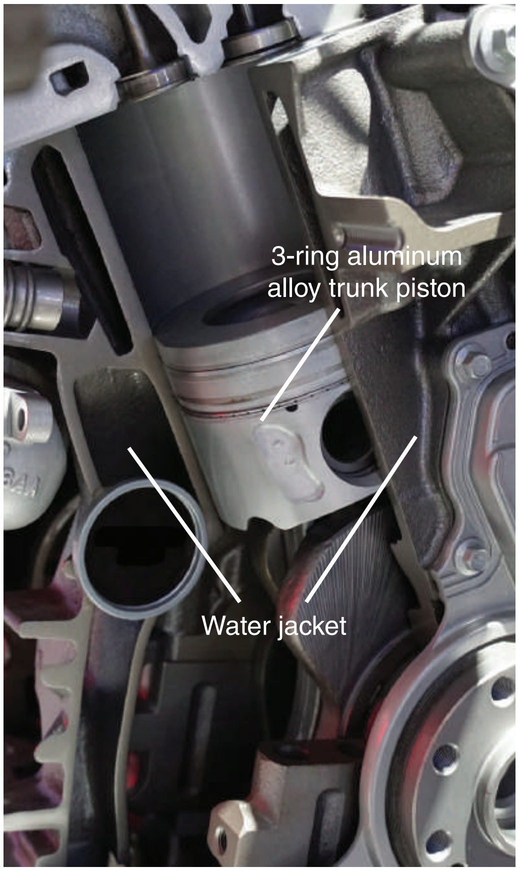


FIGURE 3–4 Aluminum alloy trunk piston used in a 2020 Ford 3.0 Power Stroke.

skirt (where it does not get so hot) slightly exceeds the outside diameter over the ring belt region. The ring belt region is exposed to more heat and expands more as the piston heats to operating temperatures.

Advantages of Aluminum Trunk Pistons

- Lightweight. This reduces the overall piston weight. Lightweight pistons reduce the inertia forces that the connecting rod and crankshaft are subject to. It also permits the use of lighter-weight components throughout the engine powertrain.
- Cooler piston crown temperatures. Because aluminum alloy pistons transfer heat so rapidly, they run cooler than equivalent steel-based pistons.
- Quieter. Engines using aluminum alloy, trunk-type pistons generally produce less noncombustion-related noise.

Forged Steel Trunk-Type Pistons

Although **forged steel trunk-type pistons** were used half a century ago in drag racing applications, they are

FIGURE 3–5 Examples of Mahle diesel engine pistons: the crown recesses in the image on the right are to accommodate cylinder head valve protrusion.

a relatively new introduction to diesel engine technology. However, they have caught on quickly with diesel engine designers, and many of today's late-model diesel engines use them. The brand names of this new generation of pistons are **Monotherm™** (manufactured by Mahle) and **Monosteel™** (manufactured by Federal Mogul). In this text, we generally refer to them as *forged steel trunk-type pistons* to avoid using brand names. **Figure 3–5** shows some examples of Mahle diesel engine pistons that are designed to reduce mass and maximize cooling efficiency.

Piston Design and Construction

The single-piece forged steel trunk piston has the appearance of an aluminum trunk piston with a large circumferential slot cut away between the pin boss and the ring belt. The skirt is designed to guide the piston over the thrust sides of the piston and is recessed across the pin boss. This permits the use of a shorter, lower-weight wrist pin. It also allows the piston pin boss support area to be increased, making the design well suited to engines producing very high cylinder pressures.

The problem of cold-start piston slap in aluminum trunk pistons has been overcome with the adoption of forged steel pistons. The steel alloy pistons expand much less than equivalent aluminum trunk pistons when heated from cold to operating temperatures. This allows them to be manufactured with a much tighter fit to the liner bore. Steel pistons run hotter than aluminum pistons because they dissipate heat more slowly. The lubricating oil cooling gallery used in a typical forged steel piston is closed to permit much higher oil feed and flow-back volumes as shown in **Figure 3–6**. The oil feed to the underside of the piston is delivered by a precisely targeted cooling jet. In some cases, the connecting rods used with steel forged pistons are not rifle-drilled with a lubrication passage. This means that the piston and wrist pin depend almost entirely on the oil cooling jet for lubrication and cooling.

