Specifics of nuclear power engineering

Specifics of nuclear power engineering

1. Introduction to Structural Reliability in Nuclear Engineering

1.1.	Risk based reliability engineering
1.2.	Mitigation Strategies
1.3.	Basics on Nuclear Power
1.4.	Pressurized components of NPP
1.5.	BWR-Fukushima Accident
1.6.	RBMK Reactor – Chernobyl accident
1.7.	**Specifics of nuclear power engineering**
1.8.	Production of medical isotopes

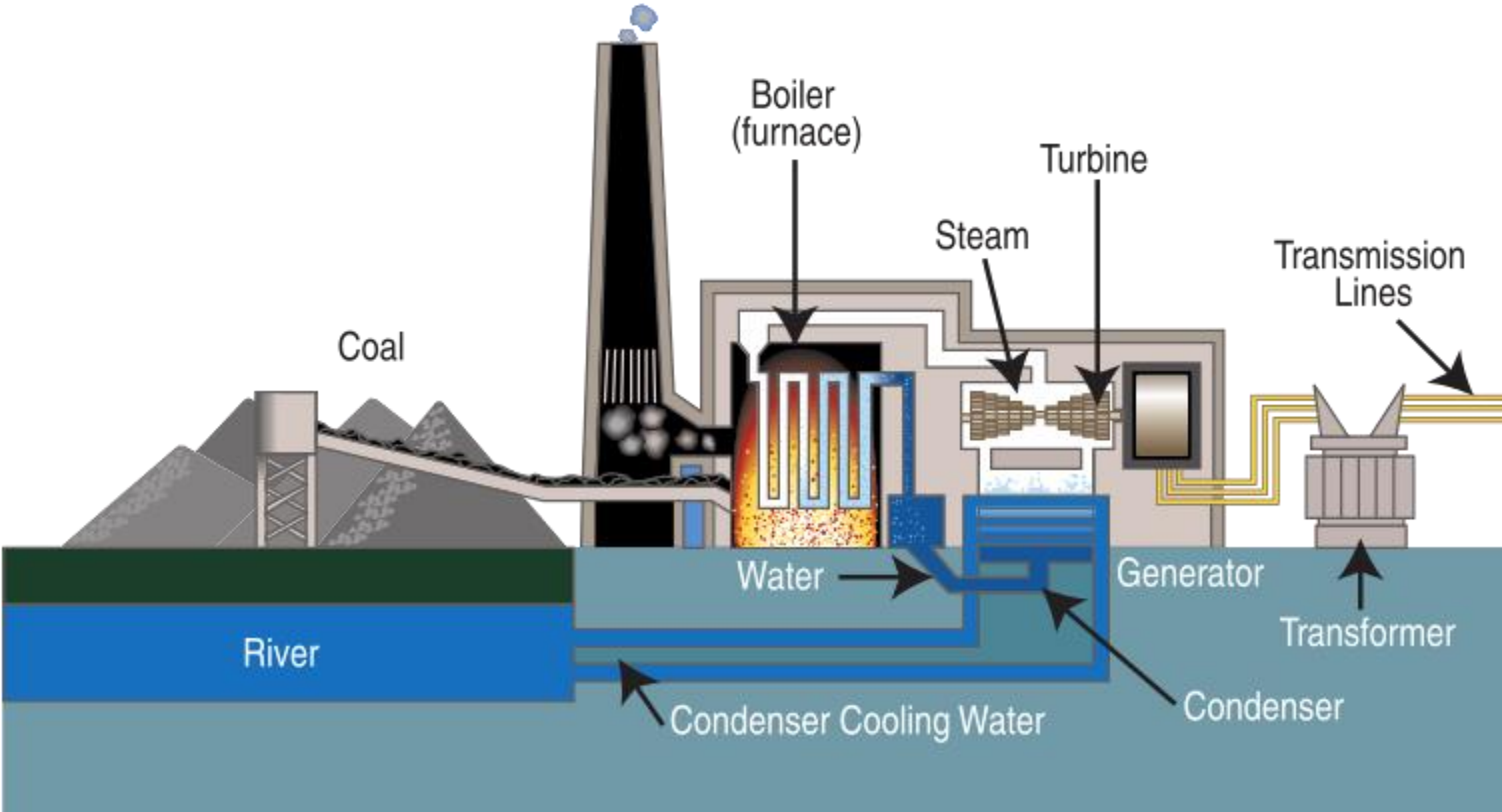


Diagram of a Coal-Fired Power Plant

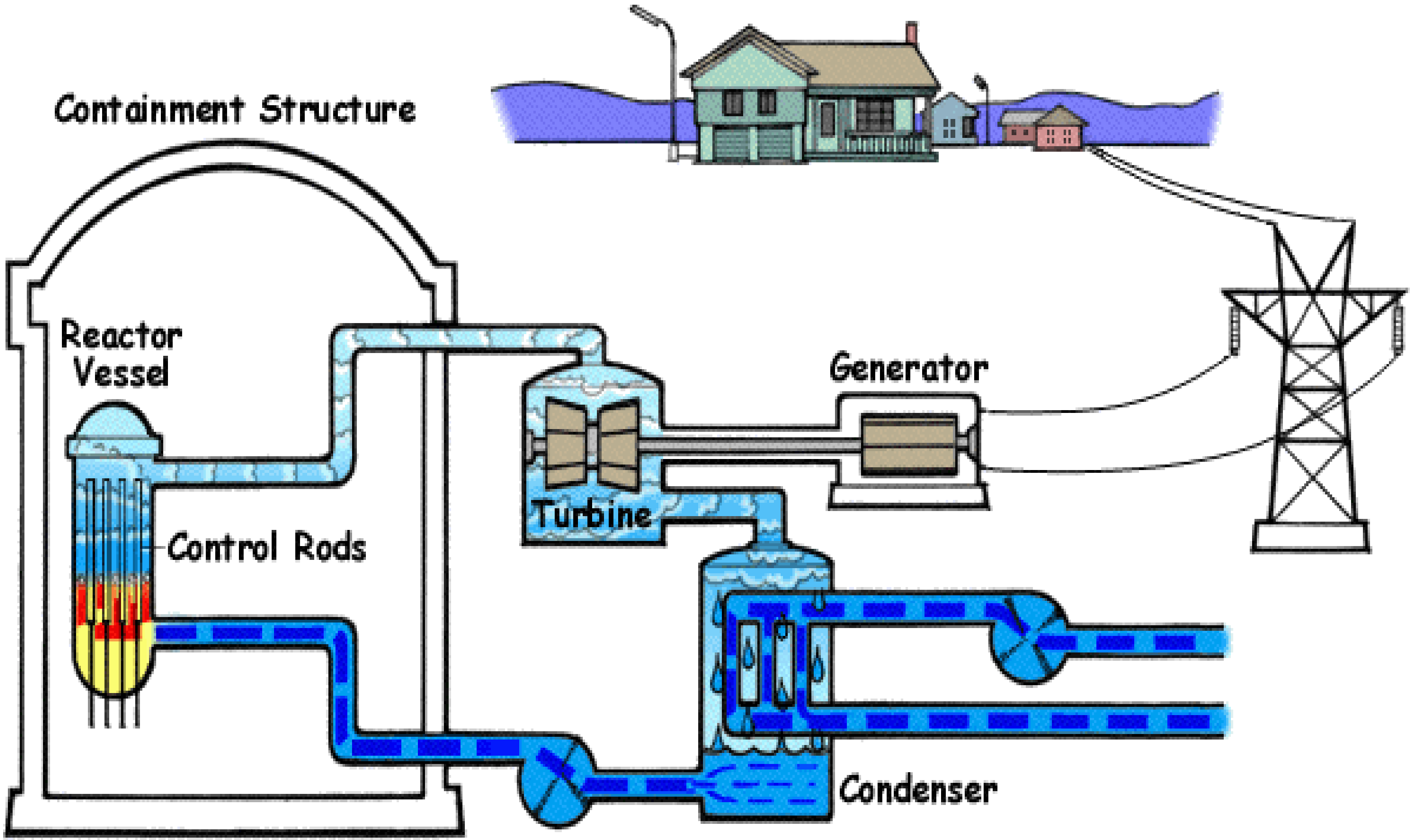


Diagram of a BWR Power Plant

Susquehanna Steam Electric Station

Krümmel Steam Electric Station

Boiling Water Reactor Plants

Fossil ⇔ Nuclear

Fuel

Characteristics

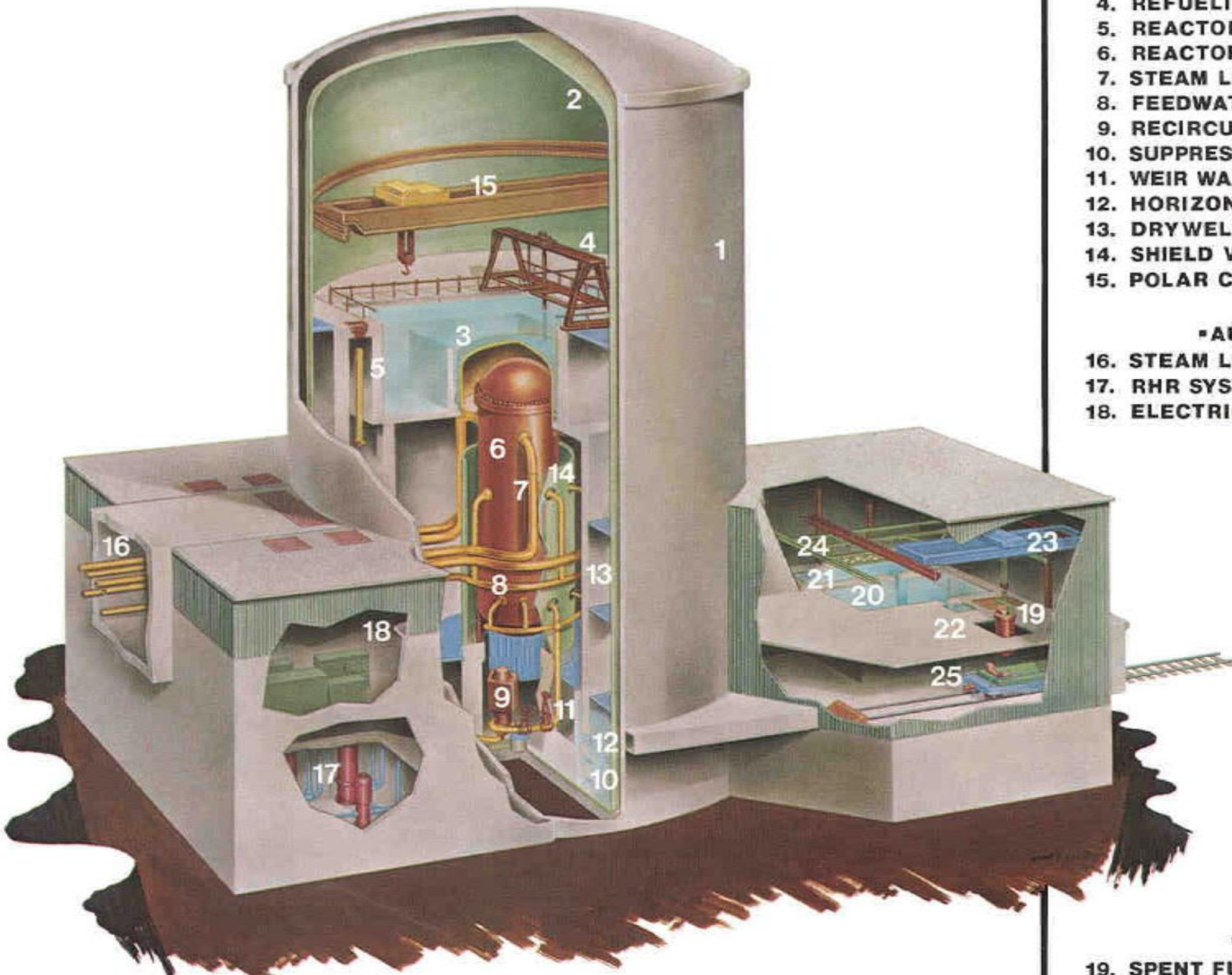
Comparable

- ***Steam Turbine***
- ***Large-Scale Power Plant***
- ***Base-load Plant***
- ***Environmental Impact***
- ***Fuel Resources***

