# Contents

# BASIC TECHNICAL KNOWLEDGE

The industrial foreman is faced with a wide array of problems that require an understanding of mathematics, physics, chemistry and technical innovations. The course curriculum therefore contains the following section within the base interdisciplinary qualifications

Consideration of scientific and technical principles

This course is intended to be presented after completing these studies:

This textbook covers the relationship between various **forms of energy** and their **economic applications**. The knowledge gained in the previous textbooks will be referenced in covering this subject matter.

# 1. CONVERSION OF ENERGY IN ENGINES

In this course unit, you will once again be faced with the **concept of energy** which will call on our previous study of physics. You will be instructed in the principles and effects of **power engines** operating with various **types of energy** and **operating media**.

## 1.1 Concept of energy, types of energy and units of energy

Note: Energy refers to stored work capacity or, in other words, the ability of a system to perform work.

You are already aware that there are various types of energy and that the employed unit of energy often allows conclusions to be drawn as to what kind of energy is in question as can be seen in table 1, which you are already familiar with:

Table 1: Energy

| Type of energy | Unit of energy |
|---|---|
| Mechanical energy | Newtonmeter = Joule → Nm, J |
| Thermal energy | Joule → J |
| Electrical energy | Watt second, kilowatt hour → Ws, kWh |

The equivalence of the different types of energy is shown by the following:

**Energy equivalence** $1\,J = 1Nm = 1Ws$

There are three other relevant forms of energy:

- **Atomic energy**
- **Chemical energy**
- **Pressure energy**

## 1.2 Conversion and conservation of energy

Energy can be converted in specific cases. This concept is illuminated the example from figure 1:

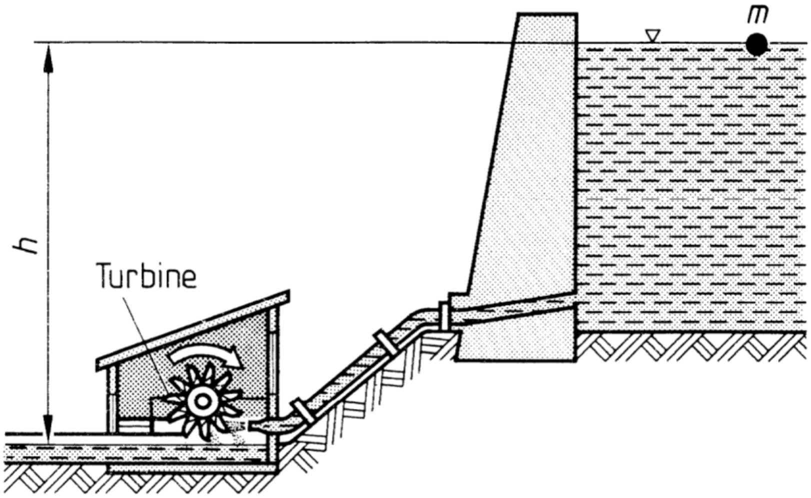


Figure 1: Water power station

Figure 1 shows the schematic representation of a hydropower station (reservoir power station). The stored water represents the **mechanical energy** and, more specifically, the potential energy.

**Potential energy** $W_{pot} = F_G \bullet h = m \bullet g \bullet h$ in Nm

The water travels at high speed when travelling down the chute that flows into the turbine which results in kinetic energy.

**Kinetic Energy** $W_{kin} = \frac{m}{2} \bullet v^2$ in Nm

Thus the mechanical energy then emerges as a different kind of energy, namely kinetic energy that is transferred to the **turbine**. The energy can now be used by a **generator** that is coupled with the turbine. This allows electrical energy in the form of Ws.

**Electrical energy** $W = U \bullet Q$

The private and business users are connected to this integrated network that, in Germany, has a total length of 25,000 km. If, for example, electrical energy is used by an immersion heater for warming a heating conductor, then the electrical energy in converted into **thermal energy**. If however, the electrical energy is used to drive a pump which feeds water back into the power station's reservoir, then the energy would be converted back into potential energy. The energy conversion chain just described confirms the following:

Note: Energy can exist in many forms and can therefore be converted.

It must be noted that **energy cannot be converted with perfect efficiency**. When energy is converted, there is usually a loss of energy in the process due to technical factors like friction. This issue can be understood using the efficiency factor that you are already aware of:

**Efficiency** $\eta = \frac{W_n}{W_a} < 1$

On the other hand, it is also possible to capture additional energy, such as heat, from the technical process. This **flow of energy** is described by the **law of conservation of energy**:

> Note: The sum of energy resulting from a technical process is the same as was expended in carrying out the technical process.

**Law of conservation of energy** $W_{end} = W_{start} + W_{in} - W_{out}$

## 1.3 Principle and function of power engines

In covering physics, you were already exposed to the concept of power transmission which divided machines into two groups:

- Work engines
- Power engines

> Note: A *power engine* is a machine that generates mechanical energy from other forms of energy to be used by *work engines* (see table 2).

Table 2: Examples of power and work engines

| Power engines | Working medium (energy source) | Work engines |
|---|---|---|
| Steam engine | Steam | Compressor |
| Steam turbine | Steam | Pumps |
| Combustion engine | Air/fuel mixture | Propeller Refrigera- |
| Gas turbine | Combustion gas and oxygen | tors |
| Water turbine | Water | Conveyors |
| Wind turbine | Wind (moving air) | Machine tools |
| Electric motor | Electric current | Vehicles |
| etc. | | etc. |

Power engines are used to generate driving forces and momentum and are divided into the following categories depending on the working medium or energy source:

- **Thermal engines,**
- **Hydraulic engines,**
- **Wind generators,**
- **Electric motors**

The generated momentum and force power the motors of the work engines. Figure 2 displays the example of a lathe:

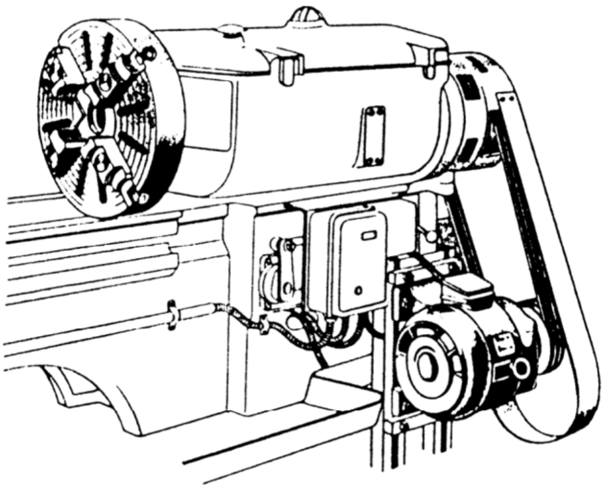


Figure 2: Coupling of a power engine (motor) with a work engine

The word **motor** is often used to describe power engines as in combustion motors, diesel motors, rotary motors, electric motors and so on.

# 2. STEAM POWER PLANTS

A focus of this textbook is the generation of steam power and its use in subsequent systems. These systems are called steam power plants.

## 2.1 Physical fundamentals of steam production

When generating steam (steam power plants use water vapor almost exclusively), there are three physical processes of significance. This unit therefore next concerns itself with the physical fundaments of steam generation.

Heat is a form of energy that can be directly attributed to the intensity of motion of molecules.

Note: When subjected to thermal energy, the kinetic energy of the individual molecules increases. When there is a decrease in thermal energy, the kinetic energy of the individual molecules decreases.

### 2.1.1 Specific heat capacity and the fundamental laws of thermal dynamics

The freezing point is at 0 °C, provided that the current air pressure ($p_{amb}$) corresponds to normal ambient air pressure.

**Normal air pressure** $p_n$ = 1.01325 bar

The freezing point is defined as a **fundamental** or **fixed point**. Another fundamental point is the boiling point of water that is 100 °C provided that the following conditions apply: $\boldsymbol{p_{amb} = p_n}$. The distance between the fundamental points is called the **fundamental distance**. Anders Celsius used this distance as the foundation in constructing the **Celsius temperature scale** which is named after him (see figure 3):

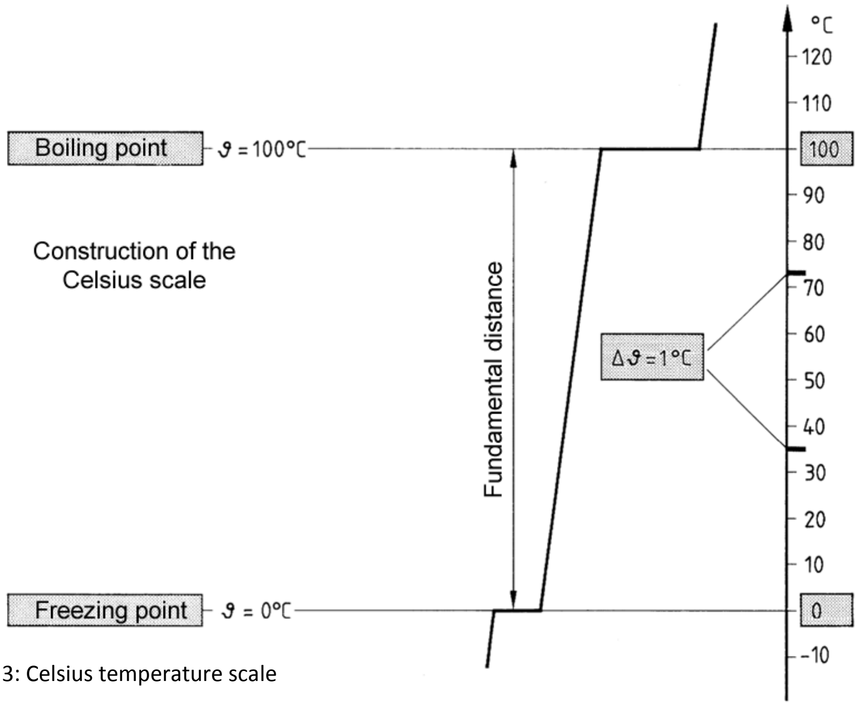


Figure 3: Celsius temperature scale

Figure 3 shows that the temperature remains constant for a certain amount of time both at the freezing point (0 °C) and the boiling point (100 °C). These temperatures are called holding points. The reason for this behavior is that the thermal energy is used to alter the physical state of the water and therefore the water does not show an increase in temperature. This means that this change in physical state cannot be measured with a thermometer. This is referred to as **hidden** or **latent** heat.

Any additional thermal energy between the freezing and boiling points results in an increase in temperature.

Note: Heat = amount of heat = thermal energy

This is referred to as sensible heat. The following applies:

| | |
|---|---|
| **Sensible heat** | Energy added or removed results in a change in temperature. |
| **Latent heat** | Energy added or removed results in a change in physical state but not in a change of temperature. |

Note**:** Temperature holding points also occur, for example, during lattice transformations in fixed metal structures. Thermal energy that results in lattice transition is considered to be latent heat. More information on this subject is available in the Material Science unit.

Before we cover the processes of melting, freezing and boiling and the associated latent heat, we will first cover the sensible temperature range. Figure 4 is very helpful in illustrating this principle:

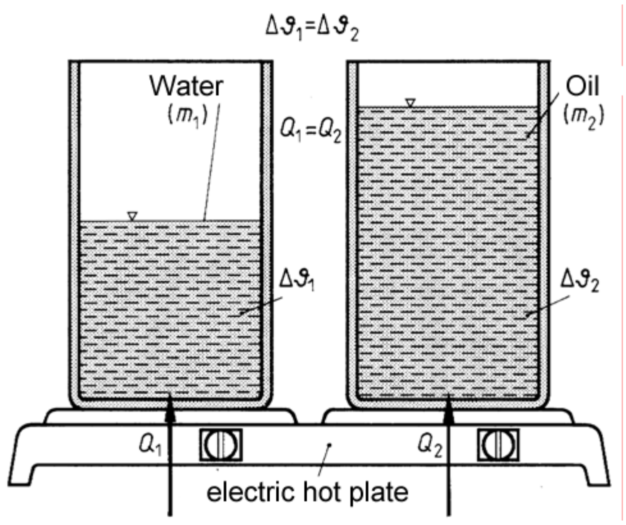


Figure 4: Heating of various materials

Figure 4 illustrates two different liquids, in this case water and an oil, being subjected to the same amount of thermal energy $\mathrm{Q}_1 = \mathrm{Q}_2$ and resulting in the same temperature change $\Delta\vartheta_1 = \Delta\vartheta_2$. It can be observed that with these conditions:

**$\mathbf{Q_1} = \mathbf{Q_2}$ and $\boldsymbol{\Delta\vartheta_1} = \boldsymbol{\Delta\vartheta_2}$**

and despite the fact that the mass oil $m_2$ is about twice that of the water $m_1$, both liquids exhibit the same temperature change when being subjected to the same amount of thermal energy. It can therefore be observed that the energy required to cause a specific temperature change is also dependent on the material that is being heated. How an individual material reacts to heat is determined by a specific matter constant. This is referred to as the specific heat capacity or in short form as specific heat. This is represented by the letter c in formulae.

| | |
|---|---|
| Note: | Specific heat capacity defines the amount of thermal energy that is required to increase the temperature of 1 kg of a solid or liquid substance by 1 K ∉ 1 °C. |

You can see that substances in gaseous form have been intentionally left out of this definition because there are additional conditions to consider when dealing with gaseous substances.

You can however recognize the:

Unit of specific heat capacity $[\mathrm{c}] = \frac{\mathrm{kJ}}{\mathrm{kg} \bullet \mathrm{K}} = \frac{\mathrm{kJ}}{\mathrm{kg} \bullet {}^\circ\mathrm{C}}$

Table 3 illustrates various material values at a temperature of 20 °C.

Table 3: Specific heat capacity at 20 °C

| **Material** | ***c* in kJ/(kg • K)** | **Material** | ***c* in kJ/(kg • K)** |
|---|---|---|---|
| Alcohol (ethanol) | approx. 2.43 | Quicksilver | 0.138 |
| Aluminum | 0.942 | Sandstone | 0.92 |
| Gasoline | 2.01 | Steel with 0.2 % C | 0.46 |
| Concrete | 0.89 | Steel with 1.0 % C | 0.49 |
| Lead | 0.13 | Pure water | 4.1816 ≈ 4.19 |
| Ice (at 0 °C) | 2.11 | Water (0.5 % salt) | 4.10 |
| Glass Diato- | 0.82 | Water (3.0 % salt) | 3.93 |
| mite Copper | 0.88 | Brick | 0.85 |
|  | 0.39 |  |  |

The data from table 3 illustrates many important facts:

Note: The specific heat capacity is temperature dependent. Water has the highest specific heat capacity of any of the solid and liquid materials. When dealing with alloys or mixtures the specific heat capacity is dependent upon the composition or concentrations.

You can easily recognize the law of thermodynamics at work in the definition of specific heat.

**Law of thermodynamics** $Q = m \cdot c \cdot \Delta\vartheta$ in kJ

Note: The amount of heat required to cause a specific change in temperature can be calculated by multiplying the mass of material *m*, the specific heat *c* and the desired change in temperature $\Delta\vartheta$

**Example 2.1:**

Write down the equation for the law of thermodynamics.

**Solution:**

$$[Q] = [m] \cdot [c] \cdot [\Delta\vartheta] = \mathrm{kg} \cdot \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}} \cdot \mathrm{K} = \mathrm{kJ}$$

**Example 2.2:**

A steel plate with a mass of $m = 8.63$ kg is to be heated from $\vartheta 1 = 22$ °C to $\vartheta 2 = 825$ °C for the purpose of heat treatment. How much thermal energy is required to heat the metal when the **average specific heat** is c = 0.45 kJ/(kg • K) and when heat loss is not considered?

**Solution:**

$Q = m \bullet c \bullet \Delta\vartheta$ $\qquad\qquad$ $\Delta\vartheta = 825\ °C - 22\ °C = 803\ °C = 803\ K$

$Q = 8.63\ kg \bullet 0.45\ kJ/(kg \bullet K) \bullet 803\ K$

$Q = 3\,118.45\ kJ$

**Example 2.3:**

Enter the calculated thermal energy from example 2.2 in kilowatt hours (kWh) see NTG

**Solution:**

$Q = 3{,}118.45\ kJ = 3118450\ J = 3118450\ Ws$

$$Q = 3118450\ Ws \bullet \frac{1}{1{,}000}\frac{kW}{W} \bullet \frac{1}{3{,}600}\frac{h}{s} = \frac{3118450}{1{,}000 \bullet 3{,}600}\ kWh = 0.866\ kWh$$

**Example 2.4:**

Ice has a specific heat of about 2.1 kJ/ (kg • K) at -10 °C. How much will the temperature increase when a 16.5 kg mass of ice is subjected to 3.8 kJ of thermal energy?

**Solution:**

$$Q = m \bullet c \bullet \Delta\vartheta \ \rightarrow \Delta\vartheta = \frac{Q}{m \bullet c} = \frac{3.8\ kJ}{16.5\ kg \bullet 2.1\ kJ\ (kg \bullet K)} = 0.11\ K = 0.11°C$$

## 2.1.2 Melting heat

If you were to continue to add heat in the example 2.4, you would see a continual temperature increase until the melting point of the ice (0 °C) was reached. The melting point $\vartheta_{melt}$ is a temperature holding point which results in the following behavior:

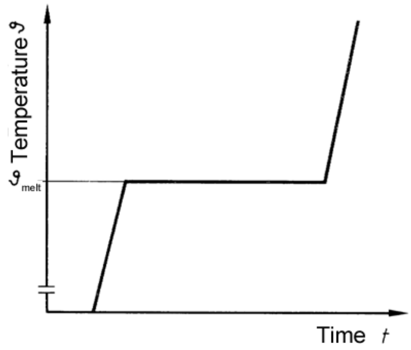


Figure 5: Melting point as a temperature holding point ϑ, t diagram

Chemically pure materials (e.g. water $H_2O$, see NTG 3) melt at a constant temperature. The thermal energy added to the ice while it is melted is a form of latent heat.

