The Abdus Salam International Centre for Theoretical Physics

**2291-2**

**Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors**

*27 June - 1 July, 2011*

**Introduction and Historical Development of Supercritical Water-cooled Reactors (SCWRs)**

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# LECTURE SC02
# Introduction and Historical Development of Supercritical Water-cooled Reactors (SCWRs)

**Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy, 27 June - 1 July 2011**

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**University of Ontario Institute of Technology, Canada**

# Objectives

Objectives of this Lecture are to:

- Introduce Thermophysical Properties of Supercritical Fluids Based on Those of Water and Carbon Dioxide;
- Present a History of Supercritical Pressures Application in Power Industry; and
- Present Historical Development of SCWR Concepts.

# GLOSSARY & DEFINITIONS OF SELECTED TERMS & EXPRESSIONS RELATED TO CRITICAL & SUPERCRITICAL REGIONS SPECIFICS

**Symbols and abbreviations in this lecture are according to book by Pioro & Duffey (2007)**

***Compressed fluid*** is a fluid at a pressure above the critical pressure but at a temperature below the critical temperature.

***Critical point*** (also called a *critical state*) is the point where the distinction between the liquid and gas (or vapour) phases disappears, i.e., both phases have the same temperature, pressure and volume. The *critical point* is characterized by the phase state parameters $T_{cr}$, $p_{cr}$ and $V_{cr}$, which have unique values for each pure substance.

***Near-critical point*** is actually a narrow region around the critical point where all the thermophysical properties of a pure fluid exhibit rapid variations.

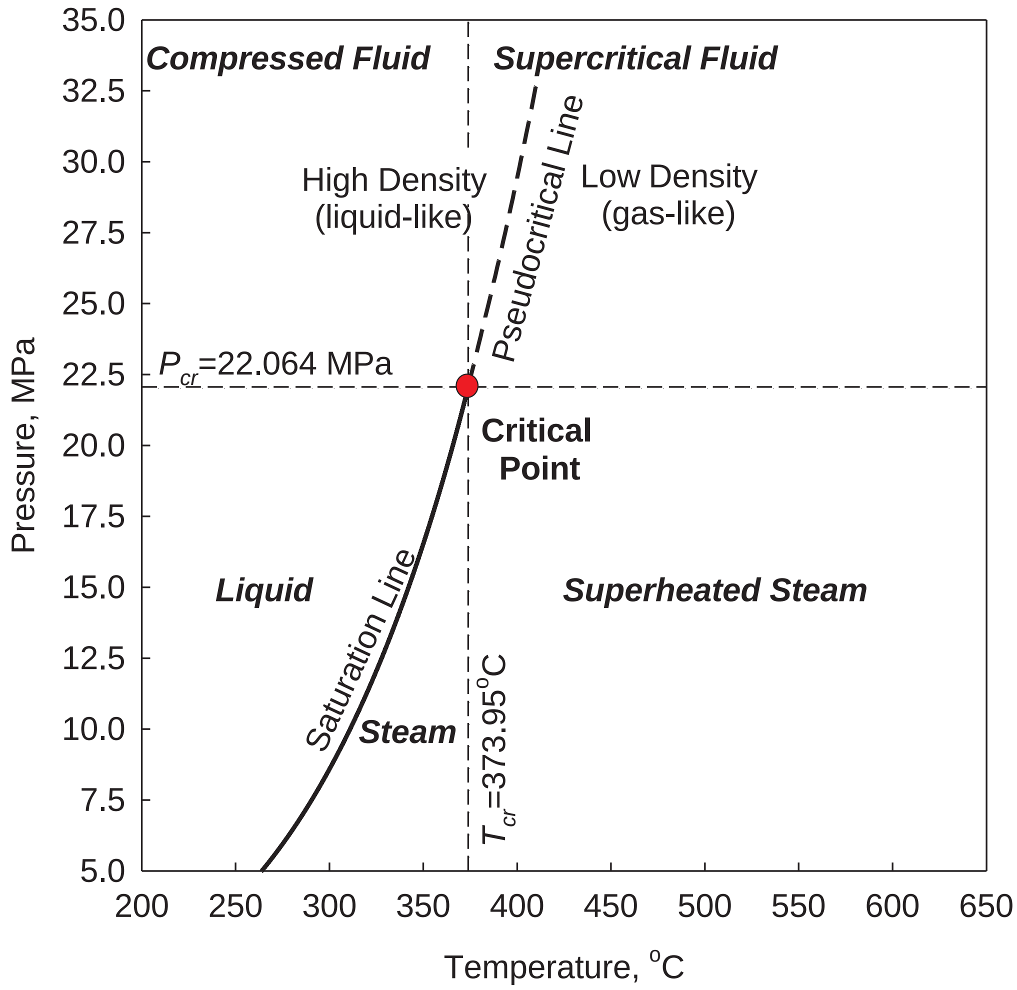
***Pseudocritical point*** (characterized with $p_{pc}$ and $t_{pc}$) is a point at a pressure above the critical pressure and at a temperature ($t_{pc} > t_{cr}$) corresponding to the maximum value of the specific heat for this particular pressure.

***Supercritical fluid*** is a fluid at pressures and temperatures that are higher than the critical pressure and critical temperature. However, in the present monograph, the term *supercritical fluid* includes both terms – a *supercritical fluid* and *compressed fluid*.

***Supercritical steam*** is actually supercritical water because at supercritical pressures there is no difference between phases. However, this term is widely (and incorrectly) used in the literature in relation to supercritical steam generators and turbines.

***Superheated steam*** is a steam at pressures below the critical pressure but at temperatures above the critical temperature.

# P-T diagram for Water



# Part 1
# Thermophysical Properties of Water and Carbon Dioxide at Critical and Supercritical Pressures

# Critical Parameters of Selected Fluids

| Fluid | $P_{cr}$, MPa | $T_{cr}$, ºC | $\rho_{cr}$, kg/m$^3$ |
|---|---|---|---|
| **Carbon dioxide ($CO_2$)** | 7.3773 | 30.978 | 467.6 |
| **Freon-134a (1,1,1,2-tetrafluoroethane, $CH_2FCF_3$)** | 4.0593 | 101.06 | 511.9 |
| **Water ($H_2O$)** | 22.064 | 373.95 | 322.39 |

## Question

## How to calculate thermophysical properties of fluids (liquid and gases) at various pressures and temperatures including critical and supercritical regions?

## Answer

## Use National Institute of Standards and Technology (USA) Reference Properties software (NIST REFPROP Ver. 9)

# Why NIST REFPROP?

**Version 9.0 includes 105 pure fluids, 5 pseudo-pure fluids (such as air) and mixtures with up to 20 components:**

**Typical natural gas constituents** methane, ethane, propane, butane, isobutane, pentane, isopentane, hexane, isohexane, heptane, octane, nonane, decane, dodecane, **carbon dioxide***, carbon monoxide, hydrogen, nitrogen, and **water***.

**Hydrocarbons** acetone, benzene, butene, cis-butene, cyclohexane, cyclopentane, cyclopropane, ethylene, isobutene, methylcyclohexane, propylcyclohexane, neopentane, propyne, trans-butene, and toluene.

**HFCs** (**HydroFluoroCarbons**) R23, R32, R41, R125, R134a, R143a, R152a, R161, R227ea, R236ea, R236fa, R245ca, R245fa, R365mfc, R1234yf, and R1234ze(E).

**HCFCs** (**HydroChloroFluoroCarbons**) R21, R22, R123, R124, R141b, and R142b.

**Traditional CFCs** (**ChloroFluoroCarbons**) R11, R12, R13, R113, R114, and R115.

**Fluorocarbons** R14, R116, R218, C4F10, C5F12, and RC318.

**“Natural" refrigerants** ammonia, carbon dioxide, propane, isobutane, and propylene.

**Main air constituents** nitrogen, oxygen, and argon.

**Noble elements** **helium***, argon, neon, krypton, and xenon.

**Cryogens** argon, carbon monoxide, deuterium, krypton, neon, nitrogen trifluoride, nitrogen, fluorine, helium, methane, oxygen, normal hydrogen, parahydrogen and orthohydrogen.