Different

- **Heater**
- **Steam Temperature**
- **Carnot Efficiency**
- **Safety Design**
- **Designed Life-Time**
- **Materials**
- **Material Degradation**
- **Security**

MARK III CONTAINMENT



GENERAL ELECTRIC

·REACTOR BUILDING·

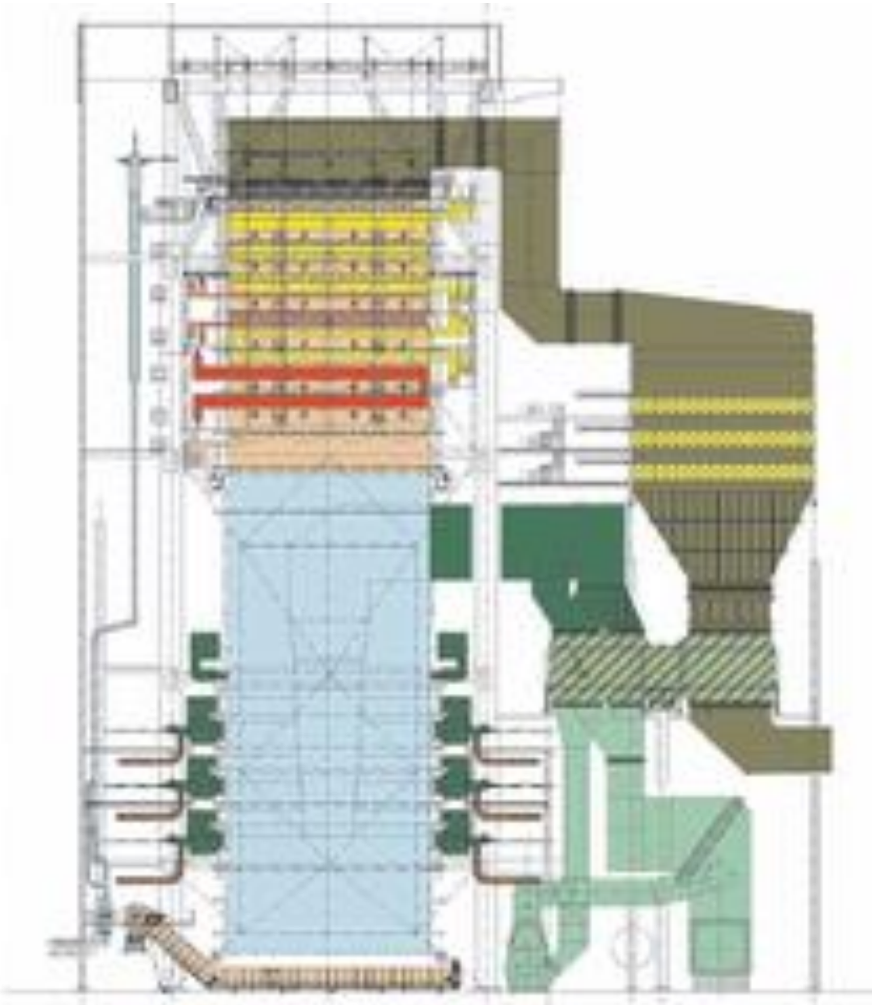
1. SHIELD BUILDING
2. FREESTANDING STEEL CONTAINMENT
3. UPPER POOL
4. REFUELING PLATFORM
5. REACTOR WATER CLEANUP
6. REACTOR VESSEL
7. STEAM LINE
8. FEEDWATER LINE
9. RECIRCULATION LOOP
10. SUPPRESSION POOL
11. WEIR WALL
12. HORIZONTAL VENT
13. DRYWELL
14. SHIELD WALL
15. POLAR CRANE

·AUXILIARY BUILDING·

16. STEAM LINE TUNNEL
17. RHR SYSTEM
18. ELECTRICAL EQUIPMENT ROOM

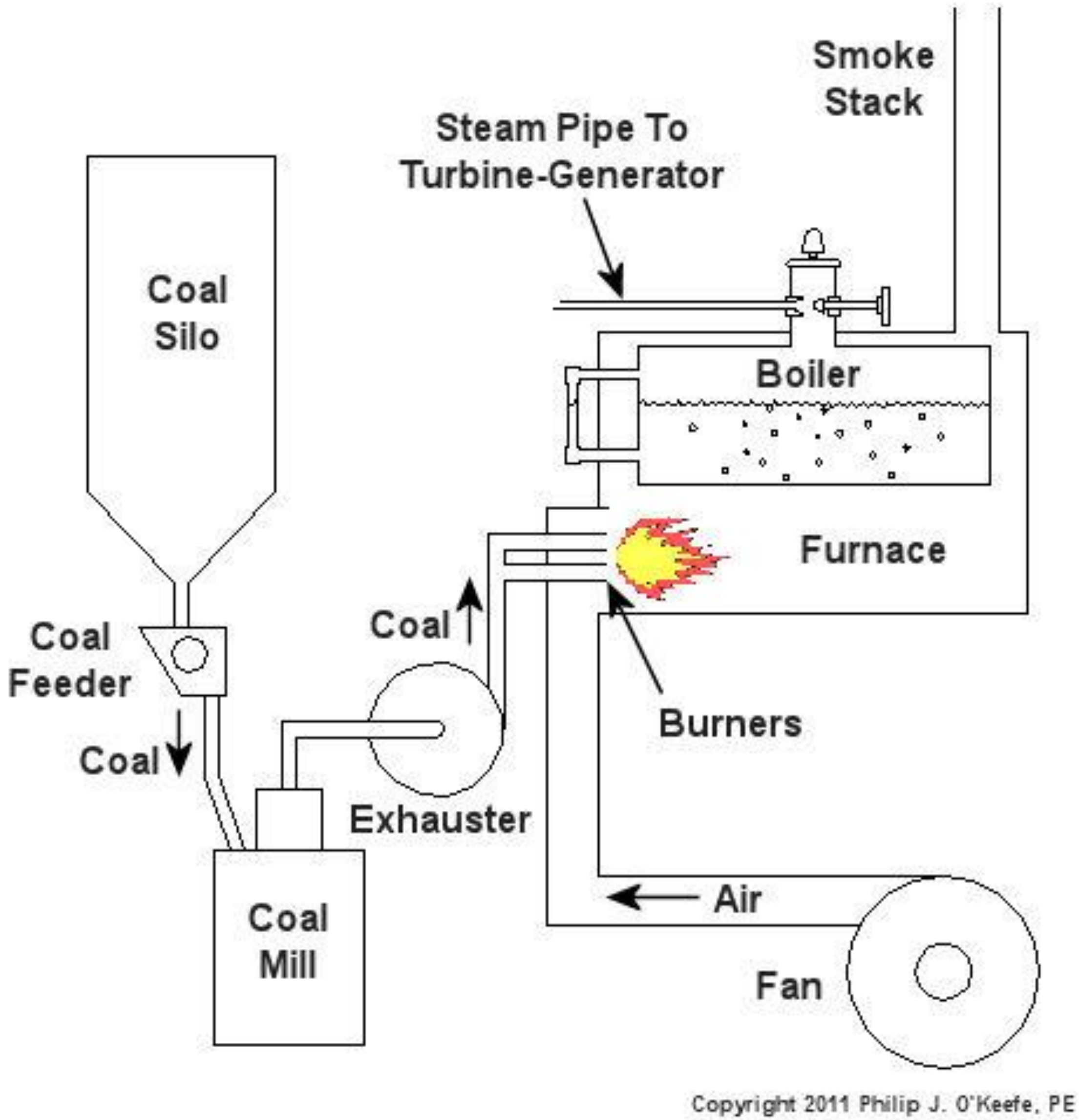
·FUEL BUILDING·

19. SPENT FUEL SHIPPING CASK
20. FUEL STORAGE POOL
21. FUEL TRANSFER POOL
22. CASK LOADING POOL
23. CASK HANDLING CRANE
24. FUEL TRANSFER BRIDGE
25. FUEL CASK SKID ON RAILROAD CAR



Tower single-pass boiler

Specific characteristics of nuclear power engineering



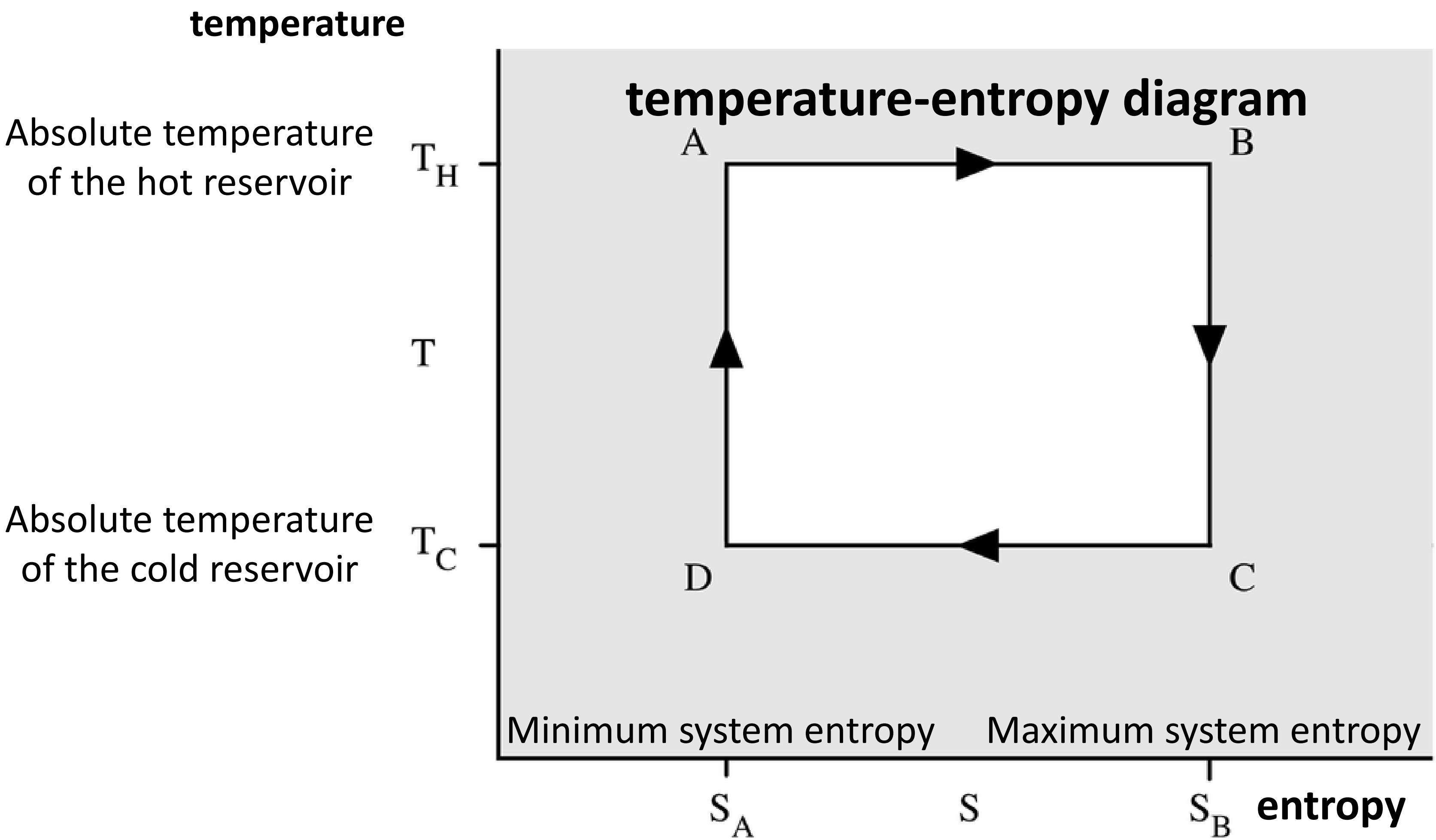
Pulverized Coal Burner for Boiler

Operation

Below CPW:
subcritical
(efficiency ≈ 37%)

