1. Explain two ways that boilers are rated. Two of the three listed
   
   a. One square meter of heating surface equals 10 kilowatts. The heating surface of a boiler must be determined by computing the area of the surface involved in square meters. Where a computation is made of a curved surface, the surface with the greater radius is used. A boiler having 92.9 m² of heating surface is rated at 92.9 x 10 = 929 kW. If, in fact, it develops 975.45 kW it is said to operate at 105% of rating.

   b. Where electric power is used as the heat source, the boiler rating shall be the maximum kilowatt rating of the heating element. Due to the fact that losses always occur, the actual output will be somewhat less.

   c. Where neither of the above determinations is applicable, an hourly boiler output of 36 megajoules is equivalent to 10 kilowatts. This is the calculation employed in determining the heat balance of a steam plant.
2. **List the steps in the field erection of a steam generator used for power generation. How is the steam drum supported?**

The major steps in the field erection of a steam generator are:

- Foundations are poured and structural steel is erected.
- The steam drum can be raised into position at the top of the boiler once the main girder steel has been erected.
- The next boiler parts to be installed are the upper headers and links. They are hung below the pressure part support steel. Included in the upper headers and links are: Main steam lines to the turbines, crossover links from the different stages of the superheater and reheater, economizer piping to the steam drum and riser tubes from various headers, and downcomers from the steam drum to the lower headers or pump manifolds.
- After the boiler headers and links have been installed, the superheater and reheater sections, or modules, can be lifted into place.
- Wall tubes are attached to drums and headers by rolling (expanding), or, in large high-pressure units, they are welded to tube stubs.
- After the pressure parts of a steam generator have been put in place, the installation of auxiliary equipment is started.
- The unit is then inspected and a hydrostatic test is done on the pressure parts.
- The boiler casing and ductwork are then installed.
- A preoperational inspection is completed before the unit is started up.
3. **List five fundamental design requirements that must be addressed in the design of a steam generator.**

The design requirements of a steam generator are: (Any five of the following)

- **Choice of auxiliaries**, such as fan drives (electric or turbine or both), type of water treatment equipment, types and numbers of pumps, fuel handling equipment, and soot blowing equipment. These can be specified in the bid documents or left to the vendors to recommend options.

- **Instrumentation and automatic controls.** The boiler must have the basic instruments to operate safely. It may also have fully computerized controls to maximize efficiency and reduce labour requirements.

- **Buildings, ladders and walkways, and cranes for maintenance.**

- **Efficiency.** The boiler must be highly efficient. It must be able to transfer a maximum of the heat available in the fuel to the water and steam within the drums and tubes.

- **Reliability.** The boiler must be capable of remaining in constant service for long periods of time. It must be constructed of materials capable of withstanding high pressures and temperatures.

- **Cost.** There are several cost factors affected by boiler design. The cost of the boiler depends to a large extent on materials used, firing equipment required, and auxiliaries necessary.

- **Serviceability** The boiler should be designed so that it is readily accessible for cleaning, inspection, and repair.

- **Safety.** Boiler design should conform to the ASME Code regarding materials used, fabrication methods, and fittings installed. Another important safety factor is the type of control system used to operate the boiler.

4. **Sketch and describe membrane wall construction of a boiler wall. Include insulation and lagging in the diagram.**

The diagram must include tubes, membranes or fins, insulation and metal cladding or casing.
5. List the effects the type of fuel has on the design of a steam generator furnace. Why is a gas-fired steam generator physically smaller than a coal-fired unit of the same output?

The type of fuel affects the size of a steam generator furnace. Furnace size is based upon the heat release of the fuel and the time taken for complete combustion of the fuel. The fuel also determines the need for equipment such as soot blowers to keep the heating surfaces clean.

Designing furnaces for gas firing is similar to oil firing, except that gas firing results in lower localized heat absorption rates. This means that the furnace temperature is more uniform than with oil. Therefore, the furnace can be slightly smaller in volume than an oil-fired furnace. Both oil and gas furnaces are smaller than coal fired furnaces, which require larger volumes. The time taken to combust solid fuels is larger.

6. Sketch and describe the ducting arrangement of an air preheater including a bypass. Explain the purpose of the bypass?

The flue gas passes over the outside of the tubes, heating the outside of the tubes. The air flows through the tubes, picking up heat. Cold air can bypass the tubes. This is to prevent cooling the flue gases below the dew point and forming corrosive liquids in the gas side. The air bypass is needed on startup and shutdown, and may be partly open in very cold ambient temperatures as well.
7. Using a simple sketch, describe natural circulation in a boiler.

In a simple water tube circuit, the downcomer is unheated and the riser is heated. The heated steam-water mixture has less mass than the cooler water on the unheated side and the unbalance forces the left-hand column to rise. After entering the drum, the steam bubbles rise to the surface of the water and fill the steam space. The circulation is produced by the difference in the mass of a column of water and a column of steam-water mixture.

8. List the parts of a steam generator that make up the casing.

Boiler casing refers to the airtight covering forming the outer layer of the boiler. It is the steel sheet or plate attached to pressure parts for supporting, insulating, or forming a gastight enclosure. It includes the outer skin over water walls, windbox and burner ducting, ducting enclosing the economizer, and the air heater.

9. Explain the difference between controlled circulation and once-through circulation in a steam generator.

Forced circulation boilers can be divided into two general classes: controlled circulation or recirculating boilers and once-through boilers. The main feature of a controlled circulation boiler is a recirculating pump, which is used to provide circulation.

In the once-through boiler, feedwater is pumped into the tubes and leaves the tubes as superheated steam. As this feedwater passes through the tubes it is first heated to saturation temperature and then transformed into steam. This steam is then superheated as it passes through the remainder of each tube.

11. Explain the difference between a direct contact attemperator and a surface attemperator.

There are two types of attemperators (desuperheaters) used: the surface type where the cooling medium is separated from the steam by a tube surface, and the direct contact type where the cooling medium is mixed with, and comes in direct contact with, the steam.
1. Explain why a fluid bed boiler produces lower NOx emissions than a boiler fed by pulverizers.

Lower combustion temperatures produce lower emissions of NOx, nitrogen oxides. Fluidized bed combustion can take place at temperatures ranging from 800°C to 900°C instead of standard combustion temperatures of 1600°C to 1900°C for pulverized coal and oil firing.

2. Using single line sketches, describe a watertube waste-heat boiler.

![Diagram of Watertube Waste-Heat Boiler]

The answer should include:

- Steam drum and mud drum,
- Flue gas flow,
- Water tubes connected to the drums.
3. **What type of steam generator uses a pinhole grate stoker? Give a simple explanation of this type of stoker.**

Boilers that burn solids, such as biomass use pinhole grate stokers. The pinhole grate stoker is a water-cooled grate that is clamped to the floor tubes of the furnace. The grates have venturi-type air holes to admit air to the burning material on the grate. This produces a semi-suspension mode of burning. The finer particles burn in suspension, and the heavier particles accumulate on the floor as ashes. The ashes are removed by raking: either by manual or mechanical means.

4. **Using single line sketches, describe the water flow through a steam-flood boiler.**

Feedwater is pumped from the deaerator to the economizer section of the chimney or stack. The preheated water then enters the combustion chamber tubes, which enclose the furnace. The water is converted to mostly steam in this section. The outlet of this section is piped to the water knock out drum or separator. Steam exits the top of the separator and flows to the wells for injection.
5. **Explain the difference between a cogeneration power generation cycle and a combined power generation cycle.**

A combined cycle power generation system can have a single gas turbine generator, an HRSG (heat recovery steam generator), and a single steam turbine generator with condenser and auxiliary systems. Many more complex configurations are possible. For example, the HRSG can be designed to supply the pressure of steam required for deaeration and feedwater heating. This steam replaces extraction steam used for feedwater heating in conventional steam plant cycles.

Cogeneration cycles are similar to combined cycles. In cogeneration, the heat recovery system is used to produce steam for process needs or for space heating. Extra steam can be used to generate electricity.

6. **Why is the design of waterwalls in supercritical boilers of special concern? Briefly describe two designs.**

The major design concern in building supercritical boilers is the once-through operation of the furnace tubing. The mass flow through the furnace tubes is much lower than in a furnace with circulation. The mass flow must still be high enough to prevent overheating and departure from nucleate boiling (DNB) while generating steam at subcritical pressures. At normal loads and at supercritical pressures the mass flow must be high enough to prevent overheating of tube metal and variations in steam exit temperatures. The two common methods of overcoming this problem are spiral furnace wall tubes, and vertical tubes with rifling inside the tubes.

With a spiral-wound furnace design, the total number of tubes that encase the furnace is reduced. The tubes are arranged at an angle and spiraled around the furnace. The pitch or spacing between the tubes remains the same as in the vertical design.

Vertical furnace walls are also used in supercritical boilers. They have rifled (internally ribbed) tubing to avoid overheating and DNB at lower pressures. The vertical tube design has a circulation pump for low rates and start up. To ensure the circulation through each tube is equal, the tubes are fitted with orifices to equally distribute the flow.
7. **Describe the safety hazards involved in firing a black liquor steam generator.**

   If water contacts molten smelt, it causes a violent explosion. It is not a chemical reaction but a physical reaction. It is a result of gases expanding very quickly and violently. They produce a shock wave type of reaction. Tube leaks onto the smelt bed cause a dangerous explosion. If a furnace tube leak is detected, many boilers have an emergency drain system to drain the boiler to just above the furnace floor.