Note: The term melting point means the temperature at which a chemically homogenous material at a constant pressure (Reference pressure is normal air pressure $p_n$ = 101 325 Pa) transforms from a solid state to a liquid state.

Table 4 illustrates the values for various materials:

Table 4: Melting points (melting temperatures) at $p_n$ = 101 325 Pa

| Material | Melting point in °C | Material | Melting point in °C |
|---|---|---|---|
| Aluminum | 658 | Brimstone | 115 |
| Lead | 327 | Titanium | 1690 |
| Iron, pure | 1527 | Water | 0 |
| Gold | 1063 | Wolfram | 3380 |
| Copper | 1083 | Zinc | 419 |
| Nickel | 1455 | Tin | 232 |
| Quicksilver | 39 | | |

While melting the **enthalpy of fusion** or **melting heat** is stored in the melting body. This thermal energy is released when the body is in the freezing process and this released heat is called **fusion heat**. The temperature at which a material freezes is called its **freezing point**.

When melting various materials, it can be observed that varying amounts of melting heat is needed for different materials with the same mass.

Note: The thermal energy that is required to melt 1 kg of a material that is already at the melting point (this means there will be no temperature change) is called the specific melting heat or specific fusion heat.

The formula symbol used for specific melting heat is q. The unit corresponds to kJ/kg.

Table 5: Specific melting heat at normal air pressure $p_n$

| Material | Spec. Melting heat in kJ/kg | Material | Spec. melting heat in kJ/kg |
|---|---|---|---|
| Aluminum | 404 | Copper | 209 |
| Ammonia | 339 | Platinum | 113 |
| Lead | 24,7 | Quicksilver | 12 |
| Ice | 335 | Wolfram | 193 |
| Iron | 270 | Tin | 59 |

The definition of specific melting heat results in:

**Melting heat** **Q = m • q** In kJ

**Example 2.5:**

Write down the equation for calculating the melting heat.

**Solution:**

$$Q = [m] \bullet [q] = \mathrm{kg} \bullet \frac{\mathrm{kJ}}{\mathrm{kg}} = \mathrm{kJ}$$

**Example 2.6:**

300 kJ of thermal energy is required to melt a lump of lead. How many kg of lead are there if heat loss is not considered? Take q lead from table 5.

**Solution:**

$$Q = m \bullet q \qquad \rightarrow = \frac{Q}{q} = \frac{300\ \text{kJ}}{24.7\ \text{kJ/kg}} = 12.15\ \text{kg}$$

## 2.1.3 Heat of vaporization

As with melting, a temperature holding point is reached when **vaporizing** a material. This process can be illustrated by a $\vartheta$, t diagram (see figure 6) which shows the **boiling temperature** $\vartheta_S$, also known as the **vaporization temperature**.

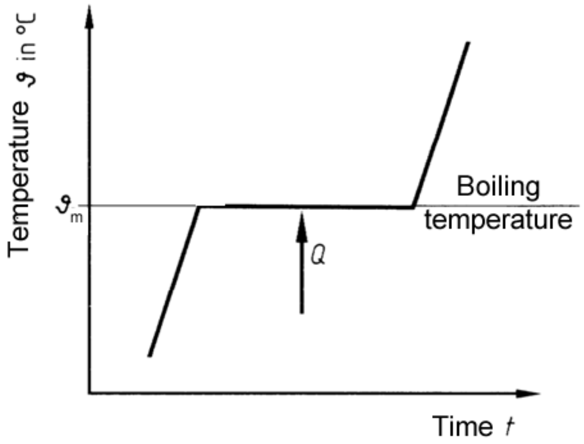


Figure 6: Boiling point as temperature holding point in a ϑ,t diagram

As opposed to melting (small pressure influence), vaporization is subject to a high degree of influence from air pressure. You are aware that:

Note: At normal air pressure $p_n$ = 1.01325 bar the boiling or vaporization point of water is $\vartheta_S$ = 100 °C.

Table 6 illustrated the boiling point of various materials at $p_n$:

Table 6: Boiling point at normal air pressure $p_n$ = 1.01325 bar

| Material | Boiling point in °C | Material | Boiling point in °C |
|---|---|---|---|
| Alcohol (ethanol) | 78.3 | Copper | 2330.0 |
| Aluminum | 2270.0 | Air | –192.3 |
| Ammonia $NH_3$ | 33.4 | Quicksilver | 357.0 |
| Benzene | 80.1 | Water | 100.0 |
| Helium | 268.9 | Wolfram | 5530.0 |

The following generally applies:

Note: Vaporization temperature $\vartheta_s$ and vaporization pressure $p_s$ are dependent upon each other.

This connection can be detected using testing equipment as seen in figure 7.

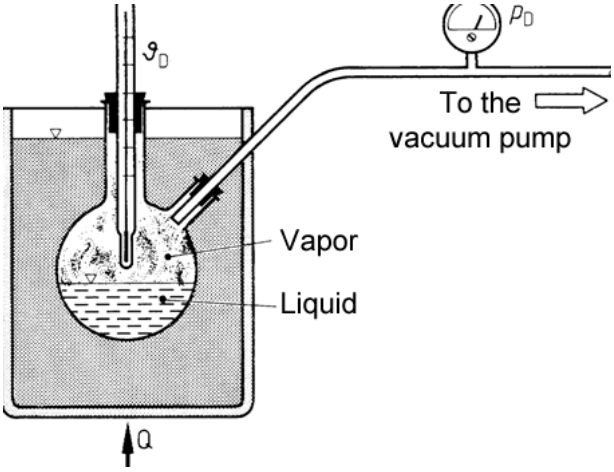


Figure 7: Determination of the pair of values ϑs and ps

If you change the pressure $p_n$ (in figure 7), the vaporization temperature $\vartheta_s$ = ϑD will also change.

You will observe that:

Note: By reducing the amount of pressure, the boiling point of a liquid will be reduced. Additional pressure results in the increase in the temperature of the boiling point.

The vaporization temperature $\vartheta_s$ is therefore a function of the vaporization pressure and vice versa:

$\vartheta_s$ = f ($p_s$) and $p_s$ = f ($\vartheta_s$)

The pair of values $\vartheta_s$ / $p_s$ can be placed next to each other in a table of values. Such a table is referred to as a vapor table. There are vapor tables for all refrigerants such as ammonia those known as frigene (halocarbons) as well as for water. Table 7 shows a small excerpt of a vapor table:

Table 7: Excerpt of a vapor table

| **Boiling pressure $p_n$ of water in bar** | 0.01 | 0.1 | 0.2 | 0.5 | 1.0 | $p_n$ | 2.0 | 10.0 | 100.0 | 200.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| Boiling temp $\vartheta_s$ of water in °C | 6.98 | 45.83 | 60.09 | 81.35 | 99.63 | 100.0 | 120.2 | 179.8 | 310.9 | 365.7 |

As you have already learned in the mathematics unit value pairs can be used to create diagrams. In this case we are referring to a vapor pressure chart or a boiling point curve. Figure 2.6 illustrates such a boiling point curve for various materials.

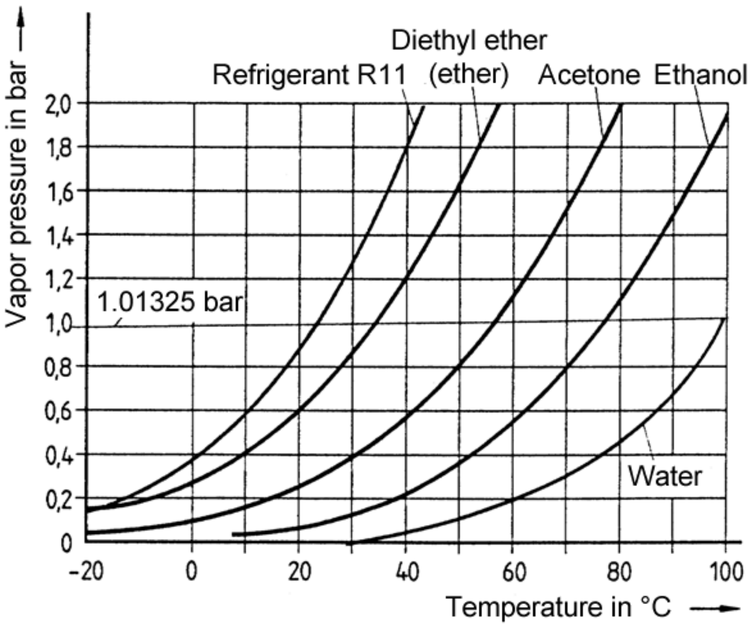


Figure 8: Boiling point curve $\vartheta_s$ = f ($p_s$)

Example 2.7:

Figure 8 displays, among other things, the boiling point curve of the refrigerant R11. Determine the boiling pressure for $\vartheta_s$ = –20 °C, $\vartheta_s$ = 0 °C, $\vartheta_s$ = 20 °C and $\vartheta_s$ = 40 °C.

**Solution:**

| $\vartheta_s$ in °C | –20 | 0 | 20 | 40 |
|---|---|---|---|---|
| $p_s$ in bar | 0.15 | 0.4 | 0.9 | 1.8 |

As with melting, when you boil various materials you can see that different amounts of thermal energy are required to boil the same amount of different materials.

Note: The amount of thermal energy that is required to boil 1 kg of material without any change in temperature is called *specific heat of vaporization*.

The formula symbol used for specific melting heat is *r*. As with the specific melting heat, the unit corresponds to kJ/kg. As opposed to specific melting heat, the following applies:

Note: The specific heat of vaporization *r*, like the boiling point, is highly dependent on the ambient air pressure.

Unlike with the boiling point, when the ambient air pressure increases, the specific vaporization heat decreases. This relationship can be seen in thermodynamic charts and tables. Table 8 shows the specific vaporization heat for various materials at normal air pressure:

Table 8: Specific vaporization heat at normal air pressure $p_n$

| Material | Spec. vaporization heat in kJ/kg | Material | Spec. vaporization heat in kJ/kg |
|---|---|---|---|
| Aluminum | 11721 | Liquid air | 197 |
| Ammonia | 1369 | Propane | 448 |
| Lead | 921 | Quicksilver | 301 |
| Chlorine | 260 | Turpentine | 293 |
| Iron | 6363 | Toluene | 356 |
| Carbon | 500232 | Water | 2258 |
| Refrigerant R11 | 183 | Zinc | 2595 |

As with the calculation of melting heat it is possible to calculate the amount of thermal energy needed to boil a specific amount of material using the specific heat of vaporization. This amount of thermal heat is defined as follow:

**Heat of vaporization** **Q = m • r** in Kj

**Example 2.8:**

Write down the equation for calculating the vaporization heat.

**Solution:**

$[Q] = [m] \bullet [r] = \text{kg} \bullet \frac{kJ}{kg} = \text{kJ}$

The heat of vaporization results in the material state to change from a liquid to a gas. When the gas is changed back into liquid, this is called **condensation**. Condensation releases the same amount of heat that was required by vaporization. The amount of heat released is called the **heat of condensation**.

Note: The heat of condensation is the same as the heat of vaporization. The condensation process also occurs without a change in temperature.

**Example 2.9:**

5 kg of water are boiled under normal air pressure $p_n$ = 1.01325 bar and at the associated boiling temperature of $\vartheta_s$ = 100 °C. What is the required heat of vaporization (from table 8)?

**Solution:**

$Q = m \bullet r = 5\text{ kg} \bullet 2{,}258\text{ kJ/kg} = 11{,}290\text{ kJ}$

**Example 2.10:**

Ammonia vapor is condensed under normal air pressure and $Q$ = 1095.2 kJ of thermal energy is released. How many kg of vapor, or condensate following the condensation, are in question ($r$ from table 8)?

**Solution:**

$Q = m \bullet r \qquad \rightarrow m = \frac{Q}{r} = \frac{1{,}095.2\ kJ}{1{,}369\ kJ/kg} = 0.8\ kg$

## 2.1.4 Vapor phases

Water can be used as a model for all materials that can be found in solid, liquid and gaseous forms. Therefore, as we take a closer look at water, which plays the decisive role in steam engines, keep in mind that the lessons learned here apply to many other materials. We will be looking at all the **phases** of water from deeply frozen ice, meaning ice at temperatures below 0 °C, to the **superheated steam** that is used as the **working medium in steam engines**. Superheated steam can be found at temperatures over 100 °C under normal air pressure. We will be looking at water in the temperature range of –100 °C to 1000 °C (although the lessons learned would also apply to temperatures both above and below this range). In today’s steam engines, the operating temperature is about 600 °C. Now we will take a look at the individual phases of water:

**1st Phase** $Q_1 = m \bullet c_{Eis} \bullet (\vartheta_{Sch} - \vartheta_1)$ In Kj (sensible heat)

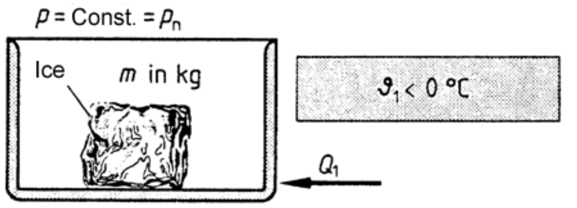


Figure 9: 1st phase

In the first phase water at $\vartheta_1 < 0$ °C is heated to the melting point $\vartheta_2 = \vartheta_{melt} = 0$ °C

**2nd Phase** $Q_2 = m \bullet q$ in kJ (latent heat)

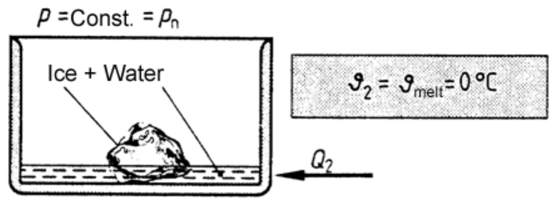


Figure 10: 2nd phase

In the second phase the ice at $\vartheta_{melt}$ = 0 °C is melted. There is no temperature difference between the melting ice and the resulting water. This is also called phase **equilibrium**.

**3rd Phase** $Q_3$ = m • $c_{Wasser}$ • ( $\vartheta_S$ - $\vartheta_{Sch}$) in kJ (sensible heat)

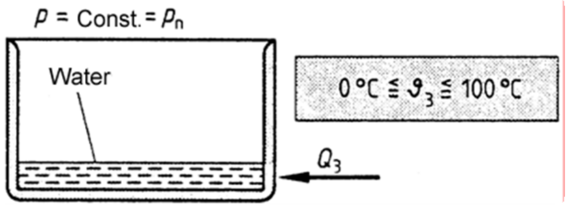


Figure 11: 3rd phase

In the third phase the ice has already melted. The resulting water heats from $\vartheta_{melt}$ = 0 °C to $\vartheta_S$ = 100 °C.

**4th phase** $Q_4$ = m • r in kJ (latent heat)

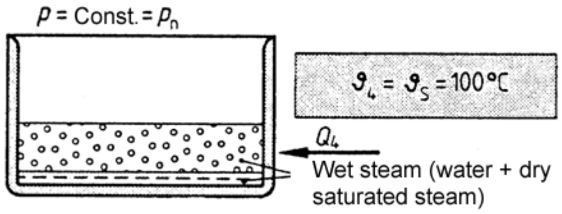


Figure 12: 4th phase

In the fourth phase the water boils at a temperature of $\vartheta_S$ = 100 °C. When the water is subjected to vaporization there is no difference in temperature between the liquid water and the resulting steam again also known as phase equilibrium. The **saturation level** is an important factor and the steam generated by this process is called **dry saturated steam** or **saturated vapor**. A mixture of water and dry saturated steam is called **wet steam**. Droplets of water can appear in this kind of steam. When the thermal energy $Q_4$ is applied, then all the water has been vaporized and only exists in the form of saturated steam. This state is illustrated in figure 13.

**5th phase** ⟶ Dry saturated steam (saturated vapor) is created.

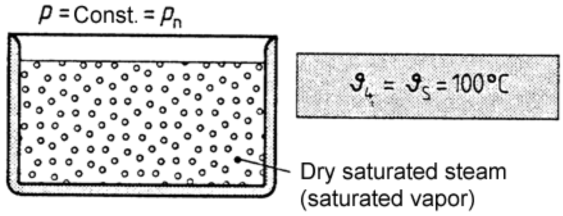


Figure 13: 5th phase

**6th phase** $Q_5$ = m • $c_{Dampf}$ • ( $\vartheta_S$ - $\vartheta_S$ ) in kJ (sensible heat)

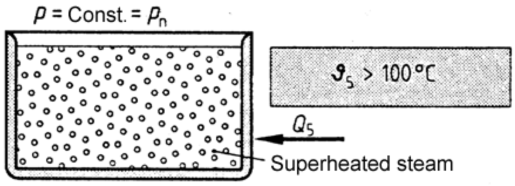


Figure 14: 6th phase

If the thermal energy $Q_5$ is applied to the dry saturated steam (figure 13), then the temperature of the vapor will increase resulting in superheated steam (figure 14).