The micro-alloyed steel construction of this class of trunk piston provides high strength, so much less material has to be used. The result is a tough steel piston of about the same weight as the older aluminum trunk pistons. In forged steel pistons featuring bushing-less wrist pin bores, the pin boss is phosphate treated over the pin bearing bore.

Advantages of Forged Steel Trunk Pistons

The growing adoption of forged steel trunk-type pistons in recent years is accounted for by the higher cylinder combustion pressures and temperatures required of today's engines. Some of the advantages of forged steel trunk pistons are:

- Reduction of headland volume. Headland volume (see **Figure 3–1**) is the volume in the cylinder above the top compression ring and below the piston crown leading edge. This volume is less affected by cylinder turbulence and the effects of cylinder scavenging, so it collects dead end gas. Headland volume can be minimized by placing the top compression ring as close as possible to the crown leading edge. Because forged steel is much stronger than aluminum, steel trunk pistons require no groove insert, and the upper ring groove can be located close to the crown leading edge. Most forged steel trunk pistons place the top compression ring just slightly under the leading edge of the piston.
- Thermal expansion factors. Thermal expansion is simply how a material responds to heat. Forged steel expands and contracts as temperature changes much less than aluminum, so cam-ground designs are not required in steel trunk pistons, and piston-to-bore clearances are tighter.
- Long life. Micro-alloyed forged steel coated with phosphate provides much longer service life than equivalent aluminum trunk pistons.
- Lightweight. Forged steel trunk pistons are designed to be as lightweight as aluminum trunk pistons but to have much higher strength. Some forged steel trunk pistons are specified to sustain cylinder pressures that reach 3,500 psi (250 bar).

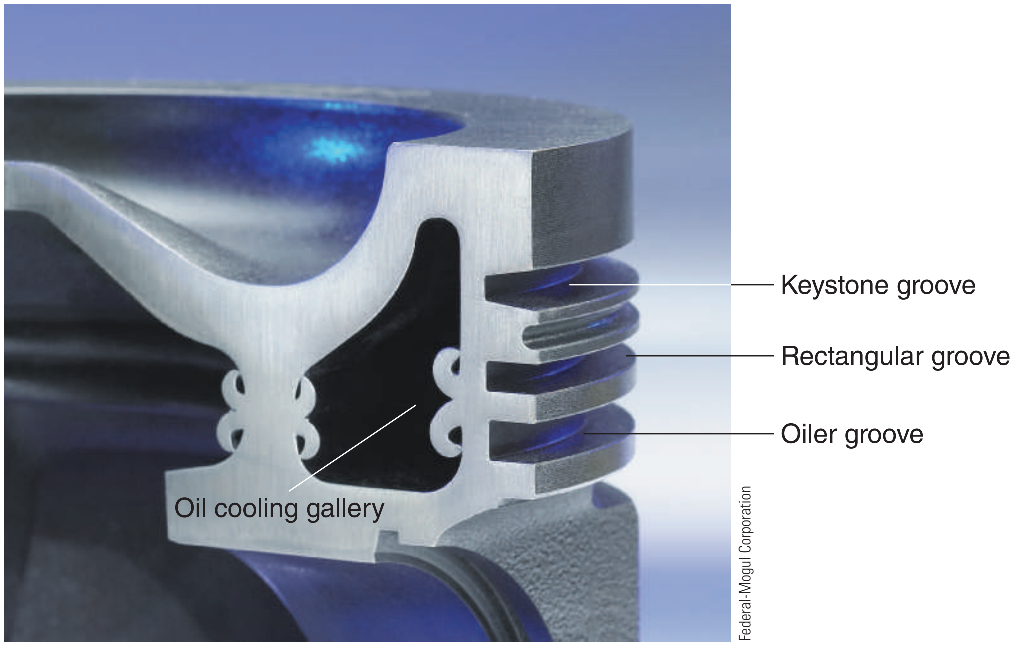


FIGURE 3–6 Sectional view of a Magnum Monosteel trunk piston highlighting its high flow oil gallery that maximizes crown cooling efficiency.