   If the black liquor is too weak, it can also cause an explosion. The black liquor furnace is designed with added structural strength in case of explosion.

8. **Sketch and describe a membrane tube wall with studs used in a refuse-fired steam generator.**

   Mass-fired refuse boilers have refractory lined lower furnace walls to protect them from corrosion. The tubes have pin studs welded to them to anchor silicon carbide refractory.

   ![Diagram of a membrane tube wall with studs](image)
9. **Describe the difference between a natural circulation type of HRSG and a once-through type of HRSG.**

Natural circulation HRSGs are usually configured for a horizontal exhaust gas path with the heat exchanger tube banks arranged vertically. The vertical tubes are usually top supported to provide for unrestricted downward expansion. Circulation of the water-steam mixture in the evaporator tubes is achieved by the difference in density of the water in the downcomers and the density of the steam/water mixture in the heated tubes. Circulation ratios vary from 8:1 to 15:1, water to steam. Natural circulation HRSGs have steam drums and mud drums similar to fired natural circulation boilers.

The once-through steam generator (OTSG), in its simplest form, is a continuous tube heat exchanger in which preheating, evaporation, and superheating of the feedwater takes place consecutively. Many tubes are mounted in parallel and are joined by headers thus providing a common inlet for feedwater and a common outlet for steam. Water is forced through the tubes by a boiler feedwater pump, entering the OTSG at the “cold” end. The water changes phase along the circuit and exits as superheated steam at the “hot” end of the unit. Gas flow is in the opposite direction to that of the water flow (counter current flow). Unlike conventional circulation heat recovery steam generators, OTSGs do not have a defined economizer, evaporator, or superheater sections. The point at which the steam-water interface exists is free to move through the horizontal tube bank depending on the heat input, mass flow rate, and pressure of the water.
1. Describe how to carry out a hydrostatic test on a steam generator.

New steam generators or steam generators that have undergone major repairs or have been out of service for an extended period of time, are subjected to a hydrostatic test of 1.5 times the design pressure. The water used for the test should be at a temperature no lower than the surrounding atmosphere and in no case lower than 21°C. This is necessary to prevent condensation forming on the outside of the tubes and plates that makes the detection of leaks difficult. The water temperature, however, must not be so high as to prohibit touching and close inspection of the various parts.

Good quality (mineral free) water is used to avoid corrosion and fouling problems. Any sections of the steam generator, which are drained immediately after the test, can be filled with clear, filtered water. Non-drainable parts are filled with distilled or demineralised water adjusted to neutral pH and chemically treated to remove oxygen.

When filling the various parts of the steam generator, ensure all air is vented otherwise a dangerous condition develops. Air trapped by the water compresses and, in the event of a leak, the air expands producing a hazardous condition. A guide to the effectiveness of the air venting during the filling of the steam generating unit is the time taken to raise the pressure after the steam generating unit shows full. An excessive time taken to raise pressure indicates that the test pump is compressing air trapped in the boiler.

For a hydrostatic test at 1½ times the design pressure, gags (Fig.1) must be used to prevent safety valves from opening. Blank flanges may be used in the case of flanged valves. To prevent excessive pressure on the safety valve spindle and to protect the valve seating surfaces, the gag should not be applied until the pressure has reached at least 80% of the valve set pressure. The gags and blank flanges should be removed after completion of the test. Instrumentation that could be damaged by the hydrostatic pressure should also be isolated until the hydrostatic test is completed.

After satisfactory completion of the hydrostatic test the steam generator is drained. The vents must be opened to aid the draining of the steam generator.

The drum internals, if removed, must be reinstalled. After installation of the drum internals, the drums are inspected again for debris. If there is any possibility that something fell into one of the tubes, then all the tubes must be proved clear using the methods described previously. After inspection of the drums, the manhole covers are replaced using new gaskets.
2. Describe the procedure for drying out a steam generator

This commissioning step takes place after the hydrostatic test has been successfully completed on the new steam generator, and all the required refractory has been put on the steam generator.

The purpose of this step is to remove all moisture that is imbedded in the refractory. Failure to do so can result in damage to the refractory.

Various shutdowns, interlocks and controllers must be proven to be in correct operation during the dry out.

This includes testing of the fuel system trips to ensure the main fuel valve closes if any of the following occur:

- Low steam drum level
- Loss of any draft fan
- Loss of main flame

Also, the feedwater level controllers can be checked for correct operation.

Follow these steps for dry out:

1. Ensure that the low water level shutdown alarm is on, indicating a low water level condition.

2. Open the drum vent and begin slowly filling the boiler with water in preparation for the refractory dry out.

3. Ensure the gauge glass is in service. This gauge glass must be a temporary glass, because the chemicals for the dry and boil out period produce a caustic solution in the water that damages the gauge glass.

4. The feedwater should be treated for proper pH and oxygen removal. The temperature of the feedwater should be such that the temperature differential between the feedwater and the metal temperature is no more than 40°C. This is to avoid undue stress to the boiler metal.

5. Continue to raise the drum water level, and as the level rises, the feedwater controllers can be commissioned. Add water until the drum level is about one-third of the gauge glass, and then add approximately 25% of the chemicals to be used for the boil out.

Note: When working with these chemicals, be sure to follow all safety precautions, and wear the appropriate safety equipment. If you are not familiar with these chemicals, consult the MSDS.

6. The superheater drains must be opened fully and left open throughout the drying process to allow the superheater tubes to circulate steam vapour and stay cool. Open drum vents to allow air to escape.
7. After purging the furnace, operate the fans on minimum output and light a low flame in the furnace. Depending upon the amount of refractory, maintain the fire for several hours or several days to control the boiler so that it only produces a vapour from the superheater drains and drum vents. The refractory manufacturer supplies a set of guidelines that indicates how fast the refractory temperature should rise each hour. Sometimes temporary thermocouples are installed in the refractory so that the rise in temperature can be tracked.

8. Once the drying out of the refractory is complete, the remainder of the boil out chemicals is mixed with the boiler water in preparation for the boil out.

3. **Describe the procedure for boiling out a steam generator**

The purpose of the boil out is to remove any oil, grease, or other contaminating materials from the internal surfaces of the waterside of the boiler. Chemicals are added to the boiler water and the steam pressure is raised and maintained in the boiler for a predetermined period of time. This dissolves any deposits present on the drum and tube surfaces.

For example, add the following chemicals for each 45 000 L of boiler water:

- 18 kg trisodium phosphate
- 2.25 kg caustic soda
- 2.25 kg sodium silicate
- 22.5 kg soda ash

**Note:** When working with these chemicals, be sure to follow all safety precautions and wear the appropriate safety equipment. If you are not familiar with these chemicals, consult the MSDS.

The following steps are required to complete the boil out of the steam generator.

1. Ensure that the gauge glass is in service. The gauge glass for the boil out must be a temporary glass, because the chemicals for the drying and boiling out period produce a caustic solution in the water that damages the gauge glass.

2. Open the drum vent. All superheater drains should be wide open unless there are special recommendations for adjustment of drains when boiling out and/or pressure-raising.

3. Open economizer and air heater bypass dampers, if provided.

4. Be sure that all the blowdown valves are closed.

5. Confirm that the boiler feedwater pump and the combustion air fans are ready for service.
6. Replace the manhole covers and fill the boiler to one-third gauge glass.

7. Pump the boil out chemicals into the drum using a chemical pump.

8. Purge the furnace and apply a small fire using a minimum number of burners that provide stable combustion and sufficient heat release to raise the boiler pressure slowly.

9. Maintain the fire until the boiler-pressure gauge registers a positive pressure of 35 kPa. Then shut down the burners and close the drum vent.

10. Allow the pressure to fall to 0 kPa.

11. Continue to raise the maximum pressure in increments of about 350 kPa \(\text{i.e.}\) the pressure before and after each stage of boiling out should be 0-35 kPa, 0-350 kPa, 0-700 kPa) to approximately half the working pressure for which the boiler was designed. These figures depend upon the size and operating pressure of the boiler.

12. During every boil out stage each blowdown valve should be opened for a few seconds to discharge concentrated sludge. Several short blows are better than one long one.

**Note:** Keep a close watch on the drum, header and brickwork or casing clearances when applying heat to the boiler. Any observed problems should be corrected at once. If any section of the boiler-pressure parts fail to expand freely according to design considerations, the fires must be extinguished, and a thorough investigation completed.

During pressure-raising periods, all downcomer pipes, drum ends and external circulating sections of the boiler should be tested frequently for temperature. Cooler sections indicate sluggish circulation. If there is poor circulation at any section of the boiler, accelerate it by blowing down the affected section.
Do not blow down more than is absolutely essential to maintain a safe working level (i.e. water in sight at bottom of gauge glass) and to encourage circulation. Otherwise, chemicals are wasted, and subsequent makeup of boiler water causes dilution of the boiling out water. After each blow down, check the water level and introduce feedwater as necessary.

During the final stages of boiling out, all nozzle joints and bolted flanges should be carefully inspected.

13. Continue the boil out until the water samples from the blow down are clear.

14. Once the boil out is complete, shut down the burners and the combustion air fans. Cool the boiler down according to the manufacturer’s recommendations.

15. While the boiler is still under pressure, open all blowdown valves for a few seconds to discharge the concentrated sludge and dislodge loose scale. Apply a short blow down to each location at intervals corresponding to approximately 170 kPa drop in boiler pressure.