**Water** (as a pure fluid, or mixed with ammonia).

**Miscellaneous substances** including carbonyl sulfide, dimethyl carbonate, dimethyl ether, ethanol, heavy water, hydrogen sulfide, methanol, nitrous oxide, sulfur hexafluoride, sulfur dioxide, and trifluoroiodomethane.

**FAMES** (**Fatty Acid Methyl ESers**, i.e., biodiesel constituents): methyl oleate, methyl palmitate, methyl stearate, methyl linoleate, and methyl linolenate.

**Siloxanes** octamethylcyclotetrasiloxane, decamethylcyclopentasiloxane, dodecamethylcyclohexasiloxane, decamethyltetrasiloxane, dodecamethylpentasiloxane, tetradecamethylhexasiloxane, octamethyltrisiloxane, and hexamethyldisiloxane.

**67 predefined mixtures** (such as R407C, R410A, and air); the user may define and store others.

*** reactors`coolants**

# Why NIST REFPROP?

**Available properties:**

**Temperature, Pressure, Density, Energy, Enthalpy, Entropy, Specific Heat at constant volume and pressure, Sound Speed, Compressibility Factor, Joule Thompson Coefficient, Quality, 2$^{nd}$ and 3$^{rd}$ Virial Coefficients, Helmholtz Energy, Gibbs Energy, Heat of Vaporization, Fugacity, Fugacity Coefficient, K value, Molar Mass, Thermal Conductivity, Viscosity, Kinematic Viscosity, Thermal Diffusivity, Prandtl Number, Surface Tension, Dielectric Constant, Isothermal Compressibility, Volume Expansivity, Isentropic Coefficient, Adiabatic Compressibility, Specific Heat Input, Exergy, dp/dr, $d^2p/dr^2$, dp/dT, dr/dT, dr/dp, and many others.**

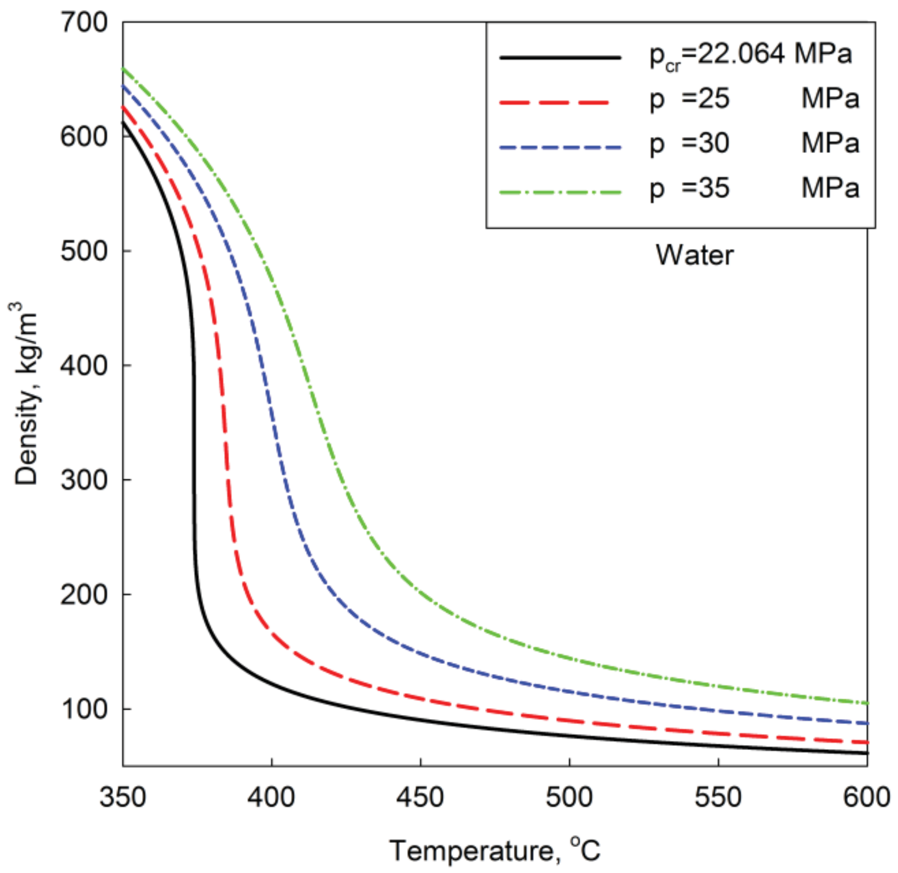
# Why NIST REFPROP?

**Source code: The FORTRAN subroutines and associated fluid data files are provided for those wishing to access REFPROP calculations from their own applications.**

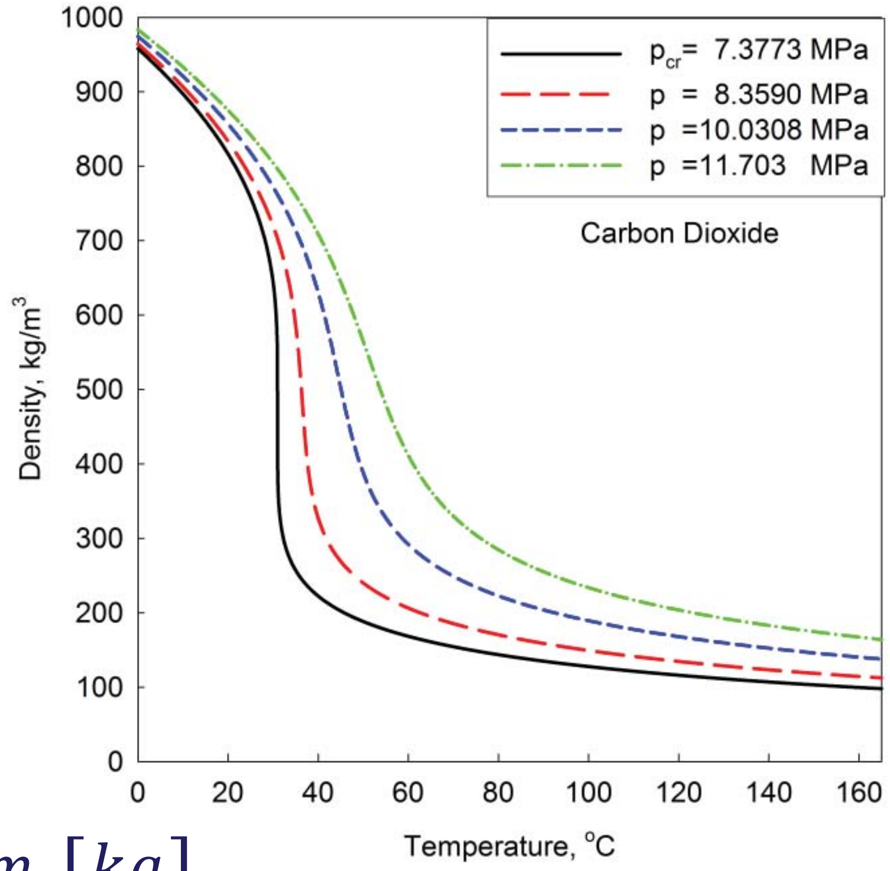
**Excel spreadsheets: Two sample spreadsheets are included that demonstrate how the REFPROP DLL can be linked to Excel. Most properties that are available in the graphical interface can also be calculated in the spreadsheets.**

