Basics on Nuclear Power

VVER 440 Loviisa, Finland

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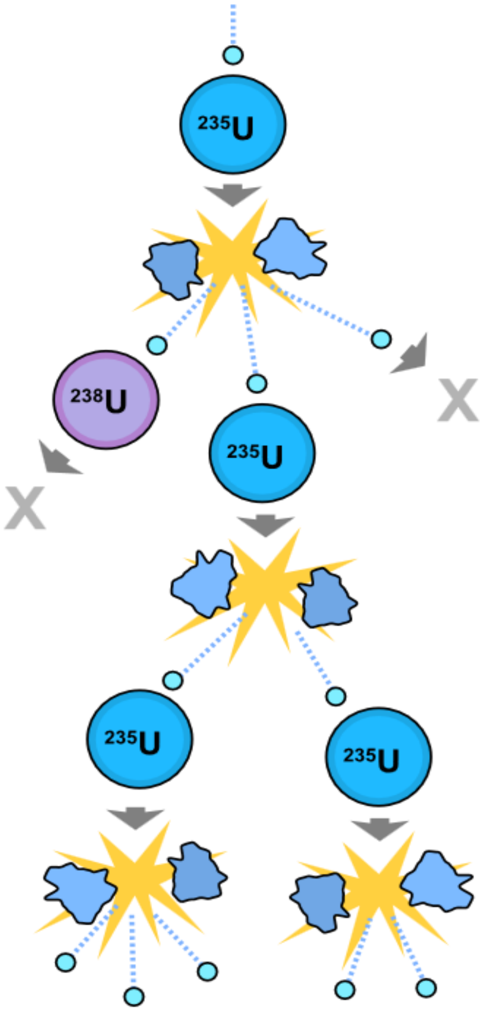
Integrity of Nuclear Structures - Material Degradation and Mitigation by NDE
TPU Lecture Course 2014/15

Basics on Nuclear Power

1. Introduction to Structural Reliability in Nuclear Engineering

Nuclear Fission



① A uranium-235 atom absorbs a neutron,
and fissions into two new atoms (fission fragments),
releasing three new neutrons
and some binding energy.

② One of those neutrons is absorbed by an atom of uranium-238, and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy.

③ Both of those neutrons collide with uranium-235 atoms, each of which fission and release between one and three neutrons, and so on.

Nuclear power plants operate by precisely controlling the rate at which nuclear reactions occur

Nuclear Fission

Mass of released energy

$$\frac{E}{c^2} = m_{\text{original}} - m_{\text{final}}$$

For thermal neutrons:

$$^{235}\text{U} + \text{neutron} \rightarrow \text{fission fragments} + 2.4 \text{ neutrons} + 192.9 \text{ MeV}$$

$$^{239}\text{Pu} + \text{neutron} \rightarrow \text{fission fragments} + 2.9 \text{ neutrons} + 198.5 \text{ MeV}$$

k

Criticality

Prompt neutron lifetime *l*:

Average time between the emission of neutrons
and either their absorption in the system or their escape from the system.

For thermal fission reactors: ***l* ~ 10^{-4} sec**

For fast fission reactors: ***l* ~ 10^{-7} sec**

Mean generation time Λ:

Average time from a neutron emission to a capture that results in fission.
The two times are related by the following formula:

Effective neutron multiplication factor *k*

$$\Lambda = l/k$$

k is the average number of neutrons from one fission
that cause another fission.

Criticality

A nuclear chain reaction proceeds:

k* < 1 sub-critically:* The system cannot sustain a chain reaction.
An average *total* of 1/(1 − *k*) fissions occur.

***k* = 1 critically:** Every fission causes an average of one more fission, leading to a fission (and power) level that is constant. Nuclear power plants operate with *k* = 1 unless the power level is being increased or decreased.

***k* > 1 super-critically:** For every fission in the material, it is likely that there will be "*k*" fissions after the next *mean generation time.*
Fission reactions increases exponentially, according to the equation , where t is the elapsed time:

$$N_f = e^{(k-1)t/\Lambda}$$

Prompt and Delayed Neutrons

Prompt Neutrons n_p:
Occur directly from fission

Delayed Neutrons n_d:
Result from radioactive decay of fission fragments

The delayed neutrons allow a nuclear reactor to respond several orders of magnitude more slowly than just prompt neutrons would alone.
Without delayed neutrons, changes in reaction rates in nuclear reactors would occur at speeds that are too fast for humans to control.