16. When the drum pressure is at 170 kPa open the drum vent.

17. Open all blowdown valves to drain the steam generator. Once the water level is below the manhole, open the manhole door.

18. Once the steam generator is drained, flush the tubes and headers with high-pressure water to remove any sludge or slime before it dries out or bakes onto the heating surfaces.

19. Inspect the drums and headers for traces of oil, grease, and scale. If there is still a large amount of oil or grease left, another boil out is required. If there is a significant amount of scale, then the boiler has to be chemically cleaned before it can be put into service. Be sure to obtain a vessel entry permit.

20. When a satisfactory boil out is complete, all manhole door covers, hand-hole caps, and blowdown valves should be carefully reinsalled, employing new gaskets. All joint seats should first be carefully cleaned.

21. Keep a careful look out for defects of any nature in the boiler, combustion equipment, and auxiliaries which can only be rectified while the unit is shutdown and cold. These should be remedied while the boiler is undergoing its final cleaning and before fires are restored for the next operation.
4. **Describe the shut down procedure for a steam generator you are familiar with.**

Before the steam generator is taken out of service, follow these steps:

1. Operate all soot blowers
2. Close the continuous blowdown
3. Blowdown the steam generator to remove sludge from the bottom drums
4. Shut off the chemical feed pumps

Follow these steps to safely shut down a steam generator:

1. When reducing load during shutdown, the combustion controls must be switched from automatic to manual before the lower limit of the automatic system is reached, usually at about 25 percent load.

2. Pulverized coal mills and feeders must be emptied as the coal-fired burners are shut down.

3. If the steam generator is gas-fired, shut off the burners sequentially as the load is reduced.

4. When the steam generator load is sufficiently reduced, shut off the remaining burners.

5. After firing has been stopped, the setting should be thoroughly purged with a 25 percent airflow for at least 5 minutes. The fans are shut down and the burner registers closed. The steam generator setting should be cooled down slowly using the manufacturer's recommendations. Use thermocouples, if equipped, to accurately regulate the rate of cooling.

6. If the steam generator is supplying a turbine, open the drain valve at the turbine stop valve, as well as other drains on the steam supply line to the turbine. If the steam generator is feeding a pressurized header, turn down the valve stem on the non-return valve, then close the header block valve, and open the drain between the header block valve and the non-return valve.

7. If the steam generator has an economizer recirculating valve, it should be open.

8. Shut down the feedwater pumps once feedwater flow is no longer needed.

9. Lock out and tag the fuel gas supply valve and the coal feeder discharge valves. For the fuel gas system, isolation should be a double block and bleed system or a spectacle flange. If the steam generator is oil fired, disconnect and remove the oil burner. Be sure to lock out and tag the oil supply valve.

10. Lock out and tag the feedwater valves.
11. Lock out and tag the non-return valve and the header block valve.

12. When the steam pressure drops to 170 kPa, open the drum vents to prevent formation of a vacuum within the unit.

13. If the steam generator requires draining, wait until it has cooled sufficiently so that personnel can enter the furnace. This prevents baking on of sludge in the lower drums.

14. When draining a steam generator that is tied into a common blowdown header, be sure to only open the blowdown valves on the steam generator to be drained. Once the steam generator is drained, close, lock out and tag the blowdown valves.

15. Lock out and tag the continuous blowdown valves.

16. Lock out and tag the feedwater pump motor breakers.

17. Lock out and tag the primary and secondary combustion air fan motor breakers.

18. Lock out and tag the induced fan motor breakers.

19. Ensure all airflow dampers are locked out and tagged in the closed position.

20. On smaller sized steam generators ensure the stack damper is closed, locked and tagged.

21. Close the chemical feed valves at the steam generator as well as at the discharge of the pumps. Lock out and tag all valves.

22. Lock out and tag the chemical feed pump motor breakers.

If the repairs are external to the steam generator, the water volume need not be blown down unless previous tests show that the chemical concentration is unsatisfactory. If there is an ample reserve of makeup, it may be desirable to change the water completely.
5. Describe how to lay up a stream generator for long period of time. List activities carried out while the steam generator is shut down.

For boilers that will be out of service and exposed to freezing ambient temperatures, dry storage is used. The cleaned boiler must be thoroughly dried, because any moisture left on the metal surfaces promotes corrosion. The drum, superheater, economizer, and other waterside vents are opened to drain the boiler completely. A small flame is used to evaporate any water left in the boiler. The source of the small flame can be from one of the burners, or a small portable heater can be placed in the bottom of the furnace. The vapours at the drum vent are analysed for moisture content. The vapour analysis indicates if the boiler waterside is moisture free. The flue gas temperature in the stack should not exceed 200°C or the temperature recommended by the steam generator manufacture.

After drying, the entry of any moisture or air into the waterside of the steam generator must be prevented. Moisture absorbing material, such as quicklime at the rate of 1 kg for 1 m³ of boiler volume or silica gel at the rate of 3 kg for 1 m³ of boiler volume, can be placed on trays inside the drums to absorb moisture from the air. The manholes and all connections on the boiler should be tightly closed. If it is readily available, a supply of an inert gas, such as nitrogen, can be connected to the drum vent to provide a positive pressure. The nitrogen pressure should be maintained at approximately 35 kPa. Warning signs and tags must be attached stating that the boiler is stored under nitrogen pressure.

The following routine should be observed throughout the shut down period:

- Inspect the interior of the boiler once each month, at the same time renewing or replenishing the drying material
- If the steam generator is to remain shutdown for longer than a month, a regular equipment “exercise” plan should be carried out
- All rotating equipment should be “turned” monthly so the rotors do not remain in the same position on the bearings
- Oil systems can be started to coat all the related equipment
1. **List the advantages of chemical cleaning versus mechanical.**
   Less time and less maintenance personnel are required. Even a large unit can usually be cleaned in less than 36 hours.

   Inaccessible areas can readily be cleaned and the cleaning is more thorough than mechanical cleaning.

   With chemical cleaning in mind, boilers can be designed without special provisions for mechanical cleaning accessibility.

2. **What are the two types of chemical cleaning methods for boilers?**
   - Circulation method
   - Soaking method

   (b) **Describe in detail how to chemically clean a boiler using one of the above methods.**

   Soaking Method
   An arrangement for chemical cleaning of a conventional type boiler by the soaking method appears in Fig. 6

   To prepare the unit for soaking, thermocouples should be installed at the steam drum, at the center of each furnace wall, and at one of the lower furnace wall headers. The unit is then filled with demineralized water and brought up to a temperature of 77 - 82°C by means of pilot burners or light firing. The firing is then stopped and the unit is drained and the superheater backfilled with treated condensate or demineralized water to prevent acid vapours from entering during the cleaning. The drum gage glass is replaced with a plastic tube gage. Then, referring to Fig. 3, the vents 5 and valve 1 are opened and the filling pump started. Heating steam is admitted through valve 6 to keep the water flowing to the unit at 77 - 82°C and the inhibited acid is admitted through valve 7. The amount of acid entering is adjusted to give the desired solution strength as sampled at valve 9. When the unit is filled to the normal operating level, the filling pump, heating system, and acid feed are stopped. Valves 2 and 8 are closed and the drum vents 5 are left open. The unit is then allowed to soak for the required period of time.
The time required will be determined beforehand by testing a sample of the deposits present in the unit. Usually the time required is from 4 to 8 hours.

After the required period of time the unit is completely drained under nitrogen pressure of about 35 kpa by closing the vents 5 and opening valves 2, 3, and 4.

After the unit has been drained, valves 3 and 4 are closed and valves 1, 5, and 8 are opened and the unit is filled with demineralized water with the filling pump until a level appears in the water gage. Then more demineralized water is flushed into the unit through the feedwater line until the drum level rises noticeably. This prevents any acid from entering the feedwater system. Similarly, the superheater should be backflushed with demineralized water until a level increase is observed in the drum. Then the unit is completely filled using the filling pump until water overflows through the vents 5. This is to ensure the removal of any acid vapours from the drum.
The unit is now drained under nitrogen pressure and the fill and flushing step is repeated. The unit is again drained under nitrogen pressure and the pH of the rinse water is tested. If the pH is below 5, the fill and flushing step must be repeated.

If the pH is satisfactory then the next step is to neutralize the surfaces. The temporary gage is replaced by the regular drum level gage and the unit is filled to slightly below operating level with a solution of 10 kg of soda ash to 100 kg water. The unit is then fired and boiled out for 4 to 6 hours. For boilers operating at 1400 kpa or less, the boil-out pressure is operating pressure. For boilers operating at above 1400 kpa, the boil-out pressure is the higher of 1400 kpa or one half the operating pressure although it is not necessary to exceed 4200 Kpa.

After the boil-out the unit is shut down and drained without using nitrogen pressure and while the unit is still hot it is filled with demineralized water containing 0.5% sodium nitrite to prevent rusting, until the drum vents overflow. The unit is drained again after one hour. If there is any evidence of loose deposits remaining in the unit then the headers and tubes should be thoroughly flushed out.

Note – The student could use the circulation method for the answer as well.