Above CPW:
(ultra)-supercritical plant
(efficiency ≈ 40% - 45%)

The idealized Carnot Cycle



The cycle takes place between a hot reservoir at temperature T_H and a cold reservoir at temperature T_C.

$$W = \oint PdV = (T_H - T_C)(S_B - S_A)$$ **work done by the system**

$$Q_H = T_H(S_B - S_A)$$ **heat put into the system**

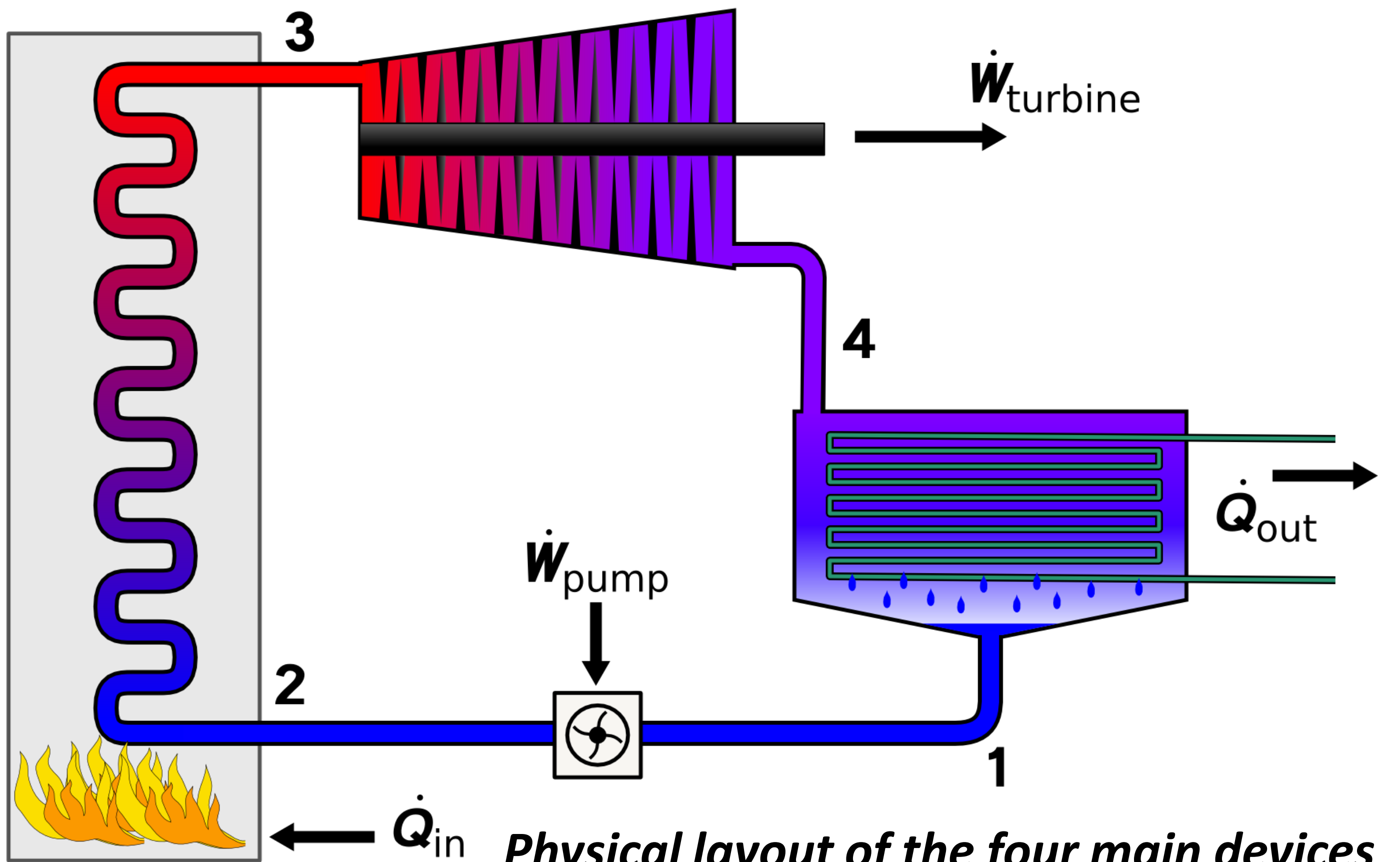
$$Q_C = T_C(S_B - S_A)$$ **heat of the cold reservoir**

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

System efficiency increases with steam temperature

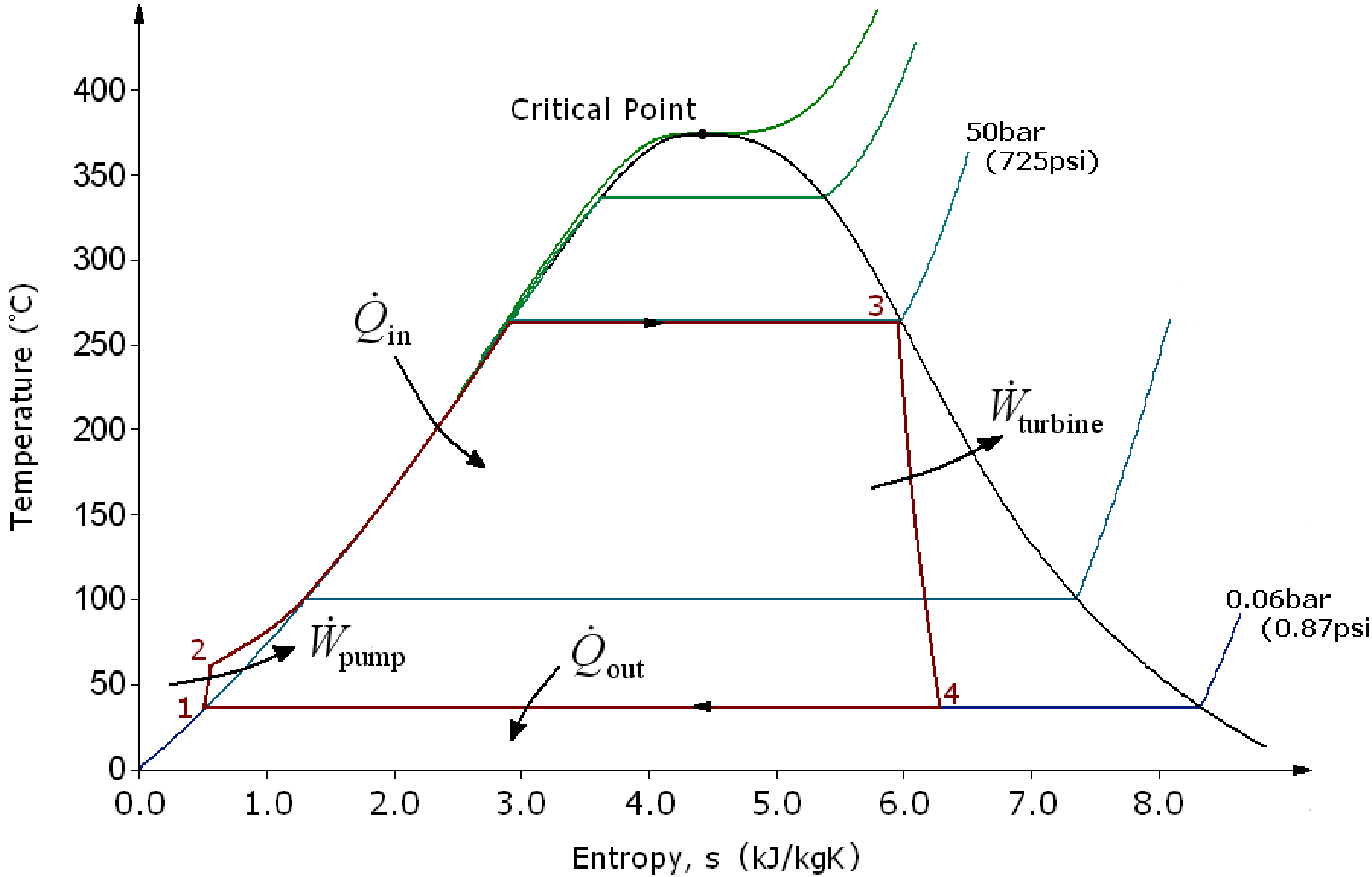
The Rankine Cycle

describes in good approximation the process
by which steam-operated heat engines generate power.



Physical layout of the four main devices

T-s diagram of a Rankine cycle



The four main processes of a Rankine cycle

Process 1-2: The working fluid is pumped from low to high pressure. As the fluid is a liquid at this stage the pump requires little input energy.

Process 2-3: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor. The input energy required can be easily calculated using Mollier diagram or h-s chart or enthalpy-entropy chart also known as steam tables.

Process 3-4: The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur. The output in this process can be easily calculated using the Enthalpy-entropy chart or the steam tables.

Process 4-1: The wet vapor then enters a condenser where it is condensed at a constant pressure to become a saturated liquid.