Definition: $\beta = n_d / n_p$

Delayed super-criticality:

The region of super-criticality between $k = 1$ and $k = 1/(1-\beta)$

It is in this region that all nuclear power reactors operate.

Void Coefficient of Reactivity

Reactivity:

Measure for the change in neutron multiplication in a reactor core

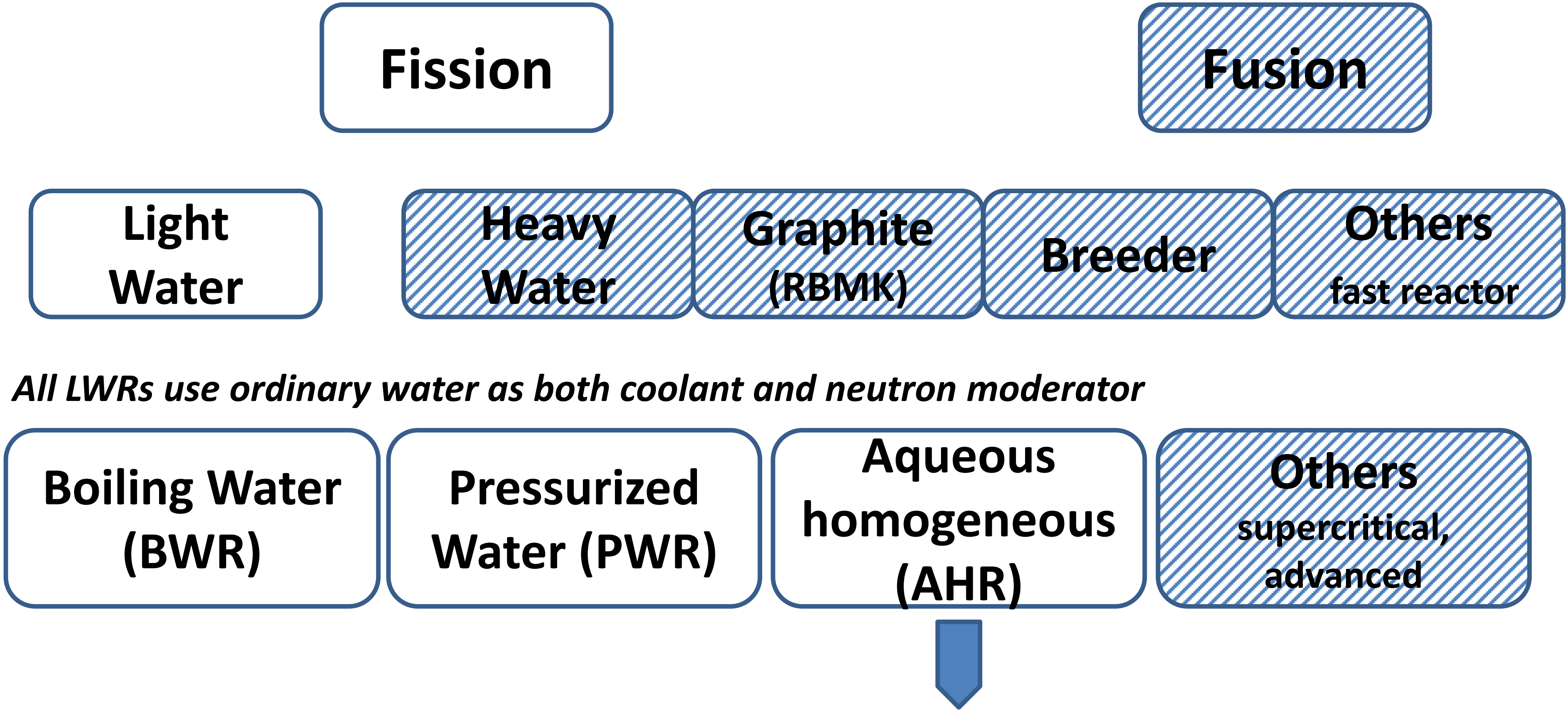
It is affected by coolant/moderator temperature and density,
Fuel temperature and density

Void Coefficient:

Measure for the change in reactivity when bubbles (VOIDS) are formed in the coolant/moderator

Light water reactors generally have a negative void coefficient;
With increasing boiling (BWR) the reactivity decreases.
In PWR, a large negative void coefficient ensures that if the water boils or is lost the power output will drop.
RBMK reactors have a dangerously high positive void coefficient (4.7 β)
(This was necessary for the reactor to run on unenriched uranium and to require no heavy water)

