Heat Transfer & Thermodynamics in Nuclear Reactors

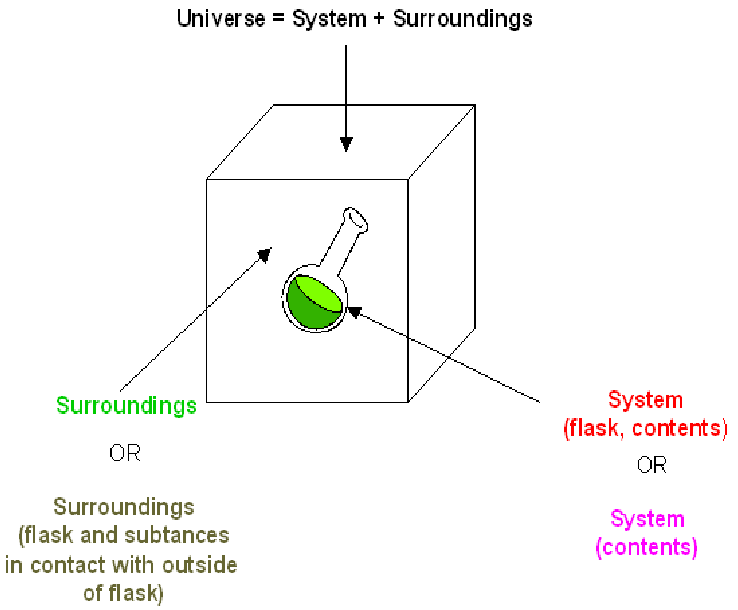
Dr. Ugur GUVEN

Heat Transfer Principles

- The most important mechanism in Nuclear Reactors is the concept of heat transfer.
- The amount of heat that is transferred determines the amount of work that the nuclear reactor is able to achieve.
- Standard rules of thermodynamics and heat transfer apply to nuclear reactors
- You want the nuclear reactor to produce as much heat as possible for higher efficiency

Laws of Thermodynamics

- The first law, also known as Law of Conservation of Energy, states that energy can not be created or destroyed; it can only be redistributed or changed from one form to another.
- The second law of thermodynamics says that the entropy of any isolated system not in thermal equilibrium almost always increases.
- The third law of thermodynamics states that the entropy of a system approaches a constant value as the temperature approaches zero.



Thermodynamic Work and Heat

The change in internal energy of a system is equal to the heat added to the system minus the work done by the system.

$$\Delta U = Q - W$$

Change in internal energy

Heat added to the system

Work done by the system

Isothermal and Adiabatic Process

- An **isothermal process** is a change of a *system*, in which the temperature remains constant: $\Delta T = 0$. This typically occurs when a system is in contact with an outside thermal reservoir (heat bath), and the change occurs slowly enough to allow the system to continually adjust to the temperature of the reservoir through heat exchange.
- In contrast, an ***adiabatic process*** is where a system exchanges no heat with its surroundings ($Q = 0$). In other words, in an isothermal process, the value $\Delta T = 0$ but $Q \neq 0$, while in an adiabatic process, $\Delta T \neq 0$ but $Q = 0$.

