Introduction to Marine Engineering

Massachusetts
Maritime
Academy

Introduction to Marine Engineering

Introduction to Marine Engineering

Massachusetts Maritime Academy
Massachusetts Maritime Academy

April 28, 2024

Contents

Chapter 1

Safety

Objectives

- `RFPEW-A1.3` Safe working practices as related to engine-room operations
- `OICEW-C1.5` Safety measures to be taken to ensure a safe working environment
- `ABE-C3.1` Mechanical safety
- `ABE-C3.1` Electrical safety
- `ABE-C3.1` Chemical and biohazard safety

Ships are dangerous places to live and work for many reasons, some general, and some specific to the marine environment. These include dynamic and unpredictable marine conditions, extended working hours with small crews, hazardous cargos, isolated work settings, and the potential for fire, explosion, collision, and sinking.

Everyone aboard needs to be aware of the potential hazards, actively engage in safety measures, and be prepared to respond to emergencies. Safety is not solely the responsibility of designated officers or management but is a collective responsibility shared by all onboard.

In this chapter we discuss some of the hazards you may encounter aboard ship, approaches to managing and reducing risk, and some things you can do personally do to protect yourself, your shipmates, the vessel, and the environment.

1.1 Hazards in the workplace

In any workplace, including aboard a ship, exposure to safety hazards is inevitable due to the nature of the work environment. These hazards can have serious repercussions such as injuries, operational disruptions, equipment damage, financial loss, environmental harm, and even loss of life.

Identifying, addressing, and avoiding hazards is crucial to maintaining a safe working environment, protecting yourself and others. In this section we describe some common workplace hazards which you should be aware of.

1.1.1 Slips, Trips and Falls

According to the US Bureau of Labor Statistics, slips, trips, and falls cause nearly 700 fatalities per year and many more injurious accidents in the workplace,

Common trip and fall hazards include obstructions on walkways, such as cables, tools, or equipment left in pathways. Uneven surfaces, loose gratings, and obstructions, can also contribute to tripping incidents. Additionally, poor lighting, cluttered work areas, improper storage of materials, and inadequate lighting can increase the risk of trips and falls.

Spilled liquids, oils, or water can make surfaces extremely slippery. Wet surfaces due to cleaning or maintenance activities, and the presence of loose debris are additional factors that can contribute to slip incidents.

Falls can be particularly dangerous when you are working at above the ground, such as on a ladder, scaffolding or staging.

Aboard ship, additional hazards exist due to the dynamic and often wet environment. Obstructions such as hatch combings, pad-eyes and container hold-downs can cause individuals to trip. Slip hazards arise from seawater or rainwater on deck surfaces, spilled liquids in galley areas, or lubricants used for machinery maintenance. In rough seas, the motion of the ship can cause unsecured objects to fall, or cause you to lose your balance and fall. You must be particularly careful when working at heights or over the side. Always follow the old adage, "one hand for the ship and one hand for yourself.

1.1.2 Mechanical Hazards

Mechanical hazards are a physical hazards associated with machines and other movable objects that may cause harm to a person.

Injuries caused by mechanical hazards include friction or abrasion, lacerations, cutting, severing, pinching, crushing, or entanglement of body parts. Additionally, non-mechanical hazards such as chips, splashes, and sparks can injure you or others in the area.

Figure 1.1.1 Rotating Shaft Hazard Sign

Mechanical hazards can be managed by adopting safe work procedures and the application of appropriate safeguards. As such, you should always wear appropriate PPE, follow the machine's operating instructions, and ensure that all machine safety features and guards are in place. Be aware that some machines may start automatically at any time, so take appropriate precautions including de-energizing and locking out machinery before working on it.

1.1.3 Electrical Hazards

Electricity is a powerful and essential source of energy, but it can cause severe injuries, fires, and even fatalities if not handled properly. Understanding the hazards posed by electricity is crucial for practicing electrical safety.

Figure 1.1.2 Danger High Voltage

Here are some of the main hazards associated with electricity:

Electrical Shock. The most immediate and dangerous hazard of electricity is electrical shock. When a person comes into contact with an electrical voltage, current can pass through their body, causing electrical shock.

Roughly speaking, the greater the current, the more severe the shock. High voltage presents more danger than lower voltages, but even normal household voltage (120 V AC) can cause severe shock or even death.

Electrical Fires. Electrical malfunctions can generate heat and sparks, leading to electrical fires. Faulty wiring, overloaded circuits, damaged electrical cords, and short circuits are common causes of electrical fires. These fires can quickly spread and pose a significant risk to property and life. The combination of electricity and flammable materials increases the likelihood of a fire and makes it more challenging to extinguish.

Arc Flash and Arc Blast. **Arc flash** refers to the release of intense heat, light, and energy that occurs during an electrical fault or short circuit. It is characterized by a sudden and violent discharge of electrical energy through the air. The arc flash generates extremely high temperatures, often exceeding 35,000 degrees Fahrenheit (19,400 degrees Celsius). The intense heat emitted during an arc flash can cause severe burns to anyone in its vicinity. Additionally, the arc flash produces a bright flash of light, which can lead to temporary or permanent vision impairment.

Arc blast, on the other hand, refers to the high-pressure shockwave produced by the rapid expansion of air during an arc flash. The rapid expansion of these vapors creates a blast wave that can cause significant physical damage. Arc blasts can result in powerful pressure waves, similar to those generated by an explosion, which can cause injuries, such as concussions, fractures, hearing loss, and even fatalities. The arc blast can propel debris, molten metal, and hot gases, further exacerbating the risk to individuals in the vicinity.

Electrical Burns. Electrical burns occur when electric current passes through the body, generating heat. These burns can be internal or external, depending on the path the electricity takes. Electrical burns can cause extensive tissue damage and may require specialized medical treatment. The severity of electrical burns depends on the voltage, current, duration of contact, and the body's resistance.

Electrocution. In the most severe cases, electric shocks can lead to electrocution, resulting in death. High-voltage shocks can cause cardiac arrest, severe internal injuries, and other life-threatening conditions. Contact with overhead power lines, unauthorized access to electrical panels or equipment, and improper handling of live wires are some situations that can lead to fatal accidents.

Effects of Electrical Current on the Human Body.

Electrical shock occurs when current passes through the body. The severity of the shock depends on the current's magnitude, the duration, the contact area, and the path taken by the current through the body.

The shock current received obeys `[provisional cross-reference: ohms-law]`, so high voltages are always more dangerous. But your body resistance is equally important. Body resistance with dry skin may be above 100,000 ohms, However, if the skin is wet or broken, the body's resistance decreases to a few thousand ohms.

Current	Reaction 1 Second contact
< 1 mA	Generally not perceptible.
1 mA	Threshold of feeling, tingling sensation.
3 mA	Painful shock. Average individual can let go.
5 mA	Accepted as maximum harmless current. Strong involuntary reactions may cause indirect accidents.
6–25 mA	Beginning of sustained muscular contraction. ("Can't let go" current.)
9–30 mA	Lung paralysis, Respiratory arrest - usually temporary, but death is possible.
50 mA	Possible ventricular fibrillation. (heart dysfunction, usually fatal.)
100–300 mA	Certain ventricular fibrillation, fatal.
1–4 Amps	Heart paralysis, severe burns. Muscular contraction and nerve damage occur; death is likely.
5 Amps	Flesh burns, defibrillation, temporary respiratory paralysis.

1.1.4 Chemical Hazards

Chemicals can pose significant risks to human health and safety. By identifying and understanding the potential hazards, following proper storage and handling procedures, and adhering to safety protocols, you can significantly reduce the risks associated with hazardous chemicals and create a safer environment for everyone.

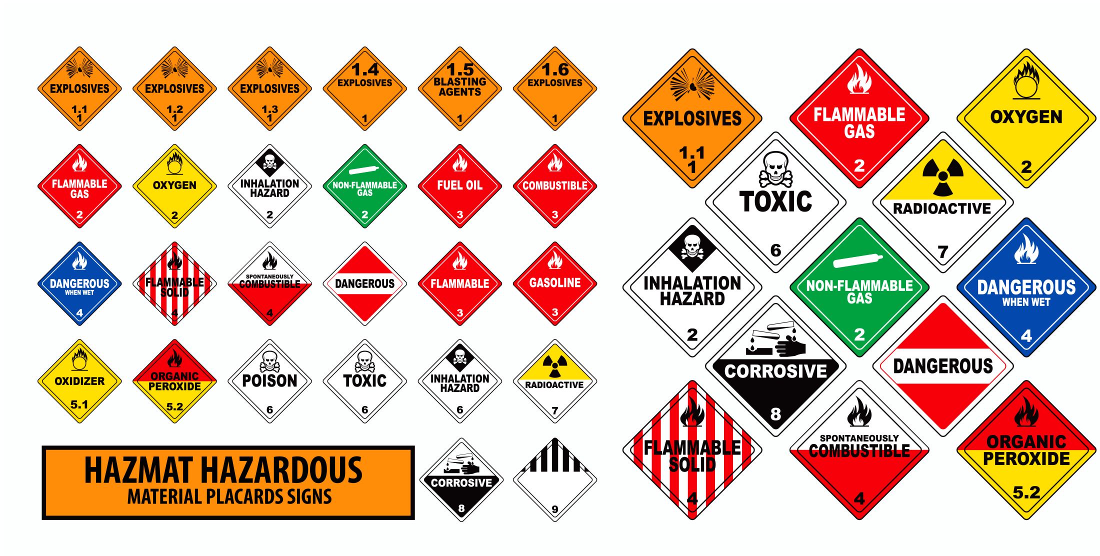


Figure 1.1.3 Hazardous Material Placards

Chemical Exposure. You may be exposed to hazardous chemicals through inhalation, skin contact, or ingestion. Prolonged exposure or exposure to high concentrations can lead to adverse health effects such as respiratory issues, skin irritation, chemical burns, organ damage, or even long-term illnesses.

You should be aware of the hazardous chemicals present in your workplace, handle them safely and take precautions to minimize exposure, such as using proper ventilation systems, wearing personal protective equipment (PPE), and following established protocols.

You can learn about the potential risks associated with a chemical, as well as instructions on how to handle and respond to accidents or exposures, in the **Material Safety Data Sheet** (MSDS), which is required to be available in your workplace. MSDSs are typically created by the manufacturer or supplier of the chemical and are designed to ensure the safe use, storage, and disposal of hazardous substances.

Chemical Storage. Chemicals that are improperly stored or incompatible substances stored in close proximity can react with one another, causing fires, explosions, or the release of toxic gases. Inadequate storage practices may also result in spills, leaks, or contamination, endangering both employees and the environment.

It is essential to follow proper storage procedures, including segregating incompatible chemicals, labeling containers correctly, ensuring proper ventilation and temperature control, and implementing appropriate containment measures such as spill kits and secondary containment systems. The MSDS will contain instructions regarding proper storage.

In particular, aboard ship chemical containers must always be secured so that they don't break free and cause accidents during heavy weather.

Handling and Transporation. Improper handling of hazardous chemicals, such as careless pouring, transferring chemicals without suitable protective measures, or failure to follow established protocols, can result in spills, splashes, or exposure.

1.1.5 Fire

Fire aboard ship is an ever-present threat that can swiftly escalate into a catastrophic disaster. With limited means of escape, a ship becomes a confined space where flames can spread rapidly, fueled by combustible materials and confined by its structure.

The close quarters, complex layout, and intricate ventilation systems aboard ship create formidable challenges for the ship's small firefighting team. In addition to the immediate threat to human lives, a shipboard fire poses a significant risk to the environment, as toxic smoke, potential oil spills, and the release of hazardous substances can wreak havoc on marine ecosystems.

Figure 1.1.4 *Hyundai Fortune* on fire 21 March 2006

Effective fire prevention measures, comprehensive emergency response plans, rigorous training, and state-of-the-art firefighting equipment are crucial in mitigating this threat and ensuring the safety of everyone on board.

Fire prevention measures play a vital role in minimizing the risk of fire and maintaining a safe environment aboard ship. These measures encompass a range of proactive strategies aimed at preventing fires from starting or spreading. One fundamental aspect is implementing rigorous safety protocols and adhering to international standards, such as the International Maritime Organization's (IMO) regulations for fire safety.

Some key fire prevention measures include:

- *Regular Inspections and Maintenance.* Conducting routine inspections of electrical systems, machinery, and fire suppression equipment is crucial. Identifying and addressing potential hazards, faulty wiring, or malfunctioning equipment can prevent fire incidents.

- *Training and Education.* Crew members should receive comprehensive training on fire safety, including proper handling of flammable substances, effective use of firefighting equipment, and emergency response procedures. Increasing awareness and knowledge among the crew can significantly reduce the likelihood of fire-related accidents.

- *Fire Detection Systems*. Installing advanced fire detection systems, such as smoke detectors, heat sensors, and flame detectors, helps in early detection of fires. These systems can trigger alarms, alerting the crew and initiating immediate response actions.

- *Fire Suppression Systems*. Equipping ships with reliable fire suppression systems, such as fixed CO2 or water mist systems, can effectively control and extinguish fires. These systems are designed to release the appropriate extinguishing agent in the affected area, limiting the fire's spread.

- *Proper Storage and Handling*. Storing flammable materials in designated areas and following strict protocols for their handling reduces the risk of accidental ignition. Implementing proper waste management procedures and ensuring the availability of suitable fire-resistant containers also contribute to fire prevention efforts.

- *Structural Fire Protection*. Regulations require fire-resistant materials and insulation in the ship's construction helps to contain fires and slow down their progression. Fire-resistant doors, bulkheads, and insulation compartmentalize the vessel, preventing the rapid spread of flames.

- *Emergency Preparedness*. Developing and regularly reviewing comprehensive emergency response plans specific to fire incidents is crucial. This includes establishing evacuation procedures, assigning roles and responsibilities to crew members, and conducting fire drills to ensure everyone knows how to respond swiftly and effectively in an emergency.

By implementing robust fire prevention measures, ships can significantly reduce the risk of fire, enhance the crew's safety, and protect the marine environment from potential devastation.

1.1.6 Fatigue

Objectives

- `PSSR-X6.1` Importance of obtaining the necessary rest

- `PSSR-X6.2` Effects of sleep, schedules, and the circadian rhythm on fatigue

- `PSSR-X6.3` Effects of physical stressors on seafarers

- `PSSR-X6.4` Effects of environmental stressors in and outside the ship and their impact on seafarers

- `PSSR-X6.5` Effects of schedule changes on seafarer fatigue

Fatigue, which refers to a state of extreme tiredness and lack of energy, can pose several risks. The primary cause of fatigue is insufficient or poor-quality sleep. To avoid fatigue, it's important to prioritize adequate rest and sleep, and maintain a healthy lifestyle.

Other factor which can contribute to fatigue include: medical conditions such as chronic fatigue syndrome, anemia, and thyroid disorders; depression and anxiety, and unhealthy lifestyle habits, including inadequate physical activity, poor nutrition, excessive caffeine or alcohol intake, and smoking. Certain medications have fatigue as a side effect.

The negative consequences of fatigue include:

Fatigue can significantly impair cognitive abilities, including attention, concentration, memory, and decision-making. This can lead to reduced performance and increased errors, particularly in tasks that require sustained focus or critical thinking, such as driving, operating machinery, or performing complex work.

Fatigue can slow down reaction times and impair alertness, making it more challenging to respond quickly and appropriately to stimuli or unexpected events. This can increase the risk of accidents, both in occupational settings and during activities like driving or operating heavy equipment.

Fatigue-related impairment can lead to an increased risk of accidents and injuries across various domains, including workplaces, roadways, and other high-risk environments. Fatigue-related accidents have been linked to major incidents in industries such as transportation, healthcare, and manufacturing.

Fatigue can impair an individual's ability to assess risks accurately and make sound judgments. This can result in poor decision-making, potentially leading to safety hazards or negative consequences in various aspects of life, including personal relationships and professional responsibilities.

The IMO has developed guidelines for rest requirements to address the issue of fatigue among seafarers. These guidelines are outlined in the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW Convention).

The STCW Convention sets out minimum hours of rest for seafarers. The standard requires that seafarers receive a minimum of 10 hours of rest in any 24-hour period and a minimum of 77 hours of rest in any 7-day period. The hours of rest may be divided into no more than two periods, with one period being at least 6 hours in length.

In situations where the safety of the ship, crew, or passengers is compromised, and in cases of emergencies or drills, the rest period may be temporarily shortened or interrupted. However, the seafarers should be provided with compensatory rest as soon as possible.

1.1.7 Confined Spaces

Objectives

- `ABE-C3.1` Working in enclosed spaces
- `PSSR-X3.3` Precautions to be taken prior to entering enclosed spaces

A confined space is defined by OSHA as a space that has limited or restricted means of entry, is not designed for continuous occupancy, and is large enough and configured so that a person can enter the space and maneuver well enough to perform tasks.

Confined spaces pose several hazards that can endanger workers who enter them due to their limited entry and exit points, restricted airflow, and potential for hazardous atmospheres.

On ships, some examples of confined spaces include: Cargo and fuel tanks, cofferdams, pressure vessels, sewage tanks, and void spaces.

Figure 1.1.5 Confined Space Hazards

Here are some hazards associated with confined spaces:

Lack of oxygen. Confined spaces often have limited ventilation, which can lead to a decrease in oxygen levels. This oxygen-deficient atmosphere can cause dizziness, loss of consciousness, or even asphyxiation.

Toxic gases and vapors. Confined spaces may contain hazardous gases or vapors, such as carbon monoxide, hydrogen sulfide, or volatile chemicals. These substances can accumulate in the confined space and pose a serious health risk to individuals who inhale them, leading to poisoning or respiratory problems.

Fire and explosion risks. Confined spaces may contain flammable substances, inadequate electrical systems, or potential ignition sources. This combination can result in the rapid escalation of fire or explosion hazards, especially in spaces with limited airflow and potential fuel accumulation.

Engulfment or entrapment. Confined spaces often have small openings or tight access points. If an individual becomes trapped or engulfed by materials, such as loose soil, water, or flowing grain, it can lead to serious injury, suffocation, or drowning.

Physical hazards. Confined spaces may have uneven surfaces, protruding objects, or low ceilings, increasing the risk of slips, trips, falls, and head injuries. Limited visibility and restricted movement within the space can further contribute to accidents and make rescue difficult.

Extreme temperatures. Some confined spaces can experience extreme temperatures due to insulation issues, lack of ventilation, or the presence of heat-generating equipment. Excessive heat or cold can cause thermal discomfort, heat exhaustion, hypothermia, or heat stroke.

Emergency repairs to boilers must sometimes be made before the boiler has had a chance to cool down.

Biological hazards. In certain confined spaces, such as sewage tanks or areas with stagnant water, there may be an increased risk of exposure to bacteria, viruses, or mold, which can lead to respiratory issues, allergies, or infectious diseases.

For safe entry into a confined space, everyone involved should be properly trained on confined space entry and rescue techniques and strictly comply with all regulations and guidelines governing confined space entry.

Begin by conducting a thorough risk assessment to identify potential hazards and establish necessary control measures. Inspect the equipment used for entry to guarantee its reliability.

Ensure proper ventilation is in place, to maintain fresh air and remove hazardous substances. Test the atmosphere using gas detection equipment before entering to verify safe conditions. Wear the appropriate personal protective equipment (PPE), including respiratory protection and fall protection gear.

Maintain proper lighting to ensure visibility within the confined space. Establish effective communication systems between individuals inside and outside the space. Designate a standby person outside the space, equipped with rescue training, to provide immediate assistance if required.

1.2 Hazard Mitigation

Objectives

- `OICEW-C2.1` Safe isolation of shipboard machinery and equipment before personnel are permitted to work
- `OICEW-C2.1` Safety measures to be taken for repair and maintenance
- `ABE-C3.1` Permit to work systems

TBD

1.2.1 Safety Management

Safety management is a systematic approach taken by regulatory bodies and companies to identify, assess, control, and mitigate risks in order to ensure the safety of personnel, assets, and the environment. It involves the development and implementation of policies, procedures, and practices aimed at preventing accidents, injuries, and damage.

Key components of safety management include risk assessment, safety planning, establishment of policies and procedures, training and education, reporting and investigation of incidents, audits and inspections, and continuous improvement efforts. The goal of safety management is to protect lives, prevent harm, and promote a culture of safety within organizations across various industries.

ISM Code

The International Safety Management Code (ISM Code) is a set of guidelines and regulations developed by the International Maritime Organization (IMO) to ensure the safe operation of ships and the prevention of marine pollution. It was adopted in 1993 and became mandatory for all vessels engaged in international voyages in 1998.

The primary objective of the ISM Code is to establish a safety management system (SMS) on board ships and ashore, providing a framework for managing safety and minimizing risks in the maritime industry. The code applies to all types and sizes of vessels, including passenger ships, cargo ships, tankers, and offshore drilling units.

Under the ISM Code, both the ship and the company have specific obligations to ensure the effective implementation of safety management systems and adherence to safety standards. The obligations of the ship and the company are as follows:

Ship Obligations.

- Implement the Safety Management System (SMS): The ship is responsible for implementing and following the SMS as defined by the company. This includes adhering to the documented procedures and instructions outlined in the SMS.
- Report Hazards and Non-conformities: The ship is obligated to report any hazards, accidents, or non-conformities that may affect the safety of the ship, its personnel, or the environment. This includes reporting incidents, near-misses, and deficiencies in the SMS.
- Participate in Training and Drills: All personnel on board the ship must undergo appropriate training to ensure they have the necessary skills and knowledge to perform their duties safely. They are also required to actively participate in safety drills and exercises.
- Comply with Safety Procedures: The ship must comply with all safety procedures and guidelines outlined in the SMS. This includes following safe working practices, adhering to emergency response plans, and utilizing safety equipment as required.
- Maintain Records: The ship is responsible for maintaining accurate records of safety-related activities, including incidents, inspections, audits, drills, and maintenance activities. These records provide evidence of compliance with the ISM Code.

Company Obligations.

- Develop and Implement the SMS: The company is responsible for developing and implementing a documented Safety Management System (SMS) for each ship under its management. The SMS should encompass policies, procedures, and instructions that promote safe operations and environmental protection.
- Appoint a Designated Person Ashore (DPA): The company must appoint a Designated Person Ashore (DPA) who serves as a liaison between the company and the ship. The DPA ensures that the SMS is effectively implemented, maintained, and continuously improved.

- Provide Adequate Resources: The company must provide the necessary resources, including personnel, equipment, training, and support, to enable the ship to comply with the ISM Code and operate safely.

- Conduct Audits and Reviews: The company is responsible for conducting internal audits and reviews of the SMS to assess its effectiveness and identify areas for improvement. These audits ensure that the SMS is being followed and that any non-conformities are addressed.

- Maintain Documentation: The company must maintain comprehensive documentation of the SMS, including policies, procedures, instructions, and records. This documentation serves as evidence of compliance and provides a reference for shipboard personnel.

By fulfilling these obligations, everyone works together to promote a culture of safety, prevent accidents, protect the environment, and continuously improve the safety standards in the maritime industry.

SOLAS

The **International Convention for the Safety of Life at Sea** (SOLAS) is an international treaty developed by the **International Maritime Organization** (IMO) in 1914, following the sinking of the Titanic, one of the most famous maritime disasters in history.

SOLAS sets out minimum safety standards for the construction, equipment, and operation of ships in order to prevent accidents at sea and ensure that ships are well-prepared to handle emergencies.

Key aspects and provisions of SOLAS include:

- *Structural Integrity*.

  It defines requirements for ship construction, stability, and subdivision to ensure that vessels are built to withstand the stresses of the marine environment.

- *Safety Equipment*.

  SOLAS mandates the provision of life-saving appliances such as lifeboats, life rafts, lifejackets, and distress signaling equipment on board.

- *Fire Safety*.

  The treaty outlines measures for preventing and combating fires on board ships, including fire detection systems, fire-fighting equipment, and fire drills.

- *Navigation Safety*.

  SOLAS includes regulations for navigational equipment, including navigation lights, radar systems, and the use of electronic navigation aids.

- *Radio Communications*.

  SOLAS establishes regulations for navigation and communication equipment, including requirements for radar systems, navigational aids, and communication devices to ensure safe navigation and effective communication, ensuring that vessels can call for assistance in case of emergencies.

- *Training and Drills*.

  SOLAS mandates regular safety training and drills for the crew, including procedures for abandoning ship, using life-saving equipment, and responding to emergencies.

OSHA & 29CFR

OSHA, the Occupational Safety and Health Administration, is a U.S. federal agency under the Department of Labor. OSHA's primary mission is to ensure safe and healthy working conditions for employees by enforcing workplace safety regulations, conducting inspections, and providing resources to help employers and workers prevent workplace injuries, illnesses, and fatalities.

OSHA regulations are found in the **US Code of Federal Regulations**, Title 29 CFR Part 1910 where they address many aspects of workplace safety, including:

- Personal Protective Equipment (PPE)
- Lockout/Tagout (LOTO)
- Confined Spaces
- Electrical Safety
- Machine Guarding
- Fall Protection
- Welding, Cutting, and Brazing
- Respiratory Protection
- Chemical Exposure
- Hazard Communication

It's important to note that OSHA regulations mainly pertain to workplaces on land. For most safety matters on board ship, the U.S. Coast Guard and international maritime regulations (such as SOLAS) take precedence; however OSHA regulations are sensible guidance that should be followed whenever possible whether you are working at sea, at a shore job, or even at home.

1.2.2 Job Hazard Analysis

A **job hazard analysis** (JHA), also known as a**job safety analysis**(JSA), is a systematic process used to identify and analyze potential hazards or risks associated with specific job tasks or activities. Its primary purpose is to reduce the risk of accidents by identifying potential hazards and developing appropriate controls to mitigate them.

The process typically involves breaking down a job into its individual steps and examining each step to identify potential hazards. Hazards can include physical hazards (e.g., machinery, equipment, or environmental conditions), chemical hazards (e.g., exposure to hazardous substances), biological hazards (e.g., exposure to infectious agents), ergonomic hazards (e.g., repetitive motion or lifting heavy objects), or any other factors that could pose a risk to worker safety and health.

The key steps in conducting a job hazard analysis typically include:

1. Select the job or task to be analyzed.
2. Break down the job into steps.
3. Identify potential hazards for each step.
4. Determine the risk level for each identified hazard. Risk level multiplies severity and the likelihood of each identified hazard.
5. Develop hazard controls to eliminate or minimize the hazards. This might include engineering controls (e.g., machine guarding), administrative controls (e.g., training or procedures), or personal protective equipment (PPE)
6. Communicate the findings to workers and stakeholders to ensure awareness and buy-in.
7. Regularly review and update the job hazard analysis.

This results of the JHA can be shared with the crew during a **toolbox talk** in order to raise awareness about known hazards, reinforce safe work practices, and promote a culture of safety. These talks are usually conducted before the start of the work day.

Systematically analyzing and communicating job hazards and implementing appropriate controls helps to create a safer workplace.

Polar Tankers Inc.

Job Hazard Analysis Form

JOB: 6.6 kV High Voltage Generator Annual Inspection	DATE: 12/16/08	PAGE: 1 OF 1
TITLE OF PERSON (S) WHO DOES THE JOB: Engine Crew	DEPARTMENT: Engine	ANALYSIS BY: Engine Dept
VESSEL: Resolution	☒ NEW	REVIEWED BY: 1 A/E
REQUIRED AND/OR RECOMMENDED PERSONAL PROTECTION EQUIPMENT: High Voltage PPE	APPROVED BY: 1 A/E	

SEQUENCE OF BASIC JOB STEPS	POTENTIAL HAZARDS	RECOMMENDED ACTION / PROCEDURE
LOTO 6.6 kV breaker and associated pumps	Electrocution, oil spillage into bilge	LOTO 6.6kV breaker and ground as per Polar HV electrical safety policy
Open generator	Dropping things into generator, capacitive shock	Empty pockets, wear HV PPE
Ground generator	Capacitive shock	Follow procedure, wear HV PPE
Inspect generator	Dropping things into generator	Follow procedure, exercise situational awareness
Button up covers	Leaving things in generator, lifting strain	Carefully look around before closing, follow safety in motion guidelines

NEW HAZARDS IDENTIFIED FOR REVISION OF JHAs

SEQUENCE OF BASIC JOB STEPS	POTENTIAL HAZARDS	RECOMMENDED ACTION / PROCEDURE

Figure 1.2.1 Sample Job Hazard Analysis Form

1.2.3 Permit to work

A **permit to work** is a document used to control hazardous activities conducted onboard a ship. It is a written authorization that specifies the work to be performed, identifies the potential hazards involved, and outlines the necessary precautions and safety measures.

Permits to work are required for dangerous jobs such as hot work (welding or burning), confined space entry, working at heights, electrical work, handling hazardous substances, hoisting operations, etc.

The permit to work system is designed to prevent accidents, injuries, and damage to the ship and its equipment by ensuring that work activities are conducted in a controlled manner. It helps to manage high-risk tasks and ensure that proper procedures are followed.

Figure 1.2.2 Hot Work Tag

1.2.4 Lockout-Tagout

Objectives

- `ABE-C3.1` Lockout/tag-out

Lockout-Tagout (LOTO) is a safety procedure used to ensure that dangerous equipment is properly shut down, isolated from energy sources, and secured while undergoing maintenance or repair. The goal of LOTO is to prevent unexpected startup or release of stored energy, which could lead to serious injuries or fatalities for workers involved in maintenance or repair activities.

Figure 1.2.3 Lockout Tag

Lockout refers to disabling a piece of equipment or machinery by isolating it from its energy sources (electrical, mechanical, hydraulic, pneumatic, chemical, thermal or other), and placing a physical lock on the isolating devices (such as switches, valves, or breakers) that control those energy sources.

Tagout refers to affixing a label or tag that communicates information about equipment's status and the ongoing maintenance activities. The tag typically includes information about the equipment being serviced, the reason for the lockout/tagout, the name of the authorized person who applied the lock and tag, contact information, and the expected duration of the job etc.

The steps of the LOTO process are:

1. Identify the equipment or machinery that needs maintenance or repair.

2. Inform all affected personell that a LOTO procedure will be performed on the identified equipment.

3. Shut down the equipment using the appropriate procedures outlined in the manufacturer's instructions or company protocols.

4. Physically isolate the equipment from its energy sources. This might involve locking out switches, valves, or other control mechanisms. In some cases, this can involve disconnecting power sources, bleeding fluids, or other actions to ensure there's no energy flowing to the equipment.

5. Place a lock on the energy-isolating device to prevent it from being operated. A tag is also attached to the lock indicating who performed the lockout and why. This helps communicate that the equipment is being worked on and should not be operated.

6. Ensure that any residual or stored energy in the equipment is safely released. This might involve releasing pressure, tension, or any other forms of stored energy.

7. Verify that the equipment is truly isolated by attempting to start or activate it. This step is important to confirm that the energy sources have been effectively disconnected.

8. Perform the necessary maintenance, repairs, or servicing on the equipment while it is in the locked and tagged state.

9. Once the maintenance or servicing is complete, the person who performed the LOTO procedure removes the locks and tags, and the equipment is ready to be safely restarted.

1.3 Personal Protective Equipment

Personal protective equipment (PPE) includes all clothing and other work accessories designed to create a barrier against workplace hazards. It provides an important link in the chain of workplace safety, but PPE alone is not a substitute for safe engineering design, proper training, good work practices, safety awareness, or hazard reduction. All these elements together are required to minimize the danger of workplace hazards and maximize the safety and health of workers.

Using personal protective equipment requires hazard awareness and training on the part of the user. You must be trained to know when personal protective equipment is necessary, what type is necessary, how it is to be worn, and what its limitations are, as well as know its proper care, maintenance, useful life, and disposal. In addition, you must be aware that the equipment does not eliminate the hazard. If the equipment fails, you can be injured. To reduce the possibility of failure, equipment must be properly fitted, and maintained in a clean and serviceable condition.

To protect yourself, you must be wearing the proper personal protective when it is needed and recognize its limitations. The equipment must not be altered or removed even though you may find it uncomfortable. In some cases however, the equipment may be uncomfortable because it does not fit properly.

In this chapter we will discuss some of the personal protective equipment normally found and used aboard ship.

1.3.1 Head Protection

Head injuries are caused by falling or flying objects, or by bumping your head against a fixed object. Head protection, in the form of protective hats, must do two things – resist penetration and absorb the shock of the blow. This is accomplished by making the shell of the hat of a material hard enough to resist the blow, and by utilizing a shock-absorbing lining composed of headband and crown straps to keep the shell away from the wearer's skull. Protective hats are also used to protect against electric shock.

Figure 1.3.1 Head Protection

There are several types of hard hats available, each designed for specific purposes and levels of protection.

Class G (General) hard hats and caps are intended for general service and they provide protection against impact hazards and a limited protection against electrical shock (up to 2,200 V). They are used in industries such as construction, manufacturing, mining, and shipbuilding. This is the most suitable hard hat for shipboard use.

Class E (Electrical) hard hats are utility service hats which are designed to protect the wearer's head from impact and penetration by falling or flying objects and from high-voltage shock (up to 20,000 V). They are used extensively by electrical workers.

Class C (Conductive) hard hats or caps, are designed to be light and comfortable while protecting against impact hazards, but they *do not* provide any protection against contact with electrical conductors. Class C hats often have a front brim to protect the face from sun, reduce glare, and help shed rain. They are used on occasions where there is a possibility of falling objects or bumping the head, but no risk of electrical shock.

Bump caps are less obtrusive than hard hats and are designed to provide comfortable, lightweight but they have limited protection against minor head bumps, knocks, and scrapes. They in environments where there is a risk of hitting the head on objects such as low ceilings, beams, or equipment. They are not meant a substitute for a hard hat because they do not afford protection from high electrical shock, high impact forces, or penetration by falling objects, and they are not OSHA approved, so they can not be used in situations where a hard hat is required.

Before using a hard hat you should inspect it for signs of damage or abuse of the helmet or any of its parts. A damaged helmet reduces the margin of safety the hat was designed to supply, and should be replaced immediately.

Correct adjustment and fit of the your hard hat is required for maximum safety. The internal cradle of the headband and sweatband forms a suspension system which keeps the helmet away from the head and cushions against impact. The headband must be adjusted to the right size in order to provide sufficient clearance between the shell and the headband.

1.3.2 Eye Protection

Every day more than 1,000 eye injuries occur in American workplaces. The US Bureau of Labor Statistics found that three out of five workers who suffered eye injuries were not wearing eye protective equipment at the time of the accident, and when asked why, the victims often claimed that eye protection was not normally used in their type of work, or it was not required for the type of work performed at the time of the accident. Eye protection can save your sight, but you must be wearing it.

Eye injuries can occur in many ways, but are primarily caused by rapidly flying objects. The BLS found that almost 70% of eye injuries were caused by flying or falling objects or sparks striking the eye. Most of these objects were smaller than a pin head, and were traveling faster than a hand-thrown object. Another 20% of eye injuries were caused by chemicals, and the remainder due to miscellaneous causes such as objects swinging into the eye, pulled into the eye or by light radiation.

Eye injuries can be prevented by wearing effective eye protection. To be effective, the eyewear must be of the appropriate type for the hazard encountered and properly fitted. The BLS survey found that 94% of the injuries to workers wearing eye protection were caused by objects or chemicals going around or under the protector. Goggles provide better protection than face shields or safety glasses, but the best protection is afforded when both goggles and a face shield are worn together.

The three main types of eye protection for general maintenance are safety glasses, goggles, and face shields. In addition, when welding, specialized equipment must be used to protect your eyes. Each method of eye protection has its own advantages and disadvantages.

Figure 1.3.2 Eye Protection

Safety glasses are lightweight glasses that have shatter resistant lenses made of materials like polycarbonate or propionate plastic and often have side shields attached to the side pieces. Safety glasses are designed to stop flying objects such as chips, fragments, sand, and dirt from injuring your eyes. They also can provide laser light filtration to prevent reflections from the laser entering the eye and causing retinal burns. Safety glasses can be purchased with prescription lenses including bifocals if necessary.

The main advantage of safety glasses is that they are lightweight and relatively comfortable to wear for long periods of time. The provide little to no protection from liquids or vapors, and some flying particles may get around the side shields.

Safety goggles provide more complete protection of the eye than safety glasses, since they protect against both frontal and side impact. They come in two different types, vented and non-vented. Vented goggles are used to protect your eyes from splashes and flying objects, while Non-vented Goggles additionally protect your eyes from hazardous vapors, mists, and fumes.

Face shields are designed to augment other types of eye protection and are not meant to be a stand alone form of eye protection. Face shields are used to protect your entire face with goggles on under the shield to catch any liquids that might make it past the shield.

Welding helmets are specialized helmets are used by welders to protect their eyes and face from the intense light, sparks, and heat generated during welding processes. They often feature auto-darkening lenses that adjust the shading based on the brightness of the welding arc.

Always wear a welding helmet when arc welding. Your eyes, face, and neck need protection against the burning rays of the arc, and from the splatter of molten metal and slag. To protect your eyesight, make sure the welding helmet has a colored lens with at least a No. 10 shade when welding with 200 amperes or less. And never strike a welding arc before your helmet is in place. Never look at an arc from any distance with your naked eyes while someone else is welding.

Never chip slag when your eyes (or those of others nearby) are not protected by goggles, an eye shield, or the clear lens of a welding helmet. If fragments of hot slag were to hit the eye, medical attention would be required for their removal, and blindness could result. The risk of permanent eye injury is so great that you should never chip slag from a weld without protecting your eyes.

1.3.3 Hearing Protection

Over the years, many marine engineers have suffered permanent hearing loss due to hours of exposure to the high noise levels in the engine room. You can prevent the loss of your own hearing by using proper hearing protection such as earplugs and earmuffs religiously whenever you are exposed to loud noises.

Your ear is a delicate instrument which contains thousands of fine hair cells called cilia to detect sounds. Prolonged exposure to loud noises can injure or break these cells or even tear off groups of these cells. Since the hair cells don't ever repair themselves, when enough of them are damaged, a hearing loss results.

Short, intense, sounds such as an explosion can cause immediate and permanent hearing loss, but most hearing loss occurs gradually due to prolonged exposure to high noise levels. Most of the time this loss is so gradual that you are not even aware that it is occurring. Hearing loss is progressive and will continue to get worse as you continue to expose yourself to a noisy environment, but if you can avoid further exposure, the hearing loss won't get any worse.

Permanent hearing loss is not the only hazard associated with noisy environments. Tinnitus is a condition where a ringing or roaring sound is heard continuously in one or both ears. Tinnitus occurs when the hair cells are damaged in such a way that they produce sound signals to the brain even in the absence of actual stimulation. This noise is sometimes described as like having a cricket permanently stuck in your ear, and is very annoying.

Sound intensity is measured in units of **decibels** (dB). The decibel scale is a logarithmic scale in which 0 dB indicates the quietest sound that can be heard by a normal person. A quiet library is about 20 dB. A normal conversation occurs at a sound level of about 60 dB. A lawnmower produces about 85 dB, and at this level you should be wearing hearing protection. Sandblasting or a rock concert has a sound intensity of about 115 dB. At this level hearing damage can occur after only about 15 minutes of unprotected exposure.

According to OSHA regulations, when the 8 hour average noise exposure is above 85 dB, employers are required to institute a noise monitoring program, provide adequate hearing protectors, and ensure employees wear them. Continual, unprotected exposure to noises louder than 85 decibels for 8 hours or more can be dangerous, and may result in hearing loss.

You can easily tell if you should be wearing hearing protection. If you find yourself in a situation where it is too noisy to carry on a conversation at arms length, or if you notice that your ears ring or feel plugged for a time after leaving a noisy environment, you can be sure that you should have been wearing your hearing protection.

Here are some commonly available hearing protection devices:

Figure 1.3.3 Hearing Protection

Disposable foam plugs Foam plugs are inexpensive devices made of a formable material designed to expand to fit to the shape of each person's ear canal. To use, roll the expandable plugs into a thin, crease-free cylinder, and insert it into the ear canal. Apply a slight pressure to the plug until the foam completely expands. These plugs can be reused a couple of times, but never reuse them if they have become dirty. Some people may find that the standard expandable plug is too large for their ear canal, and may find that the smaller plug model fits better.

Reusable, pre-molded plugs Pre-molded plugs are made from silicone, plastic or rubber and are manufactured as either as a custom fit, or are available in several standard sizes. Be sure to choose the proper size for your ear canals. In some cases, different size plugs may be required for each ear.

The advantage of pre-molded plugs are that they are inexpensive, reusable, washable, convenient to carry, and come in a variety of sizes. Nearly everyone can find a plug that will be comfortable and effective. Another advantage is that in a dirty environment like the engine room, you don't need to handle or roll the tips. You insert this type of plug by reaching over your head with one hand to pull up on your ear. Then use your other hand to insert the plug with a gentle rocking motion until you have sealed the ear canal.

Hearing Bands Hearing Bands, also called canal caps or semi-insert devices often resemble earplugs on a flexible plastic or metal band. The earplug tips of a canal cap may be a formable or pre-molded material. Some have headbands that can be worn over the head, behind the neck or under the chin. The main advantage of canal caps is their convenience They are easy to put on and take off . When it's quiet, employees can leave the band hanging around their necks, but they can quickly insert the plug tips when hazardous noise starts again. These devices are ideal for intermittent use, but they provide less protection than either plugs or muffs. Some people find the pressure from the bands uncomfortable.

Over-the-Ear Earmuffs These are designed to cover the entire ear and provide a physical barrier to block out noise. They are often adjustable for a better fit.

What is a Decibel?

The Decibel (dB) is a logarithmic unit used to describe a ratio. The ratio may be power, or voltage or intensity or several other things. To get a taste for logarithmic units, first let's look at some numbers: Suppose we have two loudspeakers, the first playing a sound with power P_1, and another playing a louder version of the same sound with power P_2, but everything else (how far away, frequency) is kept the same. The difference in decibels between the two is given by

$$10 \log(P_2/P_1) \text{ dB}$$

where the log is to base 10.

If the second produces twice as much power than the first, the difference in dB is

$$10 \log(P_2/P_1) = 10 \log 2 = 3 \text{ dB}.$$

If the second had 10 times the power of the first, the difference in dB would be

$$10 \log(P_2/P_1) = 10 \log 10 = 10 \text{ dB}$$

B. If the second had a million times the power of the first, the difference in dB would be

$$10 \log(P_2/P_1) = 10 \log 1,000,000 = 60 \text{ dB}.$$

This example shows one feature of decibel scales that is useful in discussing sound: they can describe very big ratios in power with numbers of modest size.

Sound is usually measured with microphones and they respond (approximately) proportionally to the sound pressure, p. The power in a sound wave is approximately equal to the square of the pressure. Since the log of the square of x is just $2 \log x$, this introduces a factor of 2 when we convert to decibels for pressures. Therefore the difference in sound pressure level between two sounds with p_1 and p_2 is defined as:

$$20 \log(p_2/p_1) \text{ dB}$$

where the log is to base 10.

This formula involves a ratio of pressures, so to measure the sound level for a single sound, a reference level must be chosen. For sound intensity, the reference level (for air) is usually chosen as 20 micropascals, or 0.02 mPa. This is very low: it is 2 ten billionths of an atmosphere. Nevertheless, this is about the limit of sensitivity of the human ear, in its most sensitive range of frequency. Usually this sensitivity is only found in rather young people or in people who have not been exposed to loud music or other loud noises. Personal music systems with in-ear speakers are capable of very high sound levels in the ear, and are responsible for much of the hearing loss in young adults in developed countries. So if you read of a sound intensity level of 86 dB, it means that $20\log(p_2/p_1) = 86$ dB where p_1 is the sound pressure of the reference level, and p_2 that of the sound in question. Divide both sides by 20: $\log(p_2/p_1) = 4.3$ dB. 4 is the log of 10 thousand, 0.3 is the log of 2, so this sound has a sound pressure 20 thousand times greater than that of the reference level. 86 dB is a loud but not dangerous level of sound, if it is not maintained for very long.

What does 0 dB mean? This level occurs when the measured intensity is equal to the reference level. i.e., it is the sound level corresponding to 0.02 mPa. In this case we have sound level

$$= 20\log(p/p_{ref}) = 20\log 1 = 0 \text{ dB}.$$

So 0 dB does not mean no sound, it means a sound level where the sound pressure is equal to that of the reference level. This is a small pressure, but not zero. It is also possible to have negative sound levels: - 20 dB would mean a sound with pressure 10 times smaller than the reference pressure, i.e. 2 micropascals.

1.3.4 Respiratory Protection

A respirator is a face piece, hood, or helmet that is designed to protect the user from a variety of harmful airborne agents. Respirators can protect you from dust and particulates in the air, hazardous vapors, oxygen deficiency, or a combination of these. Respirators are not necessary for routine operations in the engine room, but may be advisable during certain maintenance procedures such as chipping and painting.

OSHA regulations require that respirators shall be used in the following circumstances:

- Where exposure levels exceed the **permissible exposure limit** (PEL), during the time period necessary to install or implement feasible engineering and work practice controls;
- In those maintenance and repair activities and during those brief or intermittent operations where exposures exceed the PEL and engineering and work practice controls are not feasible or are not required;
- In regulated areas;
- Where the employer has implemented all feasible engineering and work practice controls and such controls are not sufficient to reduce exposures to or below the PEL; and,
- In emergencies.

Before using a respirator you should be thoroughly trained in its use. Some of the areas that you should be familiar with include: respiratory hazards; respirator selection criteria, limitations, adjustment, fit, cleaning, and storage procedures, etc. The selection of a suitable respirator depends on the hazard to which you are exposed, and the correct respirator cannot be selected without a thorough understanding of the hazard.

OSHA divides respirators into two categories: **Air-purifying** and **Atmosphere-supplying** respirators.

Air-purifying Respirators

Figure 1.3.4 Air-purifiying respirators

These units have filters, cartridges, or canisters that remove contaminants from the air by passing the air through the air-purifying element before it reaches the user. Air purifying respirators are further divided into:

- **Particulate Respirators**, which capture particles such as dusts, paint fumes, and mists, but do not protect against gases and vapors. The filters in particulate respirators generally work better as particles accumulate on the filter. If the filter becomes so clogged that it is difficult to breathe, it should be replaced.
- **Gas and Vapor Respirators**, which use a chemical cartridge or canister to remove dangerous gases or vapors, but which do not protect against airborne particles. These units only protect against specific gases or vapors, and only provide protection as long as the filter's absorbing capacity remains.
- **Combination Respirators**, which can be used in atmospheres that contain both hazardous gases and particles.

Atmosphere-supplying Respirators

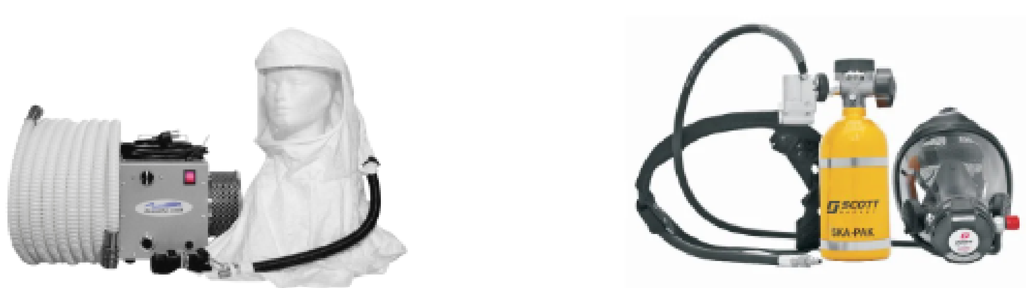


Figure 1.3.5 Atmosphere-supplying respirators

These units supply clean air directly to the user from a source other than the air surrounding the user. The types of air-supplying respirators are:

- **Air Supplied Respirators**, which have a hose which connects to a source of clean air under pressure. These units have no time limit on the air supply, but the hose limits the range and mobility of the user and is susceptible to damage.
- **Self-Contained Breathing Apparatus**, which have a wearable clean-air supply pack. These units have better mobility than the air-supplied respirator, but the clean air time is limited to the capacity of the tank.
- **Combination Respirators**, which are similar to the air-supplied respirators, but also have a small, self-contained air supply which can be used for escape if the primary supply fails.

1.3.5 Arm and Hand Protection

The National Safety Council has found that hands are the body part most frequently injured on the job. Accidents to the hand fall into these categories: abrasions, cuts, punctures, crushes, contact with moving machinery, burns, and chemical injuries. Gloves and hand protection are available to protect you from nearly all of these hazards. However, glove selection must be based on performance characteristics of the gloves, conditions, durations of use, and hazards present. One type of glove will not work in all situations.

In the engine room, particular hazards include high temperatures and moving machinery. Long sleeved shirts are advisable to protect your arms, and you should always have a pair of work gloves available to use when necessary to protect your hands when working around hot pipes. Special high temperature gloves should always be worn when changing burners, and the appropriate chemical resistant gloves should be worn when working with burner cleaning and boiler chemicals. You should also pay particular attention to avoid contact with moving parts of machinery or power tools with moving parts, and insure that safety guards are always in place. Gloves should always be inspected for damage before use.

Figure 1.3.6 Hand and Arm Protection

There is a broad selection of safety gloves available to protect your hands from workplace hazards. For example:

- Disposable Gloves - protects against mild irritants and bodily fluids
- Rubber Lineman's Gloves and sleeves - protects against shock when working on live wires
- Metal Mesh Gloves - protects against accidental cuts when using knives

- Chemical Resistant Gloves - proper selection of material can resists chemical attack
- Cleanroom Gloves - maintains cleanliness of electronic parts
- Cotton Work Gloves - improves grip and protects from heat and cold
- General Purpose Leather Gloves - protects against cuts and moderate temperatures
- Temperature Resistant Gloves - protects from high temperatures
- Welder's Gloves - protects from high temperatures and sparks

1.3.6 Foot Protection

Your feet are vulnerable to many potential hazards aboard ship. For example, slips and falls due to wet and slippery decks; heavy objects falling on or rolling over your foot because of the ship's motion or accident; punctures caused by stepping on sharp objects; and potential electrical shock when your body is grounded through the soles of your shoes. In other industries, there are other hazards to consider, chemical exposure, high temperatures, molten metal splashes, static electricity, to name a few. Proper selection of footwear can minimize the danger of these hazards.

OSHA has established regulations for safety shoe design, including impact and compression strength requirements, and they have mandated footwear requirements for many industries. For example, safety shoes or boots with impact protection are required to be worn in work areas where carrying or handling materials such as packages, objects, parts or heavy tools, which could be dropped; and for other activities where objects might fall onto the feet. Safety shoes or boots with compression protection are required for work activities involving skid trucks (manual materials handling cars) or other activities in which materials or equipment could potentially roll over an employee's feet. Safety shoes or boots with puncture protection are required where sharp objects such as nails, wire, tacks, screws, large staples, scrap metal etc., could be stepped on by employees causing a foot injury. Although there are no specific OSHA requirements for safety footwear for marine engineers, it is nonetheless sensible to select and wear safety shoes based on the hazards found in the engine room.

Figure 1.3.7 Safety Shoes

Safety Shoes and Boots. Safety shoes and boots are available in many styles depending on the job requirements. Boots provide more protection than shoes from chemicals and molten metals splashes and spark hazards, but they are heavier. Some protective features that are available in both boots and shoes include:

- Oil resistant shoes
- Chemical resistant shoes

- Heat resistant shoes
- Slip and skid resistant shoes
- Waterproof and water resistant shoes

Steel-Reinforced Safety Shoes and Boots Similar to safety shoes, these have the toe box and insole reinforced with steel, and the instep reinforced with steel, aluminum, or plastic. These shoes will protect your feet from falling objects and puncture injuries.

Composite-Toe Safety Shoes Composite-toe shoes have a protective cap made of non-metallic materials such as carbon fiber, Kevlar, or fiberglass. They offer lightweight protection and are ideal for environments where metal detection is required or in situations where electrical conductivity needs to be minimized.

Electrically Insulated Safety Shoes These shoes have non-conductive soles to prevent the wearer's feet from completing an electrical circuit to ground. They can protect workers against as much as 600 volts in dry conditions. These shoes should be used in conjunction with insulated tools and precautions to reduce or eliminate the potential for providing a path for hazardous electrical energy. Non-conductive footwear must not be used in explosive or hazardous locations; in such locations, electrically conductive shoes are required.

Electrically Conductive Safety Shoes These shoes protect against the buildup of static electricity. Essentially, these shoes ground the employees wearing them. Employees working in explosive and hazardous locations such as explosives manufacturing facilities or grain elevators must wear conductive shoes to reduce the risk of static electricity buildup on an employee's body that could produce a spark and cause an explosion or fire. During training, employees must be instructed not to use foot powder or wear socks made of silk, wool, or nylon with conductive shoes. Foot powder insulates and retards the conductive ability of the shoes. Silk, wool, and nylon produce static electricity. Conductive shoes are not general-purpose shoes and must be removed upon completion of the tasks for which they are required. Employees exposed to electrical hazards must *never* wear conductive shoes.

1.4 Personal Safety

Objectives

- `PSSR-X3.1` Importance of adhering to safe working practices at all times
- `PSSR-X3.2` Safety and protective devices available to protect against potential hazards aboard ship
- `OICEW-D8.4` Knowledge of personal safety
- `ABE-C3.1` Lifting techniques and methods of preventing back injury
- `RFPEW-A3.2` Know escape routes from machinery spaces

Safety in the workplace is everyone's responsibility, but no one is more responsible for your own personal safety than you! Here are some key safety practices to follow to ensure your own safety.

- *Maintain Situational Awareness.*

Always be attentive and aware of your surroundings and what is going on around you. Pay attention to potential hazards, changing conditions, and any applicable safety instructions or procedures. Make sure you are familiar with the escape routes from the space you are in, and the location of the nearest fire extinguisher.

- *Follow Safe Working Procedures.*

  Familiarize yourself with the safe working procedures for your assigned tasks and follow them meticulously. These procedures are designed to minimize risks and ensure your safety. Seek guidance if you are unsure about any aspect of your tasks.

- *Use PPE.*

  Wear the appropriate personal protective equipment for your tasks and the specific hazards you may encounter. This includes hard hats, safety glasses, gloves, and safety footwear. Make sure your PPE is in good condition and fits properly.

- *Maintain Cleanliness and Organization.*

  Keep your work area clean, organized, and free of clutter. Properly stow tools and equipment after use to prevent trip hazards. Promptly clean up any spills or debris to maintain a safe working environment.

- *Practice Safe Lifting Techniques.*

  To lift heavy objects safely, follow these guidelines:

  Assess the object's weight and plan your lift accordingly. Warm up your muscles with light exercises. Stand close to the object with feet shoulder-width apart, keeping your back straight and bending at the knees. Get a firm grip on the object and lift using the strength of your legs, not your back. Avoid twisting and keep the object close to your body.

  Don't hesitate to ask for help if you need it. Prioritize safety and listen to your body to prevent injuries.

- *Maintain Personal Fitness and Well-being.*

  Ensure you are physically and mentally fit for the tasks assigned to you. Get enough rest, eat well, and stay hydrated. Fatigue and exhaustion can compromise your alertness and increase the risk of accidents. Don't abuse alcohol or drugs, and certainly don't attempt to perform your duties when you're impaired.

- *Follow Emergency Procedures.*

  Familiarize yourself with the ship's emergency procedures, including evacuation routes, muster stations, and the proper use of life-saving equipment. Be prepared to respond calmly and promptly in case of an emergency.

- *Practice Good Communication.*

  Safety is a team effort. Maintain open and effective communication with your fellow crew members. Share safety-related information, ask questions, and seek clarification when needed. Don't hesitate to speak up if you notice safety hazards, near misses, or unsafe practices. Effective communication is essential for preventing, addressing and resolving safety issues promptly.

- *Learn Continuously*.

  Stay proactive in expanding your safety knowledge and skills. Participate in safety training programs, attend safety briefings, and stay updated on safety regulations and best practices. Take safety drills seriously. The more informed you are, the better equipped you will be to protect yourself contribute to a safe working environment.

By following these safety practices, you will not only protect yourself but also contribute to the overall safety of the crew and the smooth operation of the ship. Remember, safety should always be your top priority.

Chapter 2

Engineering Measurement

Objectives

- Understand the units of measurement for length, mass, time, area, volume, speed, temperature, pressure, torque, power, and speed
- Understand conversions from U.S to metric and metric to U.S.
- Understand Nautical Mile definition
- Be able to calculate conversions
- Identify and draw standard measurement symbols
- Understand basic measuring instruments
- Understand accuracy, precision, tolerance, calibration

Measurement is the process of associating numbers with quantities. Units of measurement establish a common language for engineers to communicate and quantify various physical quantities. There are two basic standard units of measurement systems that are used worldwide, the U.S. Standard Measurement System and the Metric System.

In the world of engineering, measurement is fundamental. Accurate measurements are crucial for designing, constructing, and evaluating systems. Engineers rely on standardized units and principles of measurement to ensure consistency and precision in their work.

This chapter provides an overview of the categories and units of measurement used in engineering systems, covering both the metric and US standard systems as well as nautical measurement. An overview of basic instruments used for making measurements will be discussed along with the principles of measurement **including** accuracy, efficiency, percent error and deviation.

As you study this chapter, you will encounter new terms and definitions for you to learn. At the end of the chapter, you will find example problems. Be sure to take the time to practice with these problems. They will help prepare you to apply these concepts.

2.1 Units of Measurement

Objectives

- Length
- Mass
- Time
- Area
- Volume
- Temperature
- Pressure
- Torque
- Power
- Speed

2.1.1 Length

A Brief History

The way base units of length have been determined has changed greatly over time. Long ago, the base for reference was the human body. For example, the cubit was a unit that indicated the length from the elbow to the fingertips.

Length units based on the human body were used for thousands of years. The Roman mile (In Latin *mille passus*, which means "thousand paces") consisted of a thousand paces (of 5 feet each) as measured by every other step—as in the total distance of the left foot hitting the ground 1,000 times, which equals approximately 5,000 ft. In 1592, English Parliament wanted to standardize the measurement of the mile and made the decision that it should be equal to eight furlongs. Furlongs, which are still used as a unit of measurement in horse racing, are 660 feet long. 660 times eight equals, you guessed it, 5,280 ft.

This continued until a major change took place around 200 years ago. As the Age of Discovery came to an end and industry grew primarily in Western Europe, it became necessary to unify units of length on a global scale. In the 17th century, discussions were held in Europe regarding the unification of units. After a century of discussions, France proposed the unit of the meter (meaning "to measure" in Greek) in 1791. The reference at this time was the distance of the meridian from the north pole to the equator. One meter was set as 1/10,000,000 of this distance. Today, one meter is defined as "the distance that light travels in a vacuum in 1/299,792,458 of a second," as defined in 1983.

For navigation on water (marine), air, and space the nautical mile unit of length is used. Historically, a nautical mile was defined as the meridian arc length corresponding to one minute of a degree of latitude. Nautical mile is based on Earth's circumference being 360 degrees. These degrees can then be divided into 60 minutes. One of these minutes (or minutes of arc as they are called in navigation) along a great circle on Earth represents one nautical mile. Today the international nautical mile is defined as exactly 1,852 meters (6,076 ft; 1.151 mi).

In terms of statute or land miles, a nautical mile represents 1.15 miles. This is because one degree of latitude is approximately 69 statute miles in length. 1/60th of that measure would be 1.15 statute miles.

Length Units

In the US standard system, the inch (in) 1″ (double apostrophe) is the primary unit, with the foot (ft) 1′ (single apostrophe) and mile (mi) used for larger distances.

In the metric system, the base unit for length is the meter (m). Its subdivisions include the centimeter (cm), millimeter (mm). The kilometer (km), equivalent to 1,000 m is used for longer distances.

For navigation on water (marine), air, and space, the **Nautical Mile** (NM) unit of length is used.

Table 2.1.1 Length units for US Standard and Metric systems

U.S. Standard	Metric	Conversions
12 inches = 1 foot	1 centimeter (cm) = 10 millimeters	1 inch = 2.54 cm
3 feet = 1 yard	1 meter = 100 centimeters	1 ft = 0.3048 m
1,760 yards = 1 mile	1 kilometer = 100,000 centimeters	1 yd = 0.9144 m
5,280 feet = 1 mile	1 kilometer = 1,000 meters	1 mile = 1.6093 km

Table 2.1.2 Length units for US Standard and Metric systems

1 Nautical Mile = 6,076 ft	1 Standard Mile = 5,280 ft	1 Kilometer = 3,280.84 ft

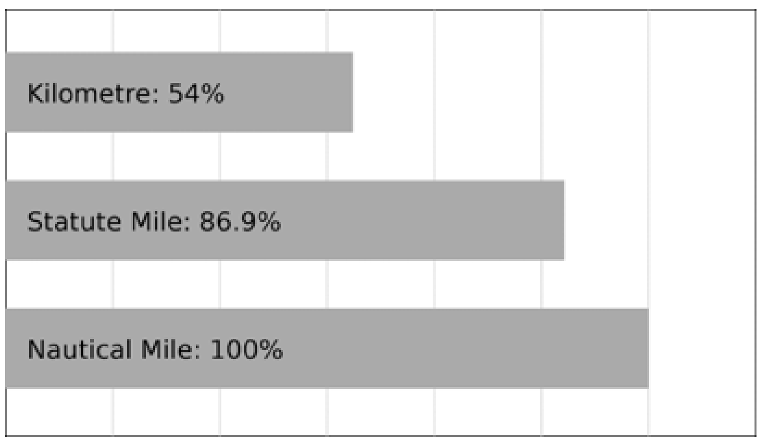
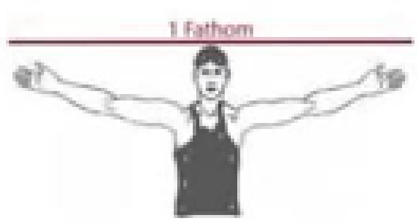


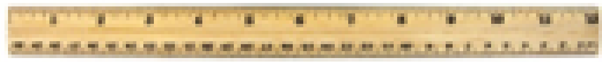
Figure 2.1.3 Visual comparison of Kilometer, Statute Mile and Nautical mile

Fathom: A nautical measurement equal to 6 feet or 1.8288 meters. It is commonly used for measuring depth in water. Finger tip to finger tip



Length Measuring Instruments

Rulers and Yardsticks are straight, flat measuring tools commonly used for shorter lengths. A ruler measure 1 ft. or 12 inches whereas a yardstick measure 3 ft. or 1 yd.



A **Tape Measure** is a flexible tape marked with inches and feet for measuring longer distances. It is often used in construction and carpentry.

Calipers or callipers are used to measure he dimensions of an object, generally by placing two movable points of the instrument across the object or span to be measured..

A **micrometer**, sometimes known as a **micrometer screw gauge**, is a device incorporating a calibrated screw widely used for accurate measurement of components. Outside, inside, and depth micrometers are all used. The outside micrometer has a unit conversion chart between fractional and decimal inch measurements etched onto the frame

A **surveyor's tape** is a long, flexible tape marked in meters used in land surveying.

A **sextant** is a navigation instrument used to measure the angle between celestial objects and the horizon. It helps determine a ship's position at sea.

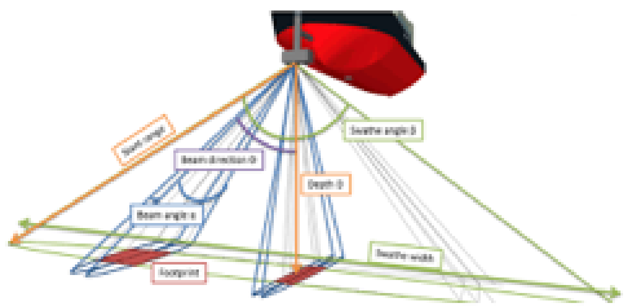
Microwave instruments use microwaves to take survey measurements. They have a range up to 100 km and are comprised of two identical units, a master unit, and a remote unit.

Infrared wave instrumentsuse amplitude modulated infrared waves and prism reflectors. They have a range up to 3 km and accuracy of +/- 10mm.

Light wave instruments rely on the propagation of modulated light waves. Their accuracy varies from 0.5mm to 5mm/km, and they have a daytime range of 3km and night range of 2.5km.

Laser measuring tools send a beam to the target, which reflects off the surface and is sent back to the device. Lasers are focused beams of light that stay at a particular frequency. And because they travel from one place to another at a fairly constant rate, they can be used to measure distance with a great deal of accuracy. A laser measuring device also has a longer range than many other measuring tools, which gives it an advantage over other devices that become less precise the farther out you measure. Lasers are less likely to disperse than white light, so they can travel at a greater distance without losing their intensity. They keep most of their intensity once they reflect off a target, which is important if you want to get accurate distance measurements.

Sonar is an object-finding system that uses sound waves to determine the distance, speed of and direction to objects within its range. ..



These instruments allow engineers, sailors, and others to accurately measure lengths and distances according to their respective systems of measurement. It's important to note that many professionals now use digital instruments, such as laser distance measurers, which can provide precise measurements in multiple units.

Unit Conversions

Frequently, engineers need to find length equivalents between different systems of measurement. For example, in the construction of a ship there may be different contractors, some of whom use US standard measurement and others who use metric. Since the agreed upon system is metric, conversions are required to standardize all measurements.

Conversion of units is the process to convert between different units of measurement for the same quantity, typically through multiplicative **conversion factors** which change the measured quantity value without changing its effects. Unit conversion is often easier within the metric or the SI than in others, due to the regular 10-base in all units and the prefixes that increase or decrease by 3 powers of 10 at a time.

The **unit-factor method** or the **unity bracket method** is a widely used technique for unit conversions using the rules of algebra.

The**factor-label method** is the sequential application of conversion factors expressed as fractions and arranged so that any dimensional unit appearing in both the numerator and denominator of any of the fractions can be cancelled out until only the desired set of dimensional units is obtained. For example, 10 miles per hour (mi/hr or mph) can be converted to meters per second (m/s) by using a sequence of conversion factors as shown below:

Example

Using unit-factor method we can express a distance in meters from feet as:

To Find distance in meters = (distance in ft) × (12 in/1 ft) × (2.54 cm/1 in) ×(1 m/100 cm)
The Conversion factor is .3048 m/ft
distance in meters = (distance in ft) x 0.3048 m/ft
1 foot = 12″/1 ft × 2.54 cm/1″ = 30.48 cm/ft
1 foot = 1 M/100 cm × 30.48 cm = 0.3048 Meters
Conversion Factor = .3048
1 meter =1ft/12 in × 1 in/2.54 cm × 100 cm/1 m=100 /30.48
1 meter = 100/30 =3.28 ft
Conversion Factor
1 foot = 0.3048 m
1 inch = 2.54 cm
Nautical Miles
1 Statute Mile= 1 Statute Mile/5280 ft x 6076 ft/1 NM = 1.15 Mile/NM
Conversion Factor = 1.15 mile/NM
1 km =1.852 NM

Example Problem

The last example explains how to convert meters to inches. We start with the same units as in the first example, but finish with different units. There will be two separate conversions. First, we convert from meters to feet. Then we convert from feet to inches. Remember, there are

.
Convert
Feet to Meters
Meters to Feet
Miles to KM
KM to Miles
7 meters to inches.7 meters × 3.28084 feet

2.1.2 Temperature

Temperature is a measure of the average kinetic energy of the particles in a substance. It quantifies how hot or cold an object or environment is relative to a standard or reference point.

The most commonly used temperature scale in the US today is the **Fahrenheit scale**, abbreviated F. In this scale, water freezes at 32 degrees and boils at 212 degrees. (This only holds strictly when atmospheric pressure equals the average sea level pressure. At high altitudes, water boils at a lower temperature, as anyone who cooks in the mountains knows.)

Another common scale is the **Celsius** (also called Centigrade) scale. In this scale, water freezes at 0 degrees and boils at 100 degrees.

There are also temperature scales in which zero is the lowest possible temperature, called **absolute zero**. (People have gotten close to absolute zero, but have never reached it. According to theory, we never will.) Absolute zero is at -273.15 Celsius, or -459.67 Fahrenheit.

The **Kelvin** temperature scale uses the same size degree as Celsius, but has its zero set to absolute zero.

The **Rankine** temperature scale uses the same size degree as Fahrenheit, but has its zero set to absolute zero

The Celsius and Kelvin scales are part of the International System of Units (SI), providing a standardized and widely adopted system for expressing temperatures. Celsius is the more common scale for everyday use, while Kelvin is often used in scientific and thermodynamic calculations.

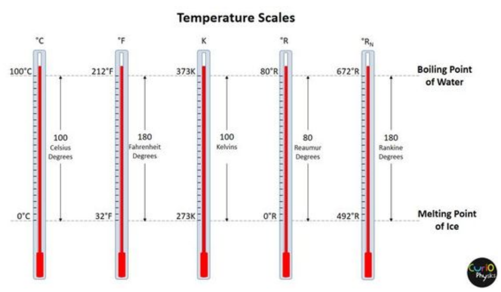


Figure 2.1.4 Temperature Scales

To convert between Fahrenheit and Celsius use these formulas:

Table 2.1.5 Temperature Conversion Formulas

Celsius to Fahrenheit[1]	° F = 9/5 (° C) + 32
Kelvin to Fahrenheit[2]	° F = 9/5 (K - 273) + 32
Fahrenheit to Celsius[3]	° C = 5/9 (° F - 32)
Celsius toKelvin[4]	K = ° C + 273
Kelvin to Celsius[5]	° C = K - 273
Fahrenheit to Kelvin[6]	K = 5/9 (° F - 32) + 273

These formulas allow you to convert temperatures between different scales. It's important to use the appropriate formula based on the units provided or required for a specific calculation or conversion.

[1] www.thoughtco.com/convert-celsius-to-fahrenheit-609228
[2] www.thoughtco.com/convert-kelvin-to-fahrenheit-609234
[3] www.thoughtco.com/fahrenheit-to-celsius-formula-609230
[4] www.thoughtco.com/celsius-to-kelvin-conversion-example-609547
[5] www.thoughtco.com/convert-kelvin-to-celsius-609233
[6] www.thoughtco.com/convert-fahrenheit-to-kelvin-609231

Instruments Used to Measure Temperature

Various instruments are used to measure temperature in different applications. The choice of temperature measurement instrument depends on factors such as the required accuracy, temperature range, and the specific application or industry. Different instruments are suitable for different temperature ranges and environments.

Here are some common instruments used to measure temperature:

Liquid in Glass Thermometer. Liquid in glass thermometers are the most common instruments for measuring temperature. This type of thermometer uses a temperature sensitive liquid, such as mercury or alcohol, sealed in a glass tube. The liquid expands or contracts with temperature changes, and the temperature is read from a scale on the thermometer.

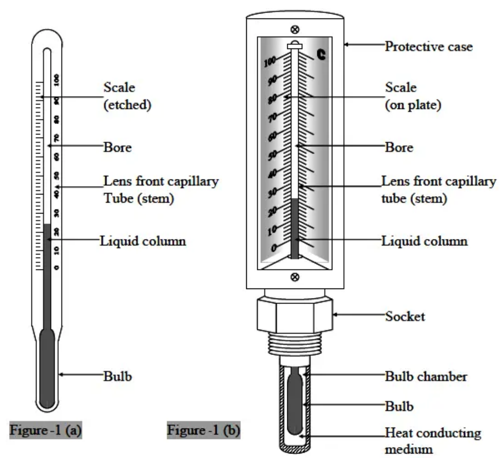


Figure 2.1.6 Liquid in Glass Thermometer

Bimetallic temperature sensors. Bimetallic temperature sensors use the differential expansion of two metals to detect temperature changes. These are often used in thermostats and mechanical temperature gauges.

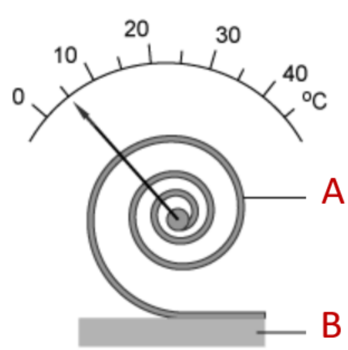


Figure 2.1.7 Bimetallic Thermometer Temperature Sensor

Thermocouple. Thermocouple are made from two different metal wires joined at one end. When exposed to temperature variations, it generates a small electrical voltage proportional to the temperature difference.

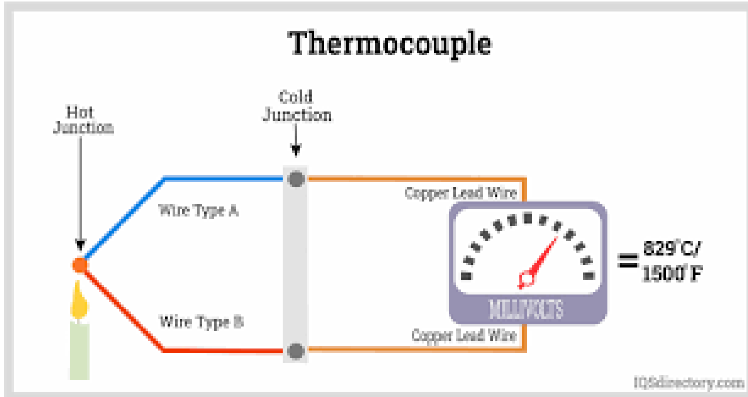


Figure 2.1.8 Thermocouple Temperature Sensor

Resistance Temperature Detector. Resistance Temperature Detectors (RTD) determine temperature by measuring the resistance of an electrical wire, which increases as the temperature rises and decreases when the temperature falls. The change in resistance of the wire indicates the temperature change.

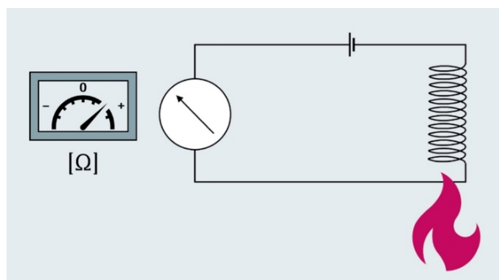


Figure 2.1.9 Resistance Temperature Detector RTD

Thermistor. Thermistors are a type of temperature-sensitive resistor whose electrical resistance changes significantly with temperature. They are commonly used in electronic devices and temperature control systems.

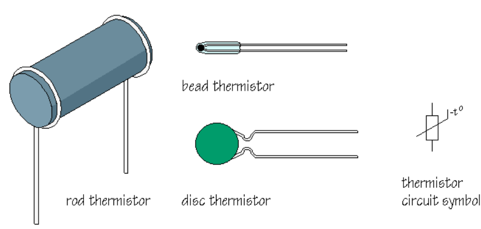


Figure 2.1.10 Thermistor

Infrared (IR) Thermometer. An Infrared (IR) thermometer measures temperature without direct contact with the object. It detects the infrared radiation emitted by the object, converting it into a temperature reading. IR thermometers are particularly useful for non-contact measurements or in hazardous environments.