# Density vs. Temperature

## Water

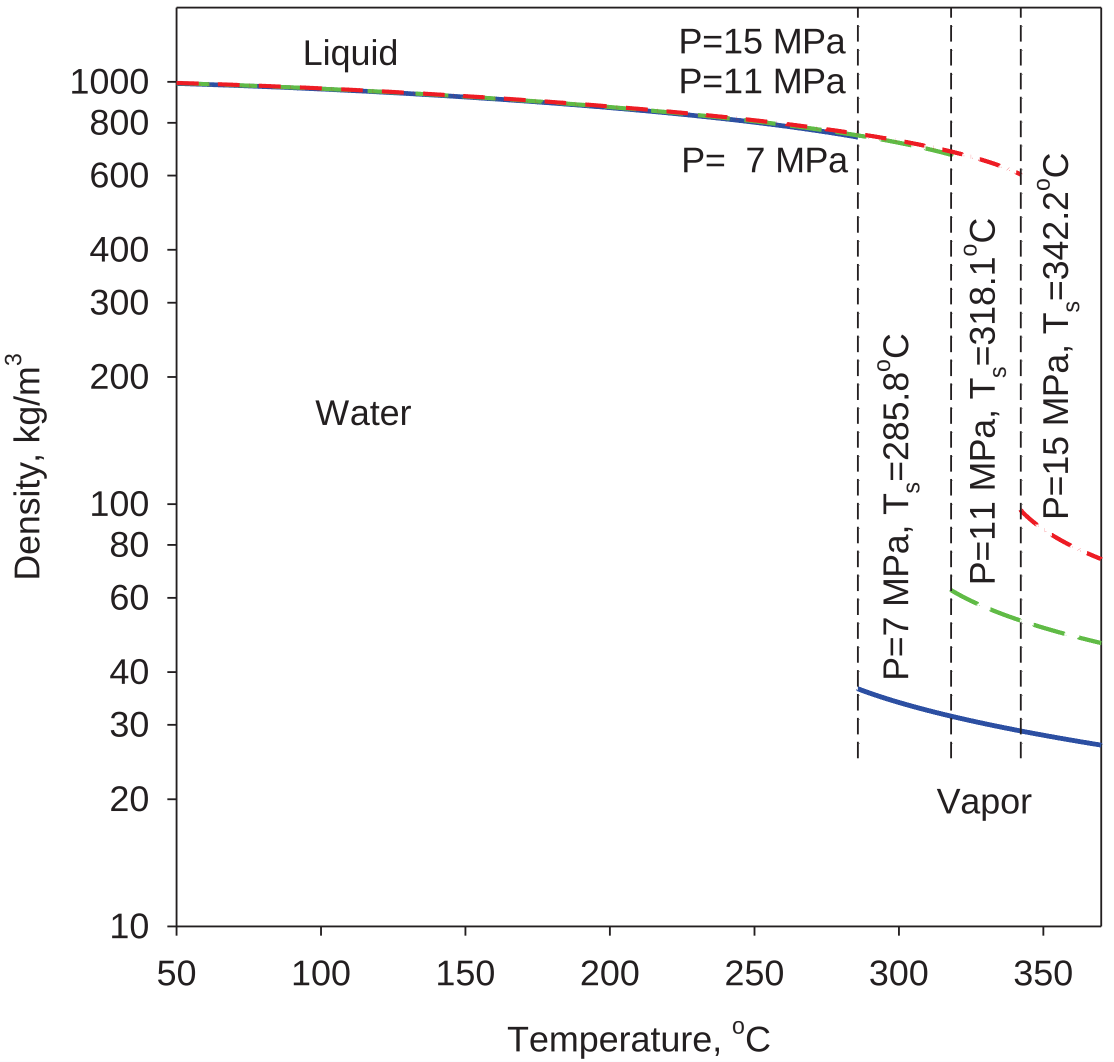



## Carbon Dioxide



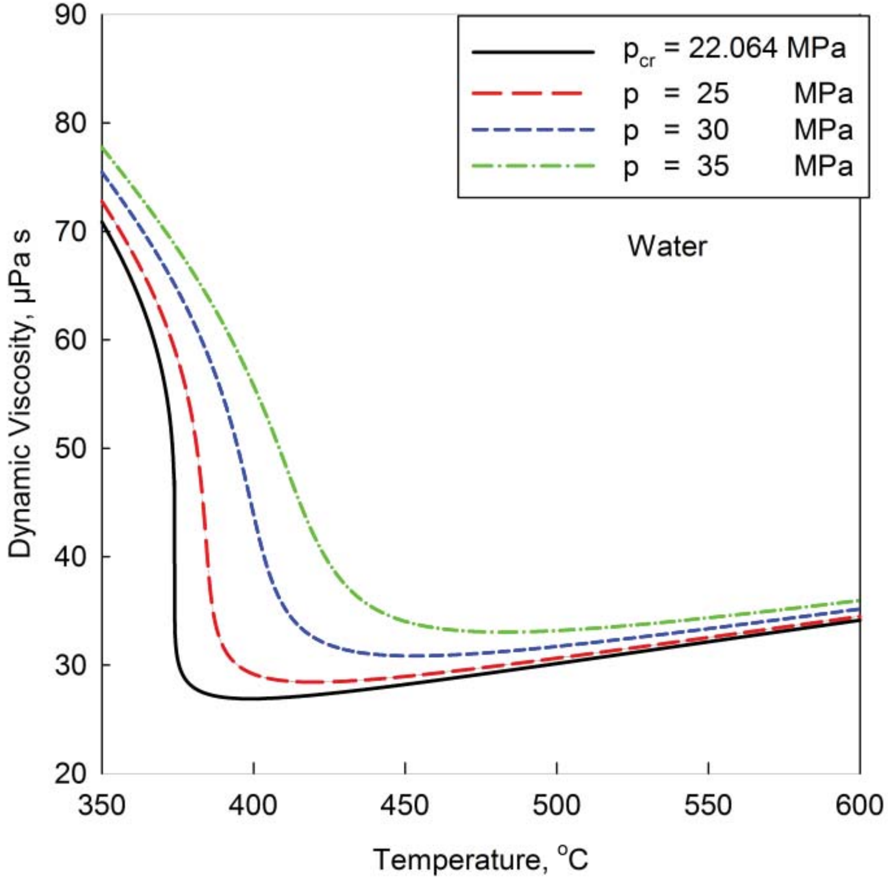

$$\rho = \frac{m}{V}\left[\frac{kg}{m^3}\right]$$

# Density Variations at Various Subcritical