3. Describe how to conduct a hydrostatic test on a boiler, including safety procedures.

**HYDROSTATIC TEST**

The purpose of this test is to prove the boiler is tight under internal pressure. The test will be carried out by the boiler manufacturer (or repair agency in the case of a boiler repair job) to the satisfaction of an authorized inspector. This authorized person will be a provincial government boiler inspector, an insurance company boiler inspector, or a qualified employee of the company purchasing the boiler, depending upon the law in the province concerned.

Boilers that have undergone presser part repairs or have been out of service for an extended period of time shall be subjected to a hydrostatic test. If any doubt exists that all tubes are clear of any obstruction, each individual tube will have to be proved to be clear of obstruction, before the hydrostatic test can be carried out. To prove each tube clear will require someone to enter the boiler drum(s) so therefore a vessel entry permit should be used, for the safety of the person(s) inside the drum(s).

**Note:** Before any operations personnel begin to prepare the boiler for the hydrostatic test, ensure that all work permits have been returned to operations and that all tools have been removed from the boiler.
Straight tubes can be sighted through with a portable light. Bent tubes can be proved clear of obstruction by passing a wooden ball through. (Compressed air can be used to blow the ball through tubes, which it will not roll through.) Alternatively a fish wire, then a rope and then a canvas plug can be pulled through. Whichever method is used, it is essential that all tubes be proved clear, and then protected against the possibility of any debris falling into the tubes until the boiler is closed up.

When all tubes have been probed, and all headers and drums have been cleaned as well as possible by mechanical means (this includes use of the mechanical tube cleaners where necessary) the boiler will be closed up in preparation for the hydrostatic test. Where possible, the safety valves should be removed and the connections blanked at this time, partly to avoid any collection of sediment or dirt entering the valves and partly because it is not good practice to gag the valves against such a high pressure. If the safety valves have to be gagged, the gags should not be applied until the hydrostatic pressure is at 80 % of the safety valve set pressure.

Be sure to isolate any instrumentation that could be damaged by the hydrostatic pressure.

Allow only essential personnel in the immediate area of the boiler during the time that the hydrostatic test pressure is applied to the boiler, in the vent of a major failure.

The water used for this test should be clean and slightly warm (20° to 30°C is recommended) and care must be taken against frost damage, if this test is carried out during the winter months, and if there is no heat in the boiler house.

When filling the boiler with water, be sure to vent all the air. Once the boiler is full, close the vents, and by means of a special test pump, raise the pressure to the required hydrostatic pressure, which is one and one-half time the design working pressure of the boiler. If this pressure is not maintained for a specified time, then there is the probability of a boiler leak.

Upon successful completion of the hydrostatic test, the boiler can be prepared for service. Be sure to remove all safety valve blanks and all safety valve gags.

4. What is the purpose of a Preventive Maintenance (PM) program?

To identify developing problems, so they can be corrected before they causes a boiler shut down or shut down of some auxiliary equipment.
5. Describe how to conduct the inspection for the water side of a boiler.

**WATER SIDE INSPECTION**

Before cleaning of the internal surfaces of the drums, tubes, and headers, they should be examined by the boiler inspector to determine the effectiveness of the feedwater and boiler water treatment programs.

After this examination, a high-pressure hose water stream should be used to wash down the internal surfaces. This high pressure water will remove loose deposits and also remove some of the scale adhering to the surfaces.

During the washing down the blow-off line should be disconnected and the water allowed to run to waste to prevent scale from plugging the blow-off valves and piping.

Any deposits still adhering to the surfaces after washing down must be removed by mechanical cleaning or chemical cleaning. This will leave a clean metal surface, which the inspector can easily examine.

**Note:** In regard to determining the need for cleaning of the internal surfaces, this can be done by visual inspection in the case of some boiler designs. However, in the case of the modern high pressure boiler having involved water circulation circuits and all-welded construction, adequate visual inspection may not be possible. In these cases it may be necessary to cut out a representative tube section in order to determine the amount of deposit present. Alternatively, a representative tube can be cleaned with a mechanical cleaner and the amount of deposit so removed can be measured by weighing.

When examining the water side surfaces, the inspector will be looking for signs of corrosion, pitting, and cracking of the metal. Cracks may appear in ligaments between tube holes. Stays must be checked for looseness and cracking at the fastened ends. Particular attention is paid to drum connections such as safety valves and steam outlet connections and to manhole and handhole openings. All drum welds are examined closely.

The plugs in the water column connections should be removed to allow inspection for scale or other deposits.

Drum internals must be closely inspected to see that all baffling and other steam separating equipment are positioned correctly and joints are tight. If baffles, plates, or separators are removed for inspection they should be marked to ensure proper reassembly.
Blow-off connections should be inspected for corrosion and weakness where they connect with the boiler. These connections must be supported and be able to expand and contract without producing excessive stress on the boiler. All other piping connecting to the boiler must be similarly checked.

Pressure gages should be tested and calibrated if necessary.

All other boiler fittings should be examined for plugged connections and for proper operation.

After the water side inspection has been completed, the inspector may wish to have the boiler closed up and a hydrostatic test carried out.

6. **Describe the information that a boiler log sheet should contain.**
   The boiler operator should have a permanent log sheet for each boiler. This log sheet should contain the following information:

   - Time
   - Boiler pressure
   - Final steam temperature
   - Rate of evaporation
   - Rate of feed flow (where indicated)
   - Draft readings at boiler, economizer and air-heater exits
   - Feedwater inlet temperature
   - Air temperature entering the air heater
   - Gas temperatures at boiler, economizer and air-heater exits
   - Forced and induced draft fan currents (or speeds, if variable)
   - Data on fuel supplies (sufficient to give an indication of the rate of consumption)
   - CO₂ and O₂ and combustible in gases, at the most convenient point of measurement.

   The above readings should be taken at regular intervals.

   Space should also be provided to indicate time and duration of soot-blowing, blowing-down, water-dosing (when applied internally to individual boilers) and ash removal.

   Provision should also be made for a record of the personnel responsible for operation of the plant while the observations are being recorded.
7. **Describe the roles and responsibilities of engineering staff in regard to boiler inspection**

   The role of the engineering staff is to provide engineering support to the boiler inspection team if the integrity of a pressure part such as a tube is questionable. For example, if a section of tube appears to be corroded or if there is severe pitting, it is the engineer’s responsibility to determine that tube wall thickness is still greater than the minimum allowable thickness for the operating condition.

   Engineers serve as project managers for any capital projects or large repairs. If changes to piping systems or pressure vessel repairs are planned, qualified professional engineers submit repair procedures to the regulatory agency in the province. The engineering drawings are stamped by the professional engineer. The accepted engineering drawings are then used by the tradesmen to order materials for the jobs. Copies of the drawings are also sent to the chief power engineer for his records, and to help plan for the work.

   Prior to an extended shutdown, engineers assist with the shutdown planning, parts and materials procurement, and labour scheduling. During the shutdown the on-site engineering staff does engineering that arises from the inspections or repair jobs. The engineering staff has day to day communication to the tradesmen and operations personal, updating them on the status of all work requiring engineering such as repairs and capital projects.

   If a boiler tube repair is required, then the engineering staff must ensure the replacement tube is made of the correct material, and is designed for the correct operating pressure.

8. **Describe one of the non-destructive inspection techniques used for a boiler.**

   **RADIOGRAPHIC EXAMINATION**

   Gamma radiation exposure devices and X-ray film are used to determine the wall thickness of boiler tubes, as well as the condition of various welded joints in boiler piping. The film is wrapped around the area to be x-rayed, and then a picture is taken of the tube or weld.

   This is the most common method used to inspect the condition of the various welded joints in a boiler.

   **ULTRASONIC INSPECTION**

   This method uses high frequency sound along with sophisticated transducers and instrumentation to determine the wall thickness of the boiler tubes. The speed at which the sound waves travel across a tube wall is related to wall thickness.

   The advantages of this method are that it does not need film, the results are immediate, and there is no danger to personnel in the area.
THERMAL RADIATION
All mechanical equipment emits heat in the form of electromagnetic radiation. Infrared cameras, which are sensitive to thermal radiation, can detect and measure the temperature differences between surfaces. Abnormal or unexpected thermal patterns on a boiler tube is indicative of a problem with the tube – a problem that could eventually lead to a tube failure. If a hot spot is detected by the infrared camera, that may be an indication of poor circulation through the tube, which is caused by a build-up of scale in the tube. Another reason for the hot spot could be corrosion or erosion of the tube.

LIQUID PENETRANT TESTING
Liquid penetrant testing is used to detect surface cracking. It is not dependant on the magnetic property of the component or its shape. LP testing detects surface flaws by capillary action of liquid dye penetrant. It is only effective if part of the flaw is touching the surface. The penetrants are portable and easy to transport into a boiler drum. The fluids are contained in aerosol cans. The test makes it much easier to see cracks than with the naked eye. Cleaning of the surface is required before applying the chemicals. The operator must be trained and have practice using the LP Test.

MAGNETIC PARTICLE TESTING
Magnetic particle testing is very useful at detecting flaws, such as cracks, in pressure vessels, drums, and headers. It applies a magnetic field to the test piece. Iron particles are placed on the surface of the area to be tested. Flaws appear in the pattern of the iron particles. Because a magnetic field is used in the test, it is only used on ferrous materials. A disadvantage of the test is that the depth of the flaw is not known. It may be deep or just a surface crack. When the crack has been found it is often necessary to use X-rays or surface grinding to ascertain the extent of the crack.

Note: Any one of these will be correct.
9. List four of the safety requirements during a boiler inspection.