There are many nuclear reactors



Fission

Fusion

Light Water

Heavy Water

Graphite (RBMK)

Breeder

Others fast reactor

All LWRs use ordinary water as both coolant and neutron moderator

Boiling Water (BWR)

Pressurized Water (PWR)

Aqueous homogeneous (AHR)

Others supercritical, advanced

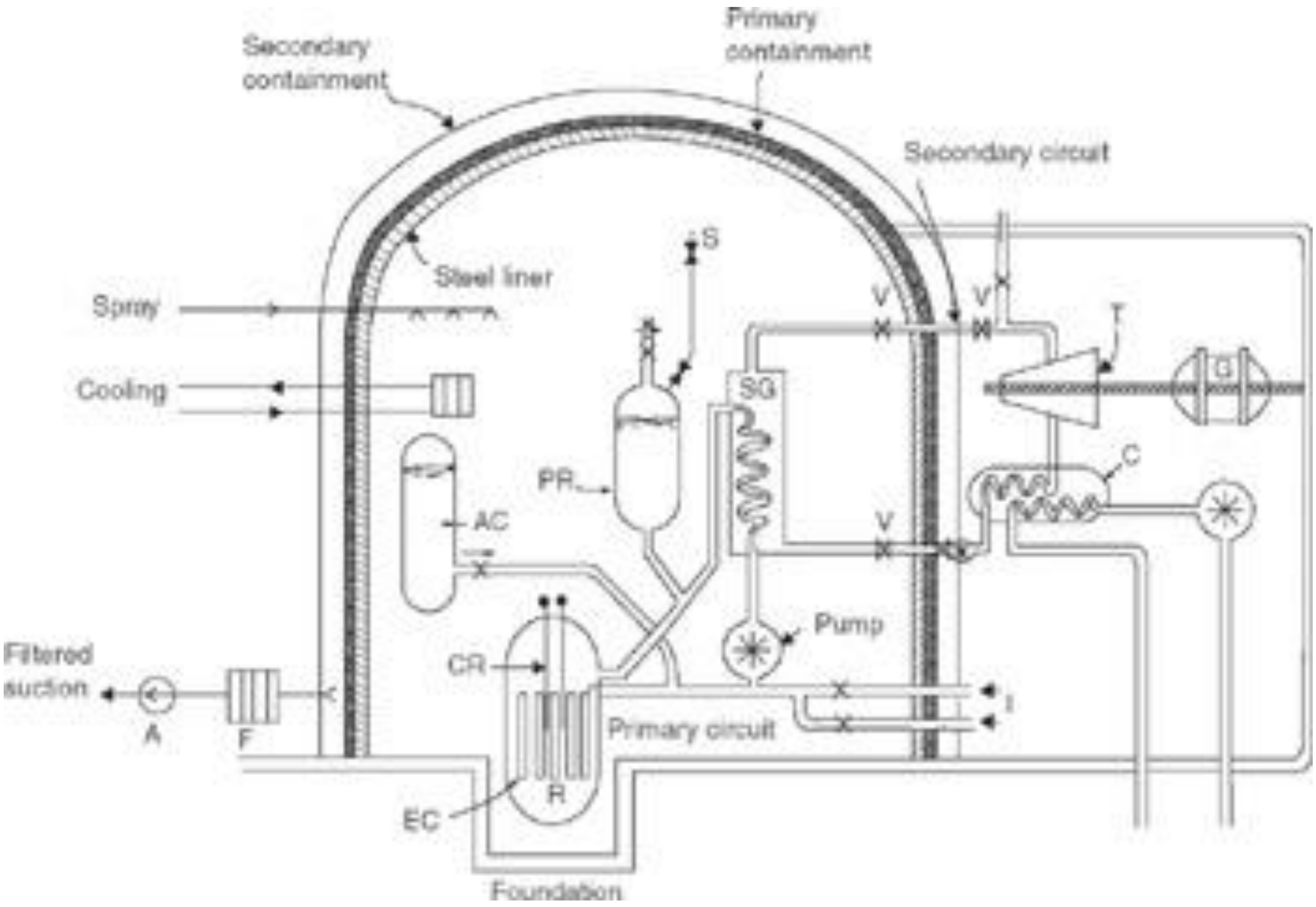
Research Reactor: Soluble nuclear salts (uranium sulfate, for example) are dissolved in water. The fuel is mixed with the coolant and the moderator.

