

Physics of Nuclear Reactors

LWR Plants

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LWR PLANTS

5.1 Pressurizer in PWR

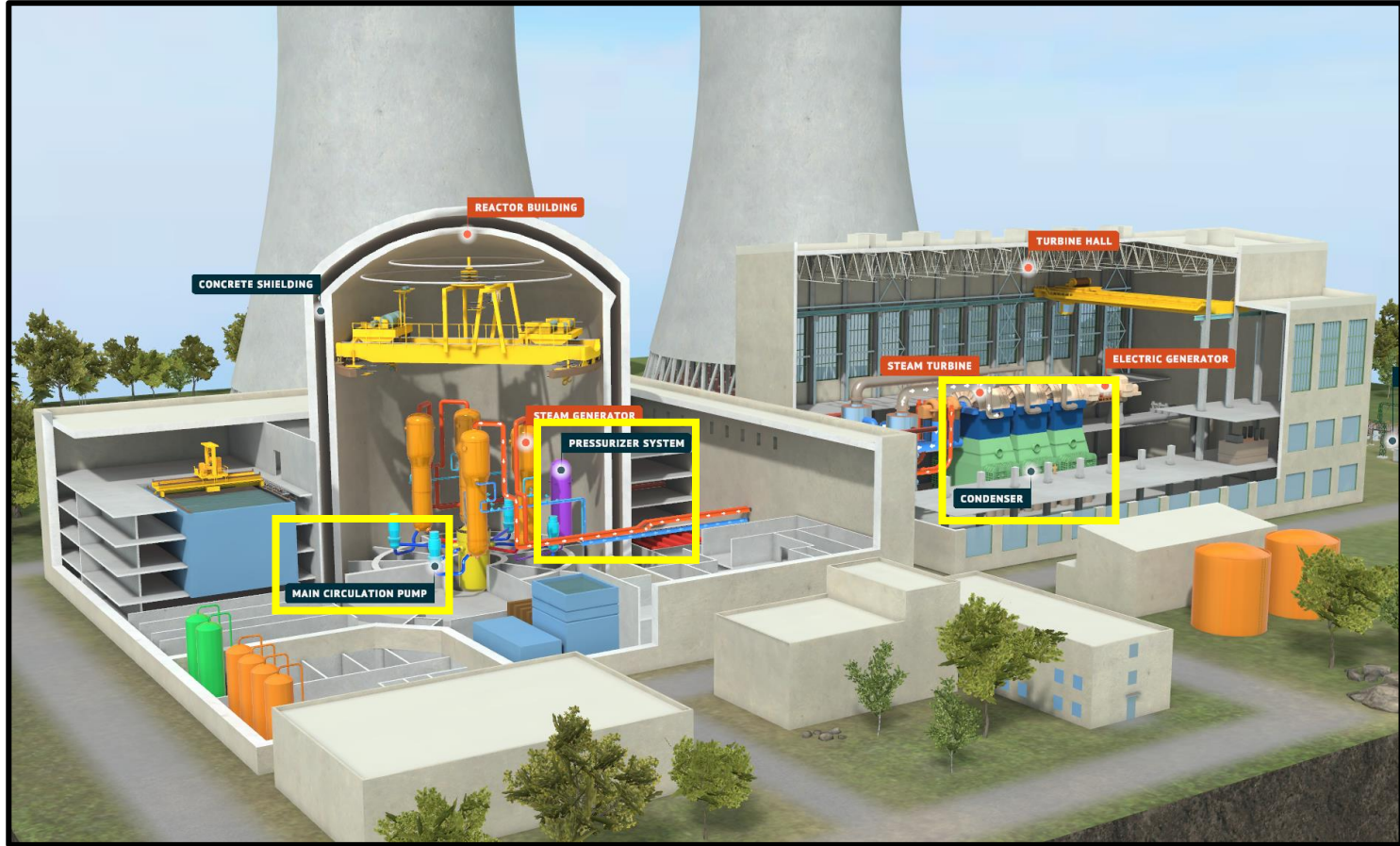
5.2 Power of a PWR main circulation pump

5.3 Energy balance on condenser

Divide in groups of 5:

- *you will solve the exercises in group*
- *we will correct them together at the board*

A typical PWR plant



1. Pressurizer in PWR

Exercise description:

Using the definition of isobaric thermal expansion and isothermal compressibility, explain why in a system completely filled with an incompressible fluid (e.g. water) subject to temperature variation there is a need for a pressurizer? Please use https://link.springer.com/chapter/10.1007/978-3-662-53219-5_5 for the numerical data.