Note: Superheated steam is the working medium of steam engines.

The thermal energy required to bring the steam to a superheated state is designated as **vapor generating heat**.

**Total thermal energy** $Q_{ges} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$ in kJ

### Example 2.11:

10 kg ice with $\vartheta_1$ = 50 °C are transformed to superheated steam with $\vartheta_5$ = 800 °C. Using the following data, $c_{Eis}$ (ice) = 2.0 kJ/(kg • K), $c_{Wasser}$ (water) = 4.19 kJ/(kg • K), $c_{Dampf}$ (vapor) = 2.1 kJ/(kg • K) (these are all average values) as well as the values from tables 2.3 and 2.6, calculate the following:

a) The required thermal energy $Q_1$, $Q_2$, $Q_3$, $Q_4$ and $Q_5$,
b) The total thermal energy (vapor generating heat).

**Solution:**

a) $Q_1 = \mathrm{m} \bullet c_{Eis} \bullet (\vartheta_{Sch} - \vartheta_1) = 10\ \mathrm{kg} \bullet 2.0 \frac{kJ}{kg \bullet K} \bullet 50\ \mathrm{K} = 1{,}000\ \mathrm{kJ}$

$Q_2 = \mathrm{m} \bullet \mathrm{q} = 10\ \mathrm{kg} \bullet 335 \frac{kJ}{kg} = 3{,}350\ \mathrm{kJ}$

$Q_3 = \mathrm{m} \bullet c_{Wasser} \bullet (\vartheta_S - \vartheta_{Sch}) = 10\ \mathrm{kg} \bullet 4.19 \frac{kJ}{kg \bullet K} \bullet 100\ \mathrm{K} = 4{,}190\ \mathrm{kJ}$

$Q_4 = \mathrm{m} \bullet \mathrm{r} = 10\ \mathrm{kg} \bullet 2{,}258 \frac{kJ}{kg} = 22{,}580\ \mathrm{kJ}$

$Q_5 = \mathrm{m} \bullet c_{Dampf} \bullet (\vartheta_S - \vartheta_S) = 10\ \mathrm{kg} \bullet 2.1 \frac{kJ}{kg \bullet K} = 14{,}700\ \mathrm{kJ}$

b) $Q_{ges} = \Sigma Q = 1{,}000\ \mathrm{kJ} + 3{,}350\ \mathrm{kJ} + 4{,}190\ \mathrm{kJ} + 22{,}580\ \mathrm{kJ} + 14{,}700\ \mathrm{kJ} = 45{,}820\ \mathrm{kJ}$

**Example 2.11 illustrates:**

Note: The enthalpy of vaporization of water is about 7 times as much as the melting heat.

## 2.2 Heat sources

This unit will cover the generation of thermal energy. There will be a focus on heat sources that are used in the operation of steam engines such as **atomic energy** and the **burning of fossil fuels**. These heat sources are known as artificial heat sources. We will also cover natural heat sources that are often referred to as alternative sources of energy.

### 2.2.1 Natural heat sources

The most important natural heat source is the sun. In the course of 24 hours, the sun radiates 15 • $10^{18}$ kJ into the Earth's atmosphere. Only a fraction of this enormous amount of energy is used. Using the laws regarding melting heat, it can be calculated that a year's worth of this thermal energy (365 • 15 • $10^{18}$ kJ) could be used to melt 1,750,000 $km^3$ of ice at a staring temperature of 0 °C. If this ice were distributed evenly across the surface of the Earth, it would be 7 m thick.

Another important source of heat is **geothermal energy**. Due to the low temperature of the earth's surface, **heat pump** is usually requires to access this energy. Geothermal energy is sometimes brought to the surface via **volcanos** and **hot springs**.

**Radionuclides** are an interesting heat source. These are unstable atoms that release heat as they decay. The total amount of thermal energy that these atoms release worldwide in a single day is approximately 4.2 • $10^{15}$ kJ. This thermal energy is released constantly and is evenly distributed across the planet. This energy plays an important role in maintaining the Earth's temperature but it cannot be directly used.

Natural heat sources, especially solar energy and geothermal energy are not only good for the environment but also offer a capacity that is much larger than the amount that we require for our energy needs:

| Note: | A primary goal of humanity in the future must be to methodically use natural heat sources. |
|---|---|

It should also be mentioned that putrefaction, fermentation as well as the lifestyle of humans and animals also generate thermal energy. Under normal conditions, the human body releases about 100 watts of thermal energy.

**Example 2.12:**

How much of a temperature increase could be affected in 10 kg of water ($c = 4.19 \frac{kJ}{kg \cdot K}$) using the average heat released from a human body in one hour?

**Solution:**

$Q_2 = \mathrm{m} \cdot \mathrm{c} \cdot \Delta\vartheta$ $\qquad$ $P = \frac{Q}{t}$ $\qquad$ =

$\Delta\vartheta = \frac{Q}{\mathrm{m} \cdot \mathrm{c}}$ $\qquad$ $Q = P \cdot t = 100\ W \cdot 3{,}600\ s = 360{,}000\ Ws = 360{,}000\ J = 360\ kJ$

$\Delta\vartheta = \frac{360\ kJ}{10\ \mathrm{kg} \cdot 4.19 \frac{kJ}{kg \cdot K}} = 8.59\ K = 8.59\ °C$

## 2.2.2 Artificial heat sources

Aside from the industrial heat sources such as atomic energy and the burning of fossil fuels, there are two other heat sources that should be mentioned. These are **frictional heat**, which plays a large role in mechanical efficiency and **electrical heat sources**. The conversion of electrical energy into thermal energy occurs through the friction of electrons rubbing against each other as the electrical energy flows through a metal filament. This heat is actually a form of frictional heat. Such metal filaments can be found in all electrical heat sources like heating ovens, heated pillows, immersion heaters, hairdryers, hot plates and so on.

### 2.2.2.1 Fossil fuels

Heat that is used or released in a chemical reaction is called the **heat of reaction**. Such chemical reactions occur, for example, in every burning process. The thermal energy released by combustible materials, usually fossil fuels but sometimes thing like garbage as well, is called the **heat of combustion**. As you learned the reaction process requires oxygen.

Note: Combustion requires combustible material and oxygen. The released heat is a reaction heat.

The most important criterion for the quality of a combustible material is how much thermal energy is released during combustion or heat of combustion. To compare combustible materials with each other, 1 kg of solid or liquid material and 1 $m_n^3$ (normal cubic meter) of combustible gas are equivalent amounts of material that can be compared. .

Note: The thermal energy released by the combustion of 1 kg or 1 $m_n^3$ of material is called the specific caloric value $H_o$ (for combustible gasses: $H_{o,n}$).

As a result, the unit of the specific caloric heat is kJ/kg or kJ/$m_n^3$.

| | | |
|---|---|---|
| **Heat of combustion** | $Q = m \bullet H_o$ | in kJ (for solid and liquid combustibles) |
| | $Q = V \bullet H_{o,n}$ | in kJ (for combustible gasses)<br>$m$ = mass in kg, $V$ = volume in $m_n^3$ |

In determining the specific caloric value $H_o$, DIN 5499 “Gross and Net Calorific Values” requires the following:

a) Both the temperature of the combustible material before the combustion and the temperature of the product of combustion after the combustion is 25 °C.

b) The water content of a fuel before combustion and the water that was created during the combustion of the bonds containing hydrogen within the fuel should be in a liquid (condensed) state.

The reasoning behind point b) is the following:

**Heat of vaporization = condensation heat**

As you are aware, the specific heat of vaporization *r* is different for every liquid. It is also pressure and temperature dependent. For water at 25 °C it is ***r* = 2442 kJ/kg**. As the water contained in combustible materials is usually vaporized and dissipates as vapor, the thermal energy that was required to vaporize the water cannot be recovered during condensation. This is taken into account in the specific caloric value $H_u$.

Note: Net *caloric value = gross caloric value* minus *vaporization heat* of the water.

The net heat value of a combustible material is always lower than its caloric value. As the only the heat value of combustion can be used, this is more important than the specific caloric value for technical calculations. The described data also explains the terminology we covered earlier:

| **current designation** | **Previous designation** |
|---|---|
| Gross caloric value $H_o$ | Upper heat value $H_o$ |
| Net caloric value $H_u$ | Lower heat value $H_u$ |

This results in the following:

**Usable thermal energy** $Q$ = m • $H_u$ in kJ (for solid and liquid materials)
$Q$ = V • $H_{u,n}$ in kJ (for gasses)

It should however be mentioned that boilers have recently been made that retain the heat of vaporization by recondensation. Such boilers are known as **condensing boilers**.

The specific caloric value $H_o$ and the net caloric value $H_u$ are measured using a **calorimeter**. This is a device which can measure thermal energy. Table 9 contains some $H_o$ and $H_u$.

Table 9: $H_o$ and $H_u$ values of solid, liquid and gaseous combustible materials at a temperature of 25 °C.

| **Material** | **$H_o$ in kJ/kg or kJ/$m_n^3$** | **$H_u$ in kJ/kg or in kJ/$m_n^3$** |
|---|---|---|
| Pure carbonate | This number varies according to the specific water content and thus the heat that is required to vaporize the water within the material. It is in any case larger than $H_u$. | 33800 |
| Black coal | | 30000 to 35000 |
| Brown coal | | 8000 to 11000 |
| Briquette | | 17000 to 21000 |
| Peat | | 10000 to 15000 |
| Wood | | 9000 to 15000 |
| Heating oil extra light | 45400 | 42700 |
| Heating oil heavy | 42300 | 40200 |
| Gasoline | 46700 | 42500 |
| Benzene | 41940 | 40230 |
| Diesel oil | 44800 | 41640 |
| Petroleum | 42900 | 40800 |
| Blast furnace gas | 4080 | 3980 |
| Coke oven gas | 19670 | 17370 |
| Natural gas H type | 41300 | 37300 |
| Methane | 39850 | 35790 |
| Propane | 100890 | 92890 |

**Example 2.13:**

60 kg of water ($c$ = 4.19 kJ/(kg • K)) are warmed from 22 °C to 84 °C in a gas oven. How much $m_n^3$ of natural gas with a specific net caloric value of $H_{u,n}$ = 37100 kJ/$m_n^3$ will be needed when you consider that 30% more thermal energy must be used to compensate for heat loss?

**Solution:**

$$Q_{erf} = \mathrm{m} \bullet \mathrm{c} \bullet \Delta\vartheta + 0.3 \bullet \mathrm{m} \bullet \mathrm{c} \bullet \Delta\vartheta = 1.3 \bullet \mathrm{m} \bullet \mathrm{c} \bullet \Delta\vartheta = \mathrm{V} \bullet H_{u,n}$$

$$V_{erf} = \frac{\mathrm{m} \bullet \mathrm{c} \bullet \Delta\vartheta}{H_{u,n}} \qquad \Delta\vartheta = 62\ °\mathrm{C} = 62\ \mathrm{K}$$

$$V_{erf} = \frac{1.3 \bullet 60\ \mathrm{kg} \bullet 4.19\ \mathrm{kJ/(kg \bullet K)} \bullet 62\ \mathrm{K}}{37{,}100\ kj/m_n^3} = 0.546\ m_n^3$$

## 2.2.2.2 Atomic heat sources

Atomic nuclei with relatively large atomic masses, especially in uranium atoms, can be split by firing neutrons at them. The resulting nuclear fission always results in a portion of the split mass being converted into thermal energy. Uranium releases $2.5 \cdot 10^6$ the amount of energy as the energy produced in the combustion of the same amount of coal. According to the German physicist Albert Einstein (1879 – 1955), nuclear fission releases the following amount of energy:

**Released atomic energy** $W = \Delta m \bullet c^2$ in Ws = J = Nm

$c$ = **Speed of light** = $3 \bullet 10^8$ m/s
$\Delta m$ = The mass converted into radiant energy.

It should be noted that a large portion of the used mass of material remains in the form **fission by-products**. The extraction of atomic energy is carried out in **nuclear reactors**. The most important reactor designs will be covered in this book. This technology always carries the danger of **radioactive contamination** and safety procedures are therefore very important.

**Example 2.14:**

$\Delta m$ = 5 g of uranium are converted into energy using nuclear fission.

a) Calculate the energy released.
b) How many kg of coal with $H_u$ = 30000 kJ/kg would have to be burned to release the same amount of energy?

**Solution:**

*a)* $W = \Delta m \bullet c^2 = 0.005\ \mathrm{kg} \bullet (3 \bullet 10^8\ \mathrm{m/s})^2 = 0{,}005 \bullet 9 \bullet 16^{16}\ \mathrm{Nm} = 45 \bullet 10^{13}\ \mathrm{J}$
$W = 45 \bullet 10^{10}\ \mathrm{kJ}$

*b)* $W = Q = m_{coal} \bullet H_u = 45 \bullet 10^{10}\ \mathrm{kJ}$
$$m_{coal} = \frac{W}{H_u} = \frac{45 \bullet 10^{10}\ \mathrm{kJ}}{30{,}000\ kJ/kg} = 15{,}000{,}000\ \mathrm{kg}$$

## 2.3 Thermal power stations

Using the fundamentals learned in the physics unit we will now look at the function of thermal power stations that are powered by fossil or nuclear fuels.

### 2.3.1 General information regarding thermal power stations

Note: Thermal power stations generate electrical energy from thermal energy.

This means that the **primary energy** (coal, heating oil, gas or nuclear fuel) is converted to thermal energy for the purpose of generating steam.

This thermal energy is used to transform warmed boiler feed water, which circulates in a closed system, into **live steam**. The parameters for this live steam in today’s power stations are usually:

**Live steam parameters: 550 °C and 250 bar**

These parameters are achieved by superheating and these temperature and pressure values correspond to the upper operating tolerances of the boilers and steam pipes.

A centerpiece of the operation of any kind of power station is the **feed water** which must be of extremely high quality. Water of this quality starts as raw water and is then purified in a **water treatment plant**. The **feed water** circulates in a closed loop. After flowing through the **turbine** the water is fed back into the boiler. The turbine is used to drive the **generator** which is responsible for generating the electrical energy. Figure 15 schematically illustrates the flow of energy in power stations. The rotational energy flows to the generator.

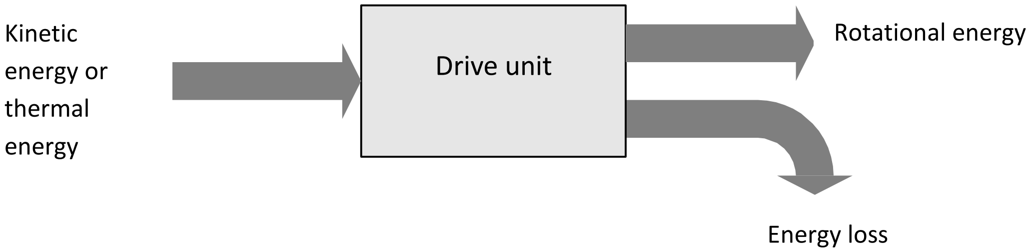


Figure 15: Energy flow to the generator

The turbine is the generator’s drive unit. The turbine is designed to convert the existing energy (hydro power or steam power) into rotational energy.

Note: In thermal power stations, thermal energy is converted into electrical energy.

The live steam (550 °C, 250 bar) generated in the boiler is fed to the turbine where it is converted to rotational energy.

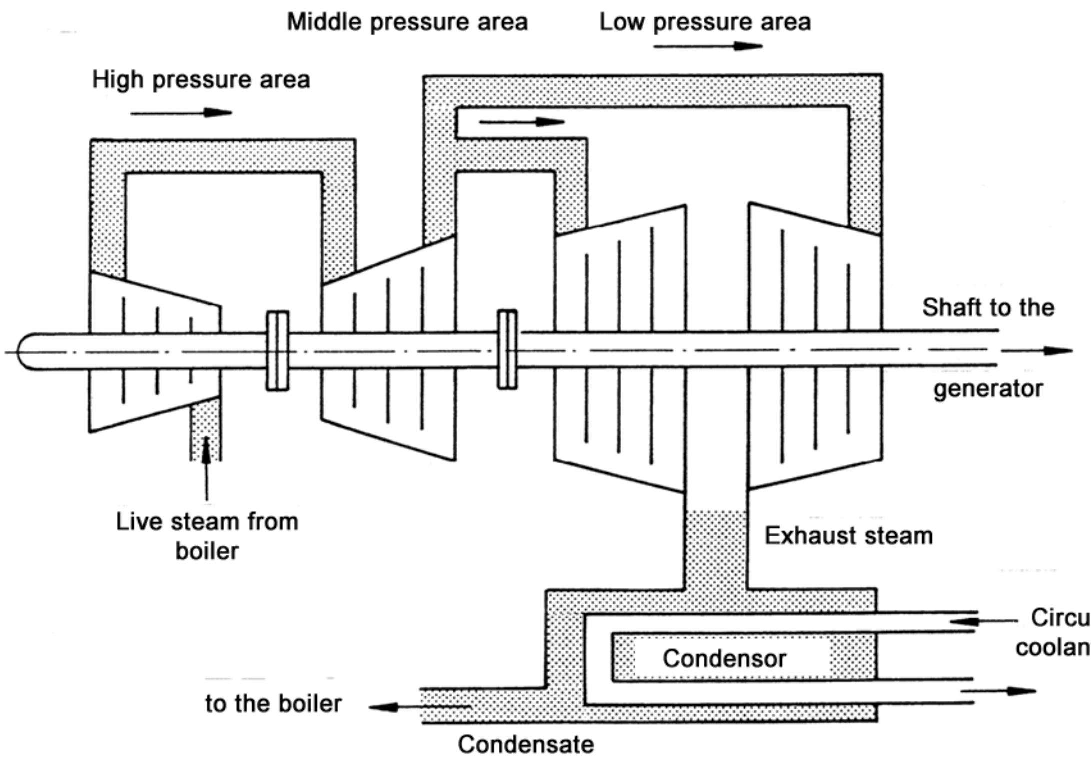


Figure 16: Principles of a turbine

The steam loses pressure and temperature as it travels through the turbine but gains speed. As the steam travels across a system of curved blades which are connected to a well, the well rotates and drives the generator which then generates the electrical power.

| | |
|---|---|
| Note: | A generator is an electrical machine that converts mechanical energy into electrical energy from the motion of an armature within a magnetic field. |

As the steam in the turbine expands, its volume increases. This means that the turbine blades must increase in size to accommodate the volume of steam which results in the turbine being divided into three stages:

- **High pressure stage,**
- **Middle pressure stage**
- **Low pressure stage.**

Due to the large volume of steam in the low pressure stage, the steam pressure must be distributed as illustrated in figure 16.