**BOILER INSPECTION SAFETY REQUIREMENTS**

When a boiler is to be inspected, the following safety precautions must be followed:

- Drum and setting must be cool and well ventilated.
- Valves must be closed, locked and tagged to prevent any steam, water, fuel or any other undesirable substances from entering the boiler.
- Draft fans motor circuit breakers must be locked out and tagged.
- Only low voltage lighting should be used. All portable electrical equipment used in the steam generator should be adequately grounded to the steam generator.
- An approved vessel entry procedure must be used for the safety of the workers entering the boiler drums, furnace or any other part of the boiler setting.
- Overhanging slag and other deposits should be dislodged by bars or rods operated from outside the setting before personnel are allowed to enter the setting.
- Cleaners should preferably work in pairs and should be warned of hazards from hot soot, dust, and slag. They should be provided with protective clothing, goggles and respirators when necessary.

**Note:** Any four of these will be correct.
1. The pump manufacturer will need some basic design information before he is able to recommend a pump for the application. List four basic things the manufacturer will need to know.

The basic data includes:
- The fluid to be pumped including the specific gravity, chemical analysis and solids content
- The suction head available
- The discharge head required
- The flow rates required (minimum, maximum, and normal operating flows)

2. A centrifugal pump is operating at 1200 rev/min and the capacity is 2000 L/min. The discharge pressure is 500 kPa and the power required is 20 kW. The speed is increased to 1500 rev/min. Find the new capacity, pressure and power.

\[
\begin{align*}
Q_1 & = 2000 \text{ L/min} \quad P_1 = 500 \text{ kPa} \quad kW_1 = 20 \\
N_1 & = 1200 \text{ rev/min} \quad N_2 = 1500 \text{ rev/min}
\end{align*}
\]

**Capacity \( Q_2 \):**

\[
\begin{align*}
\frac{Q_1}{Q_2} & = \frac{N_1}{N_2} \\
\frac{2000}{Q_2} & = \frac{1200}{1500} \\
Q_2 & = \frac{2000 \times 1500}{1200} = 2500 \text{ L/min (Ans.)}
\end{align*}
\]

**Pressure \( P_2 \):**

\[
\begin{align*}
\frac{P_1}{P_2} & = \left(\frac{N_1}{N_2}\right)^2 \\
\frac{500}{P_2} & = \left(\frac{1200}{1500}\right)^2 \\
P_2 & = \frac{500 \times (1500)^2}{(1200)^2} = 781.25 \text{ kPa (Ans.)}
\end{align*}
\]
Power = kW₂

\[
\frac{kW_1}{kW_2} = \left(\frac{N_1}{N_2}\right)^3
\]

\[
\frac{20}{kW_2} = \left(\frac{1200}{1500}\right)^3
\]

\[
kW_2 = \frac{20 \times 1500^3}{1200^3} = 39.06\ kW \text{ (Ans.)}
\]

3. A centrifugal pump with an 18 cm impeller, and running at 1800 RPM, has a capacity of 1800 L/min, a head of 50 m and requires 18 Kw to drive it. If the impeller size is increased to 22 cm, and the pump speed remains unchanged, what will be the new capacity, head, and power requirements of the pump?

Q₁ = 1800 L/min  \hspace{1cm} h₁ = 50 m  \hspace{1cm} kW₁ = 18

D₁ = 18 cm  \hspace{1cm} D₂ = 22 cm

Q₂ = Q₁ \times \frac{n₂}{n₁} \times \frac{D₂}{D₁}

h₂ = h₁ \times \left(\frac{n₂}{n₁}\right)^2 \times \left(\frac{D₂}{D₁}\right)^2

kW₂ = kW₁ \times \left(\frac{n₂}{n₁}\right)^3 \times \left(\frac{D₂}{D₁}\right)^3

η₁ = η₂

Q₂ = Q₁ \times \frac{n₂}{n₁} \times \frac{D₂}{D₁}

= 1800 \times \frac{1800}{1800} \times \frac{220}{180}

= 1800 \times \frac{220}{180}

= 2200 L/min \hspace{1cm} \text{(Ans)}
\[ h_2 = h_1 \times \left( \frac{n_2}{n_1} \right)^2 \times \left( \frac{D_2}{D_1} \right)^2 \]

\[ = 50 \times \left( \frac{1800}{1800} \right)^2 \times \left( \frac{22}{18} \right)^2 \]

\[ = 50 \times (1)^2 \times (1.22)^2 \]

\[ = 50 \times 1 \times 1.49 \]

\[ = 74.5 \text{ m} \quad \text{(Ans)} \]

\[ kW_2 = kW_1 \times \left( \frac{n_2}{n_1} \right)^3 \times \left( \frac{D_2}{D_1} \right)^3 \]

\[ = 18 \times \left( \frac{1800}{1800} \right)^3 \times \left( \frac{22}{18} \right)^3 \]

\[ = 18 \times (1)^3 \times (1.22)^3 \]

\[ = 18 \times 1.816 \]

\[ = 32.69 \text{ kW} \quad \text{(Ans.)} \]
4. Describe the method of aligning and grouting-in of a centrifugal pump which has been delivered to the site with the driving motor separate from the pump and base plate.

If the pump driver is delivered separately to the site and is to be mounted on the pump base plate in the field, then the base plate with the pump is set on the foundation and levelled with shims leaving a space for grouting. The driver is then placed on the base plate so that the coupling faces are the correct distance apart. The pump and driver should then be aligned and the anchor bolt holes for the driver marked off on the base plate. The driver is now removed and the bolt holes drilled and tapped. The driver is then replaced on the base plate, the bolts are inserted and tightened after re-aligning the driver and pump.

To properly align the pump and motor, the coupling faces should be spaced far enough apart so that they do not contact each other when the driver rotor is pushed toward the pump as far as it will go. Also space must be allowed for eventual wear of the thrust bearings.

To check the alignment of the two shafts, the anchor nuts have to be tightened against the base.

A check for angular alignment is made by inserting a taper gage between the coupling faces at four points spaced at 90 degree intervals around the coupling. The coupling faces should be the same distance apart at all points for correct angular alignment.

Parallel alignment is checked by placing a straight edge across both coupling rims at the top, bottom, and both sides. The straight edge should rest evenly on the coupling rims at all positions.

Any misalignment, either angular or parallel, can be corrected by inserting shims under the driver feet, so as the anchor nuts are tightened, the shafts will become properly aligned.

A more accurate method is to use a dial gage. The dial gage is secured to one coupling flange and the dial probe rests on the other flange. The two flanges are rotated together and spot checks of the dial give an indication of misalignment. Misalignment between the 12 o’clock and 6 o’clock position on the coupling can be corrected by the addition or removal of leveling shims. Misalignment between the 3 o’clock and 9 o’clock position is corrected by shifting the driver unit sideways on the base plate.
As the amount of movement is measured in thousands of a millimeter or thousands of an inch, precise positioning is difficult with heavy machines. Sometimes eight jack bolts are welded to the bed plate. Jack bolts are heavy pieces of plate steel that have been tapped to a given bolt size. These plates are attached to the bed plate a short distance from the corners of the motor legs. When the bolts are adjusted they force the motor into any desired position in the horizontal plane. The alignment should be checked after the anchor nuts have been tightened down against the base.

When the alignment of pump and driver is correct, the unit can then be grouted in. The base plate is completely filled with grout, with the levelling shims and wedges left in place. After the grout is hardened, about 48 hours after pouring, the foundation bolts can be fully tightened and the alignment checked once more.

The alignment should be checked again after the piping has been connected. The unit should then be operated under normal conditions until temperatures have reached operating condition. Then the unit should be shut down and the alignment checked once more.

Allowances must be made for expected temperature changes from the stopped condition to the hot running condition. The shaft of a pump handling cooling water will experience only a slightly temperature rise when running. The shaft of a high temperature boiler feed water pump will rise as the hot water enters the pump. A steam turbine shaft will rise even more than a feed water pump. Alignments should be made so that the driver shaft and pump shaft is collinear at the normal operating temperature of both components.

A final alignment check is made after the unit has been running for one week and then the pump and driver can be doweled to the base plate. In some plants only the pump is doweled. A dowel is a tapered steel pin that is secured by friction in a tapered hole through the pump base and base plate. This keeps the pump securely located. They are often made with a threaded top so that a nut can be screwed down on the dowel to pull it from the tapered hole.

The alignment should be checked after repairs, new installations, or even earthquakes.
5. (a) List 5 items that a plant operator should check on shift.
   Any 5 from the following list will do.
   - bearing temperatures (by hand)
   - suction pressure
   - discharge pressure
   - lubricating oil pressure and temperature
   - balancing disc leakoff
   - stuffing box leakoff
   - cooling water flow
   - cooling water inlet and outlet temperatures
   - driver motor amps
   - bearing oil levels
   - oil ring operation
   - recirculation or bypass flow if pump is operating at low capacity.

(b) List some of the maintenance activities that need to be done monthly, quarterly, semi-annually, and annually.

   **Monthly** - check of the temperature of each bearing should be made with a thermometer. Ball or roller bearings that are running hot may be over lubricated and this can be remedied by removing some lubricant. Hot sleeve bearings may be the result of dirty oil or insufficient oil. If this is the case, more oil may need to be added, or the oil should be changed.