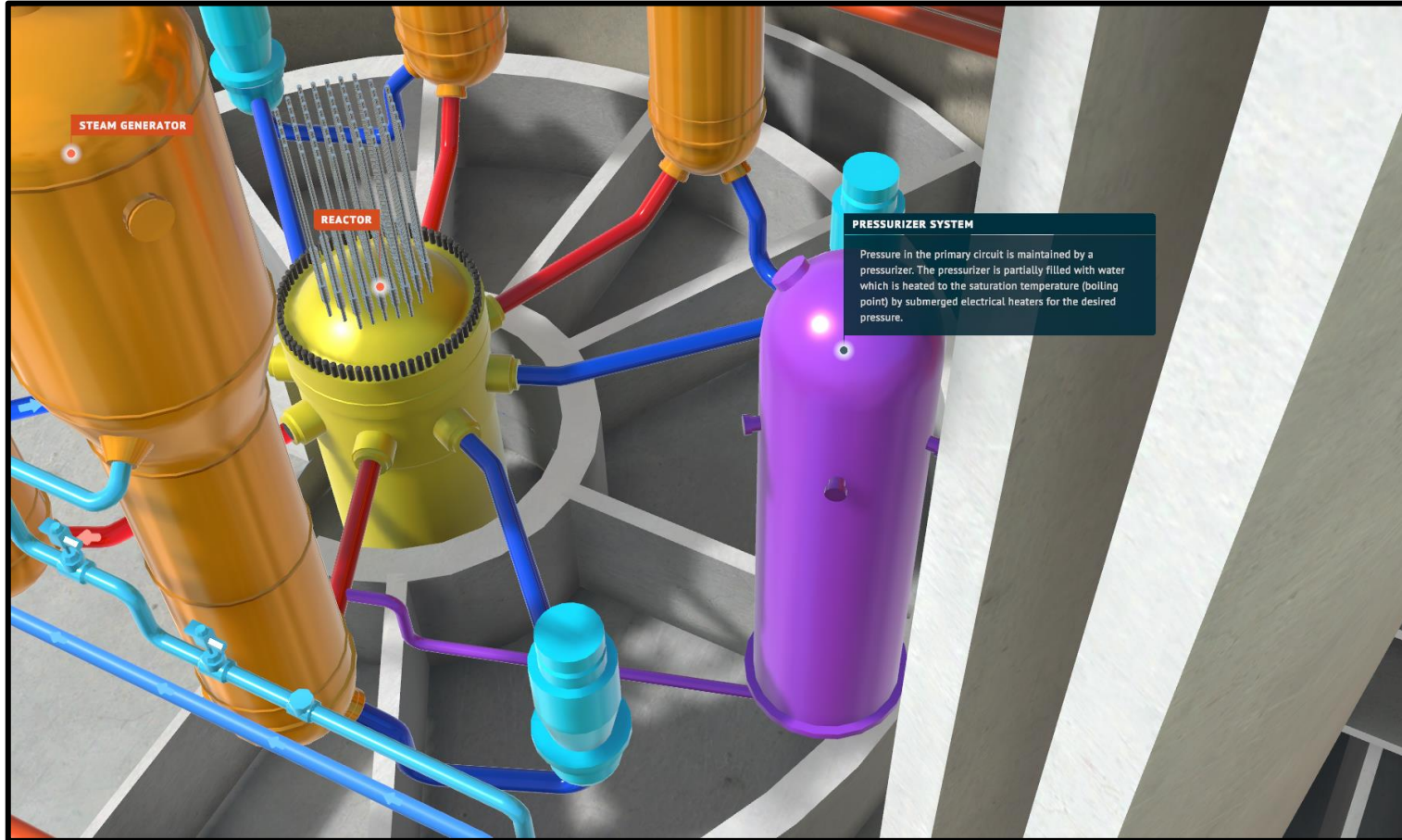
(a) A vessel having a cross-section A is filled with water at $T_0=323\text{K}$. The vessel is open. By means of a heater, the water temperature is increased by 5K . Estimate the variation of the water level in the vessel.