Pressures for Water:

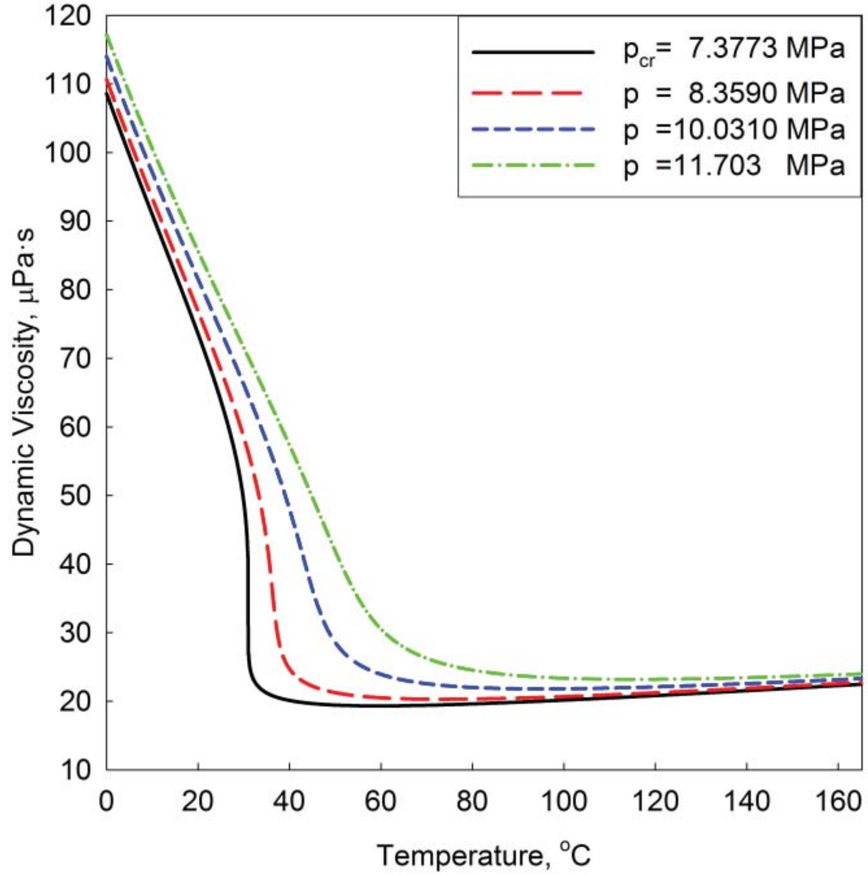


# Dynamic Viscosity vs. Temperature

## Water




## Carbon Dioxide

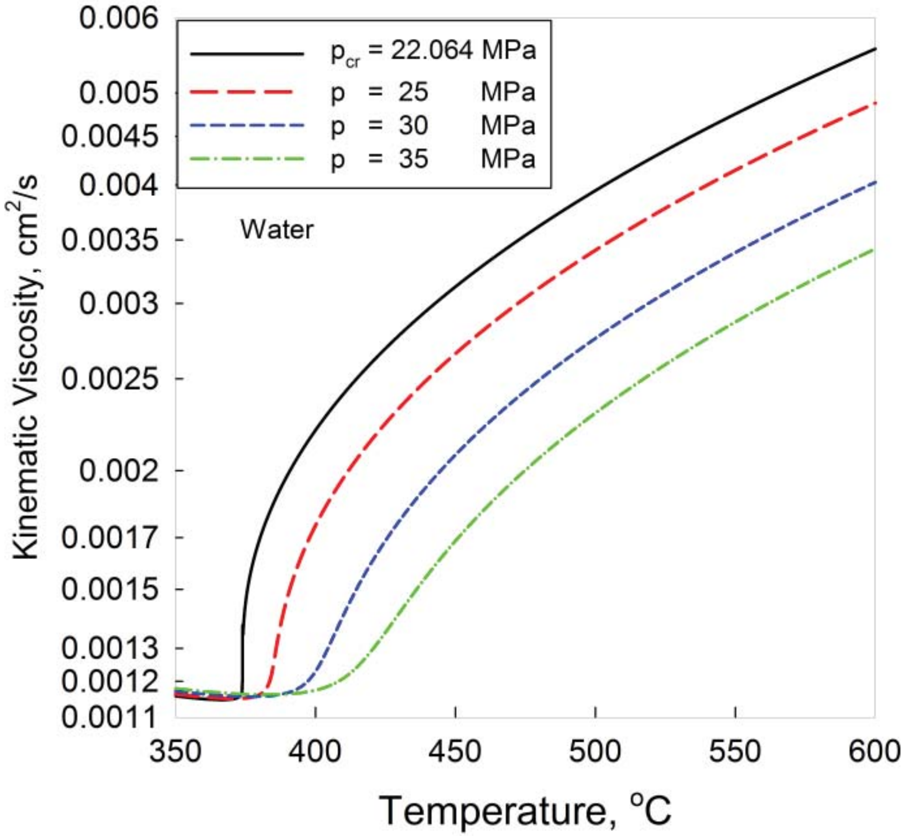


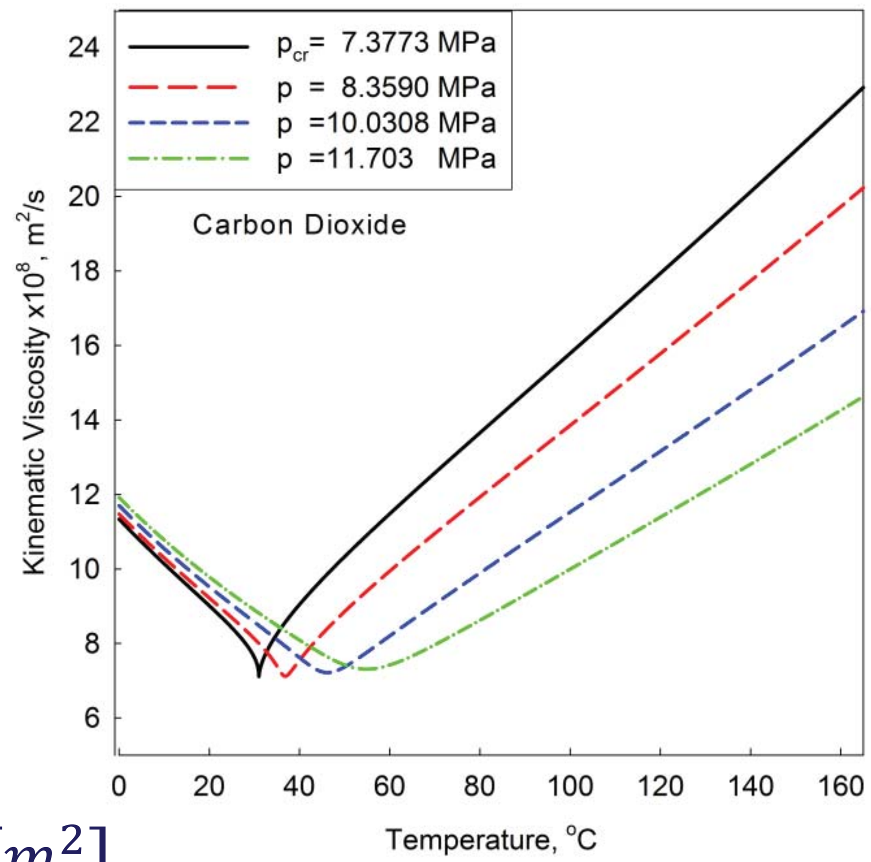

$\mu$ [Pa s]