An important factor in determining the efficiency factor of a turbine is the absolute temperature $T$ of the steam that is fed to the turbine as well as the absolute temperature $T_0$ of the steam as it leaves the turbine. This is called the **thermal efficiency**.

**Thermal efficiency** $\eta_{th} = 1 - \frac{T_0}{T}$

$T_0$ = Steam output temperature in K

$T$ = Steam input temperature in K

Note: Modern steam turbines reach a thermal efficiency of about 40%.

**Example 2.15:**

A steam turbines is fed with live steam at $\vartheta = 550$ °C. The efficiency equals $\eta_{th} = 39\ \% \notin 0.39$. What is the temperature of the steam output $\vartheta_0$

Note: Only the absolute temperatures may be used when making thermodynamic calculations!

**Solution:**

$$\eta_{th} = 1 - \frac{T_0}{T} \quad \rightarrow \quad \frac{T_0}{T} = 1 - \eta_{th} = 1 - 0.39 = 0.61$$

$$T_0 = 0.61 \bullet T = 0.61\ (\vartheta + 273.15)\ \mathrm{K}$$

$$T_0 = 0.61\ (550 + 273.15)\ \mathrm{K} = 0.61 \bullet 823.15\ \mathrm{K}$$

$$T_0 = 502.12\ \mathrm{K}$$

$$\vartheta_0 = (T_0\_273.15)\ °\mathrm{C} = (502.12 - 273.15)\ °\mathrm{C}$$

$$\vartheta_0 = 228.97\ °\mathrm{C}$$

## 2.3.2 Generating steam with coal, oil or gas

**Coal** is used in power stations where there is a reliable supply of coal and cooling water. This is the reason why many coal-fired power stations are located along large rivers. The coal is fed to the coal hopper by means of a conveyor belt where the coal is then continuously brought to the combustion chamber where there is also a steady supply of pre-heated fresh air. The combination of the coal and fresh air allows for good combustion. Figure 17 illustrates the design of a coal-fired steam power plant:

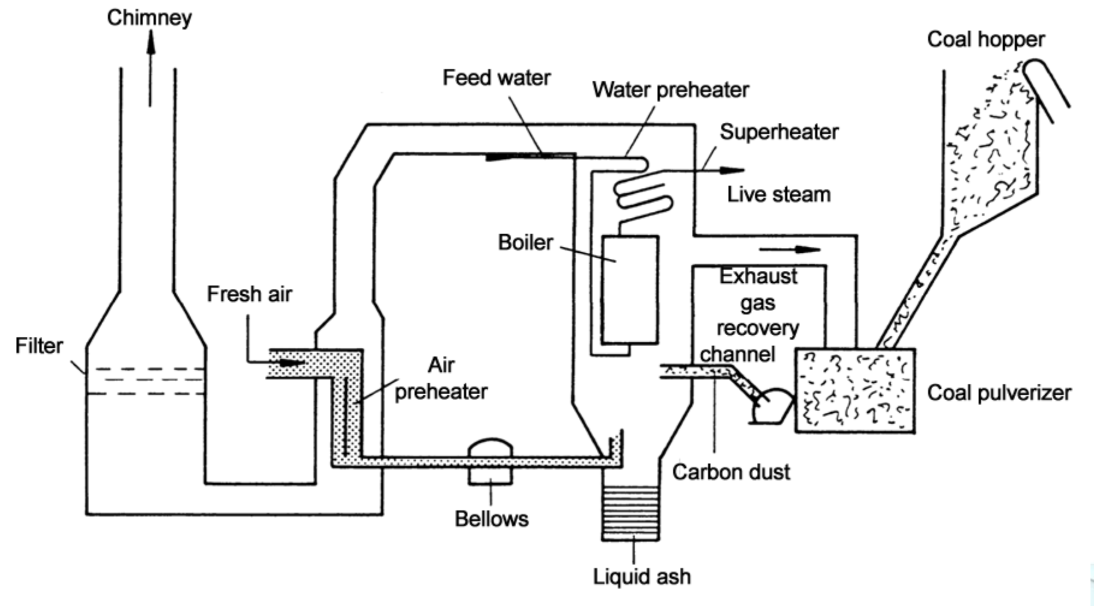


Figure 17: Principle of a boiler plant with a pulverized coal firing system

Figure 17 shows that the exhaust gasses are filtered before they enter the chimney. This filtration system aims to filter out as much carbon dioxide ($CO_2$) and solid particles such as ashes as possible (see NTG 3). The ashes fall in a water bath where they are shock-cooled resulting in granulate which can be used as a component in building materials.

Due to the variety of combustion technologies like pulverized coal firing (see figure 17), fluidized bed combustion, grate firing and so on, there are specific characteristics of each type of power station.

Note: The operating principle of oil and gas powered systems is the same as with coal-fired power stations.

The burners of such systems are optimized for the application of liquid or gaseous fuels. Due to the fact that heating oil and gas both combust and ignite similarly, a combined or mixed manner of operation is a common practice. Such combined or mixed operation has a positive effect on the operating costs or the profitability of a system.

Power stations powered by oil or gas do not emit any **combustion residue** in the form of ashes which means that ash filtration is not required in the exhaust system.

Systems using heating oil require that the heavy oils be pre-heated because heavy oils are very thick and sometimes solid at normal temperatures. The oil is can be sprayed only after it has been warmed by a secondary heating system. The exhaust from these systems must still be filtered before entering the chimney, especially to filter out to sulfur content.

### 2.3.3 Steam generation with nuclear fuels

Steam generation with **nuclear fuels** require an intermediate step in **nuclear power plants**. This means that in burning the nuclear fuels, thermal energy is produced that is used to power a steam power plant as previously described.

Note: In nuclear power plants, the boiler feed water is converted into superheated steam by ^ the nuclear reaction which is then used to power the turbine.

Thermal energy is released through **atomic processes**. The two kinds of atomic processes which can be used are called **atomic fission** and **atomic fusion:**

Note: In *atomic fission*, two lighter atoms are produced from one heavier atom.

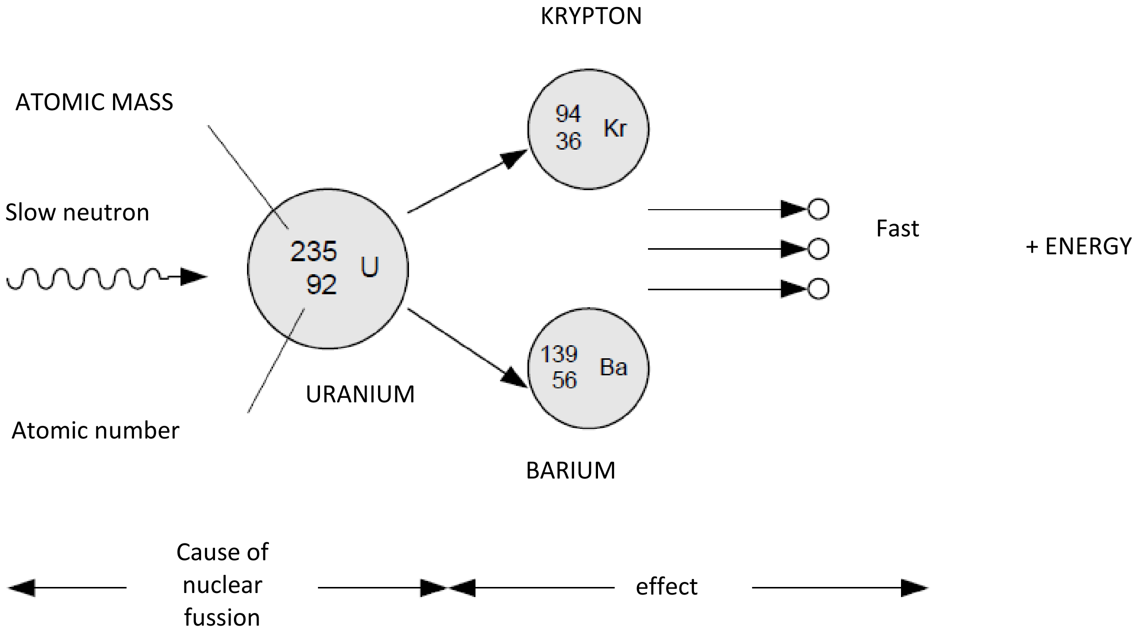


Figure 18: Principle of atomic fission

Note: In nuclear fusion, two lighter atoms fuse together to form a heavier atom. This is illustrated in figure 2.17.

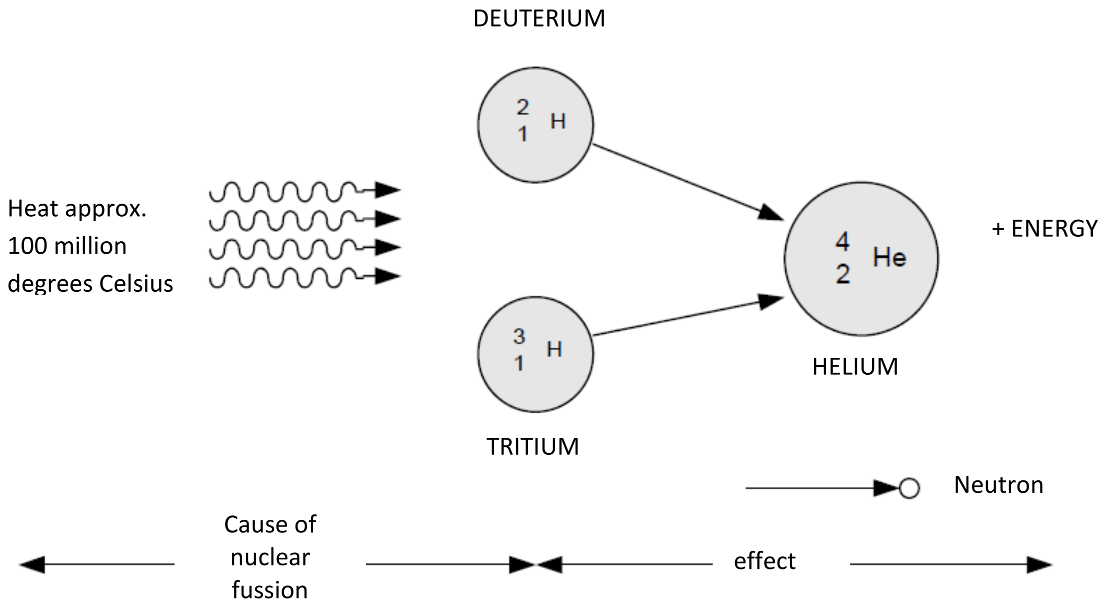


Figure 19: principle of nuclear fusion

**Activation energy** is always needed to begin either of these atomic processes. Nuclear fusion can only occur at temperatures over 100 million degrees which is why fusion reactors are not yet technically feasible.

Note: Today's nuclear reactors only use atomic energy that has been released through nuclear fission.

Nuclear fission is triggered by **neutron bombardment** (see figure 18). The released fast neutrons cause additional fission resulting in a chain reaction as long as at least the minimum required mass of uranium (**critical mass**) is on hand. This chain reaction must take place in a controlled manner within the reactor in order to make use of the released thermal energy. Water can be used as a **moderator** because, as the name implies, it can slow down fast neutrons and moderate the reaction.

Note: A *moderator* is a substance which serves reduce the speed of fast neutrons so that the desired rate of fission can be maintained.

Control rods are used to decrease the speed of the fast neutrons. The “slow” neutrons can still cause additional fission.

Note: The control rods ensure a constant rate of fission.

The **nuclear fuel** is brought into the reactor in the form of **fuel rods** (approx. 5 m long stainless steel pipes). The fuel assembly is composed of multiple fuel rods.

The reactor, the fuel assembly and the **heat exchangers** are part of the **primary area** (the safety area). In a few cases, the turbine is also in the primary area but it is usually in the **secondary area** because there is normally media separation between the two areas.

### 2.3.4 Types of reactors

Nuclear reactors are divided into five different types. The difference between them is explained below:

**Light water reactor**

The nuclear fuel is composed of 5x enriched uranium with natural and normal water $H_2O$ (also known as **light water**) serving as the moderator. There is also a type of water called **heavy water**. The difference between these two types of water is illustrated in figure 20:

Note: Light water has hydrogen atoms with only a proton in the nucleus (see NTG 3). Heavy water has hydrogen atoms with a proton and a neutron in the nucleus.

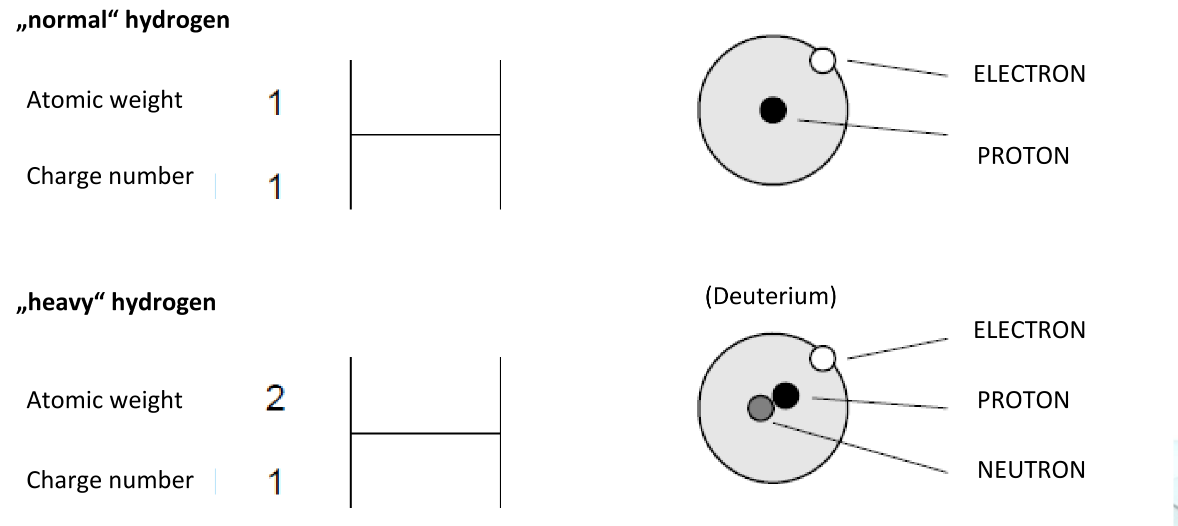


Figure 20: Difference between the two hydrogen isotopes.

Note: Deuterium, known as heavy hydrogen, has an atomic weight of 2. It consists of a proton and a neutron and is twice as heavy as normal hydrogen.

**Boiling water reactor** (see figure 21)

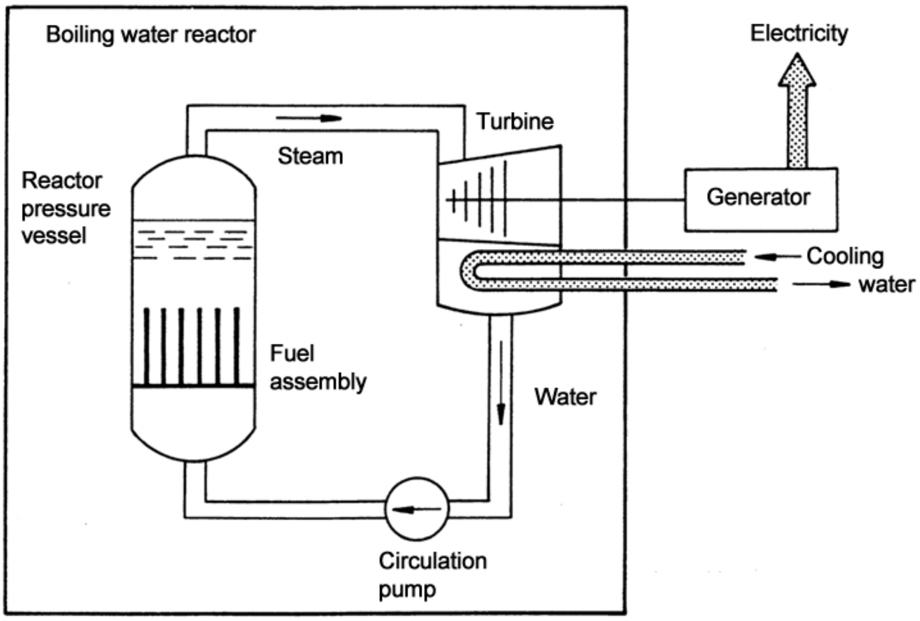


Figure 21: Principle of a boiling water reactor

In boiling water reactors, the turbine must also be in the primary area (safety area) of the reactor building because the water from the reactor is used to power the turbine directly. As with a light water reactor, light water serves as the moderator. A portion of the water is vaporized in the reactor pressure vessel at a pressure of about 70 bar. Boiling water reactors have only one cooling circuit.