(b) A closed vessel is filled with water at an initial pressure of $p_0=1\text{bar}$ and an initial temperature $T_0=323\text{K}$. By means of a heater, the water temperature is increased by 5K . Estimate the variation of pressure in the vessel.

(c) A closed vessel is filled with a mixture of steam and water at an initial pressure of $p_0=1\text{bar}$ and an initial temperature $T_0=423\text{K}$. By means of a heater, the water temperature is increased by 5K . Estimate the variation of the pressure in the vessel.

Expected results: (a) 0.00229 (b) $\Delta P = 52\text{bars}$ (c) $\Delta P = 0.012\text{bars}$

1. Pressurizer in PWR



1. Pressurizer in PWR

- Given v as specific volume, i.e. $v = \frac{V}{M} = \frac{1}{\rho} [m^3/kg]$
- Definition of **isobaric thermal expansion**

$$\beta = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p$$

- Definition of **isothermal compressibility**

$$k = -\frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_T = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_T$$

Let's do the exercises first and then comment on why we need the pressurizer.

1. Pressurizer in PWR

- What kind of transformation is (a)?

(a) A vessel having a cross-section A is filled with water at $T_0=323\text{K}$. The vessel is open. By means of a heater, the water temperature is increased by 5K . Estimate the variation of the water level in the vessel.

$$\text{ISOBARIC } \beta = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p$$

$$\beta = 4.57 \times 10^{-4} \text{ K}^{-1} \text{ at 1bar and 50C for water}$$

- Then $\Delta V = V_0 \beta \Delta T$ and $\frac{\Delta V}{A} = \Delta h = \frac{V_0}{A} \beta \Delta T$ and finally $\frac{\Delta h}{h_0} = \beta \Delta T = 0.00285$

1. Pressurizer in PWR

- What kind of transformation is (b)?

(b) A closed vessel is filled with water at an initial pressure of $p_0=1\text{bar}$ and an initial temperature $T_0=323\text{K}$. By means of a heater, the water temperature is increased by 5K . Estimate the variation of pressure in the vessel.

ISOCHORE

$\kappa = 0.44e - 6 \text{ Pa}^{-1}$ at 1bar and 50C for water

- $dv = \left. \frac{\partial v}{\partial T} \right|_P dT + \left. \frac{\partial v}{\partial p} \right|_T dp = v\beta\Delta T - v\kappa\Delta p$
- V is constant so $\Delta v = V_0(\beta\Delta T - \kappa\Delta p) = 0$
- $\Delta p = \beta \frac{\Delta T}{\kappa} = 52\text{bars!}$

1. Pressurizer in PWR

- What kind of transformation is (c)?

(c) A closed vessel is filled with a mixture of steam and water at an initial pressure of $p_0=1\text{bar}$ and an initial temperature $T_0=423\text{K}$. By means of a heater, the water temperature is increased by 5K. Estimate the variation of the pressure in the vessel.

ISOCHORE

for steam at 150 C, $\beta = 2452.4e - 6 K^{-1}$ and $\kappa = 10086e - 6 Pa^{-1}$

- $\Delta p = \beta \frac{\Delta T}{\kappa} = 0.012\text{bars}$

1. Pressurizer in PWR

- What kind of transformation is more representative of a **pressurizer**?