Figure 3–7 shows a steel trunk piston from a Ford Power Stroke 6.7 liter engine: the cylinder wall is cutaway so the piston can be seen.

Piston Thrust Faces

When cylinder gas pressure acts on a piston, especially during the initial stage of combustion, it tends to cock (pivot off a vertical centerline) in the cylinder bore because it pivots on the wrist pin. This action creates thrust faces on either side of the piston. The major thrust face is on the inboard side of the piston as its throw rotates through the power stroke. The minor thrust face is on the outboard side of the piston as its throw rotates through its power stroke. Take a close look at **Figure 3–3** in which the piston thrust faces are identified. The major thrust face is sometimes simply called the **thrust face**, while the minor thrust face is called the antithrust face. You should learn to identify the thrust faces of a piston for purposes of failure analysis. On modern steel trunk-type pistons, only the thrust faces are skirted. This allows the piston to be guided true in its bore while also reducing the weight of the piston.

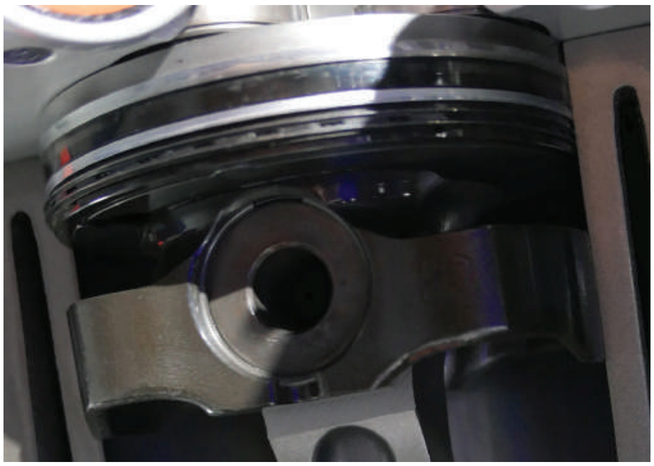


FIGURE 3–7 Steel trunk piston used by Ford in their Power Stroke 6.7.

Combustion Chamber Designs

In direct-injected diesel engines, the shape of the piston crown determines how the gas within the cylinder moves on the compression and power strokes. Up until around 1990, diesel engines tended to use piston crowns designed to produce developed high turbulence especially those using **indirect injection (IDI)**. IDI diesel engines are ones in which the fuel is injected into a cavity located remotely from the cylinder bore, usually in the cylinder head, less commonly within the piston. The cavity was known as a pre-combustion chamber, pre-chamber, or energy cell. Today, IDI engines are not common because they are not able to produce the combustion efficiency of **direct injection (DI)** diesel engines required to meet tough emissions standards.

Direct Injection

In a DI engine, the fuel charge is injected at high pressure directly into the engine cylinder above the piston. Most pickup truck and automobile diesel engines adopted DI diesel engines during the 1990s, and it is a requirement of any diesel engine meeting today's on-highway emissions standards. DI has always required high fuel injection pressures, but these have increased in recent years to improve combustion efficiency. As diesel fuel injection pressures have increased, the need for high cylinder turbulence has decreased. In fact, excessive turbulence tends to be avoided because it can propel fuel droplets away from the intended flame front.

Mexican Hat

We have already introduced the Mexican hat crown design because it is so common among recent diesel engines. While the Mexican hat crown produces desirable swirl characteristics, another reason diesel engine manufacturers use the design is that it allows injected diesel fuel droplets to be targeted into the crater around the peak of the hat. This allows atomized fuel droplets to vaporize and ignite before they make physical contact with the piston crown material. In this way, the Mexican hat piston crown provides a lower risk of fuel burnout scorching on the piston crown directly below the injector, and lengthens service life.