Figure 2.1.11 Infrared Thermometer

Chapter 3

Introduction to Thermodynamics

Adapted from Principles of Naval Engineering The process of generating steam is basically simple. You boil water and continue to add heat until the water turns into steam. But how can this steam cause a ship to move through the water? How can steam provide power for steering, ventilation, refrigeration, distillation of seawater, and all the other needs of the vessel?

Steam does not do any of these things directly. But some of the thermal energy contained in the steam can be converted into other forms of energy to move the ship through the water and to provide power for vital shipboard services.

In this chapter we will discuss some basic ideas of energy and some of the important energy transformations that occur in the engineering plant of a steam-driven ship. Study this chapter carefully. The information given here will not help you to light off a boiler, clean firesides, stand a watch, or wipe up oil from the floorplates; however, it will help you to understand the generation of steam, the use of steam in the shipboard engineering plant, and the relationship of the boilers to the rest of the engineering plant. Understanding the information given in this chapter will also give you a sound background for understanding some of the more complicated things that you will have to learn as you advance.

As you study this chapter, watch out for unfamiliar definitions. Many of the words and terms used will be familiar to you, but the definitions we use may be more precise than the ones you have heard before. Be sure that you understand the exact meaning of each word and term used in connection with energy and energy transformations.

3.1 Force

What is force? In simple terms, a force is a push or a pull. More precisely, a force is a vector quantity which tends to produce an acceleration of a body in the direction of its application. This means that if you want a stationary object to move, you must apply a force to it to get it going. If you want to keep it moving, you need to continuously apply a force to it to overcome friction, which is itself a force. Forces can exist without motion too – when an object is stationary it's usually because there are many forces acting on it which cancel each other out, leaving no net force acting on the object. Forces always occur in pairs. A push on an object is always accompanied by an equal and opposite force acting on the pusher.

In the English system of units, force is measured in pounds, tons, or long tons. In the SI system, force is measured in newtons (N) or kilonewtons (kN). For estimation purposes, a newton is about a quarter of a pound.

One important force which we experience every day is weight. Weight is the force of gravity - the attraction between an object and the earth. The weight force exerted on an object is proportional to the mass of the object according to Newton's second law, which states:

$$W = mg$$

where W is the weight, m is the mass, and g is the gravitational constant.

The constant g depends on where you are: on earth the constant is greater than it is on the moon, so you weigh less on the moon than you do on earth. In outer space, the constant is zero, making you weightless there. Be careful not to confuse weight with mass. The mass of an object will not change when it moves to another location, but its weight may. One reason why people often confuse weight with mass is because in the English system and on the surface of the earth, the gravitational constant g is equal to 1, and so one pound of mass has a weight of one pound of force. Move to the moon, and the pound of mass now weighs about six tenths of a pound. On earth in the SI system, g is approximately equal to 9.81 m/s^2.

3.2 Pressure

Pressure is defined as force per unit area. That is, a force acting over an area is a pressure, and when you multiply a pressure by the area that it acts over, you get a force.

$$P = \frac{F}{A} \qquad \text{or} \qquad F = PA$$

Many different units are used to describe pressure. The simplest pressure units are ones that indicate how much force is applied to an area of a certain size. These units include pounds per square inch, pounds per square foot, newtons per square meter, kilopascals, bars or others depending upon the system being used. Aboard ship we most commonly use pounds per square inch (psi).

3.2.1 Head

You will also find another kind of pressure unit, which appears to be a length. These units include inches of water, inches of mercury (Hg), or the height of some other liquid of known density. These units, while measured in length units, still represent a pressure. The length describes the pressure exerted by a column of liquid of the given height, and is known as the *head*.

For example, a pressure reading of 1 inch of water (1 in. H_2O) means that the exerted pressure is equal to the pressure exerted by a column of water 1 inch high, or that a column of water in a U-tube would be displaced 1 inch by the pressure being measured. Similarly, a reading of 12 inches of mercury (12 in. Hg) means that the measured pressure is sufficient to support a column of mercury 12 inches high.

What is really being expressed, even though it is not mentioned in the pressure unit, is the fact that a certain quantity of material (water, mercury, etc.) of known density will exert a certain definite force upon a specified area. Pressure is still force per unit area even if the pressure unit refers to the height of some liquid.

3.2.2 Atmospheric Pressure

Atmospheric pressure is the pressure exerted by the weight of the atmosphere. At sea level the average pressure of the atmosphere is sufficient to support a column of mercury (Hg) 760.0 millimeters or

29.92 inches high. This is equivalent to a pressure of approximately 14.7 psi. This is known as the absolute pressure of the atmosphere, and is indicated by the unit *psia* (pounds per square inch, absolute)

A barometer is the device used to measure the pressure of the atmosphere, so the absolute pressure of the atmosphere is also known as the barometric pressure. When you hear a weather report, this is the value reported. The barometric pressure changes with weather conditions, but for most purposes aboard ship, this fact can be ignored, and we can assume that the atmospheric pressure is 14.7 psia or 760 mm Hg. at all times. Notice, however, that the figure of 14.7 pounds per square inch absolute (psia.) represents the average atmospheric pressure at sea level, and does not always represent the actual pressure being exerted by the atmosphere at the moment that a gage is being read.

3.2.3 Gage Pressure

Since the absolute atmospheric pressure is always present, and acts on everything equally, we normally don't even notice it. Pressures are usually measured up or down from atmospheric pressure, and an ordinary pressure gage reads zero when it is subjected to atmospheric pressure only. Pressures measured in this way is called the gage pressure. It is important to distinguish between gage pressure and the absolute pressure described in the next section.

3.2.4 Absolute Pressure

Pressure measured on a scale increasing from zero at a perfect vacuum is known as absolute pressure. Absolute pressure is always higher than the corresponding gage pressure by the amount of the atmospheric pressure. For shipboard purposes, you can simply add 14.7 psi to the gage reading in psi to get the absolute pressure. For example, a gage pressure of 100 psig would be the same as an absolute pressure of 114.7 psia.

We sometimes say psig to indicate gage pressure and other times we merely say psi. By common convention, gage pressure is always assumed when pressure is given in pounds per square inch, pounds per square foot, or similar units. The "g" (for gage) is added only when there is some possibility of confusion. Absolute pressure, on the other hand, is always expressed as pounds per square inch absolute (psia), pounds per square foot absolute (psfa), and so forth. It is always necessary to establish clearly just what kind of pressure we are talking about, unless this is very clear from the nature of the discussion.

3.2.5 Vacuum

A pressure below atmospheric pressure is called a vacuum. The farther below the atmospheric pressure, the greater the vacuum. Vacuum can not be made greater and greater without limit, however. At some point, the absolute pressure drops as low as possible and a perfect vacuum is achieved. A perfect vacuum is the lowest possible pressure, or the absence of all pressure. When we speak of a "high" vacuum, we are talking about a low absolute pressure.

When measuring a vacuum, there are three possible methods. When vacuum is measured starting with zero at perfect vacuum and increasing as pressure rises, then the greater the value, the smaller the vacuum. This is known as the absolute pressure scale. We can also measure pressure on a scale starting at zero at atmospheric pressure, and indicating negative values when the pressure is below atmospheric (vacuum) and positive values when the pressure is above atmospheric. This is the behavior of a standard pressure gage. And finally, we can measure vacuum on a scale starting with zero at atmospheric pressure and increasing as the vacuum increases. Most vacuum gages operate this way. On this scale no vacuum would be indicated by 0 psig, and a perfect vacuum would be indicated by approximately 14.7 psi vacuum.

The most common scale used on vacuum gages aboard ship display vacuum in inches of mercury, with the vacuum gage scale marked from 0 to 30 inches of mercury. When this gage reads zero, the pressure in the space is the same as atmospheric pressure or, in other words, there is no vacuum. A vacuum gage reading of 29.92 inches of mercury would indicate a perfect (or nearly perfect) vacuum. In actual practice, it is impossible to obtain a perfect vacuum even under laboratory conditions.

3.2.6 Pressure Conversions

In interpreting pressure measurements, a great deal of confusion arises because the zero point on most pressure gages represents atmospheric pressure rather than zero absolute pressure, and both pressure and head scales are used. Thus it is important to specify the kind of pressure being measured under given conditions. To clarify the numerous meanings of the word pressure, the relationship among gage pressure, atmospheric pressure, vacuum, and absolute pressure is illustrated in Figure 3.2.1.

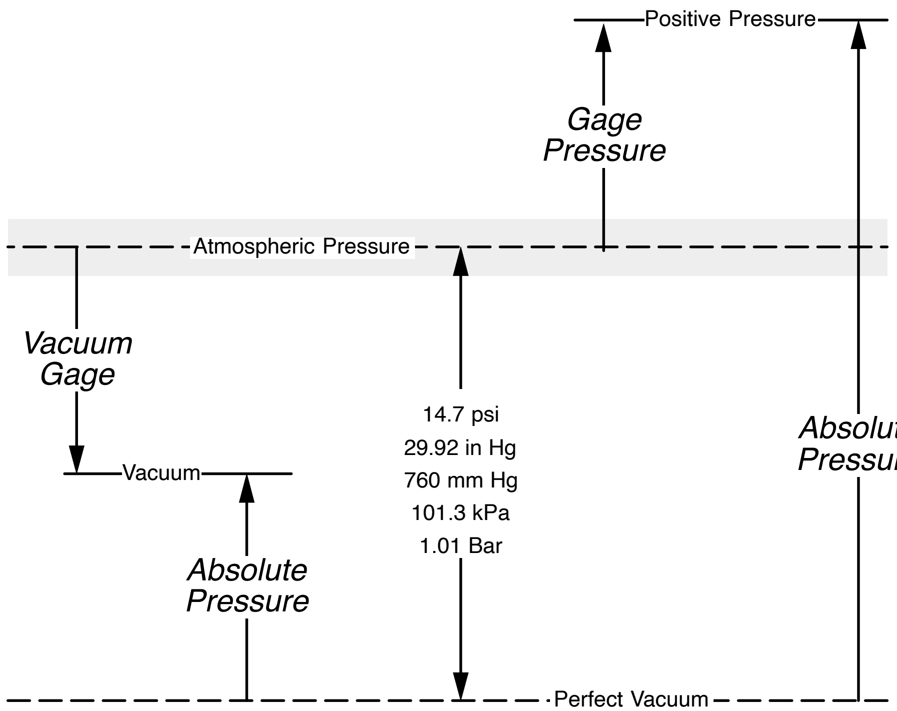


Figure 3.2.1 Pressure Relationship

If you can remember the following facts, it is relatively easy to perform unit conversions between the various pressure scales.

Atmospheric pressure equivalents:

$$\begin{aligned}\text{Atmospheric Pressure} &= 14.7 \text{ psi}\\ &= 29.92 \text{ in Hg}\\ &= 760 \text{ mm Hg}\\ &= 34 \text{ ft } H_2O\end{aligned}$$

$$= 101.3 \text{ kPa}$$
$$= 1.01 \text{ bar}$$

Absolute scales measure up from zero

Gage scales measure up or down from atmospheric pressure

Vacuum scales measure down from atmospheric pressure

Example 3.2.2 psia to vacuum conversion. Convert from 10.4 psia to mm Hg Vacuum

Answer. 10.4 psia = 222.3 mm Hg (vacuum)

Solution.

1. Set up a ratio to convert psia to mm Hg Absolute

$$\frac{10.4 \text{ psia}}{14.7 \text{ psia}} = \frac{p}{760 \text{ mm Hg}}$$
$$= 537.7 \text{ mm Hg (absolute)}$$

2. Subtract from atmospheric pressure to get vacuum

$$V = 760 - p = 222.3 \text{ mm Hg (vacuum)}$$

□

3.3 Energy

Can you define energy? Although everyone has a general idea of the meaning of energy, a good definition is hard to find. Most commonly, perhaps, energy is defined as the "ability of a system to do work." This is not a very complete definition. Energy can produce other effects which cannot possibly be considered "work." For example, heat can flow from one object to another without doing work; yet heat is a form of energy, and the process of heat transfer is a process that produces an effect.

A better definition of energy, therefore, states that "energy is the capacity for producing an effect." Energy exists in many forms. For convenience, we usually classify energy according to the size and nature of the bodies or particles with which it is associated. Thus we say that *Mechanical energy* is the energy associated with large bodies or objects, usually, things that are big enough to see. *Thermal energy* is energy associated with molecules. *Chemical energy* is energy that arises from the forces which bind the atoms together in a molecule, Chemical energy is demonstrated whenever combustion or any other chemical reaction takes place. *Electro-magnetic* energy is energy that is associated with the electron and charged particles. Light, x-rays and radio waves are examples of electro-magnetic energy. *Nuclear energy* is associated with the particles in the nucleus, and is governed by Einstein's famous equation $E = mc^2$nEach of these types of energy (mechanical energy, thermal energy, etc.) must also be classified as being either stored energy, or energy in transition. *Stored energy* can be thought of as energy that is actually "contained in" or "stored in" a substance or system. There are two kinds of stored energy: potential energy, and kinetic energy. When energy is stored in a substance or system because of the relative *positions* of two or more objects or particles, we call it potential energy. When energy is stored in a substance or system because of the relative *velocities* of two or more objects or particles, we call it kinetic energy.

1. Mechanical Energy – energy associated with relatively large bodies or objects.
   (a) Stored forms of mechanical energy
      i. Mechanical potential energy
      ii. Mechanical kinetic energy
   (b) Mechanical energy in transition
      i. Work
2. Thermal Energy – energy associated with the very small particles called molecules.
   (a) Stored forms of thermal energy
      i. Internal potential energy
      ii. Internal kinetic energy
   (b) Thermal energy in transition
      i. Heat

If you do not completely understand this classification, come back to it from time to time as you read the following sections on mechanical energy and thermal energy. The examples and discussion given in the following sections will probably help you to understand this classification.

3.3.1 Mechanical Energy

Let's consider first the two stored forms of mechanical energy.

Mechanical *potential* energy exists because of the relative positions of two or more objects. For example, a rock resting on the edge of a cliff in such a position that it will fall freely if pushed has mechanical potential energy. Water at the top of a dam has mechanical potential energy. A sled that is being held at the top of an icy hill has mechanical potential energy.

Mechanical *kinetic* energy exists because of the relative velocities of two or more objects. If you push that rock, open the gate of the dam, or let go of the sled, something will move. The rock will fall; the water will flow; the sled will slide down the hill. In each case the mechanical potential energy will be changed to mechanical kinetic energy. Another way of saying this is "energy of position will be changed to energy of motion."

In these examples, you will notice that an external source of energy is used to get things started. Energy from some outside source is required to push the rock, open the gate of the dam, or let go of the sled. All real machines and processes require this kind of "boost" from an energy source outside the system. For example, there is a tremendous amount of chemical energy stored in fuel oil; but this energy will not raise steam in the boiler until you have expended some energy to start the oil burning. Similarly, the energy in any one system affects other energy systems. However, it is easier to learn the basic principles of energy if we forget about all the energy systems that might be involved in or affected by each energy process. In the examples given in this chapter, therefore, we will consider only one energy process or energy system at a time, disregarding both the energy "boosts" that may be received from outside systems and the energy transfers that may take place between the system we are considering and other systems.

Notice that both mechanical potential energy and mechanical kinetic energy are stored forms of energy. It is easy to see why we regard mechanical potential energy as being stored, but it is not so easy to see the same thing about mechanical kinetic energy. Part of the trouble comes about because mechanical kinetic energy is often referred to as "the energy of motion," thus leading to the false conclusion that "energy in transition" is somehow involved. This is not the case, however. Work is the only form of mechanical energy that can be properly considered as energy in transition.

If you have trouble with the idea that mechanical kinetic energy is stored, rather than in transition, think of it like this. A bullet that has been fired from a gun has mechanical kinetic energy because it is in motion. The faster the bullet is moving, the more kinetic energy it has. There is no doubt in anybody's mind that the bullet has the capacity to produce an effect, so we may safely say that it has energy. Although the bullet is in transition, the energy of the bullet is not transferred to any other object or system until the bullet strikes some object which resists its passage. When the bullet strikes against a resisting object, then, and only then, can we say that energy in transition exists, in the form of heat and work.

In this example, we are ignoring the fact that some work is done against the resistance of the air and that some heat results from the passage of the bullet through the air. But this does not change the basic idea that kinetic energy is stored energy rather than energy in transition. The air must merely be regarded as a "resisting object" which causes some of the stored kinetic energy of the bullet to be converted into energy in transition (heat and work) while the bullet is passing through the air. However, the major part of the stored kinetic energy does not become energy in transition until the bullet strikes an object firmer than air which resists its passage.

In the English system of units, mechanical potential energy is measured in foot-pounds. Consider, for example, the rock at the top of the cliff. If the rock weighs 5 pounds and if the distance from the rock to the earth at the base of the cliff is 100 feet, 500 foot-pounds of mechanical potential energy exist because of the relative positions of the rock and the earth. Another way of expressing this idea is by the formula:

$$PE = mgh$$

Where:

PE = potential energy (in foot-pounds)

mg = total weight of the object (in pounds)

h = distance between the earth and the object (in feet)

Mechanical kinetic energy is also measured in foot-pounds. The amount of kinetic energy present at any one time is directly related to the velocity of the moving object and to the weight of the moving object.

$$KE = \frac{1}{2}mv^2$$

Where:

KE = Kinetic energy

m = Mass of object

v = Velocity of object relative to earth

Mechanical potential energy can be changed into mechanical kinetic energy. If you push that 5-pound rock over the edge of the 100-foot cliff, it begins to fall, and, as it falls, it loses potential energy and gains kinetic energy. At any given moment, the total amount of mechanical energy (potential plus kinetic) stored in the system is the same - that is, 500 foot-pounds. But the proportions of potential energy and kinetic energy are changing all the time as the rock is falling. Just before the rock hits the earth, all the stored mechanical energy is kinetic energy. As the rock hits the earth, the kinetic energy is changed into energy in transition-that is, work and heat.

Mechanical kinetic energy can likewise be changed into mechanical potential energy. For example, suppose you throw a baseball straight up in the air. The ball has kinetic energy while it is motion, but the amount of kinetic energy decreases and the amount of potential energy increases as the ball travels upward. When the ball has reached its uppermost position, just before it starts to fall back to earth, it has only potential energy. Then, as it falls back toward the earth, the potential energy is changed into kinetic energy again.

Work

Mechanical energy in transition is called *work*. When an object is moved through a distance against a resisting force, we say that work has been done. The formula for calculating work is:

$$W = Fd$$

Where:

W = work (in foot-pounds)

F = force (in pounds)

d = distance moved in direction of applied force (in feet)

As you can see from this formula, you need to know how much force is exerted and the distance through which the force acts before you can find how much work is done. The unit of force is the pound. When work is done against gravity, the force required to move an object is equal to the weight of the object. Why? Because weight is a measure of the force of gravity or, in other words, a measure of the force of attraction between an object and the earth. How much work will you do if you lift that 5-pound rock from the bottom of the 100-foot cliff to the top? You will do 500 foot-pounds of work-the weight of the object (5 pounds) times the distance (100 feet) that you move it against gravity.

We also do work against forces other than the force of gravity. When you push an object across the deck, you are doing work against friction. In this case, the force you work against is not only the weight of the object; but also the force required to overcome friction and slide the object over the surface of the deck.

Notice that mechanical potential energy, mechanical kinetic energy and work are all measured in the same unit, foot-pounds. One foot-pound of work is done when a force of 1 pound acts through a distance of 1 foot. One foot-pound of mechanical potential energy or mechanical kinetic energy is the amount of energy that is required to accomplish 1 foot-pound of work.

Power

Power is the rate of doing work. The amount of work done has nothing at all to do with how long it takes to do it. When you lift a weight of 1 pound through a distance of 1 foot, you have done 1 foot-pound of work, regardless of whether you do it in half a second or half an hour. A device which can do a lot of work quickly is powerful. The common unit of measurement for power is the *horsepower* (hp). By definition, 1 horsepower is equal to 33,000 foot-pounds of work per minute or 550 foot-pounds of work per second. Thus a machine that is capable of doing 550 foot-pounds of work per second is said to be a 1-horsepower machine. (As you can see, your horsepower rating would not be very impressive if you did 1 foot-pound of work in half an hour. Figure it out. It works out to be just a little more than one-millionth of a horsepower.)

3.3.2 Thermal Energy

All substances are composed of molecules. The energy associated with molecules is called thermal energy. Thermal energy, like mechanical energy, exists in two stored forms and in one transitional form. The two stored forms of thermal energy are called internal potential energy, and internal kinetic energy. Thermal energy in transition is called *heat.*Although molecules are too small to be seen, they behave in some ways pretty much like the larger objects we considered in the discussion of mechanical energy. Molecules have energy of position (internal potential energy) because of the forces which attract molecules to each other. In this way, they are somewhat like the rock and the earth we considered before. Molecules have energy of motion (internal kinetic energy) because they are constantly in motion. Thus, the two stored forms of thermal energy-internal potential energy and internal kinetic energy-are in some ways similar to mechanical potential energy and mechanical kinetic energy, except that everything is on a smaller scale.

Temperature

You are probably already familiar with temperature, and know that we use is it to describe how hot or cold an object is, but what, exactly is it? Temperature is not energy and it's not heat. It is simply a number related to the average kinetic energy of the molecules of a substance; the greater the average kinetic energy, the greater the temperature. Notice that temperature is not equal to the kinetic energy, just proportional to it, and temperature readings do not tell you anything directly about the potential energy of the substance.

Temperature can be measured in a variety of scales. When the temperature scale is measured up from the point where there is no molecular motion, it is known as an absolute scale, and is directly proportional to the average kinetic energy of the molecules in the substance. The Kelvin and Rankine scales are absolute scales. We normally use the Fahrenheit or Celsius scales, which are offset from the corresponding absolute scale, and so are only indirectly related to the kinetic energy.

Internal Energy

Although the term may be unfamiliar to you, you probably know more about *internal energy* than you realize. Because molecules are constantly in motion, they exert a pressure on the walls of the pipe, boiler, cylinder, or other object in which they are contained. Also, the temperature of any substance arises from, and is directly proportional to, the activity of the molecules. Therefore, every time you read thermometers and pressure gages you are finding out something about the amount of internal energy contained in the substance. High pressures and temperatures indicate that the molecules are moving rapidly and that the substance therefore has a lot of internal energy.

For most purposes, we will not need to distinguish between the two stored forms of thermal energy. Therefore, instead of referring to internal potential energy and internal kinetic energy, from now on we will simply use the term "internal energy." By internal energy, then, we will mean the sum total of all internal energy stored in the substance or system because of the motion of the molecules and because of the forces of attraction between molecules.

Heat

Heat is a more familiar term than internal energy, but may actually be more difficult to define correctly. The important thing to remember is that heat is *thermal energy in transition* - that is, it is thermal energy that is moving from one substance or system to another.

An example will help to illustrate the difference between heat and internal energy. Suppose there are two equal lengths of pipe made of identical materials and containing steam at the same pressure and temperature. One pipe is well insulated; the other is not insulated at all. From everyday experience you know that more heat will flow from the uninsulated pipe than from the insulated pipe. When the two pipes are first filled with steam, the steam in one pipe contains exactly as much internal energy as the steam in the other pipe. We know this is true because the two pipes contain equal volumes of steam at the same pressure and at the same temperature. After a few minutes, the steam in the uninsulated pipe will contain much less internal energy than the steam in the insulated pipe, as we can tell by measuring the pressure and the temperature of the steam in each pipe. What has happened? Stored thermal energy - internal energy - has moved from one system to another, first from the steam to the pipe, then from the uninsulated pipe to the air. This movement or flow of thermal energy from one system to another is called heat.

A good deal of confusion exists concerning the use of the word "heat." For example, you will hear people say that a hot object "contains" a lot of heat when they really mean that it contains a lot of internal energy. Or you will hear that heat is "added to" or "removed from" a substance. Since heat is the flow of thermal energy, it can no more be added to a substance than the flow of water could be added to a river. (You might add water, and this addition might increase the flow; but you could hardly say that you had added flow.) The only kind of thermal energy that can in any sense be added to or removed from a substance is internal energy. The distinction between heat and internal energy must be clear in your own mind before you can understand the basic principles of a steam plant. Remember, steam contains internal energy but it does not "contain heat." Heat exists when the internal energy flows from the steam to something else (another substance or system).

Enthalpy

When discussing a system involving work and heat, such as a boiler and turbine, you may hear the term *enthalpy*. Enthalpy is a thermodynamic quantity defined as the sum of internal energy and the work done by the substance to move its surroundings out of the way as it moves or expands, known as "flow work." One consequence of this definition is that when heat flows into a substance at constant pressure, its enthalpy increases by the amount of heat energy added. This is why enthalpy is sometimes described as the "heat content" of a substance. Remember that heat is energy in transition, and is never stored so no substance ever really "contains" heat.

Units of Measurement

In engineering, temperature is commonly measured in degrees Fahrenheit. In this scale, the boiling point of water at atmospheric pressure is designated 212°, and the freezing point is 32° with 180 equal degrees between. When working in the metric system, the Celsius scale is used. The Celsius scale (sometimes called the centigrade scale) uses zero as the freezing point of water and 100° as its boiling point, with 100 equal divisions or degrees between.

To convert from Celsius to Fahrenheit: multiply by 1.8 and add 32.

$$°\mathrm{F} = (1.8 \times °\mathrm{C}) + 32°$$

The British thermal unit (BTU) is used to measure heat. Originally, 1 BTU was defined as the quantity of energy required to raise the temperature of 1 pound of water through 1° on the Fahrenheit (F) scale. A similar unit called the calorie (cal) was originally defined as the quantity of heat required to raise the temperature of 1 gram of water through 1° on the Celsius (C) scale. The BTU and calorie are still in use, but the original definitions have been abandoned by international agreement. These units are now defined in terms of the unit of energy called the "joule." By definition, 1 BTU is equal to 1054.886 joules, and 1 cal is equal to 4.18605 joules. As may be seen, the BTU is a much larger unit than the calorie; 1 BTU is equal to approximately 252 cal.

Heat Transfer

Heat can flow from one substance to another only when a temperature difference exists. Heat flow can occur only from a higher temperature to a lower temperature. When two objects at different temperatures are placed in contact with each other (or near each other), heat flows from the warmer object to the cooler one until both are at the same temperature. Heat transfer occurs at a faster rate when there is a larger temperature difference between the two objects. As the temperature difference approaches zero, the rate of heat transfer approaches zero.

Conduction, radiation, and convection are usually considered to be the three methods by which heat transfer can occur. It is more accurate, however, to consider conduction and radiation as the two basic methods of heat transfer and to consider convection separately as a special process which involves movement within a mass of fluid.

Conduction. Conduction is the method by which heat flows from a hotter to a colder substance when there is physical contact between the two substances. For example, consider a cold metal bar which is held firmly against a piece of red-hot metal. In a short time, the end of the bar which is not touching the hotter metal will have become too hot to hold. We say that heat has been conducted from molecule to molecule, throughout the entire bar. The process of conduction will continue as long as there is a temperature difference between the two ends of the bar.

Radiation. Radiation is a mode of heat transfer that does not require any physical contact between the warmer substance and the cooler substance. For example, a person sitting near a hot stove is warmed by radiant heat even though the air between the person and the stove may remain cold. Similarly, radiant heat from the sun warms the earth without warming the space through which it passes.

Convection. At the molecular or sub-molecular level, heat transfer takes place through both the processes of conduction and radiation. If we use the term "heat transfer" in a somewhat different way, we may also include convection as a mode of heat transfer. However, it is important to understand the difference between convection and the basic heat transfer processes of conduction and radiation.

If we put a hot brick into a wheelbarrow and wheel it across the street, we have in one sense "transferred" heat. However, any heat transfer that takes place between the brick and its surroundings while we are wheeling it across the street will be by conduction and by radiation. Therefore, it would really be more accurate to say that we have "transported" the brick and all its contained thermal energy from one side of the street to the other.

Convection occurs only in fluids – liquids, gases, and vapors – not in solids, such as the brick we have just transported in the wheelbarrow. Convection is the transportation or movement of some portions of a fluid within the total mass of the fluid. As this movement occurs, the moving portions of the fluid transfer their contained thermal energy from one part of the fluid to another. The effect of convection is thus to mix the various portions of the fluid; the part that was at the bottom of the container may move to the top, or the part that was at one side may move to the other side. As this mixing takes place, heat transfer occurs from one part of the fluid to another and between the fluid and its surroundings. But this heat transfer, like any other heat transfer, takes place by conduction and by radiation. In other words, convection transports portions of the fluid; conduction and radiation transfer the thermal energy.

Convection serves a vital purpose in bringing the different parts of the fluid into close contact so that heat transfer can occur. Without convection, there can be little heat transfer from or within fluids. Most fluids are poor conductors of heat when they are not in motion.

What causes this transportation of a mass of fluid? In the case of *natural convection*, the movement is caused by differences in the density of different parts of the fluid. The differences in density are usually caused by unequal temperatures within the mass of fluid. For example, as the air over a hot radiator is heated, it becomes less dense and therefore begins to rise. Cooler, heavier air is drawn in to replace the heated air, and convection currents are thus setup. Another example of natural convection is the circulation of water in a natural circulation boiler. As the water in the generating tubes is heated, it expands and becomes much lighter (less dense) than the cooler water in the downcomers. Therefore the hotter and lighter water rises, while the cooler and heavier water flows downward. The resulting circulation of water in the boiler is thus clearly an example of convection currents established by differences in temperature (and therefore differences in density) in various parts of the fluid.

In the case of *forced convection*, some mechanical device such as a pump or a fan produces the movement of the fluid. When the main feed pump moves feedwater toward the boiler, the water is transported by forced convection. The flow of combustion gases through a boiler is partly by natural convection and partly by forced convection. Natural convection occurs because the gases of combustion are hotter and lighter than air, so they tend to rise and go up the stack. Forced convection is also involved in this process, however, because the forced draft blowers supply an air pressure which increases the rate at which the combustion gases travel across the tubes and up the stack. When you stir a cup of hot coffee, you are forcing convection and thus increasing the rate of heat transfer. Natural convection currents would be set up in the coffee if you did not stir it, because differences in density would occur as some portions of the coffee cooled before others. If you want to cool the coffee rapidly, use forced convection (stirring). If you do not want it to cool so rapidly, wait for natural convection to do the job.

In summary, then, we use the term convection to describe the transportation, or loosely, the "heat transfer" of a mass of fluid and its contained thermal energy. However, the processes by which any substance gains or loses thermal energy are most accurately described in terms of conduction and radiation.

Sensible Heat and Latent Heat

The terms *sensible heat* and *latent heat* are often used to indicate the effect that the flow of heat has on a substance. The flow of heat from one substance to another is normally reflected in a temperature change in each substance-the hotter substance becomes cooler; the cooler substance becomes hotter. However, the flow of heat is not reflected in a temperature change in a substance that is in the process of changing from one physical state (solid, liquid, or gas) to another. When the flow of heat is reflected in a temperature change, we say that sensible heat has been added to or removed from the substance. When the flow of heat is not reflected in a temperature change but is reflected in the changing physical state of a substance, we say that latent heat has been added or removed.

Does anything bother you in this last paragraph? It should. Here we are, talking about adding and removing heat. And, furthermore, we are talking about sensible heat and latent heat as though we had two different kinds of heat to consider. As noted before, this is common (if inaccurate) engineering language. So keep the following points clear in your mind: (1) heat is the flow of thermal energy; (2) when we talk about adding and removing heat, we mean that we are providing temperature differentials so that thermal energy can flow from one substance to another; and (3) when we talk about sensible heat and latent heat, we are talking about two different kinds of effects that can be produced by heat, but not about two different kinds of heat.

The three basic physical states of all matter are *solid, liquid,* and *gas* (or vapor). The physical state of a substance is closely related to the distance between molecules. The molecules are closest together in solids, farther apart in liquids, and farthest apart in gases. When the flow of heat to a substance is not reflected in a temperature change, we know that the energy is being used to increase the distance between the molecules of the substance and thus to change it from a solid to a liquid or from a liquid to a gas. Such a change is known as a *phase change*. You might say that latent heat is the energy price that must be paid for a change of state from solid to liquid or from liquid to gas. The energy is not lost; rather, it is stored in the substance as internal energy. The energy price is "repaid," so to speak, when the substance changes back from gas to liquid or from liquid to solid.

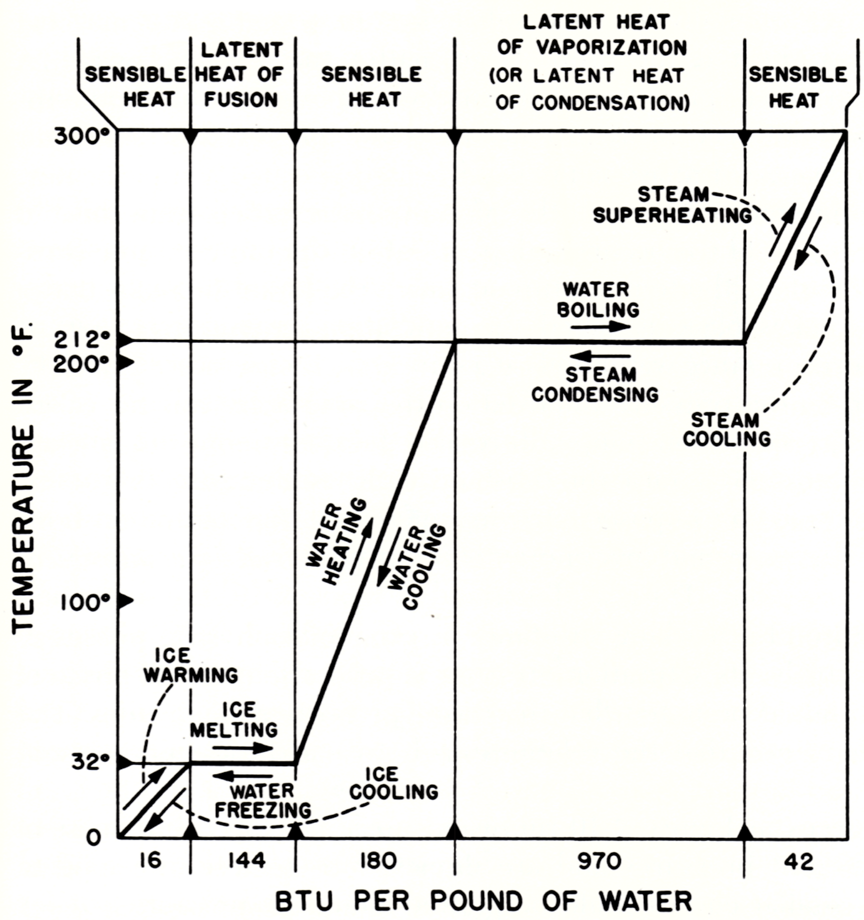


Figure 3.3.1 Phase Changes

Figure 3.3.1 shows the relationship between sensible heat and latent heat for one substance, water, at atmospheric pressure. The same kind of chart could be drawn up for other substances; however, different amounts of thermal energy would of course be required for each change of temperature and for each change of physical state.

If we start with 1 pound of ice at 0 °F, we must add 16 BTU in order to raise the temperature of the ice to 32 °F. We call this adding sensible heat. To change the pound of ice at 32 °F to a pound of water at 32 °F, we must add 144 BTU (the *latent heat of fusion*). There will be no change in temperature while the ice is melting. After all the ice has melted, however, the temperature of the water will be raised as additional heat is supplied. If we add 180 BTU that is, 1 BTU for each degree of temperature between 32 °F and 212 °F the temperature of the water will be raised to the boiling point. To change the pound of water at 212 °F, to a pound of steam at 212 °F, we must add 970 BTU (the *latent heat of vaporization*). After all the water has been converted to steam, the addition of more heat will cause an increase in the temperature of the steam. If we add approximately 42 BTU to the pound of steam which is at 212 °F, we can superheat it to 300 °F.

The same relationships apply when heat is being removed. The removal of 42 BTU from the pound of steam which is at 300 °F will cause the temperature to drop to 212 °F. As the pound of steam at 212 °F changes to a pound of water at 212 °F, 970 BTU are given off. When a substance is changing from a gas or vapor to a liquid, we usually use the term *latent heat of condensation* for the heat that is given off. Notice, however, that the latent heat of condensation is exactly the same as the latent heat of vaporization. Only the terms differ to indicate whether a substance is being changed into a liquid or into a gas. The removal of another 180 BTU of sensible heat will lower the temperature of the pound of water from 212 °F to 32 °F. As the pound of water at 32 °F changes to a pound of ice at 32 °F 144 BTU are given off without any accompanying change of temperature. Further removal of heat causes the temperature of the ice to decrease.

Specific Heat

In the discussion of sensible heat and latent heat, you may have noticed that it takes only 16 BTU to raise the temperature of 1 pound of ice from 0 °F to 32 °F that is, only 1/2 BTU for each degree of rise in temperature. However, we know that it takes 1 BTU (on the average) to raise the temperature of the same amount of water 1 °F. This difference occurs because the *specific heat* of water is about twice the specific heat of ice.

Specific heat is a thermal property of matter that must be determined experimentally for each substance. In general, we may say that specific heat is the property of matter; this explains the reason that equal quantities of thermal energy added to two different substances will not necessarily produce the same temperature rise, even when no change of state is involved. The specific heat of a substance is defined as the quantity of heat required to raise the temperature of unit mass of the substance 1 °F. For most engineering applications, specific heat is expressed in BTU per pound per degree Fahrenheit. In metric systems of measurement, specific heat is expressed in calories per gram per degree Celsius. Even though the units of measurement are different in the different systems, the *numerical value* of specific heat for any given substance is the same in all systems. The specific heat of water is 1.00 in all systems.

3.4 Energy Transformations

The machinery and equipment in the engineering plant aboard ship is designed either to carry energy from one place to another or to change a substance from one form to another. The principles of energy transformations and some of the important energy changes that occur in the shipboard propulsion cycle are discussed here.

3.4.1 Conservation of Energy

The basic principle dealing with the transformation of energy is the *Principle of Conservation of Energy*. This principle can be stated in several ways. Most commonly, perhaps, it is stated: "Energy can be neither destroyed nor created, but only transformed." Another way to state this principle is: "The total quantity of energy in the universe is always the same." Still another way of expressing this principle is by the equation

$$\text{Energy}_{in} = \text{Energy}_{out}$$

The "energy out" may be quite different in form from the "energy in," but the total amount of energy input must always equal the total amount of energy output.

Another principle, the *Principle of Conservation of Matter,* states: "Matter can be neither created nor destroyed, but only transformed." As you probably know, the development of the atomic bomb demonstrated that matter can be converted into energy; other developments have demonstrated that energy can be converted into matter. Therefore, the Principle of the Conservation of Energy and the Principle of the Conservation of Matter are no longer considered as two parts of a single law or principle but are combined into one principle: "Matter and energy are interchangeable, and the total amount of energy and matter in the universe is constant."

The interchangeability of matter and energy is mentioned here only to point out that the statement "energy in must equal energy out" is not strictly true for certain situations. However, any noticeable conversion of matter into energy or energy into matter can occur only under very special conditions that we need not consider now. All the energy transformations that we will deal with can be understood quite simply if we consider only the Principle of the Conservation of Energy, that is, *Energy in must equal Energy out*.

3.4.2 Transforming Heat to Work

The energy transformation of primary interest in the shipboard steam plant is the transformation from heat to work. To see how this transformation occurs, we need to consider the pressure, temperature, and volume relationships which hold true for gases. These relationships may be summarized as follows:

- When the temperature is held constant, increasing the pressure on a gas causes a proportional decrease in volume. Decreasing the pressure causes a proportional increase in volume.
- When the pressure is held constant, increasing the temperature of a gas causes a proportional increase in volume. Decreasing the temperature causes a proportional decrease in volume.
- When the volume is held constant, increasing the temperature of a gas causes a proportional increase in pressure. Decreasing the temperature causes a proportional decrease in pressure.

Suppose we have a boiler in which steam has just begun to form. With the steam stop valves still closed, the volume of the steam remains constant while the temperature and the pressure are both increasing. When operating pressure is reached and the steam stop valves are opened, the high pressure of the steam causes the steam to flow to the turbines. The pressure of the steam thus provides the potential for doing work; the actual conversion of heat to work is done in the steam turbines. The change in the internal energy (as indicated by changes in pressure and temperature) of the steam between the boiler and the condenser is an indication of the amount of heat that has been converted to work in the turbines.

Since heat is measured in BTU and work is measured in foot-pounds, how can we compare the amount of energy put in as heat with the amount of energy put out as work? At first glance, asking how much heat equals how much work might seem like asking how many lima beans equals playing baseball. However, the problem is not that difficult, since both heat and work are forms of energy. The formula for converting heat to work is

$$1 \text{ BTU} = 778 \text{ ft-lb}$$

or, in other words, the amount of energy required to raise the temperature of 1 pound of water 1 °F is the same as the amount of energy required to lift a 1-pound weight 778 feet against the force of gravity.

3.4.3 Energy Relationships in the Shipboard Propulsion Cycle

The movement of a ship through the water is the result of a number of energy transformations. Although most of these transformations have been mentioned, they have not been discussed in the proper sequence.

The first energy transformation occurs when fuel oil is burned in the boiler furnace. By the process of combustion, the chemical energy stored in the fuel oil is transformed into thermal energy. Thermal energy flows from the burning fuel to the water in the boiler, and steam is generated. The thermal energy is now stored as internal energy in the steam, as we can tell from the increased pressure and temperature of the steam. When the steam is admitted to the turbines, the thermal energy of the steam is converted into mechanical energy, which turns the shaft and drives the ship. Two main energy transformations are involved in converting thermal energy to work in a turbine. First, the thermal energy of the steam is transformed into mechanical kinetic energy (energy of motion) as the steam flows through one or more nozzles. Second, the mechanical kinetic energy of the steam is transformed into work (mechanical energy in transition) as the steam strikes the projecting blades of the turbine and thus causes the turbine to turn. The turning of the turbine rotor causes the propeller shaft to turn also, although at a slower speed, since the turbine is connected to the propeller shaft through reduction gears. The steam exhausts from the turbine to the condenser where it gives up its latent heat of condensation to the circulating seawater.

For the remainder of this cycle, energy is required to get the water (condensate and feedwater) back to the boiler where it will again be heated and changed into steam. The energy used for this purpose is generally the thermal energy of the auxiliary steam. In the case of turbine driven feed pumps, the conversion of thermal energy to mechanical energy occurs in the same way as it does in the case of the propulsion turbines. In the case of motor-driven pumps, the energy conversion is from thermal energy to electrical energy (in a turbogenerator) and then from electrical energy to mechanical energy (work) in the pumps.

As you can see, putting in 1 BTU at the boiler furnace does not mean that 778 foot-pounds of mechanical energy will be available for propelling the ship through the water. Some of the energy put in at the boiler furnace is used by auxiliary machinery such as pumps and forced-draft blowers to supply the boiler with feedwater, fuel oil, and air for combustion. Distilling plants, turbo-generators, steering gears, heating systems, galley and laundry equipment, and many other units throughout the ship use energy derived directly or indirectly from the energy put in at the boiler furnace.

In addition, there are many "energy losses" throughout the engineering plant. As we have seen, energy cannot actually be lost. But when it is transformed into a form of energy that we cannot use, we say there has been an energy loss. Since no insulation is perfect, some thermal energy is always lost as steam travels through the piping. Friction losses occur in all machinery and piping. There is also an energy loss at the condenser as the steam exhausted from the turbines gives up heat to the circulating seawater and turns into condensate.

Although some energy losses can be partly avoided by designing the machinery and equipment to minimize friction losses, by insulating hot surfaces, and by lubricating moving parts, some energy losses are still unavoidable. Consider, for example, the unavoidable energy loss that occurs at the condenser. To allow the flow of heat, the condenser must be at a lower temperature than the boiler since heat flow can occur only from a higher temperature area to a lower temperature area. Therefore, the energy loss at the condenser is not only unavoidable, but is also actually required for the conversion of heat to work.

As you can see, each BTU that is put in at the boiler furnace has to be divided in many ways before all the energy can be accounted for, but the energy account will always balance. *Energy in will always equal Energy out*.

3.5 The Generation of Steam

When a liquid boils, it generates a vapor, that is, some or all of the liquid changes its physical state from liquid to gas (or vapor). As long as the vapor is in contact with the liquid from which it is being generated, it remains at the same temperature as the boiling liquid. In this condition, the liquid and its vapor are said to be in *equilibrium contact* with each other.

The temperature at which a boiling liquid and its vapor may exist in equilibrium contact depends on the pressure under which the process takes place. As the pressure increases, the boiling temperature increases. As the pressure decreases, the boiling temperature decreases. For each liquid, therefore, the boiling point is determined by the pressure.

When a liquid is boiling and generating vapor, the liquid is called a *saturated liquid*, and the vapor is called a *saturated vapor*. The temperature at which a liquid boils under a given pressure is called the *saturation temperature*, and the corresponding pressure is called the *saturation pressure*. For each pressure there is a corresponding saturation temperature, and for each temperature there is a corresponding saturation pressure. A few saturation pressures and temperatures for water are listed below.

Atmospheric pressure is 14.7 psia at sea level and lesser at higher altitudes. Trying to cook potatoes at the top of a high mountain takes a great deal longer than it would at sea level. Why is this? As noted before, temperature and pressure are indications of internal energy. Since it is not possible to raise the temperature of the boiling water above the saturation temperature for that pressure, the amount of internal energy available for cooking the potatoes is much less at high altitudes than it is at sea level. By the same line of reasoning, you should be able to figure out why the potatoes cook faster in a pressure cooker than in an open kettle.

A peculiar thing happens to water and steam at an absolute pressure of 3206.2 psia and the corresponding saturation temperature at 705.40 °F. At this point, which is called the *critical point,* the vapor and the liquid are indistinguishable. No change of state occurs when the pressure is increased above this point or when heat is added. At the critical point, we can no longer refer to “water” or “steam,” since we cannot tell the water and steam apart. Instead, the substance is merely called a “fluid” or a “working substance.” Boilers designed to operate at pressures and temperatures above the critical point are called *supercritical* boilers. Supercritical boilers are not used, at present, in propulsion plants of ships; however, some boilers of this type are used in stationary steam power plants.

If we generate steam by boiling water in an open pan at atmospheric pressure, the water and the steam which is in immediate contact with the water will remain at 212 °F until all the water has been evaporated. If we fit an absolutely tight cover to the pan, so that no steam can escape while we continue to add heat, both the pressure and the temperature inside the vessel will rise. The steam and water will both increase in temperature and pressure, and each fluid will be at the same temperature and pressure as the other.

In operation, a boiler is neither an open vessel nor a closed vessel. Instead, it is a vessel designed with restricted openings which allow steam to escape at a uniform rate while feedwater is being brought in at a uniform rate. After boiler operating pressure has been reached, therefore, the process of steam generation in a boiler takes place at constant pressure and constant temperature, if we disregard any fluctuations that may be caused by changes in steam demands.

Although it is impossible to raise the temperature of the steam in the steam drum above the temperature of the water from which it is being generated, we can raise the temperature of the steam if we first remove the steam from contact with the water inside the steam drum and then add heat. Steam which has been heated above its saturation temperature for any given pressure is called *superheated steam*, and the vessel in which the saturated steam is superheated is called a *superheater.*The amount by which the temperature of the superheated steam exceeds the temperature of saturated steam at the same pressure is known as the *degree of superheat*. For example, if saturated steam at a pressure of 620 psia and the corresponding saturation temperature of 490 °F is superheated to 790 °F, the degree of superheat is 300 °F.

All ship's propulsion boilers are equipped with superheaters. The primary advantage is that superheating the steam provides a greater temperature differential between the boiler and the condenser, thus allowing more heat to be converted to work at the turbines. Another advantage is that superheated steam is dry and therefore causes relatively little corrosion or erosion of machinery and piping. Also, superheated steam does not conduct heat as rapidly (and therefore does not lose heat as rapidly) as saturated steam. The increased efficiency which results from the use of superheated steam reduces the amount of fuel oil required to generate each pound of steam, and so reduces the space and weight requirements for the boilers.

It should be noted, however, that most auxiliary machinery is designed to operate on saturated steam. Reciprocating machinery in particular requires saturated steam for the lubrication of internal moving parts of the steam end. Ship's boilers, therefore, are designed to produce both saturated steam and superheated steam.

Chapter 4

Introduction to Electricity

Objectives

- `OICEW-B2.4` Construction of electrical testing and measuring equipment
- `OICEW-B2.4` Operation of electrical testing and measuring equipment
- `OICEW-B2.6` The interpretation of electrical and simple electronic diagrams
- `OICEW-B1.1` Basic configuration and operation principles of electrical generators
- `OICEW-B1.1` Basic configuration and operation principles of electrical motors
- `OICEW-B1.1` Basic configuration and operation principles of electrical distribution systems

Electricity is the backbone of modern civilization, supporting nearly every aspect of our lives. Most people have used electricity every day of their lives without giving it much thought. Electricity is not a single thing, rather the term encompasses a broad range of phenomena associated with the presence and movement of charged particles. Electricity is related to magnetism, both being part of the phenomenon of electromagnetism, as described by Maxwell's equations.

Electrical phenomena include static electricity, electrical discharges like lightning and sparks, electromagnetic waves like light and x-rays, electromagnitism, electrical generation by induction, chemical reaction, and photoelectric effects; power transmission through conductors, resistance heating, conversion of electrical power to motion, and more.

In this chapter we will define some basic electrical concepts and describe some important electrical devices in order to give you a framework to understand how we harness and use electrical power aboard the training ship.

4.1 Fundamental Concepts

Electricity is associated with the accumulation or the flow of **charged particles**, particularly **electrons**, which are negatively-charged, subatomic particles. Charged particles will naturally flow from areas of high concentration to low concentration if a conductive path is available. The conductor is usually solid, like a copper wire, but can also be liquids such as salt water and mercury, or ionized gasses.

Static electricity is caused by the accumulation of electrons, as might occur from rubbing hard rubber on a wool carpet. The resulting static charge can be released suddenly as a spark when you touch a metal object. During a thunderstorm, large quantities of charged particles build up in the clouds and are eventually released to the earth as lightning through ionized air.

In practical devices, the charged particles are made to flow in a controlled fashion through an **electrical circuit** to supply power to **electrical loads**, such as lights, motors, heating elements, electronic devices, etc. This flow of charged particles is called **electrical current**.

Current can be initiated and sustained in a number of ways, including

- **Chemical reaction. Batteries** and **fuel cells** use this principle.
- **Electromagnetic induction**, whereby mechanical power supplied by a **prime mover** is converted to electrical power by means of a changing magnetic field This is the principle used by **electrical generators**.
- **Photovoltaic effect.** When sunlight strikes the surface of a solar cell, photons are absorbed by the semiconductor material used in the cell which causes some electrons break free from their normal positions, creating a charge imbalance.
- **Seebeck effect**. The Seebeck effect is a phenomenon where a small current is produced between two different types of metals or semiconductor materials when a temperature difference exists between them. Thermocouples use this principle to produce electric signals for temperature measurement.

In this section we introduce some important concepts and vocabulary related to electricity, electric circuits, and electrical machines.

4.1.1 Charge

Electrical **charge** is a fundamental property of matter that gives rise to the electromagnetic force, one of the four fundamental forces in nature. It is the property that describes the interaction between particles due to their electric fields. Electric charge is responsible for phenomena such as electricity, magnetism, and the behavior of charged particles.

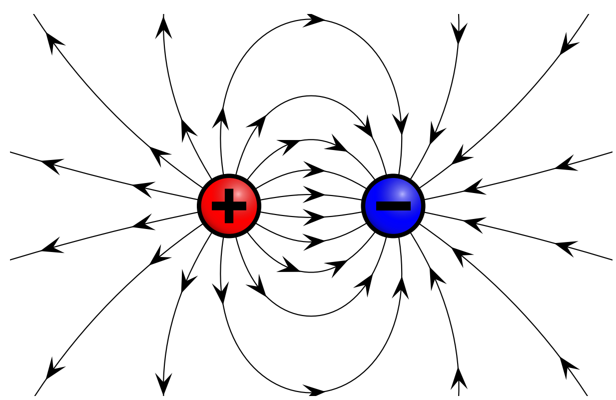


Figure 4.1.1 Electric Field between + and − charges

There are two types of electric charge:

Positive Charge: Particles with a positive charge have a deficiency of electrons compared to the number of protons in their atomic nuclei. **Protons** carry a positive charge, and when there is an excess of protons, an object is positively charged.

Negative Charge: Particles with a negative charge have an excess of electrons compared to the number of protons in their atomic nuclei. **Electrons** carry a negative charge, and when there is an excess of electrons, an object is negatively charged.

Similar charges repel each other and dissimilar charges attract.

Definition 4.1.2 The **coulomb** (unit symbol: C) is the unit of quantity of electric charge, and is equal to the charge of approximately 6.3×10^18 electrons. ◊

Objects can have a net positive, negative, or neutral charge, depending on the balance of protons and electrons they possess.

4.1.2 Current

Current refers to the flow of electric charge in an electrical circuit. It is the rate at which electric charges, typically electrons, move through a **conductor**. Electrons, which are negatively charged particles, are the primary carriers of electric charge in most conductive materials.

Definition 4.1.3 Current is measured in amperes (A) and is represented by the symbol I. It can be thought of as the quantity of charge passing through a point in a circuit per unit of time, or alternately as the rate of charge flow.

The **ampere**, or **amp** (unit symbol: A) is the unit of electrical current. One ampere is equal to one coulomb of charge moving past a point in one second. ◊

Consider the battery shown in Figure 4.1.4. The chemical reaction inside the battery causes electrons to move from the positive terminal to the negative terminal, making the negative terminal more negative and the positive terminal more positive. This creates a **potential difference**, or **voltage** across the battery terminals.

When the switch is closed, excess electrons will naturally be attracted to the positive terminal and they will migrate through the wire to attempt to equalize the charge. This create a flow of electrons that will continue until the chemical reaction is depleted and the battery "dies".

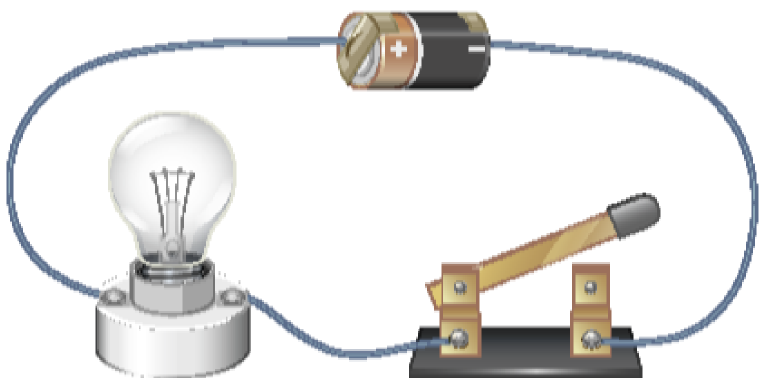


Figure 4.1.4 The battery creates a voltage to drive current through a circuit.

Whenever a potential difference exists between two points in a circuit, whether created by a battery, a generator, or some other voltage source, it will drive electrons from the more negative point towards the more positively point. This is called **electron flow**, or **electron current**.

Sadly, electron current is not technically **current**! This is because, in 1752, before the nature of electric charge and electrons was fully understood, Benjamin Franklin *defined* current as a stream of charge that flows from a more positively charged area to a more negatively charged area (less positive). That is, the direction of current is defined exactly opposite to the electron flow. This convention was adopted because it is easier to think of a flow going from a higher level (more positive) to a lower level (less positive), like water flowing down hill.

This definition of current, sometimes called **conventional current** for clarity, is the one used by physicists, engineers, and in textbooks. You should think of current as positive charge flowing from a positive terminal to a negative terminal, even though, in reality, negatively charged electrons flow in the other direction.

4.1.3 Voltage

Voltage, is a fundamental concept in electricity. In simple terms, voltage serves as the driving "push" or "force" that propels electric charges through a circuit. Other terms used for voltage include **electromotive force** (EMF), or **electric potential difference**. In electrical formulas and equations, you will see voltage symbolized with a capital E or V for steady or average values, or with an e or v for time varying values.

Definition 4.1.5 The **volt** (unit symbol: V) is the unit of electromotive force in the International System of Units. An electric potential difference of one volt between two points will impart one joule of energy per coulomb of charge moving between them. Another, more practical, definition of a volt is the potential difference required to drive one amp of current through one ohm of resistance. $\diamondsuit$

Voltage in an electrical system is equivalent to pressure in a fluid system, and just as a pump generates fluid pressure, voltage must be generated somehow. There are several methods to produce a voltage, including *chemical reactions* (such as in batteries) and the *photovoltaic effect* (as in solar cells); however, the most important method is **electromagnetic induction**. Electromagnetic induction is the process where a changing magnetic field induces (creates) an electric voltage in a nearby conductor. This phenomenon is the basis for generating electricity in devices like generators and transformers and it will be described in more detail in Subsection 4.1.9.

A voltage source (power supply) such as a battery or generator is connected to the attached circuit at two points called the **terminals**. The voltage between the terminals will drive current flow from the positive terminal to the negative terminal. The term **polarity** in typically refers to the orientation of the terminals. In simple terms, it indicates which terminal is positive and which is negative with respect to some reference point.

4.1.4 Sine Waves

Electrical systems may be described as either **DC** (direct current) or **AC** (alternating current) depending on the voltage supply.

In DC systems, the power supply maintains a constant polarity, i.e. one terminal is always positive, and the other is always negative, and the supply voltage is usually fairly steady. Batteries and solar cells are examples of DC voltage sources. In DC circuits, current always flows around the circuit in exactly one direction, from the positive to the negative terminal. Figure 4.1.4 is a simple example of a DC system. The current flows from the positive terminal of the battery, through the bulb, the switch, and then returns to the negative terminal of the battery.

On the other hand, in AC systems the polarity of the voltage switches periodically in a repeating pattern. This causes the current in the circuit to change periodically as well. In this section we discuss some important properties of period waves

Periodic Waves. A periodic waveform is a quantity, (voltage, current, power, for example) that varies in a repeating pattern over time. Standard AC voltage takes the form of a sine wave as shown in Figure 4.1.6, although other shapes such as square waves and sawtooth waves are used in electronic circuits.

Periodic waveforms are characterized by several key properties that define its behavior and shape:

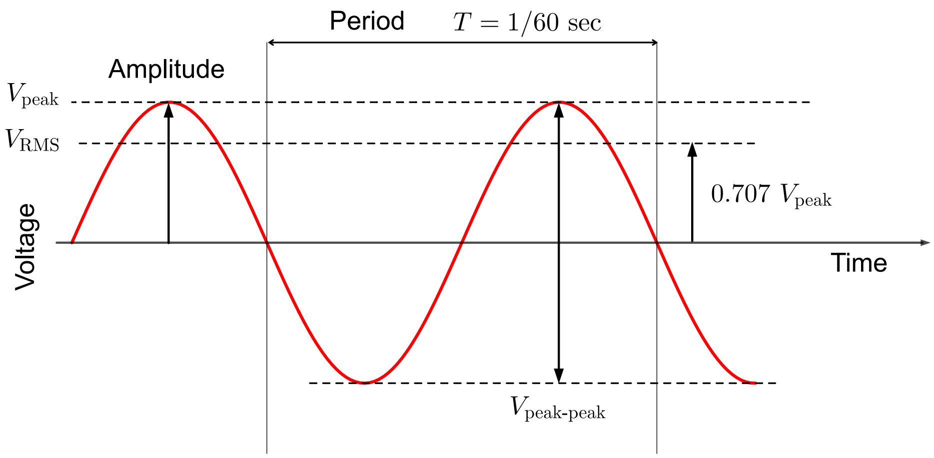


Figure 4.1.6 Periodic 60 Hz AC voltage sine wave

Amplitude (Peak value): The amplitude is the maximum value reached by the waveform during each cycle. It represents the highest positive or negative value from the reference level (usually zero volts).

Frequency The frequency f of a periodic waveform is the number of complete cycles or oscillations that occur in one second. It is measured in Hertz (Hz). Frequency determines how quickly the voltage waveform repeats itself. Standard electrical voltage in the United States is generated at 60 Hz, while 50 Hz is used in Europe and Japan.

Period The period T of a periodic wave is the time it takes for one complete cycle to occur. It is the reciprocal of frequency ($T = 1/f$) and is measured in seconds.

Peak-to-Peak Value The peak-to-peak value is the difference between the maximum positive and maximum negative values in a waveform. It represents the total range of voltage variation.

Root Mean Square (RMS) Voltage The root mean square is a mathematical concept used to represent the *effective* or *average* value of a varying quantity, such as voltage or current, in an AC waveform. It provides a way to express the magnitude of an AC signal in a manner that is equivalent to the magnitude of a DC value.

RMS values, rather than peak or instantaneous values, are used to describe the properties of AC systems. For example, when you see the voltage rating on a household electrical device (e.g., 120V for North America), it's the RMS value that's being specified. Similarly, the current rating (e.g., 15A) refers to the RMS value of the current.

For a sinusoidal waveform (like the standard AC power supply waveform), the RMS value is approximately $1/\sqrt{2} = 0.707$ times the peak value of the waveform.

$$V_{\text{RMS}} = \frac{V_{\text{peak}}}{\sqrt{2}} \qquad V_{\text{peak}} = V_{\text{RMS}}\sqrt{2}$$

The RMS value of an AC voltage is the equivalent steady DC voltage that would produce the same amount of power dissipation across a resistor as the AC voltage across the same resistor. In other words, it's the voltage that gives the same heating effect as the AC voltage. Similarly, the RMS value of an AC current is the equivalent steady DC current that would produce the same power dissipation in a resistor as the AC current through the same resistor.

Phase Shift Phase shift refers to the time difference between two periodic waveforms. It's often expressed in degrees and indicates how far one waveform is shifted in time relative to another. A phase shift of 0 degrees means the waveforms are in sync, while a phase shift of 180 degrees means they are completely out of phase. Recall that capacitors and inductors cause a phase shift between current and voltage.

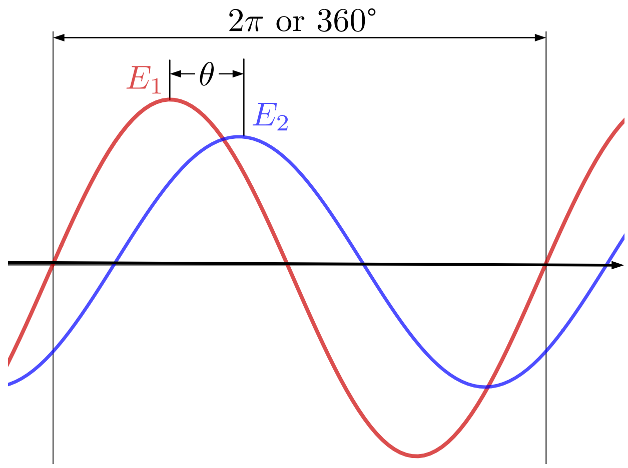


Figure 4.1.7 E_2 lags E_1 with a phase shift θ

Three phase power. Large AC generators including those on the training ship generate **three phase** power. Three phase power consists of three identical alternating voltage waveforms 120 degrees out of phase with each other, as shown in Figure 4.1.8.

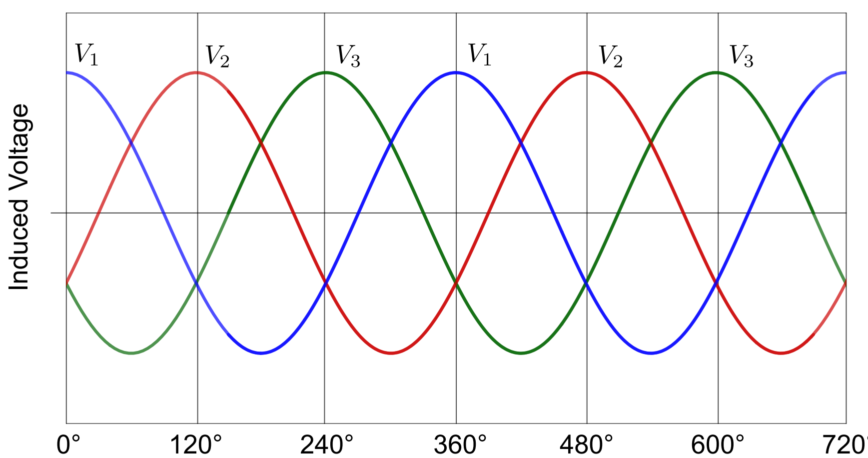


Figure 4.1.8 Three-Phase Voltages

Three-phase power is commonly used in industrial and commercial settings, as well as in larger residential complexes and power distribution networks. It's well-suited for heavy machinery, motors, large-scale industrial processes, and high-power applications.

The three voltage sine waves can be separated and used individually to supply **single phase** power for homes, small businesses, and some light commercial applications. It's suitable for powering lighting, appliances, and smaller electric loads.

4.1.5 Resistance

Resistance is a property of a material or component in an electrical circuit that opposes the flow of electric current. When a voltage is applied across a circuit component, its resistance restricts the flow of charged particles and reduces the magnitude of the current. Resistance is measured in ohms and is denoted by the symbol R. Large resistance, particularly electrical insulation resistance is measured in megohms, where 1 megohm = 1 million ohms.

Definition 4.1.9 One ohm (unit symbol: Greek Capital Omega, Ω) is defined as that amount of resistance that will produce one ampere of current when a one volt potential difference applied across the conductor. ◊

The resistance of a conductor depends on three factors

- The *material properties* of the conductor. If current flows easily the material is said to be a good conductor, with low **resistivity**. Gold, silver, copper and aluminum are all good conductors. Copper and aluminum are commonly used for wires and cables, but gold and silver only used for small electrical contacts due to the cost.
- The *conductor length*. The resistance of a conductor is directly proportional to the length of the current path.
- The conductor's *cross-sectional area*. As with fluid in a pipe, the narrower the path, the greater the resistance to flow.

The resistance of a conductor is given by

$$R = \frac{\rho L}{A} \tag{4.1.1}$$

where:

R is the resistance of the conductor, in ohms.

L is the length of the conductor, in meters.

A is the cross-sectional area of the conductor, in square meters.

ρ is the resistivity of the conductor, in ohm-meters.

4.1.6 Reactance

Reactance is a property that represents opposition to current flow in AC systems due to reactive components like **capacitors** and **inductors**. Unlike resistance, which is related to the dissipation of energy as heat, reactance is associated with the storage and release of energy in the electric or magnetic fields of the reactive components.

There are two types of reactance:

Capacitive Reactance X_C: Capacitive reactance occurs in circuits containing capacitors. When AC voltage is applied to a capacitor, it causes a displacement of charge between the plates, resulting in the accumulation and discharge of energy. This leads to a phase shift between the voltage and current waveforms. Capacitive reactance is inversely proportional to the frequency of the AC signal so is less significant at high frequencies.

Inductive Reactance X_L: Inductive reactance arises in circuits containing inductors. When AC voltage is applied to an inductor, it induces a magnetic field that stores energy. Changes in the magnetic field cause an opposing voltage that leads to a phase shift between voltage and current. Inductive reactance is directly proportional to the frequency of the AC signal so is less significant at low frequencies.

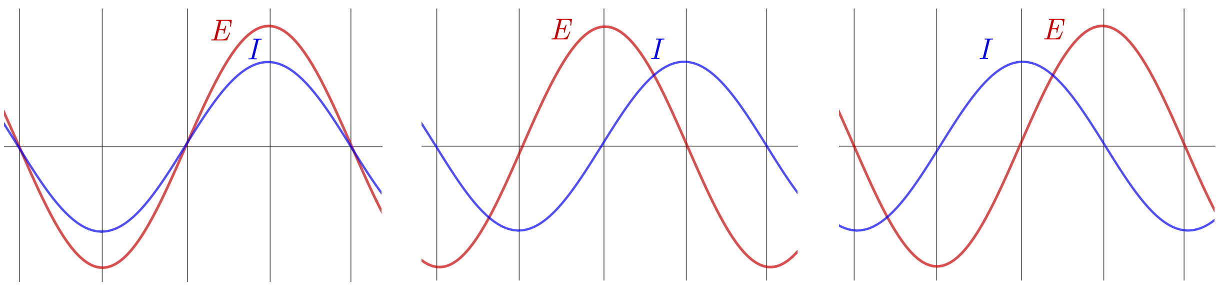
Reactance is measured in ohms (Ω), just like resistance. However, reactance has both magnitude and phase, making it a complex quantity. The magnitude of reactance determines how much opposition a reactive component offers to the AC current, while the phase shift characterizes the timing difference between the voltage and current waveforms.

Impedance Z: is a measure of the total opposition to flow of current in an AC circuit due to both resistance and reactance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}.$$

Impedance has units of ohms.

Phase shift: In a circuit with no reactive elements, the current and voltage sine waves are in phase, i.e. their peaks and valleys line up. However reactive elements cause the current and voltage waves to shift out of phase. An inductor will cause the current to **lag** behind the voltage, while a capacitor will cause the current to **lead** the voltage.



(a) Resistor. Current and voltage in phase.

(b) Inductor. Current lags voltage.

(c) Capacitor. Current leads voltage.

Figure 4.1.10 Phase shifts due to reactive elements

Note that when current is leading voltage, it is also true that voltage is lagging current.

4.1.7 Power

Electrical power is the rate at which electrical energy is transferred or converted from one form to another in an electrical circuit. Electrical power can be converted to useful forms such as mechanical power, light, or heat, with a suitable device such as a motor, lightbulb, or resistor. Electrical power is measured in watts (W) and is represented by the symbol P.

Definition 4.1.11 The watt (Unit symbol: W) is the unit of power the International System of Units (SI). One watt is the power delivered when one ampere of current is pushed through an electric circuit by one volt of electromotive force, or equivalently 1 joule per second. ◊

The watt is a relatively small quantity, so kilowatts (kW) and megawatts (MW) are commonly used. One kW is equal to 1000 W, and one MW equals 1000 kW.

To convert between SI and US customary power units, use these conversion factors:

$$\begin{aligned} 1 \text{ hp} &= 746 \text{ W} && = 0.746 \text{ kW} \\ 1 \text{ kW} &= 1.340 \text{ hp} && = 3412 \text{ Btu/hr} \end{aligned}$$

DC Circuits. In a DC circuits, where the voltage (V) is constant, electrical power can be calculated simply as the product of voltage and current

$$P = EI, \tag{4.1.2}$$

or as the product of resistance and current squared.

$$P = I^2 R \tag{4.1.3}$$

Where:

$$\begin{aligned} P &= \text{Electrical power, in watts.} \\ I &= \text{Current, in amperes.} \\ V &= \text{Voltage, in volts.} \end{aligned}$$

The second version of this equation uses the Ohm's law relation $E = IR$ to eliminate E and express power in terms of current and resistance. This equation indicates that the power dissipated by resistance is proportional to the square of the current, and that energy is lost whenever current flows through a resistor.

AC Circuits. In AC circuits the power cannot be calculated as easily as DC power for two reasons. First, the sinusoidal current and voltage are continuously changing, which means that the power is too. Second, any reactive elements in the circuit shift the current out of phase with the voltage, as shown in Figure 4.1.10.

The first issue is solved by using RMS average values for current, voltage and power, however simply applying (4.1.2) and multiplying the RMS voltage by the RMS current does not give the correct RMS power because of the second issue, the phase shift between the current and voltage waveforms.

The correct formula for calculating power in a single-phase AC circuit is

$$P = EI\cos\theta \tag{4.1.4}$$

where:

$$\begin{aligned} P &= \text{Real electrical power (RMS, in watts)} \\ I &= \text{Current (RMS, in amperes)} \\ V &= \text{Voltage (RMS, in volts)} \\ \theta &= \text{phase angle between current and voltage} \end{aligned}$$

The $\cos\theta$ term is called the **power factor**. Angle θ is the amount of phase shift, and the power factor the power factor reduces the **apparent power** $S = EI$, to the true power value, sometimes called the **real power**. The power factor gives an indication of how reactive elements affect the system. Note that since the power factor is the *cosine* of angle θ, its value is always between one and negative one.

Three phase AC Circuits. Power in a three phase circuit is $\sqrt{3}$ times larger than the power in a single phase circuit.

The correct formula for calculating power in a three-phase AC circuit is

$$P = \sqrt{3}EI\cos\theta \tag{4.1.5}$$

where:

$$P = \text{Real electrical power (RMS, in watts)}$$
$$I = \text{Current (RMS, in amperes)}$$
$$V = \text{Voltage (RMS, in volts)}$$
$$\theta = \text{phase angle}$$

4.1.8 Ohm's Law

Ohm's law describes the relationship between current, voltage, and resistance in an electric circuit. According to Ohm's Law, the current flowing through a circuit is directly proportional to the voltage across it and inversely proportional to the resistance of the circuit. Mathematically, this relationship is expressed as

$$I = V/R \tag{4.1.6}$$

where:

I is the the current in amperes

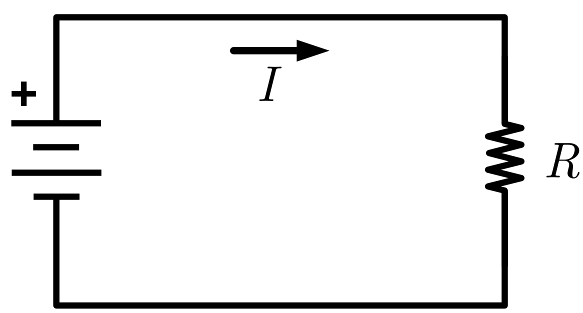
V is the voltage in volts, and

R is the resistance in ohms.

In other words, an increase in voltage leads to a corresponding increase in current if the resistance remains constant, while an increase in resistance results in a decrease in current for a given voltage.

It's important to note that Ohm's Law is most applicable to linear resistors under constant conditions. In AC circuits with reactive components like capacitors and inductors, Ohm's Law needs to be extended to include the concept of impedance, which takes into account both resistance and reactance.

Use this digram for the three example problems below.



Example 4.1.12 Find Current. Given E = 24 V and R = 100 Ω, determine the current I.

Answer. I = 0.24 A

Solution. Directly applying (4.1.6) we get:

$$I = \frac{E}{R} = \frac{24 \text{ V}}{100 \ \Omega} = 0.24 \text{ A} = 240 \text{ mA}.$$

□

Example 4.1.13 Find Resistance. Given E = 6.2 kV and I = 233 A, determine resistance R.

Answer. $R = 26.6\Omega$

Solution. Before applying (4.1.6) the given voltage must be converted from kilovolts to volts. (Recall that1 kV = 1000 V)

$$I = \frac{E}{R} \implies R = \frac{E}{I} = \frac{6200\text{ V}}{233\text{ A}} = 26.6\ \Omega.$$

□

Example 4.1.14 Find Voltage. Given I = 5 mA and R = 50 Ω, determine voltage E.