# Kinematic Viscosity vs. Temperature

**Water**

**Carbon Dioxide**

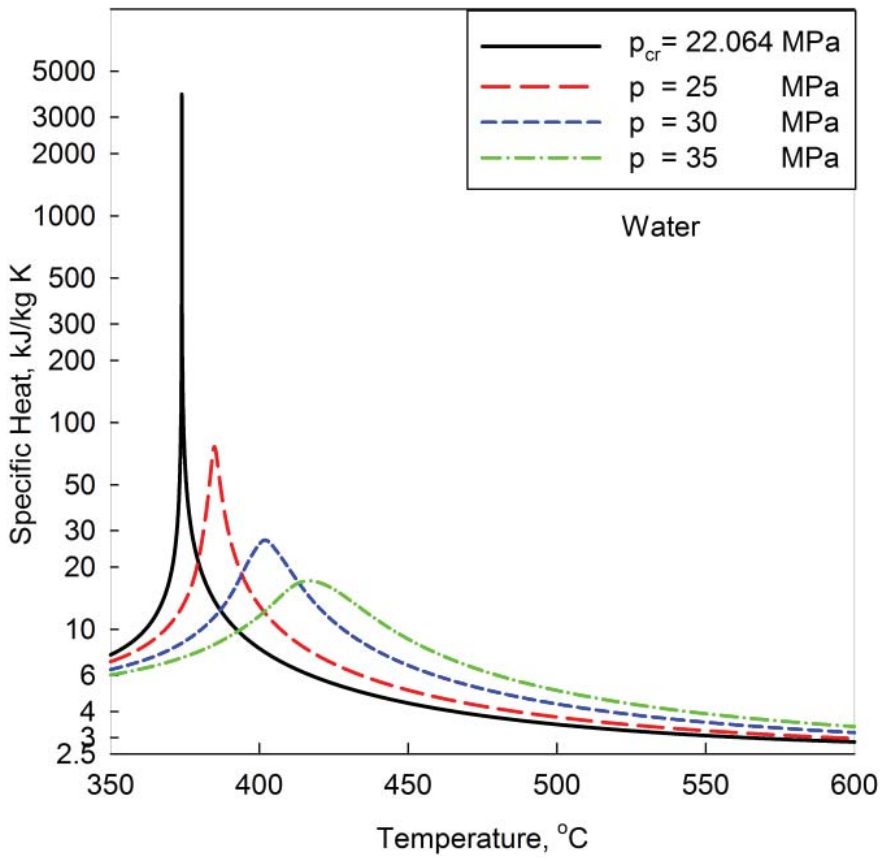


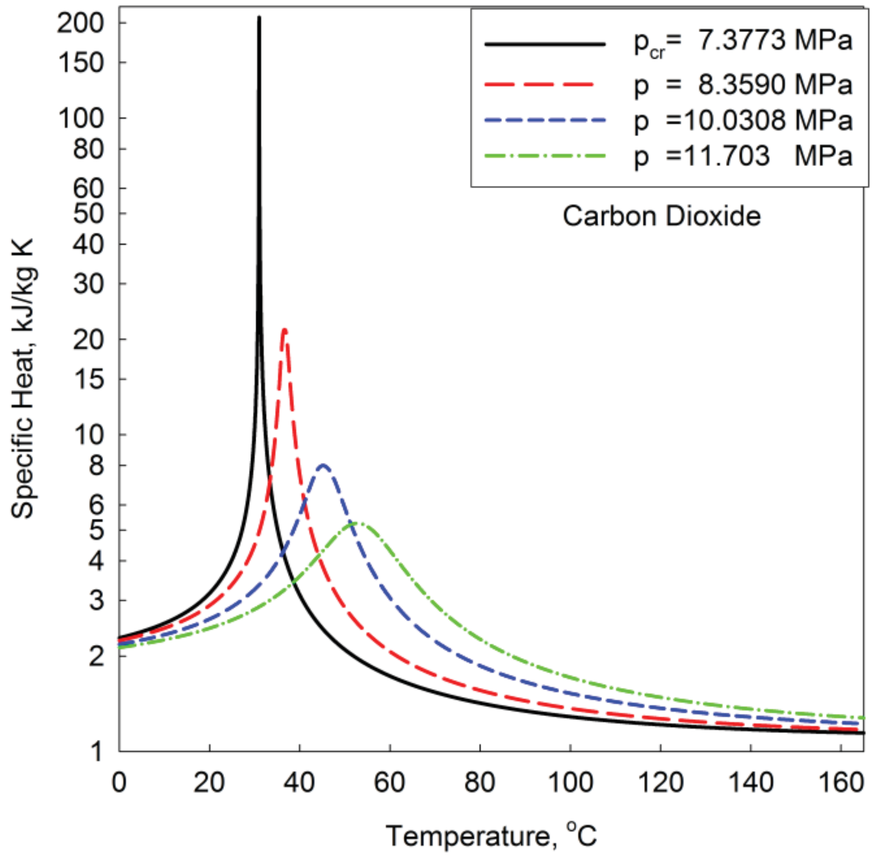

$$\nu = \frac{\mu}{\rho}\left[\frac{m^2}{s}\right]$$

# Specific Heat vs. Temperature

## Water