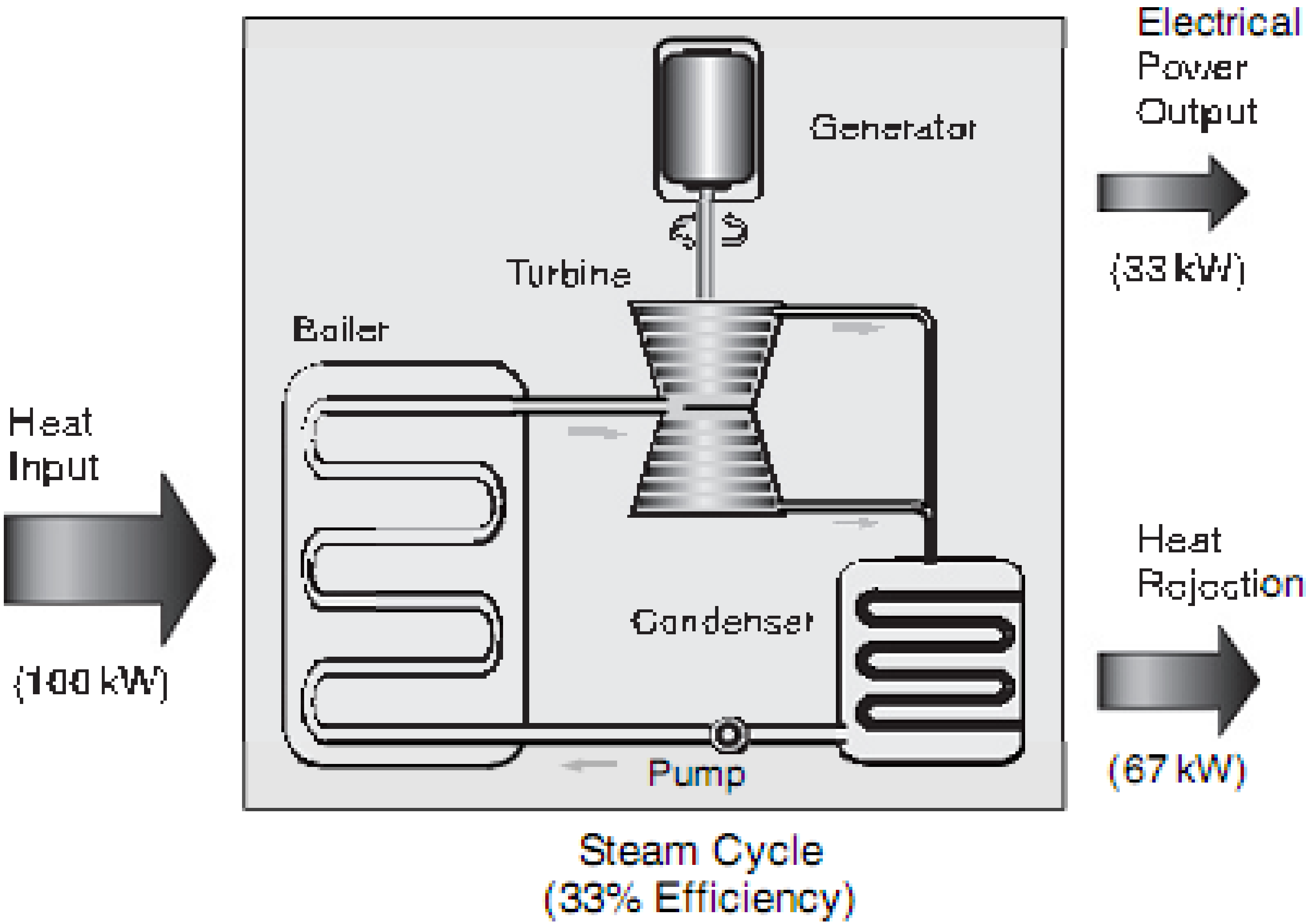
Thermodynamic Principles

- Nuclear Reactors work with the same objective of creating work through heat
- The amount of heat that is harnessed can be transformed to work through various thermodynamic processes.
- The percentage of conversion from heat to work determined the thermodynamic efficiency of the reactor

$$\mathrm{Eff}_{\mathrm{thermal}} = \text{Net Work Produced} / \text{Heat Input}$$

$$= (Q_H - Q_L)/Q_H = 1 - Q_L/Q_H$$

Standard Steam Cycle



Carnot Cycle

- If a nuclear power plant is to be taken as an ideal machine, then the best way to ideally create work out of heat would be the Carnot Cycle.
- Carnot Cycle is an ideal heat engine
- It is a well known fact that for the best thermal efficiency of a heat engine, it is essential to increase the temperatures of the heat input, while decreasing the temperature of the rejected heat.
- Hence, the equation for the efficiency of the Carnot cycle is shown by:

$$Eff_{Carnot} = 1 - T_L / T_H$$

Efficiency Sample Problem

- If the heat generator produces heat at 300 degrees Celsius and if the cooling water for the condenser comes from a source with 20 degrees Celsius, then the efficiency would be