Answer. E = 0.25 V

Solution.

$$I = \frac{E}{R} \implies E = IR = (0.005\text{ A})(50\ \Omega) = 0.25\text{ V}.$$

□

4.1.9 Faraday's Law

Electromagnetic induction was discovered by English scientist Michael Faraday in 1831. It is not an exaggeration to say that this discovery is the foundation of the modern world.

Faraday observed that a *changing* magnetic field induces an EMF in a nearby conductor. You can observe this yourself by moving a magnet around and through a coil of wire connected to a sensitive voltmeter. When the magnetic field passing through the coil changes, whether by moving the magnet through the coil, by moving the conductor through the field, or by varying the strength of the field, a voltage is induced in the conductor that can be used to drive current and deliver electrical power.

Faraday's law of electromagnetic induction states that the induced EMF in a closed coil is directly proportional to the rate of change of magnetic flux passing through the circuit. Mathematically, it is expressed as:

$$\text{EMF} = -n\frac{d\Phi}{dt} \tag{4.1.7}$$

Where:

EMF is the induced electromotive force (in volts)

n is the number of turns in the coil

$\frac{d\Phi}{dt}$ is the rate of change in magnetic flux (in webers/sec)

The opposite is also true. When an electric current flows through a conductor, it generates a magnetic field that surrounds the conductor. This phenomenon is called **Oersted's principle**, and it is principle behind motors, solenoids, and electromagnets.

The experiment setup in Figure 4.1.15 demonstrates both Faraday's Law and Oersted's Principle.

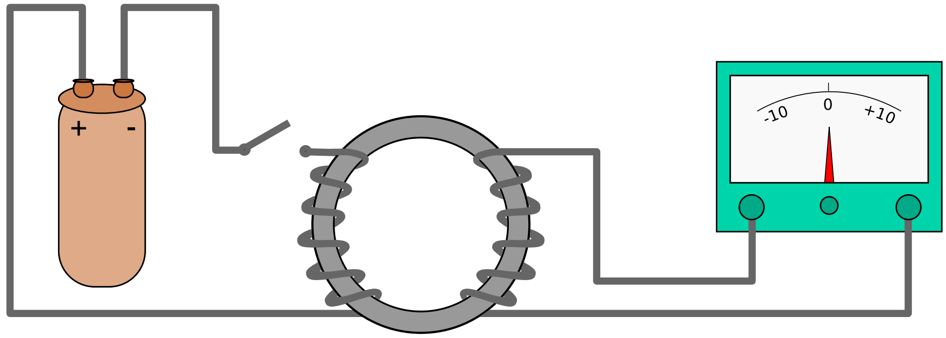


Figure 4.1.15 Faraday's Experiment

Two coils are wrapped around opposite sides of an iron ring. The left coil is connected to a battery and a switch. The right coil is connected to a galvanometer, which is an instrument that detects small voltages.

When the switch is closed, current flowing in the left coil produces a magnetic field surrounding the conductor (Oersted's principle). This field is trapped and channeled through the right hand coil by the iron ring. As the field builds up when the switch is closed, or collapses when the switch is opened, a voltage is detected on the galvanometer (Faraday's Law). However, If the switch is left in either position for very long, the voltage decays to zero, and remains that way until the switch is once again flipped. This indicates the the induced voltage is caused by a *changing* magnetic flux $\frac{d\Phi}{dt}$ and not by the flux alone.

4.2 Electrical Components

Electrical components are the building blocks of electrical systems and electronic devices. There are many types of electrical components, each with its unique properties and roles.

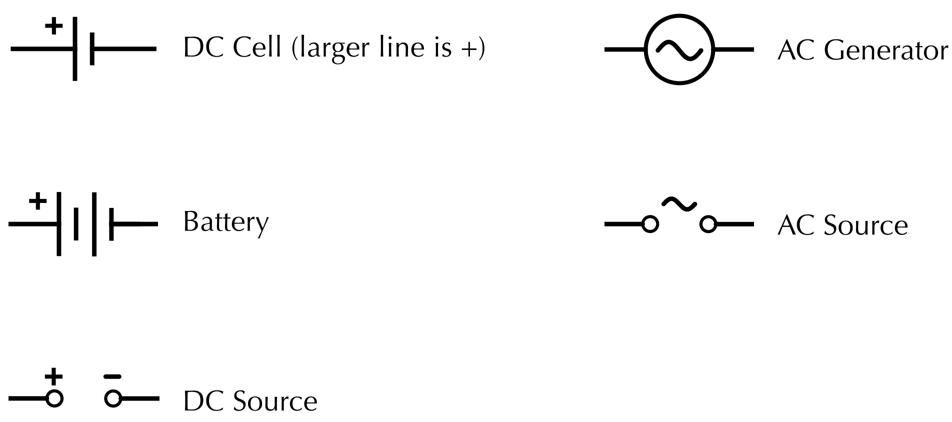
This section introduces some electrical components you should be familiar with, along with the symbols used for them on schematic circuit diagrams.

4.2.1 Power Source

The power source is the device that supplies electrical energy to the circuit. Common power sources include batteries, generators, and power supplies. An ordinary wall outlet is a convenient connection to a distance power source.

Figure 4.2.1 Diesel generator, power strip, batteries

Symbols.



4.2.2 Ground

Ground in electricity has several meanings depending on the context in which it's used. Ground primarily means the earth when ashore, or the hull aboard ship.

Circuits are **grounded** by connecting them to ground. This **ground connection** provides an alternate path for electrical currents to flow back to the source. Ashore, electrical circuits are grounded by connecting them electrically to a rod or pipe driven into the earth, while aboard ship, a connection the hull serves the same purpose. A **chassis ground**, refers to the point on the metal frame or outer casing (chassis) of an electrical or electronic device where the circuit is grounded. The chassis itself is grounded to the earth or the hull. Ground also refers to a reference point used for voltage measurements. Finally a ground or **ground fault** can refer to an accidental connection between the circuit and ground

The ground connection serves several important functions:

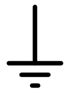
- **Reference Point** Voltage is always measured relative to a reference point. By defining a specific point as "ground," voltages at other points in the circuit are measured with respect to this reference.

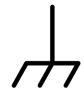
- **Safety Grounding** is crucial for safety in electrical systems. In case of a fault or short circuit, excess current can flow to the ground, allowing circuit protection devices like fuses and circuit breakers to quickly interrupt the current flow. This helps prevent electrical fires, shocks, and damage to equipment.

- **Human Safety** In the event of a fault that causes a live conductor to come into contact with a conductive surface (like a metal enclosure), the ground connection provides an alternate path for current to flow *around*, rather than *through* the victim, reducing the severity of electric shock.

- **Shielding** In electronic devices and systems, grounding is used for shielding against electromagnetic interference (EMI) and radio frequency interference (RFI). Metal enclosures and components can be connected to the ground to create a shield that prevents external electromagnetic signals from interfering with the device's operation.

Symbols.


Earth Ground


Chassis Ground

4.2.3 Load

Electrical loads consume electrical energy and convert it into another useful form like mechanical work, light, or heat. Motors, computers, light bulbs and heating elements are some common examples of electrical loads.

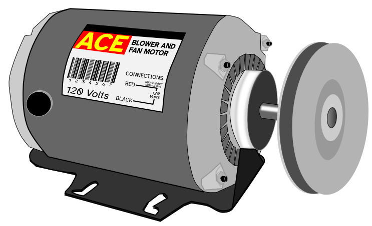
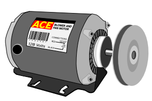
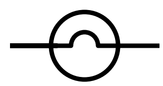
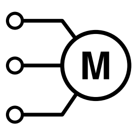


Figure 4.2.2 Electric lights, electric motor, electric stove

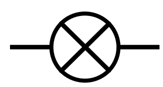
Symbols.


Motor


Lamp (lighting)



Three Phase Motor


Lamp (indicator)

4.2.4 Conductors

Conductors are materials that provide a pathway to connect the various components within the circuit, allowing the current to flow from the power source to the load.

Good conductors are materials that have low resistance because their electrons are loosely bound to their atoms. Copper, aluminum, silver, and gold, are all good conductors.

Figure 4.2.3 Stranded copper wire, power cables, circuit board traces

Three methods are commonly used to describe the size of wires and electrical conductors.

The **American Wire Gage** (AWG) system assigns a specific number to each wire size, with lower numbers representing larger wires. The system is widely used in the United States for copper and aluminum wires. For example, a common household electrical wire might be designated as *12 AWG* or *14 AWG*. Smaller numbers indicate thicker wires with larger cross-sectional area, capable of carrying higher current loads. Larger numbers represents thinner wires.

The **Metric system** simply uses the cross-sectional area of the wire measured in square millimeters (mm^2). For instance, you might see a wire labeled as 2.5 mm^2 or 4.0 mm^2. A larger number indicates a larger cross-sectional area and, therefore, a thicker wire capable of carrying more current.

Circular mils. This system is used in the United States when discussing very small or very large wire sizes. The term *circular mil* is often abbreviated as *CM*. The circular mil is defined as the area of a circle with a diameter of one mil, where one mil is a unit of length equal to one thousandth of an inch (0.001 inch).

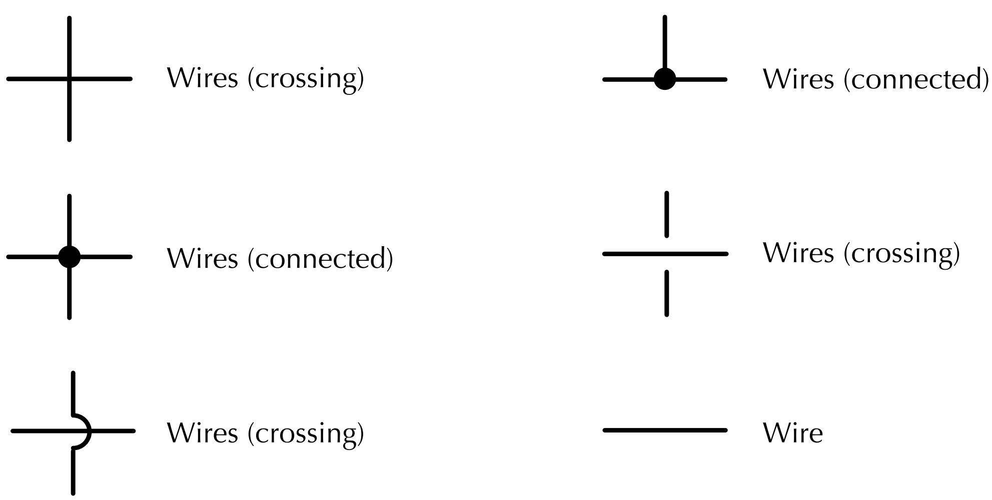
Mathematically, the formula for calculating the circular mil area, A, of a wire with diameter, d, in mils is

$$A = \frac{d^2}{4} \text{ circular mils.}$$

For example, if you have a wire with a diameter of 500 mils, you can calculate its circular mil area as follows:

$$A = \frac{500^2}{4} = 125,000 \text{ circular mils}$$

Symbols.



4.2.5 Resistors

Resistors are made of materials that conduct electricity, but offer opposition to current flow. They limit the flow of current, and can be used for various purposes, including voltage division and current limiting.

Figure 4.2.4 Carbon resistors, potentiometer, surface mount reistors

Carbon resistors are fundamental and affordable resistors made by mixing carbon granules with a binder, suitable for general-purpose applications.

Film resistors, including metal film and carbon film, have a thin resistive film deposited on a ceramic or glass substrate, and offer higher stability and precision than carbon resistors.

Wire wound resistors have a resistive wire wound around a core, often made of ceramic or fiberglass. They are used for high-power applications and where precision and stability are crucial.

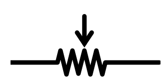
Variable resistors, also known as **potentiometers**, allow manual adjustment of resistance and are used for tuning purposes.

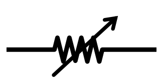
Metal Oxide Varistor MOVs are used as voltage-dependent resistors to protect circuits from voltage spikes and surges.

Surface-mount resistors are compact and designed for surface-mount technology, facilitating modern electronics assembly processes.

Symbols.

 Resistor

 Potentiometer (3 contacts)

 Rheostat (2 contacts)

4.2.6 Insulators

Insulators are materials which have very high resistance, and are extremely poor conductors. Rubber, plastic, glass, ceramic, mica, and air are examples of good insulators.

Insulators are not used as *part* of a circuit, but rather they are used to

- prevent accidental contact with live electrical components, reducing the risk of electric shock hazards.

- cover electrical wires and cables to prevent contact between conductors and to ensure that current flows along the desired path without unintentional leakage or interference.
- physically separate and electrically isolate different parts of an electrical circuit. This prevents unintended short circuits and interference between components.
- mount and support electrical components, preventing them from coming into direct contact with conductive surfaces or other components that could cause unintended connections.

Figure 4.2.5 Wire insulation, insulating tape, ceramic insualtors

4.2.7 Switches

Switches are devices that can open or close the circuit path, controlling the flow of current. They are used to turn devices on or off and control the circuit's operation.

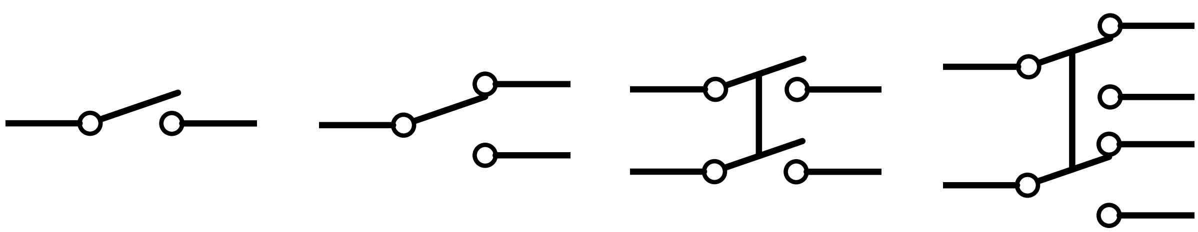
Switches are available in a wide variety of forms suitable for different applications.

Single-Pole, Single-Throw (SPST) Features a single input terminal and two output terminals, enabling a simple on-off switching action to connect or disconnect a circuit.

Single-Pole, Double-Throw (SPDT) With a single input terminal and two output terminals, this form allows toggling between two circuits or states by connecting the input to either of the two outputs.

Double-Pole, Single-Throw (DPST) Incorporates two input terminals and two output terminals, simultaneously opening or closing two separate circuits.

Double-Pole, Double-Throw switches (DPDT) Similar to SPDT but with two input and two output terminals, this form offers increased switching options by connecting each input to one of two outputs.



(a) SPST **(b)** SPDT **(c)** DPST **(d)** DPDT

Figure 4.2.6 Switch Forms

Switches are also available with many operating behaviors, including:

Momentary switches return to the default state, which can be either open or closed, when released, like a doorbell.

Latching or **maintaining contact**switches retain the switch position until manually changed, like a light switch.

Toggle switches are operated by flipping a lever to toggle between open and closed positions, providing a straightforward on-off control mechanism.

Selector switches have multiple positions to permit users to choose from different settings or options.

Relays are switches that can be operated remotely by means of an electromagnet. Relays are used in control circuits and may be operated either manually or by automation.

Contactors are relays designed to handle higher voltages and currents than typical switches or relays, making them suitable for controlling heavy loads, such as motors, heaters, and other heavy-duty equipment.

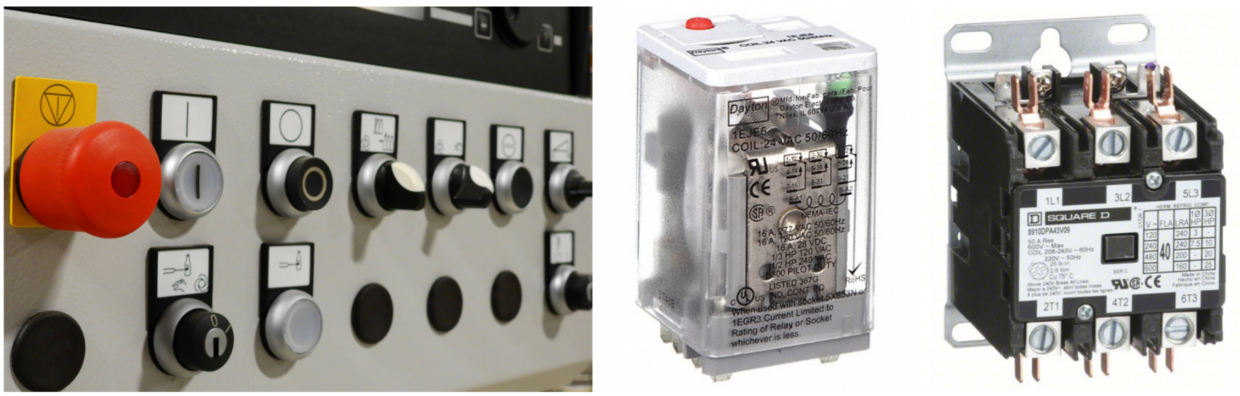
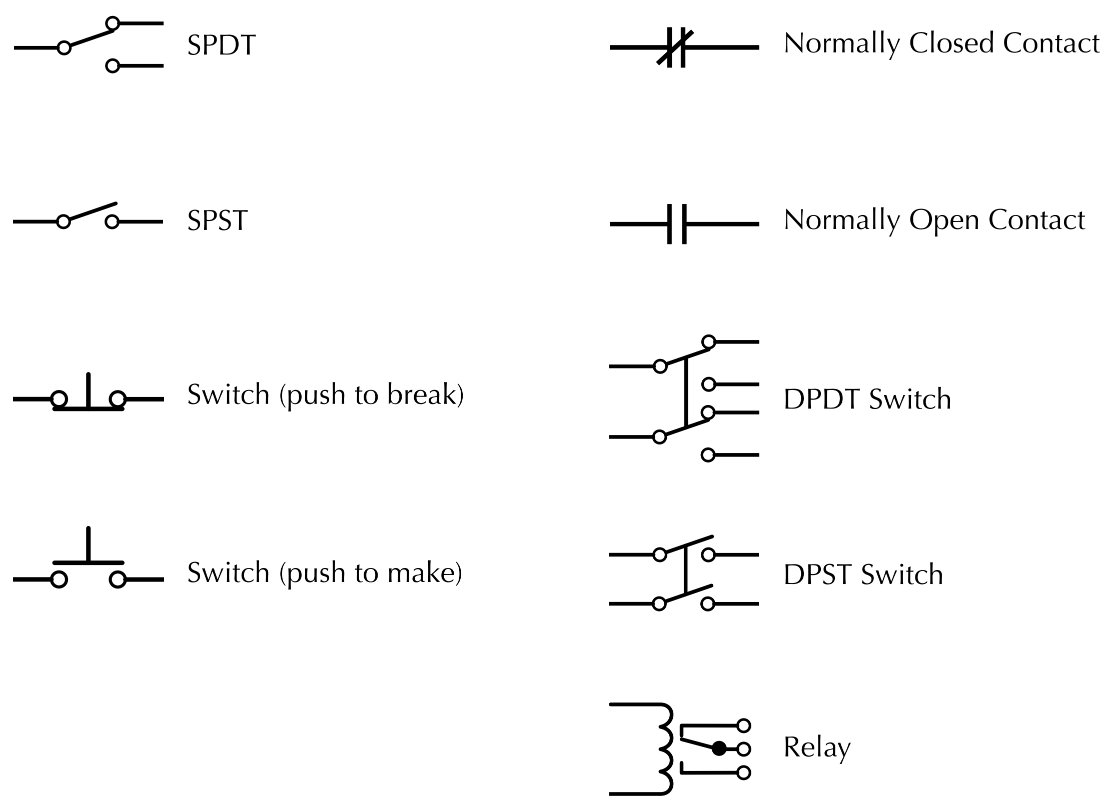


Figure 4.2.7 Switch panel, relay, and contactor

Symbols.



4.2.8 Capacitors

A capacitor is an electrical component that stores and releases electrical energy in an electric field. It consists of two conductive plates separated by an insulating material called a **dielectric**. When a voltage is applied across the plates, electric charges accumulate on the plates, creating an electric field between them.

When a capacitor is charged in this way, energy is stored in the electric field. Capacitors can be discharged to quickly provide short bursts of power. They are often used for energy storage, filtering, and smoothing voltage fluctuations.

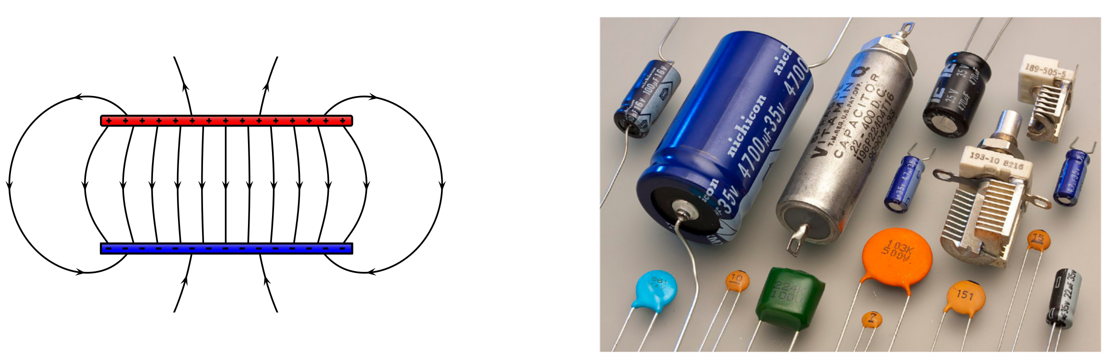


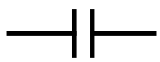
Figure 4.2.8 Electric field between capacitor plates, various types of capacitors

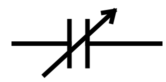
Ceramic capacitors are widely used due to their small size, low cost, and versatility. They are suitable for general applications like decoupling, filtering, and timing.

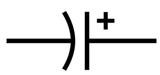
Electrolytic capacitors are used in high capacitance and energy storage applications, such as power supply filtering and voltage regulation.

Variable capacitors, also called **trimmer capacitors** or tuning capacitors, they allow manual adjustment of capacitance values, vital in tuning circuits and calibration

Symbols.

 Unpolarized Capacitor

 Variable Capacitor

 Polarized Capacitor

4.2.9 Inductors

An inductor is an electrical component that stores energy in a magnetic field when current flows through it. It consists of a coil of wire wound around a core material. When current passes through the coil, a magnetic field is created around it, and this field stores energy. Any device which uses electrical current to produce a magnetic field is an inductor.

An inductor is like a "magnetic energy storage" device. It resists changes in current and helps regulate and control the flow of electricity. They are used in applications like filtering, energy storage, and electromagnets.

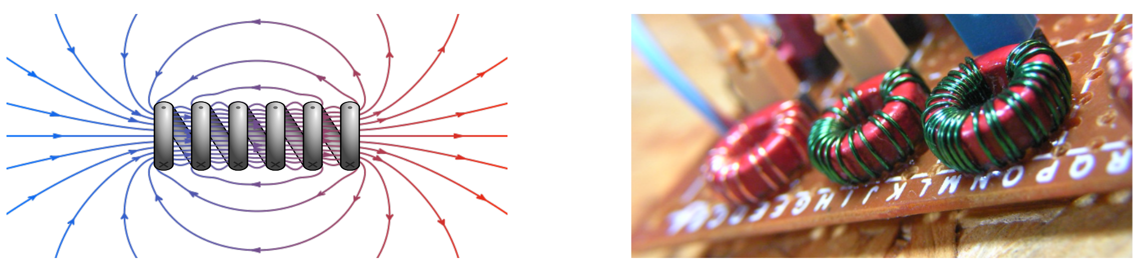


Figure 4.2.9 Magnetic Field surrounding inductor, toroidal inductors

Ferrite core inductors have a core made of *ferrite*, a ceramic material containing iron oxide and other elements. The ferrite core concentrates magnetic fields, enhancing the performance of the inductor.

Iron core inductors have a core made of iron or iron-alloy material. They offer higher inductance values and are often used in power supply and filtering applications.

Toroidal inductors have a coil wound around a doughnut-shaped (toroidal) core, providing high inductance and reduced electromagnetic interference.

Variable inductors allow manual adjustment of inductance, and are often used in tuning circuits.

Solenoids are cylindrical coils used to create strong magnetic fields to produce mechanical motion in devices like electromechanical actuators and relays.

Field windings are used to create magnetic field in motors and generators.

Symbols.

 Inductor, coil, or solenoid

4.2.10 Diodes

A **diode** is an electrical component that allows current to flow in one direction while blocking it in the opposite direction. It acts as a "one-way valve" for electric current. Diodes are made from semiconductor materials and have two terminals: an anode (positive side) and a cathode (negative side).

Rectifier Diodes are used for converting AC to direct current DC (rectification).

Zener diodes are used for voltage regulation and voltage reference applications. They maintain a nearly constant voltage across their terminals regardless of current changes.

Light Emitting Diodes (LEDs) emit light when current flows through them. They are used for indicators, displays, lighting, and optical communication.

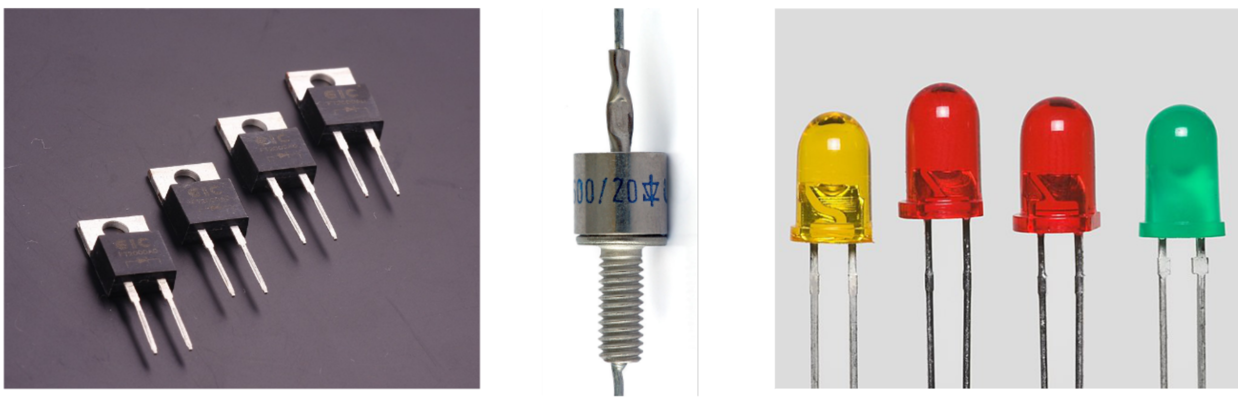
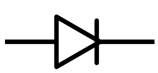
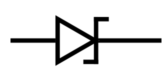
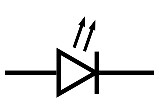


Figure 4.2.10 Rectifier diode, zener diode, LED

Symbols.

 Rectifier Diode

 Zener Diode

 Light Emitting Diode

4.2.11 Transistors and ICs

A **transistor** is a semiconductor device that acts as an electronic switch or amplifier. It can control the flow of electric current between its two main terminals, known as the collector and emitter, by using a small current at its third terminal, called the base. Transistors are used for amplification and switching purposes.and are the building blocks of modern electronics.

The most common variety of transistor is the **bipolar junction transistor** (BJT), which has two variations: **NPN** and **PNP**. In an NPN transistor, current flows from the emitter to the collector when a small current is applied to the base. A PNP transistor is the opposite of an NPN transistor. In a PNP transistor, current flows from the collector to the emitter when a small current is applied to the base.

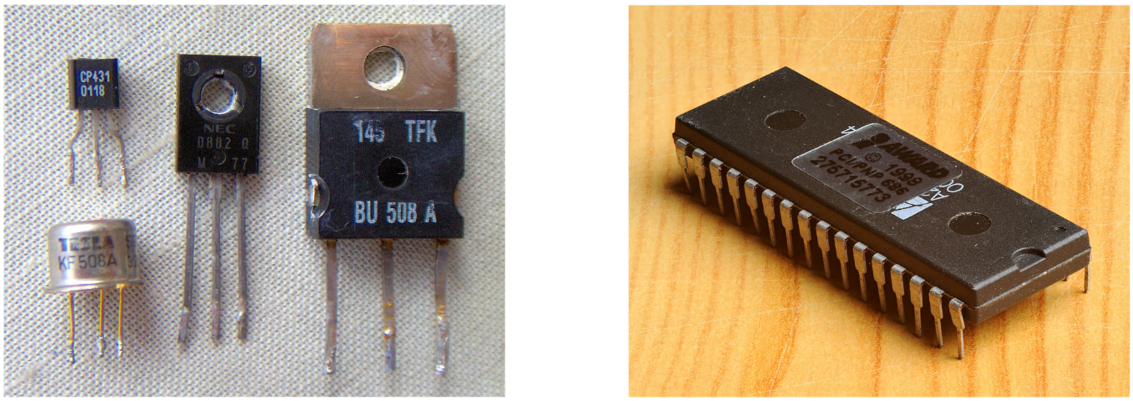
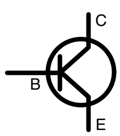


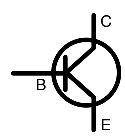
Figure 4.2.11 Transisters, integrated circuit chip

An **integrated circuit** (IC), also known as a microchip or chip, is a compact electronic device that contains a large number of interconnected electronic components, such as transistors, resistors, capacitors, and diodes, all fabricated on a single piece of semiconductor material. ICs are the building blocks of modern electronics, found in everything from microprocessors to memory chips.

Symbols.



NPN Transistor



PNP Transistor

4.2.12 Protective Devices

Electric circuits are equipped with protective devices that rapidly interrupt the flow of current when they detect abnormal conditions, in order to prevent hazards such as equipment damage, electrical fires, and personal injury.

Figure 4.2.12 Circuit breaker, fuses, ground fault circuit interupter

Circuit breakers are electromechanical devices that to swiftly interrupt current flow under short circuit and overload conditions.

Short circuits protection is provided by the **instantaneous trip mechanism**. It relies on the electromagnetic force generated by the excessive current passing through a solenoid coil. The large magnetic field generated by the high current causes the solenoid to rapidly trigger a trip mechanism and open the circuit breaker's contacts almost instantly.

The **overload trip mechanism** detects sustained high currents caused by excessive load or faulty equipment, but permits the temporary overloads that occur when a motor starts. The load current passes through a bimetallic strip or a heating element. If the current increases, the temperature of the bimetallic strip rises, causing it to bend. When the bending reaches a critical point, it triggers the trip mechanism, opening the circuit breaker contacts and cutting off the current.

Fuses are thin wires or elements designed to melt and break the circuit when excessive current flows through them. Like circuit breakers, they provide protection against overcurrents and short circuits but need to be replaced after they "blow."

Ground Fault Circuit Interrupters (GFCIs) monitor current imbalances, and swiftly shut off power if a ground fault is detected, protecting people against electric shocks.

Symbols.

 Fuse

 Molded Case Circuit Breaker

 Air Circuit Breaker (Draw-out)

 Thermal Fuse

 Overload Heater Element

4.3 Electrical Circuits

An **electric circuit** is a closed loop or pathway through which electric current flows to the various components which supply or utilize electrical power.

This section introduces four common circuit arrangements that you should be familiar with: series, parallel, wye (also known as star), and delta.

4.3.1 Series Circuit

In a **series circuit**, the components are connected in a single path, end-to-end, creating a sequential circuit. If one component fails or is disconnected, the entire circuit is broken, and the flow of current stops.

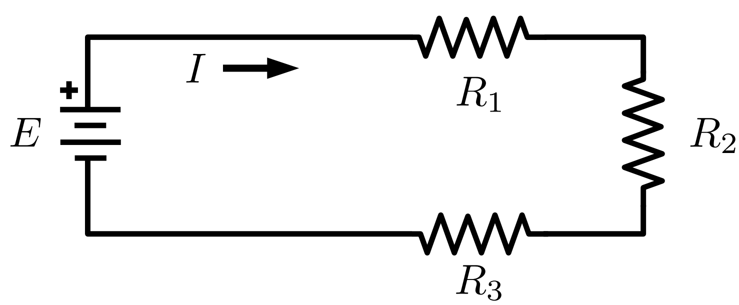


Figure 4.3.1 Three resistors in series

The key characteristics series circuits are:

- The same current flows through each series component.
- The total resistance is the sum of the individual resistances.
- The voltage drop across each component may be different, but the total voltage drop must equal the supply voltage.

Example 4.3.2 Series Resistors. Consider the series circuit in Figure 4.3.1.

If the battery supplies 48 V, and the resistors are $R_1 = 10\ \Omega$, $R_2 = 20\ \Omega$, and$R_3 = 50\ \Omega$, determine

A The current in the circuit, and

B The voltage drop across each resistor.

Answer. I = 0.6 A, E_1 = 6 V, E_2 = 12 V, E_3 = 30 V.

Solution. The total resistance is the sum of the individual resistances

$$R_t = R_1 + R_2 + R_3 = 80\ \Omega.$$

By Ohms Law, the current is

$$I = E/R_t = \frac{48\text{ V}}{80\Omega} = 0.6\text{ A}.$$

The voltage drop across each resistor is

$$\begin{aligned} E_1 &= IR_1 = 6\text{ V} \\ E_2 &= IR_2 = 12\text{ V} \\ E_3 &= IR_3 = 30\text{ V} \end{aligned}$$

Note that the three voltage drops add up to the 48 V supply. □

4.3.2 Parallel Circuit

In a **parallel circuit**, the components are connected between the same two points, creating a separate current path for each component. Parallel components all use the same power supply but can be turned on and off independently.

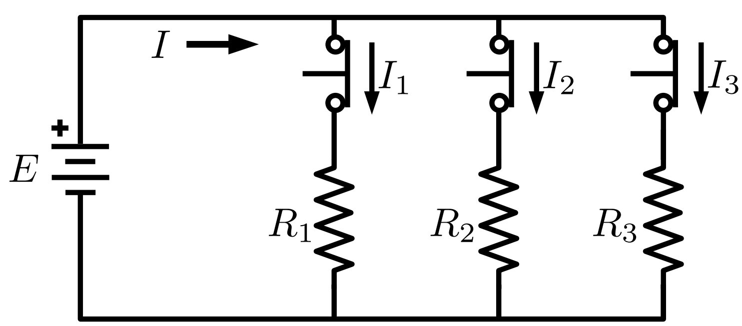


Figure 4.3.3 Three resistors in parallel

The key characteristics parallel circuits are:

- The same voltage is applied to all parallel components.
- The current through each component may be different, but the total current is the sum of the currents through each component.

- The total resistance of a parallel circuit containing n branches is given by this formula

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3 + ...1/R_n}. \tag{4.3.1}$$

Example 4.3.4 Parallel resistors. Consider the series circuit in Figure 4.3.3.

If the battery supplies 100 V, and the resistors are $R_1 = 100\ \Omega$, $R_2 = 200\ \Omega$, and$R_3 = 500\ \Omega$, determine

A The total current I in the circuit, and

B The total current if branch 3 is turned off by opening the third switch.

Answer. For all three branches in operation: I = 1.7 A.

For just the first two branches I = 1.5 A.

Solution 1. The current in each branch may be found using Ohms Law

$$I = E/R.$$

Use Ohm's Law $I = E/R$ to calculate the current through each resistor.

$$I_1 = E/R_1 = \frac{100\text{ V}}{100\ \Omega} = 1.0\text{ A}$$
$$I_2 = E/R_2 = \frac{100\text{ V}}{200\ \Omega} = 0.5\text{ A}$$
$$I_3 = E/R_3 = \frac{100\text{ V}}{500\ \Omega} = 0.2\text{ A}$$

The total current for all three branches is

$$I = I_1 + I_2 + I_3 = 1.7\text{ A}$$

When the switch in branch 3 is opened current I_3 drops to zero, so the total current drops to 1.5 A

Solution 2. An alternate solution method is to first find the equivalent resistance using (4.3.1), then use that resistance to find the current.

For all three resistors

$$R_t = \frac{1}{\frac{1}{100} + \frac{1}{200} + \frac{1}{500}} = 58.8\ \Omega,$$

and the corresponding current is

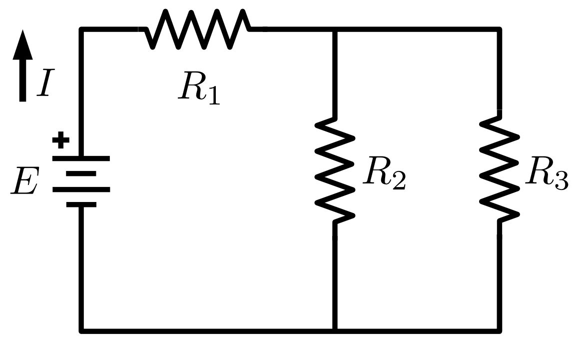
$$I = \frac{E}{R_t} = \frac{100\text{ V}}{58.8\ \Omega} = 1.7\text{ A}$$

Repeating the calculations for the first two resistors only we get

$$R_t = \frac{1}{\frac{1}{100} + \frac{1}{200}} = 66.7\ \Omega$$
$$I = \frac{E}{R_t} = \frac{100\text{ V}}{66.7\ \Omega} = 1.5\text{ A}$$

□

Example 4.3.5 Series-Parallel resistors. For the series-parallel circuit below, determine the total current I if the battery supplies 120 V, and the resistors are $R_1 = 100\ \Omega$, $R_2 = 200\ \Omega$, and $R_3 = 500\ \Omega$.



Answer. I = 0.494 A = 494 mA.

Solution. The system can be thought of as resistor R_1 in series with the parallel combination of resistors R_2 and R_3. The total resistance of this combination is

$$\begin{aligned} R_t &= R_1 + \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}} \\ &= 100 + \frac{1}{\frac{1}{200} + \frac{1}{500}} \\ &= 242.9\ \Omega \end{aligned}$$

Applying Ohm's Law with this resistance gives the current

$$I = E/R_t = \frac{120\ \text{V}}{242.9\ \Omega} = 0.494\ \text{A}$$

□

4.3.3 Wye Circuit

In a wye or star configuration, three components are connected at a common point, forming a *Y* shaped pattern. The common point is designated N for neutral, and the three power lines, designated A, B, and C, are connected to the free ends of the three components.

In three phase circuits, the voltage measured from line to line is called the **line voltage,** V_L, and the voltage measured across a component is called the **phase voltage** ,V_ϕ.The **line current**, I_L ,is the current flowing in a power line, while the **phase current**, I_ϕ, is the current flowing through a component. In a balanced system, all three line voltage are the same, as are all three line currents.

In a three-phase wye circuit,

$$V_L = \sqrt{3}V_\phi. \tag{4.3.2}$$

$$I_L = I_\phi \tag{4.3.3}$$

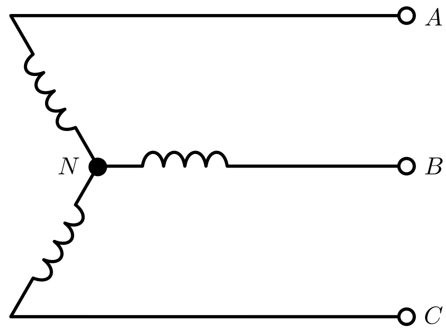


Figure 4.3.6 Three inductors, wye connected

4.3.4 Delta Circuit

In a delta configuration, three components are connected in a closed loop resembling a triangle. Each component is connected across two lines, and no neutral point is used.

In a three-phase delta circuit,

$$V_L = V_\phi. \tag{4.3.4}$$

$$I_L = \sqrt{3} I_\phi \tag{4.3.5}$$

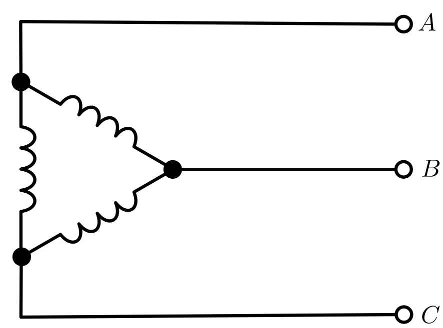


Figure 4.3.7 Three inductors, delta connected

4.3.5 Circuit Faults

Circuit faults or malfunctions can usually be grouped into one of the following categories:

An **open circuit** occurs when the conducting path has been broken, intentionally or unintentionally, stopping the flow of current. An open occurs when a switch is opened, a fuse blows or a circuit breaker trips, or when a wire breaks or becomes disconnected. The resistance of an open circuit is effectively infinite.

A **short circuit** is an unintentional low-resistance pathway between two points at different voltage levels. Shorts can occur between two points in the same circuit, or between a single point and ground.

By Ohm's law, when the resistance is small the resulting current will be large. Large short circuit currents can lead to overheating, damage, fire hazards or arc flash. Electric shock may be caused by a short circuit through the human body.

In a properly protected circuit, a circuit breaker or fuse should quickly open to interrupt the short circuit current.

Short circuits can are caused by faulty or incorrect wiring, insulation failure, and particularly by human error.

A **ground fault** occurs when an electric circuit unintentionally contacts the earth or the ship's hull. This connection allows current to return to the source through an unintended path.

Ground faults are caused by insulation failure due to age, abrasion, abuse, and especially due to moisture, either from the humidity or by direct water impingement. Salt water infiltration is a common cause of ground faults in deck equipment. When a person accidentally contacts a live wire and ground at the same time, the resulting shock is actually a ground fault.

Aboard ship, we continuously monitor for ground faults using **ground lamps** and **ground ammeters**. When a ground fault is detected the ship's engineers repair them as soon as possible to prevent bigger problems such as equipment failure.

Figure 4.3.8 Ground lamps, Ground Ammeter

Ground faults are different than short circuits because the ground fault current is usually too small to trip a circuit breaker or blow a fuse. Ground fault circuit interrupters, like those found in your bathroom at home, are designed to detect these small ground currents and quickly open to prevent electrical shock.

4.4 Electrical Equipment

Electricity is a versatile form of energy that is used for a wide range of purposes in modern society. In this chapter we introduce a few of the most important electrical equipment used aboard ship and briefly describe how they work.

4.4.1 Measuring Instruments

Here are some electric measuring instruments likely to be of interest to marine engineers.

Digital Multimeters.

A **digital multimeter** (DMM) is a versatile electronic tool that combines multiple measurement functions in one device. Most digital multimeters can measure AC and DC voltages, AC and DC currents up to a few amps, resistance, and perform continuity tests. Some meters can additionally measure capacitance, frequency, check diodes, and measure temperatures with an optional thermocouple. A good digital multimeter is a valuable tool for troubleshooting electrical and electronic devices.

Figure 4.4.1 Digital Multimeter

When using a DMM, always ensure that the test leads are correctly connected to the meter; the black lead goes in the common (COM) jack, but the red lead position depends on the measurement you intend to make. Next, select the desired measurement mode with a selector switch to configure the DMM's internal circuitry, and finally connect the test leads to the circuit and make the measurement. The DMM displays the measured values on a digital screen, showing the numerical value and unit. Some models have auto-ranging, which selects the appropriate measurement range automatically, and data hold functions to freeze the displayed value.

To measure voltage you connect the DMM probes to the circuit across two points of interest. An analog-to-digital converter (ADC) detects the voltage difference between them and converts it into a digital format which is then processed and displayed. When measuring large voltages, a potential divider circuit proportionally reduces the voltage to a suitable lower value.

To measure current, the DMM is connected in series with the circuit under test and the voltage drop across a precision internal resistor is measured to determine the current. However, to use a DMM to measure current you must disconnect and open a portion of the circuit to introduce the meter. For this reason, DMMs are rarely used for current measurement.

Resistance measurement involves applying a stabilized voltage from the meter's battery to the component being tested and measuring the resulting current. Using the applied voltage and measured current, the DMM calculates the resistance.

A continuity test is just a resistance measurement used to determine if two points are electrically connected. Often the meter will produce an audible "beep" if the resistance is below a threshold value of 50-100 ohms.

Voltage testers.

Voltage testers are simple and rugged tools used to quickly check whether voltage is present or absent. They should always be proven on a known live voltage source *before* and *after* making voltage tests for lock-out/tag-out purposes.

Figure 4.4.2 Voltage Tester "Wiggy"

Clamp-on ammeters.

Clamp-on ammeters are hand-held instruments used to measure AC currents. A plier-like pick-up coil is closed around the conductor in which current is to be measured, and the movement responds to current induced in the pick-up coil by the changing magnetic field surrounding the conductor. Clamp-on meters are preferable to digital multimeters for measuring currents because the don't require the circuit to be disturbed to use, and they can measure larger currents than a DMM, however, because they depend on a changing magnetic field they do not work with DC currents.

Figure 4.4.3 Clamp-on ammeter

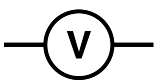
Megohmmeters.

A **Megohmmeter** or **megger** is a electrical meter specifically designed to measure very large resistances, particularly the resistance of electric insulation, resistance which is too large to be measured accurately with a DMM. It consists of an internal high voltage source (up to 1000 V), an accurate ammeter, and a display scale marked in megohms.

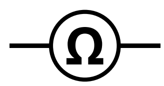
Figure 4.4.4 Megohmmeter

Before use, the equipment under test must be secured, locked out, and grounded to discharge any residual capacitive static charge. The meter is connected between an insulated conductor and ground, and then the test voltage is applied for 60 seconds or until the resistance reading stops changing, whichever comes first. The meter measures the current flow through the insulation, and using ohm's law, calculates and displays the insulation resistance.

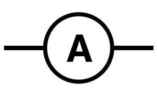
Symbols.



Voltmeter



Ohmmeter



Ammeter

4.4.2 Batteries

Batteries are electro-chemical, direct-current power supplies. Batteries store and deliver electrical energy through a chemical reaction. Batteries consist of several electro-chemical **cells**, each containing an **anode**, **cathode**, and **electrolyte**.

When connected to a circuit, the anode releases electrons into the external circuit, while the cathode absorbs them, generating an electrical current. Each cell creates around 1.5 volts depending on the battery chemistry.

The chemical energy stored in a battery is finite, and is measured as its **ampere-hour capacity**. As current is drawn from the battery the chemical energy is depleted, at which time the battery must be replaced or when possible, recharged.

Wet cell batteries contain a *liquid* electrolyte that is typically a mixture of water and sulfuric acid. **Lead-acid** batteries are the most common type of wet cell. Wet-cell batteries are used where large power capacity is required, such as for uninterruptible power supplies and for starting small engines.

Dry cell batteries contain an electrolyte in a solid, semi-solid, or gel-like state. **Alkaline**, **nickel-cadmium** (Nicad), **lithium-ion**, and **nickel-metal hydride** batteries are all dry cells. Dry cells are commonly used for low-power purposes, such as flashlights and portable equipment.

The state of charge of a battery usually cannot be determined easily or accurately. For lead-acid batteries the approximate charge is determined by measuring the density of the electrolyte with a hydrometer, while the approximate charge of the Nicad batteries is determined by measuring the cell voltage.

4.4.3 AC Generators

A synchronous generator is a device that converts mechanical energy into electrical energy by utilizing the principle of **electromagnetic induction**.

According to Faraday's law of electromagnetic induction, a moving or changing magnetic field induces an electric voltage in a nearby conductor. If the conductor forms a closed loop, an electric current will flow and electrical power will be transmitted.

An electrical generator consists of two main *mechanical* components: a rotating part called the **rotor** and a stationary part called the **stator**, and two main *electrical* components: the **armature** and the **field**.

Both the armature and the field are made of a conducting material, usually copper wire, wound into multi-loop coils called **windings**. The rotor is connected to a prime mover, such as a steam turbine or a diesel engine which supplies the mechanical energy to the generator.

The **field windings** are like an electromagnet. When direct current (DC) flows through the field windings, a magnetic field is created similar to the one which surrounds the north and south poles of an ordinary magnet, but adjustable. The strength of the field is controlled by the amount of the field current. The process of supplying electrical current to the field winding is known as **excitation**.

The **armature windings** are the part of the generator where the voltage is induced. The armature consists of several individual windings connected in a specific configuration. The end points of the armature windings are called the generator **terminals**. As long as the generator is spinning, the field will induce a sinusoidal AC voltage into the armature windings. The armature windings deliver power to the terminals and thence to the load circuit.

In a typical AC synchronous generator, the rotor carries the field windings and the stator carries the armature windings, however the opposite arrangement is also possible.

Single-phase generator. The diagram below shows a simplified AC, single-phase synchronous generator, illustrating the rotor, stator, armature and field.

A prime mover such as an engine or turbine spins the rotor and supplies the input mechanical energy. The rotor carries an externally energized electromagnet (the field) which creates a magnetic field. The rotor is surrounded by the stator, which carries multiple turns of copper windings, (the stationary armature). The ends of the armature windings are the generator terminals; the external circuit begins and ends there.

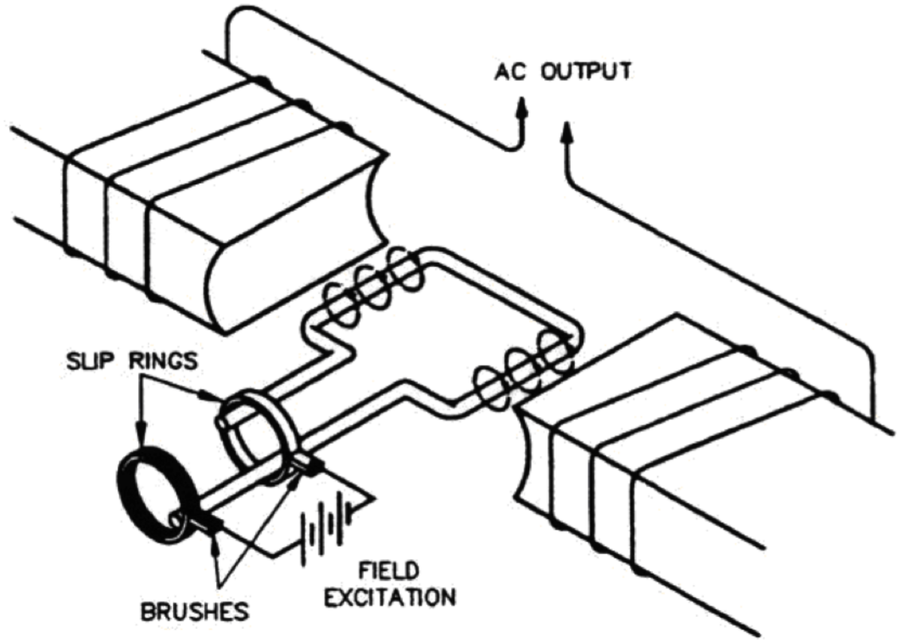


Figure 4.4.5 Simplified single-phase AC generator

As the rotating magnetic field passes by the stationary armature, a voltage is induced in the armature. This voltage varies in magnitude and direction sinusoidally, as shown in Figure 4.1.6.

The frequency is related to the rotor rpm according to this relation:

$$f = \frac{120 \times N}{2 \times 60}$$

where f is the frequency in Hz and N is the total number of poles.

For a two-pole field (one north and one south pole) rotating at 3600 rpm, the voltage will alternate through 60 cycles each second i.e. 360 Hz. With a four-pole field, the north and south poles will pass by the armature windings twice per rotation. As a result, a four-pole generator will produce the same frequency as a two-pole generator while spinning at half the speed.

Although the voltage continuously varies from instant to instant, we represent the sine wave voltage using its RMS average.The RMS voltage is proportional to the speed of rotation and also the strength of the magnetic field, therefore the generator output voltage can be adjusted by controlling the current that creates the field.

Three-phase generator. To generate three-phase power, the stator is fitted with three armature windings arranged symmetrically, 120 degrees apart from each other. The three windings are connected together with the common point designated **neutral**.

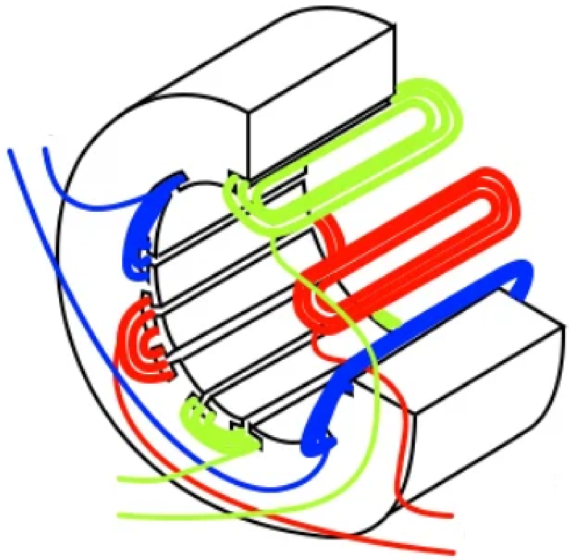


Figure 4.4.6 Three-phase generator stator, showing three individual armature windings.

As the rotor rotates, the rotating magnetic field induces voltages into each stator winding in turn, generating three sine waves of voltage, equally spaced, shown below.

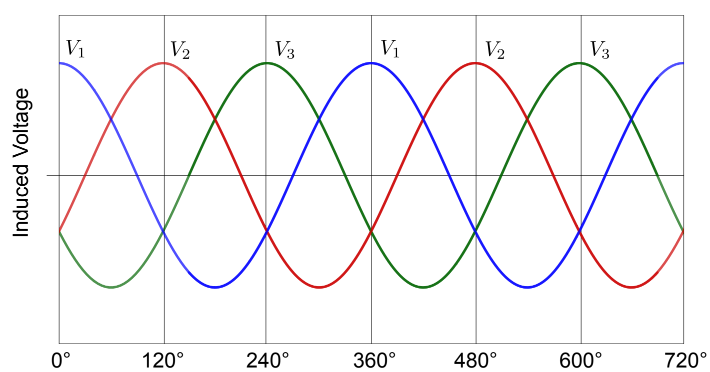


Figure 4.4.7 Three-phase AC Voltage

4.4.4 Induction Motors

Although there are dozens of different types of motors, the most important type of motor for industrial applications, by far, is the **induction motor**.

Induction motors have many advantages over other designs. First they are simple, rugged, reliable and require very little maintenance. Induction motors are relatively cost-effective to manufacture, and are widely available in a broad size range, for all common single and three-phase voltages. The can be quite efficient, especially at full load. Modern designs and technologies, such as variable frequency drives (VFDs), contribute to improved efficiency allow precise control of motor speed and performance.

Induction motors are the subject of this section.

A three-phase **induction motor** sometimes called a **squirrel-cage motor**, is a type of electric motor that operates based on the principles of electromagnetic induction.

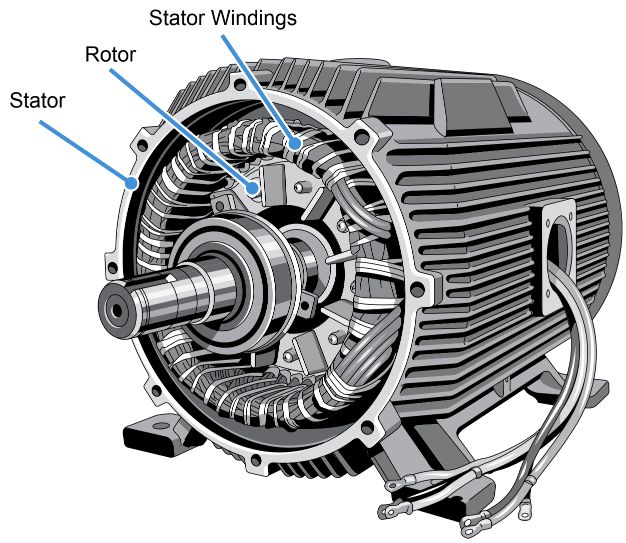
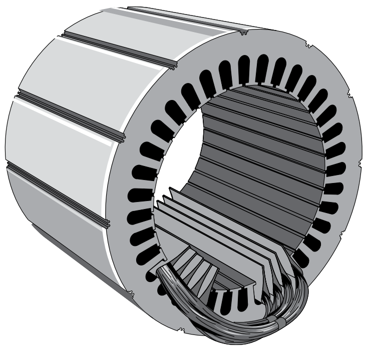
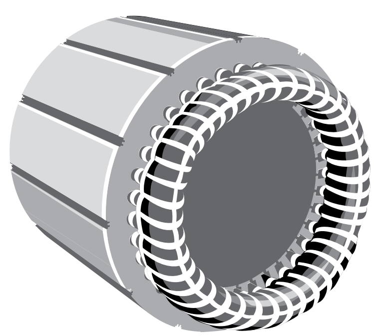


Figure 4.4.8 Three-phases Induction Motor

The stator carries three identical sets of **phase windings** placed 120 degrees apart in a symmetrical pattern and connected in wye.. The specific pattern of the windings determines the number of magnetic poles. Small motors typically have two or four poles per phase, but the ship's propulsion motors have ten poles per phase.



(a) Partially Wound



(b) Complete

Figure 4.4.9 Stator Windings

When three-phase AC power is applied to the stator windings, a **rotating magnetic field** develops rotating at the **synchronous speed**.

The synchronous speed is determined by the frequency of the power supply and the number of motor poles.

$$n_s = \frac{120f}{P}$$

Where:

n_s is the synchronous speed in revolutions per minute (RPM).

f is the frequency of the power supply in hertz (Hz).

P is the number of magnetic poles per phase.

Synchronous speed represents the speed the motor will spin under no load conditions.

The **rotor** is typically made of a laminated iron core with conductive bars embedded within it. The bars are shorted at the ends, to form closed loop **rotor windings**.

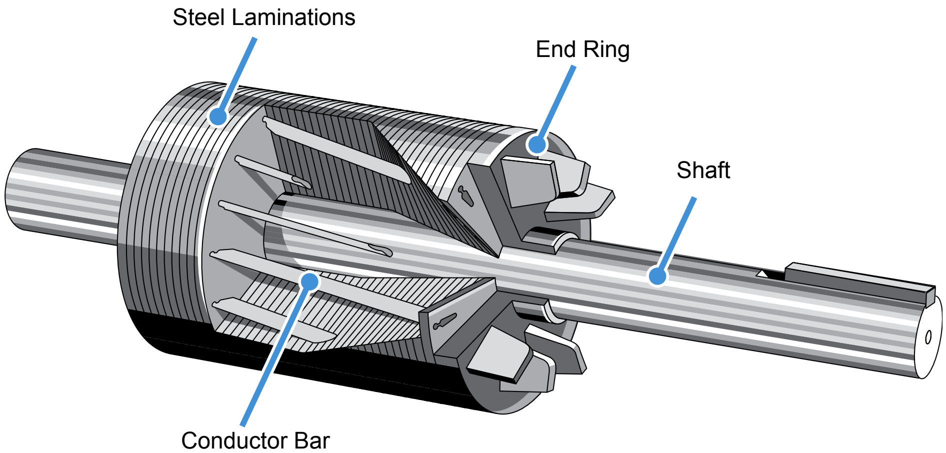


Figure 4.4.10 Rotor Cutaway Diagram

As the rotating magnetic field passes over the rotor windings, it induces a voltage, according to Faraday's law of electromagnetic induction. This voltage drives a current through the rotor windings, which, in turn, generates a magnetic field surrounding the rotor windings.

The magnetic field of the rotor interacts with the rotating magnetic field of the stator and magnetic attraction pulls the rotor in the same direction as the rotating magnetic field. As the rotor rotates, it tries to catch up with the rotating magnetic field.

However, the mechanical load on the motor retards the shaft, so the rotor speed n, always remains slightly less than the synchronous speed, n_s. The difference between the synchronous speed and the actual

operating speed is called **slip**, often expressed as a percentage of the synchronous speed

$$\%\text{ slip} = \left(\frac{n_s - n}{n_s}\right) \times 100\%.$$

The difference in speed between the rotating magnetic field and the rotor's rotational speed induces the current, torque, and power that drives the load connected to the motor shaft. Slip is required for the motor to generate torque and perform useful work.

The mechanical power produced by a motor can be calculated using the formula:

$$P = \tau\omega$$

Where:

P is the shaft power in Watt (W).

τ is torque or twisting force generated by the motor, measured in Newton-meters (Nm).

ω is the angular velocity of the motor in radians per second (rad/s). Angular velocity is equal to the shaft rpm $\times \frac{2\pi}{60}$.

In practical applications, mechanical power can also be expressed in other units such as kilowatts (kW), Horsepower (HP), or foot-pounds per minute (ft-lb/min).

An increase in load on the motor causes the shaft to slow down slightly, which increases both slip and torque. The power output of the motor automatically adjusts to match the requirements of the load.

Although the motor always has some slip, the rotor speed is generally close to the synchronous speed. For a motor with a fixed number of poles, the rotor speed can be changed by changing the frequency of the power supply with a variable speed drive or a frequency converter.

Although most large motors aboard ship are supplied with three-phase power, smaller motors, such as those driving appliances, must operate from single-phase circuits. **Single-phase motors** are most often arranged with two sets of stator windings, with the second set supplied from the line connections through a **capacitor**. The capacitor imposes a phase shift on the line current reaching these windings, to make it look like two-phase AC current. The stator is thus able to develop a rotating magnetic field to drive a rotor.

4.4.5 Variable Frequency Drives

A **Variable Frequency Drive** (VFD) is an electronic device used to control the speed and direction of an electric motor by adjusting the frequency and voltage of the power supplied to the motor. VFDs are commonly used in industrial and commercial applications to achieve energy efficiency, process control, and improved motor performance.

A basic variable frequency drive has three main components:

1. The **Diode Front End** which takes in an AC power supply from the mains and converts it into DC power using a three-phase rectifier.

2. The **DC Capacitor** The rectified power is stored in a large capacitor, which acts as a buffer to provide a stable DC voltage to the DC Bus.

3. The **Inverter** The inverter is responsible for converting the DC power back into AC power with variable voltage and frequency. This stage utilizes power electronic devices, such as **insulated gate bipolar transistors** (**IGBTs**), to switch the DC voltage in a controlled manner.

   To synthesize the desired AC waveform, the VFD uses a technique called **Pulse Width Modulation** (**PWM**). PWM involves rapidly switching the IGBTs on and off to create a series of voltage pulses with varying widths. By adjusting the width of these pulses, the VFD can control the effective voltage and frequency of the output AC waveform.

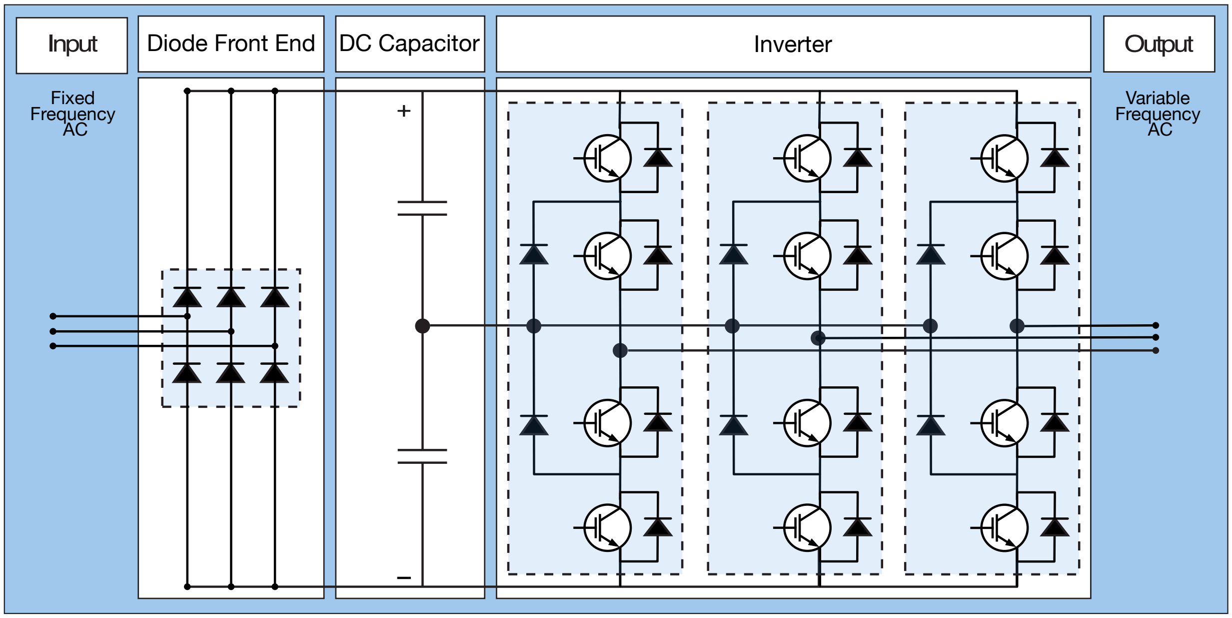


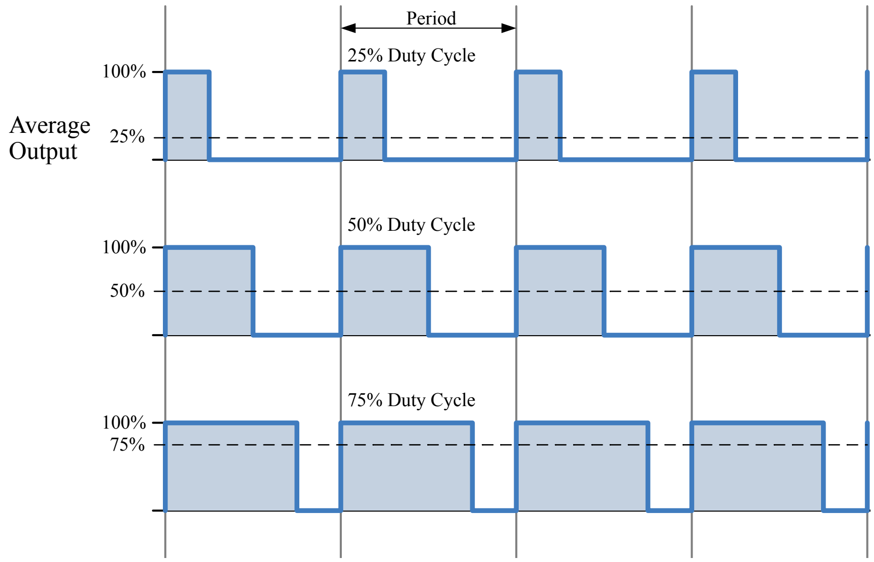
Figure 4.4.11 Main Components of a VFD

By regulating the voltage and frequency supplied to the motor, a VFD allows for precise control of motor speed and torque. This enables energy savings, improved motor performance, and enhanced control in various applications, such as industrial machinery, HVAC systems, and electric vehicle drives.

What is Pulse Width Modulation?

Pulse Width Modulation (**PWM**) is a technique used in electronics to control the average value of a signal. PWM works by rapidly turning a signal (usually a square wave) on and off. The overall effect is that the signal appears to have varying average voltage or power, depending on the width of the *on* or *high* portion of the signal.

The **duty cycle** is a parameter of PWM that represents the percentage of time the signal is on or at a high level compared to the **period** — the time to complete one cycle. It determines the average value of the signal. A duty cycle of 50% means the signal is on for half the time and off for the other half, resulting in an average voltage or power that is halfway between the high and low levels. By changing the duty cycle, the average value of the signal can be controlled. Increasing the duty cycle increases the average value, while decreasing the duty cycle decreases the average value.

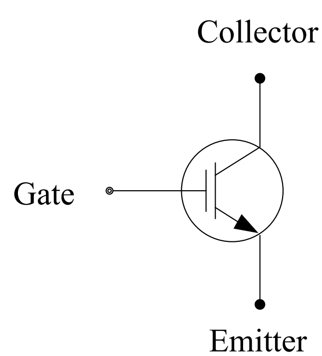


PWM requires a control signal that determines the desired average value. This control signal could come from a microcontroller, analog circuit, or other control systems.

The PWM signal is often passed through a low-pass filter. The filter averages out the rapid switching of the signal, resulting in a smoother output signal with the desired average value.

What is an IGBT?

An **IGBT** (**Insulated Gate Bipolar Transistor**) is a power semiconductor device that combines the characteristics of a MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) and a bipolar junction transistor (BJT). IGBTs are known for their high voltage and current handling capabilities, low conduction losses, and fast switching speeds. IGBTs can rapidly switch on and off in the range of microseconds to a few tens of nanoseconds. They are widely used in high-power electronic applications, such as motor drives, power converters, and inverters.



The operation of an IGBT involves three main states:

Off State When no voltage is applied to the gate, the IGBT is in an off state, and only a small leakage current flows from the collector to the emitter. It behaves like an open switch or closed valve.

On State When full voltage is applied to the gate with respect to the emitter, current freely flows from the collector to the emitter. This is the on state of the IGBT, and it can conduct high currents like a closed switch.

Control State The IGBT can be controlled by applying a variable voltage to the gate. When a positive voltage is applied, it turns on the IGBT, allowing current flow. By adjusting the gate voltage, the IGBT can regulate the current flow.

4.4.6 Motor Controllers

Motor controllers electromechanical devices that control the operation of electric motors, and allow them to be operated manually, by automation or both.

Motor controllers come in various types and forms, ranging from simple relay-based control systems to complex microcontroller-based systems. The choice of motor controller depends on factors such as the specific application requirements, the types of motors being used, and the desired levels of control sophistication.

Motor controllers usually provide three basic functions: starting, stopping, and motor protection. The controller monitors the motor circuit and will secure the motor if it detects common faults such as overload, short circuits, or low voltage conditions.

Additional functions such as direction control, speed control, regenerative braking, and reduced voltage (soft) starting, can be added to the control circuitry when required by the application. Many modern motor controllers also provide diagnostic information and feedback about motor performances, temperatures, and statuses. This information helps with troubleshooting and preventive maintenance.

Next, we will describe the operation of one simple and common motor controller: an **across-the-line** starter. It is given this name because the controller connects the motor's stator windings directly across the power lines and starts it using full line voltage. This type of motor controller is very common, and is worth studying as its basic control circuit is the foundation of many other devices.

The power and control circuits for an across-the-line starter are shown in Figure 4.4.12. The circuit consists of two parts: the three-phase power circuit (blue) , which connects the power supply, entering from the left, to the motor, and the single-phase control circuit (black) which is responsible for the control functions.

The power circuit consists of a circuit breaker (1), three main contacts (2), three overload sensors (3), and connections to the motor (4). The control circuit consists of two control fuses (5), start (6) and stop (7) buttons, an auxiliary relay, (8), the contactor operating coil (9), and normally closed overload relay contacts (10).

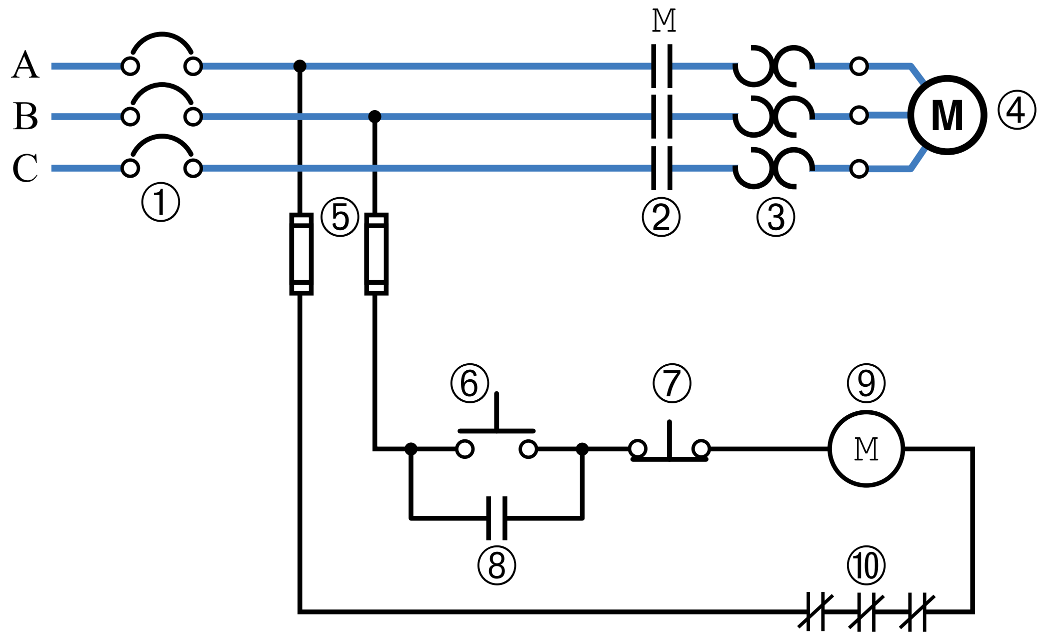


Figure 4.4.12 Across-the-line starter

The operation is as follows:

1. The **start button** is a momentary push-to-close switch. When it is closed, it completes the control circuit, and energizes the main operating coil.

2. The **main operating coil** is part of the **contactor** assembly[1]. When the main operating coil energizes it closes three **main contacts** in the power circuit and the **auxiliary contact** in the control circuit.

3. Closing the main contacts completes the circuit between the power supply and the motor, allowing current to flow directly to the motor's terminals and start the motor.

   Since the auxiliary contact is wired in parallel with the start button, after it closes the start button may be released and the motor will continue to operate. For this reason, the auxiliary contact is sometimes called the **latch** contact.

4. The motor will continue to run until one of the following happens:

   - The **stop button** is pressed. This breaks the control circuit and de-energizes the main coil. This causes the main and auxiliary contacts to open and stop the motor.
   - One of the three **overload sensors** detects the motor drawing high current. This opens the corresponding **overload contact** in the control circuit and stops the motor.
   - A **short circuit** is detected by the **circuit breaker**, tripping it. This secures power to both the power and control circuits and stops the motor. Fuses will de-energize the control circuit if a short occurs there.

[1]The contactor assembly consists of the coil (9), and contacts (2), and (8). When the coil is de-energized, the contacts are held open by a spring. When it is energized, the coil closes the contacts electromagnetically.

- A **low voltage condition** occurs when the supply voltage drops below about 90% of its nominal value. If this happens, the current through the operating coil decreases, causing its electromagnet to weaken enough to release the main contacts, which stops the motor. If the voltage returns to normal, the motor will remain stopped until the start button is pressed again.

A motor which does not restart after a power failure is described as having **Low Voltage Protection** (LVP). The alternate behavior, where the motor automatically restarts after a power failure is called **Low Voltage Release** (LVR). Critical machinery such as the steering gear and lube oil pumps have LVR, while other machines have LVP.

Because across-the-line starters provide full voltage to the motor from the start, the motor experiences a high starting current. This initial surge of current is called the **inrush current**, and it can be several times the motor's full-load operating current. This problem is more acute for large motors.

Large starting current has two negative effects. First, the high current in the windings can generate enough heat to damage the motor over time, especially if the driven load accelerates slowly. Second, very high starting current can draw down line voltage sufficiently to cause lights to dim and other equipment being supplied from the same line to malfunction.

To reduce the starting currents of large motors, several methods are employed.