Mann Type (or "M" Type)

The Mann-type piston crown is named after the German company responsible for its design. It tends to be used on older trunk-type pistons and consists of a radiused, recessed bowl located directly under the injector, though not necessarily in the center of the piston crown. Depending on the depth of this bowl, the Mann-type combustion chamber produces high turbulence and is most often seen in IDI diesel engines.

Dished

The dished piston crown has a slightly concave to almost flat design that produces low turbulence when compared with the previous types. You are most likely to see this design in some current small-bore and offshore-manufactured diesel engines.

Piston Cooling

Engine oil plays a major role in managing piston temperatures. Lube oil is routed to the pistons directly through rifled bores in connecting rods, or indirectly by piston cooling jets. Things such as the size of the piston, peak cylinder pressures, and whether the engine is turbocharged determine what type of piston cooling is required. Within the same engine family, you may find that engines with lower horsepower specifications do not use cooling jets, while those rated at higher horsepower do. Because combustion temperatures may sometimes be higher than the melting temperature of the piston materials (in cases where aluminum is used), it is essential to get rid of any heat that has not been converted to usable energy as quickly as possible. A percentage of cylinder heat is always transferred through the piston assembly. Three methods are used to cool pistons. Engines may use one or more combinations of these piston cooling methods.

1. Shaker—Oil is delivered through the connecting rod to a gallery machined into the underside of the piston crown. This oil is distributed by the motion of the piston after which it drains to the crankcase.
2. Circulation—Oil is delivered through the connecting rod rifling, through the wrist pin, and then circulated through a series of grooves machined into the underside of the piston crown. It then drains back into the crankcase.
3. Spray—A stationary cooling jet is located in the cylinder block just below the cylinder liner. This jet is fed by engine lube under pressure. The oil cooling jet is then aimed so that the spray is directed at the underside of the piston. This oil cools the piston crown (see **Figure 3–6**) and may also lubricate the wrist pin. The aiming of cooling jets is usually done using a clear perspex template that fits over the fire ring groove on the cylinder block deck; an aim rod is inserted in the jet orifice. A target window is scribed in the perspex template and the aim rod has to be positioned within the window as shown in **Figure 3–8**. The spray cooling method is highly efficient and is used in many turbocharged diesel engines that run higher piston temperatures.

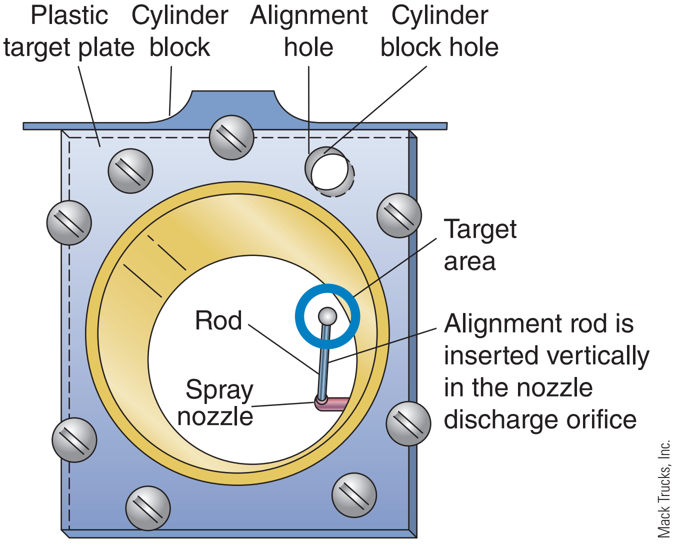


FIGURE 3–8 Spray nozzle targeting.

CAUTION

A piston cooling jet that is misaimed can destroy the piston it is intended to cool. You have to especially take care when assembling an engine to avoid clunking a cooling jet when installing piston/rod assemblies.

Piston Rings

The function of piston rings is to seal the piston in the cylinder bore. Most pistons require rings to effectively seal, and those that do not are usually found in automobile racing applications. Ringless pistons use special piston materials and are run at high rpms. Running engines at high rpms permits little *time* for cylinder leakage or blowby to occur. Rings have three important functions:

1. Sealing: They are designed to seal compression and combustion gases within the engine cylinder.
2. Lubrication: They are designed to apply and regulate a film of lubricant to the cylinder walls.
3. Cooling: Rings provide a path for heat to be transferred from the piston to the cylinder walls.