   **Quarterly** - intervals sleeve bearings should be dismantled, cleaned and the oil changed, provided the shut down of the pump will not unduly impact plant operations. Grease packed bearings should be checked for contamination of the grease by the pumped liquid and if contamination is present, the bearing should be flushed out, cleaned and repacked. All bearings should be measured for wear.

   **Semi-annually** - Stuffing box leakage should be carefully measured and the packing renewed if necessary. Shaft sleeves should be checked for scoring and wear. If shaft sleeves are not worn but packing wear is excessive, this is an indication of a bent shaft, or worn bearings, or an out of balance rotor.

   All instrumentation should be recalibrated.
In addition to the stuffing box inspection, the alignment of the pump and driver should be measured.

**Annually** - If disassembly of the pump is carried out, the following should be inspected:

- The casing should be examined for corrosion and wear and should be thoroughly cleaned.

- The rotor should be examined for wear and corrosion.

- Wear ring clearance should be measured and rings replaced if necessary.

- Worn bearings and shaft sleeves should be replaced.

- All sealant and coolant connections should be thoroughly flushed out and cleaned.

- All instrumentation should be recalibrated.

- Bypass or recirculating valves should be checked for wear and repaired or replaced.
6. (a) Sketch and describe a minimum-flow control system for a large centrifugal pump.

This method has a separate recirculation control valve (more commonly referred to as a minimum flow control valve), which allows for liquid to flow back to the pump suction supply source. For a boiler feed pump it means a minimum flow line returning to the deaerator or a feed water supply tank. The flow-sensing orifice on the suction of the pump sends a signal to the FIC (flow indicating controller). The FIC will begin to open the recirculation control valve if the flow drops below the FIC set point, and send a portion of the feed water back to the deaerator. When the flow rate goes above the FIC set point, the control valve will begin to close, and send more of the boiler feed water to the boiler.

(b) Name the other types of control for a large centrifugal pump.
- Automatic Recirculation Valve System (ARC)
- Flow orifice
- Variable Speed motors

7. (a) What are the two main types of seals that are used on centrifugal pumps.
Stuffing boxes and mechanical seals.

(b) What is the difference between a Rotating mechanical seal and a Stationary mechanical seal?
With a rotating mechanical seal the shell containing the sealing ring and springs is attached to the pump shaft, and the mating ring is held stationary within the pump casing. With a stationary mechanical seal the mating ring is attached to the pump shaft, and the shell containing the sealing ring and springs is held stationary in the pump housing.
8. **Describe an Expeller**
   This type of seal uses a liquid ring to provide the shaft sealing for the pump.

   An additional type of impeller, called an expeller, is mounted on the shaft in the sealing space. As the shaft rotates, the expeller removes the fluid being pumped from the sealing chamber, and creates a liquid ring. This liquid ring serves as a seal and prevents shaft leakage. In the shut down mode, the liquid being pumped fills the sealing space, and its inherent pressure forces a disk against the sleeve on the shaft, thereby preventing the seal from leaking when the pump is shut down.

   When the pump is started again, the expeller pumps the liquid out of the sealing chamber and again creates a liquid sealing ring. The sealing disk is no longer pressed against the sleeve and the disk rotates without any contact.

9. **What are the four different methods used to counteract thrust on a large multi-stage centrifugal pump?**
   - balancing drum,
   - balancing disc
   - combination of drum and disc
   - balance piston
Chapter 6
Water Chemistry and Analysis

1. **List four industrial contaminants that may be present in raw water supplies. What are possible sources of origin for each type?**
   
   Any four of the following contaminants and its possible source should be listed.

   **Copper**
   The water may have come in contact with copper bearing minerals, or runoff from copper production. Copper in plant water systems may be a product of corrosion of copper or copper alloy pipe from fittings inside the plant piping. The copper may be added deliberately to water supply reservoirs for algae control. It is objectionable in plant waters because it is corrosive to aluminum.

   **Lead**
   Water becomes contaminated with lead from metallurgical wastes or from lead containing poisons such as arsenic. Lead concentrations must be kept below 0.05 mg/l in drinking water. It is removed from wastewaters being discharged. It is most easily removed by filtration.

   **Phosphate**
   Phosphate compounds are widely used in fertilizers and detergents. Silt from agricultural runoff and municipal wastewaters contain phosphate compounds. Phosphate can also be precipitated at a pH over 10.0 with alum, sodium aluminate, or ferric chloride. Phosphates increase algae growths in cooling water systems that requires more chemical use to control the microbiological activity.

   **Zinc**
   Zinc is present in water because of discharges from mining or metallurgical operations. It also appears because of corrosion of galvanized steel piping. Zinc is removed by lime softening or by cation exchange.

   **Chromium**
   Chromium finds its way into water supplies from cooling tower blowdowns and chrome plating operations. It can be reduced by filtration and removed by anion exchange. It is a heavy metal and cannot be discharged into lakes or streams.

   **Mercury**
   Mercury is produced in water by wastes from caustic production and by the leaching of coal ashes. It must be restricted to very low levels in potable water supplies (below 0.002 mg/l). It can be removed by reduction and filtration.
Nickel
Nickel shows up in water from plating wastes, electric furnace slag or dust, and from nickel ore tailings. It can be precipitated or removed by cation exchange.

Hydrocarbons
Hydrocarbon contamination results from oil field, refining, or processing plant operations. Hydrocarbons form sticky compounds that can foul filter beds and demineralizer resins.

2. What are the mechanical and chemical factors that may influence boiler water carryover?
   Mechanical factors influencing carryover include the following:
   - Boiler and steam drum design
   - Operating with high steam drum levels
   - The load characteristics (the steam demand may increase very rapidly)
   - Inadequate or leaking steam separating equipment in the steam drum

   Chemical factors influencing carryover include the following:
   - High total solids concentration (dissolved and/or suspended solids) causing foaming
   - The presence of hydrocarbons or other organic contaminants, that cause foaming
   - Vaporization of solids such as silica
3. Sketch and describe an isokinetic steam sampling arrangement. Why is this arrangement necessary?

A steam sample is condensed for analysis. This is more difficult than it may seem because the steam sample must be a representative sample. The steam sample is taken with an isokinetic sampling arrangement. The nozzles used for the sampling are specially designed for each size of piping. They take a representative sample across the diameter of the pipe. Turns and other irregularities of the steam piping influence the distribution of solid and liquid impurities. A sketch can show one or two steam sampling nozzles in the steam piping.
4. **List the dissolved gases that are present in raw water. Why are they removed to make the water suitable for boiler feedwater?**

   The dissolved gases removed in the preparation of boiler feedwater are oxygen, carbon dioxide and ammonia.

   - Oxygen is often the prime cause of corrosion of boilers and heat exchangers. It causes pitting in the economizer tubes of a boiler.
   - Carbon dioxide is not as corrosive as oxygen, but it does cause corrosion in the condensate piping.
   - Ammonia passes through the boiler and exits with the steam. Ammonia attacks copper and copper alloys often found in valves and condenser tubes. If no copper is present in the system, ammonia is not a major concern.

5. **Why are water analysis reports often stated in units as CaCO₃?**

   Most minerals in water exist as ions. Ions are electrically charged particles that give the solution an electrical conductivity. The different systems of units that measure their concentration can cause confusion. For any calculation involving adding different ions to one another, it is vital that the units use the same equivalents. The most common method is the equivalent to calcium carbonate method. The results are stated in mg/l as CaCO₃. CaCO₃ has a molecular mass of 100 and is therefore a very convenient unit.

6. **Sketch a basic conductivity cell. Explain its principle of operation.**

   A voltage is applied to each of the drive electrodes of the conductivity cell. One side is positive and the other is negative. The sense electrodes detect the flow of current through the solution.
7. What are two boiler water treatment methods used to combat caustic embrittlement?

Sodium nitrate is a common treatment for inhibiting embrittlement in boilers up to 6700 kPa. The boiler water must have a sodium nitrate to sodium hydroxide ratio of 0.20-0.45.

At higher pressures, coordinated phosphate/pH control is the usual internal treatment. When properly controlled, this treatment does not produce high concentrations of caustic.
1. Name four factors that affect the time taken to settle particles in the sedimentation process.

The time taken to settle particles depends on the following variables:

**Density of the particle:** the more dense the particle, the faster it settles.

**Shape of the particle:** round particles tend to settle faster than odd-shaped particles.

**Size of the particle:** in general, the larger the particle, the quicker it settles, other factors being constant. This is true for particles falling in dense, viscous, and friction-prone water.

**Viscosity:** (the frictional resistance of water): the colder the water, the more viscous it is, and the more friction it offers to falling particles, thus slowing the settling process.

2. Describe flocculation and coagulation. What are coagulant aides?

Particles in water have a charge associated with them. It is predominantly a negative charge. Coagulation is the process of neutralizing these charges. When a coagulant mixes with the inlet water, it neutralizes the charges and the particles clump together to form tiny visible particles called microfloc. Once the charges have been neutralized, the particles no longer repel each other. They are then brought together into larger particles for flocculation and sedimentation.

Flocculation is the process of bringing together coagulated particles to form larger particles or floc. Flocculation begins when neutralized or entrapped particles start colliding and growing in size. The larger the floc, the faster it settles out of solution.