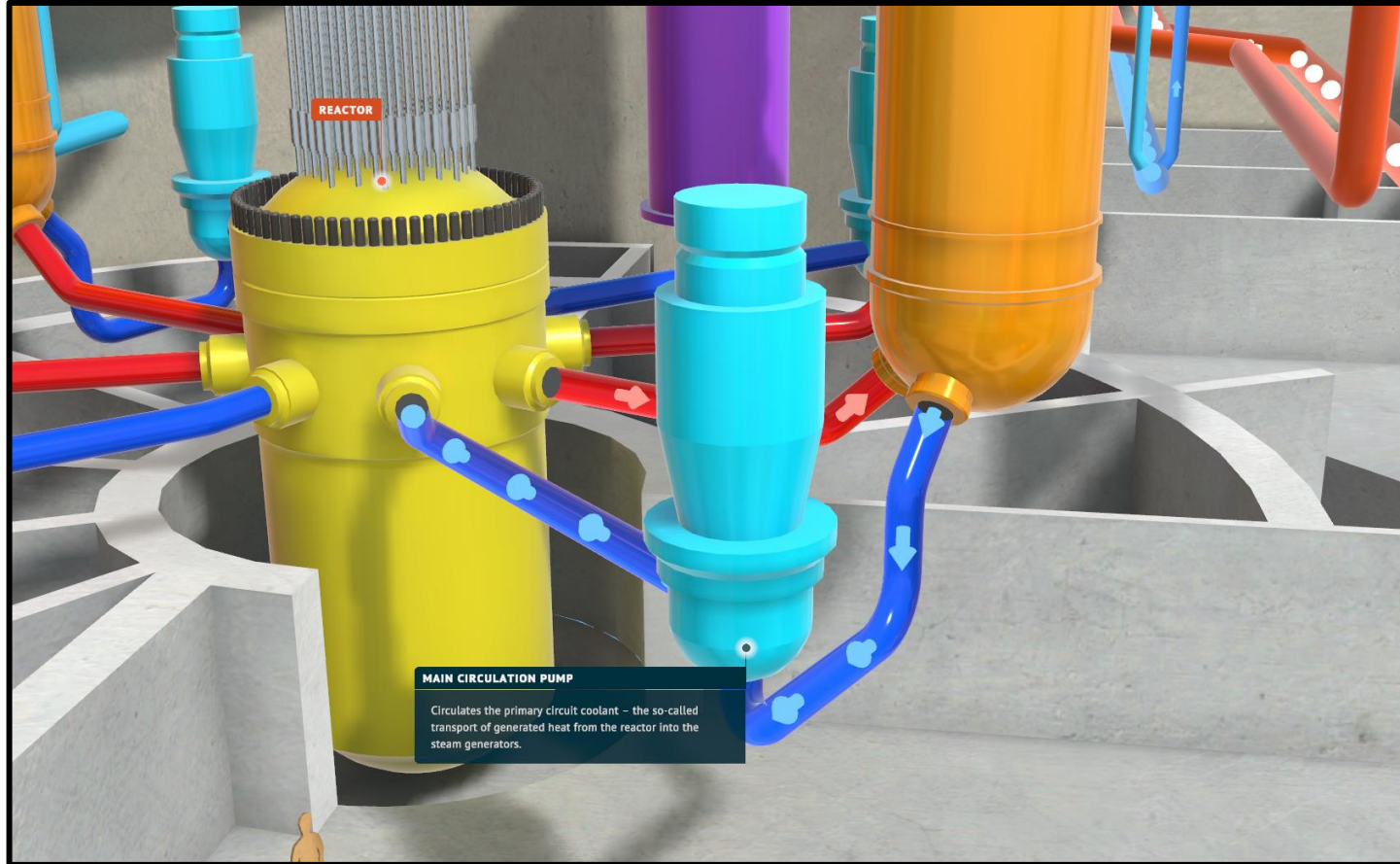
(C)

- So why do we **need** a pressurizer?

To avoid large pressure changes in the system in case of temperature rise, a pressurizer, e.g. a closed volume connected to the primary coolant loop, is needed.

$$\Delta p = \beta \frac{\Delta T}{\kappa} = 0.012 \text{ bars}$$

2. Power of a PWR main circulation pump



2. Power of a PWR main circulation pump

Exercise description:

Consider a typical 1300 MWe PWR at 155 bar, with thermal power of 3817 MWth, with temperature in cold leg and hot leg of $T_{CL} = 290$ °C and $T_{HL} = 320$ °C respectively. Knowing that there are 4 main loops and therefore 4 main circulation pumps and considering that the pressure drop across a loop is of 8 bar, compute the power needed to operate one main circulation pump. Assume a pump efficiency of 80%.



How much of the electrical output of a PWR is needed for the recirculation pumps?