The Fourth State of Water

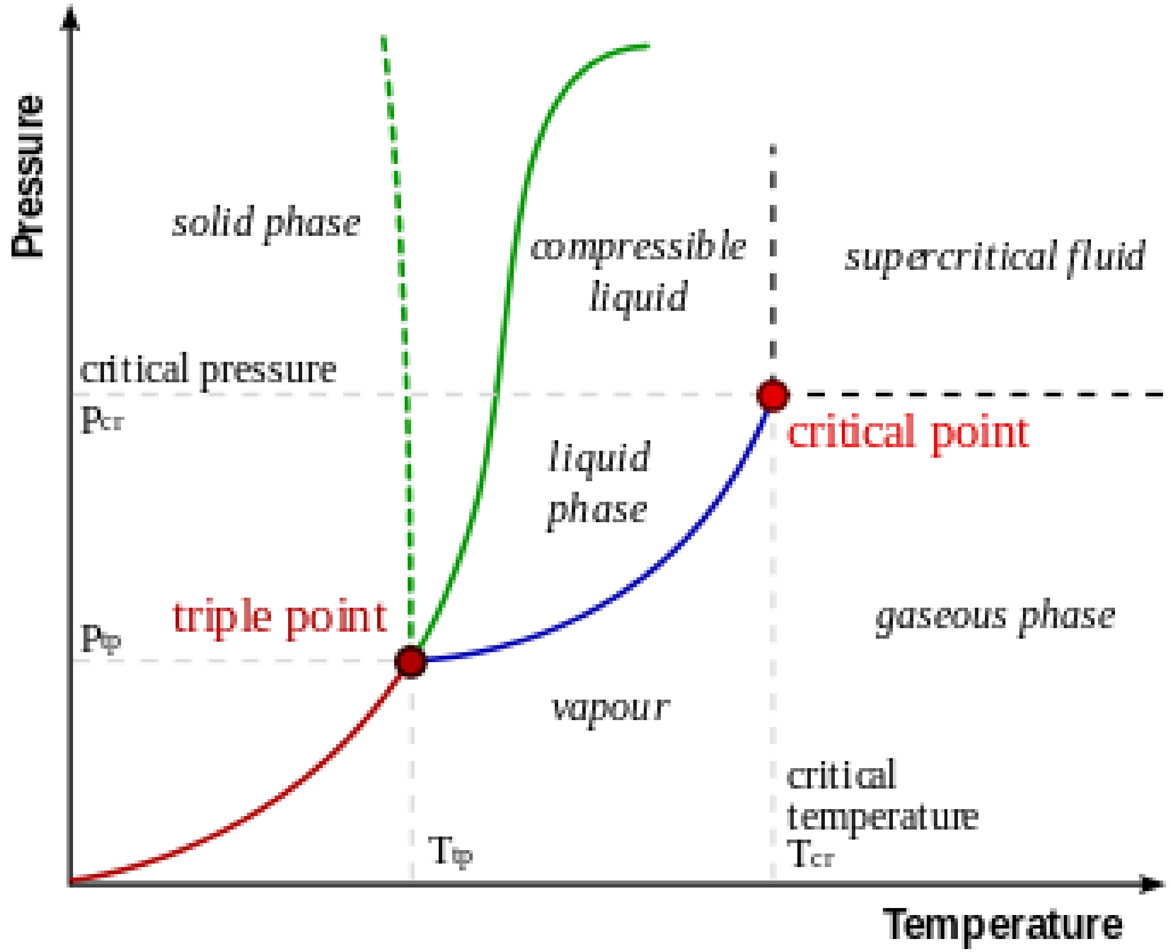
The Supercritical Fluid

Critical Point of Water (CPW):
647 ° K (374 °C)
22.064 Mpa (218 atm)

When water achieves
a ***specific critical temperature (647 K)***
and
a ***specific critical pressure (22.064 MPa***),
liquid and gas phase merge to one homogeneous fluid phase,
with properties of both gas and liquid.
The heat of vaporization is zero at and beyond this critical point,
so there is no distinction between the two phases.
Above the critical temperature a liquid cannot be formed

For pure substances, there is an inflection point in the critical isotherm on a PV diagram. This means that at the critical point:[

$$\left(\frac{\partial p}{\partial V}\right)_T = \left(\frac{\partial^2 p}{\partial V^2}\right)_T = 0$$



The vapor–liquid critical point in a pressure–temperature phase diagram at the high-temperature extreme of the liquid–gas phase boundary.
(The dotted green line shows the anomalous behavior of water.)

Steam Temperature
(thermodynamic efficiency)

Fossil Fired Power Plant

Subcritical:
- Temperature T ≈ 540°C
- Pressure P ≈ 170 bar
- Efficiency ε ≈ 38%

Supercritical:
- Temperature T ≈ 600°C
- Pressure P ≈ 230 to 265 bar
- Efficiency ε ≈ 45%

Hypercritical:
- Temperature T ≈ 700° C
- Pressure P ≈ 350 bar
- Efficiency ε ≈ 50%

Progress depends on New Materials

Supercritical power plants use special high grade materials for the boiler tubes.

The turbine blades are also of improved design and materials. In fact, the very increase in higher pressure and temperature designs are dependent on the development of newer and newer alloys and tube materials. (Nickel-base materials, eg)

Steam Temperature
(thermodynamic efficiency)

Nuclear Power Plant

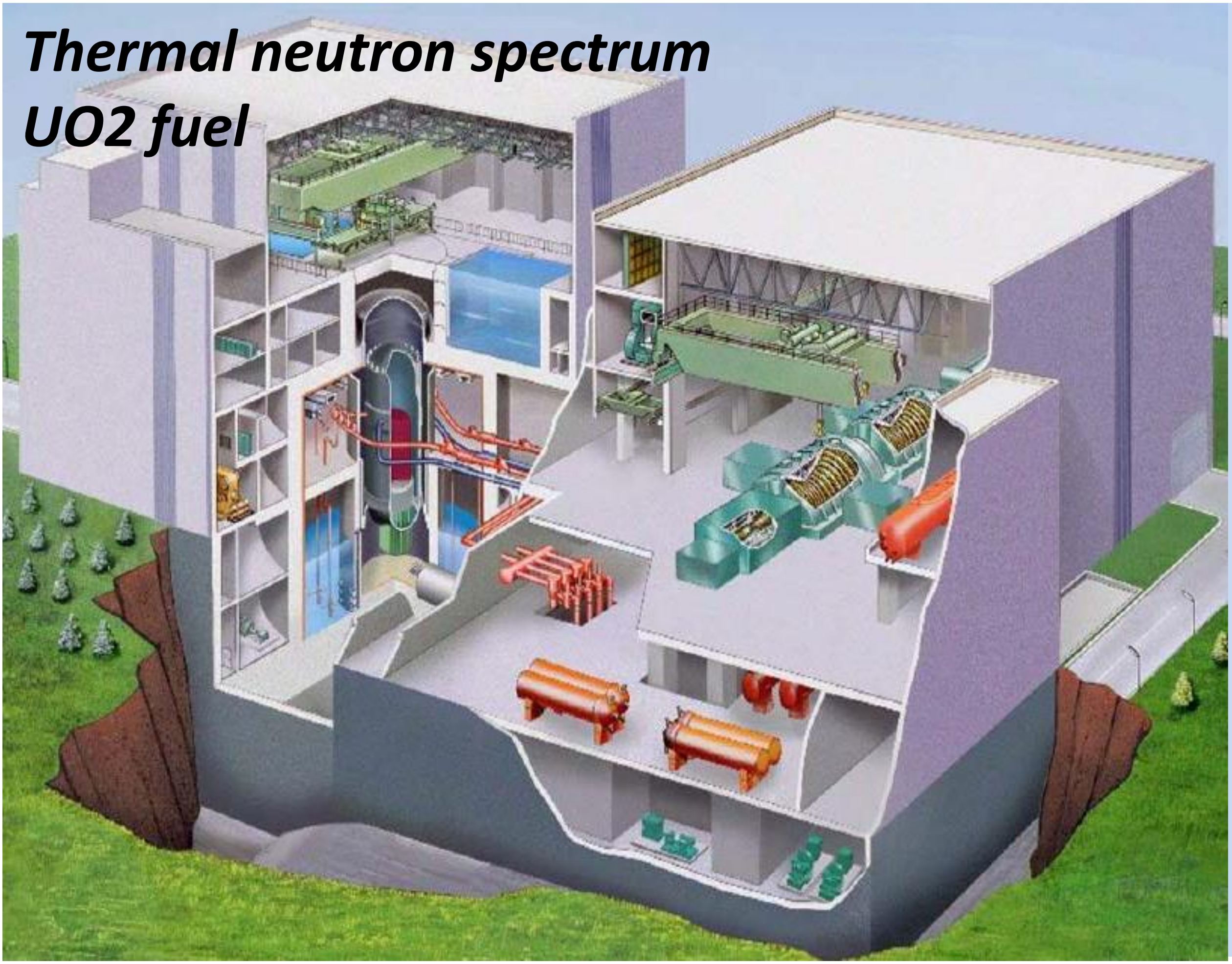
Subcritical (BWR):
- Temperature T ≈ 285° C
- Pressure P ≈ 70 bar
- Efficiency ε ≈ 30–32%.

Subcritical (PWR):
- Temperature T ≈ 324° C
- Pressure P ≈ 152 bar
- Efficiency ε ≈ 32–34%.

A Generation IV Reactor Design:

Supercritical (SCWR)
- Temperature T ≈ 500°C
- Pressure P ≈ 250 bar
- Efficiency ε ≈ 45%

The Supercritical Water Reactor
A Japanese Generation IV Design



Net electric power:
1620 MWe

Net thermal efficiency:
44%

Operating pressure:
25 MPa

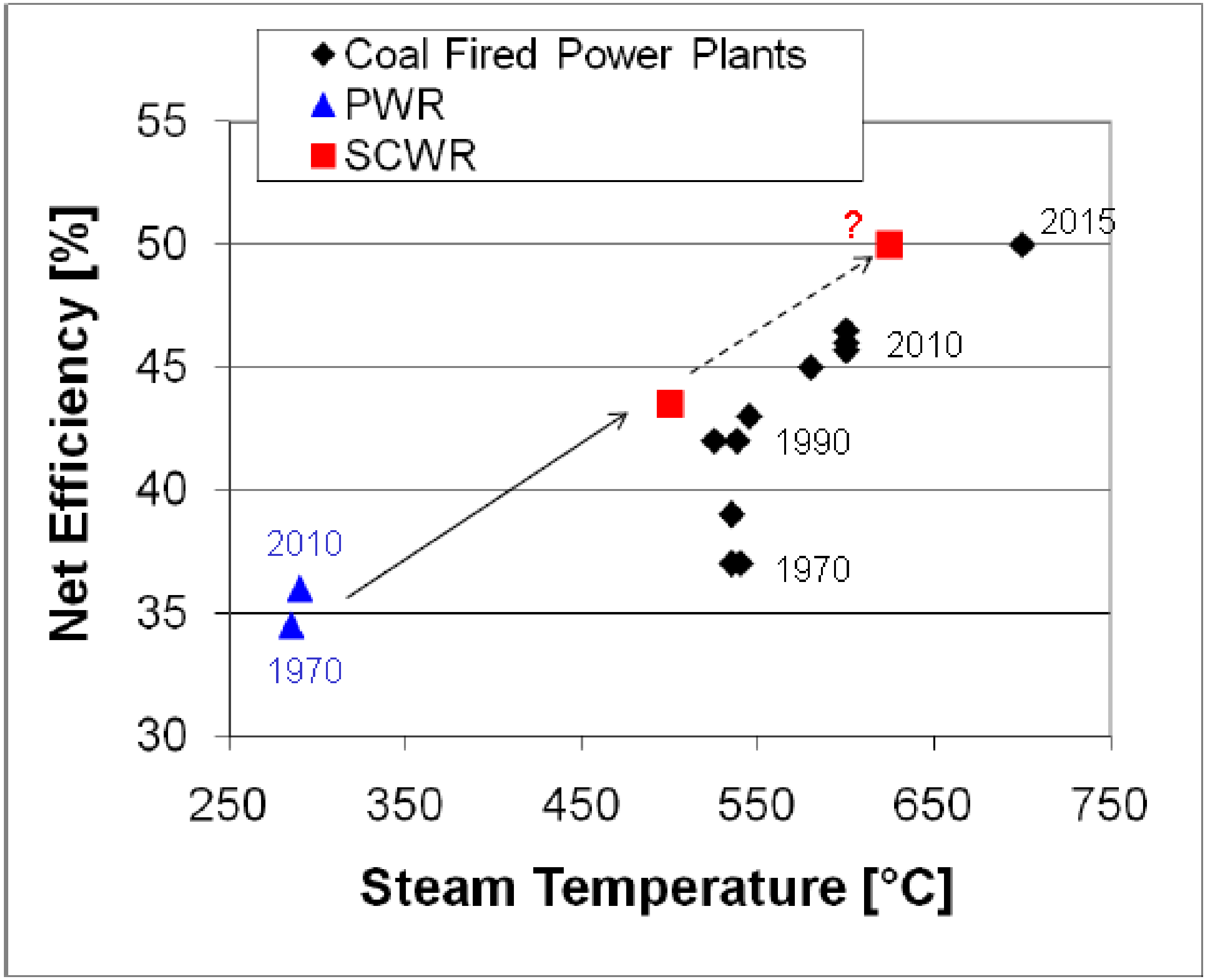
Inlet temperature:
280°C

Outlet temperature:
500°C

Plant lifetime:
60 years

From (2)

The SCWR concept is following the trend of coal fired power plants to improve the economics of LWRs.