**Pressurized water reactor** (see figure 22)

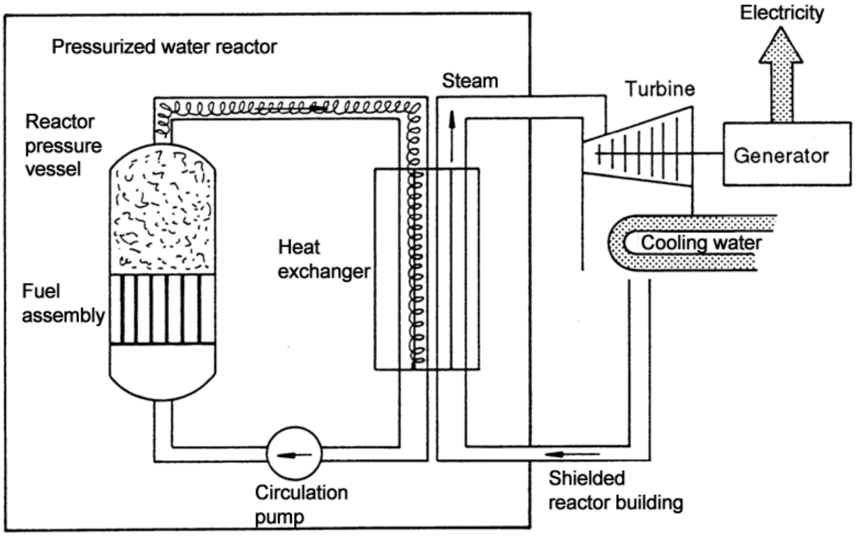


Figure 22: Principle of a pressurized water reactor

The excess pressure in the reactor prevents the water from boiling. At a pressure of about 150 bar a water temperature of 300 °C can be reached. Heat exchangers are used to generate steam to drive the turbine. The primary and secondary areas of a pressurized water reactor must be kept absolutely separate from each other.

**High-temperature reactor** (see figure 23)

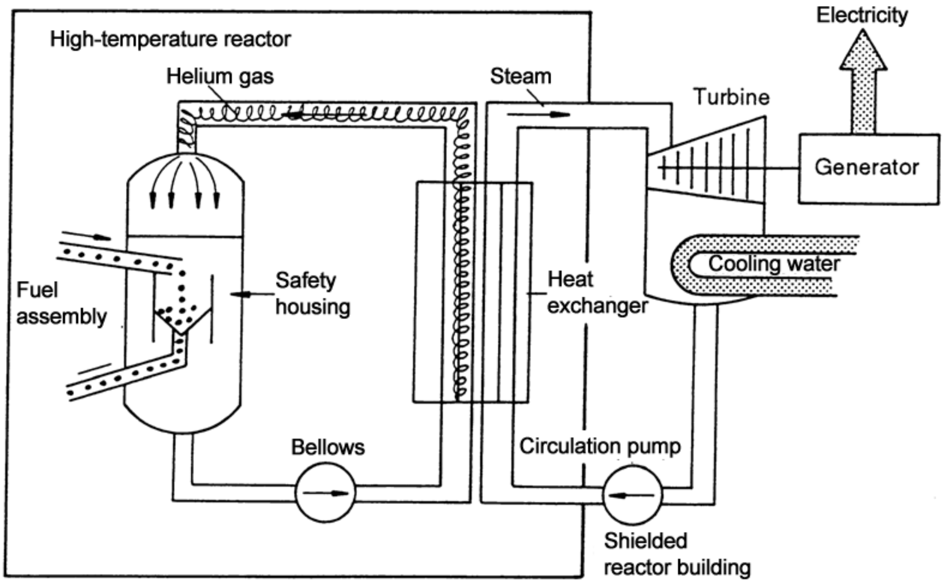


Figure 23: Principle of a high-temperature reactor

The nuclear fuel is embedded in graphite pellets. Helium is an inert or noble gas which, when used as coolant, allows the fuel rods to be used at very high temperatures and pressures (530 °C und 180 bar).

**Breeder reactors** (see figure 24)

A breeder reactor is a nuclear reactor that generates new fissile material, plutonium, from the nuclear waste produced in the reactor. The production of thermal energy is especially high in these reactors. Due to the high level of radioactivity of the water used in the reactor, the heat exchange must be carried out with two completely separate consecutive circulation systems.

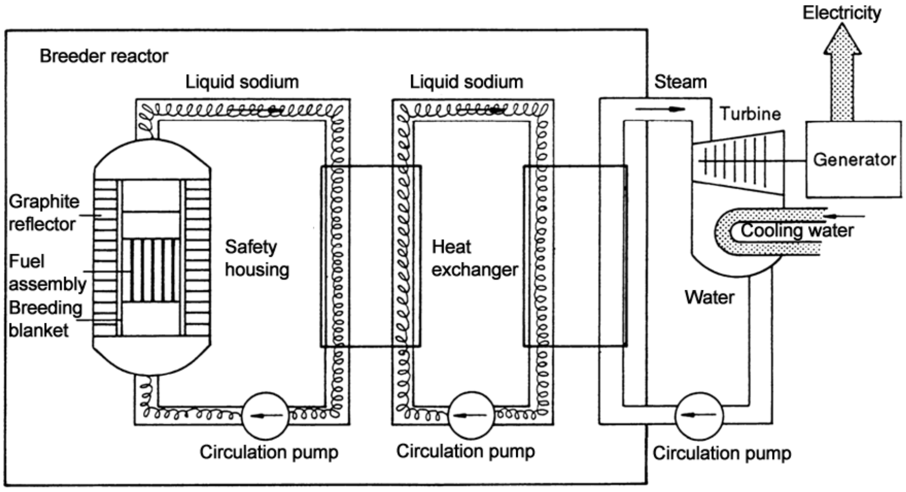


Figure 24: Principle of a breeder reactor

## 2.3.5 Comparison of the energy yields of various thermal power plants

It has been mentioned several times that the energy yield of a power plant plays a very large role in determining its profitability.

It is therefore also very important to know how much electrical energy can be generated from a kilogram of fuel. When making such a comparison, it is important to include the **efficiency factor** of the systems that are in question. It is also important to ensure that the system has been set up so that it is running under **optimal conditions** such as:

- Pre-warming the feed water
- Low water loss in the circuit
- Usage of fuels optimized for the particular system
- Continuous mode of operation (balancing of extreme operating loads).

The following comparison provides information regarding the energy yields of the most common fuels:

| | |
|---|---|
| 1 kg brown coal | 2 kWh electrical energy |
| 1 kg black coal | 7 kWh electrical energy |
| 1 kg natural gas | 9 kWh electrical energy |
| 1 kg petroleum | 11 kWh electrical energy |
| 1 kg uranium (breeder reactor) | 24,000,000 kWh electrical energy |

# 3. ENVIRONMENTALLY FRIENDLY ENERGY PRODUCTION

Regardless of the type of power plant used in a thermal power station, the environment is adversely affected by the release of combustion products and heat losses. Nuclear power plants must also be held to strict safety standards. In this unit we are going to look at systems that can generate electricity in a much more environmentally friendly way such as **hydroelectric power plants** and so-called **alternative energy sources**.

## 3.1 Hydroelectric power plants

There are three basic types of hydroelectric plants:

- **Run-of-the-river hydroelectric power plants,**
- **Reservoir power plant**
- **Tidal power plant**

Figure 1 has already illustrated the principle of a hydroelectric power plant. The relationship between the different types of energy is as follows:

Note: Hydroelectric power plants transform the kinetic energy of the water into the rotational energy of the turbine.

The **mechanical energy capacity** generated by gravity is used. Figure 25 illustrates this principle.

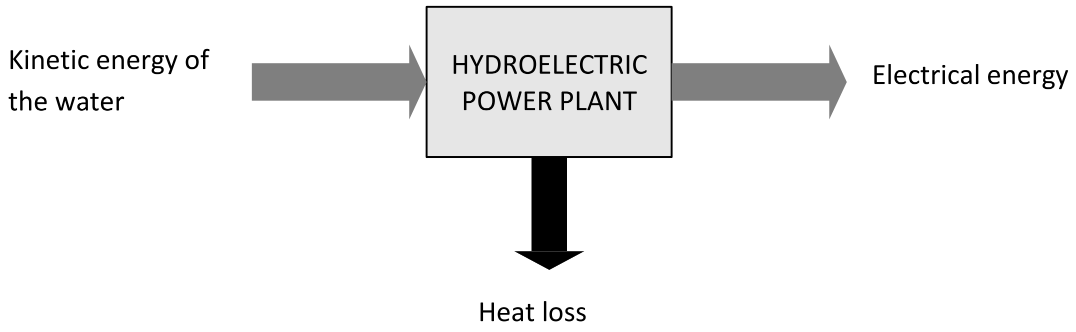


Figure 25: Operational principle of hydroelectric plants

Hydroelectric plants generally require an **upper water basin** and a **lower water basin**. A **downward slope** is created by the **geodesic difference in elevation *h***. The water is set in motion due to gravity thus turning the water's potential energy into kinetic energy. This kinetic energy is used to power a **water turbine** which drives a generator that, as in thermal power plants, generates electrical power.

### 3.1.1 Run-of-the-river hydroelectric power plants

**Run-of-the-river hydroelectric power plants** use the kinetic energy of water in the natural flow of a river. The power plant is built in the river.

The course of a river is subject to significant changes in level due to climactic factors. When snow melts, there can be flooding and during hot dry summer months the water level decreases and rivers can sometimes completely dry out.

The run-of-the-river power plant must be designed for the average river water level. Designing the power plant for a higher level of water would not be economical because this high level would only be available for short periods of time. A retaining dam regulates the required water supply by opening and closing.

Ships must still be able to travel along the river and this can be ensured using locks. Fish must also have a way to migrate along the river.

| | |
|---|---|
| Note: | Run-of-the-river hydroelectric power plants are designed with the most consistent generation of electricity in mind. The efficiency of a run-of-the-river hydroelectric power plant is about 85 %. |

The efficiency is very high. Only about 15 % of the primary energy is lost through friction of the mechanical components and heat loss (see figure 25) from internal friction in the water.

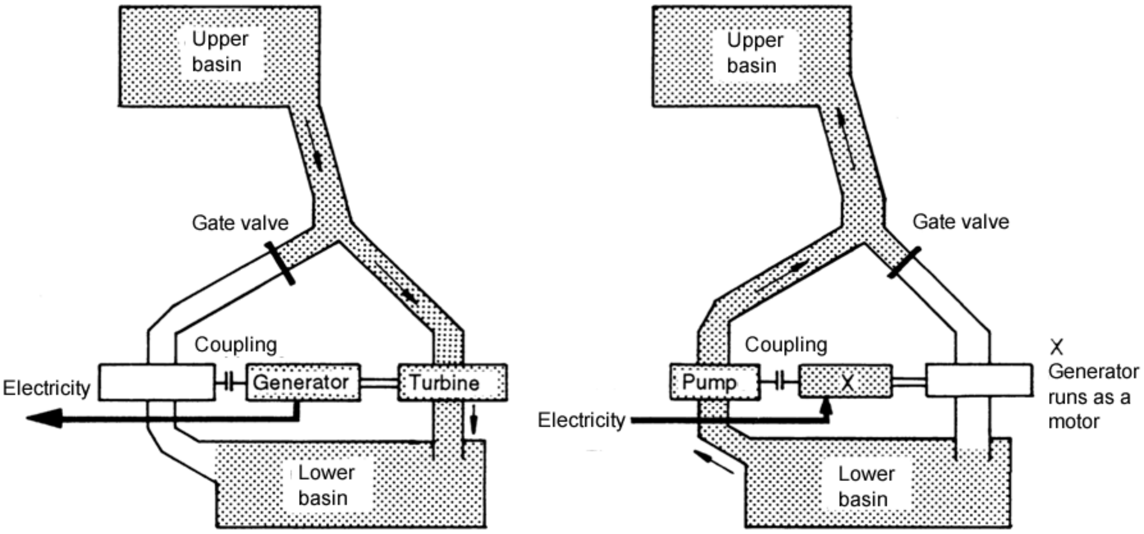
### 3.1.2 Reservoir power plants

**Reservoir power plants** can be recognized by the small amount of inlet water. Furthermore, a large slope must be created as well.

The water required for electricity generation is first stored by a **dam** (like the Hoover Dam) or  a natural upper water basin must be used (like the Walchensee hydroelectric plant). In the Walchensee hydroelectric power plant, the Walchensee serves as the upper water basin and the water flows through pipes down a slope of about 200 m into the Kochensee which serves as the lower water basin while the water drives the turbine along the way.

| | |
|---|---|
| Note: | The efficiency of a reservoir power plant is about 80 %. |

A special type of reservoir power plant is the **pumped-storage hydroelectric power station**. Figure 26 illustrates the principle:



a)

b)

Figure 26: Principle of a pumped-storage hydroelectric power station; a) power operation, b) pump operation

Figure 26a illustrates the plant while it is generating power (working operation). During the time when there is not much demand, the water that collected in the lower basin can be pumped back into the upper basin using the previously generated energy as shown in figure 26b.

Note: Pumped-storage hydroelectric power stations are only used for energy generation during times of peak demand. They have an efficiency of about 75 %.

### 3.1.3 Tidal power plants

Note: Tidal power plants use the energy that results from changes in water level caused by high and low tides.

Figure 27 illustrates a tidal power plant from above.

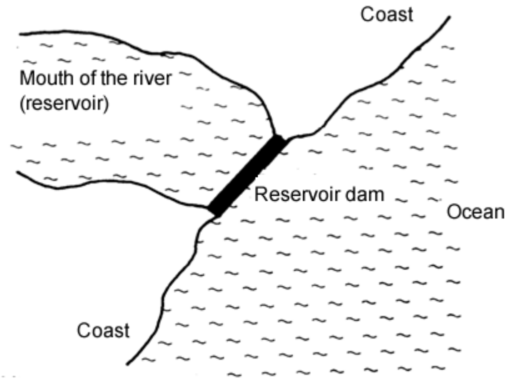
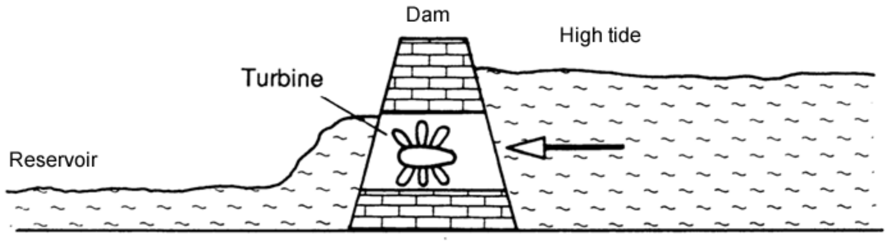
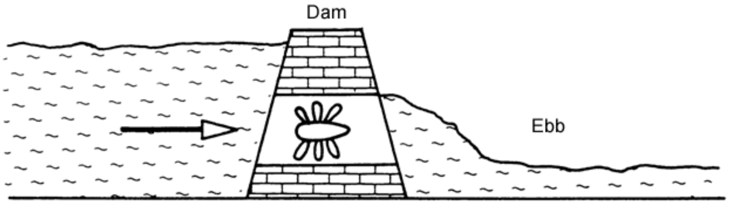


Figure 27: Tidal power plant

The mouth of a river is separated from the ocean with a reservoir dam. The turbines are located in the dam and can work in two directions as illustrated by figure 28.



Operation during high tide



Operation during ebb tide

Figure 28: Operating principle of tidal power plant

The **tidal range** can be as much as 21 m. Unfortunately, the technology has not yet developed enough to take full advantage of the available energy.

## 3.2 Alternative forms of energy

### 3.2.1 Wind energy

Power stations that use the energy provided by wind are called **wind turbines**. These turbines are extremely environmentally friendly. When you consider that one single hurricane over the North Sea contains enough energy to cover Germany's power needs for a full year, it is rather strange that much less than 1 % of our energy needs are provided by wind power. When one considers this, it could be said that there is a significant amount of development left to do.

**Low speed** wind turbines have blades with a diameter of about 10 m (the largest diameter of a propeller yet built is 48 m) that are mounted on towers that are about 25 m high (tallest tower yet built is 50 m). A generator is directly powered by the propeller. **High speed** wind turbines have towers with heights up to 200 m and have propellers with diameters up to 100 m. These wind turbines are still in the experimental stage.

| | |
|---|---|
| Note: | Efficiency ratings of 80 % can be reached with good aerodynamic designs. The power of a wind turbine increases to the third power in relation to the speed of the wind. |

### 3.2.2 Solar energy

**Solar panels** are making use of the sun's energy in ever increasing amounts, though still far too little. These panels capture solar energy and turn it into thermal energy. This energy is stored in a heat transfer medium (such as water or isobutene) which travels through a closed circuit to heat exchangers such as heating elements.