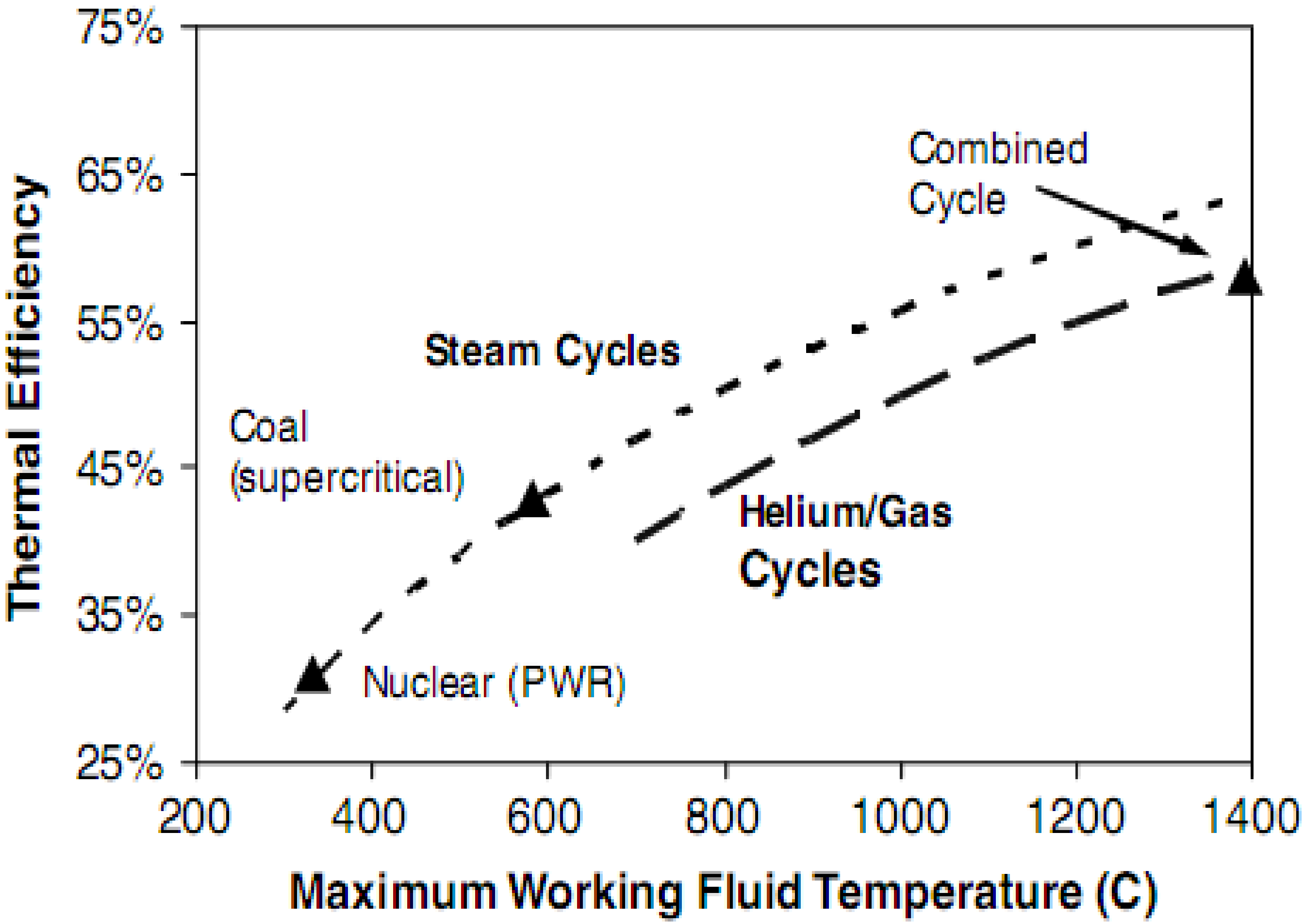
$$e = 1 - 293/573 = 0.49.$$

$$\mathrm{Eff}_{\mathrm{Carnot}} = 1 - \mathrm{T_L}/\mathrm{T_H}$$

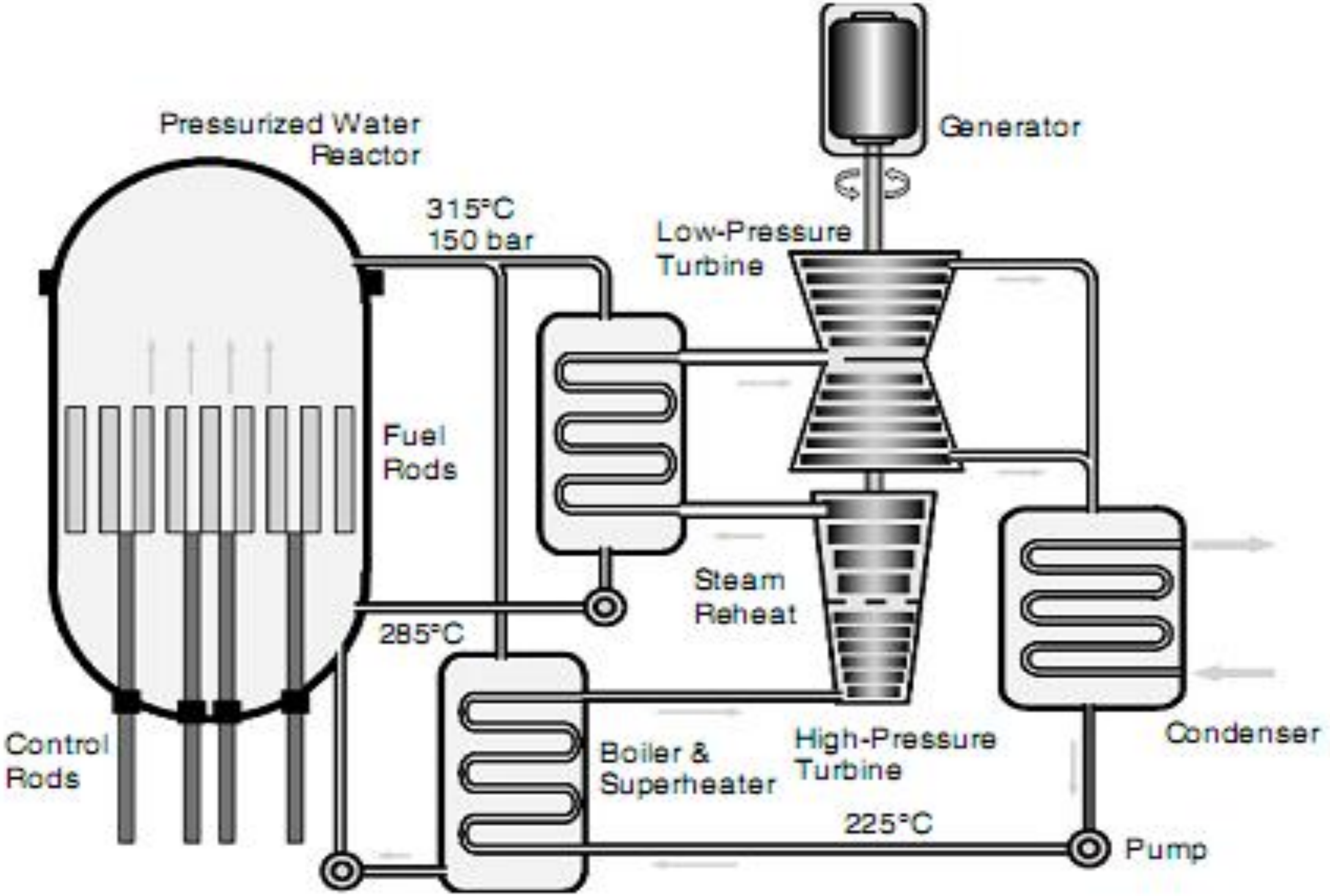
Carnot Cycle

- This is why commercial nuclear power plants (or any thermal power plant for that matter) are placed near environmental lakes and large water sources, so that the waste heat can be dissipated without a large increase in the environmental temperature T_L. Obviously, T_L will be higher in summer times or in hot geographical locations causing the efficiency of the heat cycle to be lowered.
- But, for the majority parts of the world, T_L will be changing within a reasonable frame of 20^o C to 35^o C. to **Thus, for all intents and purposes you can't change the efficiency of the nuclear reactor with T_L and so the only variable that you can really play with is the T_H or the high temperature of the heat reservoir.** Hence, increasing the heat will always increase the efficiency of an ideal Carnot cycle for which most power plants are modeled after.