From (2)

Agreements on SCWR Research and Development in the Generation IV International Forum (GIF)

SCWR System Arrangement signed

by Canada, Euratom and Japan (2006) and Russia (2011)

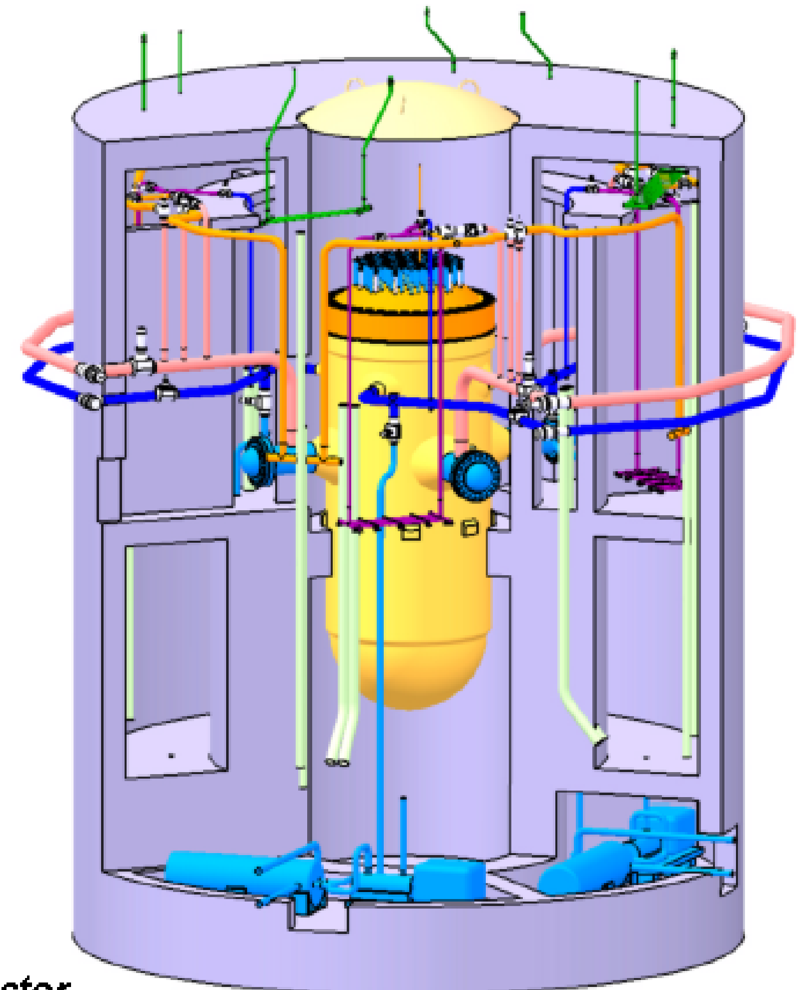
Joint Projects (Canada, Euratom and Japan):

- *Thermal-Hydraulics and Safety (PA signed in 2009)*
- *Materials and Chemistry (PA signed in 2010)*
- *Fuel Qualification Test (provisional)*
- *System Integration and Assessment (provisional)*

Safety & Materials

GIF-SCWR Project "Thermal-Hydraulics and Safety"

Including
- *Safety system configuration*
- *System code analyses of*
  - *Loss of coolant accidents*
  - *Loss of power accidents*
  - *Loss of flow accidents*
  - *… and other accident scenarios*



Example:
Safety system configuration of the High Performance Light Water Reactor

GIF-SCWR Project "Materials and Chemistry"

Project Arrangement signed Dec. 2010 by Canada, Euratom and Japan

Including
- *Corrosion tests*
- *Creep tests*
- *Stress corrosion cracking tests*
- *Out-of-pile and in-pile test*
- *Radiolysis tests*
- *Water chemistry tests*
- *…etc.*

Example: Autoclaves for supercritical water tests up to 650°C and 25 MPa at VTT and JRC Petten

Materials and Chemistry: Status 2012

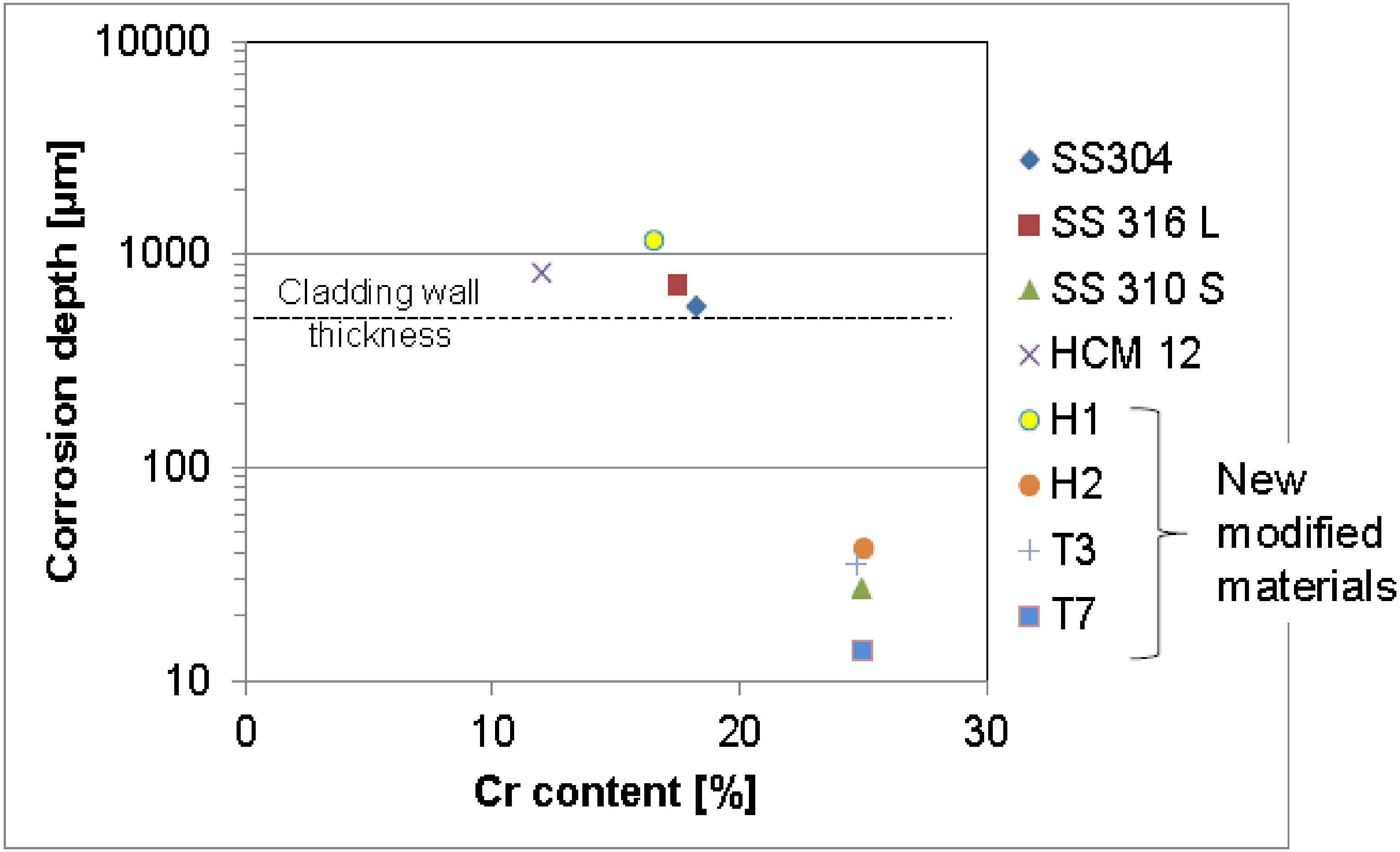
Stainless steels which are qualified for nuclear applications can be used up to 550°C surface temperature,

- *high Cr steels for higher temperatures are promising but need further qualification tests.*
- *Coatings or surface treatment are still under development.*

Autoclaves with supercritical water up to 695°C are available,

- *but an in-pile radiolysis and water chemistry test facility with continuous flow of supercritical water is still under preparation.*

Predicted corrosion depth after 50,000h at 700°C



Stainless steel cladding alloys need to be modified to meet the design target

New:
Draft Russian R&D Plan on SCWR Development in GIF

Focuses:

- *Hydrodynamics and heat/mass - transfer in SCW fluids in reactor cores and circuits, like critical flow, depressurization, transients etc.;*
- *Neutron physics: complex spectrum spatial distribution; dynamic processes; feed-backs of thermal-hydraulics;*
- *Selection of fuel and structure materials candidates of reactor, structures and core;*
- *Development of safety concept for vessel-type SCW reactors;*
- *Investigation of TH, neutron/TH instabilities, thermo-acoustic oscillations, flashing, water hammer, etc.;*

Most hydropower stations are about 90 percent efficient in converting the energy of falling water into electricity

NUCLEAR ENGINEERING IS CHALLENGING BEST TALENTS:

Different

- Heater
- Steam Temperature
- Carnot Efficiency
- Safety Design
- Designed Life-Time
- Materials
- Material Degradation
- Security

Redundancies
Passive safety design
Complexity
Safety culture
Competency & responsibility