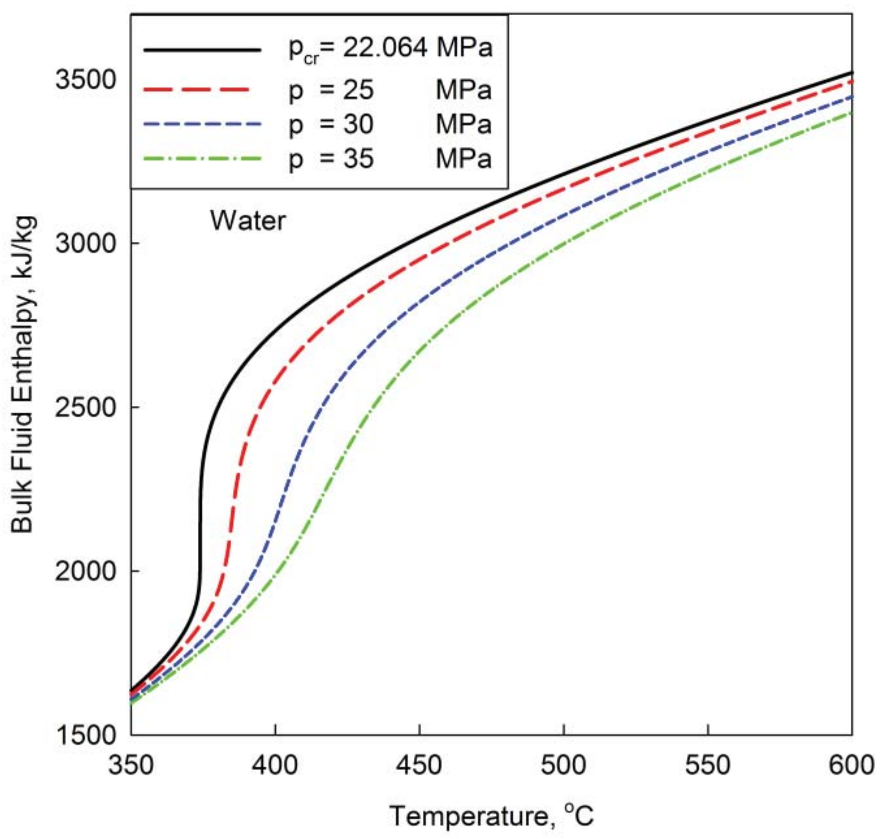



## Carbon Dioxide

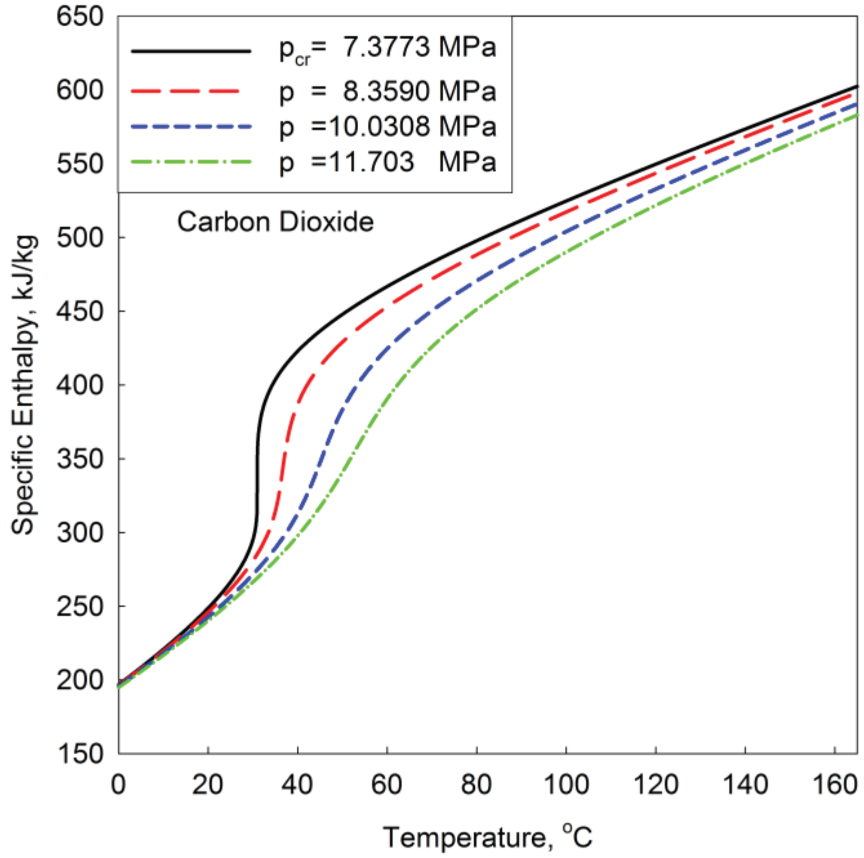


# Specific Enthalpy vs. Temperature

## Water

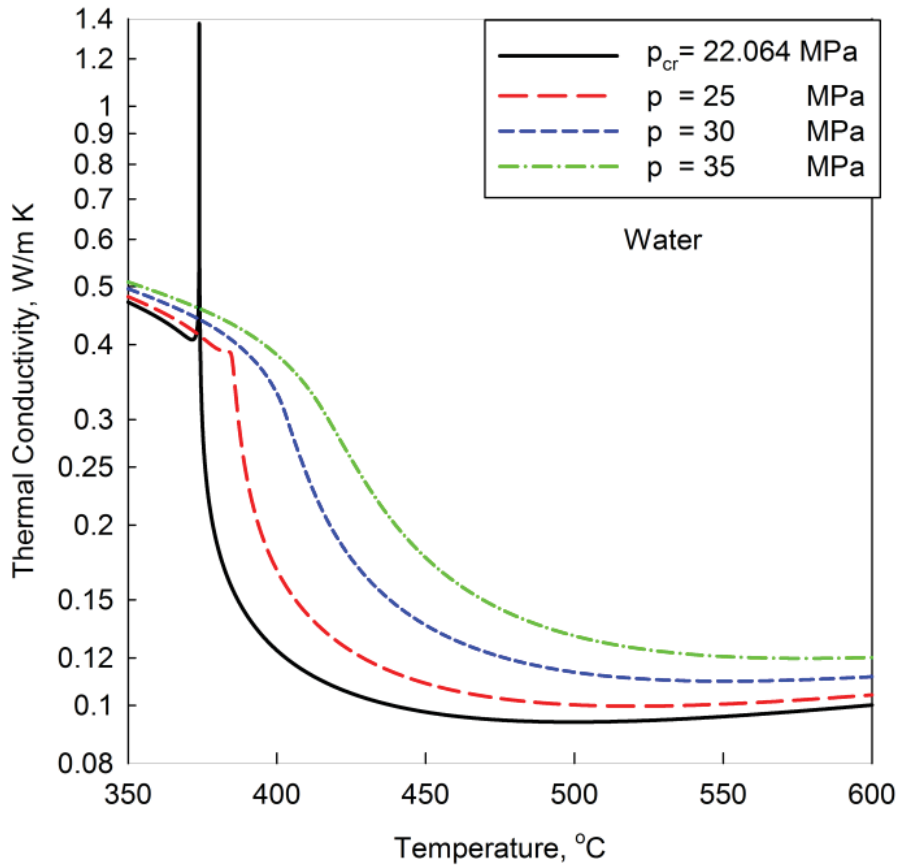



## Carbon Dioxide

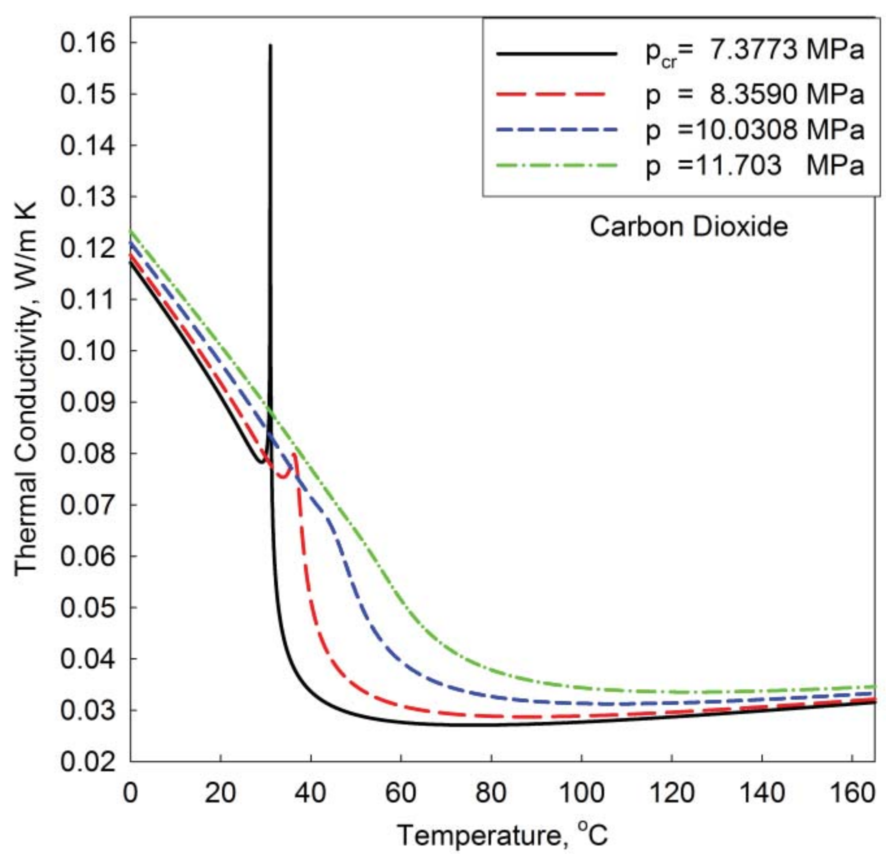