2. Power of a PWR main circulation pump

- Given $P_{th} = 3817 \text{ MW}$, $P_{el} = 1300 \text{ MW}$, $T_{in} = 290^\circ\text{C}$, $T_{out} = 320^\circ\text{C}$
- $N_{loop} = 4$, $c_p = 4.1 \times 10^3 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$
- The **mechanical power** of the pump

$$P_{m,pump} = \eta P_{e,pump} = \frac{\dot{m}}{\rho} (\cancel{\rho g \Delta H} + \Delta P_p)$$

Gravitational pressure change is zero in this case

- We can compute **the core flowrate** as follows

$$\dot{m}_{core} = \frac{P_{th}}{c_p \Delta T} = 31000 \text{ kg/s}$$

$$\dot{m}_{loop} = \frac{\dot{m}_{core}}{N_{loop}} = 7758 \text{ kg/s}$$

- We can use **the loop flowrate** to get the electrical power of the pump

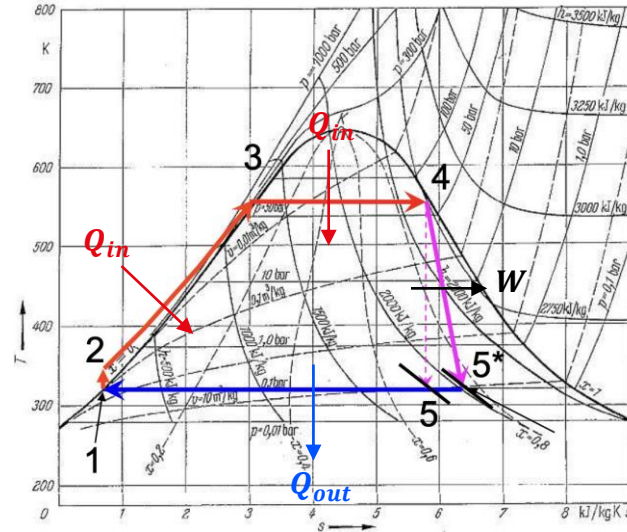
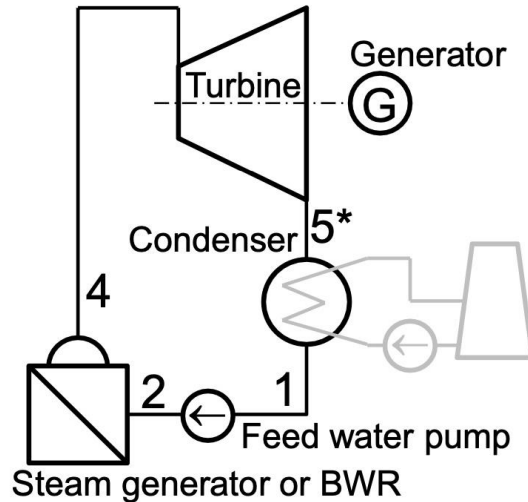
$$P_{e,pump} = \frac{\dot{m}_{loop} \Delta P_p}{\eta \rho} = 7.76 \text{ MW}$$

- In total, the 4 circulation pumps require **2%** of the electrical power of a PWR (i.e. 31 MW).