→ No catastrophic accident

60 years

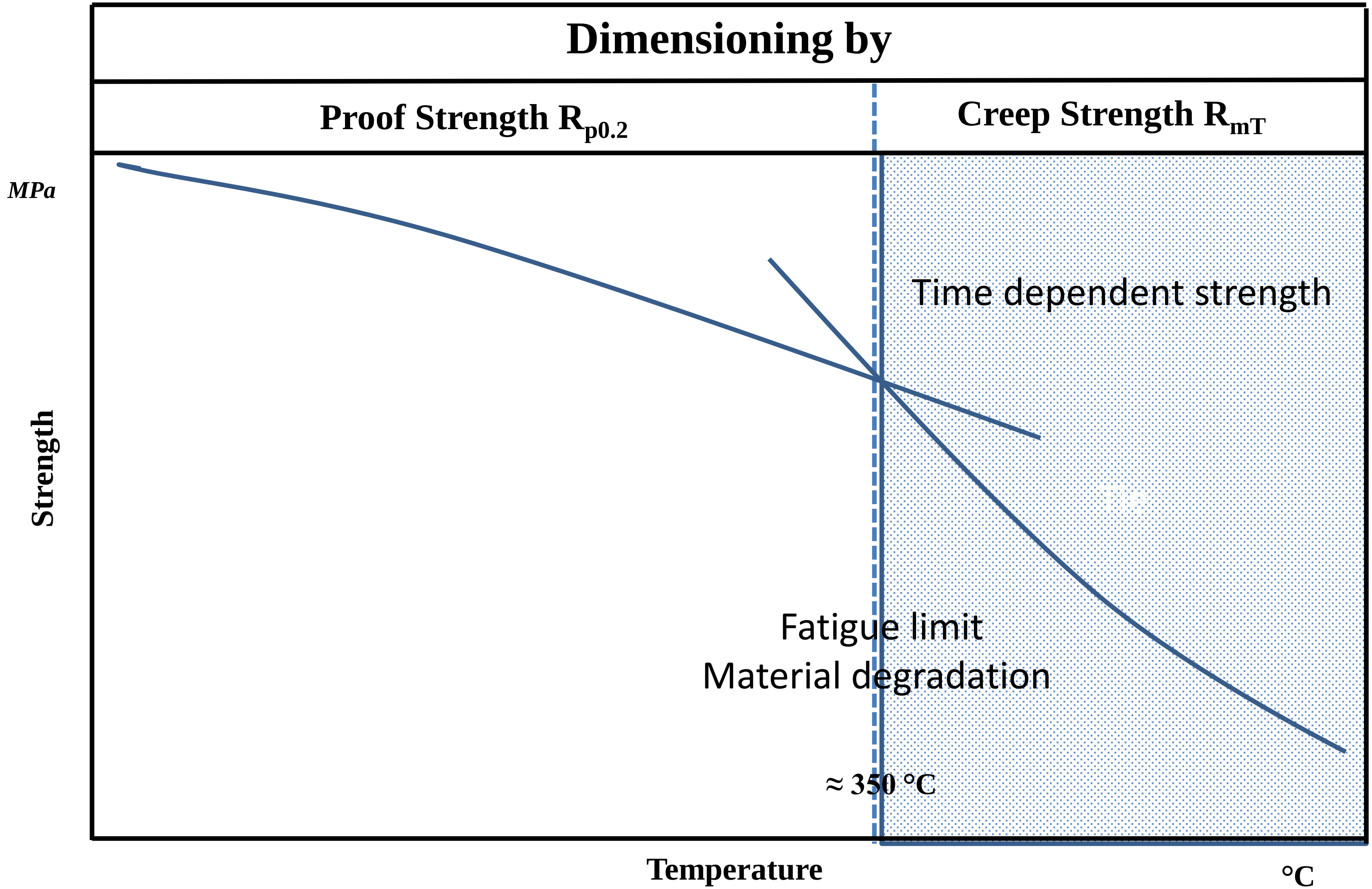
Optimized material values

- Fracture toughness
- High-grade steels
- Primary circuit: Austenitic steels
- Alloy without Cobalt

Irradiation
Boron
Specific stress corrosion cracking

- IGSCC
- PWSCC

Specific characteristics of nuclear power engineering



CREEP STRENGTH

Creep:

a time-dependent material deformation
at elevated temperature and constant stress.

appears at temperatures above 350°C

Engineering rules:

recognize creep and creep deformation
as high-temperature design limitations
provide allowable stresses for all alloys used in the creep range.

One of the criteria used in the determination of allowable stresses:
is 1% creep expansion, or deformation, in 100,000 hours of service

Creep failures are characterized by:

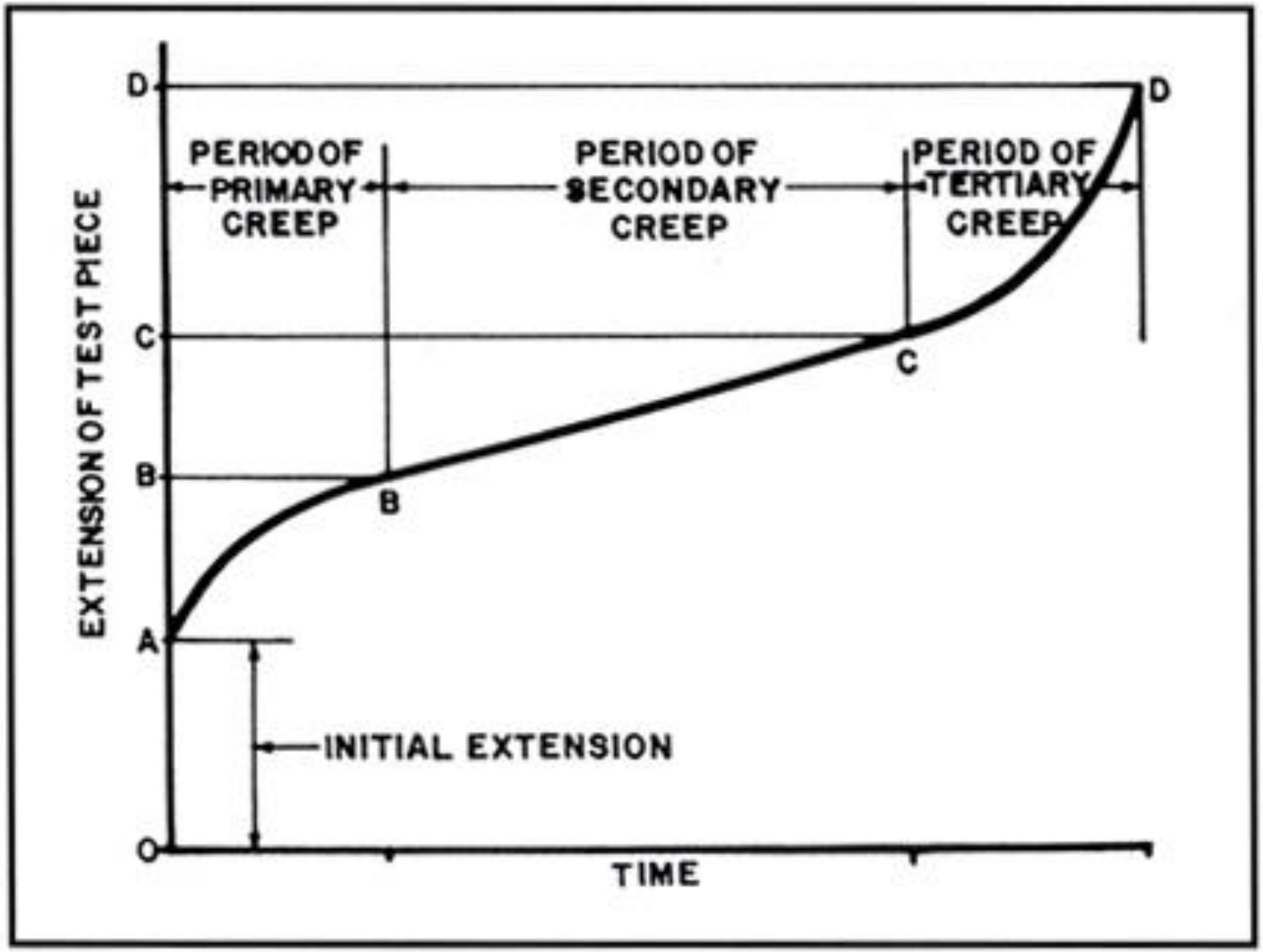
bulging or blisters in the tube

thick-edged fractures often with very little obvious ductility

longitudinal "stress cracks" in either or both ID and OD oxide scales

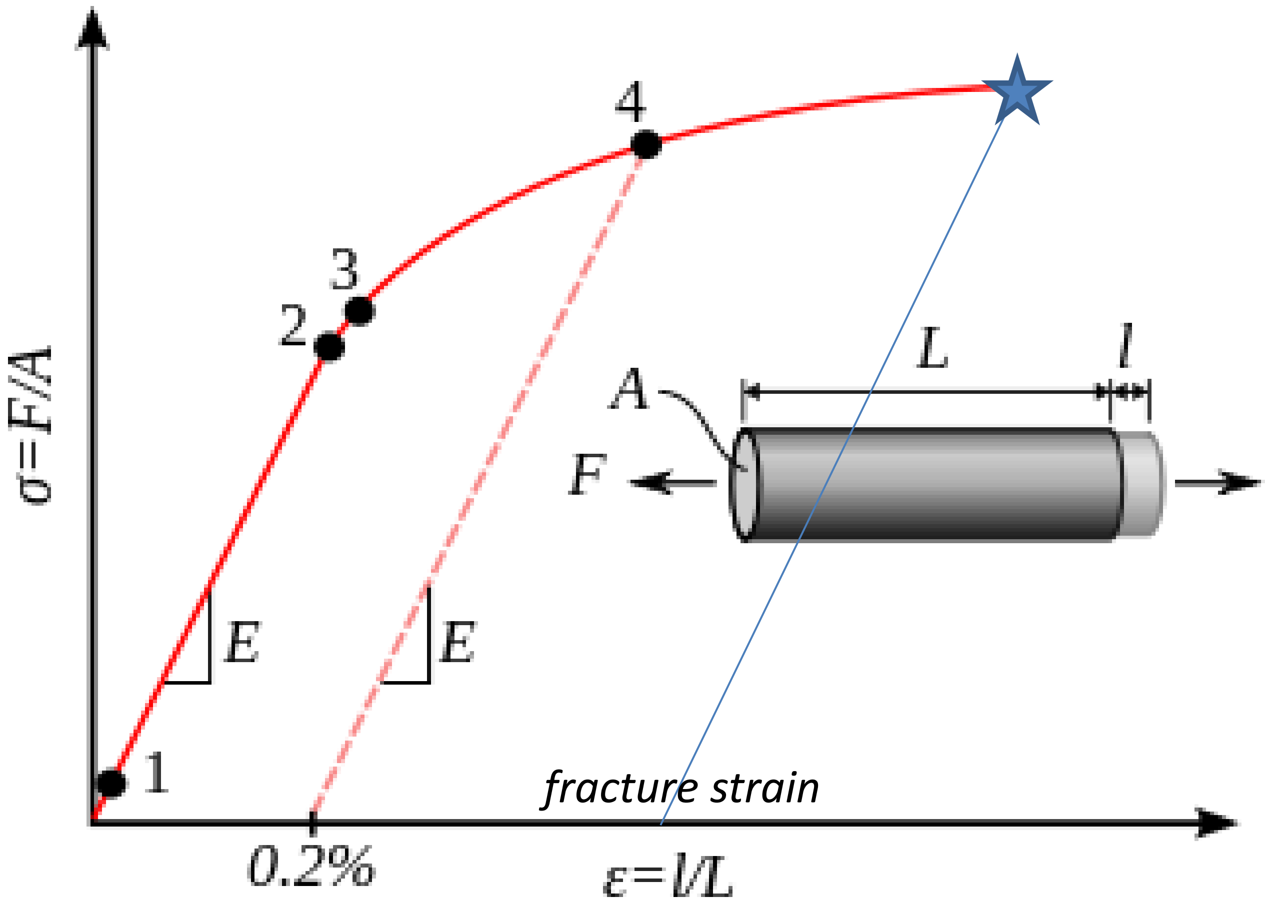
external or internal oxide-scale thicknesses that suggest higher-than-expected temperatures

intergranular voids and cracks in the microstructure



Schematic creep curve. Courtesy Babcock & Wilcox.