Thermodynamic Cycle Efficiency (Ideal)



Pressurized Water Reactor



Heat Transfer Mechanisms

- The main heat transfer mechanisms are:

  1) Conduction

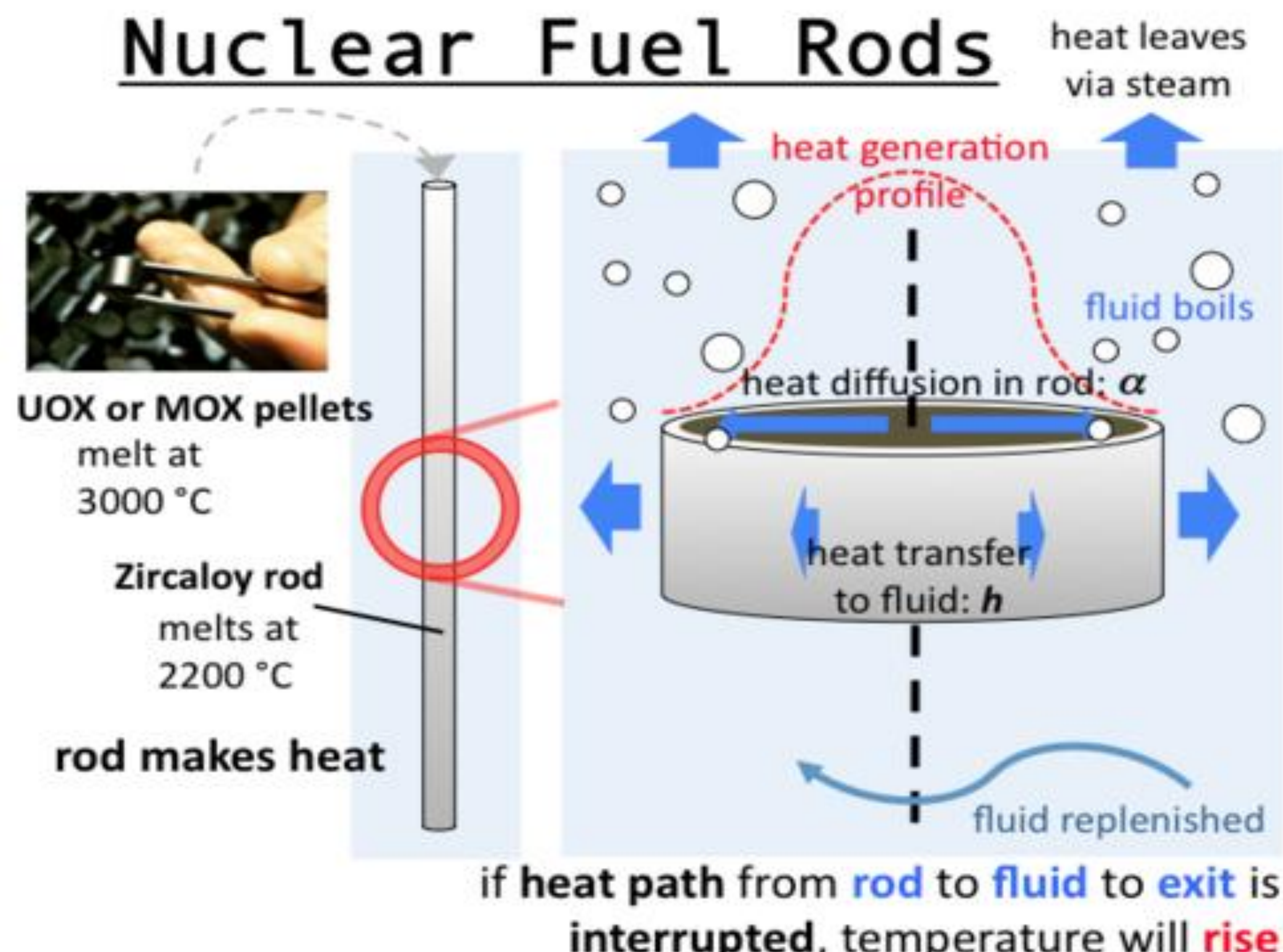
  2) Convection

  3) Thermal Radiation

Heat Transfer

- **Conduction or diffusion**: The transfer of energy between objects that are in physical contact.
- **Convection**: The transfer of energy between an object and its environment, due to fluid motion.
- **Radiation**: The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation.
- **Advection**: The transfer of energy from one location to another as a side effect of physically moving an object containing that energy. (like putting a bottle of iced water in a room)

Heat Transfer in the Fuel Rod



Heat Transfer in Nuclear Reactors

- As the nuclear reaction takes place, the fuel rods transfer heat to each other and to the rest of the reactor core that they are in contact with by conduction.
- As the coolant takes the heat from the fuel rods, the heat is transferred to the coolant by convection.
- Some of the heat is transferred by radiation as electromagnetic energy is heated away from the fission reaction to the coolant as well as to the solid body of the reactor core.