- **Wye-delta starters** initially connect the motor to the power supply using a wye connection, which provides only 57% of normal voltage. After a configurable time delay, the connection switches to delta, and full line voltage is available for normal operation.

- **Autotransformer starters** operate similarly but can supply more intermediate voltage steps.

- **Soft starters** and **variable frequency drives**, which are electronic devices, gradually increase the voltage, effectively limiting the starting current.

4.4.7 Transformers

A transformer is an electrical device that uses electromagnetic induction to increase (step-up) or decrease (step-down) AC voltages. Transformers are simple, efficient, have no moving parts, are easily maintained.

A simple single-phase transformer consists of two wire coils, called the **primary** and **secondary** windings, wound around a common **magnetic core**. The core is made of laminated soft iron sheets or other materials that have high magnetic permeability, to enhance the magnetic coupling between the windings. An AC source voltage is supplied to the primary winding, and the electrical load is connected to the secondary winding.

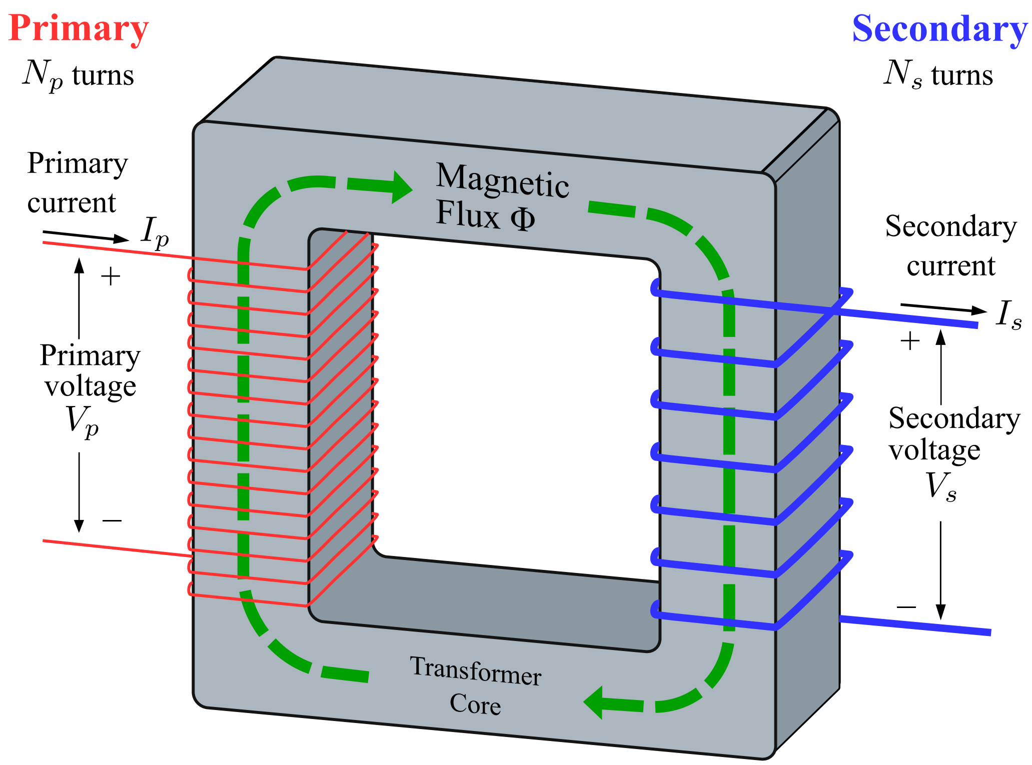


Figure 4.4.13 Transformer terminology

When alternating current flows through the primary winding, it generates an alternating magnetic field in the magnetic core. This changing magnetic field, in turn, induces a voltage in the secondary winding through electromagnetic induction. If the secondary winding has more **turns** than the primary winding, the secondary voltage will be higher than the input voltage and the transformer is referred to as a **step-up** transformer. Conversely, if the secondary winding has fewer turns than the primary winding the secondary voltage will be less than the primary voltage, and the transformer is a **step-down** transformer.

A transformer does not add any power to the electrical circuits only changes its form. Because electrical power is proportional to the product of current and voltage, when the voltage steps up, the current must step down.

The relationships between the ratios of primary and secondary voltages, currents and turns are as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \tag{4.4.1}$$

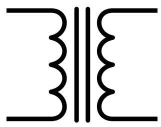
$$\frac{I_s}{I_p} = \frac{N_p}{N_s}. \tag{4.4.2}$$

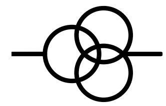
Note that when the turns ratio is greater than one, the voltage steps up and the current steps down.

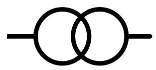
Beyond voltage transformation, transformers also furnish electrical isolation between primary and secondary circuits, creating physical and electrical separation while maintaining energy transfer.

Three-phase transformers can be made using three single-phase transformers, with the primary and secondary windings connected in wye or delta depending on the application.

Symbols.


Transformer


Three-Phase Transformer


Single Phase Transformer

4.4.8 Solenoids

A **solenoid** is an electromechanical device that consists of a coil of wire wound around a cylindrical core. When electric current passes through the wire coil, it generates a magnetic field around the coil. This controllable magnetic field is used to produce various effects.

Solenoids are used in various applications, such as in relays, solenoid valves, actuators, etc. Solenoid operated device contain an **armature**, which is a movable part placed near the solenoid coil that responds to the magnetic field generated by the current flowing through the coil and produces mechanical motion.

For example, electromagnetic relays control the switching of electric circuits. When the solenoid coil is energized, it generates a magnetic field that can either attract or repel the movable armature to open or close a contact. When the coil is de-energized a spring restores the contact to its normal position.

4.4.9 Electrical Distribution System

A shipboard electrical distribution system controls and distributes electrical power from the ship's generators to the electrical consumers around the ship.

Ships typically use 460 volt, 60 Hz, three-phase AC for major electrical machinery, and 120 volt, 60 Hz, single-phase for lights, receptacles, and small motors. These are considered Low Voltage (LV) systems, although even 120 volts can be dangerous.

High voltage (above 1 kV) is used for very large motors, 400 kW or greater, such as propulsion motors, and thrusters. Marine HV systems typically operate at 3.3 kV or 6.6 kV or 11 kV.

The advantage of higher voltages is that for a given power, higher voltage means lower current. (Recall (4.1.5)) Reduced current means that smaller diameter conductors can be used, the machine will be physically smaller and thus cheaper, and the machine will be more efficient because it will have smaller I^2R losses. (Recall (4.1.3))An extremely simplified representation of the *Patriot State II* electrical distribution system is shown in Figure 4.4.14. This diagram represents only about half the distribution system and only shows the portion of the system which is supplied from the after engine room.

The main components of the distribution system are:

Power supply. The **ship's service generators** are the primary source of electrical power for the vessel.

There are four ship's service generators on the training ship; generators one and two are located in the forward engine room, and three and four are located in the after engine room. Each can supply

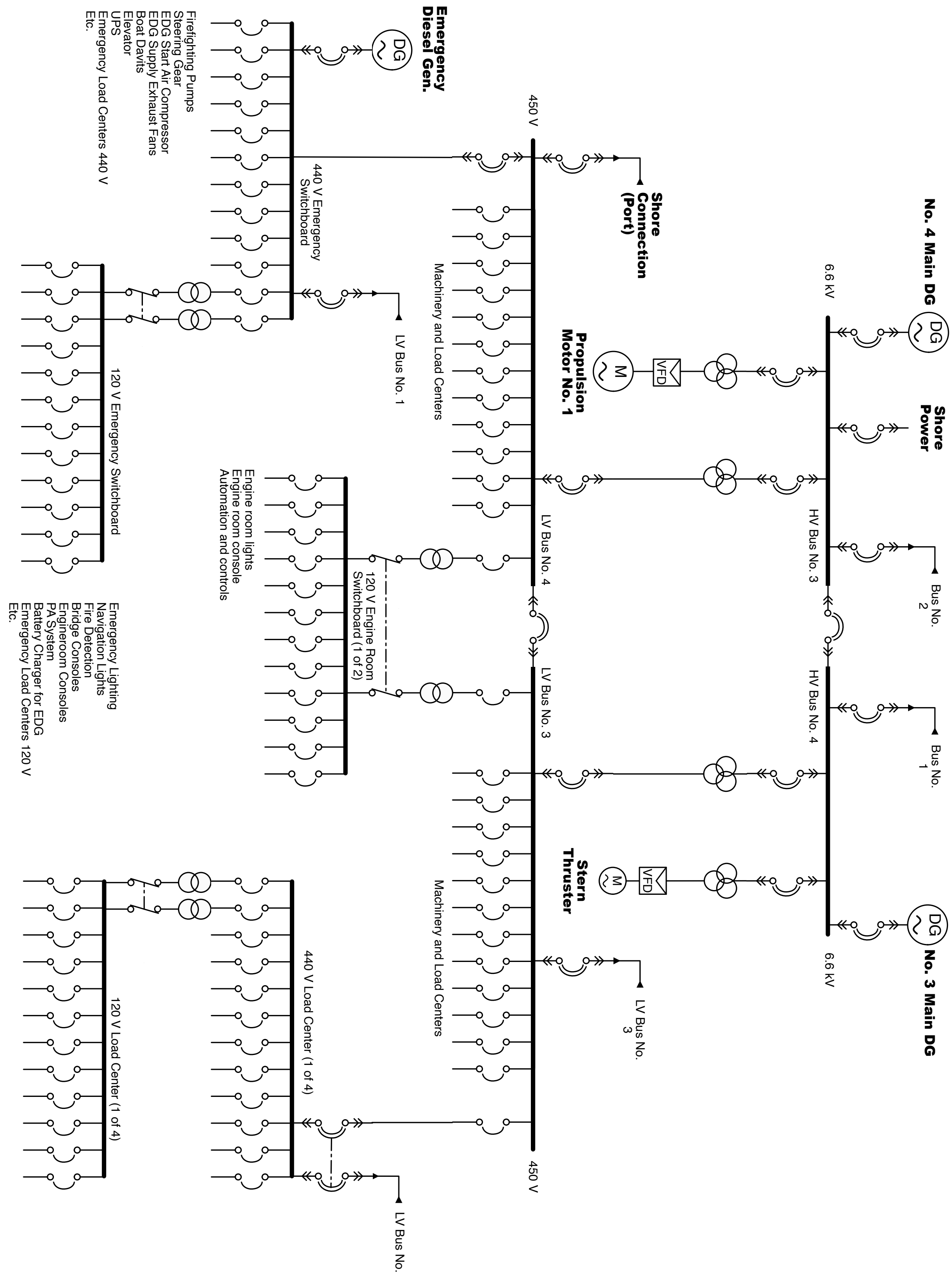


Figure 4.4.14 NSMV Electrical Distribution (simplified)

443 A of 6.6 kV, three-phase, 60 Hz AC. The ship's service generators are discussed in more detail in Section 8.2.

A backup **emergency generator** is provided for use in the event of failure of the ship's service generators or other emergency. By regulation the emergency generator must be able to start when the ship has a list of up to 22.5 °, must come on-line automatically within 45 seconds of a power failure, and must supply power for up to 18 hours.

On the training ship, a 500 kW emergency generator is located just forward of the stack on the weather deck (05 level). The capacity of the emergency generator is less than the ship's service generators, so when operating it can only supply a limited subset of the ship's equipment.

A UPS, or **uninterruptible power supply**, is a battery-powered system that provides temporary power after a blackout but before the emergency generator comes on line. UPSs can either supply DC power directly from the batteries, or supply AC by converting the DC battery output to alternating current using an electronic **inverter**. UPSs primarily supply power to vital control systems and the emergency light.

A 440 V **shore power** connection is provided to supply electrical power to the ship when alongside or in the shipyard when it would be undesirable to operate the ship's generators.

Switchboards and Load centers. A **switchboard** is an electrical enclosure containing the equipment that monitors, controls, protects, and distributes electrical power. It divides the electrical system into separate circuits and provides a central point from which electrical power can be managed and routed to different areas or equipment.

Within the switchboard, electrical current is carried by a **bus** or **bus bar**, not by wires or cables. In an electrical system, a bus refers to a conducting bar or strip that serves as a common connection point for multiple electrical circuits. It's like a highway for electrical current to flow to different destinations. Buses are typically made of copper must have sufficient cross-sectional area to handle the required current.

The training ship has two high voltage main switchboards (HVMSB); Switchboard one is located in the forward engine room, and switchboard two is the after engine room. Each switchboard is divided into two connected buses: Switchboard one contains buses one and two, switchboard two contains buses three and four. The buses are interconnected with circuit breakers to permit the power to be re-routed in an emergency.

The bus bars are connected through circuit breakers to directly supply to some of the major electrical consumers, and also supply **load centers**. Load centers are smaller switchboard or electrical panels located around the ship that contain their own bus and further distribute power to smaller, nearby electrical consumers. Load centers may also be called *group-control centers*, *distribution boards*, or *power panels*.

The NSMV power distribution system consists of the following:

- 2 **HV switchboards** (6.6kV) Supply power to the propulsion motors, bow and stern thrusters, and supply the low voltage switchboards.

- 2 **LV switchboards** (450V) Primarily supply the engine room machinery, and also lower voltage load centers and distribution boards.

- 1 **Emergency switchboard** (450/120V). This switchboard normally powered by the LV switchboard, but in the event of a power failure will be isolated and powered by the emergency generator.

- 4 **LV load center panels** (440V) Supply power to other machinery, including the galley and laundry equipment, and downstream distribution boards.
- 4 **120 V load center panels** (120V) Supply power to 120 V distribution boards, including galley and laundry.
- 3 **Emergency load center panels** (440V) Provide power to vital 440 volt loads.
- 3 **Emergency load center panels** (120V) Provide power to vital 120 volt loads,
- 16 **Distribution boards** (440V) Provide power to non-vital 440 volt loads.
- 18 **Distribution boards** (120/240V) Provide power to non-vital 120 and 240 volt loads,
- 24 **Lighting distribution boards** (120V), provide the majority of ship's lighting and outlets.
- 13 **Emergency Lighting distribution boards** (120V), supply the "E" lights which sufficient lighting to safely evacuate the ship in an emergency.

Transformers. As discussed in Subsection 4.4.7, transformers are devices that can step-up or step down AC voltage.

In the electrical distribution system, four three-phase transformers are used to drop the 6,600 volts on the HV bus to the 450 volts required on the LV bus, and four are used to supply the correct voltages to the two propulsion motors, the bow thruster, and the stern thruster.

Single-phase 440/120 volt transformers are used to supply the 120 volt lighting and distribution panels.

Protective Equipment. The distribution system is fully equipped with monitoring and metering instrumentation to measures electrical parameters like voltage, current, frequency, power factor, and electrical load, and monitors the system for ground faults. This information helps in managing the electrical system operation and identifying potential issues.

Each distribution branch is protected by multiple circuit breakers that protect the system from overloads, short circuits, and other faults. The circuit breakers are **coordinated** so that when a fault occurs, the circuit breaker closest to the fault trips, interrupting the flow of current to the fault area while minimizing disruption to the remainder of the system.

Power Management System. The electrical system aboard the training vessel is fully automated by a **Power Management System** (PMS).

The main purpose of the PMS is to ensure that there is always a sufficient power reserve available for the essential services of the vessel. The system continuously monitors the generators and the electrical loads, and automatically starts and stops generators to match electrical power generation to the ship's needs.

During critical times when energy demand is exceptionally high or during emergencies, the power management system can shed or temporarily drop non-essential loads. This ensures that essential equipment and services receive power while minimizing strain on the electrical system.

Chapter 5

Piping Systems

A **Piping System** is a network of pipe or tubing, pumps, valves, tanks and other components connected together to form a complete system for transferring, storing, and processing fluids. Piping systems are ubiquitous aboard the ship as well as in residential, industrial, and infrastructure applications.

A **Piping and Instrumentation Diagram** (P&ID) is a schematic diagram that that uses symbols to show the components of a piping system and how the are connected together. P&IDs are used for design and construction of the the system, and they provide a big picture view to help engineers understand, operate, and troubleshoot the system.

5.1 Pipe and Tubes

In industry, pipe and tube are nearly interchangeable terms. Both describe long hollow cylinders of uniform material with a certain amount of rigidity and permanence.

Pipes are primarily used for fluid transport and are almost always cylindrical. Generally, pipe and pipe fittings are sized in terms of a **Nominal Pipe Size** (NPS) or Nominal Diameter (DN), which corresponds to the approximate **inside diameter** (ID). The internal diameter is the critical dimension for fluid flow, since it is needed to calculate pipe capacity, flow rates, and frictional losses. Additionally, pipes must have sufficient **wall thickness** to handle the expected internal pressure. Pipes have somewhat lenient tolerances, and may have variations in wall thickness along their length.

Tubes, like pipes, are used for fluid transport, but also for other applications, particularly for fabricating structures. (For example, scaffolding and bike frames.) Pipes are rigid and resistant to bending but some tubes such as copper and plastic tubes are flexible enough to be easily bent.

Tubes are available with various cross-sections, including round, square, rectangular, or oval. They usually have thinner walls than pipe, making them lighter but less capable of handling high internal pressures. They are often chosen for applications where weight is a consideration.

Tubes are sized based on their exact *outside* dimensions and wall thickness. Tubes are manufactured with tighter tolerances than pipe, resulting in more precise dimensions and wall thickness consistency.

Hoses are also used for fluid transport, but hoses are typically more portable and flexible, and are made up of multiple layers of different materials.

5.1.1 Pipe Materials

Pipe and tube are manufactured using various materials. The choice depends on factors such as the fluid being transported, temperature and pressure conditions, corrosion considerations, cost, USCG and ABS regulations

Here are few of the materials used in shipboard piping systems.

Welded carbon steel tubing is used for water, steam, and oil lines where the maximum temperature is below 450° F. There are several varieties of carbon steel and it is relatively cost-effective.

Seamless carbon steel tubing is used in oil, steam, and feed water lines operating up to 775° F.

Seamless carbon-molybdenum and **chromium-molybdenum alloy** steel tubing are used for high temperature, high pressure systems, up to 1500 psig and 1050° F for chrome-moly

Copper-nickel alloy tubing and **Seamless brass tubing** are both widely used in low pressure systems which must resist the corrosive action of salt water

Nickel alloys, such as **Monel** and **Inconel**. These are two families of high-performance alloys known for their exceptional resistance to corrosion, high temperatures, and various harsh environments.

Seamless copper tubing is used for refrigeration lines, plumbing and heating systems, lubrication systems, and other shipboard systems.

Seamless aluminum tubing is used for dry lines in sprinkling systems and for some bilge and sanitary drain systems.

Stainless steel tubing has excellent strength and corrosion resistance. It is often used in hydraulic systems.

Black iron pipe is an informal name for a mild-steel pipe that is used with threaded fittings for easy assembly of low pressure piping systems. It is susceptible to galvanic corrosion, especially when it comes in contact with other materials in a salt water environment.

5.1.2 Pipe Size

Pipe sizes in the United States are specified by two numbers: The **Nominal Pipe Size** (NPS) in inches and the **Schedule** (Sch.) number. The European (ISO) equivalent designation is the ***diamètre nominal*** (DN), where the diameter is given in millimeters.

In engineering a **nominal** value is a quantity used for the *name* of an object. Nominal values are usually close to, but not the same as, the actual value. For example a 2×4 is the name of a piece of lumber with finished dimensions closer to 1-1/2 inches by 3-1/2 inches. A 120 Volt outlet may provide anywhere between 114 V and 126 V. Nominal values are a convenient shorthand; a rounded figure easy to use and remember.

The NPS is *approximately* equal to the *inside* diameter of the pipe for nominal pipe sizes up to 12 inches; above 12 inches, the nominal pipe size is equal to the outside diameter. Nominal dimensions are used in order to simplify the standardization of pipe fittings and pipe taps and threading dies. Pipe fittings with and pipe with the same nominal size are compatible.

Pipe schedule describes the wall thickness of pipes. There are eleven standard Schedule numbers: 5, 10, 20, 30, 40, 60, 80, 100, 120, 140, and 160, with higher numbers indicating thicker walls. The most common sizes found aboard ship are Schedule 40, sometimes called **standard weight**, and Schedule 80. Schedule 40 is the lightest weight used for steam applications. Schedule 40 and 80 pipes are available in the full range of nominal sizes from 1/8 inch to 48 inch. Other schedules are more limited.

As the schedule number increases, the pipe wall thickness increases, the inside diameter (**bore**) decreases and the pressure rating of the pipe increases, so for example a 1 inch Schedule 40 pipe which has an outside diameter of 1.315 inches and a wall thickness of 0.133 inches, has a bore of 1.049 inches, while a similar 1 inch Schedule 80 pipe has the same outside diameter, but a wall thickness of 0.179 inches giving a bore of 0.957 inch

Table 5.1.1 NPS Pipe Schedule - Wall thickness in inches. ASME B36.10

NPS	OD Inch.	Sch. 5	Sch. 10	Sch. 40	Sch. 80	Sch. 160
1/8	0.405	.035	.049	.068	.095	
1/4	0.54	.049	.065	.088	.119	
3/8	0.675	.049	.065	.091	.126	
1/2	0.84	.065	.083	.109	.147	.187
3/4	1.05	.065	.083	.113	.154	.218
1	1.315	.065	.109	.133	.179	.250
1-1/4	1.66	.065	.109	.140	.191	.250
1-1/2	1.9	.065	.109	.145	.200	.281
2	2.375	.065	.109	.154	.218	.343
2-1/2	2.875	.083	.120	.203	.276	.375
3	3.5	.083	.120	.216	.300	.437
3-1/2	4	.083	.120	.226	.318	
4	4.5	.083	.120	.237	.337	.531
5	5.563	.109	.134	.258	.375	.625
6	6.625	.109	.134	.280	.432	.718
8	8.625	.109	.148	.322	.500	.906
10	10.75	.134	.165	.365	.593	1.125
12	12.75	.165	.180	.365	.593	1.125
14	14		.250	.437	.750	1.406
16	16		.250	.500	.843	1.593
18	18		.250	.562	.937	1.781
20	20		.250	.593	1.031	1.968

5.1.3 Pipe Connections

Pipe or tubing alone does not constitute a piping system. To make the pipe or tubing into a system, the various components of the complete system must be connected together.

A number of different methods are available for making these pipe connections. Some common connection methods are described below.

Welded Connections

Welding involves melting the base metals (pipes) to fuse them together, typically using an electric arc or gas flame. Common welding methods for pipes include TIG (Tungsten Inert Gas), MIG (Metal Inert Gas), and stick welding.

Welding produces a strong and permanent connection suitable for high-pressure and high-temperature applications; however, welded connections are less flexible than soldered or brazed joints, which can be a disadvantage in some situations.

Figure 5.1.2 Arc Welding

Welding requires considerable skill and experience in order to make high quality connections, but properly made welded connections can last the lifetime of the ship.

Flanged Connections

Flanges are circular discs with machined faces, attached to the ends of a section of pipe. Flanges provide a method of connecting pipes, valves, pumps and other equipment to form a piping system.

Figure 5.1.3 Flanged Connections

Flanged joints are made by bolting together two adjacent flanges with a gasket between them to provide a seal. Flanged connections are used for higher-pressure applications and situations where dismantling might be necessary.

The materials and design of the flanges are governed by the requirements of service, and in most cases, a flange is of the same material as the pipe. Flanges in steel piping systems are usually screwed or welded to the pipe or tubing, while flanges in nonferrous systems are usually brazed.

A **blind flange** (also called a '**closure plate flange**') has no center hole, so nothing can flow through the flange. Blind flanges may be used to temporarily seal a piping system while testing, modifying or repairing the line, to create an access point in a piping system, or to create a long-term seal to terminate a piping system that is not used.

Figure 5.1.4 Blind Flange

A **spectacle blind flange** is shaped like a pair of glasses or *spectacles* — hence the name. One half is open to allow flow through during normal operation and the other side is solid to block flow and secure the system for maintenance. The two halves are separated by a spacer with a hole for one flange bolt. They are generally installed in the piping system permanently.

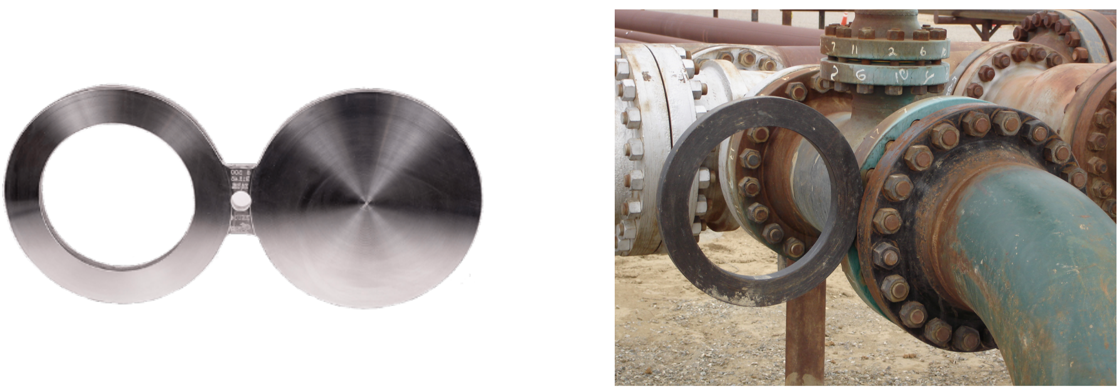


Figure 5.1.5 Spectacle Blind Flange

To change the position, the system must first be secured, depressurized and locked out. After removing the flange bolts, the spectacle blind can be rotated to the other side, the gaskets replaced, and the bolts retightened.

An **orifice flange** is used in conjunction with a differential pressure sensor to measure the rate of flow in the pipe.

An **orifice** is a hole through which fluid may pass. When fluid flows through an orifice it creates a pressure drop, which is measured by the pressure sensor. The flow rate through the orifice is proportional to the square root of the pressure drop and can be calculated knowing the orifice diameter.

Figure 5.1.6 Orifice Plates and Orifice Flange

The orifice flange assembly consists of a pair of flanges containing **pressure taps**, an **orifice plate**, **jacking screws** and the normal gaskets, nuts and bolts. The orifice plate has a precision hole (the **orifice**) drilled through its center, and a tab stamped with the hole diameter. Taps are threaded holes drilled through the flanges where the differential pressure sensor is connected. The jacking screws are used to spread the flanges when replacing the orifice plate.

Threaded Connections

In a threaded pipe connection, matching male and female threads are screwed together to create a secure and leak-resistant joint. Threaded pipe connections are widely used in plumbing systems, natural gas lines, water supply systems, etc. because they are relatively easy to fabricate and assemble; however they are not suitable for high pressure systems, nor for connections that are frequently taken apart.

Standards were first developed about 200 years ago to define the shape and tolerances of threads used for pipes and pipe fittings in order to ensure compatibility and interchangeability between different components in piping systems. Although various standards currently exist, the **National Pipe Tapered** (NPT) standard is the one most commonly used in the United States. NPTM and NPTF are abbreviations for NPT-Male and NPT-Female threads.

Unlike the straight threads used for nuts and bolts, NPT pipe threads are **tapered**; that is, they are formed on a conical surface. This conical surface tapers at an angle of $1.789° = 1°47'$, which is equivalent to 1/16 inch per inch of length.

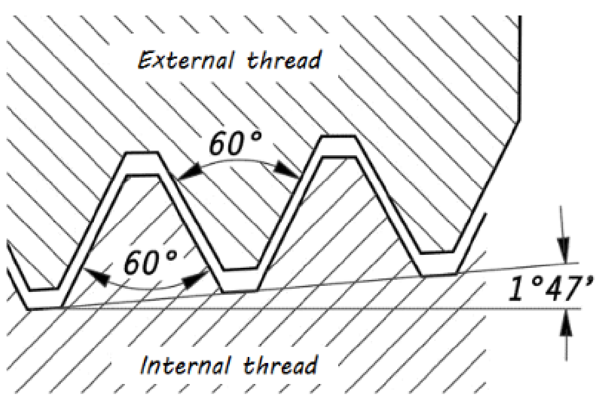


Figure 5.1.7 NPT Threads

Because of the taper, a pipe thread can only screw into a fitting so far before it jams. The standard specifies this distance as the length of hand tight engagement, the distance the pipe thread can be screwed in by hand. It also specifies another distance – the effective thread, this is the length of the thread which makes the seal on a conventional machined pipe thread. For workers, instead of these distances, it is more convenient to know how many turns to make by hand and how many with a wrench. A simple rule of thumb for installing tapered pipe threads, both metal and plastic, is finger tight plus one to two turns with a wrench.

Tapered threads rely on the deformation of the pipe material to form a secure seal. If they are properly aligned, screwed together using a pipe sealant, and not over-tightened, they will create a rigid and leak-free connection. However, they cannot be taken apart and put back together too many times before the threads will permanently wear out and leak.

Soldered and Brazed Connections

Soldering and Brazing are both processes in which two parts are joined together using a molten filler metal. After the filler material solidifies, a strong bond if formed. The difference between soldering and brazing has to do with the filler material, particularly its melting temperature.

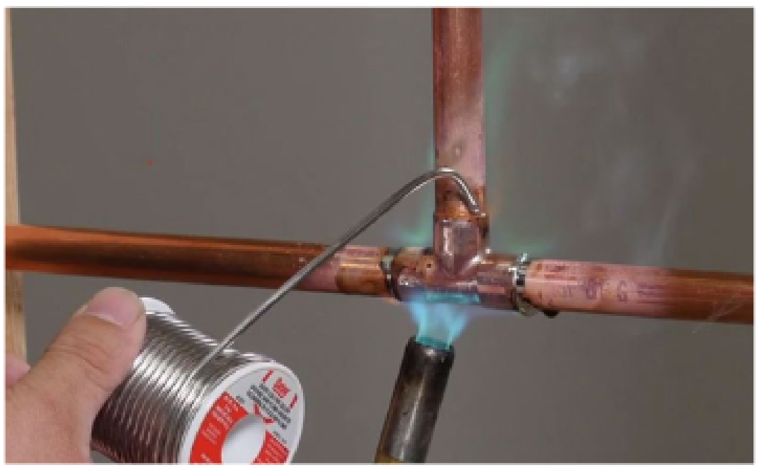


Figure 5.1.8 Soldering Copper Pipe

Solder is an alloy that melts at 840 F or less. Solder is composed primarily of tin, mixed with other metals such as nickel for added strength. Solder used to be a tin/lead mixture, but that is no longer used due to health risks of exposing drinking water to lead pipes. Soldering is easier to learn than brazing and soldered joints can be reheated and taken apart.

Brazing alloys melt above 840 degrees. Brazing alloys are typically made of a mix of copper and phosphorus or silver mixed with other elements. Brazing creates a stronger connection than soldering that is less likely to leak.

Because of the relatively low melting temperatures, neither method can be used for high-temperature applications.

Compression Connections

In some systems, mechanically strong, leak tight connections can by compressing the pipe or tube in a compression or flare fitting.

Compression fittings are made up of three basic elements: the **compression nut** , the **ferrule** , and the body. The tubing is slipped through the nut and the ferrule and then inserted into the end of the body. By tightening the nut/screw the ferrule is forced into the fitting body. As the ferrule moves axially into the fitting body, the body’s angled shape compresses the end of the ferrule onto the outer diameter of the tubing. It is this radial compression that creates a leak tight seal between the fitting, ferrule, and tubing, and gives the compression fitting its name.

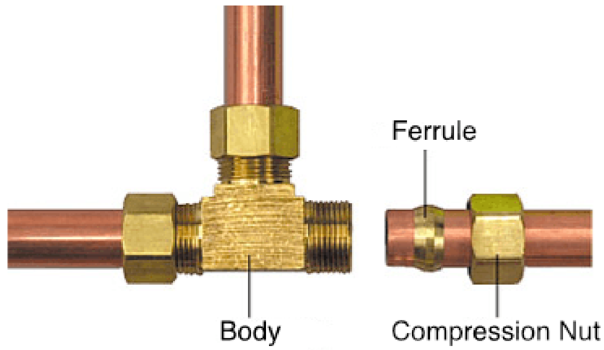


Figure 5.1.9 Compression Fitting

Flare fittings consist of a body with a flared or coned end. Special flaring tools are used to create a matching flare on the pipe. The flare nut compresses the flare into the fitting body and creates the seal. Flare fittings can handle higher pressures and a wider range of operating parameters than standard compression fittings.

Figure 5.1.10 Flare Fitting

Compression connections are quick and require little skill to make, but they cannot withstand very high pressures. Also, there are only a few materials that are suitably compressible (ex. copper, brass, plastic) to use this method.

Quick Connect Fittings

Quick-connect fittings, also called a **push fittings**, are coupling used to provide a fast connections to hoses and flexible tubing, without the need for tools. Some quick-connect fittings are self-sealing, so that upon disconnection they will automatically contain any fluid in the line.

Figure 5.1.11 Camlock, Push-to-connect, Twistlock

There are several types of quick connect fittings. Some of the most commonly used ones are:

Cam-lock connectors uses foldable tabs on the female half to lock the receiver in place. This type of connection is used in applications involving hoses, such as sewage pumping or fire hoses.

Push-to-connect fittings function by pushing one end into the other. To disconnect, a collar needs to be retracted.

Twist or bayonet fittings utilize a 1/8 to 1/4 turn to connect and disconnect. Aboard ship, compressed air hoses for pneumatic tools often use twist fittings.

Glued Connections

This method is used for connecting **PVC** (Polyvinyl Chloride) pipes like those commonly found in home plumbing systems. PVC pipes are not used in critical ship systems, because the material can fail due to the stresses caused by the motion of the vessel, and will fail in a fire .

A solvent-based adhesive is applied to the pipe ends, which chemically melts the plastic and creates a strong bond when the pipes are pushed together.

5.1.4 Pipe Fittings

Pipe fittings are the parts used to join pipe sections together with other system components like valves and pumps to build complete piping systems.

As discussed in Subsection 5.1.3, pipe fittings may be welded, threaded, mechanically joined, or chemically adhered, to name the most common mechanisms, depending on the material of the pipe. Some of the most common pipe fittings are described in the following sections. The photos show threaded iron fittings, but similar fittings are available for other materials and connection methods.

Pipe Nipples

Pipe nipples are short sections of pipe with male threads on both ends. The are used to connect two female threaded pipe fittings.

Figure 5.1.12 Nipples: Close, Short, Hex, Long

Close nipples are the shortest practical pipe nipple. The are used to connect two fittings very close to one another, leaving no unthreaded pipe exposed. Close or nipples are difficult to work with because the threads will be damaged with a pipe wrench, and the are difficult to remove without damage.

Short or **shoulder nipples** are longer than close nipples and have a very small section of unthreaded pipe in the middle. However, this unthreaded section is still not large enough to fit a pipe wrench to tighten or remove the nipple without damage.

Hex nipples are short nipples with a hexagonal center section that allows you to securely grasp the nipple with a wrench to tighten or remove it.

Long or **barrel nipples** have enough unthreaded pipe in the center to be gripped with a pipe wrench.

Threaded pipe sections longer than about one foot are not considered nipples.

Unions and Couplings

Couplings and unions are both pipe fittings used to join two pipes or nipples together, but they are used in different situations. Couplings are used to make a permanent connections, while unions are used to permit the system to be taken apart for maintenance from time to time.

Figure 5.1.13 Coupling and Union

A **coupling** is a simple, short section of pipe with internal female threads. Two sections of pipe are tightened into the coupling to make the connection. In order to disassemble the connection, one of the pipes needs to be rotated through several rotations to unscrew it. This is not too practical because the entire system may need to be taken apart to remove one piece.

A **union** consists of three parts – male and female parts with matching tapered faces, and a hexagonal union nut with internal threads which fits over the male part and screws onto straight threads on the female part.

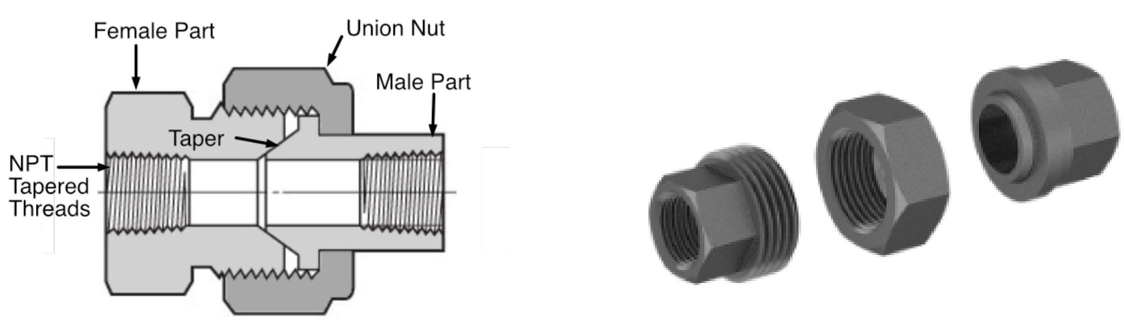


Figure 5.1.14 Union Cross-section and Disassembled

The union is assembled by sliding the union nut over the male part, then screwing the male and female parts permanently onto the pipes. After the pipes are aligned, the union nut is tightened to draw the two tapered faces together to create a seal. Pipe dope or teflon tape must be used on the tapered threads, but should not be used on the mating faces. Pipes connected with a union can be taken apart by unscrewing the union nut without affecting other parts of the piping system.

Elbow Fittings

A pipe elbow is a fitting used to join two sections of straight pipes at an angle.

Figure 5.1.15 Elbows: 90°, 45°, 22.5°, Street Ell, Reducing Ell

Standard elbows are available in 90° , 45° and less commonly 22.5° angles. A **90° Ell** is also called a **quarter-bend**.

Standard elbows fit the same size pipe and female threads on both ends. When one end is smaller than the other the fitting is called a **reducing elbow** (h), and when one end has male threads the fitting is called a **street elbow** (i).

Short radius elbows have a radius of curvature of about one pipe diameter from center of the bend to the center of the elbow face, while the radius of curvature for **long radius elbows** is about one and a half diameters. Long radius elbows produce less turbulence in the fluid which results in reduced frictional losses and pressure drop, but they take up more room and are more expensive.

Tee Fittings

Tee fittings are used to connect three sections of pipe at right angles, and are often used to make a branch line. **Cross fittings** are similar, but connect four pipe sections

Figure 5.1.16 Tee and Cross

Standard Tees and Crosses use female threads and all connections are the same size, but unequal (reducing) and street (one male thread) varieties are sometimes available.

Caps and Plugs

Caps and **plugs** are pipe fittings used to seal the end of a section of pipe. Caps are female threaded and plugs are male threaded.

Figure 5.1.17 Cap and Plug

Adapters

Adapter fittings are used to connect components that have different threads, diameters or connection methods together, for example: straight to taper thread adapters, pipe to hose adapters,etc..

Figure 5.1.18 Adapters: NPT to straight, NPT to Flare Fitting, NPT to copper pipe

Reducing adapters, as the name suggests, are used to connect pipes of different sizes. A **straight reducer** has female threads on both ends, while a straight **reducing bushing** has a large male thread and a smaller female thread. Other reducing adapters including reducing elbow and tees are available with different combinations of male and female threads.

Figure 5.1.19 Straight Reducer and Reducing Bushing

5.2 Valves

In general, a valve is a device installed in a piping system to control the amount, direction or pressure of the contained fluid flowing through the pipe lines. Most valves control fluid flow with a carefully designed moving part which can fully open, partially open (called *throttling*), or close an opening called an *orifice* inside the valve. Since the valve must stop all fluid flow when it is closed, the surface of the moving part that covers the opening and the surface surrounding the stationary opening must be precisely machined and fitted. In many valves, both these surfaces are metal and they must seal tightly against one another without the aid of gaskets or seals between them.

Various valves use one of four basic means of controlling flow:

- a moving disk or plug blocking orifice;
- sliding a flat, cylindrical or spherical surface across an orifice;
- rotating a disk across the diameter of piping;
- or, moving a flexible material into the flow path.

The movable part inside the valve has its position controlled by a shaft or valve stem that passes through the valve body to the outside. The valve stem is rotated or moved axially depending on the valve design by one or a combination of the following methods:

- Manually using a hand-wheel or lever
- Electrically using electro-magnets (solenoids) or motors
- Pneumatically using compressed air to move a piston or air motor
- Hydraulically using pressurized oil to move a piston or hydraulic motor

Several different types of valves are shown in Figure 5.2.1. Of these, the most important types for shipboard use - globe, gate, check, plug, ball, butterfly, and relief - will be discussed in this chapter.

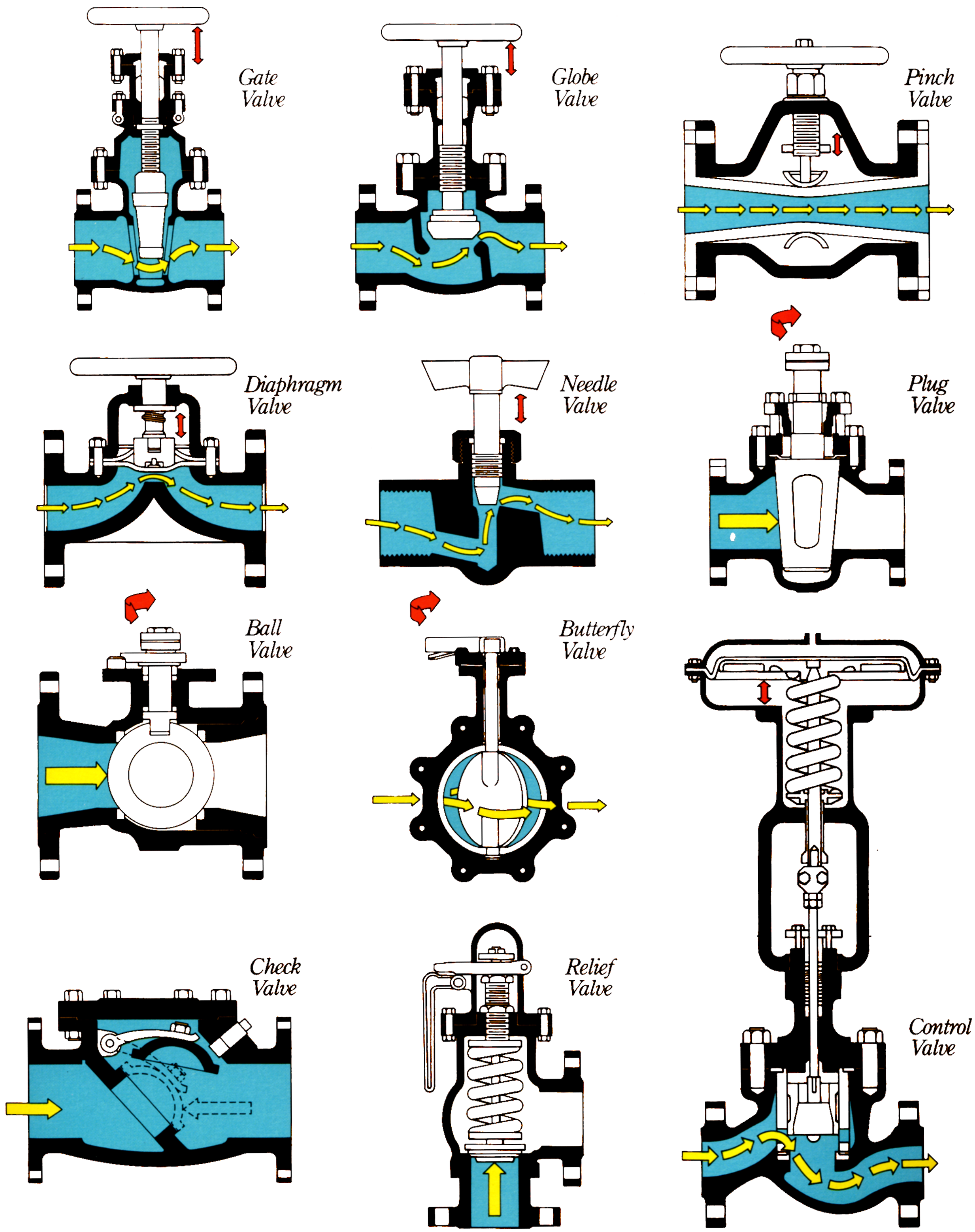


Figure 5.2.1 Types of Valves

5.2.1 Globe Valves

Globe valves are used in throttling applications, that is, anytime you want to regulate or control the amount of liquid flowing through a system, you could select a globe valve. A bathroom sink faucet or a garden hose spigot are common examples of globe valves found around the house. In a globe valve, the moving part (called the *valve disk*) blocks an opening in the valve (called the *seat*) to shut off flow, and when the valve stem is turned, the disk moves away from the seat – in the path of the fluid flow – as the valve is opened. To close the globe valve, the disk is moved back towards the seat until they touch, seal, and stop the fluid flow through the valve.

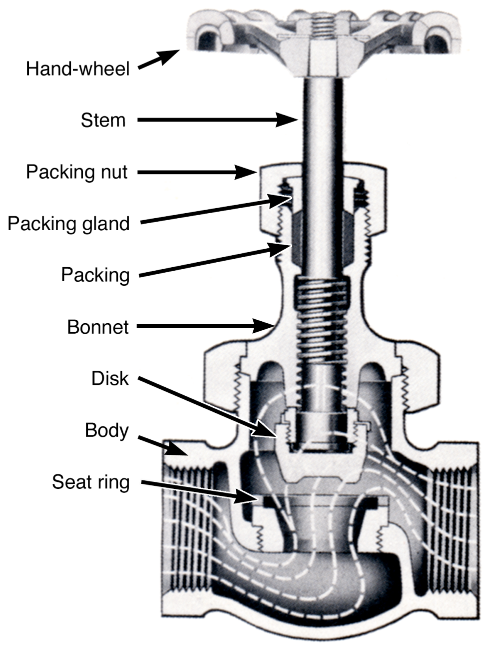


Figure 5.2.2 Globe Valve

Construction. Globe valves are designed for tight closure and throttling applications. When a globe valve is used to throttle or regulate fluid flow, the disk surface that closes against the seat should be made from metal, not synthetic materials. Throttling a fluid creates erosion (wearing away) of the disk surface and the seat surface that the fluid flows between. This erosion may show up as general roughness or as small grooves cut across the surfaces of the seat and disk, called *wire drawing*. These defects on the precisely machined surfaces of the seat and disk result in leakage when the valve is closed. In service where erosion will be a problem, the seat and disk can be fabricated from very hard materials, such as stellite, to extend the life of the seat and disk contact surfaces.

The **valve body** contains the internal opening that the fluid flows through. It is called the *seat* if the opening is machined directly into the valve body material. It is called a *seat ring* if it is a separate and replaceable part from the valve body. Replaceable seat rings are generally manufactured from harder, longer wearing materials than the valve body to be more resistant to fluid erosion at this location. Seat rings may be retained in the valve body by machine screw threads, press fit, welding or by what is known as a *shrink fit*. In shrink fit applications, the machined hole in the valve body that the seat ring fits into is a few thousandths of an inch smaller in diameter than the outside diameter of the seat ring. Therefore, it is impossible for the ring to fit into the hole in the valve body. During assembly the valve body is heated, causing the machined seat ring hole to expand. The seat ring is also frozen at the same time to decrease its outside diameter. With both parts at the proper temperature, the seat ring now has an outside diameter that is smaller than the inside diameter of the machined hole in the valve body. At this point, the seat ring is placed quickly and accurately into the valve body. As the temperature of the two parts begin to equalize, the ring expands and the machined hole shrinks and places a compressive force around the outside of the ring, locking it very tightly in place.

The valve body has two external openings (and in some special valves, more) for the entrance and exit of fluid from the piping system. These openings can be connected to the piping using pipe threads, soldering, flanges, welding, or gluing.

The top of the valve body generally has an opening for the valve disk and stem to fit through. At this opening, the other sub-assembly, called the *bonnet* is attached.

The **bonnet** normally contains the equipment necessary to operate the movable disk. It is attached to the body by machine screw threads or flanges . Large valves and valves in high pressure service normally have a gasket between the bonnet and the body made from sheet packing, flat metallic rings or spiral wound metallic type material. Small valves may have the bonnet and body sealed by a lapped metal to metal fit with no gaskets.

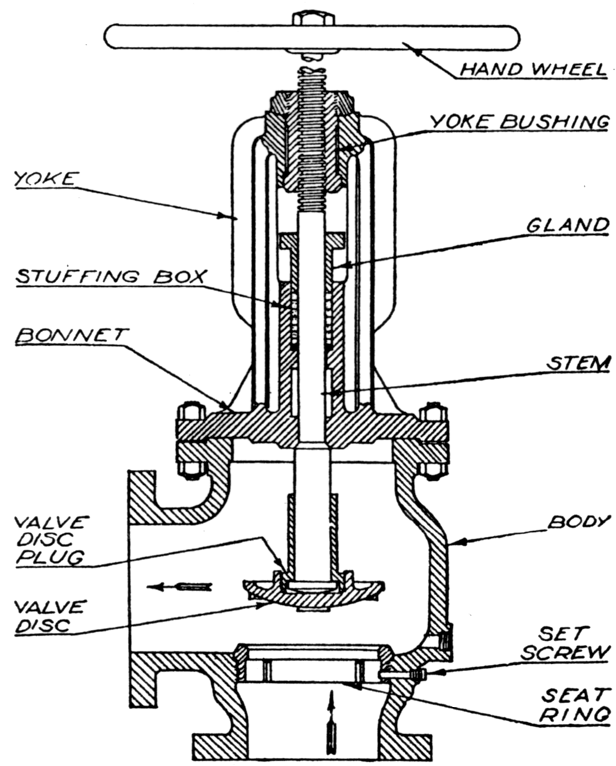


Figure 5.2.3 Angle Globe Valve

Construction Details. Several interesting construction details are shown in Figure 5.2.3, which shows a manually operated right-angle globe valve.

This valve has a **stem** with a collar machined on the end. The **disk** slides over the collar and is retained on the end of the stem by a **valve disk plug** (or **disk nut**) which is attached to the disk by machine threads. Since the disk plug is prevented from sliding off the end of the stem by the collar, it effectively fastens the disk to the stem. The disk nut does not lock the disk tightly to the stem, rather the disk is allowed to move slightly around the collar on the end of the valve stem. This small movement allows the disk to align itself properly with the seat as it closes for a leak free seal. In this valve, the stem is also the device that keeps the disk correctly aligned with the seat, regardless of how far the disk is removed from the seat.

Where the valve stem passes through the bonnet to the outside of the valve, the bonnet has a **stuffing box**, **packing**, and a **packing gland** installed to minimize fluid leakage at this point.

This valve stem uses **Acme Threads**, a thread type with no points, just below the point where the **hand-wheel** is installed. The valve stem threads engage the internal threads of the *yolk bushing*, which is made from a softer material than the valve stem, e.g. bronze, brass etc. If the stem has too much rotational force applied, the yoke bushing threads strip instead of the valve stem threads. The yoke bushing is a replaceable part and is screwed into the upper part of the bonnet with machine threads. When the valve hand-wheel is turned in the clockwise direction, the valve stem threads engaged with the yoke bushing threads cause the stem to move inward pushing the disk toward the seat closing the valve.

The upper part of the bonnet on this particular valve is split into two supporting uprights from the area where the packing gland is installed to the location of the yoke bushing. This type of upper bonnet design is called an outside yolk and stem.

Installation. Globe valves are normally installed with the incoming fluid pressure applied to the bottom of the valve disk, that is, to the side of the disk that closes against the seat. The top of the disk is the side that does not close against the seat and, in most globe valves, is the side in contact with the valve stem. When fluid pressure is applied to the bottom of the disk, the pressure helps the operator open the valve, and the pressure on the valve packing is relieved when the valve is closed.

The only time a globe valve is installed with fluid pressure applied to the top of the disk is when the valve is used as a throttle valve controlling steam flow to an engine. Installed in this manner, if the disk were to become detached from the stem, the disk would be carried toward the seat by the steam flow. Even if the disk does not close tightly against the seat, it would choke off steam flow to the engine and cause it to slow down. Globe throttle valves installed in this manner are considered fail safe. If the valve was installed with the steam pressure on the bottom of the disk, and the disk became detached from the stem, the disk would be carried away from the seat by the steam flow and cause the engine speed to rise uncontrollably. The steam would also carry the disk toward the engine where it could enter and cause damage.

Globe valves cause a relatively large pressure drop in the fluid as it flows through the valve. Pressure drops are caused by the friction created when the fluid changes direction of flow through the valve. The straight globe valve, with the pipe connections 180 degrees opposite each other, has the greatest pressure drop through it due to three to five changes in direction of fluid flow. The right angle valve has a 90 degree angle between the inlet and outlet pipe connections and fluid flow only changes direction one or two times, creating less pressure drop than the straight type. Globe valves are also constructed with 45 or 60 degree angles between the stem and the outlet side of the valve. This valve design also creates less change in direction of fluid flow, reducing pressure drop through the valve.

A globe valve is fully open when the disk is raised ¼ of the diameter, d, of the seat opening. For full flow to take place through the globe valve, the area the fluid flows in through and the area the fluid flows out through must be equal. The inlet area is the hole in the seat, and is equal to the area of a circle or . The fluid flows out through the space between the top of the seat and the bottom of the disk which is the side of a cylindrical shape. The area of the side of a cylinder is equal to the circumference of the circle on the end of the cylinder times the height, h of the cylinder .

Example 5.2.4 example. If the inside diameter of the seat is 4″ how far from the seat must the disk be lifted to be fully open?

Answer. $h = 1$ in

Solution.

$$\begin{aligned} A_1 &= A_2 \\ \pi d h &= \frac{\pi d^2}{4} \\ h &= \frac{d}{4} \\ &= 1 \text{ in.} \end{aligned}$$

□

5.2.2 Gate Valves

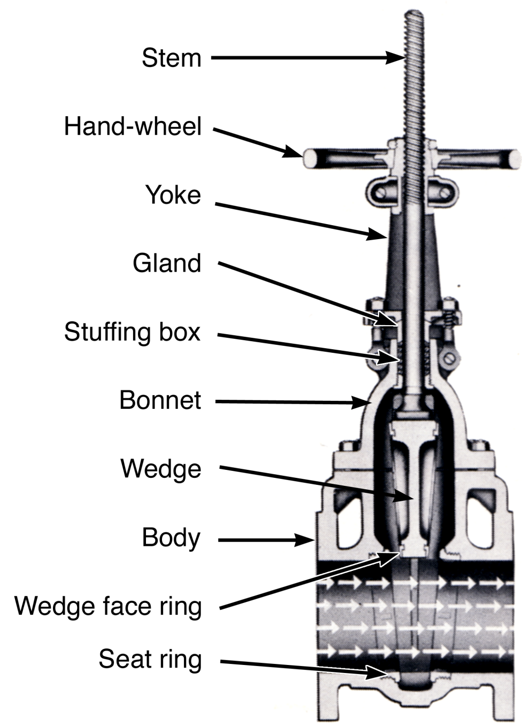


Figure 5.2.5 Rising Stem Gate Valve

A gate valve, Figure 5.2.5, is called for when you don't need to regulate flow, only turn it on or off. To open a gate valve, the moving part, called the *gate* or *wedge*, is moved across to the fluid flow path unblocking the opening in the valve, called the *seat*. The gate is actually slid off the surface of the seat sideways. Sliding the gate back over the seat blocks fluid flow and closes the valve.

When open, fluids follow a straight, unobstructed path through the valve creating a minimal pressure drop across the valve. This is the principle advantage of a gate valve over a globe valve; it has a much lower restriction to flow when fully open.

Gate valves are designed to be fully open or fully closed. They should not be left partially open to regulate fluid flow. The fluid flow under a partially open gate causes the gate to swing back and forth. This could cause the gate to hit the seats (sometimes called *chattering*) creating damage to the machined surfaces of the seat and gate leading to leakage when the valve is closed.

A gate valve, like a globe valve, is constructed in two basic parts, the body, and the bonnet.

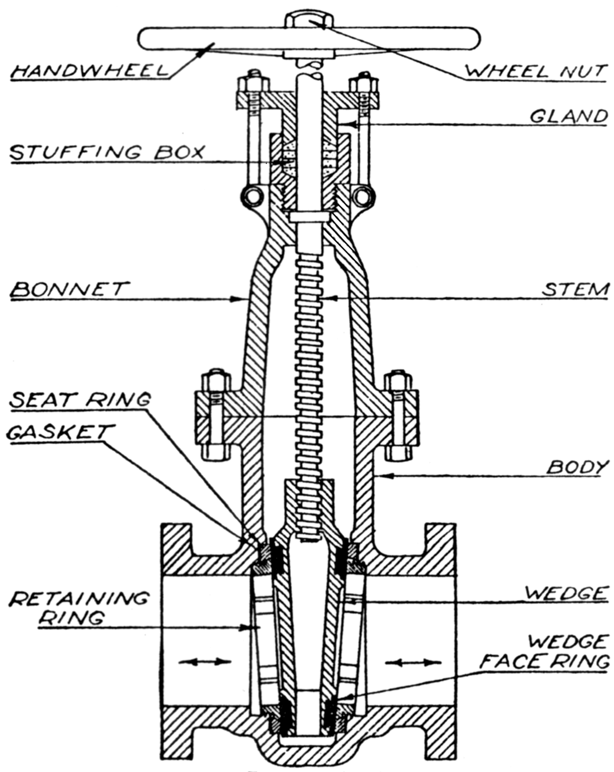


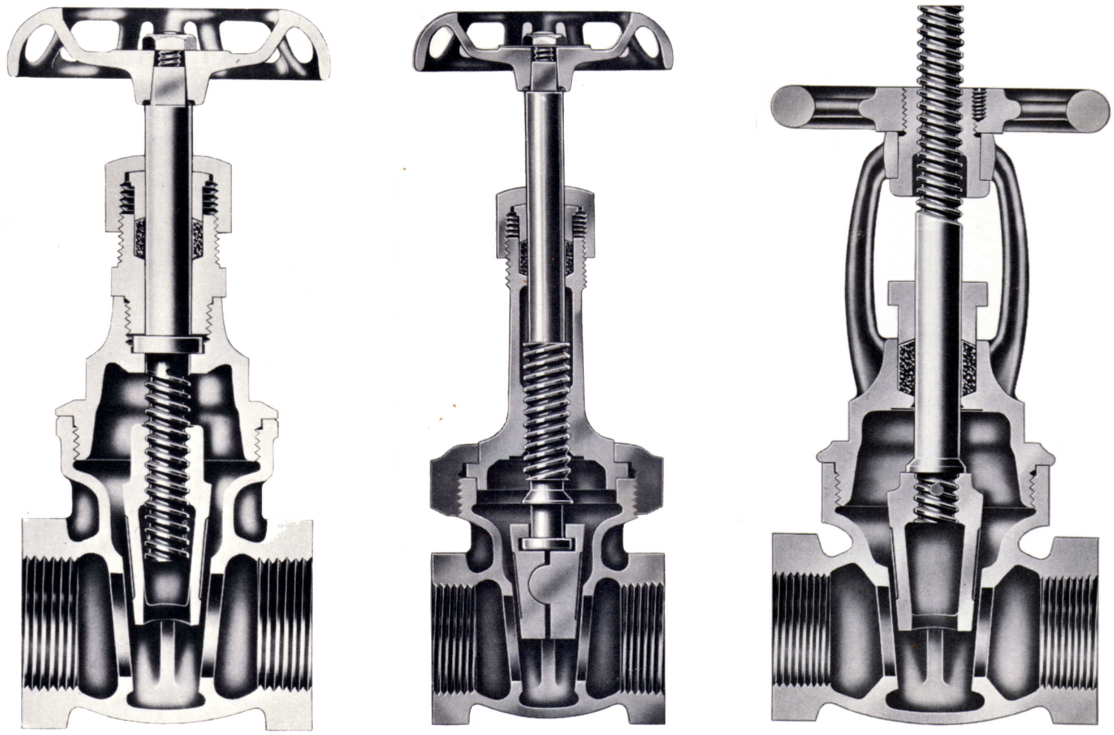
Figure 5.2.6 Gate Valve

Body. Piping inlet and outlet connections are fitted to the body 180° apart *only*, similar to the straight globe valve. Piping connections to the body are the same as a globe valve: threaded, flanged, etc.

The body has two seats inside facing each other. One surrounds the inlet opening and the other the outlet opening. The distance between the seats nearest the bonnet opening is greater than the distance between the seats at the bottom of the valve body creating a wedge shape between them. The gate is moved down from the bonnet location between the two seats. It has a machined surface on both sides and has a wedge shape that matches the two seats forcing it to seal tightly against both seats when it is pushed down between them.

The upper part of the body and sometimes the lower part of the bonnet form a large cavity for the gate to retract into as the valve is opened. Since the gate slides off the seats sideways, it must be moved more than the full diameter of the seat opening to be fully open. This is why most gate valves are taller than globe valves of a comparable size.

Bonnet. The bonnet houses the equipment necessary to operate the gate and is attached and sealed to the body using the same methods as on globe valves.



(A) Non Rising Stem Inside Screw

(B) Rising Stem Inside Screw

(C) Rising Stem Outside Screw and Yoke

Figure 5.2.7 Types of Bonnets

Gate valves are available in different types of stem connections. Figure 5.2.7 illustrates three different types.

1. *Non-rising stem, inside screw (A)* The stem screws down into the valve gate as the valve is opened. In this type the stem does not rise or fall outside the valve body as the valve is opened or closed, it simply rotates.

2. *Rising stem, inside screw (B)* The stem rises outside the valve as the valve is opened, but the stem screw operates inside the body of the valve. When operated, the valve stem in this design rises and rotates.

3. *Rising stem, outside screw and yoke (C)* The stem screw operates at the level of the hand-wheel, so the stem rises independently of the hand-wheel as the valve is opened. The valve stem rises, but does not rotate. Instead of the valve stem rotating, the hand-wheel rotates the yoke bushing pulling the stem straight up. Valve stem threads can be easily cleaned and lubricated in this design.

   Outside screw and yoke design is required on gate valves when diameters exceed 3″ and pressures exceed 600 psig.

Notice that in both type A and B, the stem threads are exposed to the fluids flowing through the valve. Fluids can eventually corrode the threads and fluids with solids entrained can cause the threads to bind up and create excessive wear.

Valves with rising stems are used when it is important to know by immediate inspection whether the valve is opened or closed. The outside screw and yoke type easily indicates valve position due to the stem extending out beyond the center of the valve wheel when it is open.

The non-rising type is the least likely to leak in the packing area and requires less installation space.

5.2.3 Check Valves

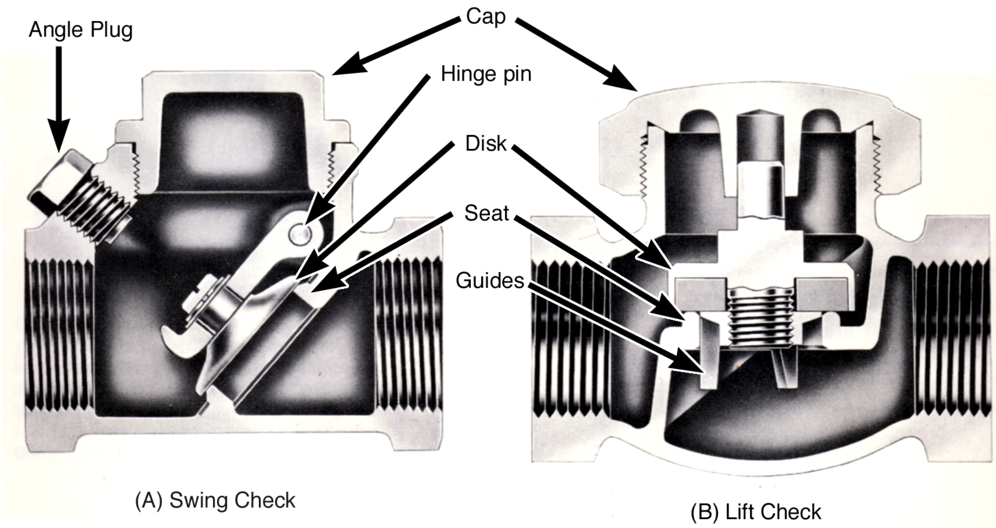


Figure 5.2.8 Check Valves

A check valve is a modified globe valve that allows fluid flow in one direction only, through a pipe line and automatically stops flow in the opposite direction. A check valve has two basic parts: the **body** which is similar to the body of a globe valve – with one seat, two external pipe connections, and an opening for the bonnet to attach to; and the **Cover** or **Cap** which replaces the globe valve bonnet assembly and fastens to the body using the same methods used to attach bonnets on globe valves. However, the cap is a blank cover with no hand operators, stuffing box or valve stem.

There are three main variations of check valves: **swing checks**, **lift checks**, and **stop checks**, and they are discussed below.

Swing Check. In a swing check valve the valve seat is angled 45° to the fluid flow path through the valve. The disk is attached by an arm to a hinge pin inside the valve body near the cover opening. The hinge pin is located just above the highest part of the seat opening. When the fluid flow is from right to left and the pressure on the bottom of the disk is greater than the pressure on the top of the disk, the disk swings away from the seat allowing flow to take place. When fluid flow tries to reverse (from left to right), the pressure on top of the disk becomes greater than the pressure on the bottom of the disk, the disk to moves back toward the seat, preventing flow in this direction. The arm and hinge pin assembly assure correct alignment between the disk and seat for a tight closure.

Lift Check. A lift check valve has a specially designed disk or ball which closes against a seat just like a typical globe valve. In this design, the disk or ball is not attached to any arm or stem. Since the disk is free to move away from the seat without an arm or stem to guide it back in correct alignment to the seat upon closing, other guidance means are employed. In most lift check valves, the disk (with higher than normal sides) or the ball just fits into to hole in the upper part of the body. When flow pushes the disk or ball away from the seat, the walls of the hole in the upper body guide the disk or ball straight up away from the seat. These walls also guide the disk straight down when it is closing assuring correct alignment between the disk and seat for tight closure.

Stop Check. A stop-check valve is very similar to a globe valve, except that the disk is not attached to the stem. When the valve hand-wheel is turned to the fully closed position the disk is held against the seat and the valve is securely closed. When the valve hand-wheel is turned to open the valve, the disk is free to lift off the seat, and will when there is a pressure difference in the correct direction. If the flow reverses direction, the valve will automatically close like a lift check valve.

The valve stem can be used to force the disk to a partially closed position to regulate the flow, or to a fully closed position to stop the flow, but the valve stem cannot be used to force the disk into the open position. Once the stem is moved away from the disk, the valve functions like a lift check valve.

A typical application would be a boiler feedwater stop-check valve. The valve can be used to stop or regulate feedwater flow to the boiler. It also automatically prevents the back flow of water out of the boiler through the feedwater line if the pressure in the feedwater line falls below the boiler steam pressure. In this application, it functions as a check valve.

In some designs, a stop-check valve can be converted to a regular globe valve, which eliminates the check function and allows the disk to be forced into the open position, by reinstalling the disk nut or drilling a hole through the upper disk and valve stem and inserting a pin to lock them together.

When installing a check valve, always remember: Check valves *must* be installed in a manner that allows gravity to help close the disk. This way the valve will close even if the flow reversal is only slight. Swing checks are normally installed in piping systems with the cap up, and lift checks are installed with the disks closing in the downward direction. There is usually a directional arrow on the valve body which indicates the direction of fluid flow.

5.2.4 Plug-type Valves

Figure 5.2.9 Plug Valve

Plug-type valves have a rotating element with a hole drilled or cast through it. When the hole lines up with the matching passages in the valve body, fluid can flow through the valve. Variations of plug valves are pet cocks, cylinder valves or ball valves.

Plug Valves. **Plug valves**, Figure 5.2.9, have a through-ported cylindrical or tapered plug which can rotate in a close-fitting body. Alignment of the ports (holes) in the plug with those in the body permit fluid flow.

Operation of a plug valve requires rotating the handle or lever on the plug stem 90 degrees. Normally the plug valves (for the most common type with two pipe connections 180 degrees apart) position (open or closed) can be determined by looking at the operating lever. When the lever is parallel to the piping system, the valve is open. When the lever is perpendicular to the piping system, the valve is closed.

Plugs valves have limited throttling ability and should be used like gate valves, either fully open or closed.

Plug valves may be built with multiple openings in the plug and multiple ports in the valve body. These designs allow a variety of fluid flow directions through the plug valve by proper positioning of the operating lever. Pointers attached to the plug stem or operating lever are sometimes used to indicate direction of flow.

When a plug valve is described as "three-way, two-port" it means the valve body has three openings to pipe connections on the outside of the body. Two port means the plug has two openings in it that fluid flows in and out through.

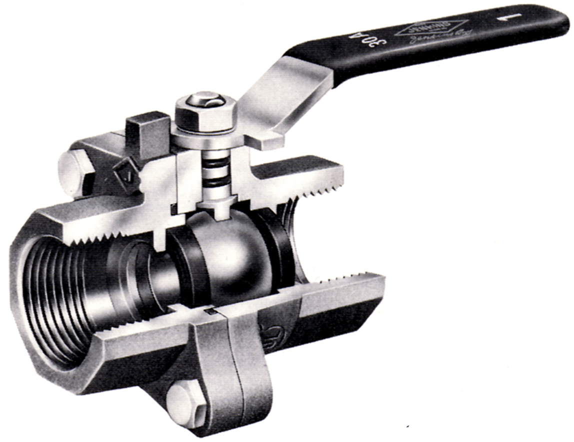


Figure 5.2.10 Ball Valve

Ball Valves.

A **ball valve**, Figure 5.2.10, is similar to a plug valve except that a spherical rather than cylindrical plug is used. The ball has a hole or port bored through it and is made tight to the two openings in the body by plastic or synthetic rubber seat seal rings. These plastic or synthetic seat rings limit most ball valves to fluid temperatures of 350° or less. When the ball is rotated to the closed position, the fluid pressure pushes the ball tightly against the outlet seat ring insuring tight closure.

Ball valves are compact, self-sealing, non-sticking, require little effort to rotate the valve stem and they provide smooth fluid flow. Since the port in the ball is normally the same I.D. as the piping, the ball valve offers little resistance to flow and low pressure drop.

5.2.5 Butterfly Valves

Figure 5.2.11 Butterfly Valve

Butterfly valves can be used for on-off operation as well as throttling or regulating fluid flow. They are light weight, require little installation space, have low initial cost, are simple in design and can be easily repaired. Like plug and ball type valves, it is only necessary to rotate the valve stem a quarter turn on a butterfly valve to go from the full open to the closed position. Manual operating levers on butterfly valves are parallel to the piping when the valve is open and perpendicular to the piping when the valve is closed. 90° valve stem operation makes them very adaptable to automatic and remote control actuators.

The disk in the butterfly valve is connected to the stem across its diameter. (See Figure 5.2.11 and Figure 5.2.12). When closed, the outer edge of the disk is in contact with a seat ring surrounding the opening through the valve body. To open the valve, the stem rotates the valve disk, until when fully open, the flat surfaces of the disk are parallel to the centerline of the pipe with fluid flowing past each side of the disk.

The seat opening is lined with resilient, elastic materials like synthetic rubber, neoprene or Teflon. The disk edge presses into this material when closed to form a tight seal.

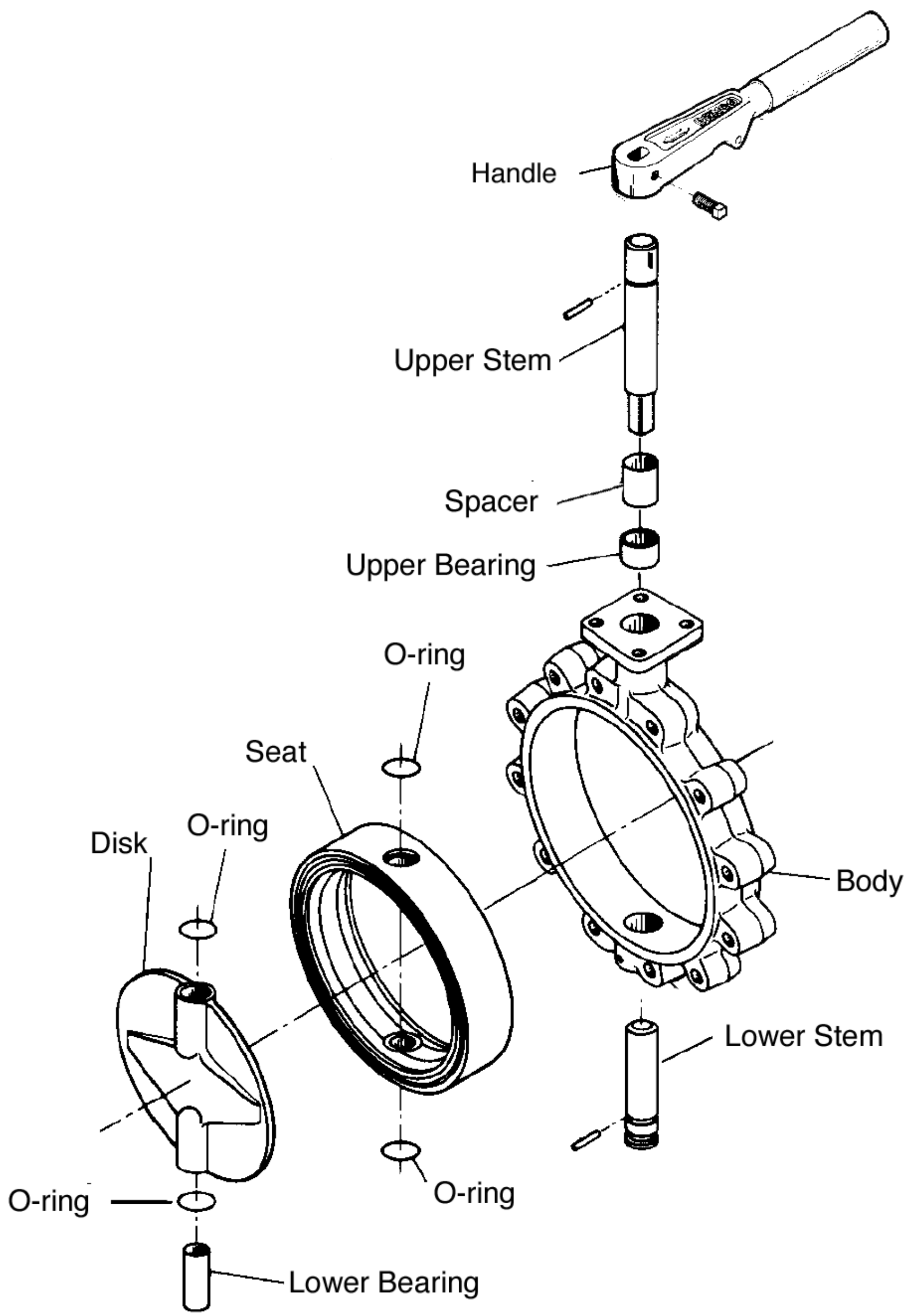


Figure 5.2.12 Exploded view, Butterfly valve

In symmetrical type butterfly valves (stem is centered on the thickness of the disk), a tight seal is a problem where the stem passes off the edge of the disk. Symmetrical butterfly valves are generally satisfactory for tightly sealing fluid leakage in fluid systems up to approximately 200 psig and 180 °F.