Piston rings are located in recesses in the piston known as **ring grooves**. Ring grooves are located between **lands**. Check out **Figure 3–1**, paying special attention to the ring area.

Roles of Piston Rings

Piston rings may be broadly categorized as:

- compression rings
- oil control rings

Compression rings are responsible for sealing the engine cylinder, and they play a role in helping to transfer piston heat to the cylinder walls. The term **scraper ring** is used to describe rings below the top compression ring that play a role in sealing cylinder gas as well as managing the oil film on the cylinder wall. Oil control rings are responsible for lubricating the cylinder walls and also provide a path to dissipate piston heat to the cylinder walls.

Piston Ring Materials

Piston rings are designed with an uninstalled diameter larger than the cylinder bore, so that when they are installed, radial pressure is applied to the cylinder wall. Some diesel engines use piston compression rings manufactured from cast iron alloys that are similar to those used in production gasoline-fueled, spark-ignited engines. Cast iron rings are brittle and fracture easily. However, some modern workhorse diesel engines use steel alloy rings that have some flexibility and will not fracture like cast iron. These new generation piston rings are much tougher and more flexible than their cast iron counterparts. They are almost impossible to fracture and often show little wear at engine overhaul. The wall section of the piston in which the set of rings is located is known as the **ring belt**. You can identify the ring belt on **Figure 3–1**.

Ring Action

The major sealing force of piston rings is high-pressure gas. Piston rings have a small side clearance. The result of this minimal side clearance is that when cylinder pressure acts on the upper sectional area of the ring, three things happen in the following sequence to make it seal on the compression stroke:

1. Pressure forces the ring downward into the land.
2. Forcing the ring into the land allows developing cylinder pressure to get behind the ring.
3. After cylinder pressure gets behind the ring, it acts against the ring wall, driving the ring outward into the cylinder wall, creating the seal.

The lower right side of **Figure 3–9** explains ring action in diagram form. Make sure you understand this. What this tells us is that cylinder sealing efficiencies increase with cylinder pressure. The higher the cylinder pressure, the more effectively rings seal the cylinder.

Number of Rings

The number of rings used is determined by the engine manufacturer, and factors are:

- bore size
- engine speed
- engine configuration

Time is probably the major factor in determining the number of compression rings. The slower the maximum running speed of the engine, the greater the total number of rings required because there is more *time* for gas blowby to occur. So, diesel engines with slower rated rpms usually require more rings. Higher speed diesels require a lower number. Most automotive diesel engines run at peak speeds of 4,000 rpm or less, and this category of engines commonly use a three-ring configuration of two compression rings and a single oil control ring. **Figure 3–10** shows two examples of three-ring configuration on trunk-type pistons. Note the proximity of the top compression ring to the crown on the piston on the left: this minimizes the headland volume reducing emissions. On this piston, the top two rings are compression rings and the third ring is an oil control ring.