In **solar cells**, which are **photovoltaic cells** with large surface areas, the solar energy is directly converted into electrical energy. The field which deals with the direct conversion of light energy into electrical energy is called **photovoltaics**.

These energy conversion systems are called **photovoltaic systems**. A measure of the amount of energy that solar energy provides is called the **solar constant** which equals **1.36 kW/m$^2$**.

Note: The solar constant is the amount of energy that is radiated on the surface of the Earth when it is at its average distance from the sun and when the solar rays strike the surface at a perpendicular angle.

**Solar power plants** have already been built. These are systems that reach very high temperatures by concentrating the sun's rays using parabolic mirrors much like a burning glass. Temperatures of about 4000 °C have already been reached. These plants, much like solar energy as a whole, do not yet play a defined role in our energy network.

When you consider the disadvantages of thermal power plant (especially the environmental impact) and the huge amounts of alternative sources of energy that nature provides, the following statement carries a lot of weight:

Note: A primary goal of humanity in the future must be to make use of alternative sources of energy.

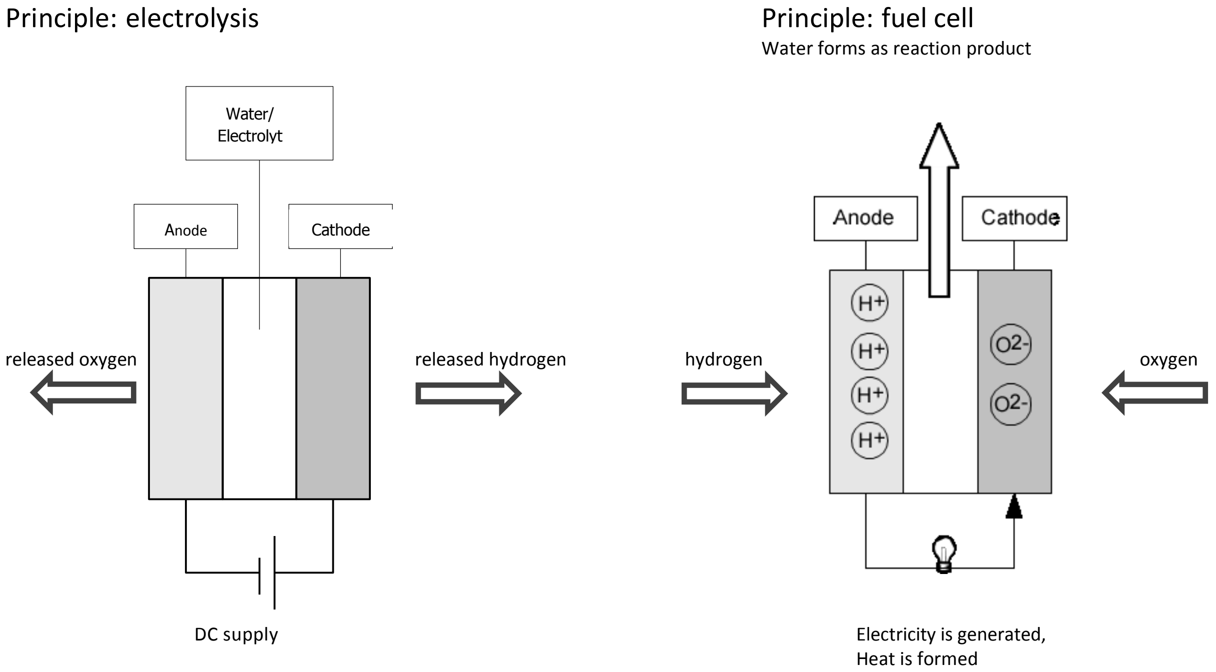
### 3.2.3 Fuel cells

As you have learned in the previous units, electrical energy is produced by the conversion of potential energy, kinetic energy or the chemical energy that is contained in various types of fuels. There is a technological chain of devices and machinery that then ends in a generator.

The so-called fuel cell is capable of delivering electrical energy without any intermediate processes. It is more efficient (efficiency of up to 80%) than conventional generators and is more reliable as well due to its simple design. Although a variety of designs and concepts have appeared on the market, the most environmentally sound variant is the hydrogen-oxygen fuel cell. The various fuel cells differentiate themselves from each other primarily through the types of electrolytes and their associated operating temperatures. Fuel cells can be used in stationary or mobile applications based on their design and size.

**Function**

A fuel cell is in principle a highly developed galvanic element that releases electrical energy from the continuous oxidation of hydrogen using a catalyst. As hydrogen is usually released from water during electrolysis (by means of solar power), the following figure illustrates a comparison of both principles:



Principle: electrolysis

Principle: fuel cell

Water forms as reaction product

Figure 29: Comparison of principles of electrolysis/fuel cells

Electrolysis: If you subject an electrolyte (strongly diluted acid) to DC current, the water molecules will split into hydrogen on the cathode and oxygen on the anode.

Fuel cell: Energy in the form of electricity is released during catalytic oxidation. The reaction product is water.

Under external pressure hydrogen ($H_2$) will be constantly fed to the “fuel electrode” (anode) and oxygen ($O_2$) will be fed to the “oxidizing electrode” (cathode). The hydrogen molecules are split into hydrogen ions (protons, $H^+$) and electrons ($e^-$) at the anode:

$$2\,H_2 \rightarrow 4\,H^+ + 4\,e^-$$

The protons flow through the electrolytes to the cathode and the electrons load the node with a negative charge. The oxygen molecules in the cathode decay into oxygen ions ($O^{2-}$) through the addition of electrons whereas the cathode becomes positively charged:

$$O_2 + 4\,e^- \rightarrow 2\,O^{2-}$$

A voltage of about 1 volt forms between the two electrons. If both electrodes are connected via an external electrical circuit with an electrical appliance such as a light bulb or a propeller, the electrons flow from the anode to the cathode and perform the electrical work along the way. In the cathode, the hydrogen and oxygen ions combine into water that is continuously separated from the electrolytes. The formula for the reaction is below:

$$2\,H_2 + O_2 \rightarrow 2\,H_2O + \text{energy}$$

The total reaction corresponds to the oxyhydrogen reaction that occurs in a controlled form through the spatial separation of the oxidation of the $H_2$ from the reduction of the $O_2$.

Because of the low voltage level (1V) that the individual fuel cells produce, many fuel cells must be combined to form a fuel cell battery.

## Design and use

Fuel cells have a very simple design. Each cell is composed of three layers: Two field flow plates and an electrolyte membrane between them (see figure 30).

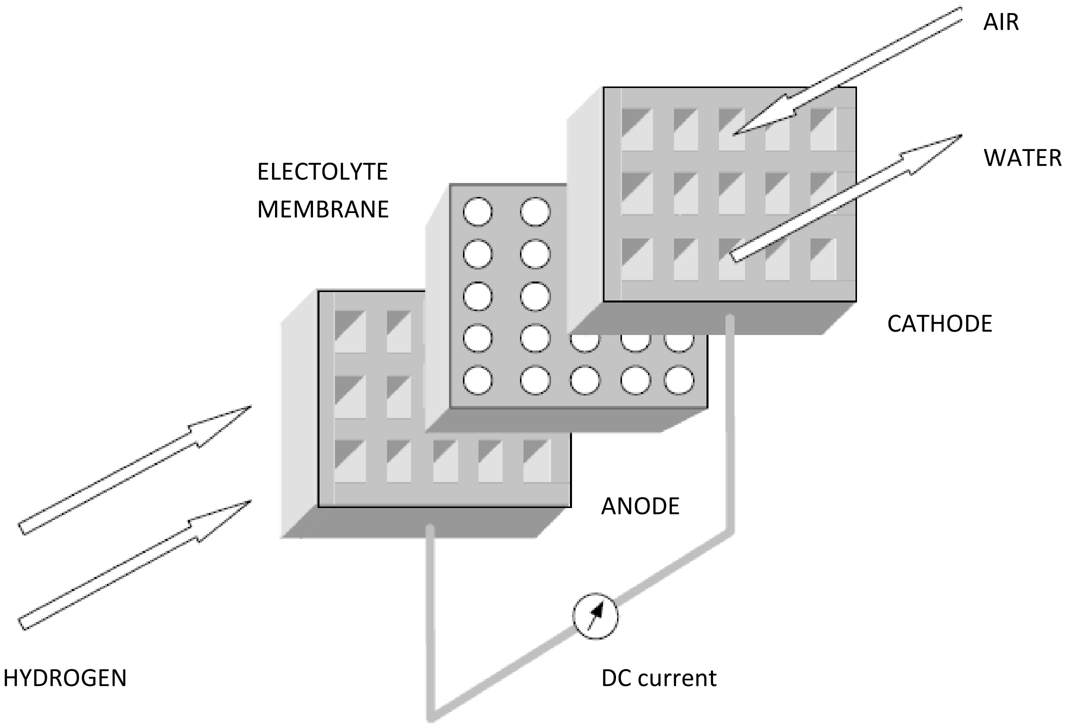


Figure 30: Schematic assembly of a fuel cell

The first field flow layer is the anode, the second layer is the electrolyte and the third is the cathode. The anode and cathode serve as catalysts. The middle layer is made in a carrier structure that takes in electrolytes. The type of electrolyte used depends on the type of fuel cell in question. Some electrolytes are liquid while others are solid and have a membrane structure. PEM fuel cells are common and use a polymer electrolyte membrane as the electrolyte.

The first time that fuel cells were used was in space travel where the high costs were less important than the advantages that were offered by this technology. These advantages are that fuel cells are lighter and more efficient than batteries and more reliable and quieter than generators. Since then, the scope of application for fuel cells has become much larger.

Examples:

- Drive mechanism in automobiles
- Energy sources for mobile energy needs (notebooks, etc.)
- Supply of heat and electrical energy in combined heating power units

# 4. COMBUSTION ENGINES

This unit will cover the most important principles of **combustion engines**, the **Otto cycle** and **diesel engines**. The various fuels will also be a subject of this unit.

## 4.1 Overview and the fundamental differences between combustion engines

The name **combustion engine** was given because **liquid or gaseous combustible materials** that are also known as **fuels** undergo the process of combustion. In these engines, chemical energy is transformed into thermal energy on its way to becoming mechanical energy. As you are already aware, the energy released from combustion is called:

**Heat of combustion** $Q = m \bullet H_0$ (for liquid fuels) *m* = Mass

$Q = V \bullet H_{0,n}$ (for gaseous fuels) *V* = Volume

Note: The following energy conversion take place in a combustion engine:

Chemical energy of the fuel → Combustion → Heat of combustion → Mechanical energy

Combustion engines have proven themselves to be particularly suitable for use in **vehicles** as well as in **stationary applications** for the following reasons:

- Fast and reliable **operational availability**
- Inexpensive and easy **procurement of fuel**
- Flexible **operating behavior**
- Optimal **power-to-weight ratio**

Combustion engines can be defined as **internal combustion engines** or **external combustion engines** according to table 10.

Table 10: Overview of combustion engines

| **Combustion engines** | | |
|---|---|---|
| **Internal combustion** | | **External combustion** |
| **Single ignition system** | **Continuous combustion** | Stirling engine<br>Steam engine |
| Otto engine<br>Diesel engine<br>Wankel engine | Gas turbine | |

**Internal combustion** means that the combustion of the **air-fuel mixture** occurs within the motor itself, either in **cylinders** or **combustion chambers**. This can occur via a single ignition system or with a **continuous combustion** system. Single ignition systems are found in Otto, diesel and Wankel engines (rotary engines) while gas turbines have a continuous ignition system.

**External combustion** takes place outside of the engine. For example, a steam engine receives its steam from a steam generator. The combustion that creates the steam takes place in a boiler. Heat engines like the **Stirling motor** also have the combustion occurring outside of the engine itself.

Note: Stirling and steam engines are only built as stationary machines, While both are relatively friendly to the environment, they are fairly complicated to construct.

## 4.2 Gas turbines

Gas turbines are usually used as stationary machines for applications like small power stations. In individual cases, they are also used as motors for vehicles. As opposed to piston motors, turbines can only operate efficiently when within a very limited range of high rotational speeds and they can only function as a two-stage unit with high and low-pressure stages.

A **high-pressure turbine** operates with a **low-pressure turbine** in a serial configuration which means that they are not mechanically connected to each other. The first turbine, in concert with a compressor, blows compressed air into a combustion chamber where it combines with injected fuel and ignited. The hot expanding combustion gases drive the turbine compressor. These gasses then enter the second turbine, the **power turbine**, at high speed. This turbine which is fed with the exhaust flow of the first turbine is the real motor of the vehicle. The turbine compressor should really be seen as an auxiliary system.

Turbine engines in automobiles have not progressed past experimental prototypes, racecars and sports cars.

If gas turbines are to become competitive with piston engines in the automotive world, the following issues will have to be dealt with and overcome:

- Turbines are very expensive to manufacture due to their extremely high rotational speed (about 40000 rpm) and high operating temperature (the gas combusts at 900 °C).
- Fuel consumption, especially while idling, is very high.
- Acceleration, especially from a full stop, is too slow for today’s traffic requirements. This is caused by the sluggishness of the turbine compressor.

## 4.3 Otto and diesel engines

These motors are named for their inventors Nikolaus August Otto and Rudolf Diesel. Otto built the first atmospheric engine in 1863 and the first four-cycle engine. Diesel built his first motor in 1893 and. His third motor achieved an efficiency of 26.2 % in 1897.

The Otto engine works with **spark ignition**. The fuel is mixed with air before entering the cylinder which is known as **external mixture formation**. In order to prevent pre-ignition of the air-fuel mixture, the compression ratio cannot be too high. In diesel engines, **only air is compressed** which heats up as a result. Fuel is then injected into this hot air which then ignites on its own due to this heat of compression.

The **Diesel engine** is characterized by the **self-ignition** of the air-fuel mixture. The fuel is only injected into the cylinder shortly before the ignition point to prevent pre-ignition. In contrast to the Otto engine, the Diesel engine features **internal mixture formation**. In order for the fuel to ignite, the air in the cylinder must be at a very high temperature which can be reached with a **high compression ratio**. The air heats to about 700 °C during compression.

## 4.3.1 Design and operating principles of Otto and Diesel engines

In Otto engines, a combustible air-fuel mixture is created outside of the cylinder which is then ignited in the cylinder by controlled spark ignition using **spark plugs**. The air-fuel mixture is usually created by suction of the combustion gas in the carburetor. It is becoming more common for vehicles with Otto motors to use mechanically or electrically controlled fuel injection which injects liquid fuel in front of the intake valve. This technique results in better performance, less fuel consumption and cleaner exhaust fumes.

Otto motors can also use **gaseous fuels** that are also ignited by spark plugs. These gaseous fuels are stored in the vehicle in liquid form in a pressurized tank. Such vehicles are only used in regionally limited areas because the vehicles require a special fuel system that is often very heavy and because it can be difficult to find this special fuel outside of a few specific locations.

Engines that operate according to the principle developed by Diesel, which means that they do not use spark ignition, are called **Diesel engines**. These motors **suck in combustion air** that is then compressed, and thus, heated to the point that it ignites on its own when fuel is injected into the cylinder.

Otto and Diesel engines can operate in both **two-cycle** and **four-cycle** configurations. These processes will be covered in this unit.

The previously described engines are also known as **reciprocating engines**. Figure 31 illustrates such an engine alongside the most important terminology as well as a **working diagram** or **p,V diagram**.

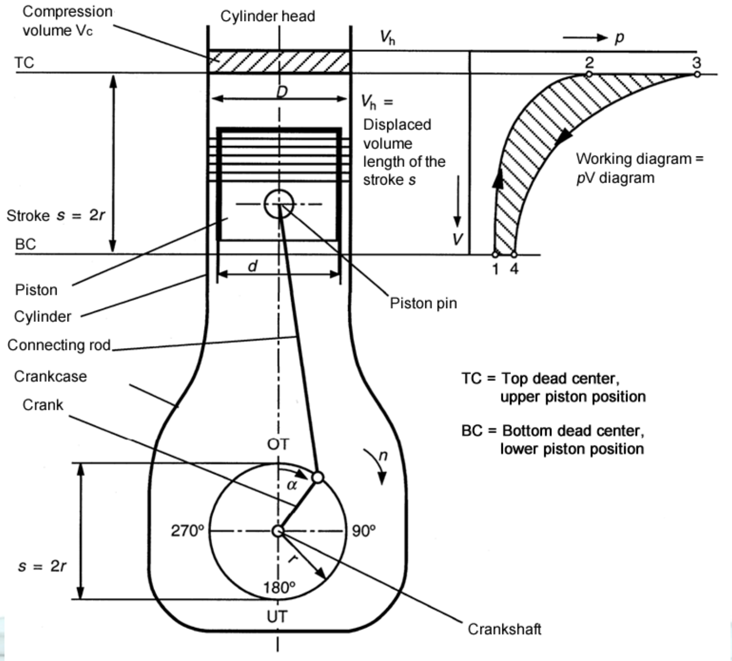


Figure 31: Terminology of reciprocating engines

| | |
|---|---|
| Note: | The space between the expansion lines and the compression lines in the p,V diagram is a measure of the change in volume caused by the piston $W_v$. |

**Example 4.1:**

The change in volume is calculated from the product of the pressure *p* and volume *v*. Deduce the unit of change in volume using this information.