Tc-99m production: Extraction of medical isotopes directly from in-line fuel

Light Water Reactor

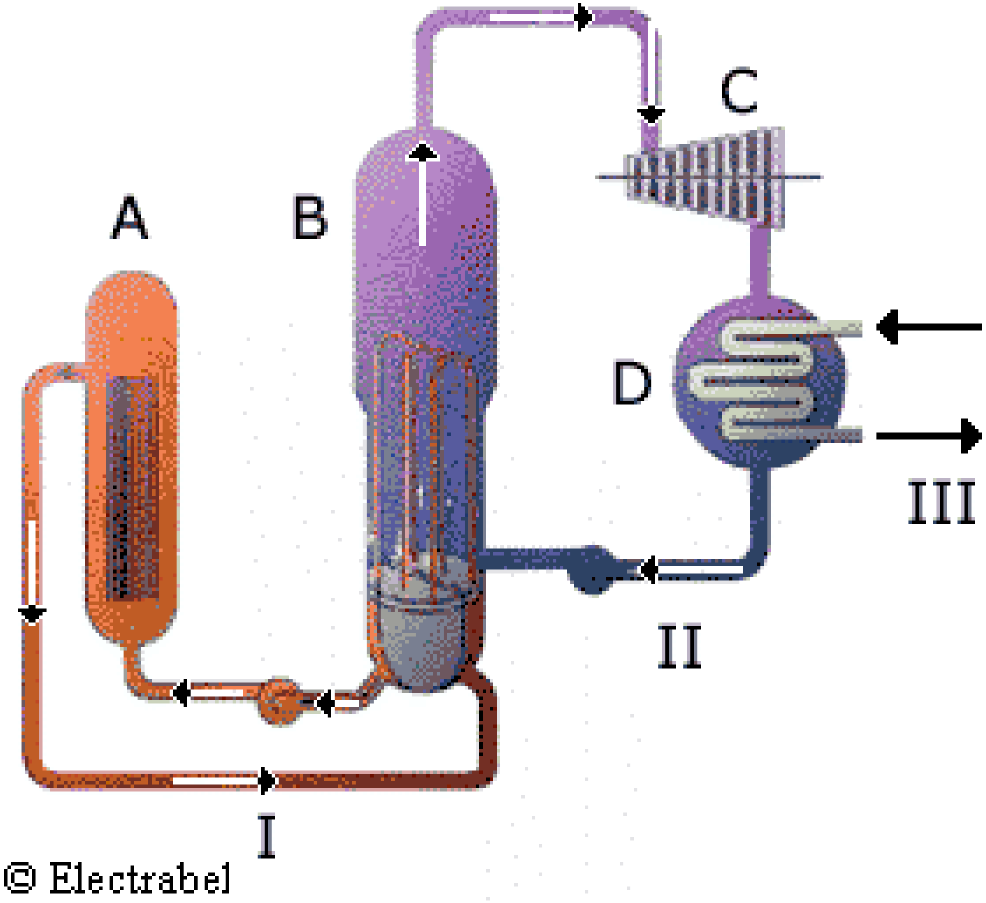
In light water reactors the water
which passes over the reactor core
acts as moderator and coolant.
In the boiling water reactor (BWR),
it is also the steam source for the turbine.
The disadvantage of this is
that any fuel leak makes the turbine
and the rest of the loop radioactive.
The low operating temperature
gives a Carnot efficiency of only 42%
with a practical operating efficiency of around 32%.