To improve sealing, the eccentric or offset design butterfly valves are used. The stem is offset to one side of the disk so it does not interrupt the edge of the disk's seal with seat ring. The stem may also be installed across the disk to one side of the maximum diameter. This allows a major portion of the disk's edge to push it's way into the seat material rather than slide into it.

Offset butterfly valves seal tightly and have reasonable seat ring life up to about 700 psig with water to temperatures slightly above ambient. Pressure ratings drop with the rise in temperature with maximum temperature limits being 450 to 500 °F.

5.2.6 Pressure Relief Valves

Relief valves are protective devices designed to open automatically when the pressure in the line unit becomes too high. Although there are different types of relief valves, the most common type has a disk that is held in the closed position by a coil spring. When the pressure in the line or machine creates a force great enough to overcome the spring force, the disk moves upward and is opened. After the pressure has been relieved by the escape of fluid through the relief valve, the spring again exerts enough force to close the disk.

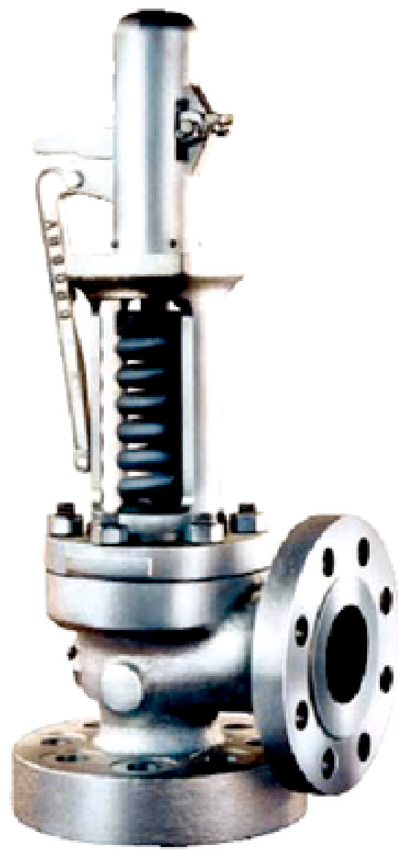


Figure 5.2.13 Relief Valve

Relief valves have no hand-wheel operator, but may be equipped with a lever attached to the valve stem which the operator can use to momentarily open the valve, in order to test that the valve can open properly, or to blow out debris such as rust or dirt, which if lodged between the disk and seat would cause the valve to leak.

Relief valves are designed to work properly with any type of fluid, while safety valves are only designed to work with gases.

Most relief valves are set to open when the pressure against the disk reaches 110% of the *Maximum Allowable Working Pressure* (called the MAWP) of the system or machine. For example, if a system operates with a MAWP of 100 psi, then the relief valve would open at 110 psi.

Relief valves are designed to close at a pressure lower than their opening pressure (The difference between opening and closing pressure is called *blowdown*). This is done to prevent *valve chattering*, which is a rapid opening and closing of the valve. Chattering is undesirable because it can damage the seat and disk. If the valve opened and closed at exactly the same pressure, it would chatter, because as soon as it opened, the pressure would drop and cause the valve to close, and as soon as it closed the pressure would cause it to open again.

Chattering is prevented by exposing an additional disk surface area to the fluid pressure immediately after the valve opens. This increased area, acted upon by the fluid pressure, increases the force against the spring, and makes the valve open rapidly once it starts to open, but it will not close again until the pressure falls significantly below the opening pressure.

It must be remembered that the coil spring force acting when the valve begins to open is the same as the spring force acting when the valve closes. Since $F = PA$:

$$P_o A_o = P_c A_c$$

Where:

P_o is the Opening pressure.

P_c is the Closing pressure.

A_o is the Opening area.

A_c is the Closing area.

Remember, the extra surface area is not available until the valve disk opens.

Example 5.2.14 Relief Valve Closing Pressure. A relief valve opens at 250 psi and has a bottom surface area when closed of 0.75 in^2. When the valve opens, the bottom surface area increases by 10%. What pressure does the valve close at?

Answer.

$$P_c = 227 \text{ psi}$$

Solution.

$$\begin{aligned} P_o A_o &= P_c A_c \\ 250(0.75) &= P_c(1.1)(0.75) \\ P_c &= 227 \text{ psi} \end{aligned}$$

□

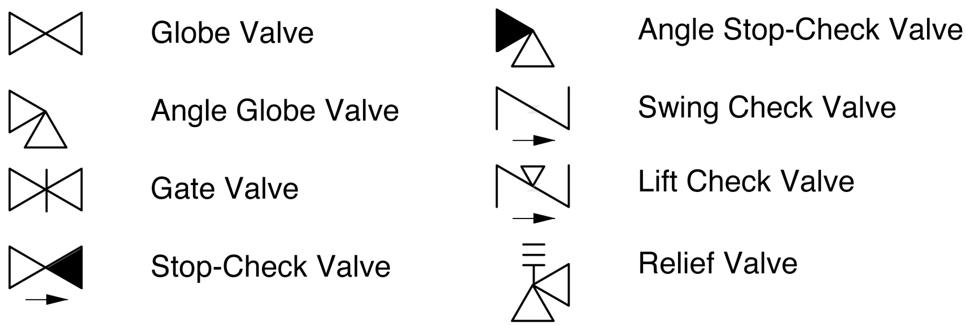


Figure 5.2.15 Valve Symbols

5.3 Pumps

A **pump** is a device used to increase the pressure and move *liquids*, such as water or oil, or *slurries,* which are mixtures of liquids and solids, through pipes. If a pump is used to move gases, it is usually referred to as a **fan**, **compressor**, or **blower**.

The fluid inlet to the pump is called the **suction**. Fluid flows from the suction into the pump chamber, and then out the pump **discharge**. While the fluid is in the pump chamber, an external power source imparts energy to the fluid in order to:

- move the fluid from a lower to a higher level
- move the fluid from a lower to a higher pressure
- overcome fluid friction in the passages and pipelines

Most of the energy from the external power source is transformed into usable fluid *pressure*, which is a form of potential energy, or into *velocity*, which increases the kinetic energy of the fluid. The remainder of the energy is absorbed by frictional losses in the pump and fluid passages, and shows up as heat. The fluid, now at a higher energy level, is led to the pump outlet called the discharge.

The external energy supplied to most pump shafts is in the form of *torque*, produced by electric motors, diesel or gas engines, or gas or steam turbines. Some pumps use a sliding, back-and-forth, external motion and are known as reciprocating. Pressurized gas or liquid is used as an energy source to operate a jet type pump.

The **capacity** of a pump is the volume of fluid that the pump can move (under specific operating conditions) per unit of time and is usually expressed as "Gallons per Minute" or "GPM" for short. The pressure that a pump is capable of delivering is described as the **pump head**, and will be discussed in the next section.

5.3.1 Head

Head is defined as the vertical distance between two liquid levels. Head, for a pump, is simply the distance, measured in "feet of fresh water," between the pump suction connection centerline and the liquid level in the supply tank, or between the pump discharge connection centerline and the liquid level in the discharge tank. **Static head** in feet can be related to the pressure that the pump must generate in the fluid to create these differences in liquid levels. Static head also influences the output capacity of the pump.

When discussing pumps, we are always referring to static head. In other engineering courses, you will learn about other types of head. For example, in Fluid Mechanics, you will calculate the pressure necessary to overcome friction in the pipelines, called **friction head**, and the pressure required to impart velocity to the fluid, known as **velocity head**.

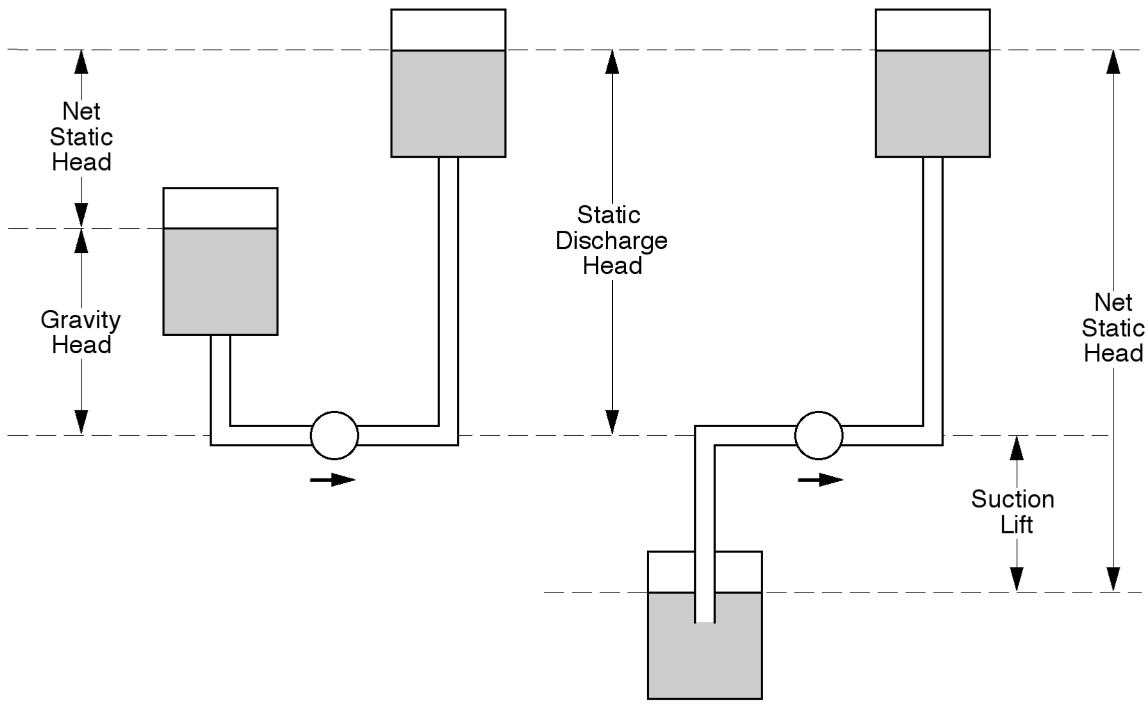


Figure 5.3.1 Static Pump Head

Head can also be thought of as the pressure necessary to support a column of water of a height equal to the head. Since head can be related to pressure, you may be wondering how atmospheric pressure affects the pump. Usually there is no effect at all. Since atmospheric pressure acts on the surface of the liquid in both the suction and discharge tanks, the effect is equal but in opposite directions on each side of the pump, and the result is that the net effect of the atmospheric pressure on the pump, is canceled out.

Several different head measurements are used to describe the operation of a pump. The relationship between these heads is illustrated in Figure 5.3.1.

Suction Head

The distance between the surface of the liquid in the supply tank and the centerline of the pump suction describes the pump **suction head**.

Positive suction head, also called gravity head, occurs when the liquid level in the supply tank is *above* the center of the pump suction. The height of the liquid creates a pressure on the suction side of the pump that is greater than atmospheric pressure, and gravity causes the liquid to flow into the pump suction. In this situation, very little power is required to draw the liquid into the pump.

Negative suction head, also called **suction lift**, occurs when the liquid level in the supply tank is *below* the center of the pump suction. In this case, the pump must create the force necessary to lift the liquid uphill against the force of gravity and draw it into the pump suction. This process obviously requires more pumping power than when there is a positive suction head.

To pump when there is a suction lift, we use the atmospheric pressure on the surface of the liquid in the supply tank to push the liquid up the pipe to the pump suction, much like sucking on a straw. If the pressure inside the suction pipe is reduced to 13.7 psia compared to the 14.7 psia on the surface of the water in the supply tank, than the water level in the suction pipe should be 2.31 feet higher than the water level in the supply tank. (remember: 1 psi = 2.31 feet of fresh water!). Now if the pressure in the suction pipe is lowered to 0 psia, the atmospheric pressure should theoretically push the water up against the force of gravity (14.7 x 2.31 = 33.96 feet) 34 feet inside the suction pipe. The suction side of the pump will be operating at a pressure lower than atmospheric (under a vacuum) when the pump is lifting. 34 feet of suction lift is the theoretical maximum for fresh water, but in the real world, the maximum suction lift is less.

Discharge Head

Static discharge head is the vertical distance above the pump, in feet, between the centerline of the discharge connection and the liquid level in the discharge tank. The greater the discharge head, the more energy will be required to pump the liquid. Also, as the discharge head is increased, the pump capacity decreases; at a certain point the discharge drops to zero GPM, and the pump is no longer pumping.

Net Static Head

Net static head is the distance the pump has to raise the pumped fluid between the liquid level in the supply tank to the liquid level in the discharge tank.

Net static head = Static Discharge Head - Static Gravity Head

Net static head = Static Discharge Head + Static Suction Lift

5.3.2 General Pump Classifications

Hundreds of different types of pumps have been invented and improved over the years to meet every conceivable pumping requirement. These pumps differ in principles of operation and in design details; nevertheless, they may be broadly categorized according to their *displacement characteristics*, their *delivery characteristics*, and their *suction characteristics*. These broad categories are described in this section.

By Displacement Characteristics

A **positive displacement pump** is one in which a definite volume of liquid is delivered for each cycle of pump operation, regardless of the discharge pressure the pump operates against, and provided the capacity of the power unit driving the pump is not exceeded.

A **non-positive displacement pump** is one in which the volume of liquid delivered for each operational pump cycle depends on the resistance to flow in the discharge line. This type of pump produces a force on the liquid that is constant for each particular operating speed of the pump. Pressure in the discharge line produces a force in the opposite direction. When these two forces are equal, the liquid is in a state of equilibrium and does not flow.

If the discharge valve of a positive displacement pump is completely closed, the discharge pressure will rise to a point where either the unit driving the pump will stall or parts of the pump exposed to discharge pressure will fail. This situation should be avoided. On the other hand, closing the discharge valve on a non-positive displacement pump will cause the discharge pressure to rise to a maximum for that type of pump operating at a specific speed. Nothing more will happen except the pump will churn the liquid trapped in the pump chamber and produce frictional heat in the liquid.

Most positive displacement pumps deliver liquid in slugs, with no delivery in between, and this causes a rise then a drop in discharge pressure and flow. Pumps equipped with many small pumping chambers generally have overlapping delivery that minimizes this effect. Non-positive displacement pumps deliver a practically continuous even flow for a given operating speed and discharge pressure.

By Delivery Characteristics

All shaft driven pumps will deliver liquids at different volume rates if they are run at different speeds. Most pump designs require a change in speed to change their capacity (**constant delivery**). However, some rotary type pumps, and some radial or axial piston pumps are designed to vary the quantity of liquid delivered while maintaining the prime mover at a single speed. Pumps with these characteristics are known as **variable delivery** pumps.

Variable delivery pumps are most commonly found in hydraulic systems, where the delivery rate can be adjusted to control the rate of motion of hydraulic cylinders and actuators.

By Suction Characteristics

Some types of pumps are designed with such close clearances between moving and stationary parts in the pump chamber that they will actually pump air, gases, or vapors as well as liquids. These pumps can be started with no liquid in the pump chamber and will pump the air out of the suction pipe, lowering the pressure, eventually causing the liquid to lift up and enter the pump. These types of pumps are considered to be **self-priming**.

Other types of pumps, because of larger internal clearances, will not pump air or gases and will not lower the pressure in the suction pipe enough to lift the liquid to the pump chamber. These types of pumps must have the suction pipe and the pump chamber completely flooded with the liquid to be pumped or they will not lift the liquid. Filling the suction pipe and pump chamber with liquid to place these pumps in operation is called **priming** the pump.

5.3.3 Types of Pumps

Centrifugal Pumps

Centrifugal pumps use centrifugal force to transfer the mechanical energy supplied to the pump into primarily kinetic energy (velocity) in the fluid being pumped. Centrifugal force is the force generated by rotation which acts outward from the center of rotation. Using the terminology already covered, centrifugal pumps are classified as: non-positive displacement pumps, non-self priming, and are constant delivery for a given operating speed and discharge pressure. Because of their simplicity, low cost and ability to operate under a wide variety of conditions, centrifugal pumps are widely used. They can be adapted to produce any head up to several thousand feet and will handle liquids at temperatures up to 1000° F. They can also be designed to handle liquids containing a high proportion of rather large solid particles.

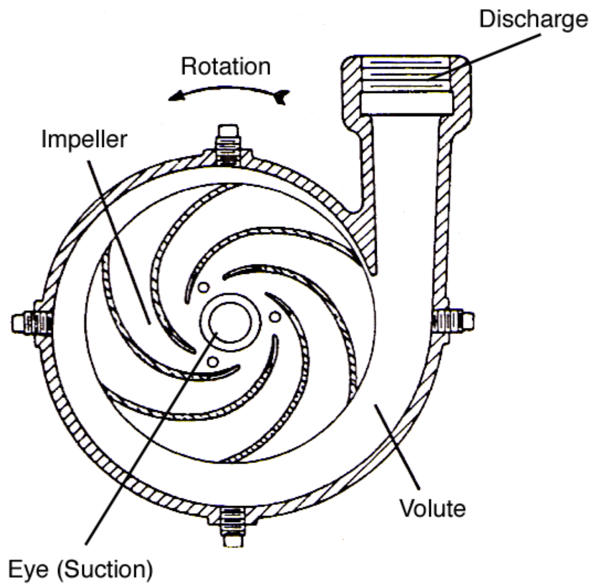


Figure 5.3.2 Centrifugal Pump

A centrifugal pump consists of a rotating element called the **impeller**, which is the only moving part in the pump, and a specially shaped housing, or pump casing. In practically all centrifugal pumps, liquid enters the rotating element at the center through the **eye**, and is given a rotary motion in the pump chamber by the rotation of a number of impeller blades (generally called **vanes**). The rotation of the impeller in a true centrifugal pump does two things. Centrifugal force drives the liquid directly out from the center of the impeller, setting up a greater pressure in the chamber at the outer edge of the impeller than at the eye. At the same time the liquid is also pushed around and around by the turning of the vanes, and is given more and more velocity as it moves farther out from the eye. The liquid finally leaves the impeller tangentially at the end of the vanes with a high velocity, and flows into the discharge passage of the pump housing surrounding the impeller.

The discharge passage gradually widens as it leads the liquid away from the impeller to the discharge nozzle on the pump housing. The gradual widening of the discharge passage reduces the velocity of the liquid. Since the reduction in velocity does not produce work, it results in a change in the type of energy contained in the liquid. Most of the velocity (kinetic energy) in the liquid produced by the centrifugal pump is transformed into pressure (potential energy) by the widening discharge passage. This type of energy is more available for doing work. On most centrifugal pumps this widening passage is built into the pump casing that surrounds the impeller and is called the **volute**. Additional conversion of velocity to pressure may be accomplished in the **discharge nozzle** and sometimes in the piping leading away from the pump.

Recall that a reduction in the velocity of a liquid (without producing any work) changes the type of energy contained in the liquid into increased pressure. The reverse is also true. If the pressure in a liquid is reduced (without producing any work) then the velocity of the liquid must increase.)

When liquid is forced away from the eye by centrifugal force, a reduced pressure area is created in the eye causing more liquid to flow in. This creates a constant flow through the impeller and out through the discharge of the centrifugal pump.

In a centrifugal pump, the velocity that can be imparted to the liquid, and the resulting discharge pressure depends upon both the impeller diameter and the impeller RPM. Increasing either results in:

- higher centrifugal force

- higher liquid velocity
- higher pressure

The centrifugal pump, with a certain size impeller operating at a set speed, will only put enough energy in the liquid to create a specific discharge pressure. If the resistance in the discharge piping rises to the maximum pressure the pump can create, liquid flow through the pump stops. The centrifugal pump is said to be operating at its shut-off head and no liquid is delivered by the pump. Friction between the rotating impeller and the liquid trapped in the pump casing increases the liquid temperature, possibly causing it to vaporize. To prevent vaporization of the liquid in a high speed centrifugal pump handling very hot liquids, a small pipeline is installed on the discharge side of the pump to divert a small amount of liquid back to the supply tank on the suction side of the pump. This small quantity of liquid flowing through the pump acts as a cooling system constantly removing the heated liquid from the pump casing and replacing it with cooler liquid from the supply tank. These lines are called recirculating lines and are always found on shipboard turbine-driven centrifugal feed pumps because they are frequently subjected to shut-off head when the ship's main engine is stopped or maneuvering.

Impeller vanes which curve backwards with respect to their direction of rotation are more efficient and give better performance than straight vanes; however, the pump must be turned in the correct direction to obtain this efficiency. The advantage of straight vane impellers is that they have the same efficiency in either direction of pump rotation. In Figure 5.3.2, the impeller rotation is counter-clockwise allowing the liquid to be pushed around the pump chamber by the vanes, rather than being carried by them. If a curved vane impeller was operated in the wrong direction rotation, it would still deliver some liquid, but the following would be observed:

- The pump would require more power to turn the impellor backwards.
- The pump discharge capacity would decrease.
- The pump efficiency would decrease.

Centrifugal Pump Design. Centrifugal pumps come in two basic designs, **volute** and **diffuser**, and many variations, including: **single**- or **double-suction**, single or multiple stages, and horizontal or vertical layout.

In the **volute pump**, the one most commonly used, the impeller discharges into a progressively expanding casing, as shown in Figure 5.3.2. The casing is proportioned to produce equal velocity of flow all around the circumference of the casing and then gradually to reduce the velocity as the liquid passes from the casing into the nozzle to be discharged from the pump, thereby transforming a considerable part of the velocity head into pressure head.

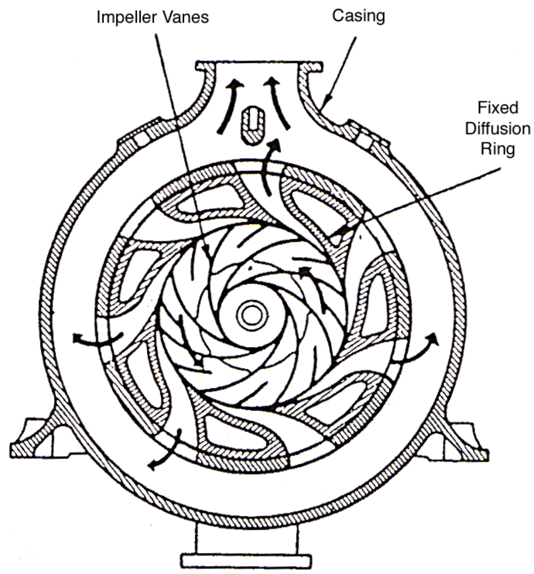


Figure 5.3.3 Diffuser Type Centrifugal Pump

In the **diffuser pump**, the impeller is surrounded by gradually expanding passages formed by stationary guide vanes, sometimes called a diffusion ring, as shown in Figure 5.3.3. In these expanding passages the direction of flow is changed and velocity largely converted to pressure before the liquid enters the volute. It is worth noting that the diffuser vanes are set approximately tangent to the ends of the impeller blades. In this kind of casing, efficiency may be slightly higher than in volute pumps, since velocity is more completely converted into pressure. The added cost of manufacture and more complicated construction of diffuser pumps, however, is generally not considered justified except occasionally in the case of large high pressure pumps.

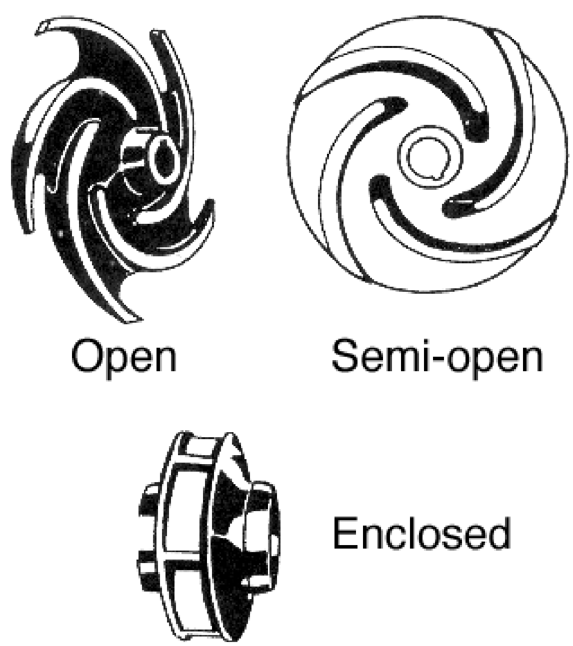


Figure 5.3.4 Impellers

The impellers used in volute and diffuser pumps are of three kinds, *open*, *semi-open*, and *enclosed* as shown in Figure 5.3.4. The open impeller consists only of blades attached to a hub. The semi-open impeller is constructed with a circular plate, called the web, on the inside edge of the blades. The web need not extend all the way out to the ends of the blades. The use of a web makes it possible to use thinner blades. In the case of the enclosed impeller, a shroud is added on the outside edge of the blades, so that the liquid is in large measure confined in the blade region, between the web and the shroud. Holding the liquid between these plates reduces friction losses in the pump. Open and semi-open impellers are normally found in pumps that must handle relatively large solids in the liquid, such as sewage pumps.

Impellers may also be single or double-suction. The former consists of a single impeller drawing liquid in from one side through one eye, while the double suction impeller is similar to a pair of single suction impellers placed back to back, placing an eye on each side of the impeller so that the liquid is drawn into the impeller from opposite directions. Double suction impellers can handle greater capacities of liquid than a single suction impeller of the same size and operating speed. This is because the larger inlet area of the two suction eyes provides less resistance to liquid flow into the impeller.

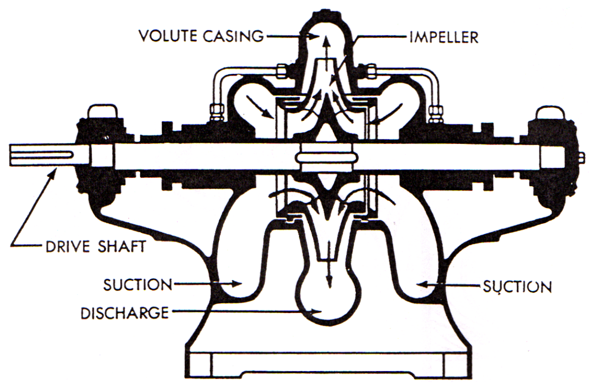


Figure 5.3.5 Double Suction Pump

Single stage pumps contain only one impeller, drawing in the liquid and expelling it through the discharge into the liquid system. A double-suction, single-stage pump is shown in Figure 5.3.5. A disadvantage of the single-stage pump, however, is that discharge pressure cannot be increased above the maximum working pressure of the impeller design operating at a given speed. Above this limit, under practical working conditions, the pump will not deliver any further increase in pressure. Most volute type, single stage pumps do not operate at speeds in excess of 3600 RPM and typically produce maximum discharge pressures in the 150 to 200 psi range. Diffuser type, single stage pumps may operate at speeds as high as 8000 RPM and produce discharge pressures in excess of 1000 psi; turbine driven boiler feed pumps are sometimes this type.

In **multistage pumps**, this disadvantage is overcome by combining several single-stage pumps, whether single or double suction, so that the discharge of one impeller is delivered to the suction of the next impeller. The liquid is delivered to each succeeding stage under the pressure imparted to it by the preceding stage, and additional velocity and pressure are added. As the liquid passes through each impeller in turn, additional pressure is imparted to it. A much higher working head can be produced than is possible with a single impeller. For the sake of compactness the several impellers of multistage pumps are almost invariably placed on one shaft, and the whole unit is built into one housing. The impellers are arranged in multistage pumps to eliminate or minimize end thrust.

Both volute and diffuser pumps will be found in single and multi-stage construction. Because of the greater cost and complexity of diffuser pumps, they are rarely used.

The pump itself can have a *vertical* or *horizontal* layout, determined by the direction of the pump shaft axis when the pump is installed. Horizontal designs, in most applications, are easier for maintenance personnel to work on, while vertical designs require less floor space for installation. Both designs work equally well.

Centrifugal Pump Principles. The discharge capacity, discharge pressure and horsepower required to drive the pump varies as shown below with changes in impeller speed n or impeller diameter d.

The discharge capacity Q varies DIRECTLY as the impeller speed n or impeller diameter d.

$$\left(\frac{Q_2}{Q_1}\right) = \left(\frac{n_2}{n_1}\right) = \left(\frac{d_2}{d_1}\right)$$

The discharge pressure p from the AS THE SQUARE of the impeller rpm or diameter.

$$\left(\frac{p_2}{p_1}\right) = \left(\frac{n_2}{n_1}\right)^2 = \left(\frac{d_2}{d_1}\right)^2$$

The horsepower necessary to drive the pump varies AS THE CUBE of the impeller rpm or diameter.

$$\left(\frac{HP_2}{HP_1}\right) = \left(\frac{n_2}{n_1}\right)^3 = \left(\frac{d_2}{d_1}\right)^3$$

Operations. The following steps describe the procedure for safely starting a centrifugal pump.

List 5.3.6 Centrifugal Pump Starting Procedure

1. Rotate the pump by hand to insure it is free to turn.
2. If the pump has a packed shaft and is to operate with a high vacuum on the suction side, open the seal water line to the stuffing box (if fitted with a valve), and the suction vent line to remove vapors from the suction casing. On a high speed boiler feed pump, open the recirculating line.
3. Open the suction valve and close the discharge valve.
4. Prime or flood the pump casing with liquid.
5. Start the pump prime mover.
6. As the pump comes up to running speed, briefly open the casing vent valve (if installed) to expel any air from the casing.
7. When the pump is up to its normal running speed, open the discharge valve.
8. Check the suction and discharge pressure gages to insure the pump is operating normally and make sure a packed pump shaft has a small amount of liquid leakage.
9. After the pump has run for a little while, check the casing, stuffing box area (on a packed pump), and the bearing housings for excessive temperatures.

Reciprocating Pumps

In **reciprocating pumps**, a power source drives a piston or plunger back and forth in a cylinder. This action pushes liquid out into the discharge on the discharge stroke, and draws liquid into the cylinder, from the source of supply, on the suction stroke. For each stroke, the same quantity of liquid enters and leaves the cylinder. The fluid flow through the pump is controlled by two check valves, one in the suction line and the other in the discharge line of the pump.

Figure 5.3.7 shows a steam driven reciprocating pump. The steam piston (7) is driven up and down by steam, delivering power to the liquid piston, or (69), which pumps the liquid. When the liquid piston (69) is moved down, the area above the piston is on a suction stroke. As the piston moves down in cylinder (72), the increase in cylinder volume causes a decrease in cylinder pressure. When the pressure in the cylinder drops below atmospheric pressure (creating a vacuum in the cylinder), the atmospheric pressure on the liquid in the suction tank forces the liquid up the suction pipe, through suction valve (85) and into the cylinder. Atmospheric pressure plus the liquid pressure in the discharge pipe create a pressure higher than the pressure in the cylinder. This holds the discharge valve (84) closed. When the piston begins to move up on the discharge stroke, a decrease in cylinder volume occurs, attempting to compress the liquid. This results in an increase in liquid pressure in the cylinder. As soon as the cylinder pressure exceeds the pressure in the suction pipe, the suction valve (85) is forced closed. As the piston continues to move up, the liquid pressure in the cylinder continues to rise. When the liquid pressure in the cylinder exceeds the pressure in the discharge pipe, the discharge valve (84) opens and fluid flows from the cylinder into the discharge line. This process repeated many times can build up a considerable discharge head (pressure) on the discharge side of the pump.

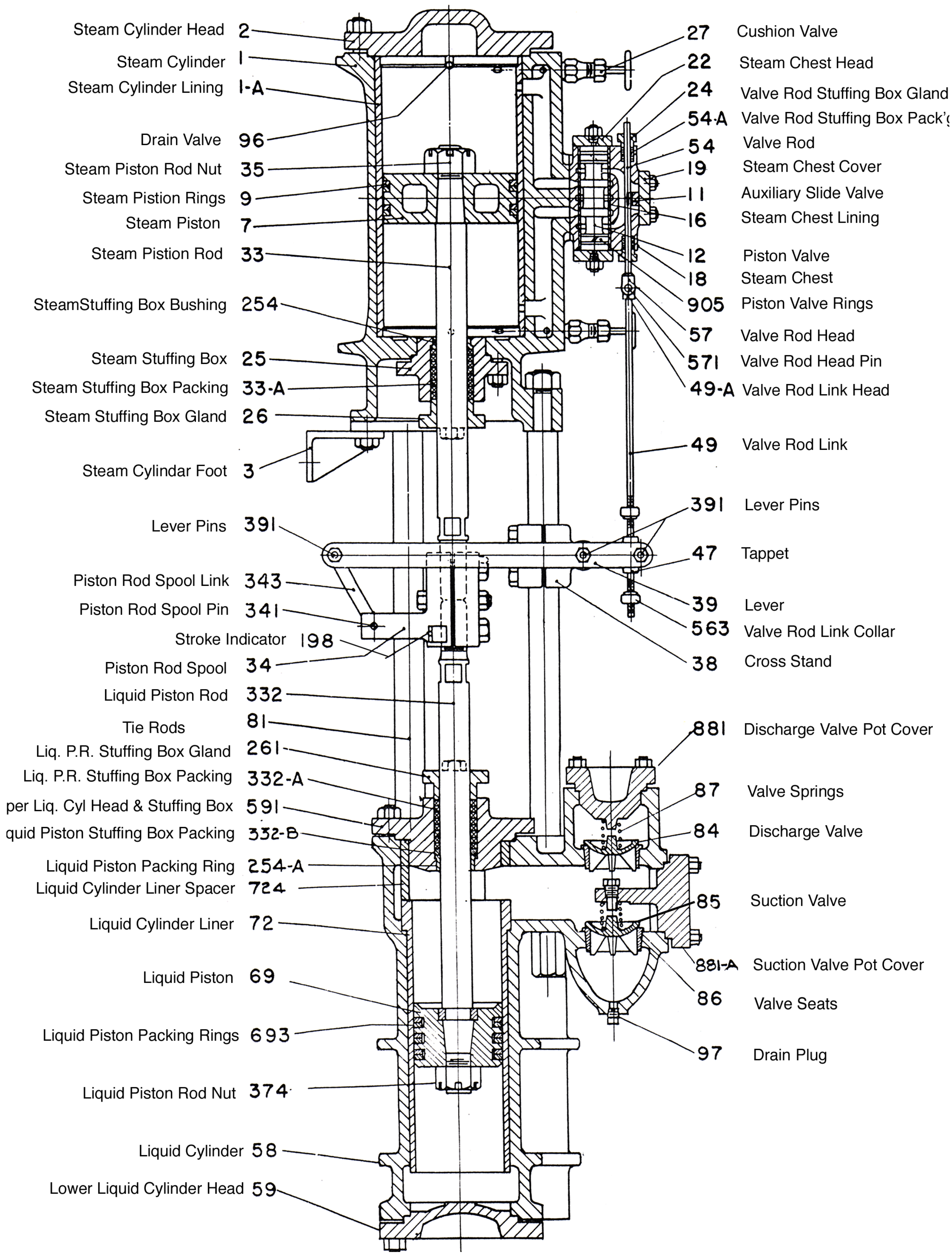


Figure 5.3.7 Simplex Reciprocating Pump

Reciprocating pumps are classified as positive displacement, self-priming and most are constant delivery, except for some specialized hydraulic pumps. Reciprocating pumps are additionally classified by the characteristics in List 5.3.8

List 5.3.8 Reciprocating Pump Terminology

Bore The bore is the inside diameter (ID) of the cylinder, usually measured in inches.

Stroke The stroke of a pump is the maximum distance the piston can travel from one end of the cylinder to the other, usually measured in inches.

Single stroke The motion of the piston from one extreme to the other.

Double stroke The motion of the piston from one end of the cylinder to the other and back to its original starting point. It is equal in distance to two single strokes. It is also a complete operating cycle for that piston (piston has returned to its original starting point and now the cycle repeats.)

Single-acting A single acting pump uses only one side of the piston to pump liquid. It is normally the side not attached to the piston rod or the connecting rod.

Double-acting A double acting pump is fitted with suction and discharge valves on both sides of the piston, allowing the piston to pump liquid on both strokes of the pump cycle.

Direct-acting The engine used is a steam reciprocating engine. The steam piston is pushed back and forth in the steam cylinder and the rod attached to the steam piston extends into the liquid cylinder and is directly attached to the liquid piston in the reciprocating pump. The engine produces the mechanical motion the reciprocating pistons require, hence; direct-acting.

Indirect-acting The power sources provide rotary motion to this type of reciprocating pump. The rotary motion of the power supply source must be converted to reciprocating motion at the pistons using a mechanical device called a crankshaft.

Simplex Only one liquid cylinder and piston are built into the pump. They may be operated by a steam reciprocating engine or more commonly today from a rotary engine via a crankshaft and connecting rod.

Duplex Two liquid cylinders and pistons are built into a common pump housing. Each cylinder may be operated by its own separate reciprocating engine. (with both engines built into the common housing) More commonly today, they are driven from a rotary engine via a crankshaft and connecting rods.

Triplex Three liquid cylinders and pistons are built into a common pump housing. Normally driven by a rotary engine via a crankshaft and connecting rods. Although direct-acting and indirecting-acting pumps can be built with more than three cylinders, they are not very common.

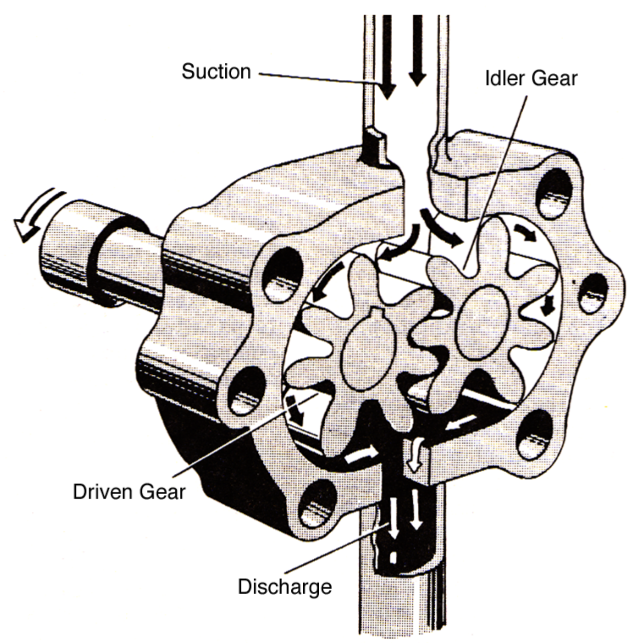
Rotary Pumps

All the many varieties of **rotary pumps** operate on the same principle. An element called the is rotated in the pump chamber in such a way that the liquid is carried or pushed from the suction side of the pump to the discharge side.

Rotary pumps are positive displacement, since they deliver a fixed quantity of liquid for each operational cycle or revolution of the pump shaft. This means that they want to move liquid even when the pump discharge is blocked. If the discharge of a rotary pump were closed with the pump operating, and if no pressure relief valve was installed in the pump discharge line, pressure would build up till the shaft seal failed, the electric motor overloaded and stopped, the engine driving the pump stalled, the pump casing or discharge piping ruptured, or some other casualty resulted.

When a rotary pump is operating at a constant speed, the amount of liquid delivered to the discharge line decreases slightly as the discharge pressure working against the pump increases. The drop in discharge capacity is due to increased internal leakage through the close clearances between stationary and moving parts in the pump housing. As the discharge pressure increases, the leakage rate from the discharge to the suction side of the pump, through the internal clearances, increases. This internal leakage reduces the pump's discharge capacity, and is known as

There are dozens of designs for the rotors of rotary pumps. Gears may be used as in Figure 5.3.9, but with almost any number of teeth, and in a variety of forms; elements that look like gears may be employed, although one of the pair may not be capable of rotating the other; two, three, or more lobes may be used; screws may be used which carry the liquid through the pump in their hollowed-out channels; sliding or swinging vanes may be used which form a seal with the walls of the chamber because they are pushed from the center of the rotor by mechanical arrangements or are thrown out by centrifugal force; small pistons moving in and out from the center of the rotor may be used to push liquid through the pump; and there are still more varieties. A few representative designs of rotary pumps will be described in the following sections.



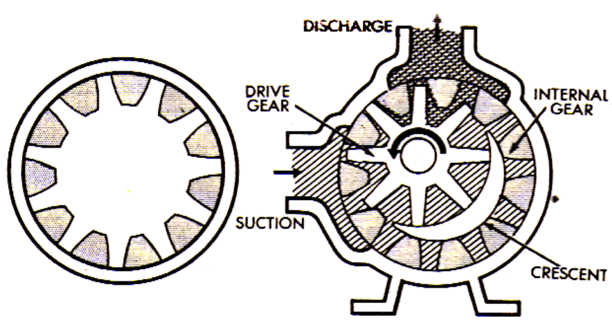
Gear Pumps. **Figure 5.3.9** Gear Pump

Gear pumps are probably the most common type of rotary pump, and Figure 5.3.9 illustrates a typical example. The liquid is carried from the suction to the discharge in the spaces between the gear teeth and the surface of the pump casing as the gears rotate. One of the gears is directly driven by the source of power, while the other, called the rotates with it in the opposite direction. This is accomplished either because motion is imparted from the drive gear to the idler gear by the meshing of the two gears at the center of the pump chamber, or because outside the pump chamber transmit motion from one gear shaft to the other.

There are close clearances between the gear teeth and the pump casing, and between the teeth of the two gears at their point of contact where they form a continuous fluid-tight joint. As the gears rotate in the direction indicated by the arrows, liquid is trapped in turn between each pair of teeth and the casing and carried away from the suction side of the pump. At the same time, as the teeth un-mesh at the center of the pump chamber, a low pressure is left in the empty space between the gear teeth. Liquid flows in to fill the low pressure areas between the gear teeth. As the gear teeth re-mesh on the discharge side of the pump, the liquid in between the gear teeth is forced out, eventually flowing to the discharge connection on the pump casing.

Three kinds of true gears are used: **spur**, **helical** and **herringbone**. Spur and helical gear pumps can be rotated in the opposite direction to reverse the flow through the pump while generally that is not possible with the herringbone design. When the latter is rotated in the wrong direction, liquid is trapped in the middle of the "V" resulting in pressure strains on the shafts and bearings.

The herringbone gear pump utilizes gears with a very steep "V" shape to the gear teeth. These designs are employed when very smooth discharge is desired. The steep angle on the gear teeth, however; prevents the gear driven by an outside source from turning the idler gear. The steep angle causes the gear teeth to jam together rather than rotate freely. Rotary motion is transmitted to the idler shaft via a set of timing gears instead. The timing gears prevent driving contact between pumping gears to eliminate the jamming problem.



Internal Gear Pumps.

Figure 5.3.10 Internal Gear Pump

In an internal gear system, the teeth of one gear project outwards , but the teeth of the other gear project inwards toward the center of the gear as shown in Figure 5.3.10. One gear stands inside the other in the internal gear pump. A gear directly attached to the drive shaft of the pump is set off-center in a circular chamber fitted around its circumference with the spurs of an internal gear. The two gears mesh on one side of the pump chamber, between the suction and discharge. On the opposite side of the chamber a crescent shaped form (a stationary part of the pump) stands in the space between the two gears in such a way as to provide a close clearance with them.

The rotation of the central gear by the shaft causes the outside gear to rotate, since the two are in mesh. Everything in the chamber rotates except the crescent, causing the liquid to be trapped in the gear spaces as they pass the crescent. This liquid is carried from the suction to the discharge, where it is forced out of the pump by the re-meshing of the gear teeth. As liquid is carried away from the suction side of the pump, the pressure is lowered and more liquid is drawn in.

The direction of flow through this type of pump can be reversed by rotating the crescent (and the pump cover it is attached to) 180 degrees.

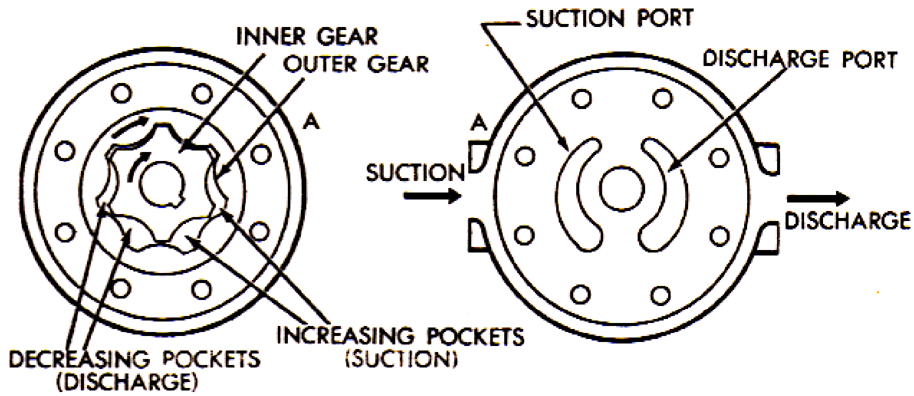


Figure 5.3.11 Gerotor Pump

Gerotor pumps.

The **gerotor** mechanism consists of pair of gear shaped elements, one within the other, mounted in a pump chamber, see Figure 5.3.11. The inner gear is directly connected to the drive shaft and the source of power, and drives the outer gear through direct contact. The inner gear has one fewer teeth than the outer gear. The tooth form of each gear is related to that of the other in such a way that each tooth of the inner gear is always in sliding contact with the surface of the outer gear. Each meshing pair of teeth only fully engages at one point, 12 o'clock in the figure above.

On one side of the point of mesh, pockets of increasing size are formed as the gears rotate (suction pockets), while the pockets on the other side decrease in size (discharge pockets).

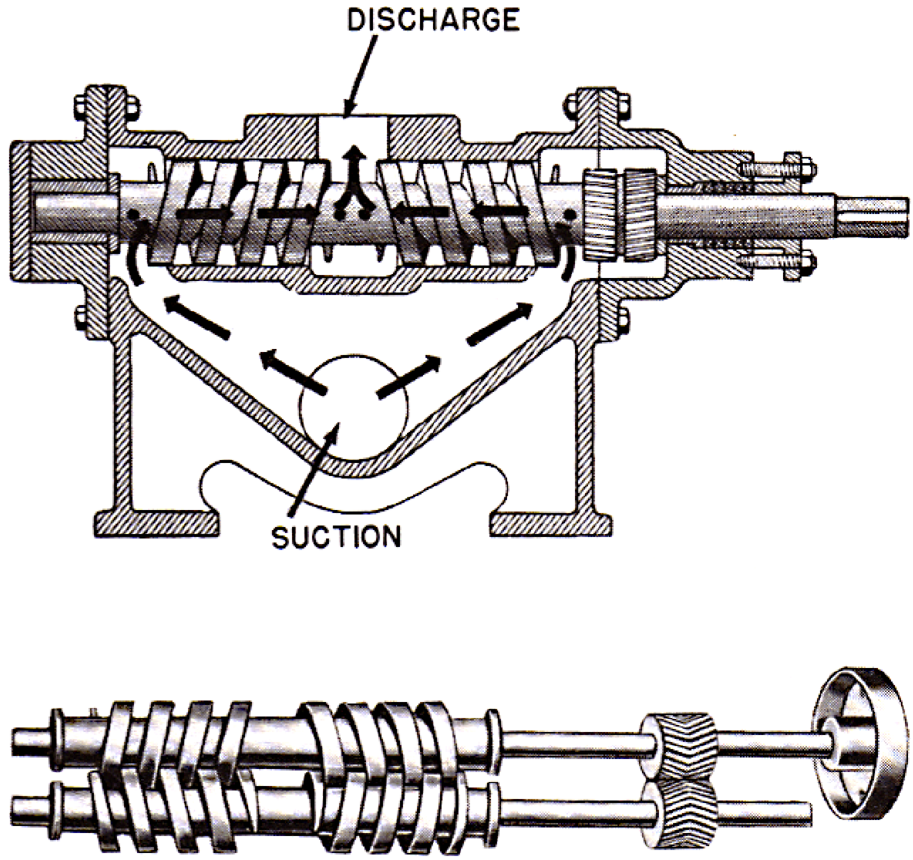
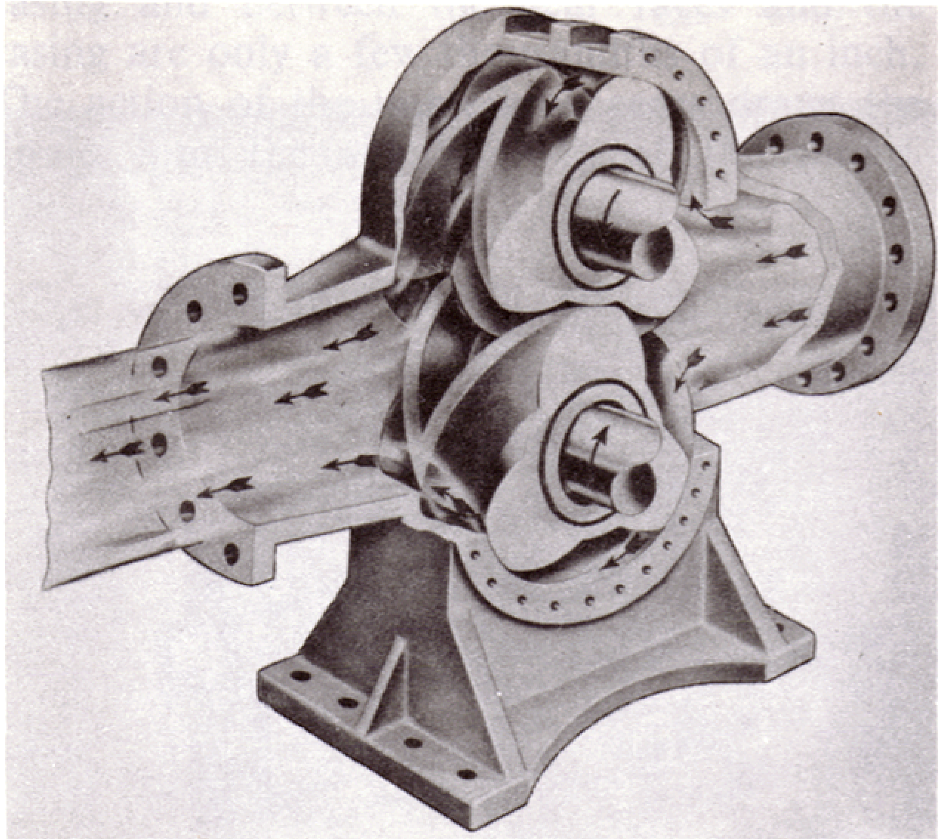


Figure 5.3.12 Screw Pump

Screw Pumps.

Most **screw pumps** consist of two to four intermeshing screws rotating in a closely fitted chamber. Liquid, trapped in the channels between the intermeshing screws, is pushed to the pump discharge as the thread of one screw rotates onto the channel of another screw. One screw, generally called the , is driven by an outside power source. The other screws, generally called , have their shafts turned by timing gears or by direct contact between the intermeshing screw threads.



Lobe Pumps. **Figure 5.3.13** Lobe Pump

Lobe pumpsoperate on the same principle as gear pumps. There are two rotors turning in the pump chamber operating through timing gears on the shafts outside the pump chamber. Most rotors are fitted with two to three lobes (similar to large gear teeth) to push fluid from the suction to the discharge side of the pump. Although the design will handle both liquids or gases, they are more commonly found pumping gases. A common application is an air pump to supply or increase the air flow to diesel and gasoline engines as part of the system necessary to make them run or increase the horsepower of the engine. In most cases they are considered high volume, low pressure pumps.

Vane Pumps. In **vane pumps**, the rotor is fitted with a number of slots into which movable vanes are installed. The pump chamber is larger in diameter than the rotor and the rotor is offset in the pump chamber so that they almost come in contact with each other at the 12 o'clock position and are separated by some distance at the 6 o'clock position. As the rotor revolves, the vanes are thrown out by centrifugal force to bear against the inside surface of the pump chamber. (Liquid pressure behind the vanes also pushes them in contact with the chamber wall and sometimes springs are used behind the vanes to force them against the chamber wall) As the rotor turns from the 12 o'clock position to the 6 o'clock position, it moves away from the chamber wall and liquid flows into the space between the moving vanes. From approximately the 5 o'clock to the 7 o'clock position, the liquid is trapped between two vanes, the rotor and the chamber wall and is pushed to the discharge side of the pump. As the rotor revolves back to the 12 o'clock position, the space between the rotor and the chamber wall decreases, forcing the liquid to the discharge connection on the pump casing. Different designs of vanes may be used, as shown in Figure 5.3.14, but the sliding vane type is most common.

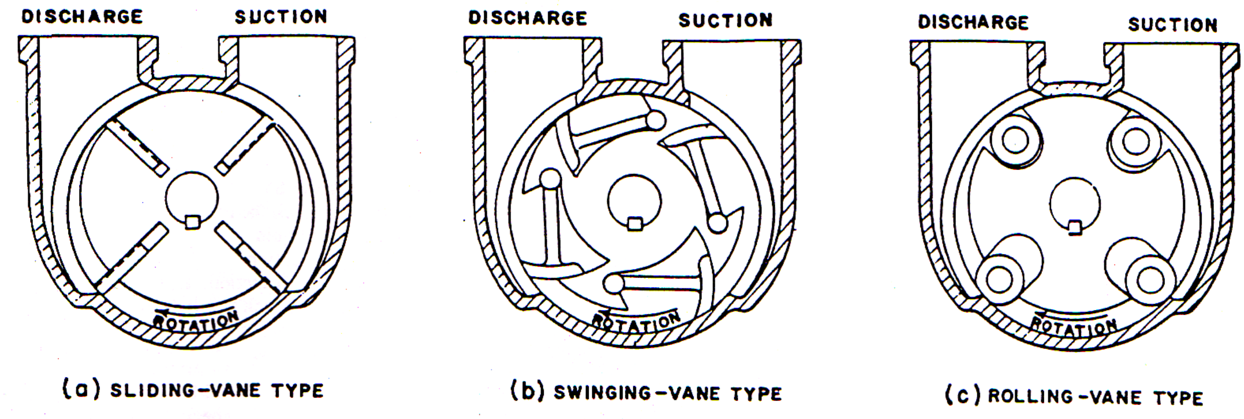


Figure 5.3.14 Vane Pump

5.4 Piping and Instrumentation Diagrams

STANDARD P&ID SYMBOL LIBRARY

VALVE

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
	B'FLY LUG TYPE		PRESS. CONT. PRIM./SEC. PNEU./DIRECT
	B'FLY WAFER TYPE		PRESS. REDUCING
	B'FLY FLANGE TYPE		QUICK CLOSING PNEU. (STR./ANG.)
	BALL FULL BORE SOLID		QUICK CLOSING WIRE (STR./ANG.)
	BALL 3-WAY (T-TYPE/L-TYPE)		REM. HYD. B'FLY LUG
	COCK 2-WAY		REM. HYD. B'FLY WAFER
	COCK 3-WAY (T-TYPE/L-TYPE)		REM. HYD. B'FLY FLANGE
	DEAERATING (STR/ANG)		SELF CLOSING SPRING (STR./ANG.)
	FLOW CONT. BALL FLOAT		SAFTY (STR./ANG.)
	FLOW CONT. BALL FLOAT CHECK		STORM VERT. SDNR (STR./ANG)
	GLOBE (STR/ANG)		STORM VERT. SWING CHECK STR.
	GLOBE SDNR		TEMP. CONT. 2-WAY WAX
	GATE VALVE		TEMP. CONT. 2-WAY PNEU.
N.O N.C	LOCK (OPEN/CLOSE)		TEMP. CONT. 3- WAY WAX
	HOSE VALVE (STR/ANG)		TEMP. CONT. 3- WAY ROTARY PISTON
	SOLENOID 2-WAY (STR/ANG)		TEMP. CONT. 3-WAY PNEU.
	SOLENOID 3-WAY		3-WAY MOTOR VALVE
	NON-RETURN FLAP		HOSE CONN. BALL VALVE
	NON-RETURN SWING TILTTING CHECK		ORIFICE PLATE
	NON-RETURN LIFT (STR/ANG)		ORIFICE VALVE
	NEEDLE STRAIGHT		NEEDLE 3-WAY TEST

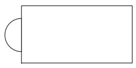
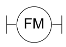
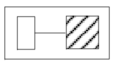
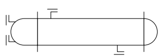
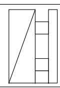
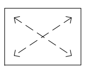
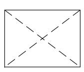
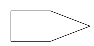
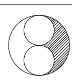
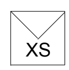
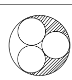
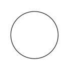
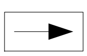
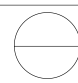
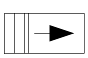
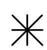
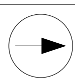
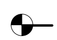
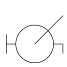
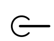
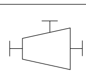
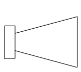
STANDARD P&ID SYMBOL LIBRARY

VALVE,FITTING

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
	AIR VENT GOOSE NECK PIPE		SEPARATOR
	AIR VENT GOOSE NECK PIPE WITH SCREEN		SLEEVE COUPLING
	AIR VENT GOOSE NECK PIPE WITH SCREEN & DRAIN COWL		SOUNDING CAP DK PIECE
	AIR VENT HEAD (FLOAT BALL/FLOAT DISC)		SOUNDING CAP NORMAL
	BELL MOUTH		SOUNDING CAP SELF CLOS'G WEIGHT PEDAL WITH COCK
	BELLOWS COUPLING		SOUNDING CAP SELF CLOS'G WEIGHT WITH COCK
	BLANK FLANGE		SOUNDING CAP SELF CLOS'G GATE TYPE
	BOSS & PLUG		SPECTACLE FLANGE (NORMAL OPEN/CLOSE)
	SIGHT GLASS		SPOOL PIECE
	DRESSER COUPLING		STEAM TRAP DISC TYPE WITH VALVE
	FILLING CAP		STEAM TRAP BALL FLOAT TYPE
	FLEXIBLE HOSE		STRAINER DUPLEX
	HOPPER		STRAINER SIMPLEX
	LEVEL GAUGE WITH VALVE (FLAT/CYLINDRICAL TYPE)		STRAINER Y-TYPE
			REDUCER
	LEVEL GAUGE (FLOAT/DIAL FLOAT) TYPE		ROSE BOX
		H H	REM. HYD. GLOBE SDNR
	DIAL LEVEL GAUGE WITH VALVE (CONTENT TYPE)		DECK STAND NORMAL
			DECK STAND LOCAL HYD.
	MUD BOX (STR/ANG)		SACRIFICIAL FLANGE
	OVERBOARD		

STANDARD P&ID SYMBOL LIBRARY

EQUIP, LINE FONT, INSTRU

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION	
	F.W FOUNTAIN		CAPILLARY TUBE	
	FLOW METER		CONTROL AIR PIPE	
	AUTO FILTER		DECK	
	TUBULAR TYPE HEAT EXCHANGER		ELECTRIC CABLE	
	COOLER PLATE TYPE		HYD. OIL PIPE	
	HULL TANK		INSULATION	
	INDEPENDENT TANK		INSULATION WITH STEAM TRACING	
	MAKER SUPPLY		CONNECTED TO MARKED PAGE (OTHER SYS DWG)	
	GEAR PUMP		AUX. SWITCH	
	SCREW PUMP		LOCAL INSTRUMENT	
	MONO PUMP		REMOTE CONTROL INSTRUMENT	
	PISTON PUMP		MAKER SUPPLY ITEM	
	CENTRIFUGAL PUMP		PIPE UP	
	HAND PUMP		PIPE DOWN	
	EJECTOR			
	HORN			

INSTRUMENT SYMBOL LIST

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
CP	COMPOUND GAUGE	SAH	SALINITY ALARM HIGH
DPI	DIFFERENTIAL PRESS. INDICATOR	SD	SALINITY DETECTOR
DPS	DIFFERENTIAL PRESS. SWITCH	SI	SALINITY INDICATOR
DPT	DIFFERENTIAL PRESS. TRANSMITTER	TAH	TEMPERATURE ALARM HIGH
FD	FLOW DETECTOR	TAL	TEMPERATURE ALARM LOW
FS	FLOW SWITCH	TI	TEMPERATURE INDICATOR
FT	FLOW TRANSMITTER	TIAH	TEMP. INDICATOR ALARM HIGH
LAH	LEVEL ALARM HIGH	TIAL	TEMP. INDICATOR ALARM LOW
LAL	LEVEL ALARM LOW	TIAHL	TEMP. INDICATOR ALARM HIGH LOW
LCH	LEVEL CONTROL HIGH	TIC	TEMPERATURE INDICATING CONTROLLER
LCL	LEVEL CONTROL LOW	TS	TEMPERATURE SWITCH
LI	LEVEL INDICATOR	TT	TEMPERATURE TRANSMITTER
LIAHL	LEVEL INDICATOR ALARM HIGH LOW	VAH	VISCOSITY ALARM HIGH
LIC	LEVEL INDICATING CONTROLLER	VAL	VISCOSITY ALARM LOW
LS	LEVEL SWITCH	VCA	VACUUM ALARM
LT	LEVEL TRANSMITTER	VCT	VACUUM TRANSMITTER
PAH	PRESSURE ALARM HIGH	VI	VISCOSITY INDICATOR
PAL	PRESSURE ALARM LOW	VIAHL	VISCOSITY INDICATOR ALARM HIGH LOW
PI	PRESSURE INDICATOR	VT	VISCOSITY TRANSMITTER
PIAH	PRESS. INDICATOR ALARM HIGH	VIC	VISCOSITY INDICATING CONTROLLER
PIAL	PRESS. INDICATOR ALARM LOW	XA	ABNORMAL ALARM
PIAHL	PRESS.INDICATOR ALARM HIGH LOW	XS	AUX. UNSPECIFIED SWITCH
PIC	PRESSURE INDICATING CONTROLLER	ZI	POSITION INDICATOR
PS	PRESSURE SWITCH	ZS	LIMIT SWITCH
PSL	PRESSURE LOW SWITCH	EP	E/P TRANDUCER
PT	PRESSURE TRANSMITTER	RS	REMOTE SOUNDING (AIR PURGE TYPE)

Chapter 6

Diesel Propulsion

A diesel engine is one type of internal combustion engine in which chemical energy of a fuel is converted directly into power available for doing work. These prime movers are built in sizes ranging from a few horsepower to over 100,000. Within the limits of its range of horsepower, the diesel engine is the most efficient source of power available.

This very efficient and self-contained source of power is quite versatile in its application. Diesels are widely used for electrical power in a wide variety of commercial and industrial application. In the field of transportation, they power locomotives, trucks and all varieties of oceangoing vessels.

Diesel engines will operate on a wide variety of liquid fuel oils. Most large slow speed engines operate on Heavy Fuel Oil (HFO). With a growing trend for engines to run on gaseous fuels such as natural gas or bio-gas, many engines operate on a combination of liquid and gaseous fuels and called "dual-fuel" engines.

The burning of fuel and air in the engine cylinder with the piston close to the top point of travel (top dead center) causes a marked increase in the pressure and temperature in the combustion space over the piston. This pressure "P" on pounds per square inch, Figure 1-1, on each square inch of top of the piston acts through a connecting rod to exert a force on the crank pin. This causes the crankshaft to rotate as indicated by the arrow.

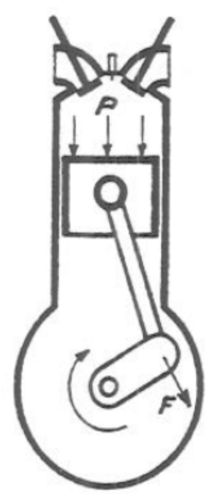


Fig. 1-1, Conversion of cylinder pressure to a rotating force, or torque in the crankshaft.

Figure 6.0.1

As the piston is forced down, the pressure of 800 to over 1400 PSI and temperatures that can reach 3,500° will decrease as the gas expands. As the piston approaches the bottom point of travel (bottom dead center), pressure will be approximately 50 PSI and temperature close to 800° just before the exhaust valve or ports opens. During this stroke of the piston, a large portion of the energy released from the fuel during combustion will have been converted into rotational force on the crankshaft. The crankshaft is then capable of transmitting this rotational force and doing work.

6.1 History of the Internal Combustion Engine

Figure 6.1.1 Nicolaus Otto (1832)

Born in 1832 in Germany, Nicolaus August Otto invented the first practical alternative to the steam engine - the first successful four-stroke cycle engine. Otto built his first four-stroke engine in 1861. Then, in partnership with German industrialist Eugen Langen, they improved the design and won a gold medal at the World Exposition in Paris of 1867.

In 1876, Otto, then a traveling salesman, chanced upon a newspaper account of the Lenoir internal combustion engine. Before year's end, Otto had built an internal combustion engine, utilizing a four-stroke piston cycle. Now called the 'Otto cycle' in his honor, the design called for four strokes of a piston to draw in and compress a gas-air mixture within a cylinder resulting in an internal explosion. He received patent #365,701 for his gas-motor engine. Because of its reliability, efficiency, and relative quietness, more than 30,000 Otto cycle engines were built in the next 10 years. He also developed low-voltage magneto ignition systems for his engines, allowing a much greater ease in starting.

Figure 6.1.2 Rudolf Diesel (1858)

Dr. Rudolf Diesel was born in 1858 in France and began his career as a refrigeration engineer. For ten years he worked on various heat engines, including a solar-powered air engine. Diesel's ideas for an engine where the combustion would be carried out within the cylinder were published in 1893.

The modern diesel engine came about as the result of the internal combustion principles first proposed by Sadi Carnot in the early 19th century. Dr. Rudolf Diesel applied Sadi Carnot's principles into a patented cycle or method of combustion that has become known as the "diesel" cycle. His patented engine operated when the heat generated during the compression of the air fuel charge caused ignition of the mixture, which then expanded at a constant pressure during the full power stroke of the engine. Dr. Diesel's first engine ran on coal dust and used a compression pressure of 1500 psi to increase its theoretical efficiency. Also, his first engine did not have provisions for any type of cooling system. Consequently, between the extreme pressure and the lack of cooling, the engine exploded and almost killed its inventor. After recovering from his injuries, Diesel tried again using oil as the fuel, adding a cooling water jacket around the cylinder, and lowering the compression pressure to approximately 550 psi. This combination eventually proved successful. Production rights to the engine were sold to Adolphus Bush, who built the first diesel engines for commercial use, installing them in his St. Louis brewery to drive various pumps.

6.2 The Basic Diesel Cycle

All diesel engines fall into one of two categories, two-stroke or four-stroke cycle engines. The word cycle refers to any operation or series of events that repeats itself. In the case of a four stroke cycle engine, the engine requires four strokes of the piston (intake, compression, power, and exhaust) to complete one full cycle. Therefore, it requires two rotations of the crankshaft, or 720° of crankshaft rotation (360° x 2) to complete one cycle. In a two-stroke cycle engine the events (intake, compression, power, and exhaust) occur in only one rotation of the crankshaft, or 360°.

In the following discussion of the diesel cycle it is important to keep in mind the time frame in which each of the actions is required to occur. Time is required to move exhaust gas out of the cylinder and fresh air in to the cylinders, to compress the air, to inject fuel, and to burn the fuel. If a four-stroke diesel engine is running at a constant 2100 revolutions per minute (rpm), the crankshaft would be rotating at 35 revolutions, or 12,600 degrees, per second. One stroke is completed in about 0.01429 seconds.

Ignition occurs in a diesel by injecting fuel into the air charge which has been heated by compression to a temperature greater than the ignition point of the fuel.

A diesel engine converts the energy stored in the fuel's chemical bonds into mechanical energy by burning the fuel. The chemical reaction of burning the fuel liberates heat, which causes the gasses to expand, forcing the piston to rotate the crankshaft.

A four-stroke engine requires two rotations of the crankshaft to complete one cycle. The event occur as follows:

> Intake - the piston passes TDC, the intake valve(s) open and the fresh air is admitted into the cylinder, the exhaust valve is still open for a few degrees to allow scavenging to occur.
>
> Compression - after the piston passes BDC the intake valve closes and the piston travels up to TDC (completion of the first crankshaft rotation).
>
> Fuel injection - As the piston nears TDC on the compression stroke, the fuel is injected by the injectors and the fuel starts to burn, further heating the gasses in the cylinder.
>
> Power - the piston passes TDC and the expanding gasses force the piston down, rotating the crankshaft.
>
> Exhaust - as the piston passes BDC the exhaust valves open and the exhaust gasses start to flow out of the cylinder. This continues as the piston travels up to TDC, pumping the spent gasses out of the cylinder. At TDC the second crankshaft rotation is complete.

A two-stroke engine requires one rotation of the crankshaft to complete one cycle. The events occur as follows:

> Intake - the piston is near BDC and exhaust is in progress. The intake valve or ports open and the fresh air is forced in. The exhaust valves or ports are closed and intake continues.
>
> Compression - after both the exhaust and intake valves or ports are closed, the piston travels up towards TDC. The fresh air is heated by the compression.
>
> Fuel injection - near TDC the fuel is injected by the injectors and the fuel starts to burn, further heating the gasses in the cylinder.
>
> Power - the piston passes TDC and the expanding gasses force the piston down, rotating the crankshaft.
>
> Exhaust - as the piston approaches BDC the exhaust valves or ports open and the exhaust gasses start to flow out of the cylinder.

6.2.1 Four Stroke Cycle

In a four-stroke engine the camshaft is geared so that it rotates at half the speed of the crankshaft (1:2). This means that the crankshaft must make two complete revolutions before the camshaft will complete one revolution. The following section will describe a four-stroke, normally aspirated, diesel engine having both intake and exhaust valves with a 3.5-inch bore and 4-inch stroke with a 16:1 compression ratio, as it passes through one complete cycle. We will start on the intake stroke. All the timing marks given are generic and will vary from engine to engine.

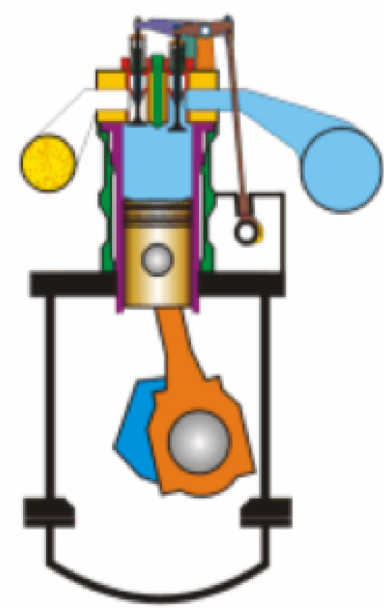


Figure 6.2.1 16-Intake

As the piston moves upward and approaches 28° before top dead center (BTDC), as measured by crankshaft rotation, the camshaft lobe starts to lift the cam follower. This causes the pushrod to move upward and pivots the rocker arm on the rocker arm shaft. As the valve lash is taken up, the rocker arm pushes the intake valve downward and the valve starts to open. The intake stroke now starts while the exhaust valve is still open. The flow of the exhaust gasses will have created a low pressure condition within the cylinder and will help pull in the fresh air charge as shown in Figure 16. The piston continues its upward travel through top dead center (TDC) while fresh air enters and exhaust gasses leave. At about 12° after top dead center (ATDC), the camshaft exhaust lobe rotates so that the exhaust valve will start to close. The valve is fully closed at 23° ATDC. This is accomplished through the valve spring, which was compressed when the valve was opened, forcing the rocker arm and cam follower back against the cam lobe as it rotates. The time frame during which both the intake and exhaust valves are open is called valve overlap (51° of overlap in this example) and is necessary to allow the fresh air to help scavenge (remove) the spent exhaust gasses and cool the cylinder. In most engines, 30 to 50 times cylinder volume is scavenged through the cylinder during overlap. This excess cool air also provides the necessary cooling effect on the engine parts. As the piston passes TDC and begins to travel down the cylinder bore, the movement of the piston creates a suction and continues to draw fresh air into the cylinder.

Figure 6.2.2 18- Compression

At 35° after bottom dead center (ABDC), the intake valve starts to close. At 43° ABDC (or 137° BTDC), the intake valve is on its seat and is fully closed. At this point the air charge is at normal pressure (14.7 psia) and ambient air temperature (~80°F), as illustrated in Figure 17. At about 70° BTDC, the piston has traveled about 2.125 inches, or about half of its stroke, thus reducing the volume in the cylinder by half. The temperature has now doubled to ~160°F and pressure is ~34 psia. At about 43° BTDC the piston has traveled upward 3.062 inches of its stroke and the volume is once again halved. Consequently, the temperature again doubles to about 320°F and pressure is ~85 psia. When the piston has traveled to 3.530 inches of its stroke the volume is again halved and temperature reaches ~640°F and pressure 277 psia. When the piston has traveled to 3.757 inches of its stroke, or the volume is again halved, the temperature climbs to 1280°F and pressure reaches 742 psia. With a piston area of 9.616 in2 the pressure in the cylinder is exerting a force of approximately 7135 lb. or 3-1/2 tons of force. The above numbers are ideal and provide a good example of what is occurring in an engine during compression. In an actual engine, pressures reach only about 690 psia. This is due primarily to the heat loss to the surrounding engine parts.

Figure 6.2.3 18 Fuel Injection

Fuel in a liquid state is injected into the cylinder at a precise time and rate to ensure that the combustion pressure is forced on the piston neither too early nor too late, as shown in Figure 18. The fuel enters the cylinder where the heated compressed air is present; however, it will only burn when it is in a vaporized state (attained through the addition of heat to cause vaporization) and intimately mixed with a supply of oxygen. The first minute droplets of fuel enter the combustion chamber and are quickly vaporized. The vaporization of the fuel causes the air surrounding the fuel to cool and it requires time for the air to reheat sufficiently to ignite the vaporized fuel. But once ignition has started, the additional heat from combustion helps to further vaporize the new fuel entering the chamber, as long as oxygen is present. Fuel injection starts at 28° BTDC and ends at 3° ATDC; therefore, fuel is injected for a duration of 31°.