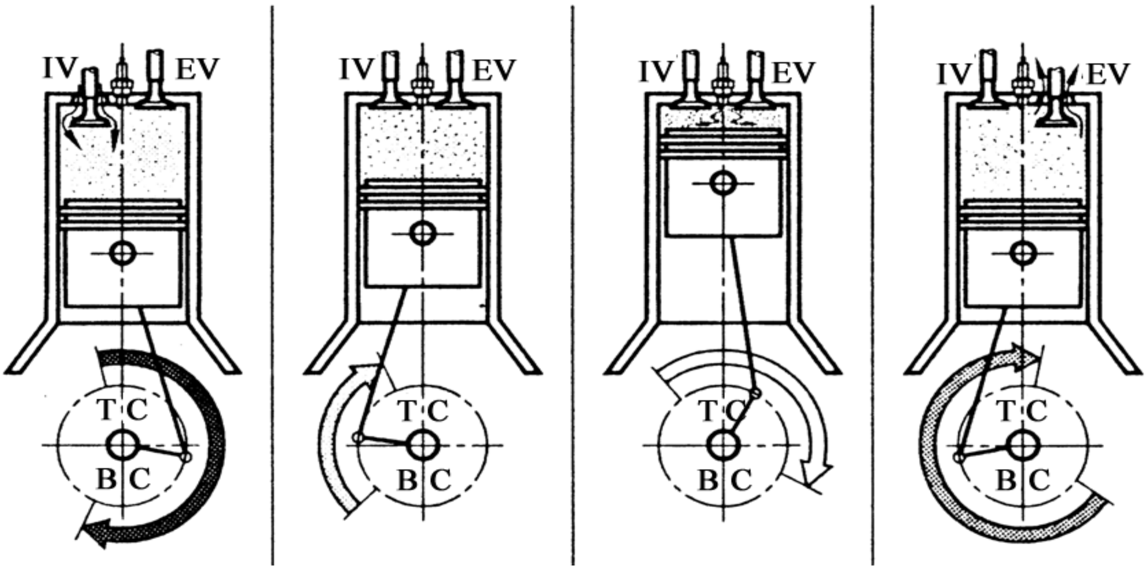
**Solution:**

$[W_v] = [p] \bullet [V] = \frac{N}{m^2} \bullet m^3$ = Nm → as a reminder 1 J = 1 Nm = 1 Ws

For many years, vehicles have also been made with r**otary piston engines** which, in honor of their inventor Felix Wankel, are also known as **Wankel engines**. These engines are relatively uncommon. The pistons in these engines have a rotary motion.

## 4.4 Four-cycle and two-cycle operation

Figure 32 illustrates the operating principle of a four-cycle combustion engine:



| $1^{st}$ cycle | | $2^{nd}$ cycle | | $3^{rd}$ cycle | | $4^{th}$ cycle | |
|---|---|---|---|---|---|---|---|
| Intake | | Compression | | Power | | Exhaust | |
| T<br>V<br>P | small<br>large<br>small | T<br>V<br>p | large<br>small<br>large | T<br>V<br>P | very large<br>small<br>very large | T<br>V<br>P | large<br>large<br>small |

Figure 32: Four-cycle process

In **four-cycle operation** an amount of gas corresponding to the defined cycle sequence travels through the engine. The variables that are constantly changing throughout the process are:

Temperature T    Volume V    Pressure p

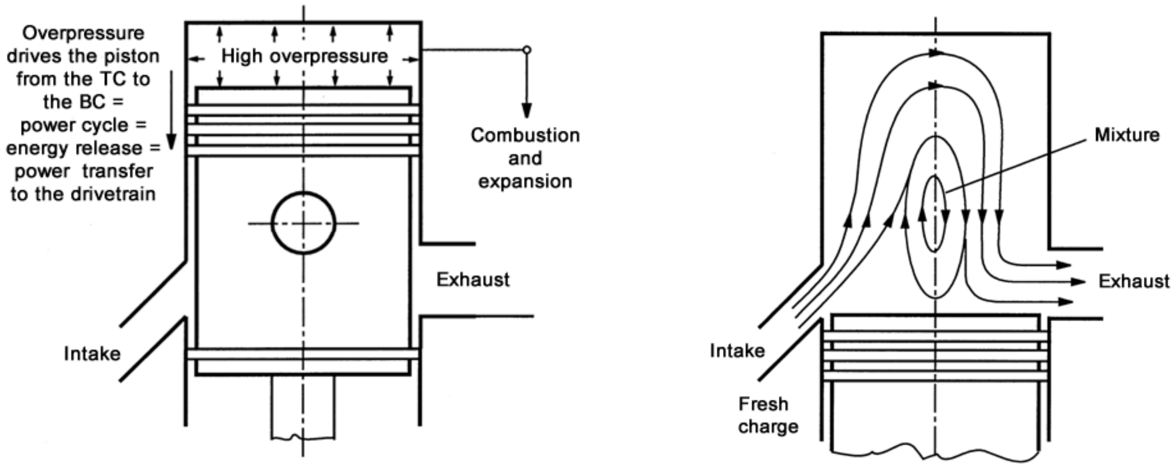
In this case, the **engine is controlled** by the **intake valve** (IV) and the **exhaust valve** (EV) which are both actuated by the **camshaft** which is mechanically connected to the crankshaft (usually with a **timing chain** or **timing belt**. The pistons are driven by the crankshaft and they travel between **top dead center** (TC) and **bottom dead center** (BC).

Note: In *four-cycle operation*, every fourth cycle is a power cycle.

1st cycle → Intake
2nd cycle → Compression
3rd cycle → Power
4th cycle → Exhaust

Note: In *two-cycle operation*, every second cycle is a power cycle.

This is made possible by **piston-controlled inlet ports** as illustrated by figure 33:



a) Combustion and expansion (power cycle)    b) Purge cycle

Figure 33: Two-cycle reciprocating piston engine

## 4.5 Fuels

We have already discussed that the material used to power a motor is called **fuel**. Fuels are divided into three types:

- **Solid fuels,**
- **Liquid fuels**
- **Gaseous fuels**

Solid fuel was used in the past in the form of **pulverized coal**. **Pulverized-coal motors** are only interesting in an historical context as they have no longer have any practical application.

Note: In the modern era, only liquid and gaseous fuels are used.

The most common gaseous fuel in use is hydrogen but there are other combustible gasses and mixtures that are either in use or are being tested. Liquid fuels are by far the most important and most common with a market share of over 99 %.

Fuels are produced from petroleum or natural gas which means that they derive from a variety of about 200 **hydrocarbons**.

## 4.5.1 Structural and chemical composition of hydrocarbons

We will be referring back to content covered in NTG 3. Hydrocarbons can be divided into the following categories:

a) **Saturated,** chained **hydrocarbons** with single bonds (Paraffins, Isoparaffins) $C_nH_{2n+2}$
b) **Unsaturated,** chained **hydrocarbons** with double bonds (olefins) $C_nH_{2n}$ and $C_nH_{2n-2}$Carbon rings with single bonds (naphthene)
c) Carbon rings with double bonds (aromatic hydrocarbons)

**Example 4.2:**

Propane is a saturated hydrocarbon with $n = 2.$ Write down the chemical formula of propane.

**Solution:**
The general formula is: $C_nH_{2n+2}$
With $n$ = 3, this becomes: $C_3H_{2\bullet3+2} = C_3H_{6+2} = C_3H_8$

## 4.5.2 Physiochemical properties

### Boiling point

This plays a role in fractional distillation. The boiling point increases with the same molecular structure with an increasing carbon number.

### Caloric value

The net caloric value $H_u$ and the gross caloric value $H_o$ (previously known as upper heat value) are measurements for the energy content of fuels. Normal hydrocarbons have $H_u$values between 40 and 45 MJ/kg.

**Density**

This helps in designating certain fuel types and/or components. The density increases with the carbon number. When the carbon number is the same, ring structures have higher densities then chain structures.

**Ignitability (cetane number = *CN*)**

This is a very important factor in determining how suitable a material would be as a fuel. This measurement indicates how easily an air-fuel mixture can ignite. Fuels for Otto motors should have a low ignitability quotient which increases the antiknock value.

A measure for the ignitability of for Diesel fuels is the **cetane number** (*CN*). This number is closely related to the ignition delay time which is the time between the start of injection and the pressure increase due to combustion.

Note: Diesel fuels should have high ignitability which translates to short ignition delay times.

A shorter **ignition delay time** (the more ignitable the fuel) translates to a higher cetane number which reduces the amount of fuel injected into the cylinder during the ignition delay time which reduces the pressure increase during combustion.
Fuels with a low *CN* (longer ignition delay time) will require that much more fuel be injected into the cylinder before ignition takes place. This results in a strong increase in pressure and sometimes in abrupt combustion and significant soot production.

The *CT* is standardized according to **DIN 51773.**

Note: Diesel fuel has a minimum cetane number of 45 and a maximum of about 55.

**Antiknock value (octane = *Oct.*)**

A measure for the **antiknock value** of Otto fuels is the **octane number** (ON). The larger the octane number is, the more resistant to knocking the fuel is. The *RON* (research octane number) indicates knocking during acceleration and the *MON* (motor octane number) indicates knocking when at high speeds. There is another measure called the *FON* (front octane number) that measures the *RON* of the portion of the fuel that dissolves into a vapor state during distillation at up to 100 °C. This is a reference point regarding knocking during acceleration. The *MON* is determined by preheating the fuel mixture in the testing motor. The rpm is higher and the ignition timing is a little earlier than with the *RON* which results in a higher thermal strain on the fuel. This results in the *MON* values always being lower than the *RON* values. Gas stations always show the *RON* number.

Table 11 presents an overview of the *RON* and *MON* values of normal Otto fuels.

Table 11: RON and MON values of Otto fuels

| Fuel type | *RON value* | *MON* value |
|---|---|---|
| Super unleaded | 95 | 86 |
| Normal unleaded | 90 | 82 |
| Super plus unleaded | 98 | 88 |
| Super leaded | 98 | 88 |
| Normal leaded | 91 | 83 |

Note: The cetane number and the octane number have an inverse relationship which means that as the *ON* increases, the *CN* decreases and vice versa.

**Rule of thumb for *ON*** OZ ≈ 120 – 2 • CT

**Example 4.3:**

A fuel has a *CN* value of 51. What is the *ON* value?

**Solution:**

$ON = 120 - 2 \cdot CN = 120 - 2 \cdot 51 = 120 - 102 = 18$

# 5. ENERGY DISTRIBUTION IN INDUSTRY

This unit covers the topic of the supply of energy in industry. Utility companies are the partners in making this possible.

Note: The supply of power refers above all to the supply of water, steam, compressed air, heat and electricity.

## 5.1 Water supply

We have already covered the water as a consumer product in NTG 3. Industry draws a distinction between **industrial water** and **drinking water**. Industrial water is often taken from rivers and lakes and must be prepared for its intended use. Drinking water is usually supplied by **public water utilities**. Every connection to a public water utility includes the following:

- The **connecting pipe** up to the water meter
- The **water meter**
- The **service pipes.**

If it is not possible to connect to a public water utility, the building will be supplied with water using compressed air. Industrial water is also often supplied in this manner which is illustrated in figure 34.

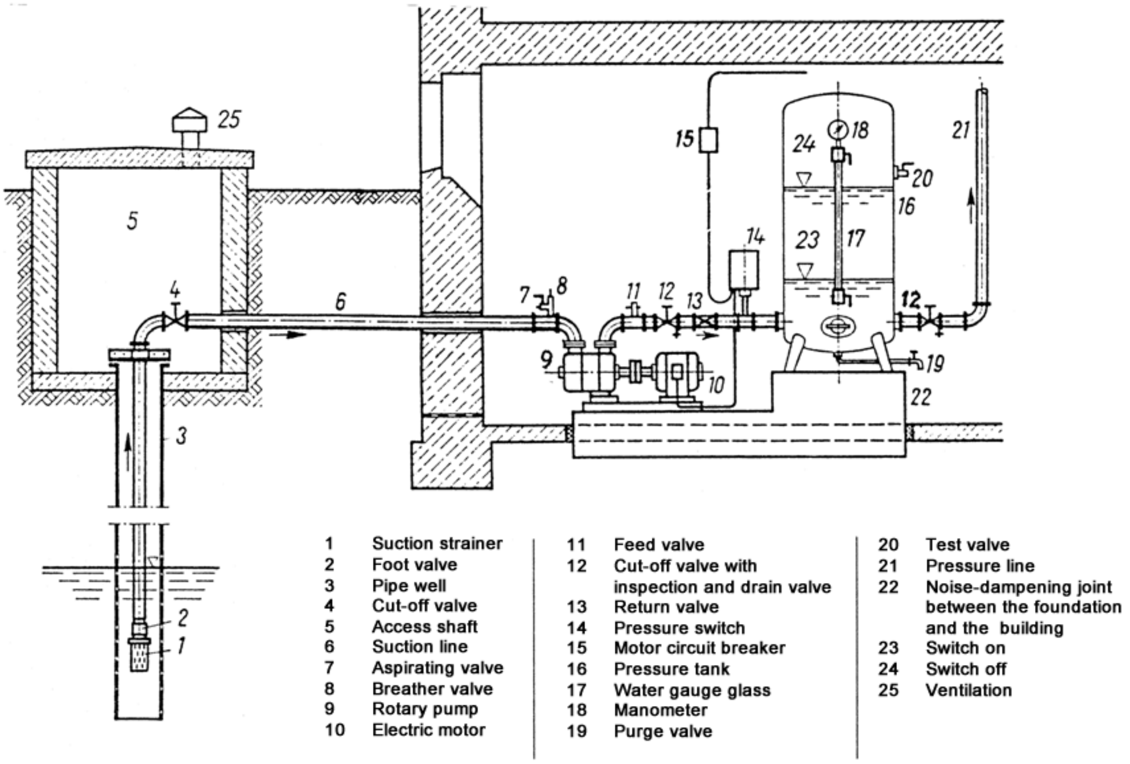


Figure 34: Compressed air water supply

## 5.2 Gas supply

Gas is often used for firing stations. This can be **natural gas** or **liquefied gas** such as propane. Due to the danger of explosions it is very important that **safety precautions** and **regulations** such as DIN norms, guidelines and other rules are followed.

Note: Industrial energy supply must always be carried out with special safety precautions.

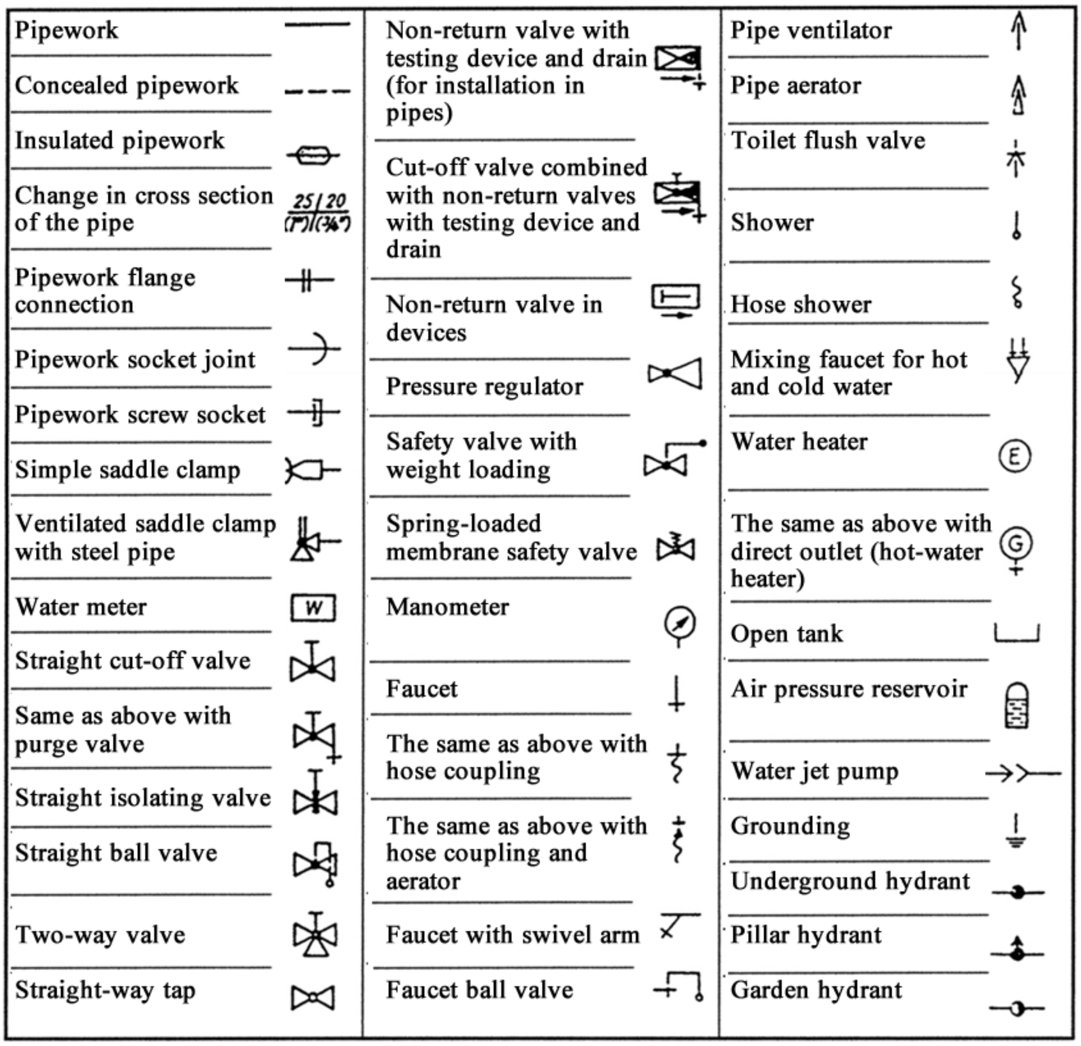
When dealing with gas or water, it is very important to follow the **regulations of the DVGW** (German Technical and Scientific Association for Gas and Water).