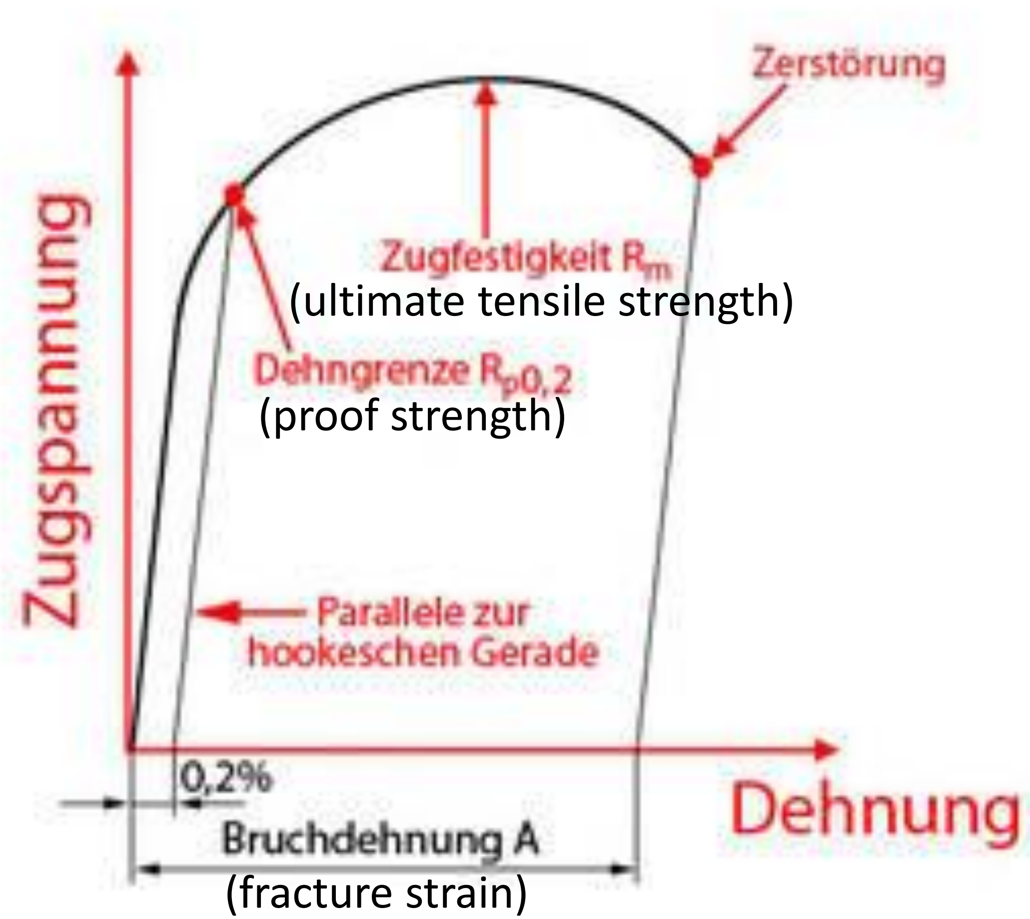
Specific characteristics of nuclear power engineering

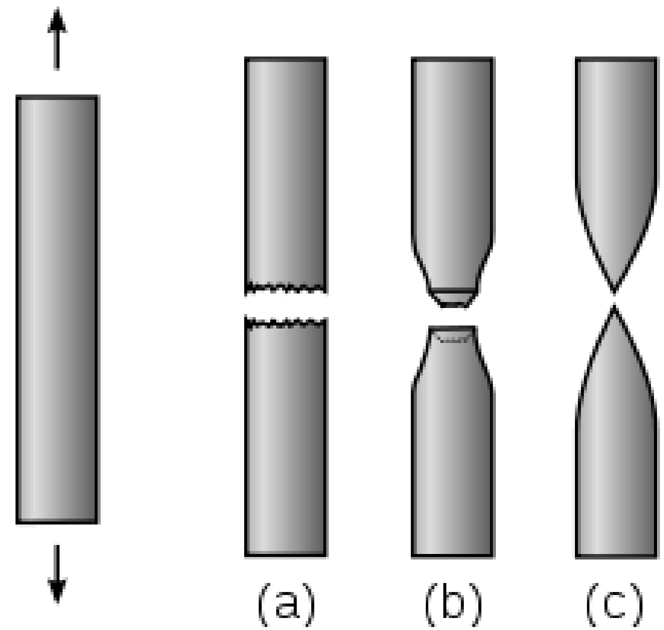


1- true elastic limit
2- proportionality limit
3-elastic limit
4-offset yield strength (proof strength)
★-rupture

Yield strength of:
Steel, high strength alloy: 690 MPa
Titanium alloy: 830 Mpa
Spider silk: 1140 MPa

Spannungs- Dehnungsdiagramm bei Werkstoffen ohne ausgeprägte Streckgrenze



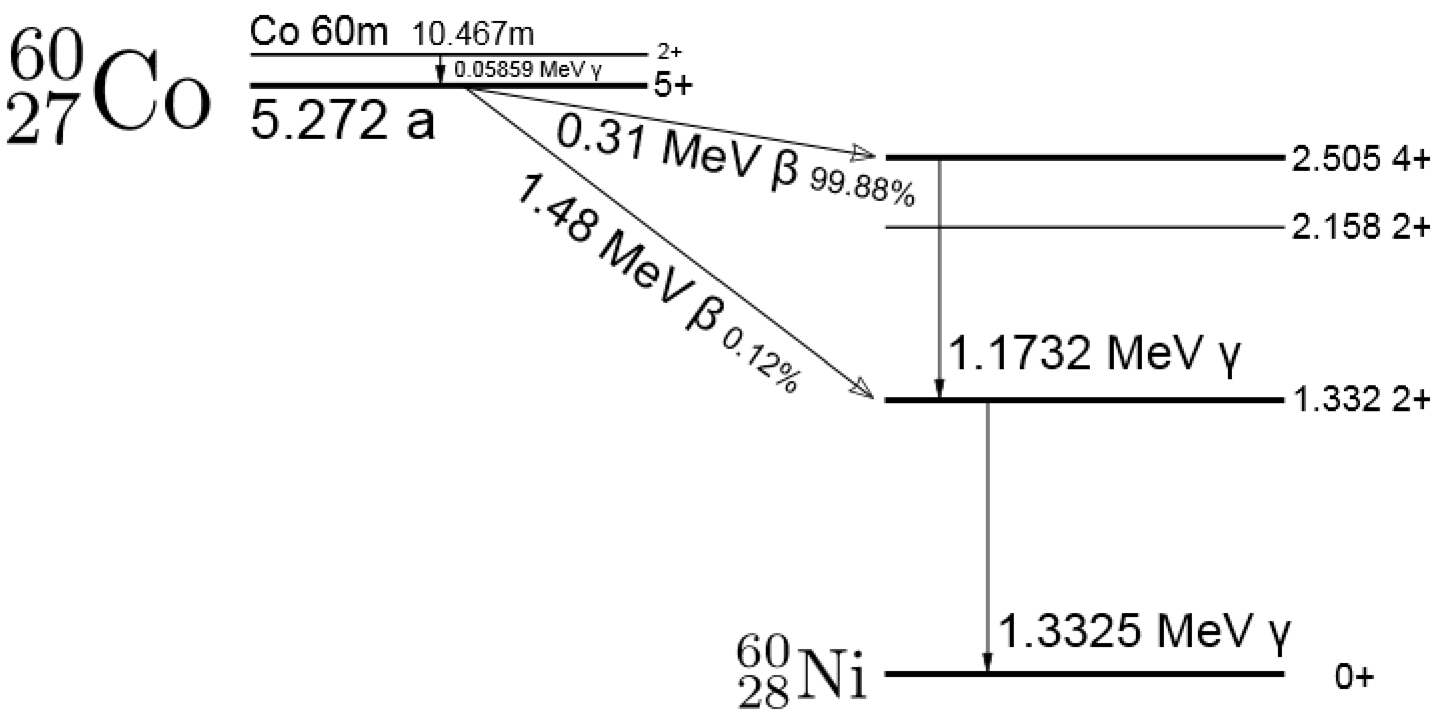


a) Sprödbruch (brittle fracture)
b) duktiler Bruch (ductile fracture)
c) vollständig duktiler Bruch

COBALT

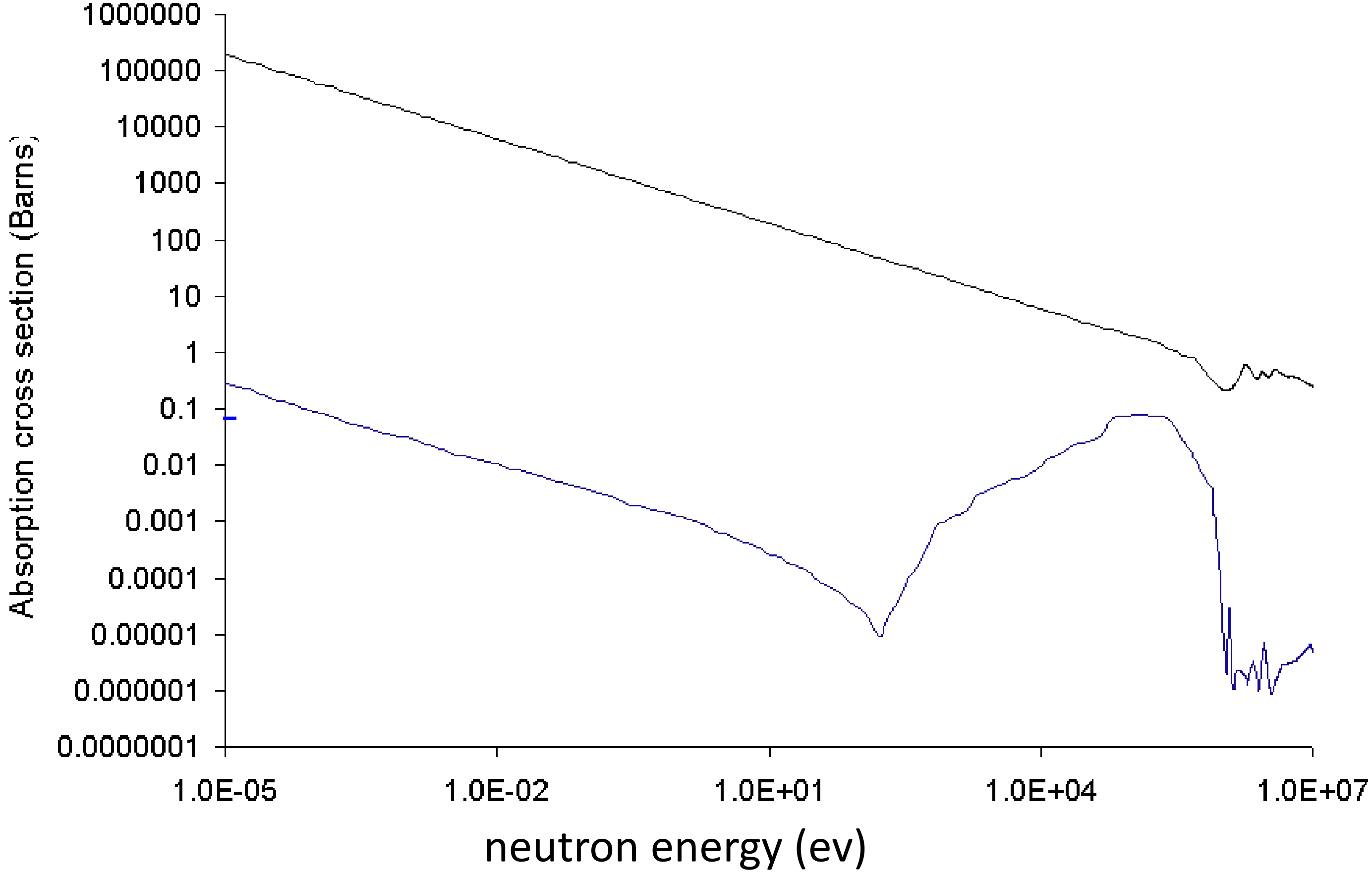
$$^{59}_{27}Co + n \rightarrow ^{60}_{27}Co$$

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + e^- + v_e + \gamma_1 + \gamma_2$$



Boron

The most important neutron absorber is ^{10}boron as $^{10}B_4C$ in control rods, or boric acid as a coolant water additive in PWRs