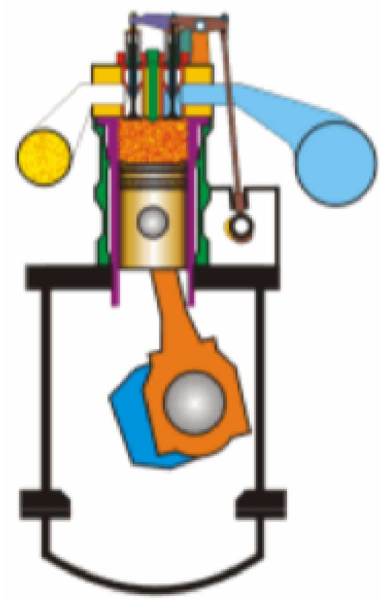


Figure 6.2.4 19- Power

Both valves are closed, and the fresh air charge has been compressed. The fuel has been injected and is starting to burn. After the piston passes TDC, heat is rapidly released by the ignition of the fuel, causing a rise in cylinder pressure. Combustion temperatures are around 2336°F. This rise in pressure forces the piston downward and increases the force on the crankshaft for the power stroke as illustrated in Figure 19. The energy generated by the combustion process is not all harnessed. In a two stroke diesel engine, only about 38% of the generated power is harnessed to do work, about 30% is wasted in the form of heat rejected to the cooling system, and about 32% in the form of heat is rejected out the exhaust. In comparison, the four-stroke diesel engine has a thermal distribution of 42% converted to useful work, 28% heat rejected to the cooling system, and 30% heat rejected out the exhaust.

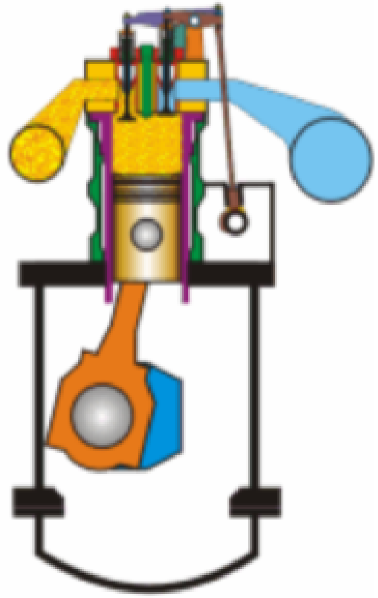


Figure 6.2.5 20- Exhaust

As the piston approaches 48° BBDC, the cam of the exhaust lobe starts to force the follower upward, causing the exhaust valve to lift off its seat. As shown in Figure 20, the exhaust gasses start to flow out the exhaust valve due to cylinder pressure and into the exhaust manifold. After passing BDC, the piston moves upward and accelerates to its maximum speed at 63° BTDC. From this point on the piston is decelerating. As the piston speed slows down, the velocity of the gasses flowing out of the cylinder creates a pressure slightly lower than atmospheric pressure. At 28° BTDC, the intake valve opens and the cycle starts again.

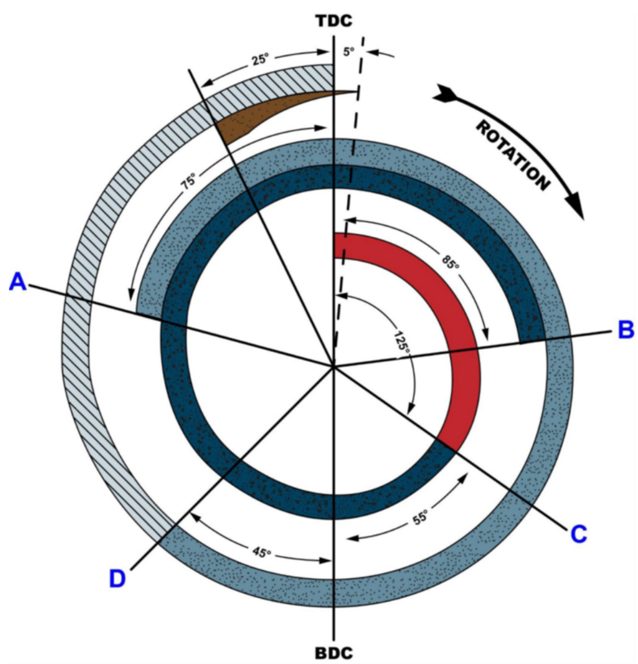


Figure 6.2.6 21-Four Stroke Timing Diagram, Naturally Aspirated Engine

A-Intake valve Opening, B- Exhaust Valve Closing, C- Exhaust Valve Opening, D- Intake Valve

Closing

6.2.2 Two Stroke Cycle

Like the four-stroke engine, the two-stroke engine must go through the same four events: intake, compression, power, and exhaust. But a two-stroke engine requires only two strokes of the piston to complete one full cycle. Therefore, it requires only one rotation of the crankshaft to complete a cycle. This means several events must occur during each stroke for all four events to be completed in two strokes, as opposed to the four-stroke engine where each stroke basically contains one event.

In a two-stroke engine the camshaft is geared so that it rotates at the same speed as the crankshaft (1:1). The following section will describe a two-stroke, supercharged, diesel engine having intake ports and exhaust valves with a 3.5-inch bore and 4-inch stroke with a 16:1 compression ratio, as it passes through one complete cycle. We will start on the exhaust stroke. All the timing marks given are generic and will vary from engine to engine. Exhaust and Intake

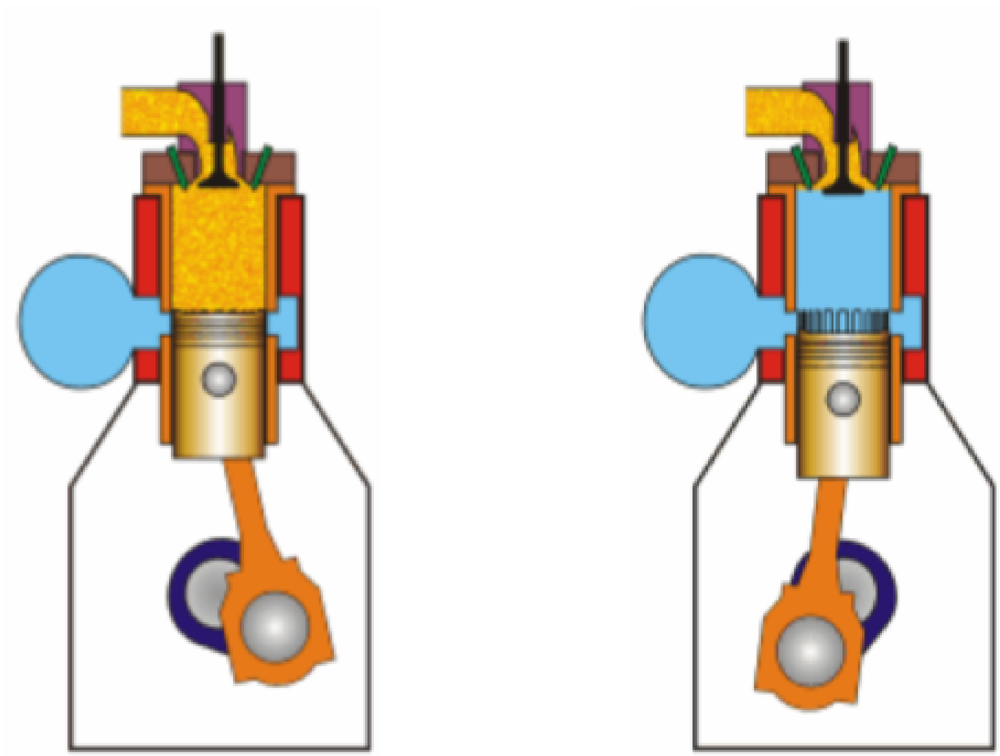


Figure 6.2.7 Figure 22- Exhaust Figure 23- Intake

At 82° ATDC, with the piston near the end of its power stroke, the exhaust cam begins to lift the exhaust valves follower. The valve lash is taken up, and 9° later (91° ATDC), the rocker arm forces the exhaust valve off its seat. The exhaust gasses start to escape into the exhaust manifold, as shown in Figure 21. Cylinder pressure starts to decrease. After the piston travels three-quarters of its (down) stroke, or 132° ATDC of crankshaft rotation, the piston starts to uncover the inlet ports. As the exhaust valve is still open, the uncovering of the inlet ports lets at 43° ABDC, the camshaft starts to close the exhaust valve. At 53° ABDC (117° BTDC), the camshaft has rotated sufficiently to allow the spring pressure to close the exhaust valve. Also, as the piston travels past 48°ABDC (5° after the exhaust valve starts closing), the intake ports are closed off by the piston. The compressed fresh air enter the cylinder and helps cool the cylinder and scavenge the cylinder of the remaining exhaust gasses

(Figure 22). Commonly, intake and exhaust occur over approximately 96° of crankshaft rotation.

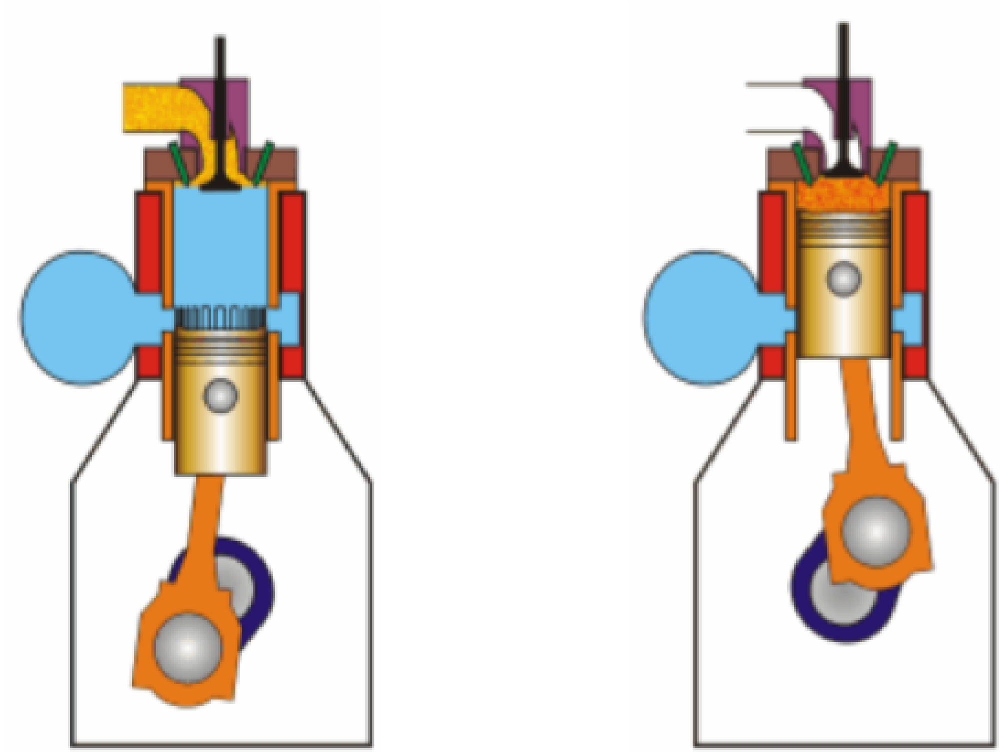


Figure 6.2.8 Figure 24- Compression Figure 25- Power

After the exhaust valve is on its seat (53° ATDC), the temperature and pressure begin to rise in nearly the same fashion as in the four-stroke engine. Figure 24 illustrates the compression in a 2-stroke engine. At 23° BTDC the injector cam begins to lift the injector follower and pushrod. Fuel injection continues until 6° BTDC (17 total degrees of injection).

The power stroke starts after the piston passes TDC. Figure 25 illustrates the power stroke which continues until the piston reaches 91° ATDC, at which point the exhaust valves start to open and a new cycle begins.

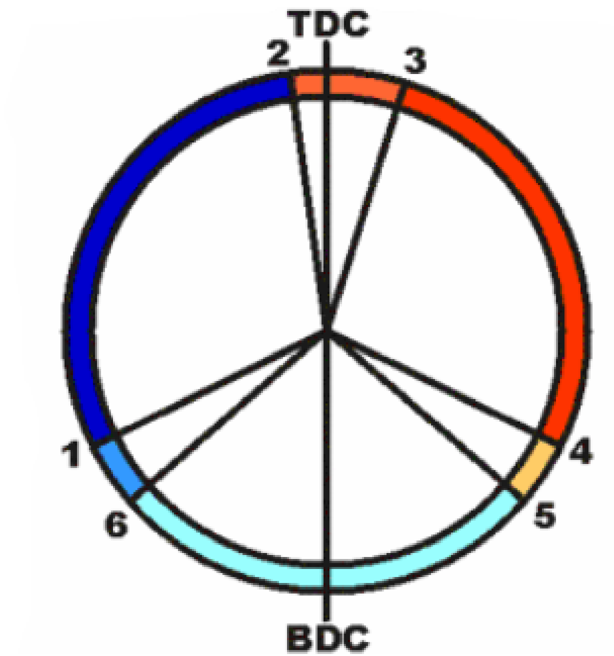


Figure 6.2.9 Figure 26- 2 Stroke Cycle Timing Diagram 1-2 Compression, 2-3 Injection, 3-4 Power, 4-5 Exhaust, 5-6 Scavenging, 6-1 Supercharging

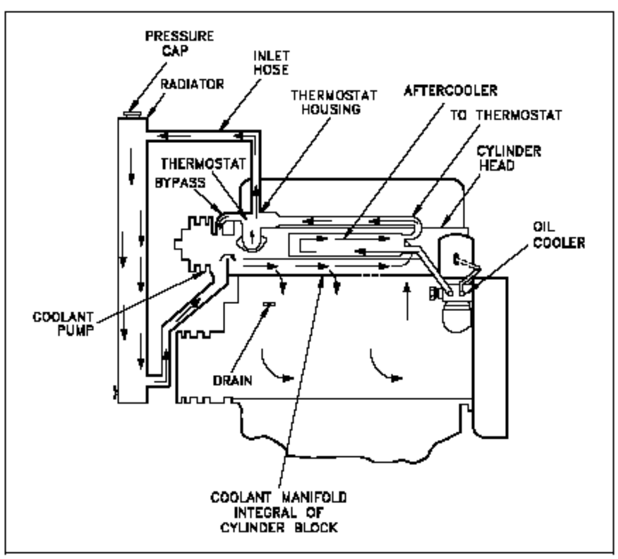


Figure 11 Diesel Engine Cooling System

Figure 6.2.10

6.3 Engine Specifications

6.3.1 Bore and Stroke

Bore and stroke are terms used to define the size of an engine. As previously stated, bore refers to the diameter of the engine's cylinder, and stroke refers to the distance the piston travels from the top of the cylinder to the bottom. The highest point of travel by the piston is called top dead center (TDC), and the lowest point of travel is called bottom dead center (BDC). There are 180o of travel between TDC and BDC, or one stroke.

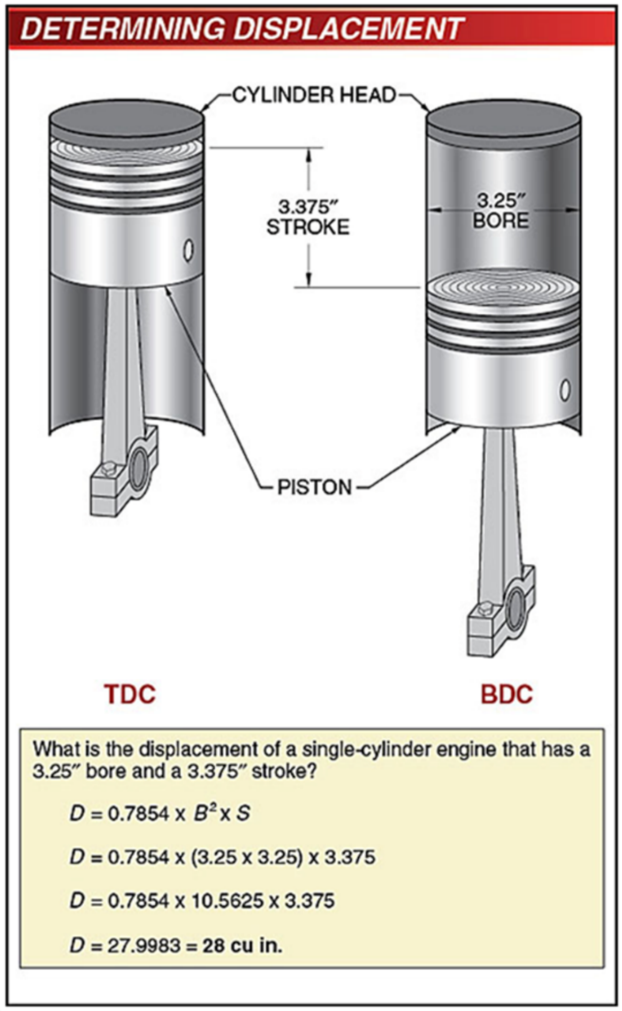


Figure 6.3.1

6.3.2 Engine Displacement

Engine displacement is one of the terms used to compare one engine to another. Displacement refers to the total volume displaced by all the pistons during one stroke. The displacement is usually given in cubic inches or liters. To calculate the displacement of an engine, the volume of one cylinder must be determined (volume of a cylinder = (□ r2)h where h = the stroke). The volume of one cylinder is multiplied by the number of cylinders to obtain the total engine displacement.

6.3.3 Degree of Crankshaft Rotation

All events that occur in an engine are related to the location of the piston. Because the piston is connected to the crankshaft, any location of the piston corresponds directly to a specific number of degrees of crankshaft rotation. Location of the crank can then be stated as XX degrees before or XX degrees after top or bottom dead center.

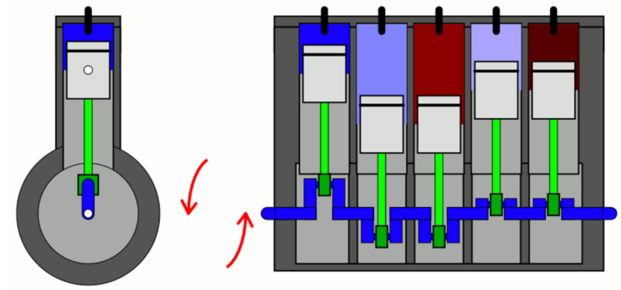


Figure 6.3.2

6.3.4 Firing Order

Firing order refers to the order in which each of the cylinders in a multi-cylinder engine fires (power stroke). For example, a four cylinder engine's firing order could be 1-4-3-2. This means that the number 1 cylinder fires, then the number 4 cylinder fires, then the number 3 cylinder fires, and so on. Engines are designed so that the power strokes are as uniform as possible, that is, as the crankshaft rotates a certain number of degrees, one of the cylinders will go through a power stroke. This reduces vibration and allows the power generated by the engine to be applied to the load in a smoother fashion than if they were all to fire at once or in odd multiples.

6.3.5 Compression Ratio and Clearance Volume

Clearance volume is the volume remaining in the cylinder when the piston is at TDC. Because of the irregular shape of the combustion chamber (volume in the head) the clearance volume is calculated empirically by filling the chamber with a measured amount of fluid while the piston is at TDC. This volume is then added to the displacement volume in the cylinder to obtain the cylinders total volume. An engine's compression ratio is determined by taking the volume of the cylinder with piston at TDC (highest point of travel) and dividing the volume of the cylinder when the piston is at BDC (lowest point of travel), as shown in Figure 15. This can be calculated by using the following formula: Compression Ratio displacement volume clearance volume clearance volume.

Figure 6.3.3

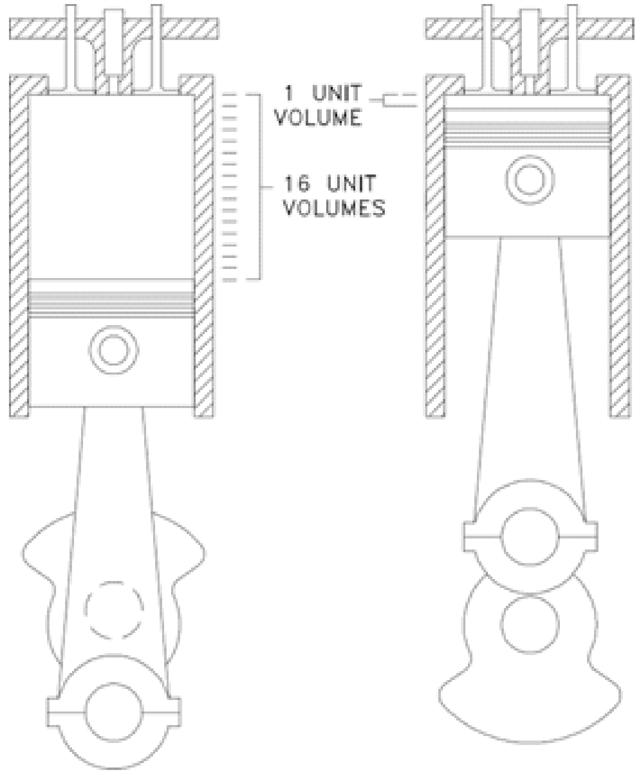


Figure 6.3.4 15 Compression Ratio

6.3.6 Horsepower

Power is the amount of work done per unit time or the rate of doing work. For a diesel engine, power is rated in units of horsepower. Indicated horsepower is the power transmitted to the pistons by the gas in the cylinders and is mathematically calculated.

Brake horsepower refers to the amount of usable power delivered by the engine to the end crankshaft. Indicated horsepower can be as much as 15% higher than brake horsepower. The difference is due to internal engine friction, combustion inefficiencies, and parasitic losses, for example, oil pump, blower, water pump, etc.

The ratio of an engine's brake horsepower and its indicated horsepower is called the mechanical efficiency of the engine. The mechanical efficiency of a four-cycle diesel is about 82 to 90 percent. This is slightly lower than the efficiency of the two-cycle diesel engine. The lower mechanical efficiency is due to the additional friction losses and power needed to drive the piston through the extra 2 strokes.

Engines are rated not only in horsepower but also by the torque they produce. Torque is a measure of the engine's ability to apply the power it is generating. Torque is commonly given in units of lb-ft.

6.4 Major Components of a Diesel Engine

To understand how a diesel engine operates, an understanding of the major components and how they work together is necessary. Figure 2 is an example of a medium-sized, four-stroke, supercharged, diesel engine with inlet ports and exhaust valves. Figure 3 provides a cross section of a similarly sized V-type diesel engine.

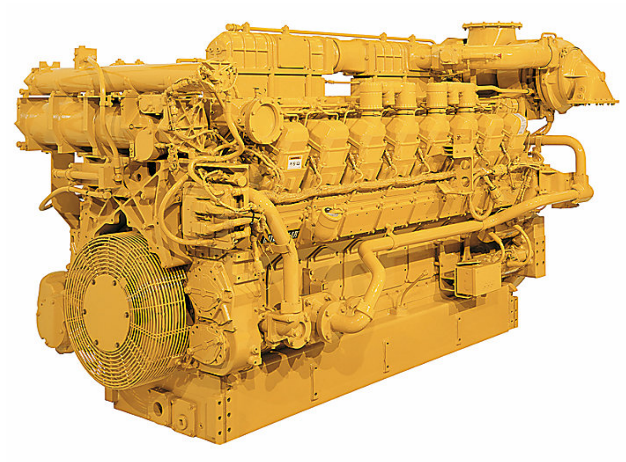


Figure 6.4.1 2- 16 cylinder, 4 stroke, turbocharged diesel engine

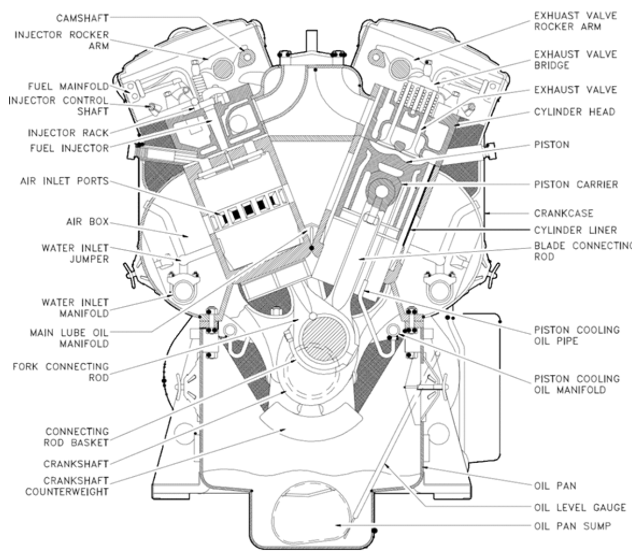


Figure 6.4.2 3 Cross Section of a V-type Four Stroke Diesel Engine

6.4.1 The Cylinder Block

The cylinder block, as shown in Figure 4, is generally a single unit made from cast iron. In a liquid-cooled diesel, the block also provides the structure and rigid frame for the engine's cylinders, water coolant and oil passages, and support for the crankshaft and camshaft bearings.

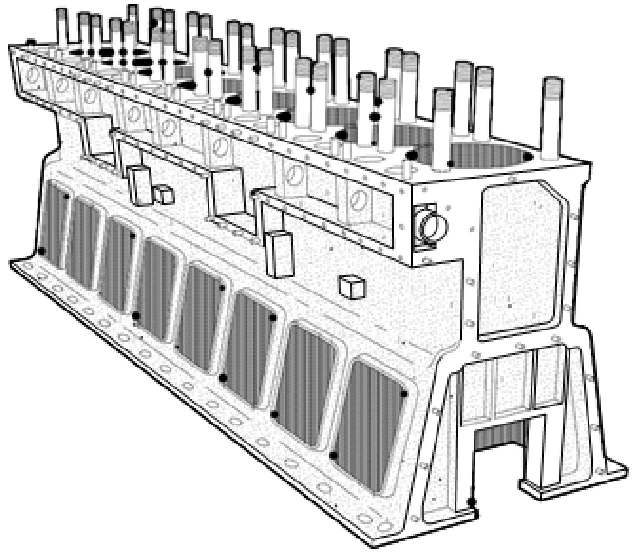


Figure 6.4.3 4 Cylinder Block

6.4.2 Crankcase and Oil Pan

The crankcase is usually located on the bottom of the cylinder block. The crankcase is defined as the area around the crankshaft and crankshaft bearings. This area encloses the rotating crankshaft and crankshaft counter weights and directs returning oil into the oil pan. The oil pan is located at the bottom of the crankcase as shown in Figure 2 and Figure 3. The oil pan collects and stores the engine's supply of lubricating oil. Large diesel engines may have the oil pan divided into several separate pans.

6.4.3 Cylinder Sleeve or Bore

Diesel engines use one of two types of cylinders. In one type, each cylinder is simply machined or bored into the block casting, making the block and cylinders an integral part. In the second type, a machined steel sleeve is pressed into the block casting to form the cylinder. Figure 2 and Figure 3 provide examples of sleeved diesel engines. With either method, the cylinder sleeve or bore provides the engine with the cylindrical structure needed to confine the combustion gasses and to act as a guide for the engine's pistons.

Four Stroke Cylinder Liner Two Stroke Cylinder Liner/air ports

In engines using sleeves, there are two types of sleeves, wet and dry. A dry sleeve is surrounded by the metal of the block and does not come in direct contact with the engine's coolant (water). A wet sleeve comes in direct contact with the engine's coolant. The volume enclosed by the sleeve or bore is called the combustion chamber and is the space where the fuel is burned. In either type of cylinder, sleeved or bored, the diameter of the cylinder is called the bore of the engine and is stated in inches. For example, the bore of a 350 cubic inch Chevrolet gasoline engine is 4 inches. Most diesel engines are multi-cylinder engines and typically have their cylinders arranged in one of two ways, an in-line or a ″V″, although other combinations exits. In an in-line engine, as the name indicates, all the cylinders are in a row. In a ″V″ type engine the cylinders are arranged in two rows of cylinders set at an angle to each other that align to a common crankshaft. Each group of cylinders making up one side of the ″V″ is referred to as a bank of cylinders.

6.4.4 Piston and Piston Rings

The piston transforms the energy of the expanding gasses into mechanical energy. The piston rides in the cylinder liner or sleeve as shown in Figure 2 and Figure 3. Pistons are commonly made of aluminum or cast iron alloys. To prevent the combustion gasses from bypassing the piston and to keep friction to a minimum, each piston has several metal rings around it, as illustrated by Figure 6. These rings function as the seal between the piston and the cylinder wall and also act to reduce friction by minimizing the contact area between the piston and the cylinder wall. The rings are usually made of cast iron and coated with chrome or molybdenum. Most diesel engine pistons have several rings, usually 2 to 5, with each ring performing a distinct function. The top ring(s) acts primarily as the pressure seal. The intermediate ring(s) acts as a wiper ring to remove and control the amount of oil film on the cylinder walls. The bottom ring(s) is an oiler ring and ensures that a supply of lubricating oil is evenly deposited on the cylinder walls.

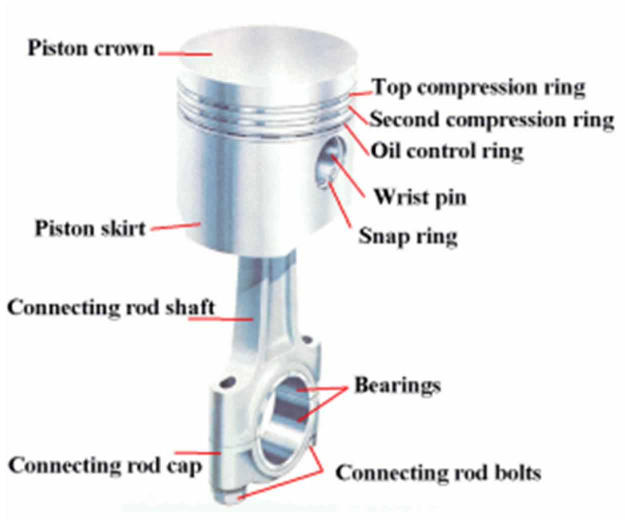


Figure 6.4.4 5 Piston and Connecting Rod

6.4.5 Connecting Rod

The connecting rod connects the piston to the crankshaft. See Figure 2 and Figure 3 for the location of the connecting rods in an engine. The rods are made from drop-forged, heat-treated steel to provide the required strength. Each end of the rod is bored, with the smaller top bore connecting to the piston pin (wrist pin) in the piston as shown in Figure 6. The large bore end of the rod is split in half and bolted to allow the rod to be attached to the crankshaft. Some diesel engine connecting rods are drilled down the center to allow oil to travel up from the crankshaft and into the piston pin and piston for lubrication.

A variation found in V-type engines that affects the connecting rods is to position the cylinders in the left and right banks directly opposite each other instead of staggered (most common configuration). This arrangement requires that the connecting rods of two opposing cylinders share the same main journal bearing on the crankshaft. To allow this configuration, one of the connecting rods must be split or forked around the other.

6.4.6 Crankshaft

The crankshaft transforms the linear motion of the pistons into a rotational motion that is transmitted to the load. Crankshafts are made of forged steel. The forged crankshaft is machined to produce the crankshaft bearing and connecting rod bearing surfaces. The rod bearings are eccentric, or offset, from the center of the crankshaft as illustrated in Figure 7. This offset converts the reciprocating (up and down) motion of the piston into the rotary motion of the crankshaft. The amount of offset determines the stroke (distance the piston travels) of the engine (discussed later).

The crankshaft does not ride directly on the cast iron block crankshaft supports, but rides on special bearing material as shown in Figure 7. The connecting rods also have bearings inserted between the crankshaft and the connecting rods. The bearing material is a soft alloy of metals that provides a replaceable wear surface and prevents galling between two similar metals (i.e., crankshaft and connecting rod). Each bearing is split into halves to allow assembly of the engine. The crankshaft is drilled with oil passages that allow the engine to feed oil to each of the crankshaft bearings and connection rod bearings and up into the connecting rod itself.

The crankshaft has large weights, called counter weights, that balance the weight of the connecting rods. These weights ensure an even (balance) force during the rotation of the moving parts.

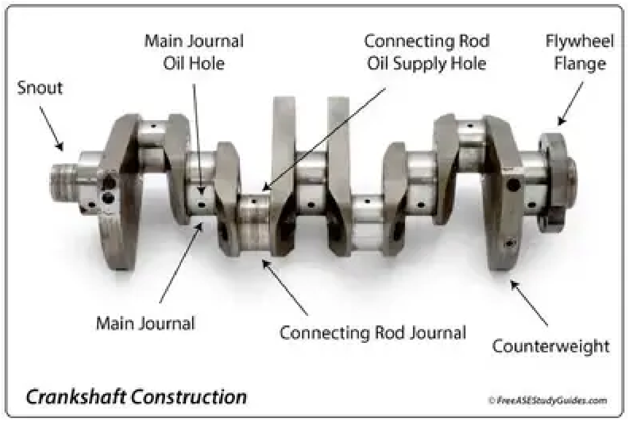


Figure 7 Crankshaft and Bearings

6.4.7 Flywheel

The flywheel is located on one end of the crankshaft and serves three purposes. First, through its inertia, it reduces vibration by smoothing out the power stroke as each cylinder fires. Second, it is the mounting surface used to bolt the engine up to its load. Third, on some diesels, the flywheel has gear teeth around its perimeter that allow the starting motors to engage and crank the diesel.

6.4.8 Cylinder Heads and Valves

A diesel engine's cylinder head performs several functions. First, they provide the top seal for the cylinder bore or sleeve. Second, they provide the structure holding exhaust valves (and intake valves where applicable), the fuel injector, and necessary linkages. A diesel engine's heads are manufactured in one of two ways. In one method, each cylinder has its own head casting, which is bolted to the block. This method is used primarily on the larger diesel engines. In the second method, which is used on smaller engines, the engine's head is cast as one piece (multi-cylinder head).

Diesel engines have two methods of admitting and exhausting gasses from the cylinder. They can use either ports or valves or a combination of both. Ports are slots in the cylinder walls located in the lower 1/3 of the cylinder liner. See Figure 2 and Figure 3 for examples of intake ports, and note their relative location with respect to the rest of the engine. When the piston travels below the level of the ports, the ports are "opened" and fresh air or exhaust gasses are able to enter or leave, depending on the type of port.

The ports are then "closed" when the piston travels back above the level of the ports. Valves (refer to figure 8) are mechanically opened and closed to admit or exhaust the gasses as needed. The valves are located in the head casting of the engine. The point at which the valve seals against the head is called the valve seat. Most medium-sized diesels have either intake ports or exhaust valves or both intake and exhaust valves.

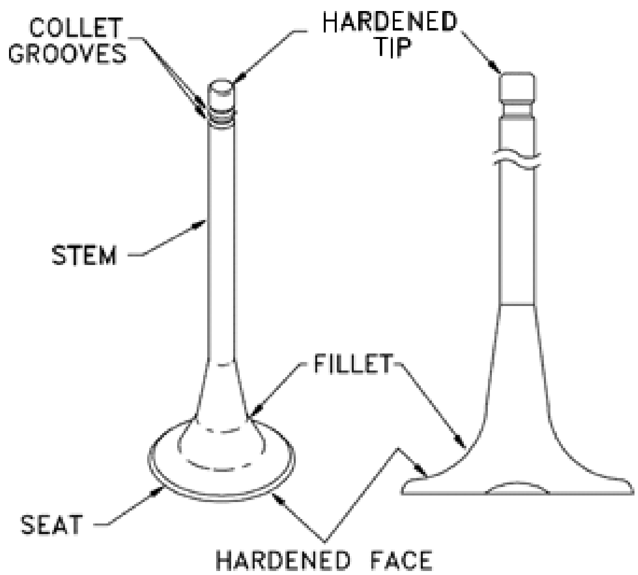


Figure 6.4.5 8 Diesel Engine Valves

6.4.9 Timing Gears, Camshaft, and Valve Mechanism

In order for a diesel engine to operate, all of its components must perform their functions at very precise intervals in relation to the motion of the piston. To accomplish this, a component called a camshaft is used. Figure 9 illustrates a camshaft and camshaft drive gear. Figure 2 and Figure 3 illustrate the location of a camshaft in a large overhead cam diesel engine. A camshaft is a long bar with egg-shaped eccentric lobes, one lobe for each valve and fuel injector (discussed later). Each lobe has a follower as shown on Figure 10.

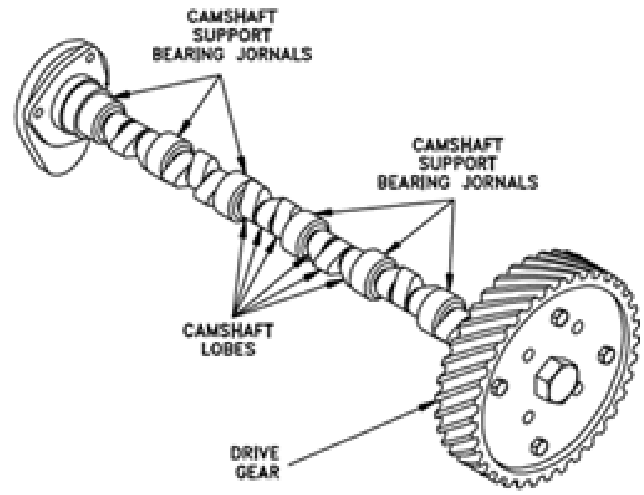


Figure 6.4.6 9 Camshaft and Drive Gear

As the camshaft is rotated, the follower is forced up and down as it follows the profile of the cam lobe. The followers are connected to the engine's valves and fuel injectors through various types of linkages called pushrods and rocker arms. The pushrods and rocker arms transfer the reciprocating motion generated by the camshaft lobes to the valves and injectors, opening and closing them as needed. The valves are maintained closed by springs.

As the valve is opened by the camshaft, it compresses the valve spring. The energy stored in the valve spring is then used to close the valve as the camshaft lobe rotates out from under the follower. Because an engine experiences fairly large changes in temperature (e.g., ambient to a normal running temperature of about 190 F), its components must be designed to allow for thermal expansion. Therefore, the valves, valve pushrods, and rocker arms must have some method of allowing for the expansion. This is accomplished by the use of valve lash. Valve lash is the term given to the "slop" or "give" in the valve train before the cam actually starts to open the valve.

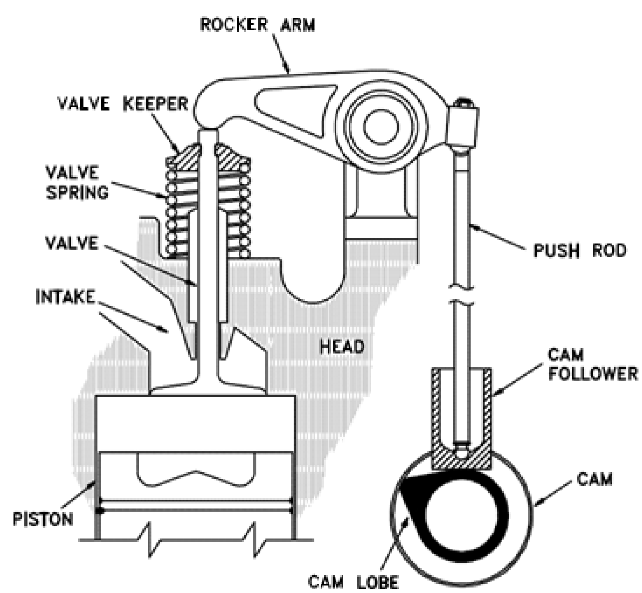


Figure 6.4.7 10 Diesel Engine Valve Train

The camshaft is driven by the engine's crankshaft through a series of gears called idler gears and timing gears. The gears allow the rotation of the camshaft to correspond or be in time with, the rotation of the crankshaft and thereby allows the valve opening, valve closing, and injection of fuel to be timed to occur at precise intervals in the piston's travel. To increase the flexibility in timing the valve opening, valve closing, and injection of fuel, and to increase power or to reduce cost, an engine may have one or more camshafts. Typically, in a medium to large V-type engine, each bank will have one or more camshafts per head. In the larger engines, the intake valves, exhaust valves, and fuel injectors may share a common camshaft or have independent camshafts.

Depending on the type and make of the engine, the location of the camshaft or shafts varies. The camshaft(s) in an in-line engine is usually found either in the head of the engine or in the top of the block running down one side of the cylinder bank. Figure 10 provides an example of an engine with the camshaft located on the side of the engine. Figure 3 provides an example of an overhead cam arrangement as on a V-type engine. On small or mid-sized V-type engines, the camshaft is usually located in the block at the center of the "V" between the two banks of cylinders. In larger or multi-cam shafted V- type engines, the camshafts are usually located in the heads.

6.5 Supporting System

6.5.1 Engine Cooling

Nearly all diesel engines rely on a liquid cooling system to transfer waste heat out of the block and internals as shown in Figure 11. The cooling system consists of a closed loop similar to that of a car engine and contains the following major components: water pump, radiator or heat exchanger, water jacket (which consists of coolant passages in the block and heads), and a thermostat.

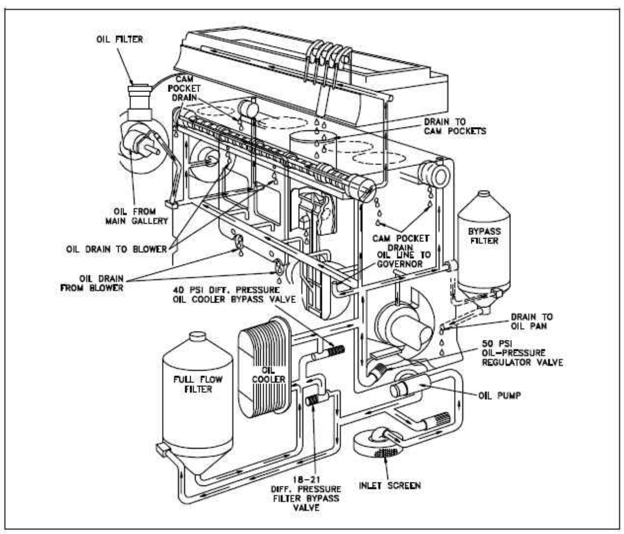


Figure 12 Diesel Engine Internal Lubrication System

Figure 6.5.1

6.5.2 Engine Lubrication System

An internal combustion engine would not run for even a few minutes if the moving parts were allowed to make metal-to-metal contact. The heat generated due to the tremendous amounts of friction would melt the metals, leading to the destruction of the engine. To prevent this, all moving parts ride on a thin film of oil that is pumped between all the moving parts of the engine. Once between the moving parts, the oil serves two purposes. One purpose is to lubricate the bearing surfaces. The other purpose is to cool the bearings by absorbing the friction generated heat. The flow of oil to the moving parts is accomplished by the engine's internal lubricating system. Oil is accumulated and stored in the engine's oil pan where one or more oil pumps take a suction and pump the oil through one or more oil filters as shown in Figure 12. The filters clean the oil and remove any metal that the oil has picked up due to wear. The cleaned oil then flows up into the engine's oil galleries. A pressure relief valve(s) maintains oil pressure in the galleries and returns oil to the oil pan upon high pressure. The oil galleries distribute the oil to all the bearing surfaces in the engine. Once the oil has cooled and lubricated the bearing surfaces, it flows out of the bearing and gravity-flows back into the oil pan. In medium to large diesel engines, the oil is also cooled before being distributed into the block. This is accomplished by either an internal or external oil cooler. The lubrication system also supplies oil to the engine's governor, which is discussed later in this module.

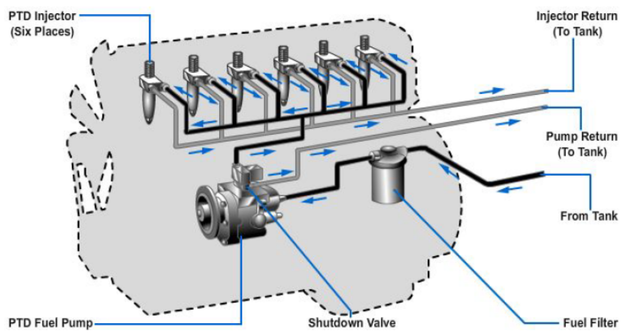


Figure 5-13 — Pressure-time fuel system.

Figure 6.5.2

6.5.3 Fuel System

All diesel engines require a method to store and deliver fuel to the engine. Because diesel engines rely on injectors which are precision components with extremely tight tolerances and very small injection hole(s), the fuel delivered to the engine must be extremely clean and free of contaminants. The fuel system must, therefore, not only deliver the fuel but also ensure its cleanliness. This is usually accomplished through a series of in-line filters. Commonly, the fuel will be filtered once outside the engine and then the fuel will pass through at least one more filter internal to the engine, usually located in the fuel line at each fuel injector. In a diesel engine, the fuel system is much more complex than the fuel system on a simple gasoline engine because the fuel serves two purposes. Figure 13 Diesel Engine Fuel Flow path, one purpose is obviously to supply the fuel to run the engine; the other is to act as a coolant to the injectors. To meet this second purpose, diesel fuel is kept continuously flowing through the engine's fuel system at a flow rate much higher than required to simply run the engine, an example of a fuel flow path is shown in Figure 13. The excess fuel is routed back to the fuel pump or the fuel storage tank depending on the application.

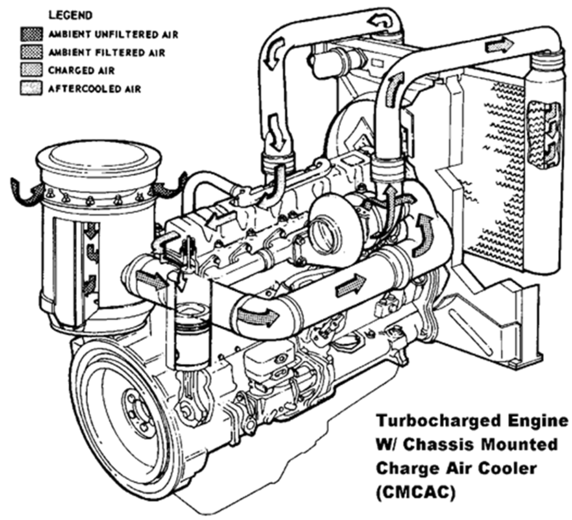
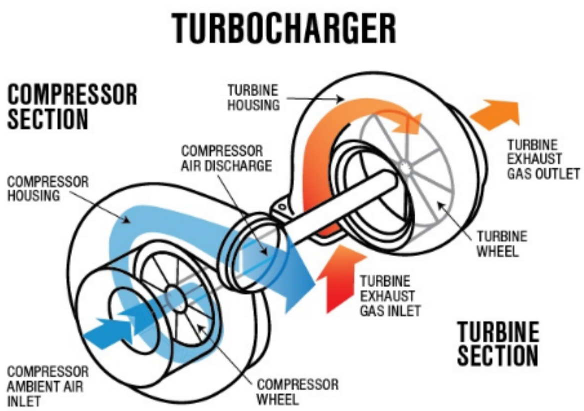


Figure 6.5.3 Figure 14 Air Intake System

6.5.4 Air Intake System

Because a diesel engine requires close tolerances to achieve its compression ratio, and because most diesel engines are either turbocharged or supercharged, the air entering the engine must be clean, free of debris, and as cool as possible. Turbocharging and supercharging are discussed in more detail later in this chapter. Also, to improve a turbocharged or supercharged engine's efficiency, the compressed air must be cooled after being compressed. The air intake system is designed to perform these tasks. Air intake systems vary greatly from vendor to vendor but are usually one of two types, wet or dry. In a wet filter intake system, as shown in Figure 14, the air is sucked or bubbled through a housing that holds a bath of oil such that the dirt in the air is removed by the oil in the filter. The air then flows through a screen-type material to ensure any entrained oil is removed from the air. In a dry filter system, paper, cloth, or a metal screen material is used to catch and trap dirt before it enters the engine (similar to the type used in automobile engines). In addition to cleaning the air, the intake system is usually designed to intake fresh air from as far away from the engine as practicable, usually just outside of the engine's building or enclosure. This provides the engine with a supply of air that has not been heated by the engine's own waste heat. The reason for ensuring that an engine's air supply is as cool as possible is that cool air is more dense than hot air. This means that, per unit volume, cool air has more oxygen than hot air. Thus, cool air provides more oxygen per cylinder charge than less dense, hot air. More oxygen means a more efficient fuel burn and more power. After being filtered, the air is routed by the intake system into the engine's intake manifold or air box. The manifold or air box is the component that directs the fresh air to each of the engine's intake valves or ports. If the engine is turbocharged or supercharged, the fresh air will be compressed with a blower and possibly cooled before entering the intake manifold or air box. The intake system also serves to reduce the air flow noise.



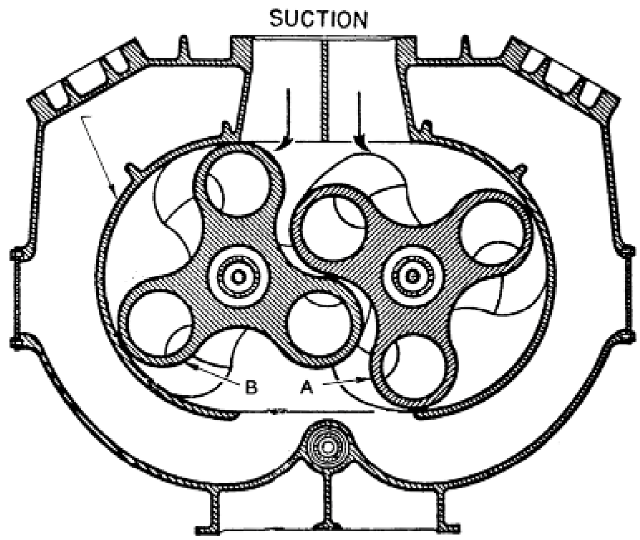


Figure 6.5.4 Turbocharger Supercharger

Turbocharging an engine occurs when the engine's own exhaust gasses are forced through a turbine (impeller), which rotates and is connected to a second impeller located in the fresh air intake system. The impeller in the fresh air intake system compresses the fresh air. The compressed air serves two functions. First, it increases the engine's available power by increasing the maximum amount of air (oxygen) that is forced into each cylinder. This allows more fuel to be injected and more power to be produced by the engine. The second function is to increase intake pressure. This improves the scavenging of the exhaust gasses out of the cylinder. Turbocharging is commonly found on high power four-stroke engines. It can also be used on two-stroke engines where the increase in intake pressure generated by the turbocharger is required to force the fresh air charge into the cylinder and help force the exhaust gasses out of the cylinder to enable the engine to run.

Supercharging an engine performs the same function as turbocharging an engine. The difference is the source of power used to drive the device that compresses the incoming fresh air. In a supercharged engine, the air is commonly compressed in a device called a blower. The blower is driven through gears directly from the engines crankshaft. The most common type of blower uses two rotating rotors to compress the air. Supercharging is more commonly found on two-stroke engines where the higher pressures that a supercharger is capable of generating are needed.

6.5.5 Exhaust System

The exhaust system of a diesel engine performs three functions. First, the exhaust system routes the spent combustion gasses away from the engine, where they are diluted by the atmosphere. This keeps the area around the engine habitable. Second, the exhaust system confines and routes the gasses to the turbocharger, if used. Third, the exhaust system allows mufflers to be used to reduce the engine noise.

6.5.6 Diesel Engine Fundamentals

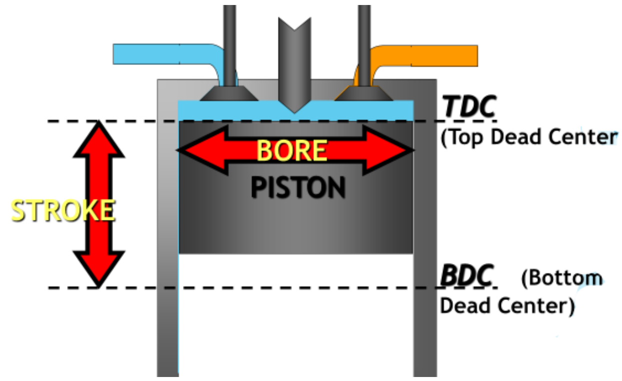


Figure 6.5.5

6.6 Fuel Injection

The control of a diesel engine is accomplished through several components: the camshaft, the fuel injector pump, fuel injector and the governor. The camshaft provides the timing needed to properly inject the fuel, the fuel injector pump provides the components that meters and injects the fuel, and the governor regulates the amount of fuel that the injector is to inject. Together, these three major components ensure that the engine runs at the desired speed.

6.6.1 Requirements of Fuel Injection System

The external fuel system stores and delivers clean fuel to the fuel injection system.

In delivering. fuel to the cylinders, the fuel injection system must fulfill the following requirements:

1. Meter or measure the correct quantity of fuel injected.
2. Time the fuel injection
3. Control the rate of fuel injection
4. Atomize or break up the fuel into fine particles according to the type of combustion chamber
5. Pressurize and distribute the fuel to be injected

The desired condition is to create a homogeneous mixture in the combustion space, in the correct proportions, of the smallest possible fuel particles and air. Although it is not possible to achieve an ideal condition, a good fuel injection system will come close.

6.6.2 Metering

Accurate metering or measuring of the fuel means that, for the same fuel control setting, the same quantity of fuel must be delivered to each cylinder for each power stroke of the engine, only with accurate metering can the engine operate at uniform speed with a uniform power output.

6.6.3 Timing

In addition to measuring the amount of fuel injected, the system must properly time the injection to ensure efficient combustion so that maximum energy can be obtained from the fuel. When fuel is injected too early into the cylinder, it may cause the engine to detonate and lose power, and have low exhaust temperatures. If the fuel is injected late into the cylinder, it will cause the engine to have high exhaust temperatures, smoky exhaust, and a loss of power. In both situations, fuel economy will be low and fuel consumption will be high.

6.6.4 Control of the Rate of Fuel Injection

A fuel system must also control the rate of injection. The rate at which fuel is injected determines the rate of combustion. The rate of injection at the start should be low enough that excessive fuel does not accumulate in the cylinder during the initial ignition delay (before combustion begins). Injection should proceed at such a rate that the rise in combustion pressure is not excessive, yet the rate of injection must be such that fuel is introduced as rapidly as possible to obtain complete combustion. An incorrect rate of injection will affect engine operation in the same way as improper timing. If the rate of injection is too high, the results will, be similar to those caused by an excessively early injection; if the rate is too low, the results will be similar to those caused by an excessively late injection.

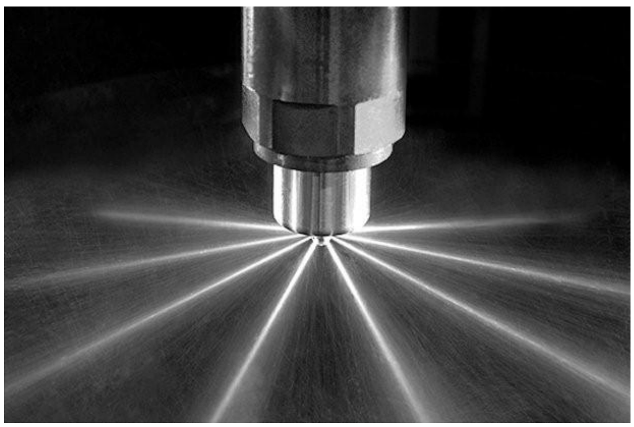


Figure 6.6.1

6.6.5 Atomization of Fuel

As used in connection with fuel injection, atomization means the breaking up of the fuel, as it enters the cylinder, into small particles which form a mist-like spray. Atomization of the fuel must meet the requirements of the type of combustion chamber in use. Some chambers require very fine atomization, others can function with coarser atomization. Proper atomization facilitates the starting of the burning process and ensures that each minute particle of fuel will be surrounded by particles of oxygen with which it can combine.

Atomization is generally obtained when the liquid fuel, under high pressure, passes through the small opening, or openings, in the injector or nozzle. The fuel enters the combustion space at high velocity because the pressure in the cylinder is lower than the fuel pressure. The friction, resulting from the fuel passing through the air at high velocity, causes the fuel to break up into small particles.

6.6.6 Pressurizing and Distribution of Fuel

Before injection can be effective, the fuel pressure must be sufficiently higher than that of the combustion chamber to overcome the compression pressure. The high pressure also ensures penetration and distribution of the fuel in the combustion chamber. Proper dispersion is essential if the fuel is to mix thoroughly with the air and to bum efficiently. While pressure is a prime contributing factor, the dispersion of the fuel is influenced, in part, by atomization and penetration of the fuel. (Penetration is the distance through which the fuel particles are carried by the kinetic energy imparted to them as they leave the injector or nozzle. Friction between the fuel and the air in the combustion space absorbs this energy.)

If the atomization process reduces the size of the fuel particles too much, they will lack penetration. Lack of sufficient penetration results in ignition of the small particles of fuel before they have been properly distributed or dispersed in the combustion space. Since penetration and atomization tend to oppose each other, a degree of compromise in each is necessary in the design of fuel injection equipment, particularly if uniform distribution of fuel within the combustion chamber is to be obtained. The pressure required for efficient injection and, in turn, proper dispersion is dependent on the compression pressure in the cylinder, the size of the opening through which the fuel enters the combustion space, the shape of the combustion space, and the amount of turbulence created in the combustion space.

To control an engine means to keep it running at a desired speed, either in accordance with, or regardless of, the changes in the load carried by the engine. The degree of control required depends upon two factors: the engine's performance characteristics, and the type of load which it drives.

In diesel engines, a varying amount of fuel is mixed with a constant amount of compressed air inside the cylinder. A full charge of air enters the cylinder during each intake event. The amount of fuel injected into the cylinders controls combustion and thus determines the speed and power output of a diesel engine. A governor is provided to regulate the flow of fuel.

Other devices, either integral with the governor or mounted separately on the engine, are used to control overspeed or overload.

6.6.7 Fuel Injection System

Although there are several types of fuel injection systems in use, their functions are the same. The primary function of a fuel injection system is to deliver fuel to the cylinders at the proper time and in the proper quantity, under various engine loads and speeds.

The fuel injection system may be of the mechanical (solid) type or electronic with the aid of a engine control module (computer).

Mechanical injection systems may be divided into three main groups: (1) common-rail, (2) individual pump or jerk type.

6.6.8 Common Rail System

The basic common-rail system consists of a high-pressure pump which discharges very high-pressure fuel into a common rail, or header, to which each fuel injector is connected by tubing. A spring-loaded bypass valve on the header maintains a constant pressure in the system, returning all excess fuel to the fuel supply tank. The fuel injectors are operated mechanically, and or electrically by the engine computer which controls the amount of diesel fuel oil injected into the cylinder at each power stroke by the lift of the needle valve in the injector. The principal parts of a basic common-rail system are shown in figure below.

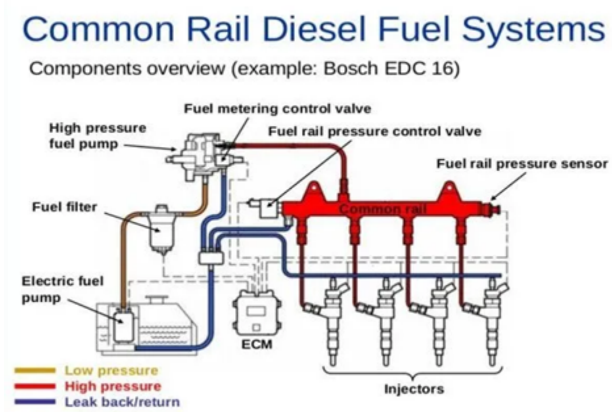


Figure 6.6.2

6.6.9 Individual Pump Injection System

Individual-pump injection systems of the original jerk pump, or basic, type include high-pressure pumps and pressure-operated nozzles which are separate units. In some engines, only one pump and nozzle are provided for each cylinder. In other engines, such as the Fairbanks Morse, each cylinder is provided with two pumps and two nozzles.

Type APF pumps are of single-cylinder design, the plunger pump for each cylinder being in a separate housing. In a 6-cylinder engine, for example, there are six separate APF pumps. Each pump is cam-driven and regulated by an individual control rack.

Type APE pumps are assembled with all the individual cylinder plungers in a single housing. The left side of figure 7-7 shows the pump assembly for a 6-cylinder engine. The injection pumps are operated from a single camshaft in the bottom part of the housing. The cams dip into lubricating oil and brush against felt cushions at the bottom of each revolution. At the top of each revolution, the cams force the spring-loaded plungers up against the plunger spring resistance.

Each plunger moves up and down in a barrel which contains fuel oil at the supply pressure.

The plunger traps oil above it during part of the upward stroke and forces it through the delivery valve and· high pressure tubing to the injector nozzle, where it is injected into the combustion chamber. The action of the plunger, control rack, delivery valve, and injector nozzle are the same in both APE and APF types of pumps.

By studying figure 7-7, you can obtain a better understanding of the fuel injection mechanism and the control of the amount of fuel injected. The fuel oil sump is filled with clean oil from the supply pump and fuel oil filter. Oil enters the barrel above the plunger through a pair of ports. The amount of fuel forced out through the injector nozzle of each upward stroke of the plunger depends on how the plunger is rotated. In figure 7-7, notice that the control rack has teeth all along the side, meshing with a gear segment on each pump. Lengthwise movement of the control rack rotates all the plungers the same amount and in the same direction.

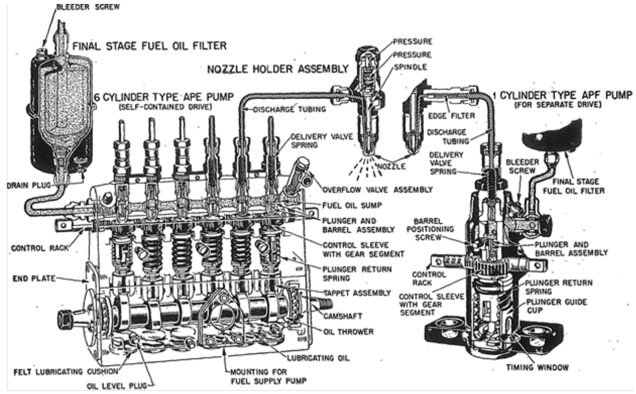


Figure 6.6.3 7-7.-Phantom views of APE and APF Bosch fuel injection pumps.

Rotation of the plungers changes the part of the plunger helix that passes over the spill port (on the right side of each barrel in fig. 7-7), thus changing the time at which injection ends. The pumping principle of the Bosch pump is illustrated by figure 7-8, in which four steps of a pumping stroke are shown. In figure 7-8A, the plunger is below the inlet and spill ports. Fuel oil enters the barrel, as indicated by the dotted white arrow, and fills the barrel chamber (between the plunger and the delivery valve). The plunger has a flat top, and the two ports are set at the same level. The two ports are closed by the plunger at exactly the same moment the plunger travels upward. In figure 7-8B, the ports have just closed. The fuel above the plunger is trapped and placed under high pressure by the rising plunger. The pressure forces the. delivery valve up at once, allowing the high-pressure oil to go to the spray nozzle. In figure 7-8C, the plunger is in the effective

part of its stroke with both ports closed. Fuel is passing through the delivery valve to the spray nozzle. The effective stroke will continue as long as both ports remain covered by the plunger.

At the moment that the spill port is uncovered by the edge of the helix, as shown in figure 7-8D, fuel injection ends. As soon as the port is opened, the fuel oil above the plunger flows out through the vertical slot in the plunger and goes to the low-pressure fuel oil sump. Thus, the pressure above the plunger is released and the delivery valve is returned to its seat by the valve spring.

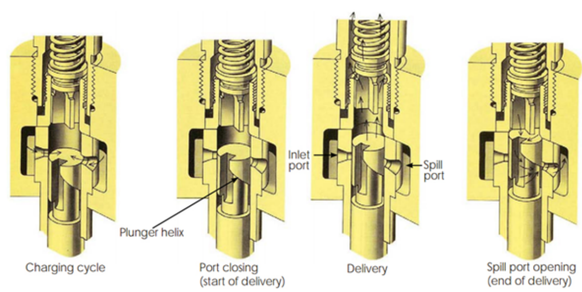


Figure 6.6.4

Delivery Valve

Figure 7-8.-Upward stroke of Bosch plunger, showing pumping principle.

The effect of ·plunger rotation on fuel delivery is shown in figure 7-9. In figure 7-9A, the plunger is rotated to bring the vertical slot to the edge of the inlet port, which is the setting for maximum delivery. In this plunger position, the lowest part of the helix is in line with the spill port, allowing the longest possible effective stroke before the spill port is uncovered, ending the injection of fuel. Figure 7-9B shows the setting for medium or normal delivery. This brings a higher part of the helix in line with the spill port and leaves a short effective stroke before the spill port is uncovered.

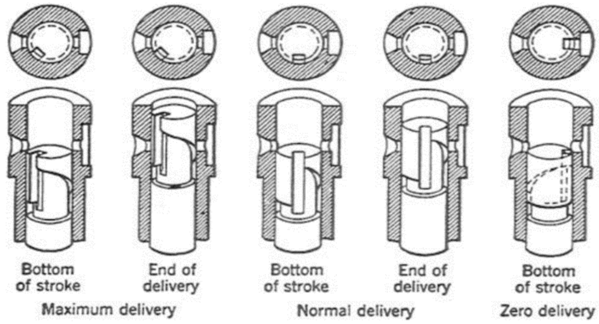


Figure 6.6.5 Figure 7-9.-Effect of plunger rotation on fuel delivery. A B C

The position of "no fuel delivery" is reached when the plunger has been rotated to bring the vertical slot in line with the spill port (fig. 7-9C). In this plunger position, the fuel above the plunger will not be under compression during any part of the upward stroke.

The amount of fuel injected can be regulated by setting the plunger in any position between no delivery and maximum delivery. The plunger setting is controlled by the position of the control rack, which regulates all the plungers at the same time. Movement of the control rack, either manually or by governor action rotates the plunger and varies the quantity of fuel delivered by the pump.

Figure 7-10 illustrates a cutaway view of the Bosch injection pump and control rack assembly. The gear segment is secured to the control sleeve, which is free to rotate on the stationary barrel. The control sleeve has a slot at the bottom into which fits the plunger flange. The flange moves in the slot as the plunger moves up and down. When the control rack is moved lengthwise, the gear segment and the control sleeve rotate around the outside of the barrel. The plunger flange and the plunger (inside the barrel) follow the rotation of the control sleeve. ·

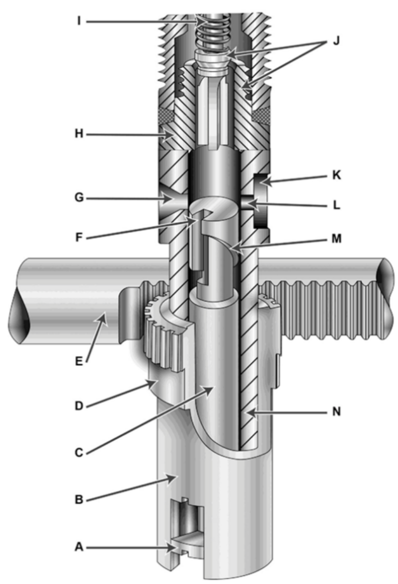


Figure 6.6.6 7-10.-Bosch injection pump and control rack assembly

The Bosch plunger, shown in figures 7-8, 7-9, and 7-10, has a flat top surface and has only a lower helix. With this type of plunger, fuel injection will always begin at the same point in the piston cycle, whether it is set for light load or heavy load. Injection begins when the ports are closed; the end of injection can be varied by plunger rotation. This type of plunger is used in pumps marked "Timed for port closing." Injection has a constant beginning and variable ending.

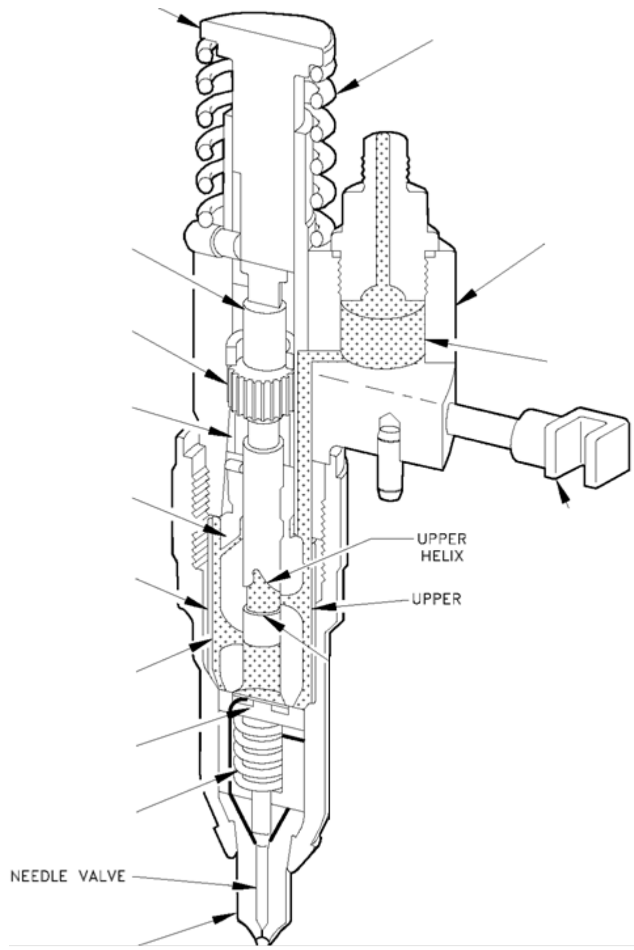


Figure 6.6.7 7- 11 Detroit Diesel Unit Injector

A high pressure pump and an injection nozzle for each cylinder are combined into one unit. This type of unit, generally used with Detroit engines, is often referred to as a UNIT INJECTOR system.

6.7 Governor

Diesel engine speed is controlled solely by the amount of fuel injected into the engine by the injectors. Because a diesel engine is not self-speed-limiting, it requires not only a means of changing engine speed (throttle control) but also a means of maintaining the desired speed. The governor provides the engine with the feedback mechanism to change speed as needed and to maintain a speed once reached.

A governor is essentially a speed-sensitive device, designed to maintain a constant engine speed regardless of load variation. Since all governors used on diesel engines control engine speed through the regulation of the quantity of fuel delivered to the cylinders, these governors may be classified as speed-regulating governors. As with the engines themselves there are many types and variations of governors. In this module, only the common mechanical-hydraulic type governor will be reviewed.

The major function of the governor is determined by the application of the engine. In an engine that is required to come up and run at only a single speed regardless of load, the governor is called a constant-speed type governor. If the engine is manually controlled, or controlled by an outside device with engine speed being controlled over a range, the governor is called a variable- speed type governor. If the engine governor is designed to keep the engine speed above a minimum and below a maximum, then the governor is a speed-limiting type. The last category of governor is the load limiting type. This type of governor limits fuel to ensure that the engine is not loaded above a specified limit. Note that many governors act to perform several of these functions simultaneously.

6.7.1 Operation of a Governor

The following is an explanation of the operation of a constant speed, hydraulically compensated governor using the Woodward brand governor as an example. The principals involved are common in any mechanical and hydraulic governor.

The Woodward speed governor operates the diesel engine fuel racks to ensure a constant engine speed is maintained at any load. The governor is a mechanical-hydraulic type governor and receives its supply of oil from the engine lubricating system. This means that a loss of lube oil pressure will cut off the supply of oil to the governor and cause the governor to shut down the engine. This provides the engine with a built-in shutdown device to protect the engine in the event of loss of lubricating oil pressure.

The governor controls the fuel rack position through a combined action of the hydraulic piston and a set of mechanical flyweights, which are driven by the engine blower shaft. Figure 28 provides an illustration of a functional diagram of a mechanical-hydraulic governor. The position of the flyweights is determined by the speed of the engine. As the engine speeds up or down, the weights move in or out. The movement of the flyweights, due to a change in engine speed, moves a small piston (pilot valve) in the governor's hydraulic system. This motion adjusts flow of hydraulic fluid to a large hydraulic piston (servo-motor piston). The large hydraulic piston is linked to the fuel rack and its motion resets the fuel rack for increased/decreased fuel.

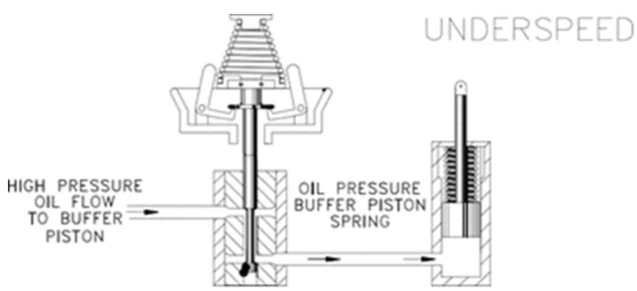


Figure 6.7.1

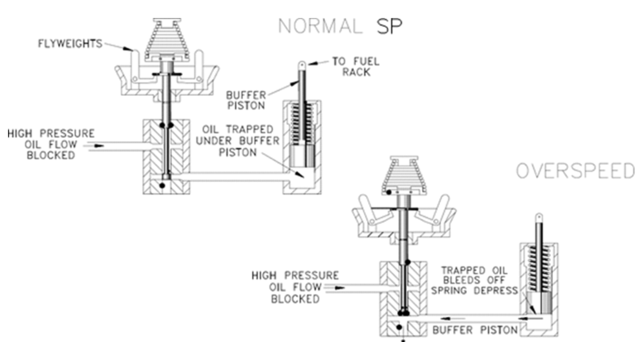


Figure 6.7.2 28 Simplified Mechanical-Hydraulic Governor

6.7.2 Starting a Diesel Engine

Diesel engines have as many different types of starting circuits as there are types, sizes, and manufacturers of diesel engines. Commonly, they can be started by air motors, electric motors, hydraulic motors, and manually. The start circuit can be a simple manual start pushbutton, or a complex auto-start circuit. But in almost all cases the following events must occur for the starting engine to start.

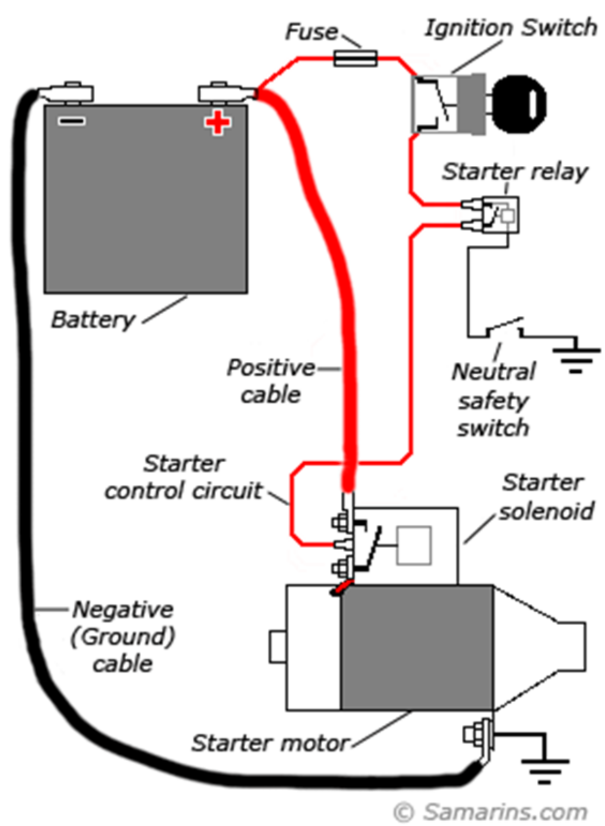
1. The start signal is sent to the starting motor. The air, electric, or hydraulic motor, will engage the engine's flywheel.