Pressurized Components of Nuclear Power Plants



Pressurized Water Reactor

Diagram of a PWR-nuclear power station



I. Primary circuit

II. Secondary circuit

III. Tertiary circuit

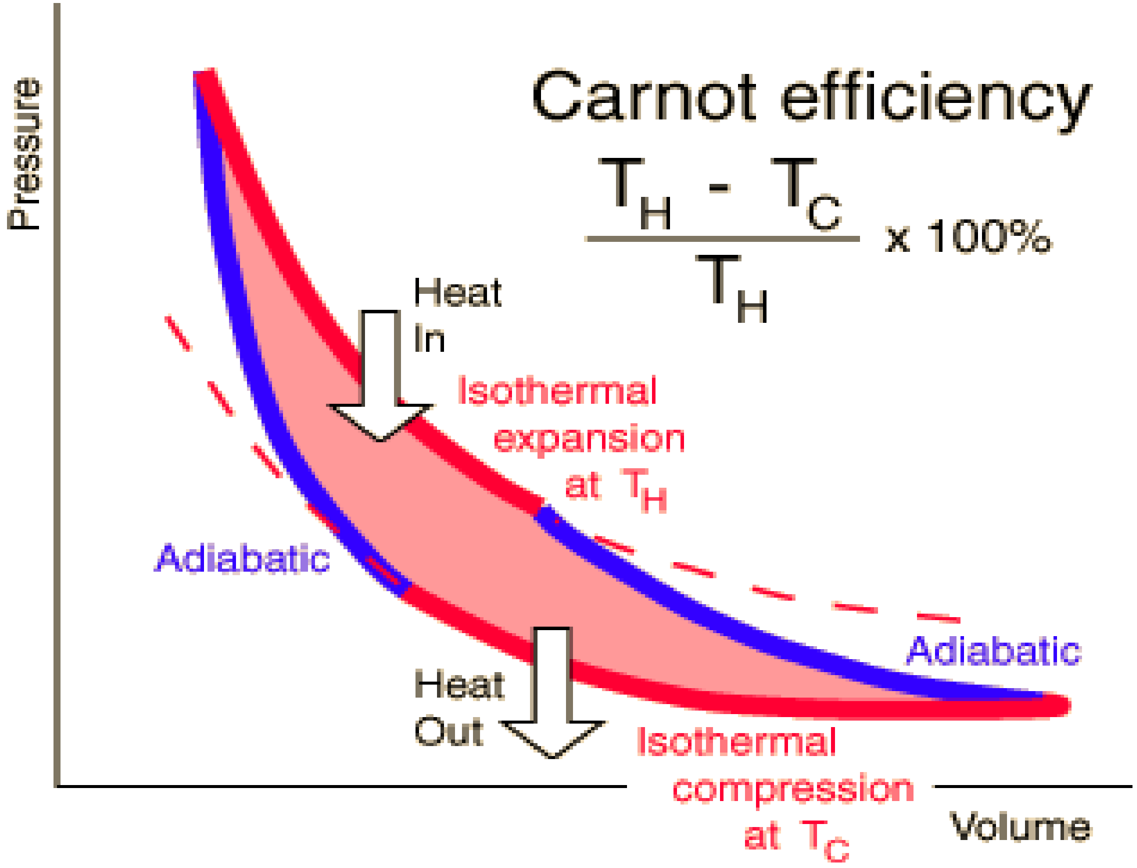
A. Reactor

B. Steam generator

C. Turbine

D. Condenser

CARNOT CYCLE - The most efficient heat engine cycle



The Carnot Cycle is an idealization,
since no real engine processes are reversible
and all real physical processes
involve some increase in entropy