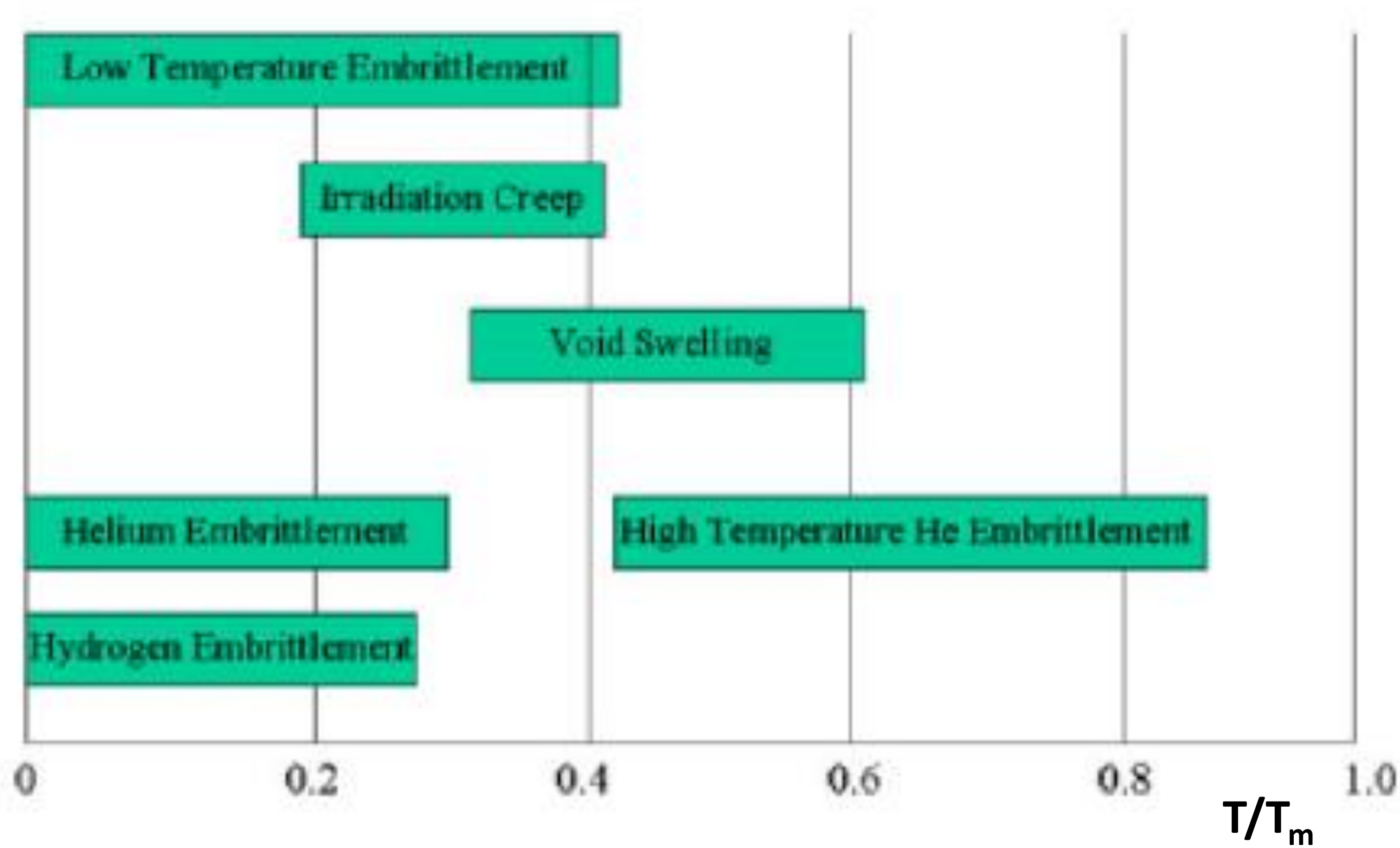


Neutron cross section of boron

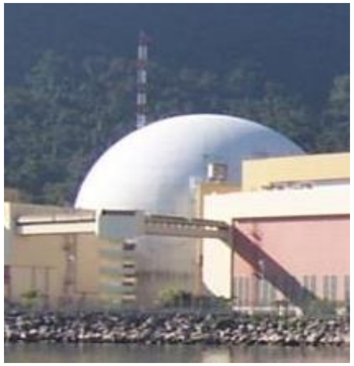
(top curve is for ^{10}B and bottom curve for ^{11}B)

Damage Regimes as a Function of Homologous Temperature

Homologous Temperature: Temperature in fractions of melting temperature



ANY LARGE SCALE HUMAN MADE TECHNOLOGY POSES RISKS TO ENVIRONMENT AND HUMANS



radioactive contamination	**environmental contamination**
misuse by proliferation	**climate change**
Three Miles Island **Chernobyl** **Fukushima**	**Casualties** **(mining)**

Specific characteristics of nuclear power engineering

Fuel-Dependent Emission Factors
Based on actual emissions from EU power plants (2008)

Pollutant	Hard coal	Brown coal	Fuel oil	Other oil	Gas
CO_2 (g/GJ)	94,600	101,000	77,400	74,100	56,100
SO_2 (g/GJ)	765	1,361	1,350	228	0.68
NO_x (g/GJ)	292	183	195	129	93.3
CO (g/GJ)	89.1	89.1	15.7	15.7	14.5
Non methane organic compounds (g/GJ)	4.92	7.78	3.70	3.24	1.58
Particulate matter (g/GJ)	1,203	3,254	16	1.91	0.1
Flue gas volume total (m^3/GJ)	360	444	279	276	272

Source:
European Environment Agency (EEA): 2008

Radioactive trace elements

coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes whose release into the environment leads to radioactive contamination.

A 1,000 MW coal-burning power plant could have an uncontrolled release 5.2 tons per year of uranium (containing 34 kg of uranium-235) and 12.8 tons per year of thorium.

In comparison, a 1,000 MW nuclear plant will generate about 30 tons of high-level radioactive solid packed waste per year. It should also be noted that during normal operation, the effective dose equivalent from coal plants is 100 times that from nuclear plants

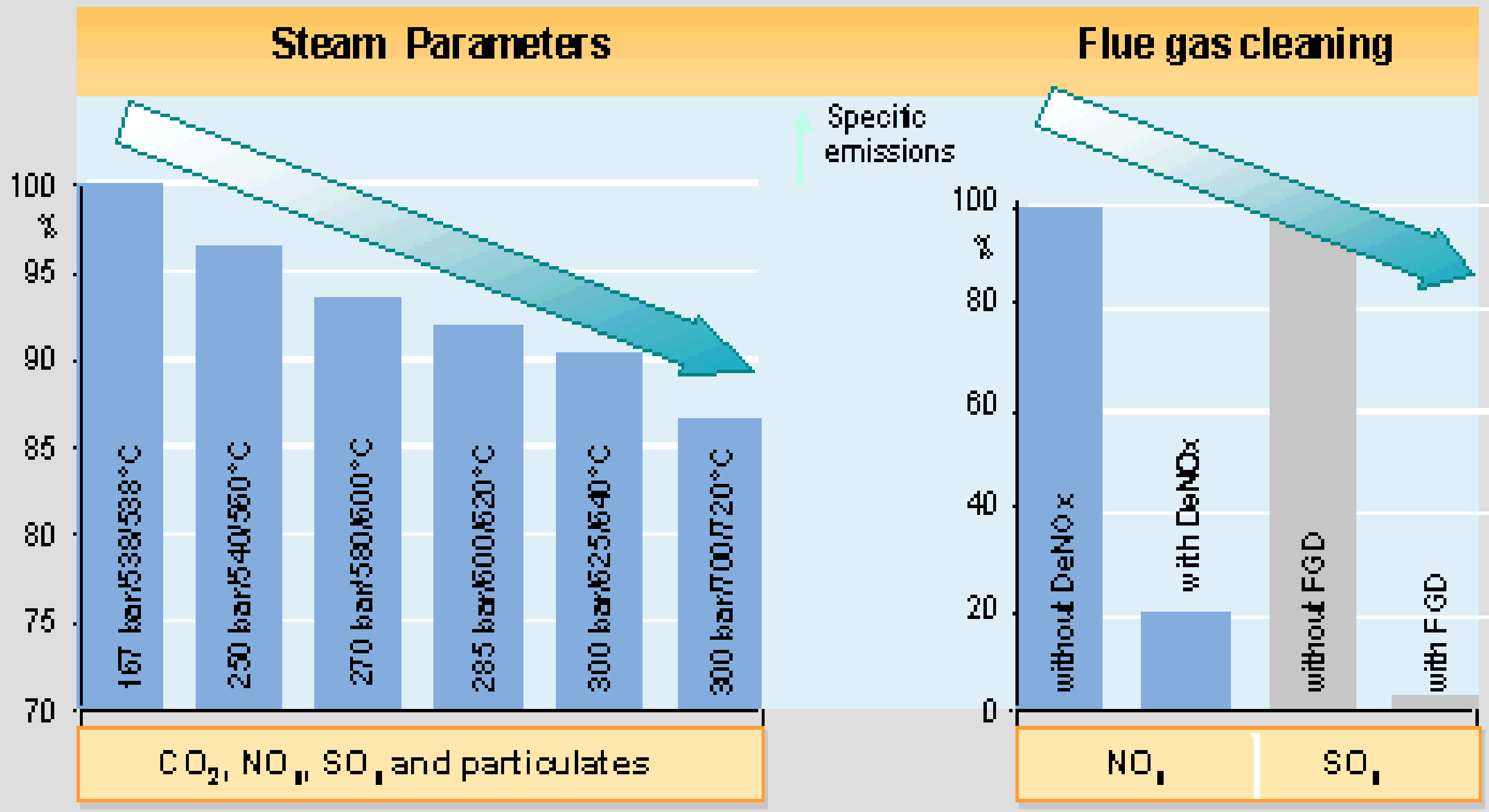
Mercury Contamination

U.S. government scientists tested fish
in 291 streams around the country
for mercury contamination.

They found mercury in every fish tested,
even in fish of isolated rural waterways.
Twenty five percent of the fish tested had mercury levels
above the safety levels.

The largest source of mercury contamination in the US
is coal-fueled power plant emissions

Low Emission Levels - Achieved by High Steam Parameters and Flue Gas Cleaning



LITERATURE

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2. J. Starflinger: *Super-Critical Water-cooled Reactors (SCWRs).* SCWR System Steering Committee (T. Schulenberg, H. Matsui, L. Leung, A. Sedov), GIF-INPRO Meeting, Vienna, Feb. 28 to March 1, 2013, Generation IV International Forum (GIF), www.iaea.org/NuclearPower/.../9.starflinger.pdf
3. D. Wilson, H. Khartabil: *Evaluation of Materials for Supercritical Water-Cooled Reactors,* I-NERI Project No. 2004-003-C, I-NERI 2005 Annual Report, pp. 23-27

Radioactive trace elements

Coal is a sedimentary rock formed primarily from accumulated plant matter, and it includes many inorganic minerals and elements which were deposited along with organic material during its formation. As the rest of the Earth's crust, coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes whose release into the environment leads to radioactive contamination. While these substances are present as very small trace impurities, enough coal is burned that significant amounts of these substances are released. A 1,000 MW coal-burning power plant could have an uncontrolled release of as much as 5.2 metric tons per year of uranium (containing 74 pounds (34 kg) of uranium-235) and 12.8 metric tons per year of thorium.[22] In comparison, a 1,000 MW nuclear plant will generate about 30 short tons of high-level radioactive solid packed waste per year.[23] It is estimated that during 1982, US coal burning released 155 times as much uncontrolled radioactivity into the atmosphere as the Three Mile Island incident.[24] The collective radioactivity resulting from all coal burning worldwide between 1937 and 2040 is estimated to be 2,700,000 curies or 0.101 EBq.[22] It should also be noted that during normal operation, the effective dose equivalent from coal plants is 100 times that from nuclear plants.[22] But it is also worth noting that normal operation is a deceiving baseline for comparison: just the Chernobyl nuclear disaster released, in iodine-131 alone, an estimated 1.76 EBq .[25] of radioactivity, a value one order of magnitude above this value for total emissions from all coal burned within a century. But at the same time, it shall also be understood that the iodine-131, the major radioactive substance which comes out in accident situations, has a half life of just 8 days.