Note: The relevant regulations are the foundation for planning of new power supply facilities.

Relevant information can also be provided by the corresponding labor unions and public utilities. Technical drawings are subject to DIN standards of their corresponding fields such as water, gas, steam, and electricity.

Table 12 contains an excerpt from DIN 1988 for water installations.

Table 12: Symbols for water installations according to DIN 1988 (excerpt)



| | | | | | |
|---|---|---|---|---|---|
| Pipework | | Non-return valve with testing device and drain (for installation in pipes) | | Pipe ventilator | |
| Concealed pipework | | Cut-off valve combined with non-return valves with testing device and drain | | Pipe aerator | |
| Insulated pipework | | Non-return valve in devices | | Toilet flush valve | |
| Change in cross section of the pipe | 25/20<br>(1")/(¾") | Pressure regulator | | Shower | |
| Pipework flange connection | | Safety valve with weight loading | | Hose shower | |
| Pipework socket joint | | Spring-loaded membrane safety valve | | Mixing faucet for hot and cold water | |
| Pipework screw socket | | Manometer | | Water heater | E |
| Simple saddle clamp | | Faucet | | The same as above with direct outlet (hot-water heater) | G |
| Ventilated saddle clamp with steel pipe | | The same as above with hose coupling | | Open tank | |
| Water meter | W | The same as above with hose coupling and aerator | | Air pressure reservoir | |
| Straight cut-off valve | | Faucet with swivel arm | | Water jet pump | |
| Same as above with purge valve | | Faucet ball valve | | Grounding | |
| Straight isolating valve | | | | Underground hydrant | |
| Straight ball valve | | | | Pillar hydrant | |
| Two-way valve | | | | Garden hydrant | |
| Straight-way tap | | | | | |

[a] Flow direction →

[b] Abbreviations: S Steam, E Electricity, G Gas, C Coal, O Oil, W Hot or cold water

## 5.3 Supply of steam, heat and compressed air

Many physical laws must be considered when dealing with the supply of **steam, heat**, and **compressed air**. We will discuss some of these issues here but keep in mind that, as with the supply of water and gas, system specific rules and regulations must be taken into account. The following three important regulations are representative of the many other regulations that can apply:

- **Heat Insulation Ordinance,**
- **Heating Systems Ordinance,**
- **VDI guideline 2055:** “Thermal insulation for heated and refrigerated industrial and domestic installations”

## 5.4 Electrical energy supply

Electricity is a highly valuable form of energy that, as opposed to other forms of energy, can easily be converted into other types of energy such as heat (electric oven), light (lamps), chemical energy (charging a battery) or mechanical energy (electric motor).

The conversion of primary energy into electrical energy occurs in large power plants. The primary energy could be, for example, the chemical energy contained in coal, oil, natural gas, the bonding energy of atoms, the mechanical energy of a waterfall or the radiant energy of the sun.

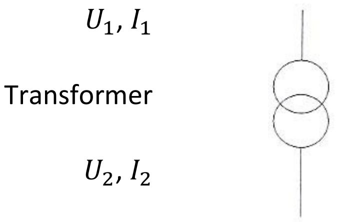
### 5.4.1 Electrical networks

### 5.4.1.1 Line voltages

The electricity generated in the power plant must be transmitted to the users via a network of power lines, substations and transformers. Transmission loss is kept small when the voltage is high and the current is therefore small. Multiple voltage levels are used in power transmission.

Depending on the voltage, power grids are divided into super grids, high-voltage networks, medium-voltage networks and low-voltage networks. The individual network levels are connected to each other via transformers.

The following principle applies for loss-free transformer transmission: $U_1 / U_2 = I_2 / I_1$



**Example 5.1:**

A transformer has a nominal voltage of 20kV at the input side (primary side) and a nominal current of 5.8 A. The nominal current of the output side (secondary side) is 400 V. What is the nominal current of the secondary side if there is lossless transmission?

$I_2$ = $U_1$ / $U_2$ * $I_1$
$I_2$ = 20,000 V / 400 V * 5.8 A
$I_2$ = 290 A

The *super grid* transmits electricity from the large power plants to the demand centers in the networks of the subordinate voltage levels. Furthermore it makes national and international exchange of electrical energy possible.

The nominal voltages of the super grid are 380 kV and 220 kV. The nominal voltage of the *high-voltage network* is predominantly 110 kV. This network is supplied with electricity from the super grid or from medium-sized power plants and supplies electricity to large scale industry and cities. These large scale customers have a power demand in the range of 5 MW – 50 MW.

The high-voltage network takes over power transmission duties in a few cases but is usually used for regional energy supply. The *middle-voltage networks* supply electricity to industrial enterprises, large commercial enterprises as well as small cities and communities. These networks supply nominal voltages of 10 kV, 20 kV and occasionally 30 kV. These networks are supplied from high-voltage networks and small power plants. The electricity demands of these customers are in the range of 500 kW – 5MW.

Low-voltage networks (local networks) are responsible for supplying electricity to business and standard customers (households, agriculture, small businesses) with a nominal voltage of 400 V. The local networks receive power from local network stations where middle-voltage power is converted to 400 V power.

The following rule of thumb applies to low-voltage networks:
The amperage can be approximately calculated by I = 1.5 · P

**Example 5.2**:

Power P = 200 kW
Amperage I = approximately 300 A.

The power is supplied in the form of three-phase alternating current. The alternating current network of the super, high and middle-voltage levels are equipped with 3 conductors while the low-voltage network is equipped with 4 conductors. The following pictures indicate the alternating current conductors using dashes.

Furthermore, figure 35 illustrates the individual voltage levels and their interaction with each other. The power companies decide which customers are special contract customers and which are standard customers.

### 5.4.1.2 Network structures

The reliability of the supply of energy is often a decisive economical factor for consumers of electricity. This results in the network structures being optimized to meet individual needs.

Electricity is often supplied over multiple lines from one or multiple sources depending on the required reliability of the supply of electricity.

There are two basic network frameworks:

- non-meshed networks
- meshed networks

Meshed means that the individual lines are interconnected.

In Germany, the super grid is intermeshed, the high-voltage network largely intermeshed while only portions of middle and low-voltage networks are intermeshed.

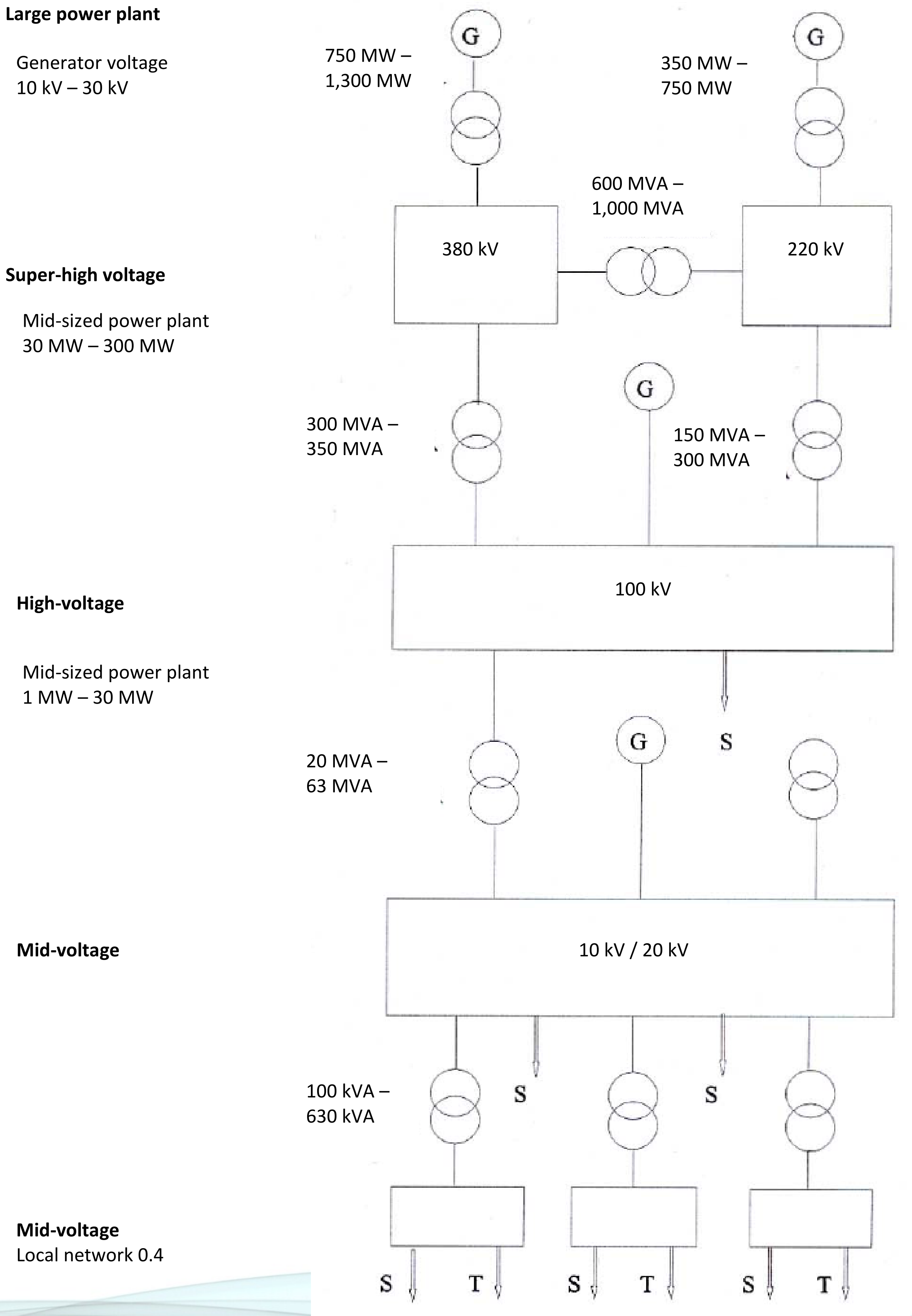


Figure 35: Overview of Germany’s electricity supply network
S = special contract customers, T – Standard customers

The non-meshed network, often called the radial network, is fed on one side and flows radially to the receiving connections. The supply point can be a substation or a node (figure 36).

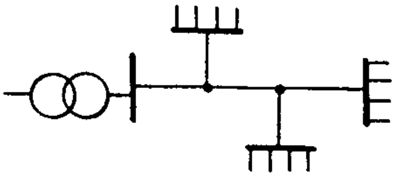


Figure 36: Radial network

Radial networks are easy to construct and monitor. The investment and maintenance costs are relatively low. A disadvantage is that the voltage decreases as the line progresses. Another disadvantage is the low reliability because if there is a problem with the supply or with a power line, the users down the line will be cut off from the network.

Intermeshed networks increase reliability because the recipients are supplied by at least two lines and sometimes with additional feeds. This allows a power line or a power feed to be taken off line in case of a malfunction. Furthermore, the voltage drop is smaller and the line loss decreases. Meshed networks are more difficult to monitor and the financial cost of their construction and maintenance is higher.

You can differentiate ring and meshed networks by the degree to which they are intermeshed. A ring network (figure 37) transmits electricity to the recipients via two routes. A ring network can also be expanded to include additional feeds.

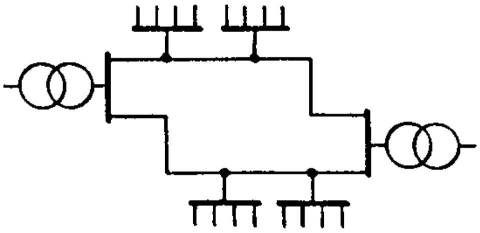


Figure 37: Ring network

A meshed network (figure 38) arises when a ring network is interlinked with additional connections.

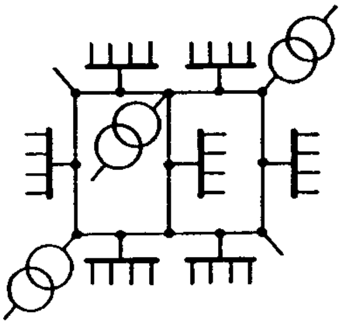


Figure 38: Meshed network

Meshed networks are often constructed but then separated during operation so that non-meshed branches are created. This allows the advantages of radial networks to be used when there are no operational problems. If there is a malfunction, the faulty portion of the network can be cut off and the users can be reconnected to the network by switching to another line.

## 5.4.2 Construction and operation of electrical networks

Public electricity networks are constructed and operated by the network operators. Private networks, including industrial networks and the electrical wiring in apartments or homes, are constructed and operated by the owners.

A host of safety regulations exist to prevent electrical accidents. Designers and operators of electrical systems are responsible for following all applicable laws, codes and regulations to ensure that electrical systems and devices do not cause any harm to people, animals or property.

The legal basis for these regulations is the **rules and procedures of the German Electrical Engineering Association (VDE)**. The rules, regulations and guidelines laid out by the VDE must be followed.

The fundamental VDE provisions are:

- For construction:
  VDE 0100 Erection of power installations with rated voltages below 1000 V
  VDE 0101 Erection of power installations with rated voltages above 1000 V

- For operation
  VDE 0105 Operation of power installations

Of the many applicable accident prevention provisions of the **Association of Commercial and Industrial Workers' Compensation Insurance Carriers**, BGV A1 and BGV A3 are especially important. According to the provisions of the VDE as well as the regulations set forth by the BGV, electrical systems can only be erected by **qualified electrical specialists**. This also applies to the operation of electrical systems.

The term “operations” includes:

- The observation of measurement values, warning alarms and monitoring systems
- Switching and control
- Inspections, repairs and maintenance
- Modification and expansion
- Commissioning

A business must ensure that electrical systems and equipment are erected, modified or repaired by qualified electrical specialists or by people under the supervision of such specialists so that all regulations and codes are adhered to.  The business must also ensure that the electrical systems and equipment are operated according to the all applicable rules and regulations. The business can transfer these obligations to an employee.

A **qualified electrical specialist** is someone who, because of his technical education, knowledge, experience and familiarity with the regulations relevant to the work that he has been given, can determine the possible dangers associated with the work he has been given. Years of experience in the applicable field of work are valid in place of a technical education.

An **electro-technically trained person** is someone who has been informed of the tasks that have been assigned to them and the associated dangers caused by improper work methods. They have also received training in the necessary safety systems and safety measures.

### 5.4.3 Securing the supply of energy in industry

Alongside the investments in erecting, modernizing or expanding electrical systems, the maintenance of these systems also plays a role in ensuring the supply of electricity.

**Maintenance** is therefore very important in minimizing the wear and tear of equipment, preventing damage to people and property as well as ensuring a reliable energy supply.

According to DIN 31051, maintenance includes all measures undertaken to maintain and restore equipment and systems to their optimal condition. Maintenance also includes the determination of the current state of said systems.

Maintenance is divided into the following three categories

- Inspection
- Maintenance
- Repairs

**Inspection** includes measures undertaken to determine the current state of electrical systems by taking measurements, checking error alerts and by performing visual inspections.

Maintenance or repairs can be ordered depending on the results of these inspections. **Maintenance** includes all measures taken to keep the condition of the systems at a consistent level. Typical maintenance work includes cleaning, lubricating and replacing wear parts such as bearings and seals.

**Repairs** include measures taken to restore a system to its standard condition. This usually means repairing or replacing components within these systems.

According to the accident prevention regulations in “BGV A3 - Electrical installations and equipment”, businesses are required to ensure that electrical systems and equipment are operated and maintained by qualified electrical specialists or by people under the supervision of such specialists so that all regulations and codes are adhered to. VDE 0105 and BGV A3 require that high-voltage installations be kept in line with construction standards, that damage be repaired as soon as possible (immediately if the damage causes any danger) and that the systems are inspected regularly. Inspection and maintenance work is to be carried out not only according to VDE provisions and accident prevention regulations, but also according to rules and regulations from government agencies and the relevant manufacturers.

Until now, maintenance has been performed as a preventative measure with strict deadlines and with a defined scope.  It should be noted that maintenance work does not always result in a reduction in malfunctions just because some equipment comes up as “defective” during inspections.

Modern maintenance ranges from **preventative to condition-oriented maintenance**. This requires a sophisticated inspection process but ends up saving money in the end.

### 5.4.4 Energy conservation

Energy conservation is the reduction in energy use through technical and organizational measures as well as personal behavior.

The most important ways to save energy are:

- Minimizing or avoiding energy use by, for example, not letting machines or equipment idle.
- Increasing the efficiency of systems and machines.
- Modifying procedures such as switching from combustion engines to electric motors.

Implementing energy circuits such as using exhaust heat.