The flocculation process is aided or speeded up by the addition of water-soluble organic polymers or flocculants. They belong to the chemical class of polyelectrolytes. Because coagulants form macrofloc from microfloc, they are considered coagulant aids.
3. **State the differences between clarification and softening.**

Clarification refers to increasing the clarity of the water. This is accomplished by removing the suspended solids from the water. Processes such as flocculation coagulation and filtration are used. These processes are limited to improving the clarity of the water. No softening or reduction in dissolved ions occurs.

Softening refers to reducing the quantity of hardness causing ions (calcium and magnesium) in the water. Processes such as lime softening, and sodium zeolite softening are used for softening water.

4. **State the three primary functions of deaerators. Why is mechanical deaeration often followed by chemical deaeration?**

Deaerators are an integral part of steam cycles. They serve three primary functions:

- Removal of dissolved gases in the water. The dissolved gases are mainly oxygen and carbon dioxide and occasionally ammonia.
- They provide heat to the feedwater, or are a stage of feedwater heating. Deaerators are often referred to as deaerating heaters.
- The storage compartment serves as storage for deaerated and heated water. It is normally the suction or inlet to the boiler feedwater pumps.

Mechanical deaerators reduce oxygen to very low levels. Even trace amounts of oxygen may cause corrosion damage. The last traces of oxygen have to be removed with a chemical oxygen scavenger, such as sulphite, hydrazine, or a hydrazine replacement.
5. Sketch and describe a simple makeup evaporator arrangement used for makeup water in a power plant.

The sketch should include:
Evaporator with steam coil, steam heating coil, vapor outlet at the top of the evaporator, blowdown, and treated water makeup. The vapor outlet can be directed to either the deaerator or a low-pressure heater.

6. Why is it necessary to keep oil out of cooling tower water? What problems will oil cause in boiler water?

Oil in cooling water systems will form sludge in the cooling water basin. The oil may also deposit in cooling water exchangers in the shell side. It is a more serious problem if deposits form on the inside or outside of heat exchanger tubes. Corrosion will occur under these deposits. Eventually, the corrosion can result in tube leaks.

Oil should be kept out of boiler water. It causes boiler water to foam, resulting in poor steam quality from carryover (carryover of boiler water with the steam). The oil will also deposit in the tubes and form sludge and deposits.

7. Explain why microfiltration is often used upstream of reverse osmosis.

Often microfiltration is used upstream of reverse osmosis to protect the RO membranes from particulates. Reverse osmosis membranes are susceptible to clogging unless the water being processed is free of particulates.
8. Sketch a gravity sand filter showing the main components as well as the flow of water through the filter.
1. Using simple sketches, explain the difference between osmosis and reverse osmosis.

When two solutions, one dilute and one concentrated, are separated by a semi-permeable membrane, the solvent (water) from the dilute solution diffuses through the membrane into the concentrated solution. This phenomenon is called osmosis. If pressure is applied to the concentrated solution, the solvent (water) diffuses through the membrane into the dilute solution. This phenomenon is called reverse osmosis.

2. What are two RO membrane types? Describe the construction of each type.

RO membranes are made in a variety of configurations. Two of the most commercially successful are spiral-wound and hollow fibre. The construction of the membrane and pressure vessel varies depending on the manufacturer and expected salt content of the feedwater.

The spiral-wound construction the membranes are produced in flat sheets. The membranes and the spacers are wound around the permeate or outlet collection tube in the middle. The membrane and the spacers create the flow channels for the permeate and the reject water.

Hollow fibre RO membranes are composed of bundles of fine hair-like membrane tubes. The pressured feedwater tries to pass through the outside of the tube walls into the centre of the tube. The permeate is collected from the hollow centre of the fibre or tubes. The concentrate remains in the module housing on the outside of the tubes.
3. Why must the water fed to an RO unit be filtered? What other types of pretreatment are commonly used?

Filtration is important in RO because the feedwater must pass through very narrow passages during the process. Suspended solids must be removed and the water pretreated so that salt precipitation or microorganism growth does not occur on the membranes. Usually the pretreatment consists of fine filtration and the addition of acid or other chemicals to inhibit precipitation. Sometimes a sodium zeolite softener is used upstream of the RO filters. The softener removes the calcium and magnesium hardness replacing them with sodium ions. The sodium does not foul or scale the membranes as the calcium and magnesium do.

4. List the six reactions that occur in lime-soda softening.

1. Calcium bicarbonate + Calcium hydroxide → Calcium carbonate + Water
   \[ \text{Ca(HCO}_3\text{)}_2 + \text{Ca(OH)}_2 \rightarrow 2 \text{CaCO}_3 + 2 \text{H}_2\text{O} \]

2. Magnesium bicarbonate + Calcium hydroxide → Magnesium hydroxide + Calcium carbonate + Water
   \[ \text{Mg(HCO}_3\text{)}_2 + 2 \text{Ca(OH)}_2 \rightarrow \text{Mg(OH)}_2 + 2 \text{CaCO}_3 + 2 \text{H}_2\text{O} \]

3. Magnesium sulphate + Calcium hydroxide → Magnesium hydroxide + Calcium sulphate
   \[ \text{MgSO}_4 + \text{Ca(OH)}_2 \rightarrow \text{Mg(OH)}_2 + \text{CaSO}_4 \]

4. Calcium sulphate + Sodium carbonate → Calcium carbonate + Sodium sulphate
   \[ \text{CaSO}_4 + \text{Na}_2\text{CO}_3 \rightarrow \text{CaCO}_3 + 2 \text{NaCl} \]
5. What are the variables that may cause operating problems in a hot process softener? Explain.

Temperature variations of more than 4⁰C may cause carry-over out of cold or warm process units. In hot process units, poorly operating inlet sprays reduce the temperature of the reaction. This reduces the hardness reduction and increases the dissolved gases in the outlet water.

Flow variations can upset the systems. They cause carry-over in cold units and added hardness to both cold and hot processes.

Chemical control is necessary for control of all softening processes. Accurate control involves frequent testing and adjustments of chemical feeds. For well waters the quality of the makeup water changes little. Surface waters, especially rivers, change with the seasons. The operator must anticipate changes and make the proper adjustments to the chemical feeds.

Systems that feed powdered lime can require a lot of maintenance. Most often the chemicals are fed in direct proportion to the raw water flow.

6. What is the difference between sodium zeolite softening and hydrogen cation exchange?

In the sodium cation exchange softener the calcium and magnesium salts are replaced with salts of sodium. While this method removes the scale forming calcium and magnesium, it does not reduce the total amount of salts dissolved in the water. The sodium salts take the place of the calcium and magnesium salts.

A hydrogen zeolite softener is used to remove the scale forming salts without the formation of sodium bicarbonate. The material used in the hydrogen zeolite softener may be zeolite or synthetic cation resin. The ion exchange process removes calcium, magnesium, and sodium cations from the mineral salts and replaces them with hydrogen ions.

7. What are three processes that remove silica from water?

Coagulation techniques in clarifiers and softeners are effective at removing colloidal silica. The lime-soda process and the hot phosphate process remove silica from water with magnesium hydroxide.

Strong base anion exchange resins remove virtually all reactive silica reaching part-per-billion levels in many applications.
Membrane treatment can remove virtually all colloidal silica. Both reverse osmosis and ultrafiltration are effective in this respect. Reverse osmosis offers the additional advantage of significant reduction (98%+) of reactive silica as well.

8. Sketch a demineralizer system consisting of a strong base cation, a degasifier, and a strong base anion exchanger. List the ions that are removed in each of the three steps.

- The cation exchanger removes calcium, magnesium, and sodium
- The degasifier removes carbon dioxide
- The anion remove sulphates, chlorides, silica, and bicarbonates

9. Using a simple sketch, show the six steps in regenerating a mixed bed polisher.
10. What are the three processes that occur in an EDI unit?

Continuous demineralization in an EDI system has three coupled processes:

**Ion exchange:** the feedwater is passed through a bed of ion exchange resin. The ions in the feedwater become attached to the resin beads as in conventional ion exchange.

**Continuous ion removal:** ions are transported into the concentrate stream from the ion exchange resin and membranes. This process is unique to EDI and is powered by the applied direct current.

**Continuous regeneration:** the applied direct current causes water to break down into hydrogen and hydroxyl ions. The hydrogen and hydroxyl ions attach themselves to the resin, regenerating the beads. This process is particular to EDI and proceeds even in the absence of ions in the feedwater.
1. Explain the effect of scale on boiler heat transfer surfaces (waterside).
   - Scale restricts heat transfer and causes metal to overheat:
   - On the waterside of a heating surface, the scale acts as an insulator that restricts the transfer of heat from the furnace or combustion gases to the water. This results in a reduction in the cooling effect that the water has on the metal and causes the temperature of the metal to increase.
   - Scale traps water beneath it and may result in corrosion:
   - When scale forms, there may be voids or pockets created between the scale and the tube surface. Water can be trapped in these pockets, and when the trapped water boils, steam escapes. As this process continues, the remaining water becomes highly concentrated and often has a high pH. This can lead to a condition called caustic gouging or underdeposit corrosion. Caustic gouging is possible in all boilers, but it is more frequent in high-pressure boilers.

2. What does the term caustic gouging mean?
   Caustic gouging or under deposit corrosion occurs when scale has voids or pockets created between the scale and the tube surface. Water can be trapped in these pockets, and when the trapped water boils, steam escapes. As this process continues, the remaining water becomes highly concentrated and often has a high pH. The concentrated high pH water corrodes or gouges the metal.