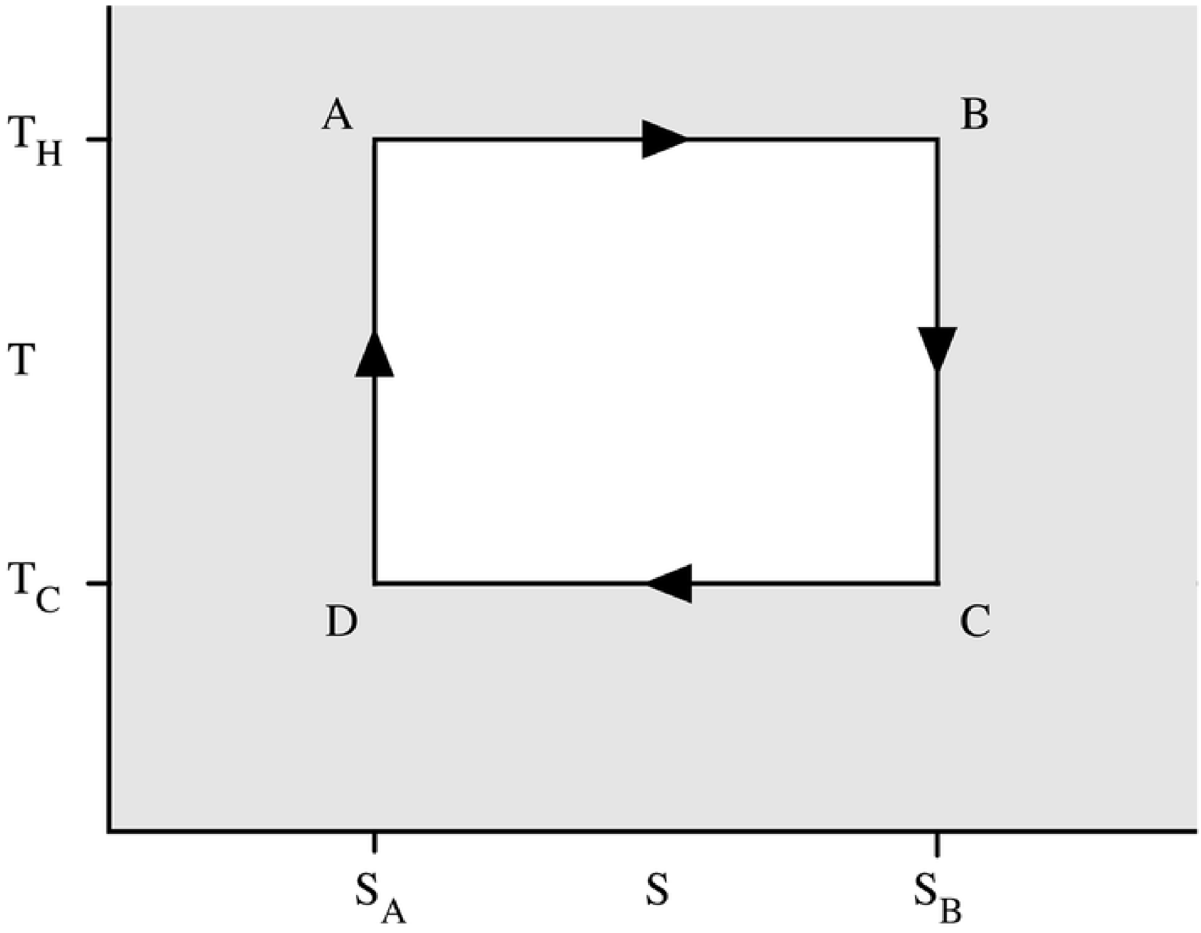
2nd Law of Thermodynamics:
limits conversion
Heat → Work

Carnot Efficiency:
sets the limiting value
on the fraction of the heat
which can be used

Entropy:

In order to approach
the Carnot efficiency,
the processes involved
in the heat engine cycle
must be reversible and
involve no change in entropy.

CARNOT CYCLE



Temperature-Entropy Diagram

A Carnot cycle acting as a heat engine. The cycle takes place between a hot reservoir at temperature T_H and a cold reservoir at temperature T_C. The vertical axis is temperature, the horizontal axis is entropy.

CARNOT CYCLE

The amount of energy transferred as work is

$$W = \oint PdV = (T_H - T_C)(S_B - S_A)$$

The total amount of thermal energy transferred between the hot reservoir and the system will be

$$Q_H = T_H(S_B - S_A)$$

the total amount of thermal energy transferred between the system and the cold reservoir will be

$$Q_C = T_C(S_B - S_A)$$

The efficiency *η* is defined to be

$$\eta = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

CARNOT CYCLE

The second law of thermodynamics states that any closed-loop cycle can only convert a fraction of the heat produced into mechanical work. The rest of the heat, called waste heat, must be released into a cooler environment during the return portion of the cycle.

The fraction of heat released into a cooler medium must be equal or larger than the ratio of absolute temperature of the cooling system (environment) and the heat source.

Fuel Cells do not have the same thermodynamic limits as they are not heat engines

PWR Coolant Circuits

- INDIRECT CYCLE: Primary and Secondary Coolant Loops
- Single Phase (Liquid) Reactor Coolant