Heat Transfer in Fuel Rod

- Let the rate of supply of thermal energy by fission to be uniform throughout the rod. If the rod is long in comparison with its radius R, then most of the heat flow is in the radial direction.
- If the surface is maintained by temperature Ts by the flow of the coolant, then the temperature at the center of the rod To must be higher.

$$T_o - T_s = \frac{q_1}{4\pi k} = \frac{R^2 q}{4k}$$

Problem 1
Heat Transfer in Fuel Rods

- Calculate the temperature difference for a reactor fuel rod with radius of 0.5 cm at a point where the power density is q=200 W/cm^3. Take conductivity of U02 as k=0.062 W/cm.C

$$T_o - T_s = \frac{q_1}{4\pi k} = \frac{R^2 q}{4k}$$

- To-Ts = ((0.5)^2)(200) / (4 * 0.062)
- Hence we get:

  To-Ts = 201.61 Celsius

Reactor Thermal Power

- As coolant flows along the many channels surrounding fuel pins in a reactor, it absorbs thermal energy and rises in temperature.
- If coolant of specific heat c enters the reactor at temperature Tc(in) and leaves at Tc(out) then the reactor thermal power is:
- Where M is coolant flow in kg/s

$$P = cM(T_{c-out} - T_{c-in})$$

Problem 2

- If the mass flow rate of a nuclear reactor with 3000 MW power is 19,800 kg/sec and if water enters at 300 degrees Celsius calculate the temperature at which the water leaves. Take specific heat of 6.06 x 10^3 J/kg-C

$$P = cM(T_{c-out} - T_{c-in})$$

- With the equation above:

  19,800 = (3000 x 10^6)/((6.66 x 10^3)(300-T))

  T(out) = 325 C

Coolant Mass Flow for PWR

- If we calculate the condenser coolant mass flow for a reactor with Rate M, we can use the following formula where P is power:

$$M = \frac{P}{c\Delta T};$$

- Coolant flow will be received in terms of kg/sec. You can turn this to volume flow rate by dividing into specific gravity multiplied by 1000. You will get the rate in meter cube per second.

Problem 3

- Convert the volume flow rate in the previous problem to liters per minute. Take specific gravity of 0.687

- V=(19800 kg/s)/(687 kg/m^3) = 28.8 m^3/s

  Since 1 min = 60 sec

  V= 28.8 x 60 = 1728 m^3 / min

  1 m^3 = 1000 liters

  V= 1,728,000 liters per minute

Waste Power

- A nuclear plant operating at electrical power 1000 MWe with an efficiency of 33% would have a thermal power of