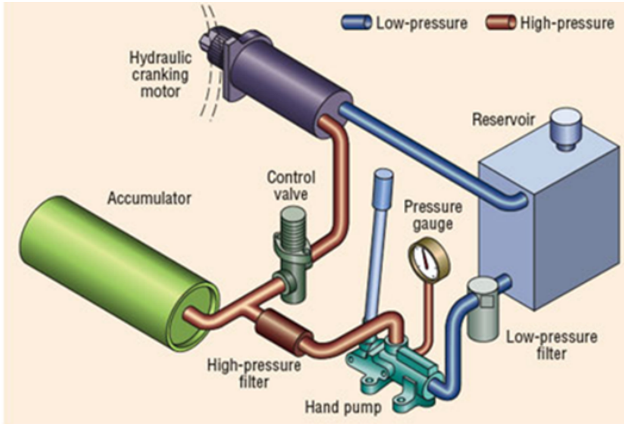
2. The starting motor will crank the engine. The starting motor will spin the engine at a high enough rpm to allow the engine's compression to ignite the fuel and start the engine running.

3. The engine will then accelerate to idle speed. When the starter motor is overdriven by the running motor it will disengage the flywheel.

Because a diesel engine relies on compression heat to ignite the fuel, a cold engine can rob enough heat from the gasses that the compressed air falls below the ignition temperature of the fuel. To help overcome this condition, some engines (usually small to medium sized engines) have glowplugs. Glowplugs are located in the cylinder head of the combustion chamber and use electricity to heat up the electrode at the top of the glowplug. The heat added by the glowplug is sufficient to help ignite the fuel in the cold engine. Once the engine is running, the glowplugs are turned off and the heat of combustion is sufficient to heat the block and keep the engine running.

Larger engines usually heat the block and/or have powerful starting motors that are able to spin the engine long enough to allow the compression heat to fire the engine. Some large engines use air start manifolds that inject compressed air into the cylinders which rotates the engine during the start sequence.





Electric Starting System Hydraulic Starting System

6.7.3 Engine Shutdowns

A diesel engine is designed with protection systems to alert the operators of abnormal conditions and to prevent the engine from destroying itself.

6.7.4 Overspeed Device

Because a diesel is not self-speed-limiting, a failure in the governor, injection system, or sudden loss of load could cause the diesel to overspeed. An overspeed condition is extremely dangerous because engine failure is usually catastrophic and can possibly cause the engine to fly apart.

An overspeed device, usually some type of mechanical flyweight, will act to cut off fuel to the engine and alarm at a certain preset rpm. This is usually accomplished by isolating the governor from its oil supply, causing it to travel to the no-fuel position, or it can override the governor and directly trip the fuel rack to the no-fuel position.

6.8 Engine Alarm Systerm

6.8.1 Water Jacket

Water-cooled engines can overheat if the cooling water system fails to remove waste heat. Removal of the waste heat prevents the engine from seizing due to excessive expansion of the components under a high temperature condition. The cooling water jacket is commonly where the sensor for the cooling water system is located.

The water jacket temperature sensors provide early warning of abnormal engine temperature, usually an alarm function only. The setpoint is set such that if the condition is corrected in a timely manner, significant engine damage will be avoided. But continued engine operation at the alarm temperature or higher temperatures will lead to engine damage.

6.8.2 Exhaust Temperatures

In a diesel engine, exhaust temperatures are very important and can provide a vast amount of information regarding the operation of the engine. High exhaust temperature can indicate an overloading of the engine or possible poor performance due to inadequate scavenging (the cooling effect) in the engine. Extended operation with high exhaust temperatures can result in damage to the exhaust valves, piston, and cylinders. The exhaust temperature usually provides only an alarm function.

6.8.3 Low Lube Oil Pressure

Low oil pressure or loss of oil pressure can destroy an engine in short order. Therefore, most medium to larger engines will stop upon low or loss of oil pressure. Loss of oil pressure can result in the engine seizing due to lack of lubrication. Engines with mechanical-hydraulic governors will also stop due to the lack of oil to the governor.

The oil pressure sensor usually stops the engine. The oil pressure sensors on larger engines usually have two low pressure setpoints. One setpoint provides early warning of abnormal oil pressure, an alarm function only. The second setpoint can be set to shutdown the engine before permanent damage is done.

Chapter 7

Steam Propulsion

Over the last 50 or so years steam and steam turbines as a means of ship propulsion have been supplanted by low and medium speed diesel engines, mainly because motor ships have better fuel efficiency, are easier to automate, requires less maintenance, and can be operated with smaller crews — all factors leading to lower operating costs — than steam ships. Nevertheless, steam propulsion remains important, because steam power is still used extensively in industry and power generation ashore, and the skills of a steam engineer find high demand in the shoreside job market.

In this chapter we will discuss the basics of marine steam propulsion and the steam cycle. The steam cycle is the thermodynamic process which marine engineers use to transform the energy contained in the ship's fuel oil or *bunkers* into the power to turn the ship's propeller and supply all the other requirements necessary to move a steamship from one point to another.

We will begin with a discussion of a very simplified version of the steam cycle, which nevertheless illustrates all its important principles. Then, we will progress to a more detailed, practical, and efficient version of the cycle, which more closely represents the cycle used on real steamships. The function of each of the components of the cycle will be briefly described here, but you will learn much more about them in your *Steam Generator*, *Steam and Gas Turbines*, and *Thermodynamics* classes.

7.1 Basic Steam Cycle

Figure 7.1.1 shows a very simplified version of the steam cycle, which is an appropriate starting point for our discussion of ship's propulsion.

The steam cycle is an example of what is known by engineers as a **cyclic heat engine**. It is called *cyclic*, because it operates on a cycle. It uses a working fluid, water, which travels from point to point through the cycle, changing form and carrying energy, but eventually returning to the starting point restored to the same state that it started with. It is called a *heat engine*, because it transforms *heat*, which is a form of energy, into *work*, another form of energy. The thermodynamic name for this cycle is the **Rankine Cycle**.

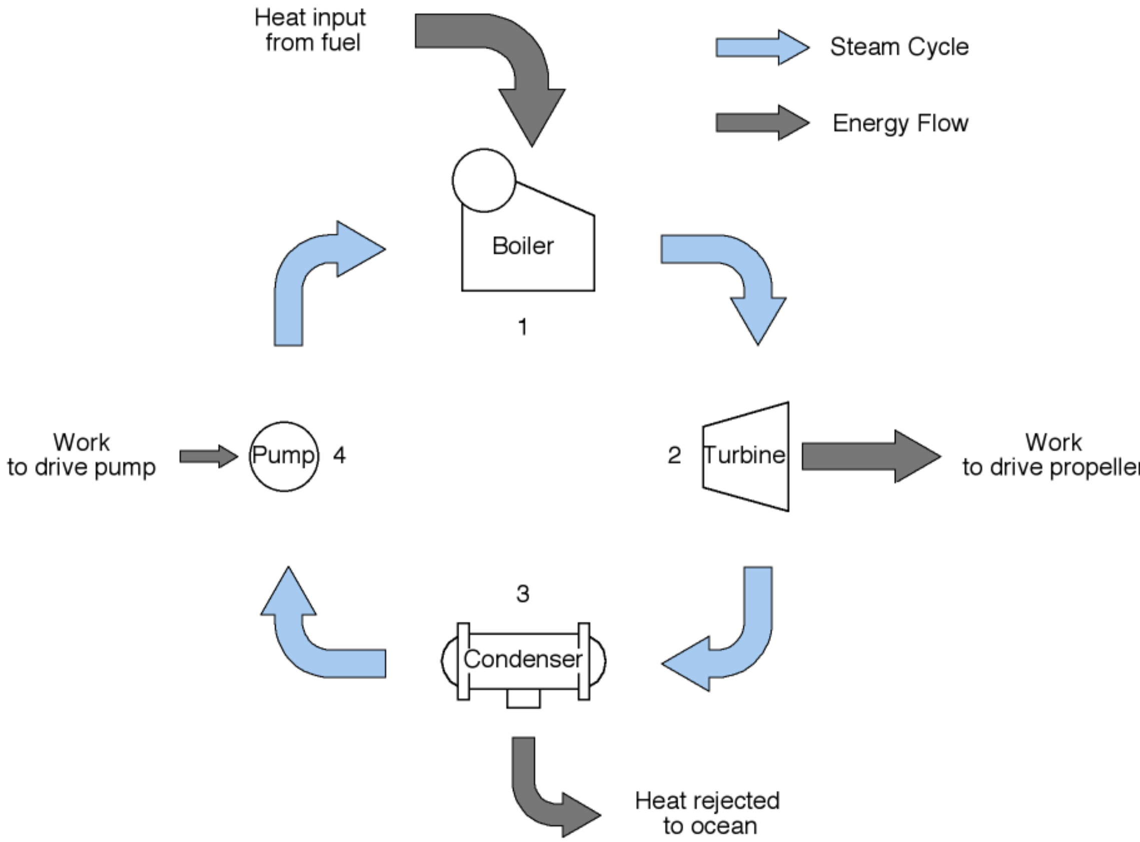


Figure 7.1.1 Simplified Steam Cycle

The four stages of the steam cycle will be described, and then the cycle will be described again, this times from the perspective of the Rankine Cycle.

7.1.1 Generation

Since this is a cycle, it has no beginning or end, but *we* have to start somewhere, so let's begin with the generation stage.

Steam generation occurs in the boiler. The boiler is simply a device used to boil water. Like a teakettle on the stove, it contains liquid water and a heat source. As the water is heated, its temperature rises and soon it begins to boil. On the stove, the water vapor or steam rises and dissipates into the kitchen, but not so in a boiler. The boiler is a closed vessel, like a pot with a lid, and any steam generated in the boiler rises to the top and is collected before being sent on to the next step of the cycle.

In the generation stage, the chemical energy stored in the ship's fuel is released when the fuel is burned in the boiler furnace, and some of this energy is transferred to the working fluid – the water. The water gains energy, and we can detect this in two ways: the water's temperature goes up, and the water changes *state* from a liquid into water vapor, which we call steam. Steam leaves the boiler at high pressure and high temperature.

As we will learn in Chapter 3, heat energy which raises the temperature of a substance such as water or steam is sometimes called **sensible heat** while the heat energy that actually boils the substance is called **latent heat**.

You probably remember that water boils at 212 °F at standard atmospheric pressure (14.7 psia). If you put a thermometer into a pan of water boiling on the stove, this is what it will read. Even if you turn the flame up to add more heat energy, you won't be able to make the water temperature rise above 212 °F. This is because you are adding latent heat, which is not reflected by an increase in the water's temperature. All of the heat energy is being used to turn the liquid water into a vapor.

The boiling or condensing temperature of a liquid is known as its **saturation temperature**. The saturation temperature for a particular liquid is determined by its pressure, and cannot be changed. For example, 212 °F is the saturation temperature for water at atmospheric pressure, and there is nothing anybody can do to change it.

In order to reach high steam temperatures, which is necessary for high steam cycle efficiency, the boiler must be operated at a pressure far above atmospheric pressure. A typical marine boiler operates at about 600 psi while some have operated as high as 1200 psi, although this introduces additional maintenance difficulties. Shoreside steam power plants operate at 3000 psi or even higher.

Steam temperature is raised even further by **superheating** the steam. Superheating steam raises its temperature above the saturation temperature for the corresponding steam pressure by continuing to add heat to the steam after it has completely vaporized. This must take place in a separate area, called the *superheater,* away from liquid water, or the additional heat would simply boil more water rather than superheating the steam. Superheated steam is said to be *dry*, which means that all liquid water has vaporized and it contains no moisture droplets. Drops of liquid water would damage the turbine in the expansion step described below.

Improving efficiency is a major concern of mechanical and marine engineers. High efficiency means that fuel is not wasted, and operating costs are minimized. Practical boiler designs incorporate many techniques to maximize efficiency. For example, not all of the chemical energy originally contained by the fuel ends up transferred to the steam. A large portion of this energy is lost up the smokestack, carried away by the combustion gases. Practical boilers usually contain some sort of heat exchanger in the smokestack in an effort to recover some of this energy.

7.1.2 Expansion

The thermal energy added to the working fluid in the generation stage is converted to mechanical energy, or work, in the expansion stage. This work is produced in the form of a rotating turbine shaft which drives the propeller and moves the ship through the water. The more energy we can remove at this stage, the higher the efficiency of the steam cycle. Unfortunately, it is not possible to remove all the energy from the steam in the turbine. Some energy remains in the steam and is carried to the next stage of the cycle.

A **turbine** is the device used to accomplish the energy transformation in the expansion stage. Like a pinwheel or a fan, a turbine has a freely rotating shaft with many carefully designed **turbine blades** attached. However, unlike a fan, the turbine rotor is completely enclosed in a casing which also contains **nozzles** and **stationary blades** designed to direct the steam towards the **rotating blades**.

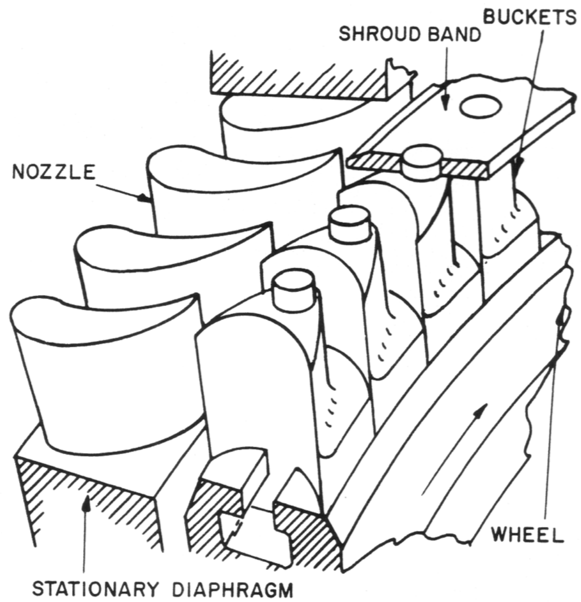


Figure 7.1.2 Turbine Blades

High-pressure, high-temperature steam passes through the nozzle, which has a very small opening, and it emerges with a high velocity. The thermal energy of the steam is converted into mechanical kinetic energy in the nozzle. This high velocity steam jet hits the blades and imparts a turning torque to the rotor shaft and converts its kinetic energy to rotational kinetic energy of the shaft. Most turbines have several rows of blades, forming multiple stages to extract the maximum energy from the steam. As the steam gives up its thermal energy, its temperature and pressure both drop. The steam leaves the turbine at a low temperature and low pressure.

High steam pressure at the inlet to the turbine is important for energy conversion, but it is equally important to have a low pressure at the turbine outlet. Steam, or any fluid for that matter, will only flow from high pressure to lower pressure. Without a pressure drop across the blades of the turbine, there would be no steam flow, and no energy conversion. To maximize the energy conversion, we must also maximize the pressure drop across the turbine.

7.1.3 Condensation

As stated previously, a large pressure drop across the turbine is required to get maximum energy extraction from the steam. The boiler supplies the high pressure at the inlet to the turbine, it is the job of the condenser to create a low pressure condition at the turbine outlet.

The condenser is a shell-and-tube heat exchanger cooled by seawater. It consists of a large, rectangular or cylindrical sealed shell containing thousands of tubes. A circulating pump forces cold seawater in at one end, through the tubes, and it exits overboard at the other end. Steam exiting from the turbine enters the condenser at the top, condenses on the tube surfaces and drains out the bottom. That is, the steam gives up its latent heat of condensation to the seawater, and returns to the liquid water state. Once the steam passes across the condenser tubes, it is no longer steam. It has condensed to liquid water, and from this point in the cycle is referred to as **condensate**. Condensate leaves the condenser as a low temperature, low pressure liquid.

Because the condensation is occurring at approximately the temperature of the seawater, the pressure in the condenser will be approximately equal to the saturation pressure of steam at this temperature, assuming that no air or other gases are present. For example, if the seawater temperature is 80 °F, the corresponding saturation pressure would be 0.5073 psia. This is a very high vacuum, and the greater the vacuum, the better the plant efficiency.

The latent heat removed from the steam by the seawater raises the temperature and increases the energy contained by the seawater, and this cooling water is discharged overboard.

It is unfortunate that some of the energy once contained by the fuel, and then passed on to the steam in the boiler, is eventually thrown away with the seawater. Wouldn't it be better to somehow use this energy to power the ship? Absolutely, but there is nothing we can do about it! The only way to extract more energy from the steam is by having the turbine discharge to an even lower absolute pressure than we do. The only way to do that is to condense the steam at even lower temperatures than we are. But we can't do that, because aboard ship there's nothing colder than the surrounding ocean available to reject the heat to. If we decided not to reject any heat to the ocean at all, the pressure in the condenser would build up to the point where it would equal the steam pressure entering the turbine, and without a pressure drop, the steam would stop flowing altogether. There's no win, but we're doing the best we can.

7.1.4 Recovery

The only thing that remains to complete the cycle is to return the condensate to the boiler to be heated up again. Unfortunately, the condensate leaving the condenser is at a low pressure and the boiler operates at a much higher pressure. Condensate won't flow back into the boiler by itself. A pump is required to raise the pressure and return the condensate to the boiler.

The pump, known as the **feed pump**, draws condensate from the condenser discharge, raises its pressure slightly above the boiler pressure, and discharges it back into the boiler to restart the cycle. Condensate leaving the feed pump is known as **feedwater**.

Work is required to drive the feed pump, and this energy reduces the net work produced by the cycle and available to turn the shaft. Fortunately, since water is incompressible it takes much less work to raise its pressure back to the boiler pressure than we get from an equivalent pressure drop across the turbine, and so there is a net positive amount of work produced by the cycle.

7.1.5 Rankine Cycle

The diagram shown in Figure 7.1.3 is an idealized representation of the **Rankine Cycle** used in the study of thermodynamics, and known as a **temperature-entropy diagram**. The heavy dome shaped curve is known as the **vapor dome** and points under the curve are saturated steam, while points to the left of the curve are liquid water and points to the right of the curve are superheated steam.

Feedwater enters the boiler at point 1, and is heated by the fuel. Initially, the water temperature rises, until it reaches the saturation temperature for the boiler pressure, point 1_f, where the water begins to boil. Additional heat added at this point does not raise the temperature any further until all the liquid water is completely vaporized, point 1_g. The heat added between 1_f and 1_g is the **Latent Heat of Vaporization**. After the steam has reached point 1_g, any additional heat added causes the temperature to rise again, and the steam becomes superheated.

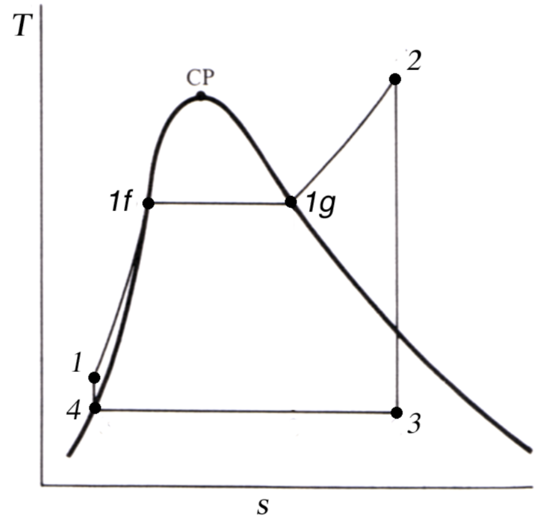


Figure 7.1.3 Temperature - Entropy Diagram

Superheated steam leaves the boiler at point 2 and enters the turbine. During the expansion process, the steam pressure and temperature both drop as energy is extracted from the steam. Steam leaves the turbine and enters the condenser at point 3, which is saturated or wet steam.

In the condenser, heat is removed from the steam and it returns to the liquid state at point 4. The feed pump raises the water pressure back up to the boiler pressure and the cycle begins again at point 1. The feed pump causes a small temperature rise in the feedwater as well as a pressure increase.

The area under the curve from 1 to 2 represents the heat energy added in the boiler and the area under the curve from 3 to 4 represents the heat rejected to the ocean. The area inside the curve represents the net work done by the cycle.

7.2 Steam Propulsion System

While the simplified steam cycle discussed in the previous section could be built, and it would work, several modifications are required to make it practical for steam propulsion and to improve its efficiency.

The actual steam cycle that was used for propulsion on MMA's old ship *TS Kennedy* is shown in Figure 7.2.1. Each of the components of this cycle will be briefly discussed in the following sections, in its order in the cycle.

7.2.1 Boiler

Heat energy is added to the cycle by burning fuel oil in the boiler. The high temperature flames raise the temperature of the water in the boiler and eventually cause it to boil. Not all energy of the fuel is transferred to the water, some remains in the combustion gases and travels up the stack. This energy will be lost to the atmosphere unless it is recovered by economizers or air heaters located in the exhaust path. Any heat energy lost to the atmosphere represents waste and steam cycle inefficiency.

Marine boilers supply the steam required for propulsion, as well as any other steam requirements of the vessel. Marine propulsion boilers are normally fired with heavy fuel oil, or in a few cases today, coal. Marine boilers, while similar to boilers found ashore, are designed to meet the particular

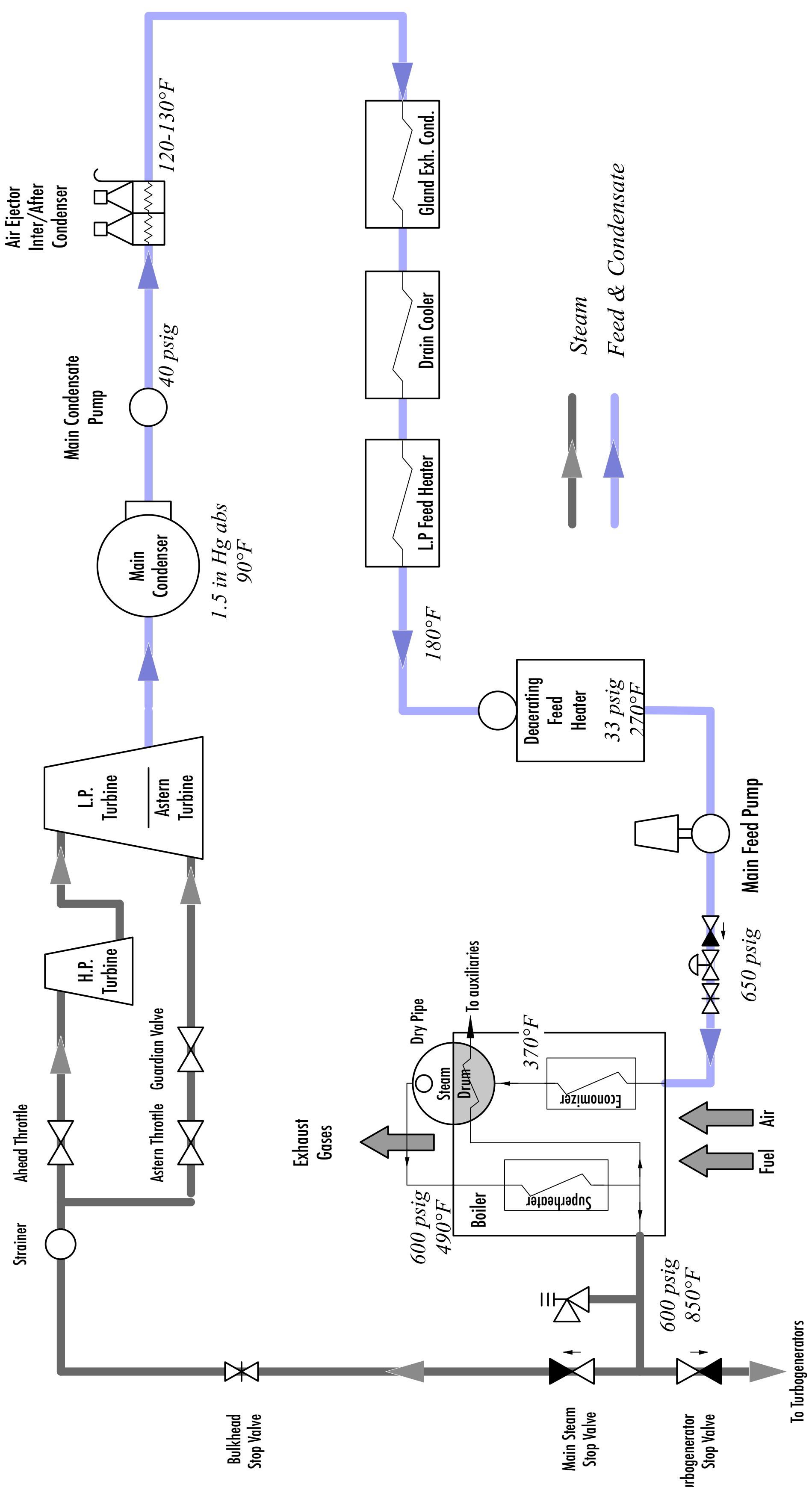


Figure 7.2.1 Main Steam Cycle

requirements of shipboard use. They are designed to be light and compact to fit into small engine rooms, capable of operating under rapidly changing loads when the vessel is maneuvering, and to operate reliably while the vessel is pitching and rolling during a storm.

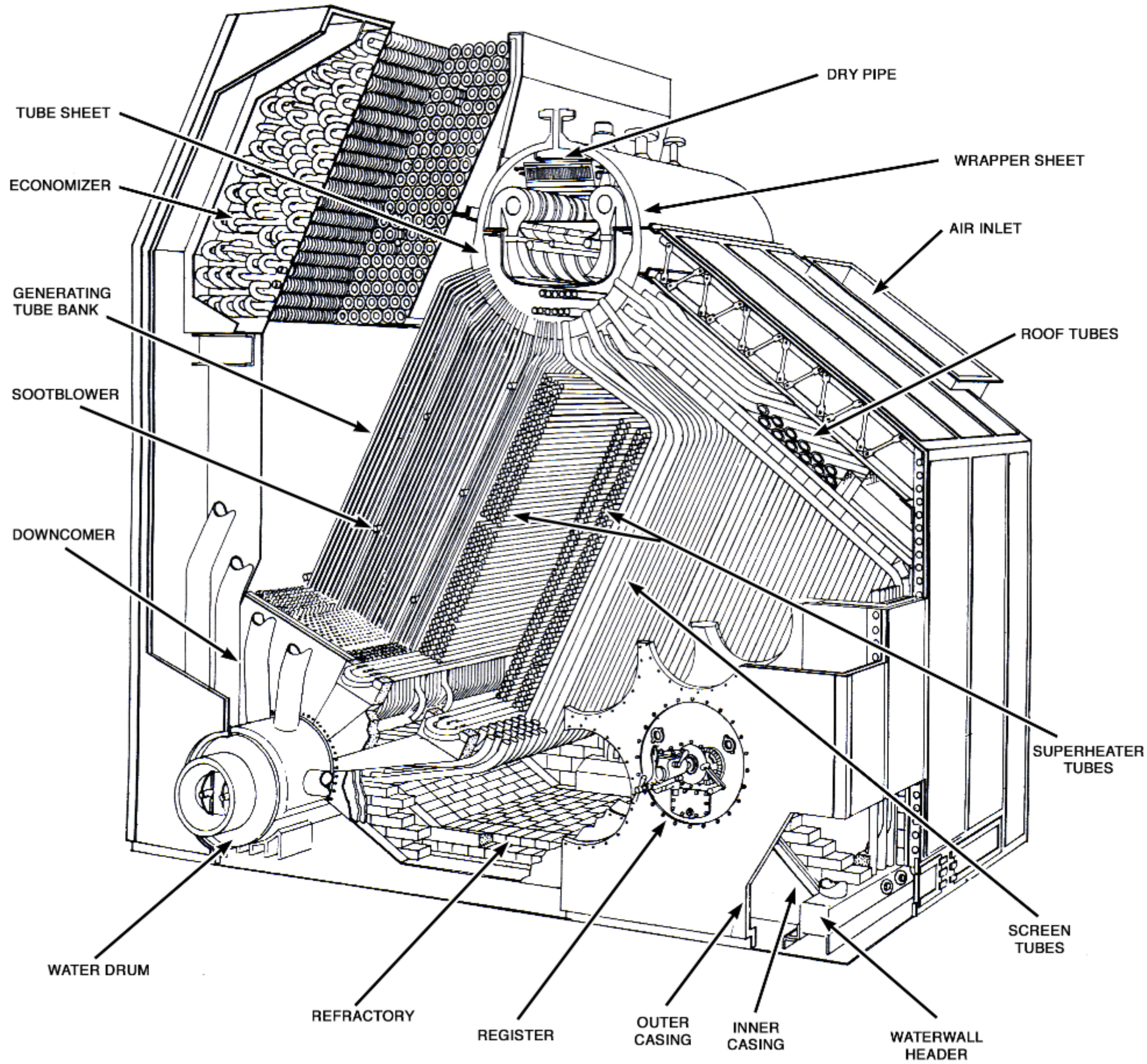


Figure 7.2.2 Typical Marine Boiler

Diesel and gas turbine powered ships are often equipped with smaller **auxiliary boilers** to supply the steam for quarters and cargo cargo heating, etc. The heat source for auxiliary boilers can be fuel oil, diesel oil, or the waste heat from the main propulsion diesel engine.

7.2.2 Steam Drum

The **steam drum** is located near the top of the boiler and should normally be half filled with water and the remainder filled with steam. A **gage glass** on the steam drum allows the operator to determine the water level in the boiler. Too little water would be very dangerous, because without water in the boiler the heat of the flames would melt the boiler tubes and destroy the boiler.

Steam is formed in the boiler tubes, and since steam bubbles are less dense than the surrounding liquid water, they float up to the top of the boiler and eventually rise above the surface of the water in the steam drum. If the steam was allowed to build up in the drum, the boiler pressure would quickly rise, and if not relieved by the safety valves, would cause the boiler to explode. The system is designed to remove steam as quickly as it is created, so a properly operated boiler will maintain a constant pressure.

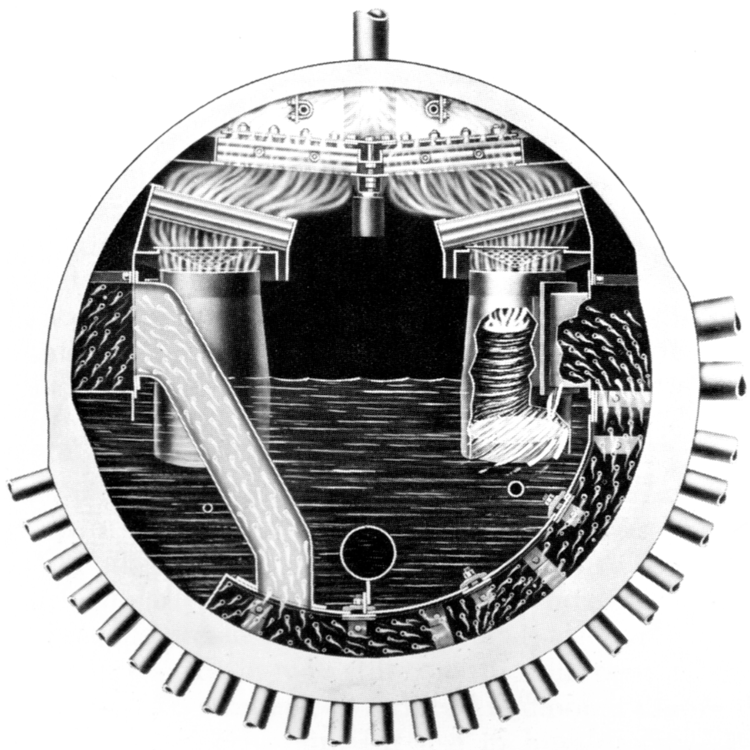


Figure 7.2.3 Steam Drum

A steam drum **safety valve** is located on top of the steam drum to prevent boiler explosions. This valve will open automatically to relieve the steam pressure up the stack if it rises too high.

7.2.3 Dry Pipe

The **dry pipe** is located inside the steam drum, near the top. In its simplest form the dry pipe is simply a pipe with holes drilled into the top portion. Steam enters the dry pipe before it leaves the boiler.

The dry pipe is designed to allow steam to enter, but to exclude water droplets and moisture. Moisture in the steam, known as **carryover** is bad, because high velocity water droplets in the steam can cause damage to the blades and thrust bearings in the turbine. Improper operation of the boiler, for instance letting the steam drum water level get too high, can cause carryover.

7.2.4 Superheater

Steam collected in the dry pipe is directed to the **superheater** section of the boiler, where it is **superheated** to improve the efficiency of the steam cycle.

Water boils at a particular temperature which is determined by the pressure of the surroundings called the **saturation temperature**. For example, water at atmospheric pressure always boils at 212 °F, while water at 600 psia always boils at 486 °F. The saturation temperature for water at a given temperature can be looked up in **steam tables**.

Steam temperature can be raised above the saturation temperature by adding additional more heat energy, but this must occur in an area where there is no liquid water present, or the heat would simply boil more water and would not raise the temperature.

This heating occurs in the superheater, which is a bank of boiler tubes located in the hottest portions of the combustion gas path. Since there is no liquid water in the superheater, all heat added there produces superheat.

7.2.5 Stop Valves

No practical boiler could function without valves. Valves permit the operator to control fluid flow, and to isolate sections of the system for maintenance. There are dozens of valves used in the main steam cycle but in this discussion we will only mention a few of them. You may assume that valves are located throughout the system wherever they are necessary.

The **main steam stop valve** is located at the outlet of the superheater, and it is the primary valve used to connect or isolate the boiler from the remainder of the steam cycle.

According to US Coast Guard regulations, boilers are required to have **two valve protection**, that is, they are required to have two valves in series in all boiler connections. This insures that at least one valve will be functional when the time comes to secure the boiler. The valve which provides this protection is called the **bulkhead stop valve**. It is located in the main steam line, downstream of the main steam stop valve.

7.2.6 Strainer

A **steam strainer** is placed in the steam line upstream of the main engine to prevent objects other than steam from entering the turbines, since solid objects impacting the turbine blades would quickly destroy them. Steam lines would normally be expected to be quite clean, but a strainer is cheap insurance against nuts, tools, and gloves left in the lines by shipyard workers, or rust flakes formed during a layup period. Unfortunately, water droplets due to wet steam or carryover will pass through the steam strainer.

7.2.7 Throttles

The **throttle valves** are used to throttle (control) the amount of steam allowed to enter the turbines, and hence they control the speed of the ship. On the *TS Kennedy*, the throttle valves were manually opened and closed by the engineer on watch but on more modern ships they are remotely operated from the bridge.

There are two throttles, the **ahead throttle**, and the **astern throttle**. The ahead throttle controls steam to the high pressure turbine and controls the speed of the ship in the ahead (forward) direction. If the ahead throttle is closed, and the astern throttle is opened, steam will be directed to the astern section of the low pressure turbine and the turbine will rotate in the reverse direction.

The ahead and the astern throttles should not be opened at the same time, because this would cause two opposing torques on the low pressure turbine rotor. While this would not necessarily be damaging, it would be a colossal waste of energy. The **Astern Guardian Valve** is installed in the astern steam line between the astern throttle and the astern turbine to protect against leakage of the astern throttle while the ship is underway. This valve normally remains closed, and is only opened when the ship is expected to maneuver.

7.2.8 Turbines

The simplified steam cycle uses a single turbine to extract power from the steam, but most ships use two turbines to do the same job. Two shorter turbine shafts are more advantageous than one large shaft for several reasons, including reduced manufacturing cost and increased flexibility in the arrangement of machinery in the engine room.

The first of these two turbines is known as the **high pressure turbine** (HP) and the second is the **low pressure turbine** (LP). A steam line, called the **crossover** carries steam from the outlet of the HP turbine to the inlet of the LP turbine. A set of **reduction gears** are used to reduce the turbine speed to the shaft and propellor speed.

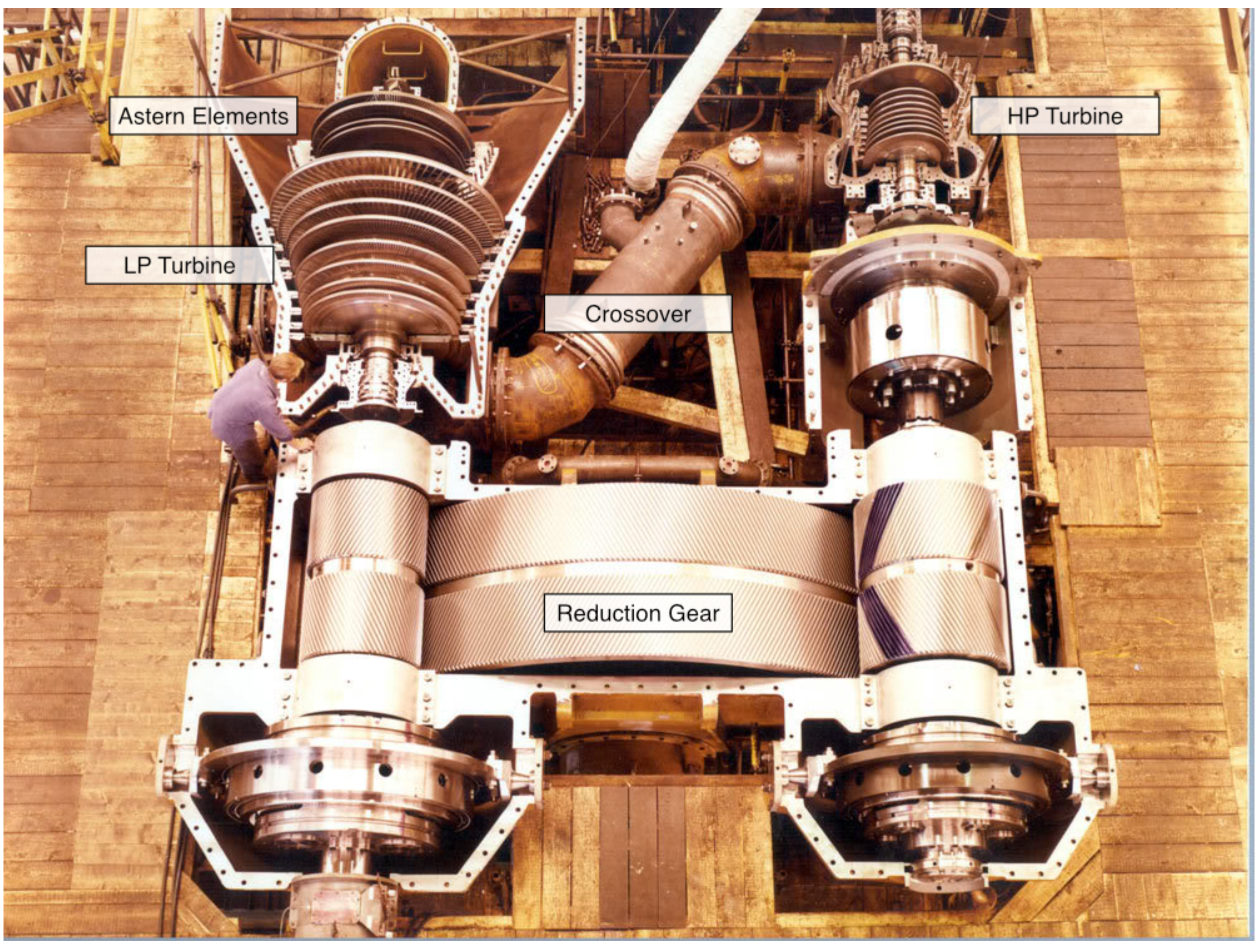


Figure 7.2.4 Main Engine and Gears for Tanker *Batillus* under construction. Photo by Jorgen Lonn.[1]

[1] `www.aukevisser.nl/supertankers/id316.htm`

Superheated steam from the throttles enters the HP turbine where its pressure drops and its thermal energy is converted to mechanical energy. The LP turbine follows the HP turbine and continues to extract energy from the steam. The steam enters at a low pressure (a vacuum actually, at low loads) and exits at an even lower pressure into the main condenser. The specific volume of steam at these low pressures is large, which means that the turbine blades and the LP turbine itself are also large. When looking at the two turbines, it is always easy to identify the LP turbine because of its size; eight to ten feet in diameter is not unusual.

The forward end of the LP Turbine rotor contains the **Astern Elements**. These are two or three rows of blades designed to rotate the shaft in the astern direction. Since there are so few rows of astern blades, the power the turbine is capable of producing in the astern direction is limited.

The HP and LP turbines and the reduction gear together are known as the **Main Engine**.

7.2.9 Main Condenser

As stated before, the **main condenser** is a shell and tube heat exchanger which provides the low pressure zone for the turbine to discharge into. A typical main condensers consists of three main parts: the **shell**, the **tubes**, and the **tube sheets**. Cold sea water enters the shell at the inlet water head or water box, flows across the condenser through the tubes, and is discharged overboardThe steam entering the condenser turns back to liquid water when it comes in contact with the cold condenser tubes. The newly formed condensate drains down to the bottom of the condenser, where it collects in the **hot well** until it is pumped out.

In order to maintain high plant efficiency it is necessary to maintain a good vacuum in the main condenser. This vacuum is formed by the collapse of the steam as it condenses, since the specific volume of water is so much less than the specific volume of steam. A properly operating main condenser operates at 28.5 in Hg vacuum or greater.

Vacuum will be maintained in the condenser as long as the shell of the condenser does not fill up with air or other gases, however vacuum tends to draw air into the condenser through any available leaks, such as those found at the **turbine glands** where the turbine shafts penetrate the turbine casing. This air must be pumped back out to the atmosphere as fast as it leaks in, or else vacuum will be lost. This is accomplished with a steam driven pump known as the **air ejector** which takes suction on top of the main condenser and discharges air to the engine room.

Vacuum will also be lost if condensing stops. This could happen if the supply of cooling water through the condenser tubes was interrupted, perhaps due to failure of the main circulating pump, blocked condenser tubes, or if the condensate pump failed which would cause the condenser to fill up with condensate.

7.2.10 Condensate pump

At this point in the simplified cycle, you will find a feed pump to return the condensate back to the boiler. In an actual cycle you will find a number of additional items which are installed to increase the efficiency of the steam cycle by adding essentially *free* energy to the working fluid.

The first new item is the **condensate pump**, which is a centrifugal pump that takes suction on the condenser hot well and raises the condensate pressure enough to move it on to the DC heater. The condensate pump must pump from a vacuum, which is a difficult job for a pump. It is important to properly vent and seal the pump, or it will not pump well.

7.2.11 Heat Exchangers

Following the condensate pump, condensate passes through a series of heat exchangers designed recover otherwise lost heat energy and improve the efficiency of the steam cycle.

First the condensate passes through the **Air Ejector Condenser**. The **Air Ejector** is a steam powered air pump that removes air that leaks into the condenser. The steam used by the air ejector is condensed here, where it preheats the condensate. Any heat added before the condensate reaches the boiler represents fuel that doesn't need to be burned, so the cycle efficiency is raised.

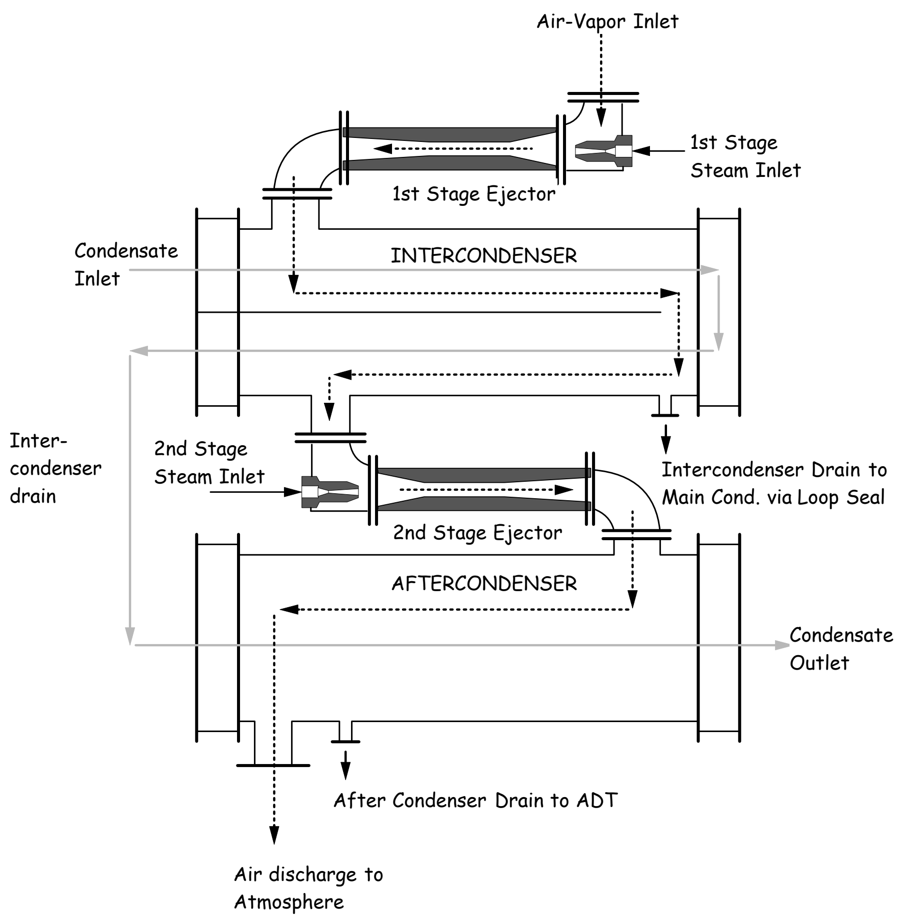


Figure 7.2.5 Air Ejector and Air Ejector Condenser

Next, the condensate passes through **gland exhaust condenser**. This unit condenses steam that leaks out of the turbine glands, and simultaneously recovers more energy and recaptures the leakage. This is an example of the way a practical cycle takes every opportunity to recover "free" energy and increase the overall cycle efficiency

The **drain cooler** and **first stage heater** follow, in that order. The first stage heater uses partially expanded steam to pre-heat the condensate. This steam condenses in the first stage heater, but still is quite hot, so the remaining energy is recovered in the drain cooler. The condensed drains are returned to the system so no water is lost.

The first stage heater is an example of **regenerative feed heating**, a process that improves the overall efficiency of the cycle. In regenerative heating, steam is partially expanded in the turbine to drive the propeller, then bled off at an appropriate temperature where it is used to preheat the condensate. Some shore power plants have four or more stages of regenerative heating.

The flow order through these heat exchangers is always from coolest to hottest. Therefore the air ejector and exhaust condensers come first, followed by the drain cooler, and finally the first stage heater.

7.2.12 DC Heater

The first stage heater is followed by the second stage heater, which is usually referred to as the **DC Heater**. The DC Heater is the point in the steam cycle where *condensate* becomes *feed water*.

The DC heater provides a second stage of regenerative feed heating, which is accomplished by mixing low pressure steam directly with the condensate. In other words, the heat exchange occurs by **direct contact**, hence the name. The DC Heater is also sometimes called *deaerating feed tank*, the *DFT*, the *deaerator*, as well as the *second stage heater*. All these names refer to the same piece of equipment.

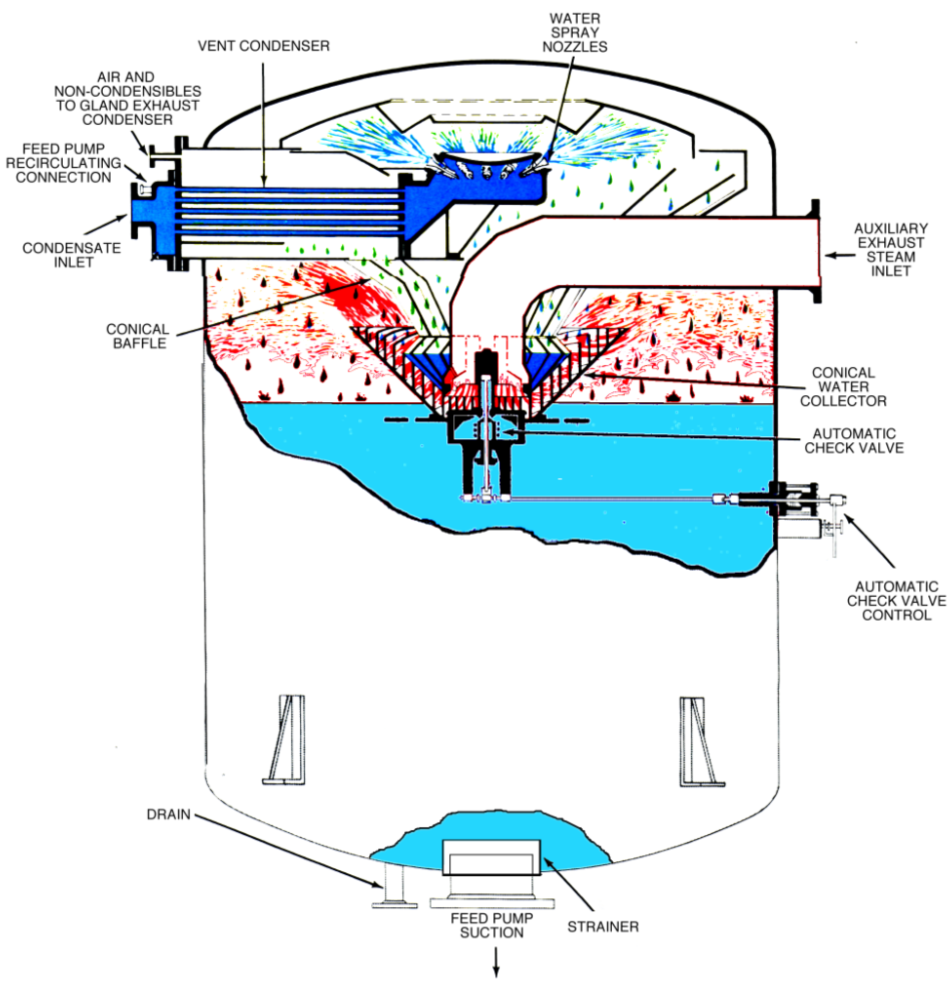


Figure 7.2.6 DC Heater

The DC Heater serves three important functions in the steam cycle:

Heat. The first function of the DC Heater is to heat the feedwater prior to returning it to the boiler. Thermodynamically, it is known as the regenerative second stage heater. Using the exhaust steam from steam powered auxiliaries to heat the DC Heater increases the overall plant efficiency and saves fuel.

Deaerate. The second function of the DC Heater is to remove dissolved gases (oxygen and free carbon dioxide) from the condensate and make-up water used for boiler feed. Removal of oxygen and free carbon dioxide protects piping and pumps, as well as boilers and condensate return lines from these corrosive gases.

Store. Finally the DC Heater acts as a storage location for feedwater. It acts as a surge tank for the system, allowing fluctuations in the amount of water contained in the cycle to occur without upsetting the feed pump and feedwater regulators.

7.2.13 Feed Pump

The feed pump serves the same purpose here as it does in the simplified cycle; that is, it raises the pressure of the feedwater sufficiently to force it into the boiler to begin the cycle again.

The feed pump is usually a turbine driven centrifugal pump, and the discharge pressure is about 50 to 100 psi above the pressure in the steam drum.

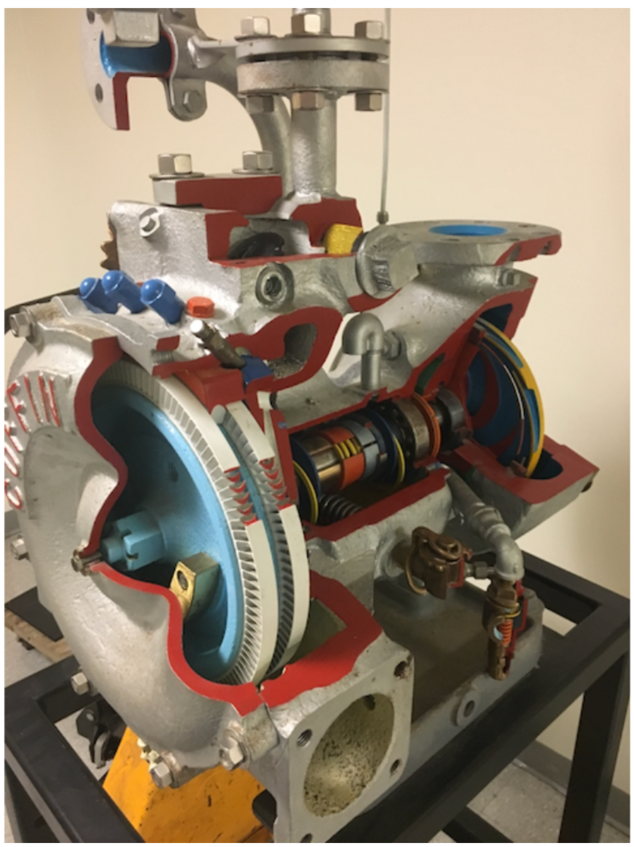


Figure 7.2.7 Cutaway Coffin Steam-driven Feed Pump from *TS Patriot State I*

7.2.14 Feed Valves

Three valves in the feed line before the boiler are used to control the flow of feedwater into the boiler.

The **feed check valve** comes first. It is a stop-check valve which is normally left open, but which can be used to regulate the feed water flow to the boiler if necessary. The feed check valve is always fitted with a reach rod or other means to permit it to be manually operated from the boiler control station.

The feed check is followed by the**feed water regulator**which is an automatic, pneumatically actuated regulating valve that responds to changes in boiler drum level and steam demand to automatically maintain a constant water level half-way up the steam drum.

The final valve of the set is the **feed stop valve**. This valve is provided to permit the feed system to be secured at the boiler when necessary.

7.2.15 Economizer

After the feedwater enters the boiler it passes through the **economizer**.

The economizer is a heat recovery device. It consists of a finned-tube heat exchanger which captures the heat in the boiler exhaust gases before they pass up the stack and uses it to heat the feedwater. This is the final effort to improve the efficiency of the steam cycle, by recovering heat energy that would otherwise be lost.

After leaving the economizer the feedwater enters the steam drum where the generation stage occurs, where the steam cycle begins again.

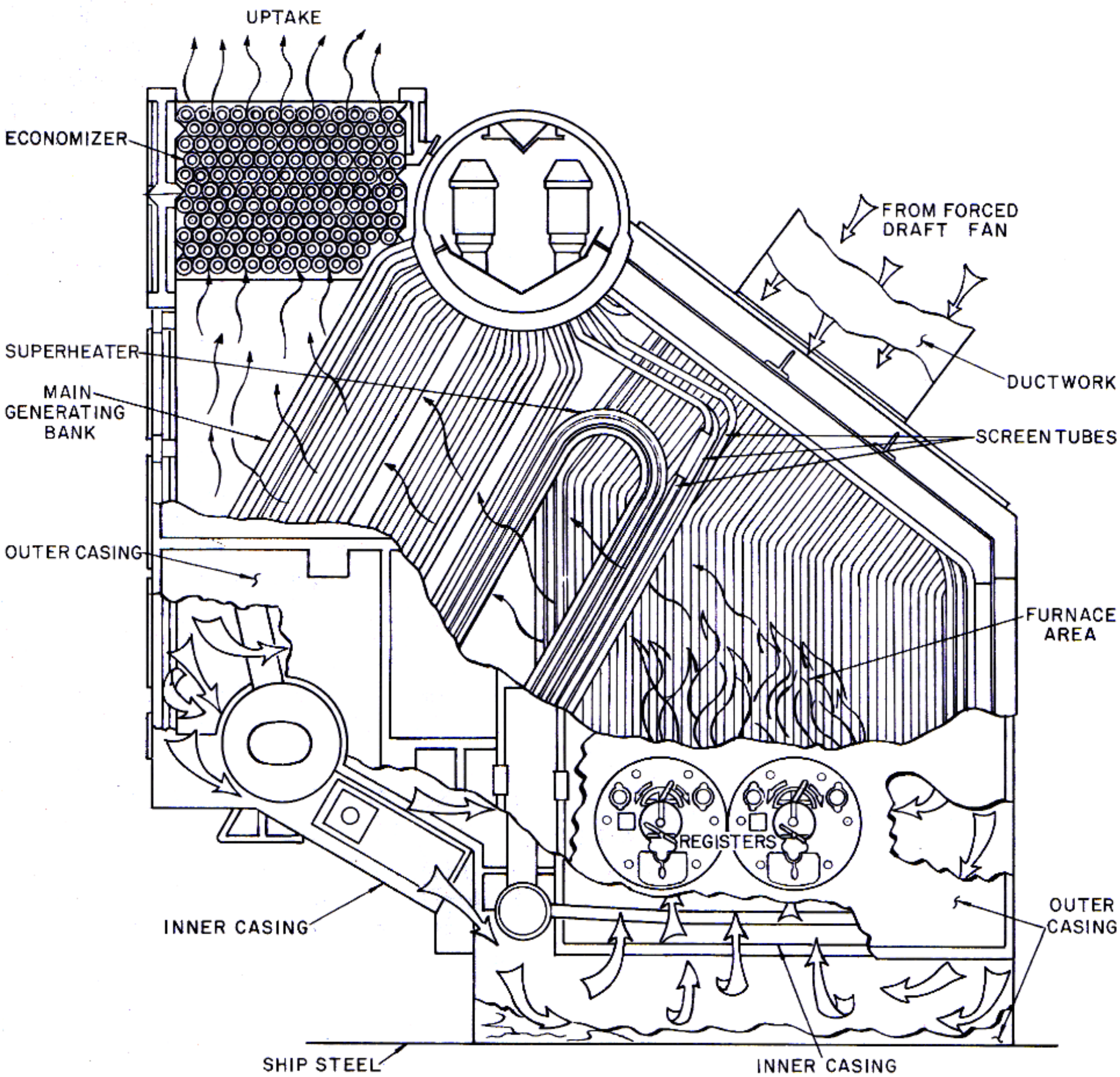


Figure 7.2.8 Economizer and Exhaust Gas Flow Path

Chapter 8

Electrical Propulsion

Marine electric propulsion systems utilize generators to provide power for electric motors, which in turn drive the ship's propeller. The electric generators may be driven by any suitable prime mover, most commonly, diesel engines. While it may initially seem counterintuitive to interpose complex and costly equipment between the prime mover and the propeller when a simple line shaft and gearbox could transmit the power instead, there are valid justifications for the added complexity and expense.

The advantages of electric propulsion include:

- *Layout Flexibility.*

  The ability to install the prime mover in any convenient location, without being restricted to a direct line with the propeller. Power is transmitted through flexible cable runs, as opposed to rigid line shafts. Furthermore, instead of relying on a single large main engine, multiple smaller engines can be used, allowing for placement in smaller spaces and more convenient locations.

- *Efficient Operation.*

  Eliminating the need for reduction gears. Typically, diesel engines and steam turbines operate most efficiently at high or medium speeds, while propellors are most efficient at low speed, below about 100 RPM. When propulsion power is supplied electrically, speed reduction is accomplished by selecting the appropriate number of poles in the generator and varying the electrical frequency supplied to the motor. This setup allows each component to operate within its most efficient range, maximizing overall energy efficiency and reducing fuel consumption.

- *Redundancy and Reliability.*

  Inherent redundancy and enhanced reliability compared to traditional propulsion systems. With multiple smaller generator sets, the system can continue to function even if one or more generators or motors fail or require maintenance. This redundancy reduces the risk of complete propulsion failure and ensures that the propulsion system remains operational.

- *Economical Part-Load Operation.*

  Improved efficiency at low loads. Ships can secure one or more engine/generator sets if they are not needed. The remaining engines can then operate at nearly full load, resulting in improved efficiency compared to having more engines operating at part-load. Load management systems continuously monitor the electrical demand and promptly initiate the startup of an additional generator when necessary.

8.1 Overview

An overview of the electric propulsion system of the *Patriot State II* is shown in the one-line diagram below, Figure 8.1.1.

Electrical power for both propulsion and ship's services is produced by four Hyundai HSJ9 913-08P diesel driven generators. These are 6600 Volt, three-phase AC synchronous generators capable of producing up to 4053 kW at 80% power factor, or 5066.25 kVA.

Generators 1 and 2 are located in engineroom 1 and directly feed main switchboard No.1, and generators 3 and 4 are located in engine room 2 and feed main switchboard No. 2. The switchboards can be split or cross-connected as necessary for emergency operations.Each switchboard supplies electrical power at 60 Hz, 1850 Volts to a **Propulsion Converter** via a step-down **transformer**. The purpose of the propulsion converters is to change input voltage and frequency to the voltage and frequency needed to spin the propulsion motor in the desired direction, at the desired speed, as ordered by the bridge.

Each propulsion converter provides power to a **Propulsion Motor**. The two propulsion motors drive a common shaft which is directly connected to the ship's single propeller, as shown in Figure 8.4.2.

The generators, transformers, propulsion converters, and propulsion motors will be discussed in more detail in the sections that follow.

8.2 Generators

Four 4000 kW, 6600 volt, three-phase generators provide electrical power for propulsion and for all other normal ship's requirements. Each generator is directly driven by a 16-cylinder, 4-stroke, 4200 kW diesel engine. Since the generators have eight poles, when driven at 900 rpm they produce 60 Hz AC.

Table 8.2.1 Main Generator Specifications

Manufacturer	Hyundai
Model	HSJ9 913-08P
Type	8 pole, cylindrical rotor, brushless, separately excited
Rated Output	5066 kVA / 4053 kW
Rated Voltage	6.6 kV AC
Current	443.2 A
Speed	900 rpm
Frequency	60 Hz
Power factor	0.8
Excitation voltage	60 V DC
Excitation current	4 A DC

8.2.1 Description

As discussed in Subsection 4.4.3, the essential components of an AC generator are the armature and the field, one of which is located on the rotor and the other on the stator. However a practical

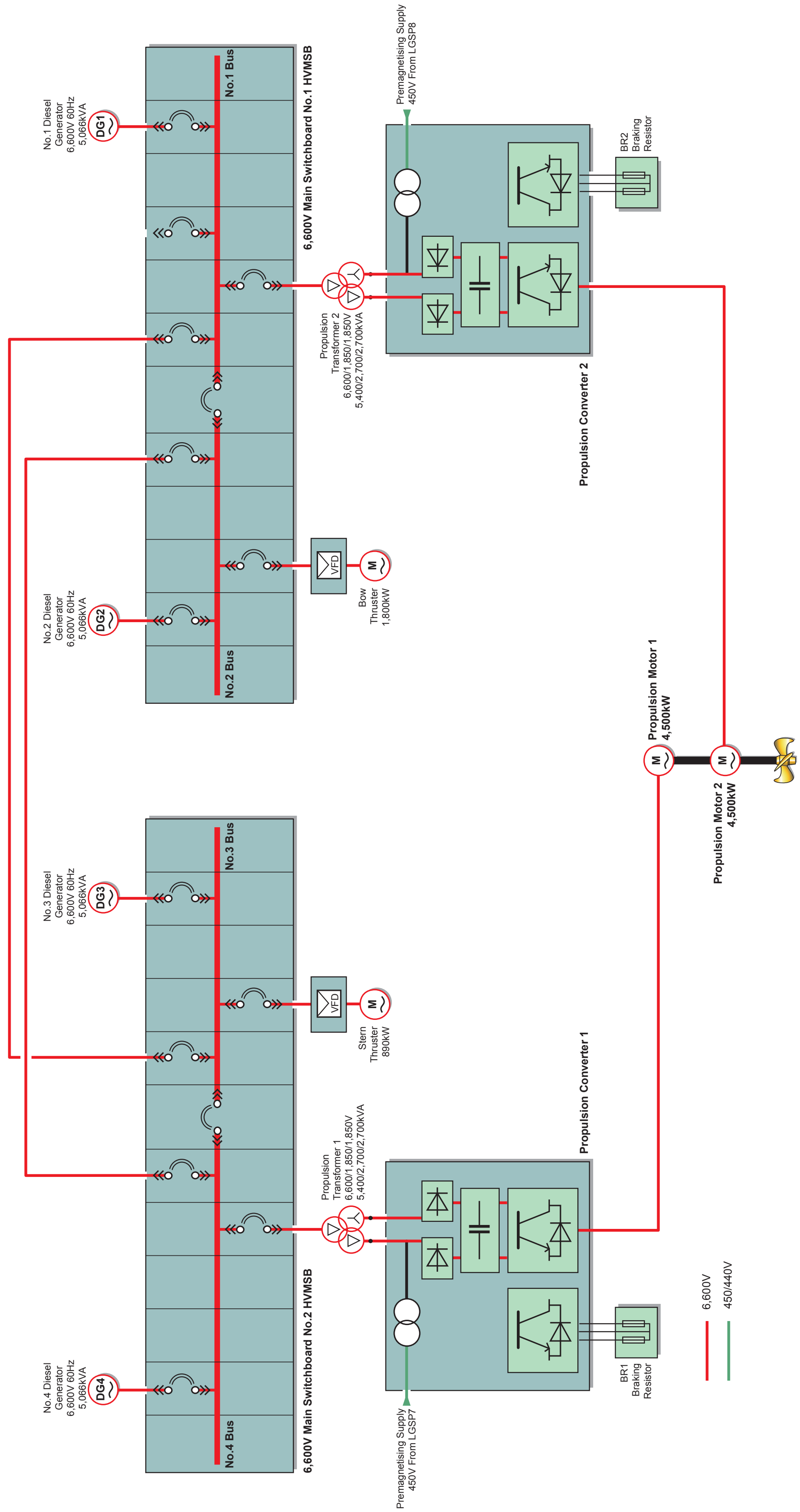


Figure 8.1.1 Propulsion System One Line Diagram

generator requires many other components, including an enclosure, bearings, cooling, lubrication, instrumentation and control, and a method to excite the field.

These components are shown in Figure 8.2.2 and Figure 8.2.3 and discussed below.

The shaft is supported by two journal bearings (7 and 13), one on the drive end (**DE**) and the other on the non-drive end (**NDE**). Each bearing has its own integral oil sump with sight glass, cooling fins, and an oil ring that circulates the oil to the top of the shaft as it rotates.

The shaft itself supports and carries the rotating components: primarily the main rotor core (9) and the 8-pole main field windings (4), but also a cooling fan (2) and several other components (10, 11, 12, 14, 16, and 19) that are required to excite the generator. Excitation systems will be discussed in Subsection 8.2.2.

The main field (4) on the rotor is wound to create eight alternating north and south poles. The main stator core (8) surrounds the main rotor (9) and is wound with three main armature windings (3). As the shaft rotates, the rotor's magnetic field sweeps by the each of the three armature windings in turn, and induces a sinusoidal voltage in each as shown in Figure 4.4.7. The resulting 3-phase AC is directed to the generator terminals (23), and from there connections are made to the main switchboard.

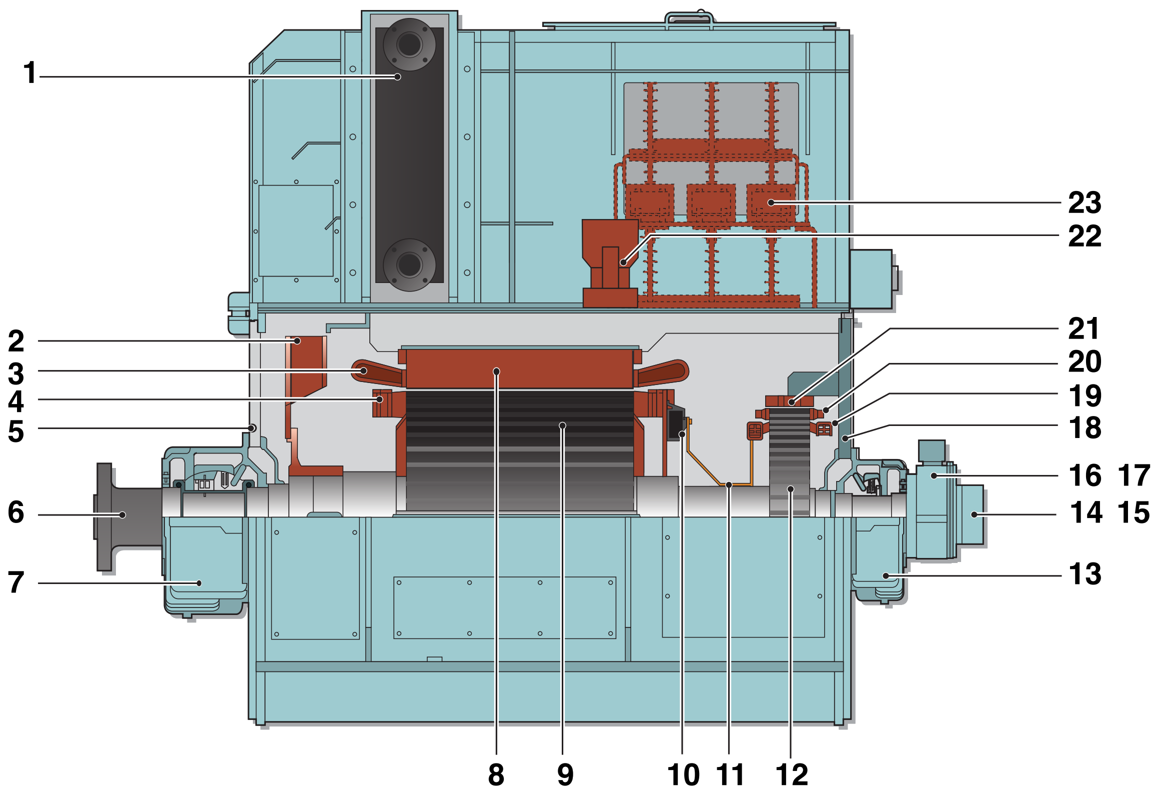


Figure 8.2.2 Hyundai HSJ9 Generator

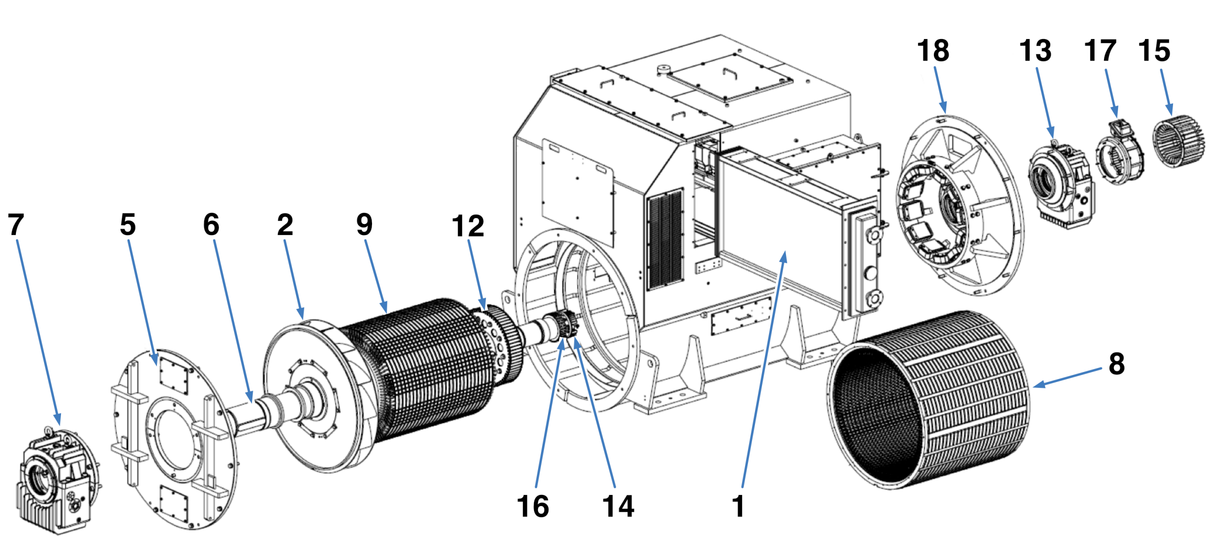


Figure 8.2.3 Generator Exploded View

1. Water cooled Air Cooler
2. Ventilation Fan
3. Main Armature Winding
4. Main Field Windings
5. End Shield (DE)
6. Shaft
7. Bearing (DE)
8. Main Stator Core
9. Main Rotor Core
10. Main Field Terminals
11. Leads to/from Rectifier
12. Exciter Rotor Core
13. Bearing (NDE)
14. Rotating Rectifier
15. Rectifier Cover
16. Permanent Magnet Rotor
17. Permanent Magnet Stator
18. End Shield (NDE)
19. Exciter Armature Winding
20. Exciter Field Winding
21. Exciter Stator Core
22. Current Transformer
23. Main Terminal Box

Both the main core and the stator core are made of thin sheets of **electrical steel**, called **laminations**, clamped tightly together. The stationary armature windings (3) and the rotating field windings (4) are inserted into slots formed when the laminations were pressed out, and are firmly wedged in to hold them in position.

Electrical steel is a speciality steel used in the cores of electrical machines such as motors, generators, and transformers. It is an iron alloy with silicon (instead of carbon) as the main additive element. Silicon increases the electrical resistivity of iron by a factor of about 5. Electrical steel also has favorable magnetic properties which tend to reduce magnetic **hysteresis** — an energy loss caused by the repeated magnetization and de magnetization of the core. These properties reduce energy losses in the core by about three times compared to conventional steel,

The laminations are insulated from each other to prevent current from flowing axially along the core. These currents, called **eddy currents**, are another source of energy loss, so using insulated laminations improves the generator efficiency.

Generators produce lots of heat while they are operating due to unavoidable losses caused by mechanical friction and electrical resistance, and other factors. If this heat is not removed as it is produced, the generator temperature will rise to unacceptable limits, and high temperature is extremely damaging to electrical insulation. Electrical machines are designed to run for 100,000 hours or more when operated at or below their design temperature limit, however for every 10° C rise above this temperature, the thermal life expectancy of the electrical insulation is reduced by half, so generator cooling is critical.

The generator's cooling system uses the shaft driven internal fan (2) to circulate the air through the machine. This hot air passes over a water-cooled heat exchanger where it is cooled and then recirculated. The cooling water tubes are double walled with slotted plate fins. Water flows through the inner tube and cools the outer tube and the slotted fins. Air flows between the fins and around the outer tubes and so is cooled.

In the case of a tube leak, water will flow between the inner and outer tubes to a leak detector and trigger an alarm. This prevents water from leaking on to the electrical components.

If for some reason the cooling water is not available, an emergency cooling mode is available. In this mode cover plates on the generator are removed to allow the fan to draw cool air from the engine room and discharge the heated air outside the generator.

8.2.2 Excitation System

The purpose of the excitation system is to **excite** the generator's field. That is, the system supplies the DC voltage and current to the generator's main field windings that creates the magnetic field required for electrical generation. The amount of excitation current determines the strength of this field, which in turn affects the generator output.

Generator excitation systems consists of several components that work together excite the field, maintain a constant and correct output voltage despite fluctuations in the load or other system conditions, and balance the reactive power when the generator is operating in parallel.