3. How can caustic embrittlement be controlled?
   The embrittlement factor most easily controlled is the water chemistry. If the boiler water does not have embrittlement characteristics, the other factors of stress and leakage can be ignored. At pressures below 6200 kPa, sodium nitrate is the standard for treating embrittlement. The ratio of sodium nitrate to sodium hydroxide must be kept in the desired range.
4. **Name three methods used to control foam in boilers.**

   **Eliminate all sources of oil** and other organics that might contaminate the feedwater. Oil is almost impossible to deal with once it enters the boiler. The best control is in the pretreatment system.

   **Inject an antifoam agent** into the boiler water. These chemicals do not eliminate the cause of the foam, but they act upon the foam itself to weaken the bubble film and cause the bubbles to burst more easily.

   **Use blowdown** to control the concentration of solids in the boiler water. Blowdown removes concentrated boiler water so the accumulation of solids cannot reach a level that contributes to carryover.

5. **What is a chelant treatment program? How does it differ from a phosphate program?**

   Chelate treatment uses chemicals, called **chelates** (or chelating agents), to hold scale-forming impurities in solution, not allowing them to precipitate out of the boiler water. It could be considered the opposite of phosphate treatment, which relies on precipitation.

6. **How is the pH of condensate return lines controlled?**

   Control of condensate chemical treatment is usually based on feeding sufficient chemical to raise the pH of the condensate above 7.0. Satisfactory reduction of carbon dioxide corrosion is obtained with the use of neutralizing amines or ammonia in the absence of oxygen.

7. **What are the two main types of caustic corrosion in boilers?**

   **General corrosion** or widespread corrosion may occur throughout the boiler due to caustic entering with the treated water from a demineralizer system. A common contaminant from the demineralizer process is sodium hydroxide.

   A more frequent cause is the accumulation of caustic between scale or iron deposits and the boiler surface. This phenomenon is called **under-deposit corrosion or caustic gouging.**

8. **Explain why the oxygen scavenger sodium sulphite is not used on boilers with operating pressures above 6000 kPa.**

   In boilers over 6000 kPa with sulphite residuals greater than 15 ppm, the sulphate breaks down into sulphur dioxide and hydrogen sulphide. They carry over with the steam and contribute to condensate return line corrosion.
9. **List three effects of carryover.**

   - If the boiler has a superheater, the entrained water will be heated, and some of it will boil, while passing through the superheater. Solids will deposit from the water onto the superheater tubes, and a scale will form restricting heat transfer.
   - Steam turbine blades will become fouled as solids in the water deposit on them. **Silica** is particularly harmful as it forms a very hard deposit on turbine blades. Water may cause erosion of turbine blades. This results in turbine imbalance and loss of efficiency and capacity.
   - Large slugs of water may cause thermal shock on piping and equipment, with subsequent damage.

10. **Explain why deposits on turbine blades are most frequently composed of silica.**

    Boiler water salts can vaporize with the steam. At pressures below 16.5 mPa, the only salt that is volatile is silica. As operating pressures increase, the steam phase has greater solvent properties. Silica was the first material known to exhibit vaporous carryover. It has been found that other salts, such as sodium phosphate and chloride, exhibit some vaporous carryover above 18.0 mPa. Silica can vaporize into steam at pressures as low as 3000 kPa.

11. **Sketch and describe a continuous chemical feed system with day tanks. Include a phosphate tank, an oxygen scavenger tank, and a neutralizing amine tank.**

    ![Diagram of continuous chemical feed system with day tanks](image)
The day tanks are used to mix the chemical solutions. The mixers are used to mix the chemical solutions with water (high purity or condensate). Each tank has two chemical feed pumps, a main and a backup. Piping includes check valves and valving to check the operation of the pumps. Drawdown cylinders are often used to verify the flow rates of the pumps. The pumps have adjustments to set the flow rate of chemical being pumped.

12. **Explain need for continuous blowdown in boilers using high purity water.**

Boiler feedwater always contains a certain amount of impurities. Even ultrapure demineralized water still contains trace levels of calcium, magnesium, silica, and other impurities. Returning condensate also contains impurities. The water treatment chemicals also add to the level of solids in the boiler water.

When the boiler water is evaporating and producing steam, the impurities in the boiler water remain in the boiler water. The overall result of pure water leaving the boiler, and impure water entering the boiler, is a steady increase in the level of solids in the boiler water. There is a limit to how concentrated the boiler water may become. This is based on the operating pressure of the boiler and the chemical treatment system being employed. To avoid exceeding the concentration limits, boiler water must be removed by blowdown. The blowdown is set so that the solids leaving the boiler equal those entering the boiler.

13. **Name two types of synthetic polymers used as dispersants in boiler water.**

Modern sludge conditioners consist of synthetic polymers, the most common being sulphonated and carboxylated polymers. A polymer is a substance that contains large molecules formed by the joining of several smaller molecules into chain-like structures. A polymer has an ionic or negative charge, which attracts positively charged ions from the water.
Chapter 10

Non-Boiler Water Treatment

1. Name three factors necessary for stress corrosion cracking in cooling water systems.

The 3 factors necessary for stress corrosion cracking are:

- Temperatures above 150°C

- High chloride content of the cooling water (for stainless steel). The chlorides concentrate under deposits and in crevices. For brass, the ammonium ion is the contributing ion for corrosion.

- Metal that is under thermal or mechanical stress such as heat exchanger shells or tubes.

2. Name three types of cooling water systems. Which type is the most common in power and process plants?

Three types of cooling water systems are once-through systems, closed recirculating systems, and open recirculating systems. The most common type used in power and process plants is the open recirculating type.

3. How is potable water disinfected? What are the three forms of chlorine used?

Disinfection refers to the removal or destruction of all pathogenic (disease-causing) organisms in water. The most common materials used for disinfection are chlorine, sodium hypochlorite, ozone, ultraviolet light, and iodine.

The 3 forms of chlorine used are:

- **Chlorine gas** (Cl₂) is often fed directly into the water.
- **Sodium hypochlorite** (NaOCl(aq)) is an aqueous, or liquid, form of chlorination.
- **Calcium hypochlorite** (Ca (OCl)₂) is fed as granules (dry) or mixed with water and fed as a liquid.

4. How is potable water treatment different from water pretreatment in an industrial plant?

Potable water treatment means the preparation of water to drinking water standards. The water may still contain dissolved minerals that are not suitable for plant use. The plant water often contains chemicals that are not meant for human consumption.
5. What streams in a power or industrial plant are considered wastewater streams? Explain how some of these streams may be reused or recycled.

Wastewater streams are such streams as demineralizer regeneration waste, cooling tower blowdown, boiler blowdown, sanitary waste, and process waters. Some methods of reusing the waste streams are:

- Recycling the best quality (lower conductivity) water. An example of this is discharging boiler blowdown water to the clarifier inlet or cooling tower makeup.
- Routing makeup water filter backwashes back to the inlet of the clarifier.
- Reusing some of the regeneration waste from the demineralizer regenerations on the next regeneration.
- Using the cooling tower blowdown for irrigation of crops.
- Concentrating all effluent water into a low volume stream using methods such as reverse osmosis or vapor recompression.

6. Name three basic types of corrosion inhibitors. Explain what is meant by delignification of cooling tower wood.

The different types of corrosion inhibitors are:

- **Passivation inhibitors** form a protective oxide film on the metal surface.
- **Precipitating inhibitors** are cathodic, meaning that they form insoluble films that coat the heat exchange surfaces.
- **Adsorption inhibitors** are adsorbed on the surface of the metal.
- **Oxygen scavengers** are compounds that react with dissolved oxygen in the water so that the oxygen is unable to react corrosively with the metal.

Delignification is the removal of the lignin in the wood by chemical attack. The wood looks more white, or bleached, in appearance. Its surface takes on a rougher appearance. As the wood fibers lose the lignin gluing them together, some fibers may wash off in areas of high flow or turbulence.

7. Explain the significance of organic compounds and suspended solids in wastewater discharge.

The amount of organic compounds that may be discharged depends upon the effect they have upon the oxygen level in the water. Organisms in the water will use the organic compounds for food. These biochemical reactions consume oxygen in the water. The oxygen is replenished at a slow rate from contact with air. When the organisms are consuming more oxygen than is being dissolved from the atmosphere, the level of dissolved oxygen in the water drops off.

Suspended solids in a water stream may settle out of the water or stay suspended. They increase the turbidity of the water and inhibit the sunlight. With no light source, some photosynthetic organisms such as algae and other plants die.
8. Describe the three main types of mechanical wastewater treatment.

**Gravity separation** is used to remove suspended solids as well as oil. The equipment used for gravity separation in waste treatment is similar to clarification equipment in water pretreatment.

**Filtration** is used in wastewater treatment to remove suspended solids. Filters are often found upstream of biological treatment to remove oil and suspended solids. Filtration is often the final cleanup step after a clarifier.

**Air flotation** is used to separate oil and water. The oil may be emulsified, or mixed, with the water or it may be a separate layer floating on the surface of the water.

9. What is the Langelier Saturation Index (LSI) and what is it used for?

The Langelier Saturation Index (LSI) can be used to predict the tendency of a water to deposit or dissolve calcium carbonate. If the LSI number is positive, the calcium carbonate tends to deposit. A negative LSI means the calcium carbonate tends to dissolve or stay in solution. If the value is 0 the water is in equilibrium.

The LSI of the water is a useful tool for selecting types of treatments used for cooling water.