  1000 / 0.33 = 3030 MWt

  Thus, it must reject a waste power of

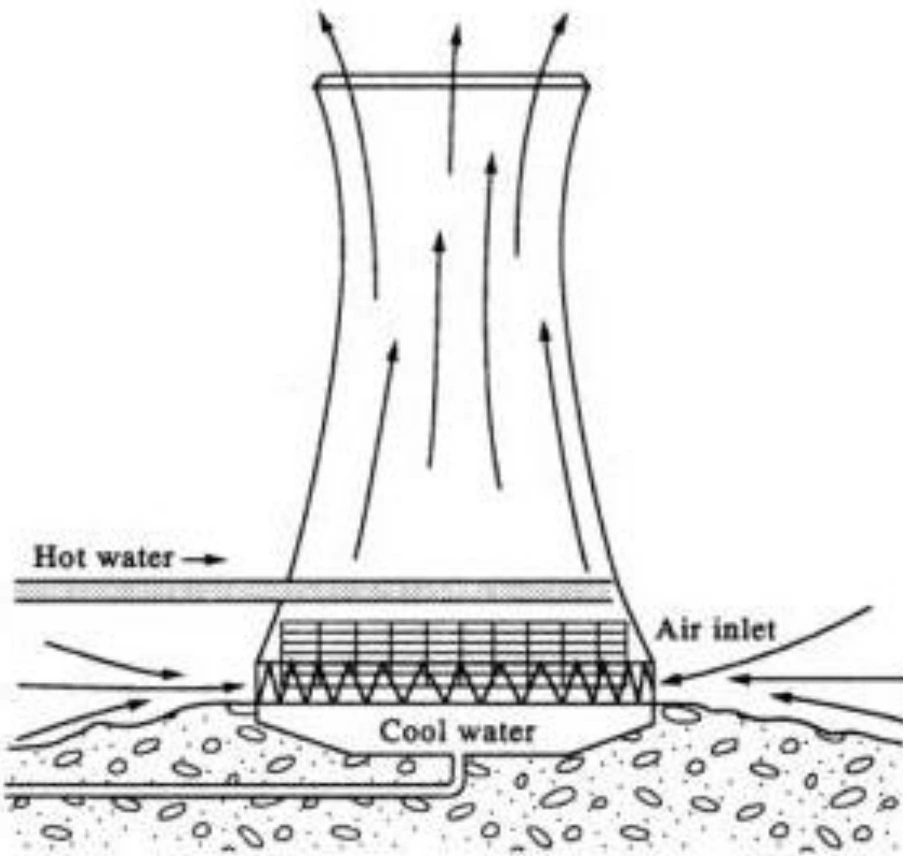
  P= 2030 MWt

- This waste power is lost as internal energy and as waste heat. It is transferred to coolant and then to coolant towers for discharge into atmosphere and / or to the body of water.

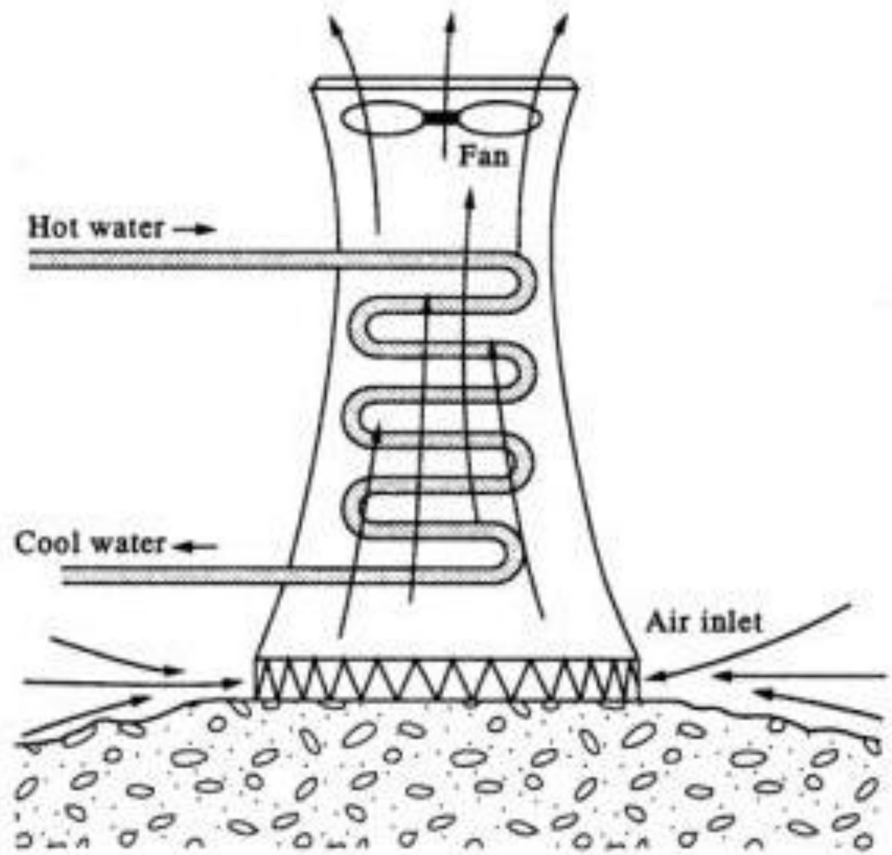
Cooling Towers

- Waste heat is extracted to the atmosphere by cooling towers in nuclear reactors. Usually, water vapor is given out.

Cooling Tower Structure



(a) "wet" (evaporative)



(b) "dry" (air flow)

Heat in Reactor Shutdown

- Even when the reactor is shut down, there will be some heat that is being generated by the fuel rods. The amount of heat that is generated even after shutdown will occur for some time.
- It is essential to keep the coolant circulating even after the reaction has been stopped in order to protect the reactor containment from having a steam explosion or from having a meltdown.