# Thermal Conductivity vs. Temperature

## Water

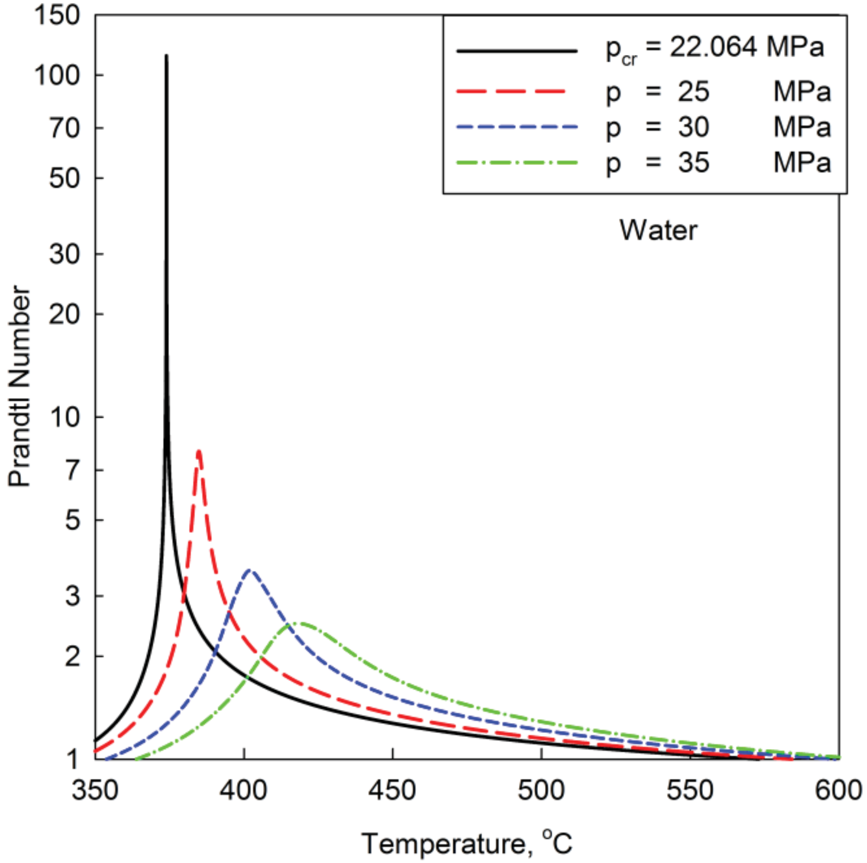



## Carbon Dioxide

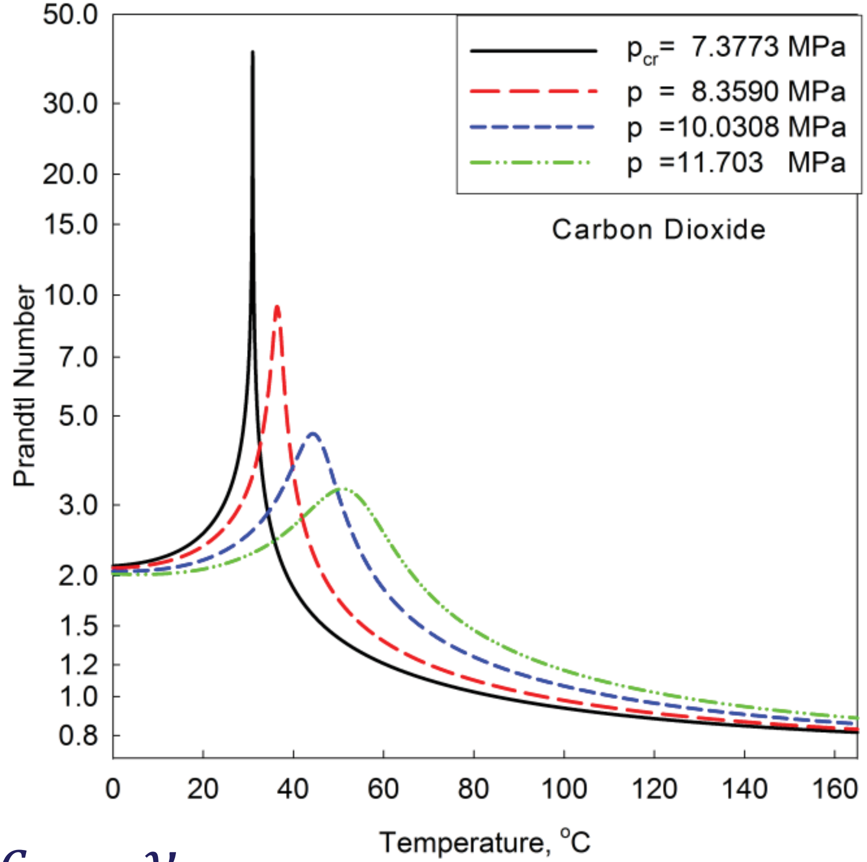


# Prandtl Number vs. Temperature

## Water



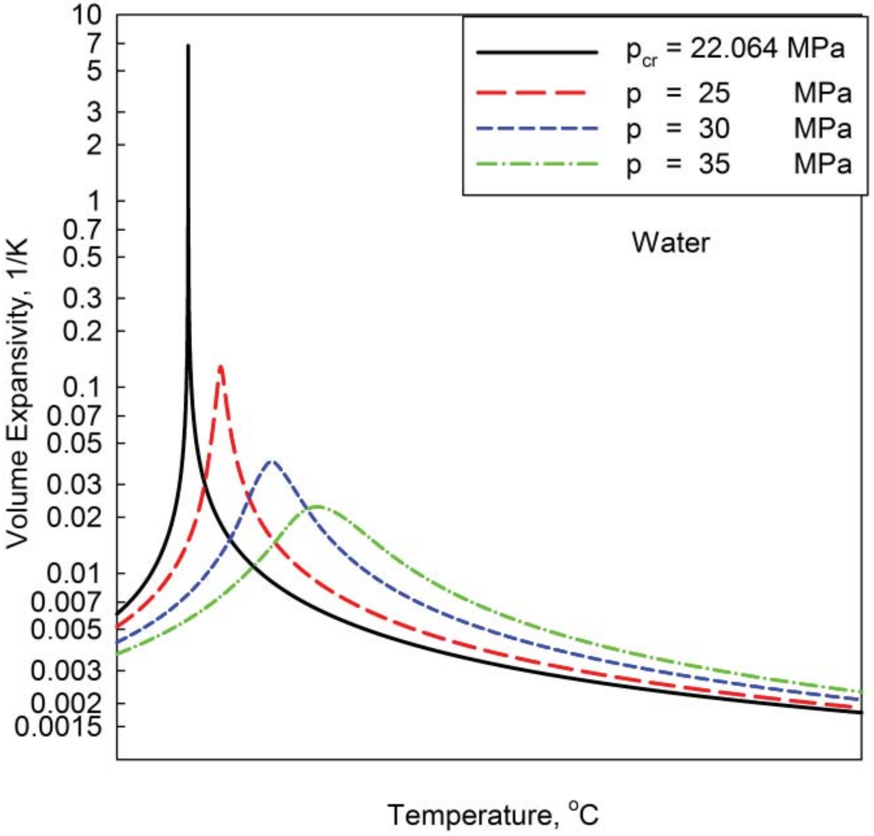