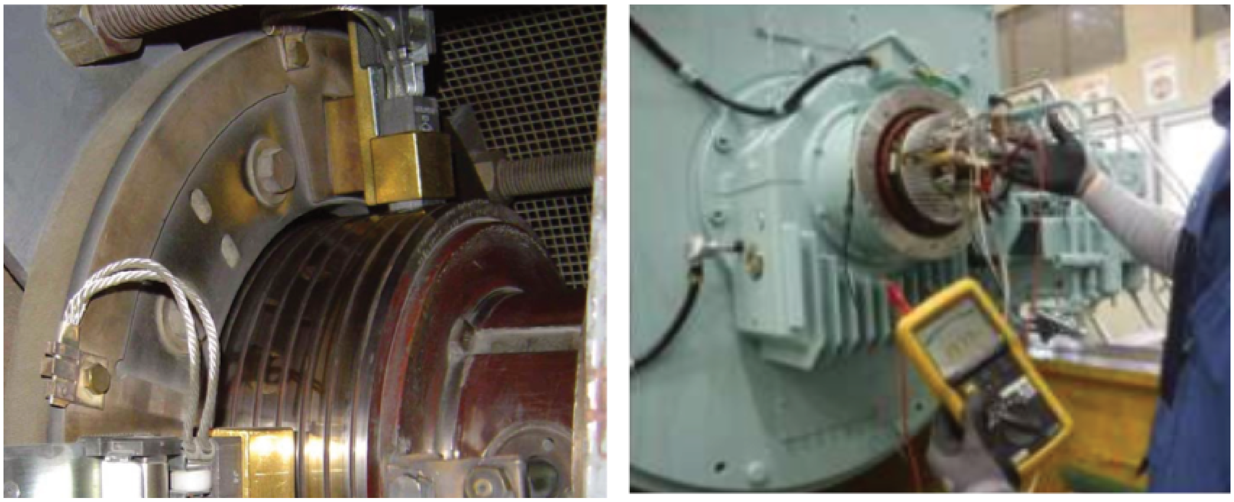
There are several different excitation system designs in use, each with particular advantages and disadvantages. These can be broadly categorized as separately or self excited, and brushed or brushless excitation systems.

In a **separately excited** excitation system, the excitation current is provided by an external DC power source. The generator's field winding is connected to a separate power supply, which is independent of the generator's output. Separately excited generators tend to be more stable and less sensitive to load fluctuations because the excitation current is not affected by the generator's output. They provide better voltage regulation and are commonly used in applications that require precise control.

A **self-excited** system, on the other hand, uses the generator's own output voltage to produce the excitation current. The generator's output voltage is connected, in parallel, to both the field circuit and to the load. In this design, generator excitation is effectively an additional load on the generator. Self-excited generators are simpler and less expensive, but are inherently less stable and more sensitive to load changes due to the coupling between the generator load, output voltage, and excitation current. Voltage regulation is more difficult, especially under sudden changes in load.

Brushed exciters use carbon brushes and copper slip rings to transmit the excitation current to the rotating generator rotor winding. Brushed exciters are simple and inexpensive and they were once widely used; however, they require significant maintenance including cleaning, adjustment, and periodic replacement of worn brushes. They are being superseded by brushless exciters in new generators.

Brushless exciters use solid-state devices, such as diodes, thyristors, and transistors mounted on the rotating shaft, to rectify the output voltage of the exciter generator. They eliminate the need for brushes and slip rings, so are more reliable, require less maintenance, and offer better voltage control than brushed exciters.



(a) Brushes and Slip Rings **(b)** Rotating Diodes

Figure 8.2.4 Brushed vs. Brushless Excitation

The excitation system used aboard the training ship is shown in Figure 8.2.5. This system is categorized as a brushless and self-excited. The main components include the the **exciter generator** and **rotating diodes**, the **pilot generator**, and the **voltage regulator**, each of which will be discussed in the following sections.

Exciter

An **exciter**, also known as an **excitation generator**, is a second generator which spins on the same shaft as the main generator. The function of the exciter is to produce the direct current required to energize the main rotor windings, thereby creating a magnetic field.

There are several important differences between the main generator and the exciter. Although both are 3-phase generators, the main generator has a rotating field and a stationary armature while the exciter has a stationary field and a rotating armature. The exciter is much smaller than the main generator; the main generator can generate more than 440 A, while the exciter generates less than 4 A.

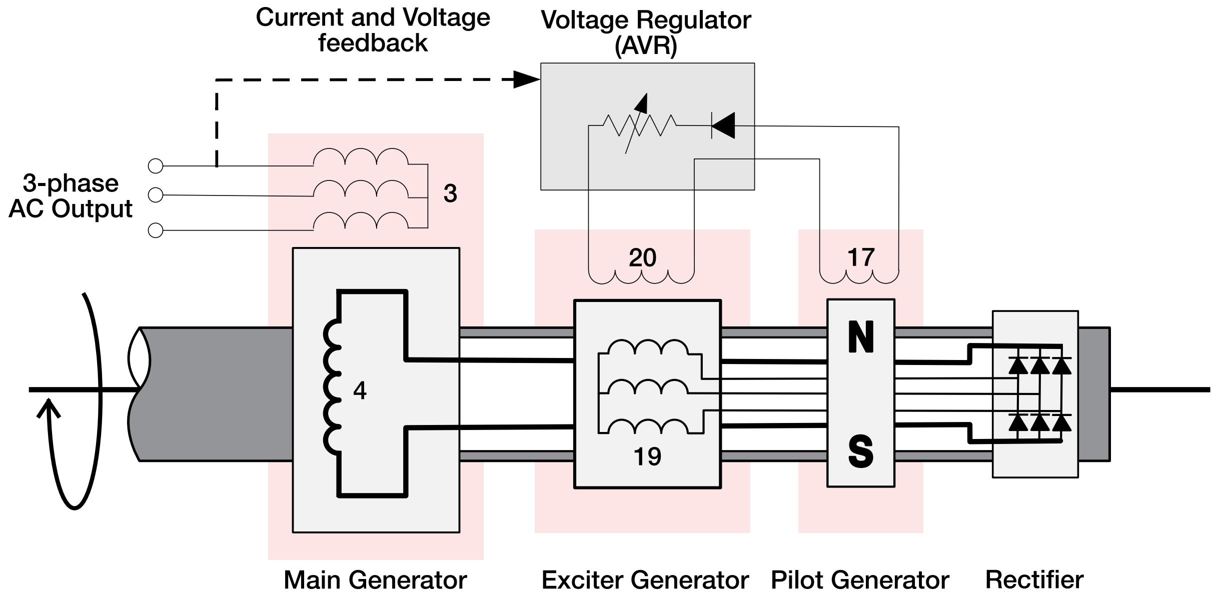
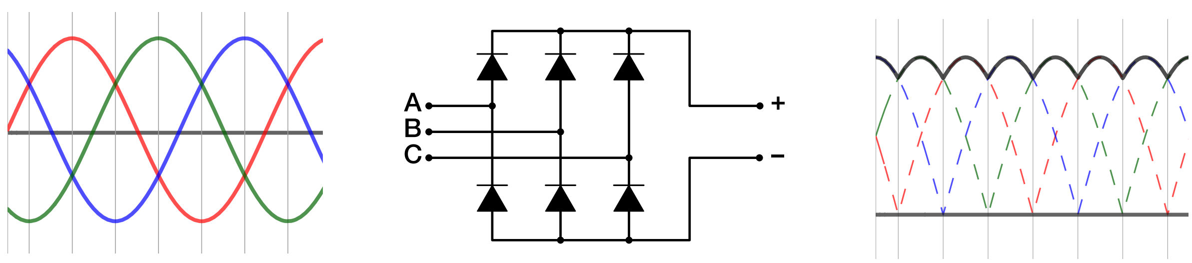


Figure 8.2.5 Hyundai HSJ9 Excitation System

The 3-phase output of the exciter is directed through the hollow drive shaft to the **rotating rectifier** mounted on the non-drive end of the shaft. The rectifier is a solid-state electronic device which uses six diodes arranged as shown in Figure 8.2.6 to convert the three-phase AC produced by the exciter generator into direct current. From there, DC current travels back through the shaft to excite the rotating main field windings.



(a) 3 phase AC in **(b)** Rotating Diodes **(c)** DC out

Figure 8.2.6 3-phase, full-wave rectifier

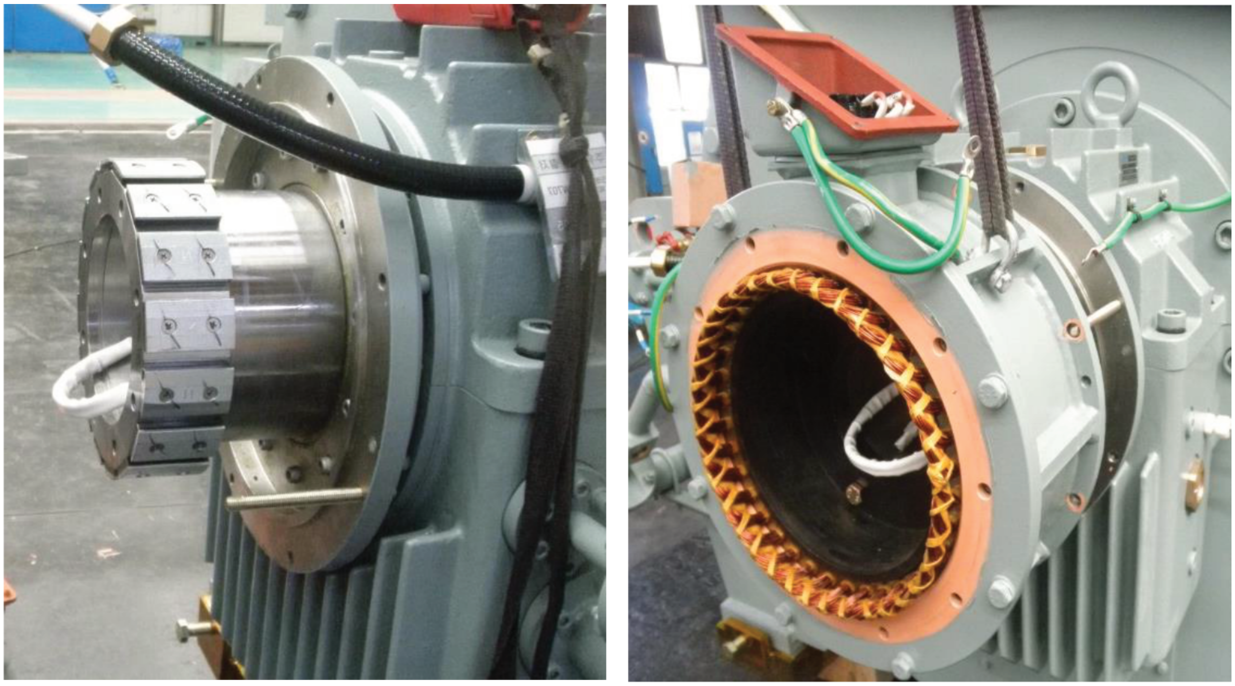
Pilot Generator

Just as the exciter generator is needed to supply the field for the main generator, a third generator is needed to supply the field for the exciter. This is the **pilot generator**.

In other words, the main generator is excited by the exciter, and the exciter is excited by the pilot generator. This process stops here however, because the field of the pilot generator is produced by permanent magnets, not a field winding. For this reason, the pilot generator is alternately called the **permanent magnet generator** or the **PMG**.

The pilot generator is shown in Figure 8.2.7. It is located at the end of the shaft outboard of the bearing on the non-drive end of the generator unit . The rotor carries sixteen permanent magnets of alternating polarities bolted to the rotating shaft. The stator is bolted onto the bearing housing and carries 3-phase wye-connected armature windings. The rotating magnets induce a three-phase AC voltage into the stator windings.

The output of the pilot generator is transmitted to the automatic voltage regulator where it is rectified to DC, and then used to excite the stationary exciter field.



(a) Permanent Magnet Rotor **(b)** PMG Stator

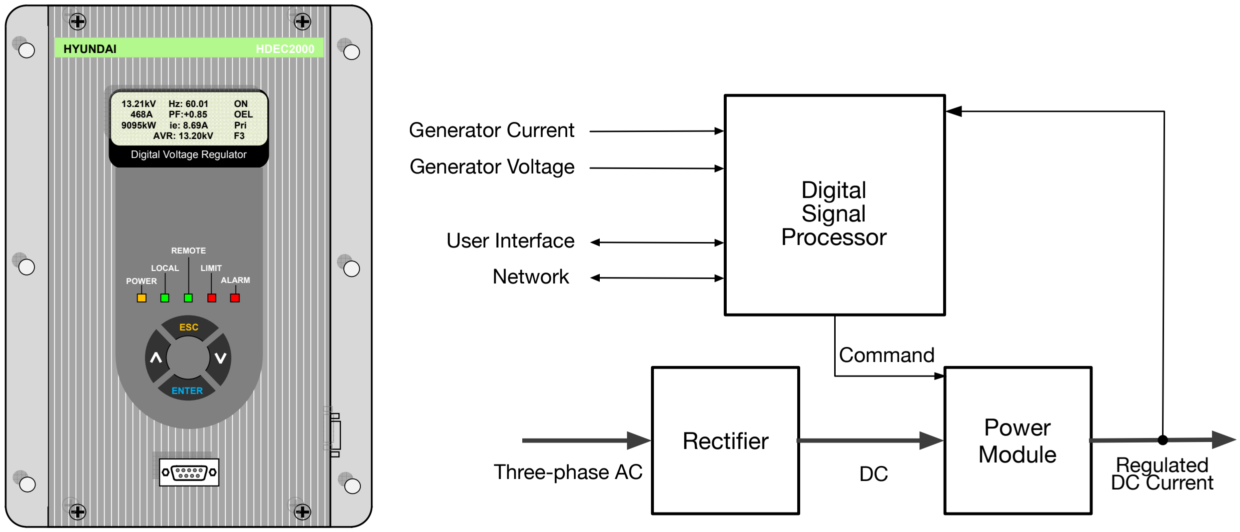
Figure 8.2.7 Permanent Magnet Generator (PMG)

Because the source of the excitation in this generator is from permanent magnets, rather than an electromagnet excited by the output of the main generator, the generator is considered separately excited. The main advantage of separate excitation is that fluctuations in the voltage of the main generator do not affect the excitation supply. Voltage fluctuations can be quickly corrected and the generator output can be maintained within tight tolerances..

Voltage Regulator

An **automatic voltage regulator** (**AVR**) is a control device which detects any fluctuation in a generator's voltage and adjusts the excitation current to offset the fluctuation and so keep the output voltage constant regardless of load changes.

A simplified block diagram of the components of the Hyundai HDEC2000 AVR used on the training ship is shown in Figure 8.2.8(b). The primary function is to provide continuous voltage regulation of the generator through excitation current control with a **PID** (**proportional, integral, derivative**) software control algorithm, but the device also includes function blocks which provide monitoring, alarm, and system protection. Two-way communications are provided through a network interface or via the front panel.



(a) Front Panel **(b)** Simplified Block Diagram

Figure 8.2.8 Automatic Voltage Regulator (AVR)

The three main components of the AVR are the Digital Signal Processor, the Rectifier, and the Power Module. The device uses a combination of hardware and software to perform its functions.

The **Digital Signal Processor (DSP)** is a specialized microprocessor designed to process and manipulate digital signals in real time. The DSP software is executable code stored in nonvolatile Flash memory. The DSP executes code and controls hardware to enable the AVR to perform functions such as regulation, measurement, monitoring, protection, and communications.

The DSP accepts both digital and analog inputs, the most important being the generator voltage and current, which are measured using current and potential (voltage) transformers on the generator output, and digitized by an **analog to digital converter** (**ADC**) in the DSP. Based on these values and the system requirements, the DSP calculates the amount of excitation current required and produces a command signal that is transmitted to the Power Module.

The **Rectifier** module supplies DC power to the power module. The power source for the module may come from a Permanent Magnet Generator, as done on the training ship, or directly from the main generator terminals if the generator is self-excited. The module uses a three-phase full-wave rectifier, Figure 8.2.6, to convert the supply to a DC voltage.

The Power Module uses **pulse width modulation (PWM)** to trigger a set of **insulated gate bipolar transistors** (**IGBT)** that supply the requested excitation current An excitation current signal is transmitted back to the DSP to be used for to PID feedback, and for over-excitation limitation, protection functions and monitoring. PWM and IGBTs are discussed in more detail in What is Pulse Width Modulation? and What is an IGBT?.

8.3 Propulsion Converters

Propulsion Converters are very large **variable frequency drives**. Recall from Subsection 4.4.5 that VFDs are electronic devices that take fixed frequency AC and convert it to variable-voltage, variable-frequency AC. A VFD can drive an induction motor at any combination of speed and torque within the motor's operating range.

The ship's propulsion converters convert the fixed 6,600 V, 60 Hz AC from the High Voltage Main Switchboard (HVMSB) into a variable voltage and frequency which is used to drive the two electric propulsion motors at any speed commanded by the bridge.

Table 8.3.1 Frequency Converter Specifications

Manufacturer	General Electric
Model	MV7306 DFE 12P [1]
Rated output power	4.75 MW
Input voltage	1,850 V
Output voltage	variable 0 – 3,150 V
Output current	1,035 A maximum
Supply frequency	60H
Output frequency	variable 15 – 90 Hz

8.3.1 Description

The ship has two General Electric MV7306 propulsion converters, one for each propulsion motor. The converters include the three main components shown in Figure 4.4.11, as well as other supporting components housed in a row of cabinets located in converter rooms 1 and 2, on the 4th deck. The converters operate at extremely dangerous high voltages, so these rooms are normally locked and off-limits to all unauthorized personnel.

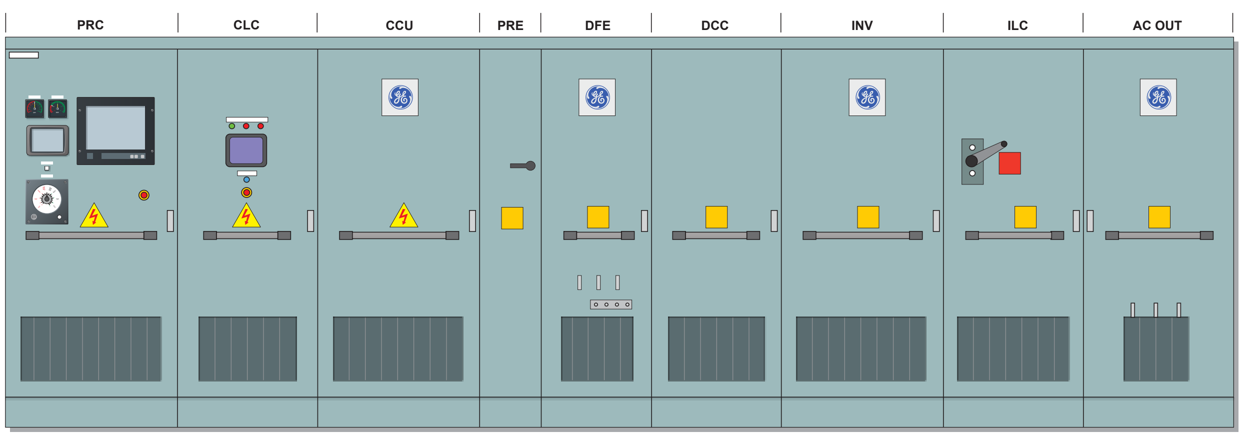


Figure 8.3.2 Propulsion Frequency Converter, exterior

8.3.2 Drive Cabinets

The components of the propulsion converter are housed in eight connected cabinets. Each cabinet supports a particular function, as described below:

[1] 3.3 kV Diode Front End, 12 pulse, Neutral Point Clamped (NPC)

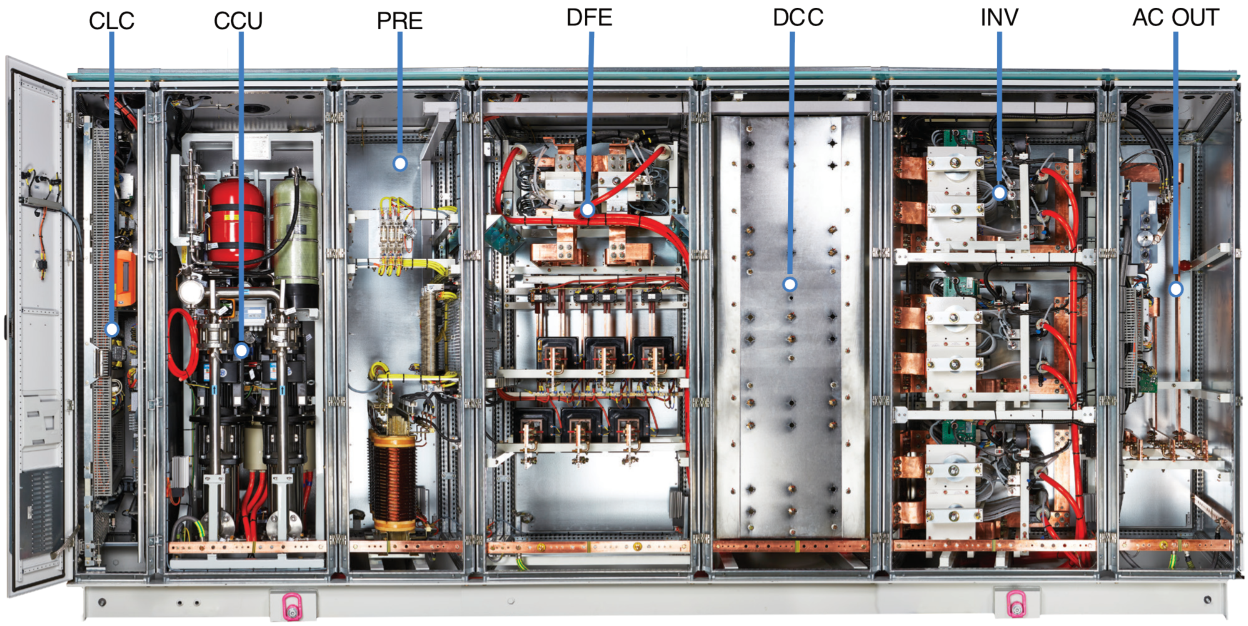


Figure 8.3.3 Drive Cabinets, interior

Process Control (PRC)

The Process Control cabinet contains control and management modules for the propulsion system. It also contains a 230V AC 1.5 kVA **uninterruptible power supply** (**UPS**) which will take over immediately in the event of failure of the normal power supply. The UPS output goes to the CLC section for distribution.

The front panel of the PRC contains a panel mounted supervision computer with touch-screen, which provides local control to monitor system parameters and alarms including:

- Speed setting dial and reply pointer.
- Propeller rpm meter.
- Power meter.
- Emergency stop pushbutton.
- Alarm Acknowledge pushbutton.

Within the PRC, **programmable logic controllers (PLCs)** and circuit boards automatically monitor and control many aspects of the propulsion system including:

- Control the propulsion motor speed, torque, flux and current.
- Connections, via fiber optic cables to the bridge and engine control rooms.
- Ethernet communications with instruments that monitor the system conditions.
- Fault management, safety shutdowns and interlocks.
- Provide the trigger pulses for the IGBTs.
- Automatically start and stop system auxiliaries.

Converter Local Control (CLC)

This Converter Local Control cabinet contains equipment to monitor and control the converter, including:

- **Main PLC.** The primary function of this Programmable Logic Controller is to control the sequences, safeties and regulation of the converter and control of motor speed and torque. It acquires signals from various current and voltage measurements and gates the inverter IGBTs accordingly.

  Additional tasks of the controller include control of the incoming AC supply breaker, protection of motor and converter, auxiliaries and the interface to the customer application software.

- **I/O modules.** These input/output modules connect to establish communication with the various parts of the system. Non-time-critical I/O units are connected to MV7306 main controller through an Ethernet link.

- **Low voltage auxiliaries.** These auxiliary components use 120 V supplied from UPS. The control cabinet also includes relays used to control circuit breakers, contactors, and DC supply for internal measuring devices.

- **Touch screen display.** This display provides functionality to configure the drive, and provides the operator with local control, diagnostic and monitoring functions.

Converter Cooling (CCU)

The Converter Cooling cabinet contains the equipment required to remove the heat generated by diodes and IGBTs when the converter is operating. The cubicle contains two circulating pumps (one always in stand-by), a stainless steel plate-type heat exchanger, an expansion tank, a resin deionizing cartridge, stainless steel piping and high pressure hoses.

Deionized water is used as the primary cooling medium. because its low conductivity minimizes corrosion and improves heat transfer, while its purity reduces the accumulation of scale formation.

De-ionized water is circulated by the pump to the cooling pipes and ducts of the high voltage sections. Returning coolant then passes through a the heat exchange and the heat from the de-ionized water is removed by raw water. A three-way thermostatic bypass valve controls the flow of raw water to through the heat exchanger to maintain the coolant temperature at an optimum level.

The coolant pressure, temperature, flow rate and conductivity are closely monitored. A high temperature coolant alarm will sound at 43°C (110° F). If a high conductivity is detected, the coolant is shunted through a resin de-ionizing cartridge until until a satisfactory conductivity level is restored,

Pre-charging (PRE)

The pre–magnetization (pre–charging) transformer and switchgear for the pre–magnetizing of the propulsion transformer and the DC filter capacitors is located in this section.

During startup, magnetizing the main transformers and charging the DC filter capacitors will draw a large (> 400 A) current which can affect other parts of the electrical distribution system if not controlled. The pre-charging system reduces the peak currents by limiting the charging rate with resistors and spreading the charging/magnetizing cycle out over about 10 minutes.

Power for pre-charging is supplied by a 440 V circuit from the main switchboard.

DFE – Diode Front End Section (DFE)

This section contains the Diode Front Edge bridge. This bridge receives the output of the two secondary windings of the **propulsion transformer** and rectifies this to a DC voltage in the **diode bridge**.

The propulsion transformers reduce the network voltage (6,600 V) to the requirements of the frequency converters (1,850V). The transformers have a single primary winding, delta connected, and two secondary windings, one is delta connected and the other is wye connected. This provides a 30° phase shift in one of the supplies to the diode front end. This arrangement effectively provides a 12-pulse configuration that reduces harmful harmonics.

The diode bridge is made up of four stacks of six diodes, one stack to each transformer secondary. The output is passed to the DC Capacitor and filter circuit in the DCC cabinet .

DC Capacitor Section (DCC)

This section houses the DC filter capacitor banks.These capacitors store energy and filter the rectified AC to remove any residual ripple from the waveform to provide a more stable DC supply. The capacitors are water cooled. During the power sequence they are all pre-charged.

Inverter (INV)

The inverter section contains three subassemblies called **stacks**, one for each phase of the output. Each stack consists of four IGBT and two diode **press pack** modules, a gate driver, water-cooled heat sink and balancing resistors.

The term press pack refers to the physical packaging of electronic components. It typically consists of a semiconductor chip, along with its associated control and protection circuitry, mounted between two metal plates which serve as electrical contacts and provide mechanical support. These plates are made of good thermal conductors such as copper or aluminum. This design allows for efficient heat dissipation, as the metal plates can be directly attached to a heat sink.

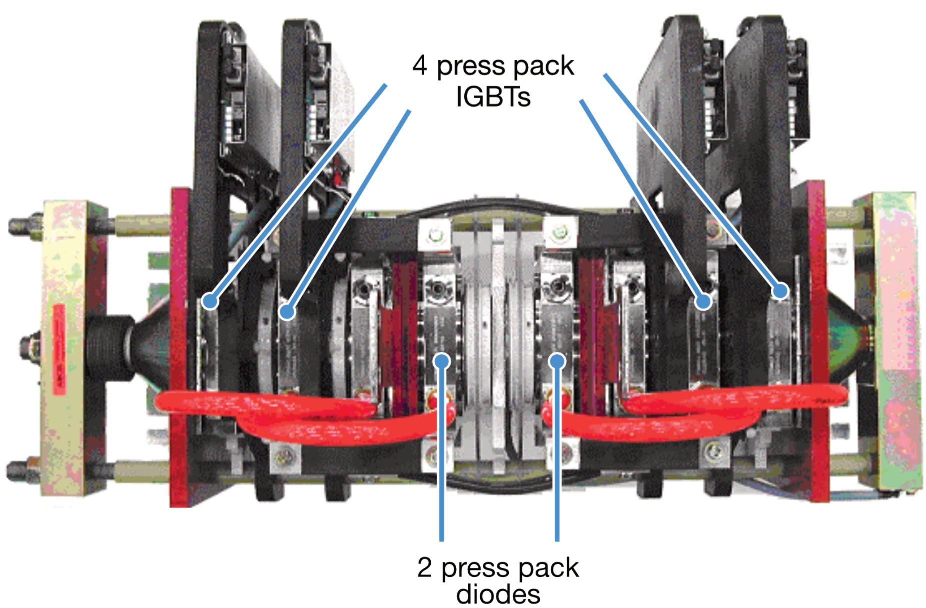


Figure 8.3.4 IGBT Stack

The IGBT gates are triggered by pulse width signals produced in the CLC section which change the direct current stored in the DC capacitors into variable voltage, variable frequency alternating current.

Inverter Local Contol (ILC)

The ILC cubicle contains instrumentation to measure the DC link voltage, output current measurements, and the DC link grounding switch.

This module also protects the inverter and DC bus from damage caused by the propulsion motors when the ship is slowing down. During these periods the momentum of the ship will drive the propellor and motor, causing the motors to behave like generators and produce electrical power.

Excessive electrical power cannot be fed back into the electrical distribution system, so when the DC bus reaches a certain voltage, the excess energy is shunted through a chopper unit to braking resistors. The braking resistors are located near the converter rooms, and are capable of dissipating up to 10 MJ for 20 seconds once every 30 minutes

AC Output (AC OUT)

This section contains the connections between the output of the inverter and the cabling to the propulsion motor.

8.4 Propulsion Motors

The ship is propelled by two 4500 kW (6000 HP) General Electric three-phase induction motors. The motors drive a single propeller shaft, which passes through the stern tube and drives a fixed-pitch propeller. The speed and direction of the motors are varied by the Propulsion Converter in response to commands from the bridge.

Table 8.4.1 Propulsion Motor Specifications

Manufacturer	GE Power Conversion
Type	Three-phase AC Induction
Model	N3 HXC 1250 L/10 [1]
No. of sets	2
Rated Power	4,500 kW
Voltage	3,150 V
Current	1,035A
No. of Poles	10
Speed	0-115 rpm

The propeller shaft is supported by journal bearings which maintain radial alignment, and a thrust bearing which transmits thrust from the propeller to the hull and maintains axial alignment. The shaft is equipped with turning gear and a shaft lock. When either of these is engaged, propulsion is blocked.

[1] Series NC, H=Air/water cooling, X=Medium Voltage, C=Copper Cage, 1250 mm shaft height, L=magnetic circuit type, 10 pole

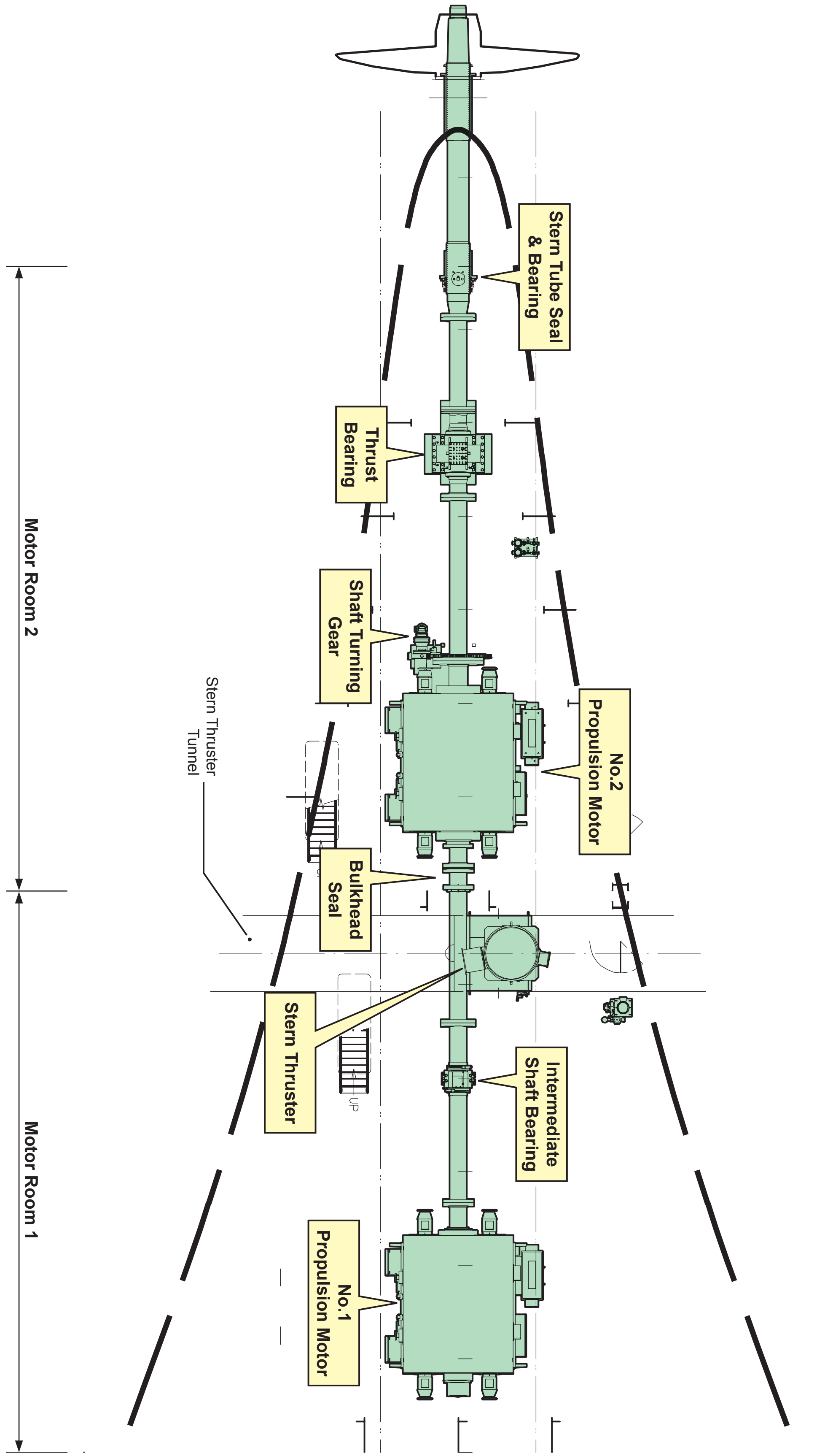


Figure 8.4.2 Drive Train

8.4.1 Description

The stator core is made up of electrically insulated sheets, braced with clamping bolts and rings and mounted in the stator housing. The stator windings consists of layered coils mounted in the open slots of the stator core. The stator has two terminal boxes on the stator housing for electrical connections.

The rotor is comprised of a forged shaft with a shrunk on rotor body. The rotor windings are formed by bars and rings embedded together and brazed by an induction heating method to form a squirrel cage.

The rotor is supported with self-lubricated, bushed bearings. There are two jacking oil pumps for the drive end bearings and two jacking oil pumps for the non-drive end bearings, normally with one operating and one in standby.

The motors are fitted with two air-water heat exchangers providing cooled air which is forced through internal cooling openings via four 440V 9.2 kW electric-motor driven fans. This air is then circulated back to the coolers. In the event of fan failure, it is still possible to operate at a reduced speed. In the event of cooling water failure, the motor is provided with emergency air openings in the cooler hood and in the stator housing which can be removed for natural cooling.

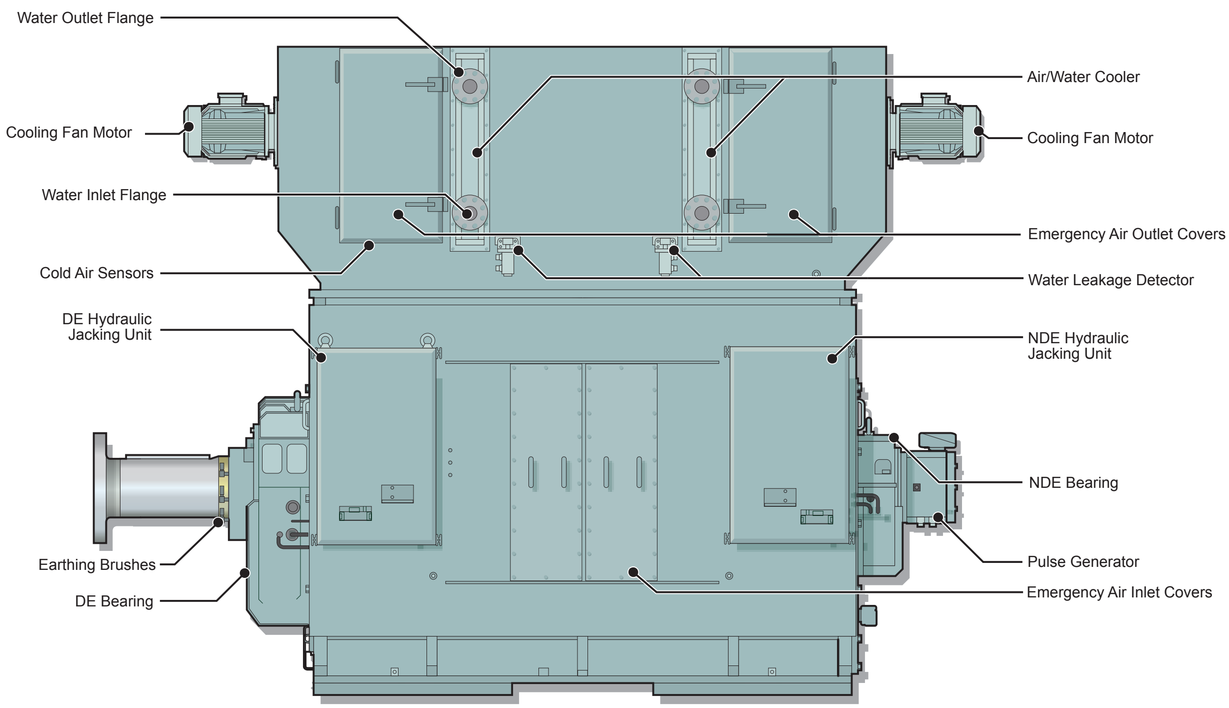


Figure 8.4.3 No. 1 Propulsion Motor

Chapter 9

Auxiliary Systems

9.1 Lubrication Systems

9.1.1 Requirements of a Lubrication System

TBD

9.1.2 Rotating Machinery

TBD

9.1.3 Axial and Radial Bearings

TBD

9.2 Fuel oil Systems

TBD

9.3 Cooling Systems

TBD

9.4 Refrigeration

TBD

9.5 Fresh Water

TBD

9.6 Sewage Treatment

TBD

Chapter 10

TS Patriot State

The *Patriot State II* is the second of five National Security Multi-mission Vessels (NSMV) S5-ME-155a class vessels built for the U.S. Department of Transportation's Maritime Administration (MARAD).

Figure 10.0.1 NSMV Rendering

The ship has dual missions: its primary mission is to provide a modern platform for training future Merchant Marine Officers, additionally, she is also an available government resource to provide Humanitarian Assistance end Disaster Relief (HA/DR) where and when needed.

The NSMVs are passenger-type vessel with capacity for on-deck cargo and container stowage as well as a ramp for roll-on roll-off (RORO) cargo.

Accommodation for 600 cadets and 100 officers and crew are located over the forward and midships portions of the vessel. 60 additional berths are available for HA/DR missions by doubling up single-occupancy staterooms.

Diesel-electric propulsion: 4 engines, 2 motors, single fixed-pitch propeller, Azimuthing Bow Thruster, Stern Thruster.

10.1 Principle Dimensions

Table 10.1.1 Principle Dimensions

Length, overall	160 m	(525 ft)
Beam	27 m	(89 ft)
Depth, to main deck	16.8 m	(55 ft)
Draft, load line	7.35 m	(24 ft)
Masthead Height, above keel	44 m	(144 ft)
Total installed Power	16,800 kW	(22,500 hp)
Design Speed	18 knots	(20.7 mph)

Table 10.1.2 Capacities

Cadet Berths	600
Officers and Crew Berths (Single Occupancy)	100
Additional Berths (Double Occupancy)	60
RO-RO Cargo Space	990 m^2
Deck Container Capacity	60 TEU
Fuel Marine Gas Oil	2169 m^3
Fresh Water	1234 m^3
Salt Water Ballast	3567 m^3
Fresh Water Ballast	1275 m^3
Gray Water	655 m^3
Black Water	166 m^3

10.2 Deck Plans

10.3 Main Engines

Turbocharged, 4-stroke, single acting, trunk piston, non-reversible, direct fuel injection

Table 10.3.2

Manufacturer	**GE Wabtec**
Model	16 V250MDC
Maximum Continuous Power	4200 kW (5632 hp)
Rated Speed	900 rpm
Arrangement and number of Cylinders	V-16
Bore	250 mm (9.8 in)
Stroke	320 mm (12.6 in)

10.4 Ship's History

Construction History: design started, keel laid, ship launched, ship delivered, first cruise,$300 million cost, Philly shipyard, TOTE services.

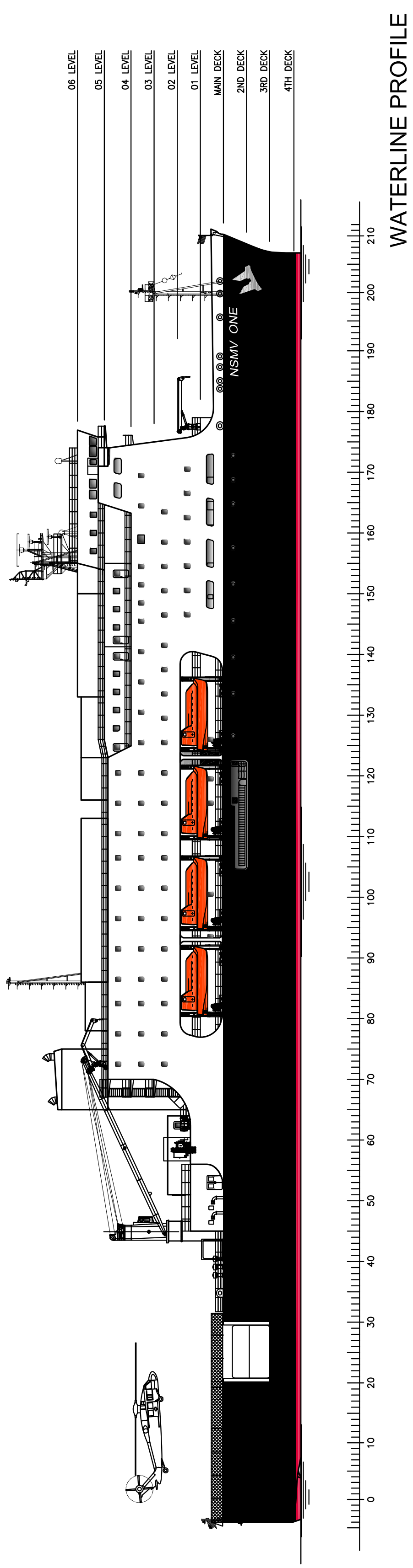


Figure 10.2.1 *Patriot State* Waterline Profile

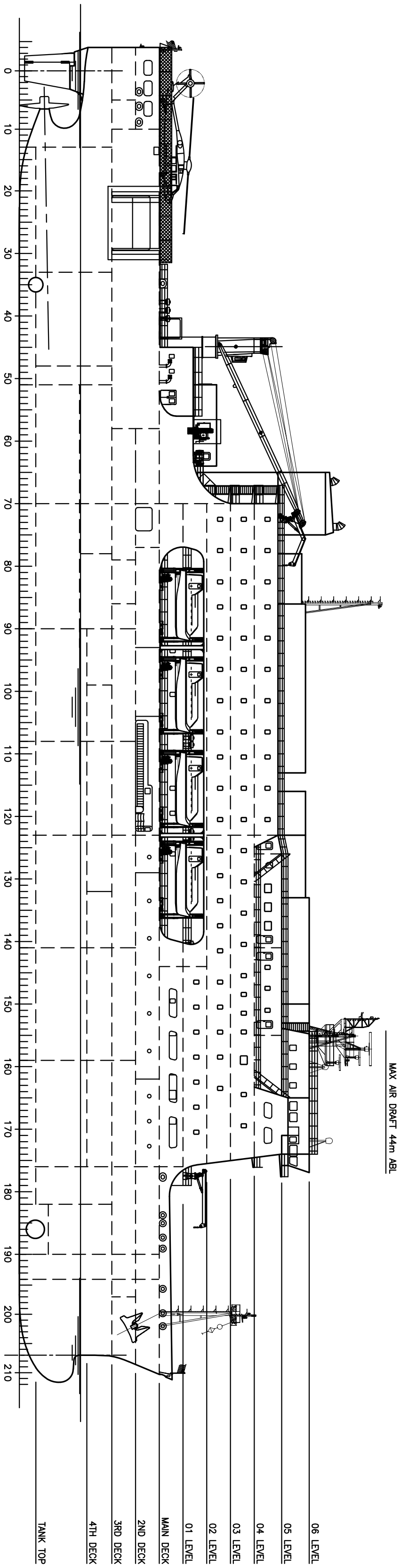


Figure 10.2.2 *Patriot State* Outboard Profile

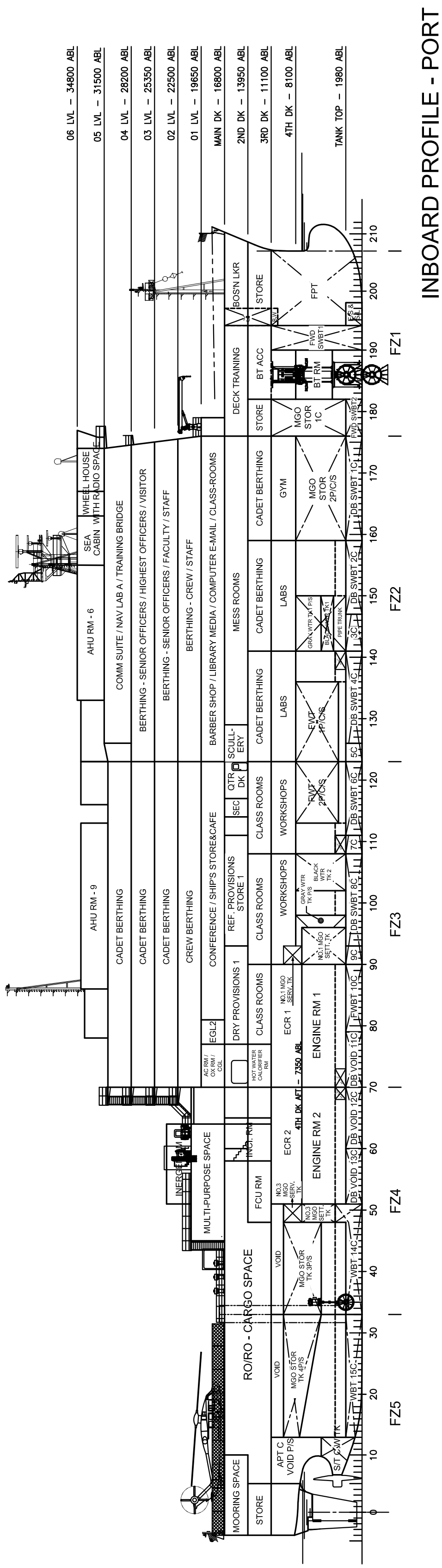


Figure 10.2.3 *Patriot State* Inboard Profile Port

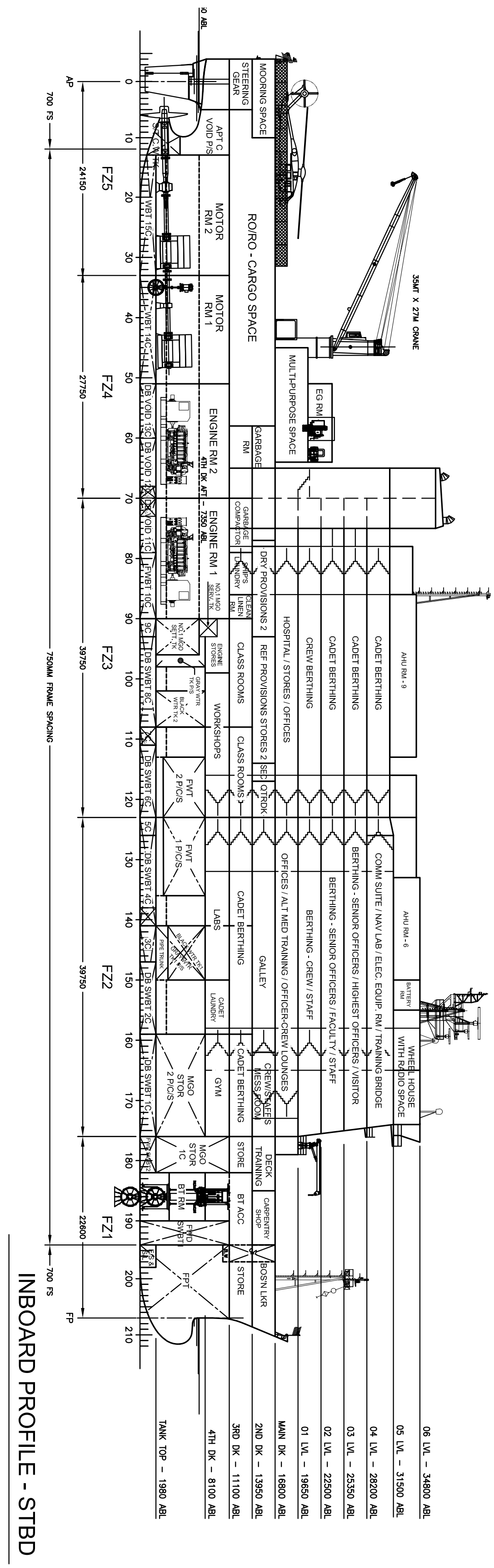


Figure 10.2.4 *Patriot State* Inboard Profile Starboard

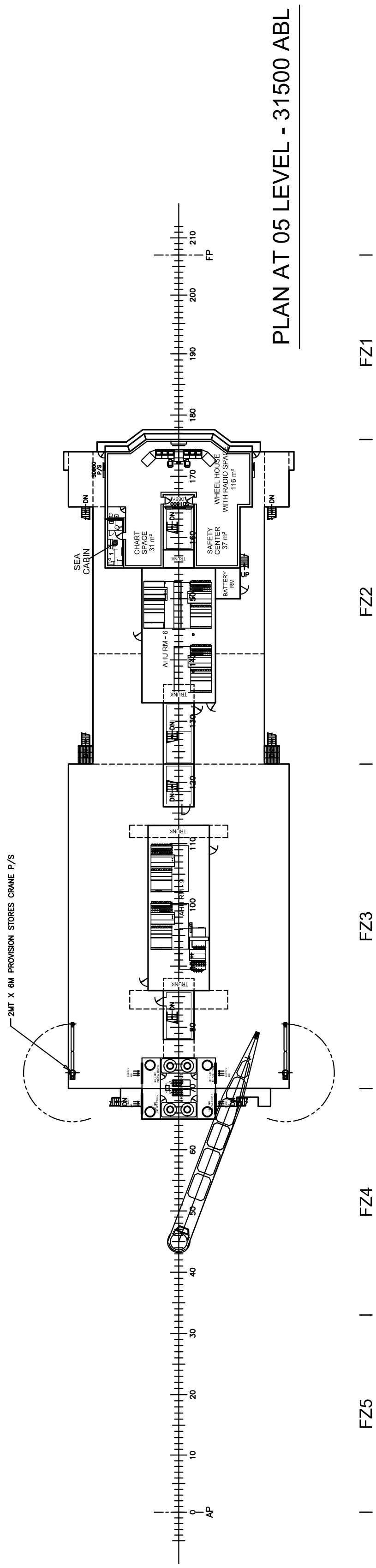


Figure 10.2.5 *Patriot State* 05 Level

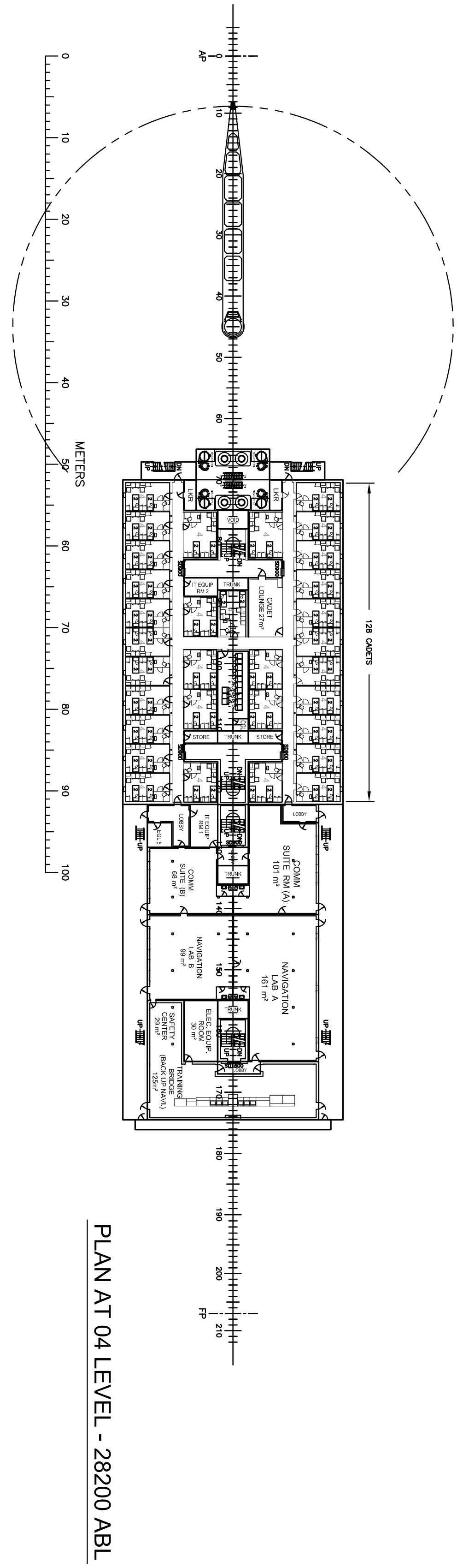


Figure 10.2.6 *Patriot State* 04 Level

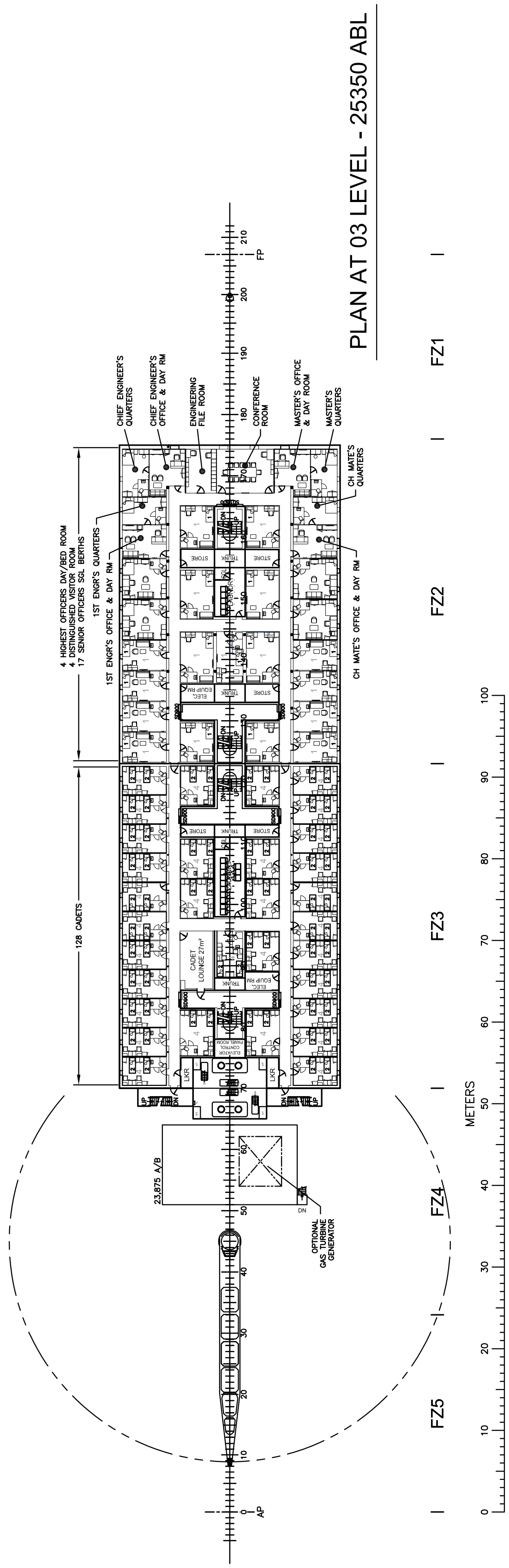


Figure 10.2.7 *Patriot State* O3 Level

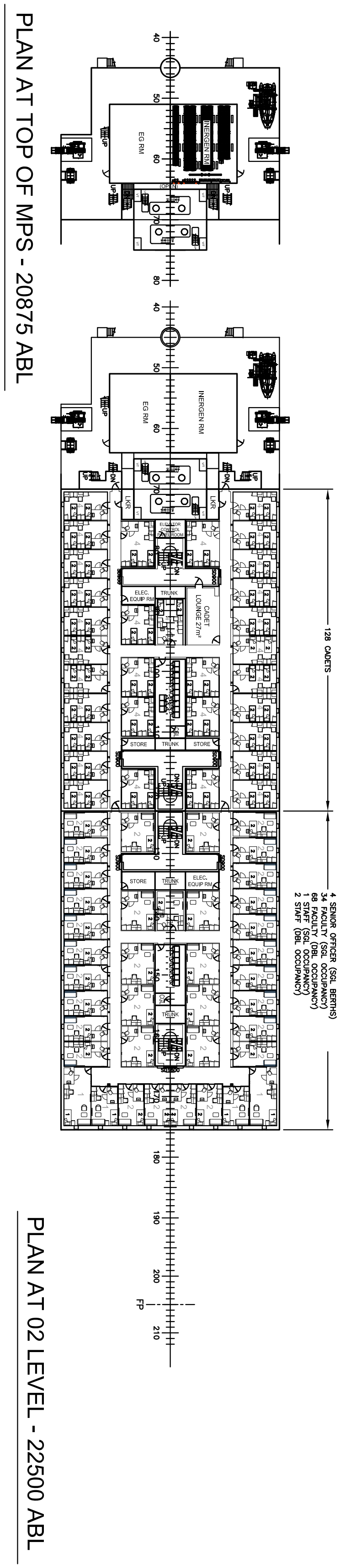


Figure 10.2.8 *Patriot State* 02 Level

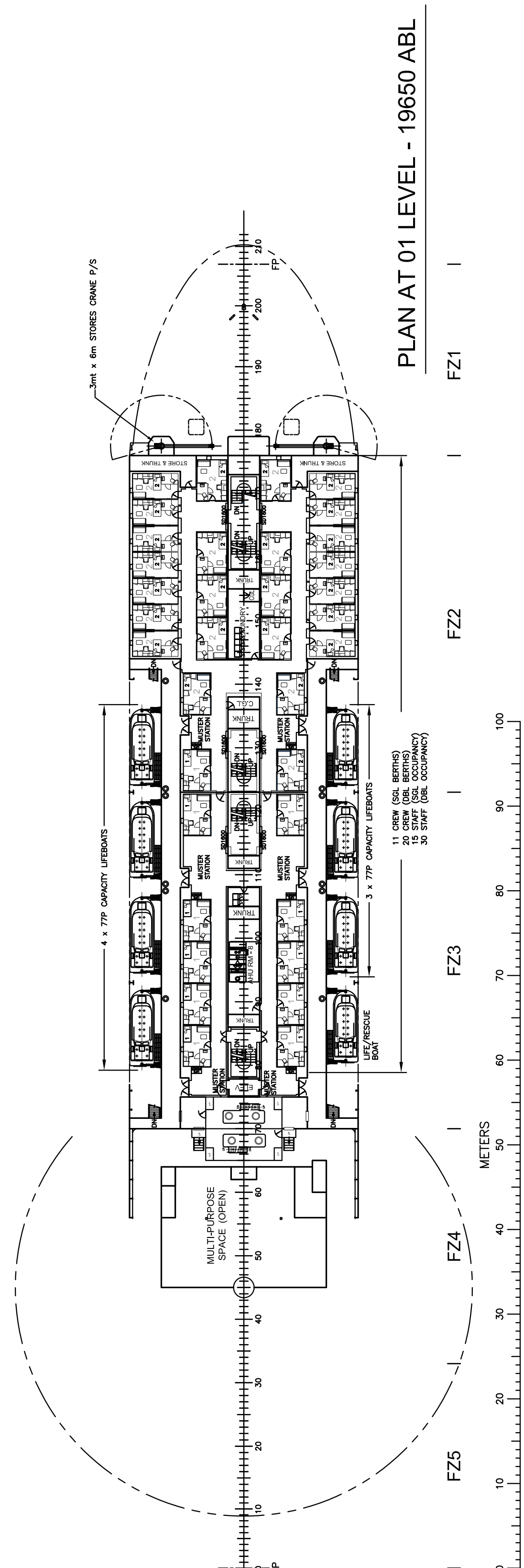


Figure 10.2.9 *Patriot State* 01 Level

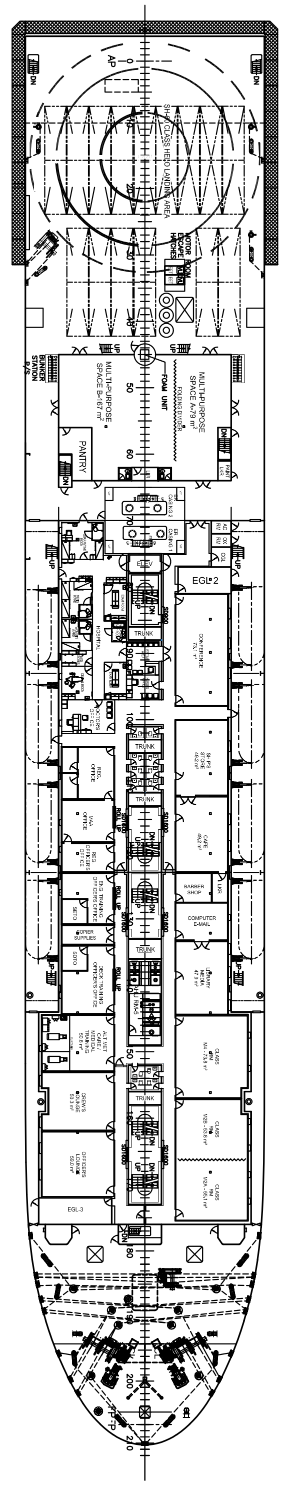


Figure 10.2.10 *Patriot State* Main Deck

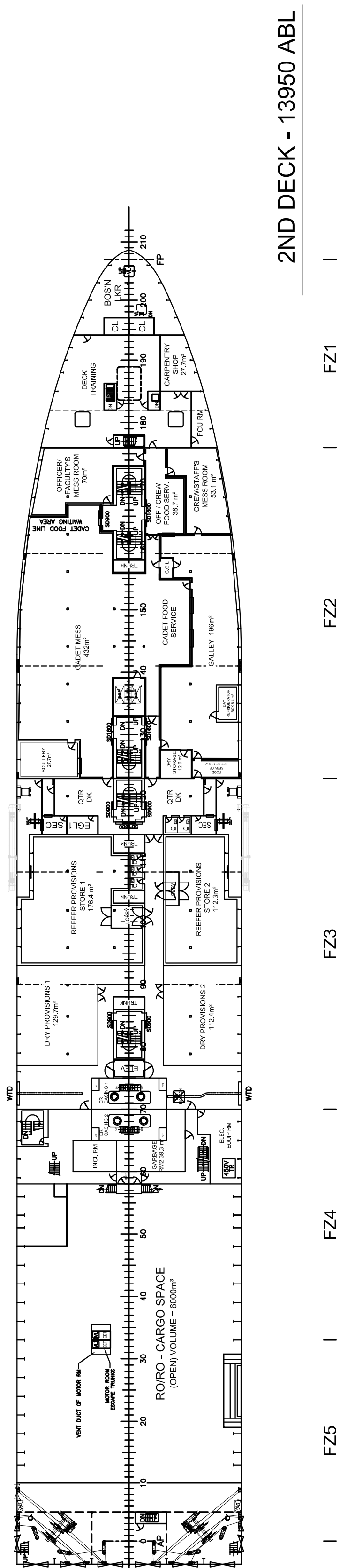


Figure 10.2.11 *Patriot State* 2nd Deck

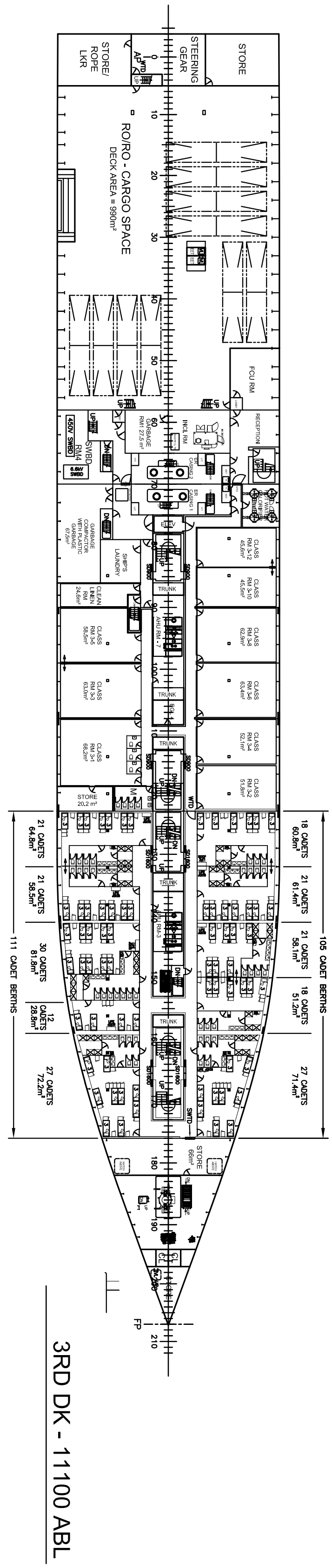


Figure 10.2.12 *Patriot State* 3rd Deck

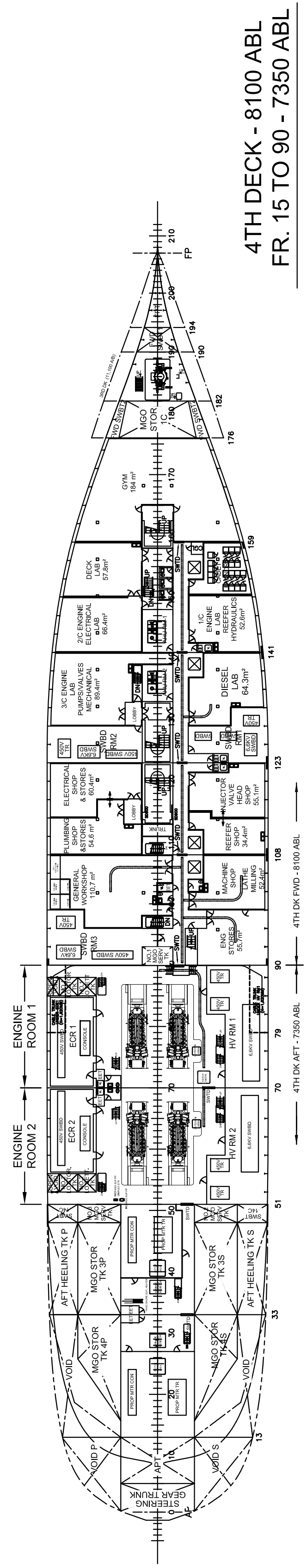


Figure 10.2.13 *Patriot State* 4th Deck

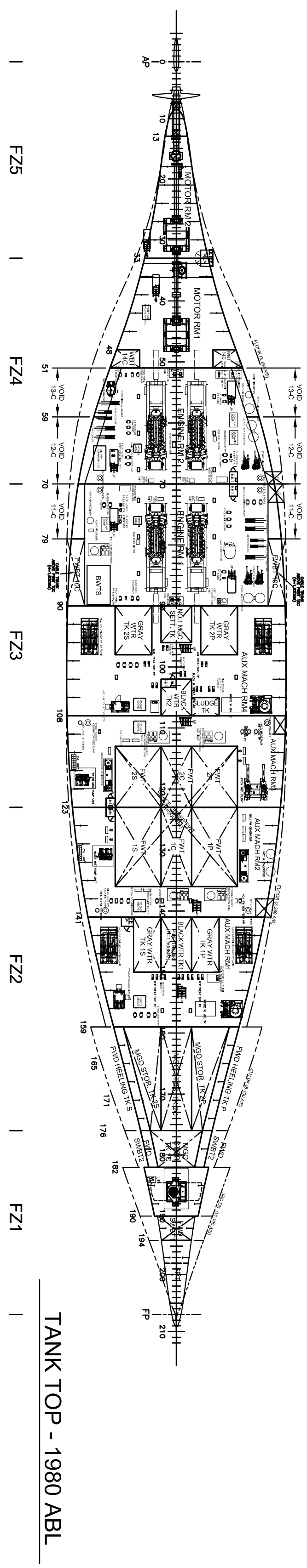


Figure 10.2.14 *Patriot State* Tank Tops

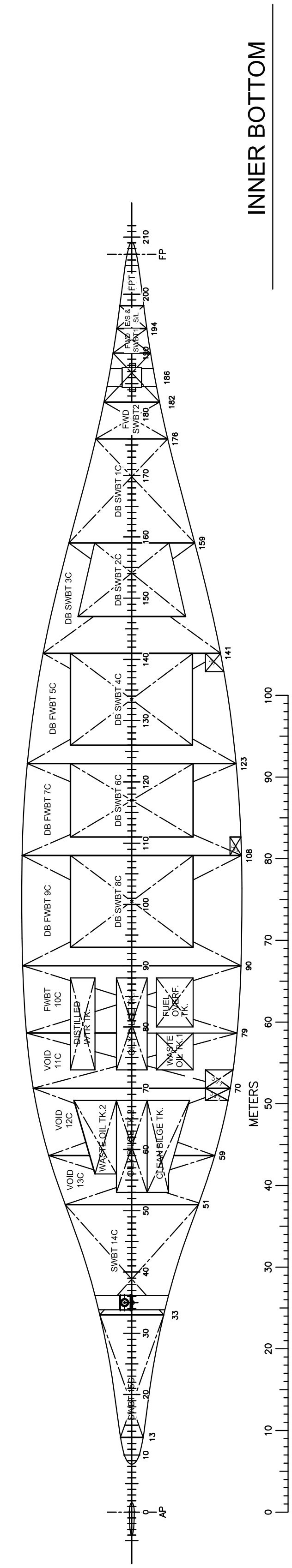


Figure 10.2.15 *Patriot State* Inner Bottom

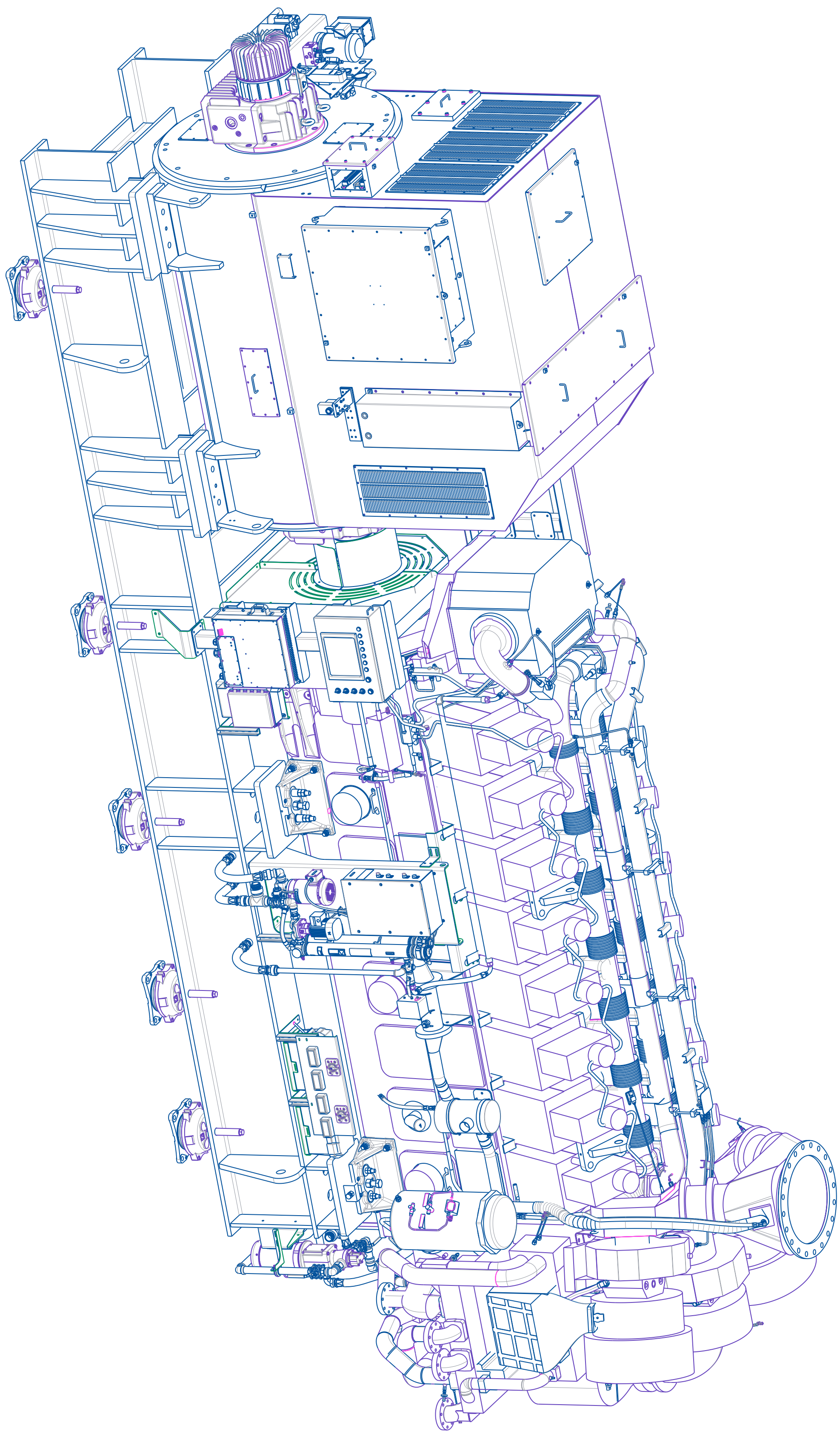


Figure 10.3.1 Main Engine and Generator