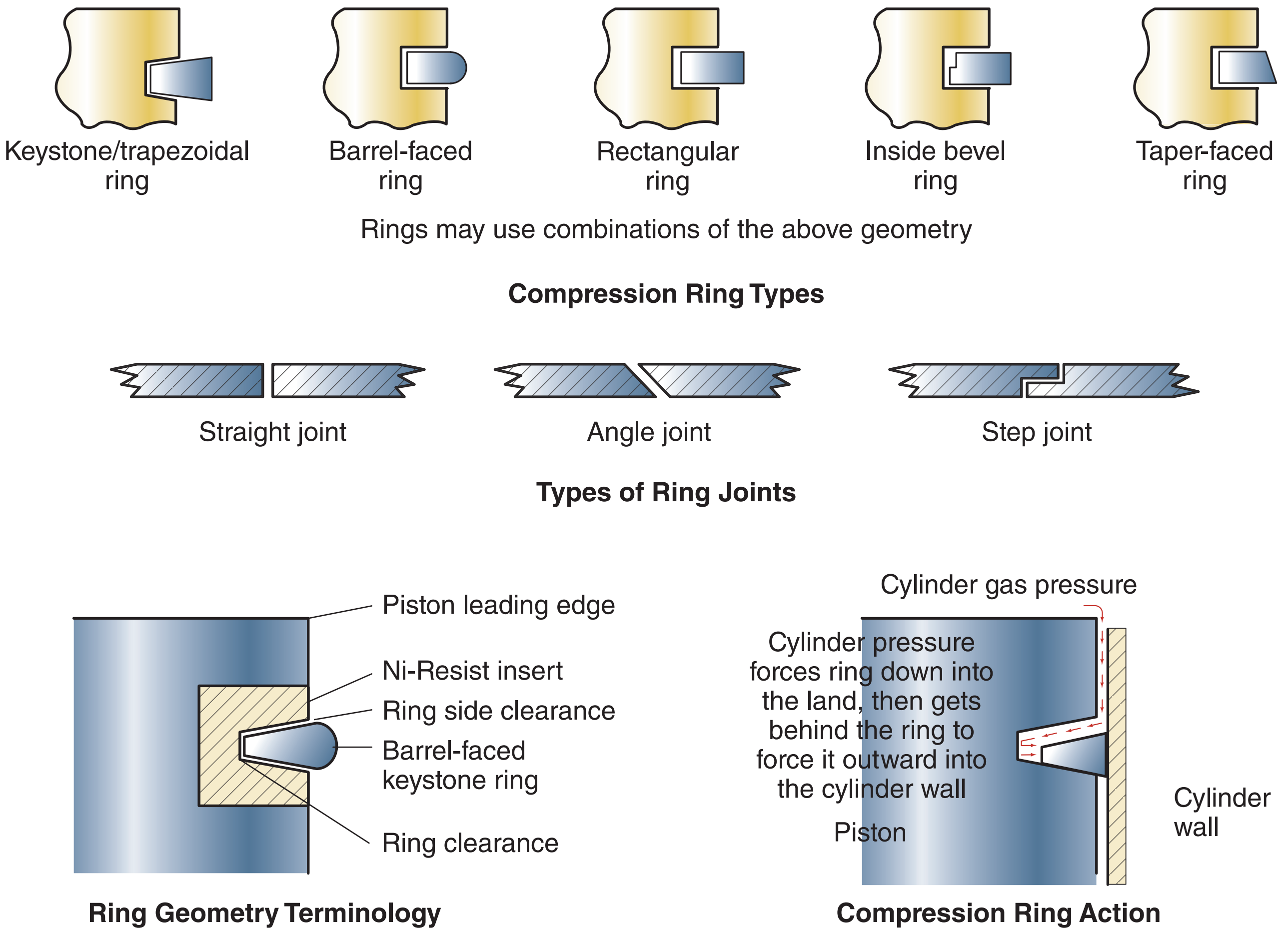


FIGURE 3–9 Piston ring geometry and action.

Gas Blowby

The top compression ring gets the greatest sealing assist from cylinder pressures. Gas blowby from the top compression ring passes downward to seal the second compression ring, and so on. Gas that blows by all the rings enters the crankcase, so high crankcase pressures are often an indication that an engine is wearing out. Because an engine cylinder is sealed by rings, some cylinder leakage past the ring belt is inevitable. The limiting factor is time. When an engine is operated at 2,000 rpm, one full stroke of a piston takes place in 15 milliseconds (0.015), so there is quite simply insufficient time for significant cylinder leakage to take place.

You are likely to see the most gas blowby when an engine is lugged. When an engine is lugged, cylinder pressures are high and the engine is running at a lower rpm meaning that there is more time for leakage. All the piston rings play a role in controlling the oil film on the cylinder wall, including the top ring. The role the rings play in controlling the oil film on the cylinder wall becomes increasingly important as emissions standards get tougher. Any excess oil on cylinder walls is combusted and subsequently exhausted to the aftertreatment circuit as unwanted emissions.

FIGURE 3–10 Two examples of three-ring configurations on trunk-type pistons.