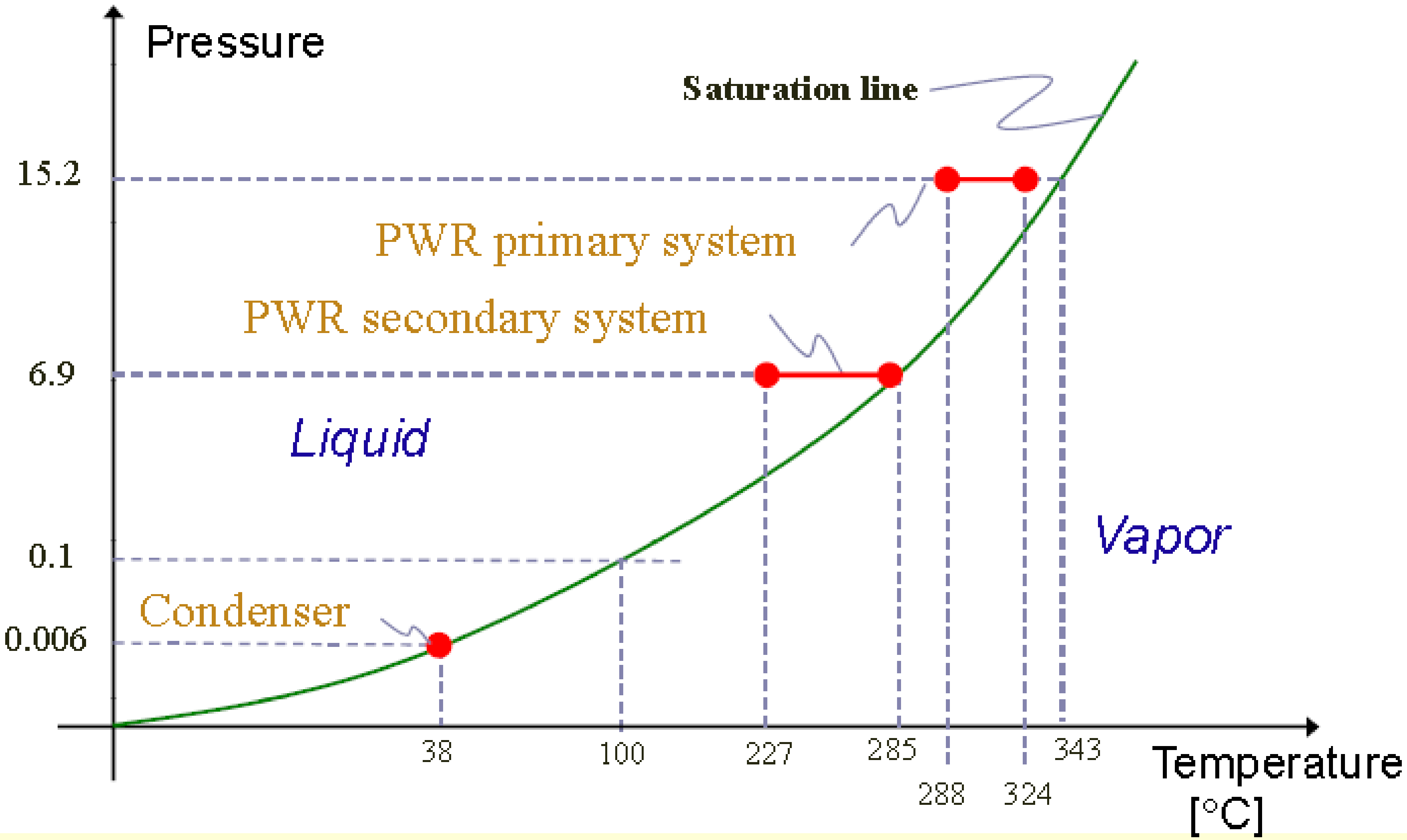
[T_{in}=287.7°C, T_{out}=324°C, P=15.2 MPa, T_{sat}= 343.3°C]

- Two-Phase (Steam-Water) Power Conversion Cycle Loop

[$T_{SG,in}$=227°C, $T_{SG,out}$=285°C, P=6.9 MPa, T_{sat}=285°C]

[$T_{Condenser}$= 37.8°C, P=6.6 kPa]

Phase Diagram of Water



Connection of PWR Core Design to Neutronics

- **Why is Zr used as structural material in fuel assemblies?**
- **What functions does water perform?**
- **What determines the fuel rod spacing?**
- **Why are the fuel rods so small?**
- **Why are the control rods arranged in clusters?**
- **Why is boron dissolved in the coolant? What is Gd used for?**

USED MATERIALS

USNRC Technical Training Center: *Pressurized Water Reactor (PWR) Systems*, Reactor Concepts Manual

Jacopo Buongiorno: *PWR Description,* MIT open course ware: 22.06: Engineering of Nuclear Systems, CANES (Center for Advanced Nuclear Energy Systems), MIT

John Lamarsh, Anthony Baratta: *Introduction to Nuclear Engineering*. Prentice Hall, 2001, ISBN 0-201-82498-1