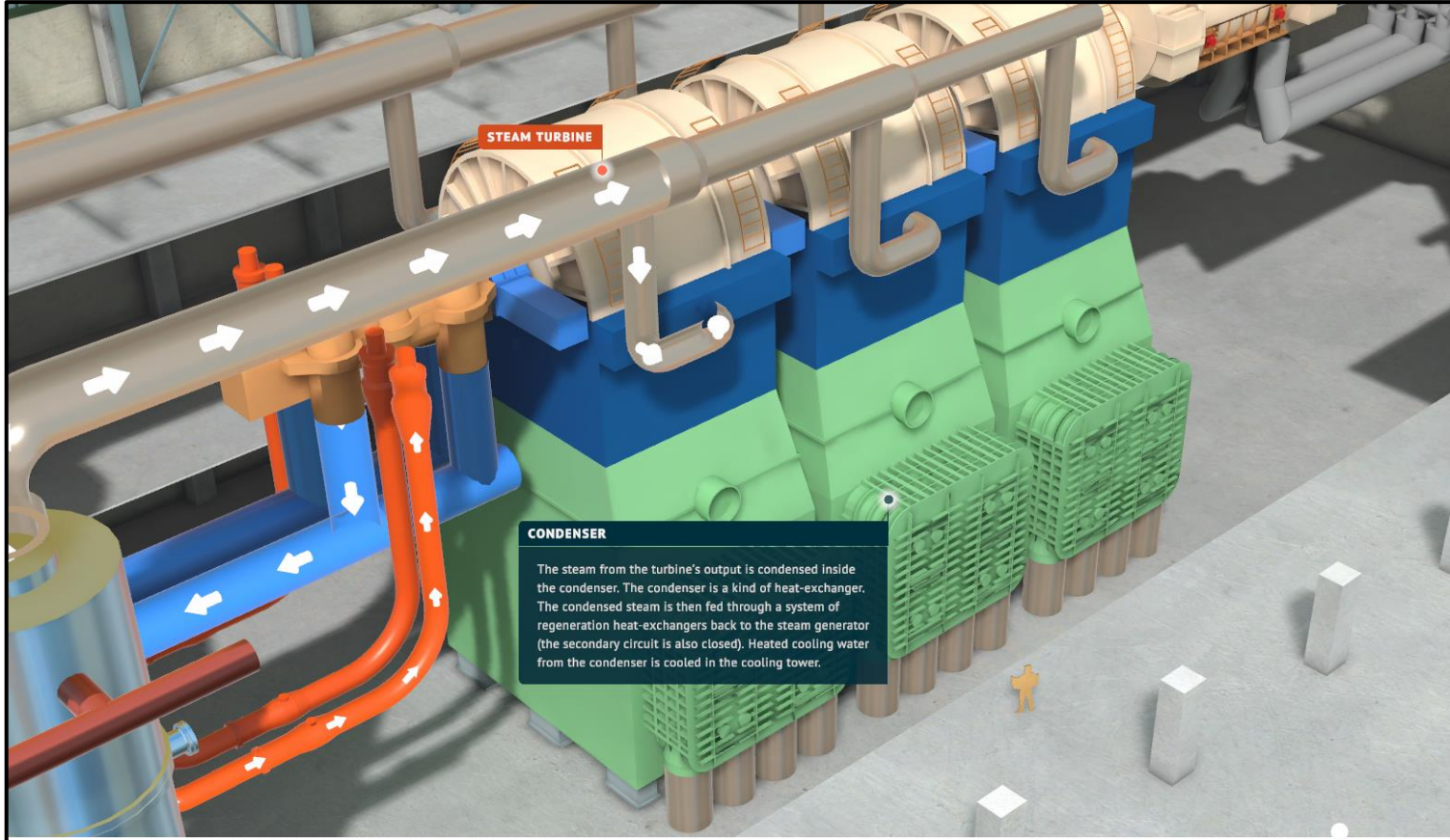
3. Energy balance on condenser

Exercise description:

Consider a 900 MWe reactor with a Rankine cycle efficiency of about 30%. Knowing that, for environmental reasons, the temperature increase on the secondary side of the condenser cannot exceed 10 K, compute the mass flow-rate needed for the secondary side of the condenser.



3. Energy balance on condenser



3. Energy balance on condenser

- Given $P_{el} = 900 \text{ MWe}$, $\eta_{plant} = 30\%$, $\eta_{cycle} = 30\%$, $c_p = 4.2 \times 10^3 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$, $\Delta T = 10 \text{ K}$
- We can compute the thermal power of the reactor:

$$P_{th} = P_{el}/\eta_{plant}$$

- We can compute **the flowrate of the secondary side, considering the definition of cycle efficiency** as follows. Q_H is the thermal power of the reactor ($= P_{th}$), Q_C is the power dumped in the condenser.

$$\eta_{cycle} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - Q_C/Q_H$$

- Q_c is the energy dumped in the condenser, 70% of the reactor power

$$\dot{m}_{sec} = \frac{P_{th} * (1 - \eta_{cycle})}{c_p \Delta T} = 50000 \text{ kg/s}$$