Piston Ring Types

There are many different types of piston rings. We name them by function and shape. Make sure you reference **Figure 3–9** as we run through the following explanation.

Compression Rings

Compression rings seal cylinder compression and combustion pressures. They also play a role in managing the oil film applied to the cylinder wall. As indicated earlier, some current diesel engine piston rings can be substantially deformed without fracturing because they have metallurgical properties similar to stainless steel. Whether steel base or cast iron, compression rings may also be surface coated by tinning, plasma, and chrome cladding to reduce friction.

Some ring coatings are break-in coatings. These temporary coatings wear off and end up in the crankcase lube, something that has to be taken into account when studying an oil sample analysis. Sometimes the upper compression ring is known as the fire ring, but more often this term is used to describe the cylinder seal at the top of the liner that is often integral with the cylinder head gasket.

Combination Compression and Scraper Rings

Combination compression and scraper rings assist in sealing combustion gases and controlling the oil film on the cylinder wall. Manufacturers who use this term are referring to a ring or rings located in the middle of the ring belt, between the top compression ring and the oil control ring(s).

Oil Control Rings

Oil control rings are designed to control the oil film on the cylinder wall. Too much oil on the cylinder wall will end up being combusted. Too little oil on the cylinder wall will result in scoring and scuffing of the cylinder wall. The action of first applying (piston traveling upward) and then wiping (piston traveling downward) lubricant from the cylinder wall helps remove heat from the cylinder by transferring it to the engine oil. Most oil control rings use circular scraper rails that are forced into the cylinder wall by a coiled spring expander. They are sometimes known as *conformable* rings because they will flex to conform to a moderately distorted liner bore.

Piston Ring Designs

Piston rings are described by their sectional shape; the term *ring geometry* is often used to describe this sectional shape. **Figure 3–9** shows some examples of ring geometry used in diesel engines today. Most piston rings use combinations of the characteristics outlined here. Following are some examples.

Keystone Rings

Keystone rings (sometimes known as *trapezoidal rings*) are wedge shaped. A keystone ring is fitted to a wedge-shaped ring groove in the piston. This design is commonly used for the top compression ring, especially in high-performance diesel engines. The shape of a keystone ring allows cylinder pressure to first act on its upper sectional area to get behind the ring and then force it against the cylinder wall. Keystone rings are also less likely to form carbon deposits due to the scraping action that takes place as the ring twists within its groove. They are also less prone to sticking.

Rectangular Rings

The sectional shape of the ring is rectangular as you can see in **Figure 3–9**. Rectangular rings are loaded evenly (they do not twist so much) into the cylinder wall when cylinder pressure acts on them. Some pistons that use a keystone top compression ring use a rectangular second or third compression ring as you can see in **Figure 3–1**.

Barrel Faced

A barrel-faced piston ring is one in which the outer face is "barreled" with a radius (rounded). This increases the service life. The downside is that they do not seal quite as effectively because there is no sharp edge to bite into the cylinder wall when the ring twists within the groove. Keystone rings are often barrel faced. **Figure 3–9** shows an example of a barrel-faced keystone ring.

Inside Bevel

An inside bevel ring is one in which a recess is machined into the inner circumference of the ring as shown in **Figure 3–9**. This helps cylinder pressure to get behind the ring and causes it to twist in the groove. This twisting action produces high unit-sealing pressures because the ring bites into the cylinder wall, providing an effective seal.

Taper Faced

The design is similar to the rectangular ring but its outer face is angled, giving it a sharp lower edge. Once again, this enables the ring to achieve high unit-sealing pressures; that is, to bite into the cylinder wall when loaded with cylinder gas pressure. A taper-faced ring is shown in **Figure 3–9**.

Channel Section

Channel section rings are used as oil control rings. They usually consist of a grooved ring with a number of slots to allow oil to be first applied, and then scraped from the cylinder walls. In most cases, an expander ring is used with channel section rings. This spring-loads the ring into the cylinder wall, allowing it to adapt to minor variations in the liner bore. The expander ring is a coiled or trussed spring installed into a groove behind the rails of the channel section.