## Carbon Dioxide



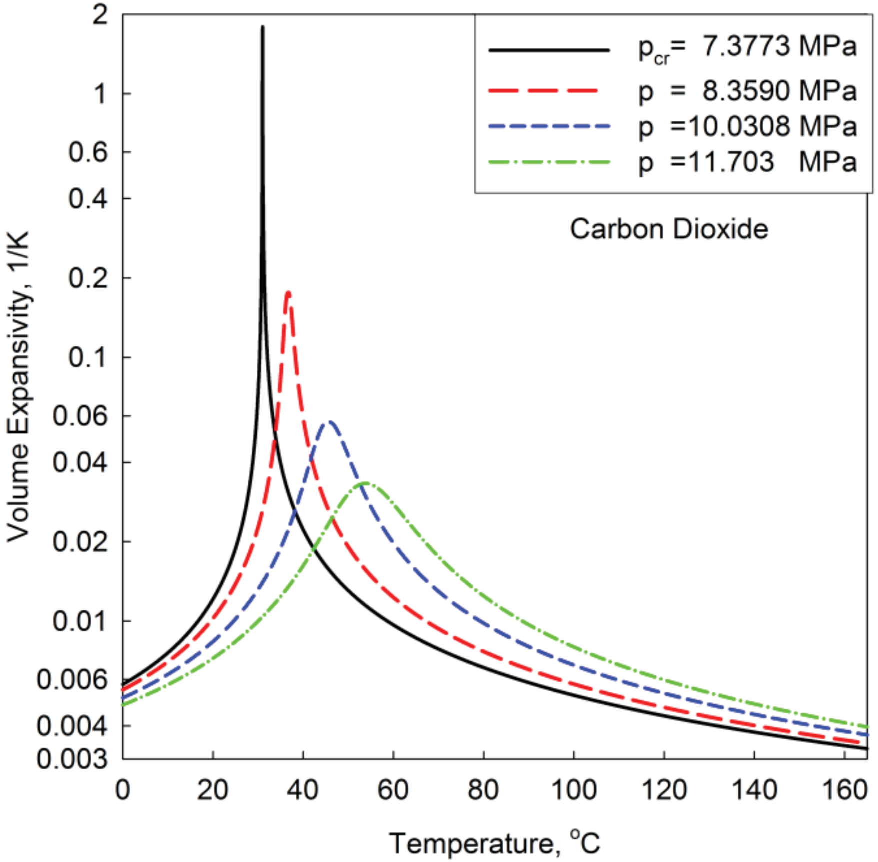

$$\mathbf{Pr} = \frac{\mu \, c_p}{k} = \frac{\nu}{\alpha}$$

# Volume Expansivity vs. Temperature

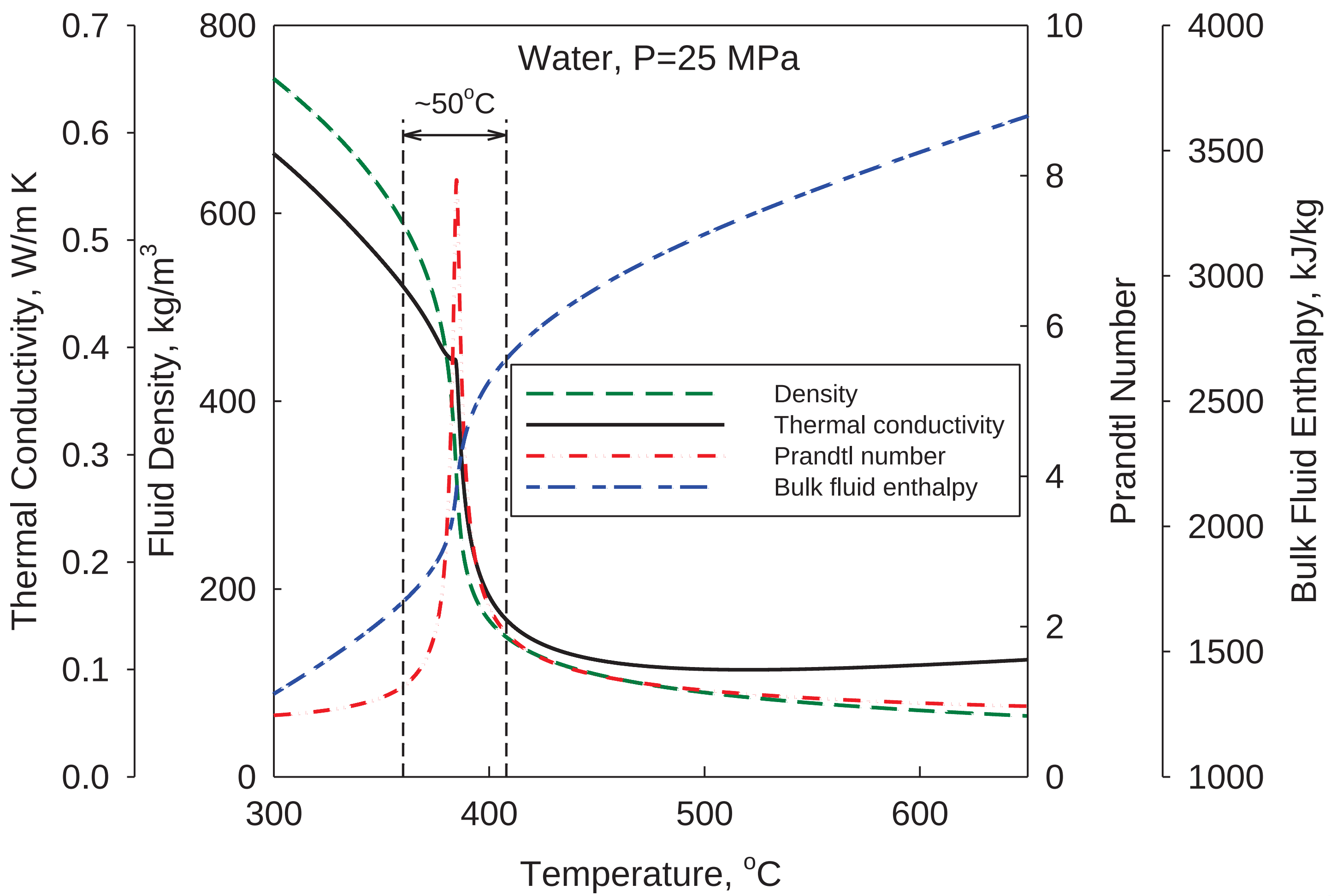
## Water



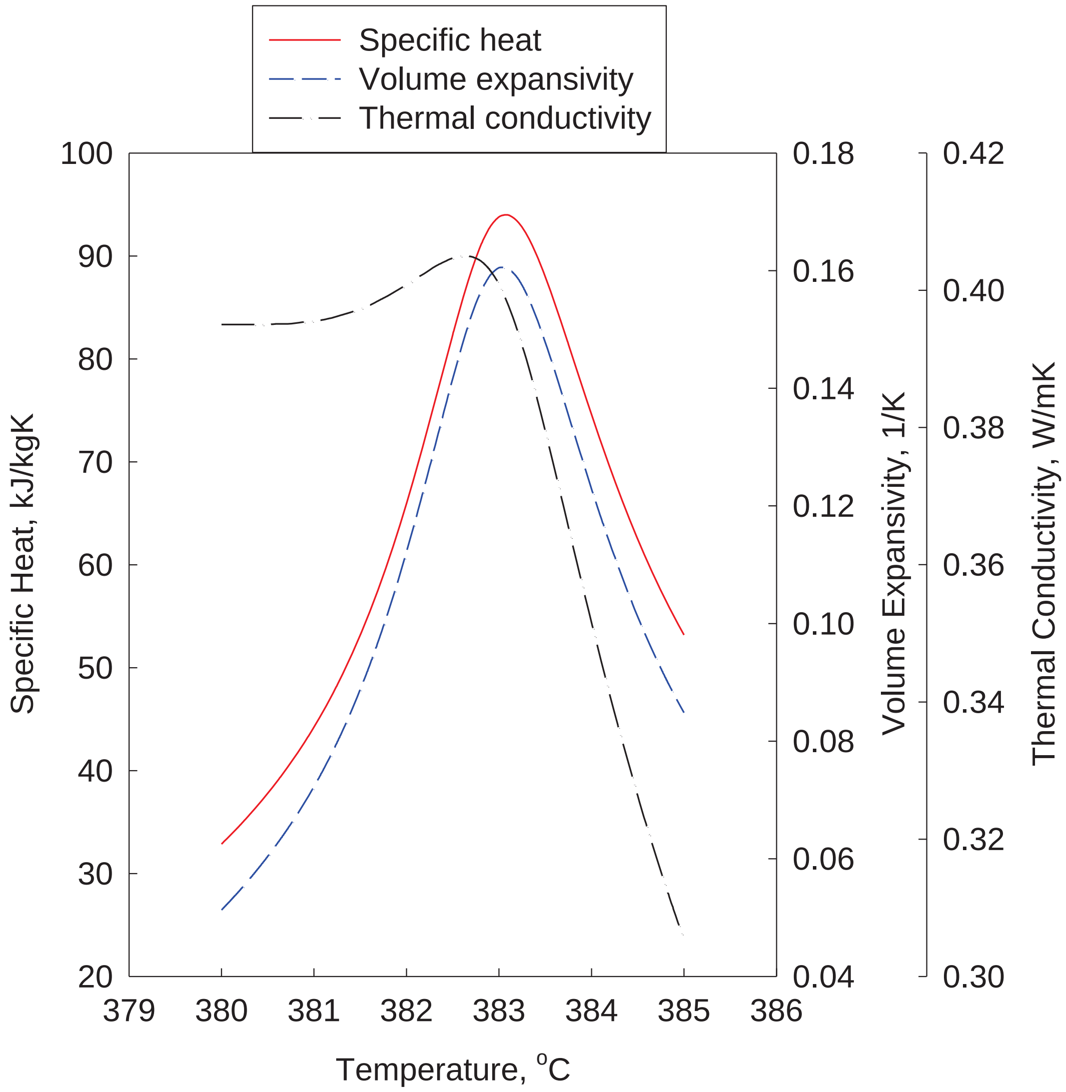

## Carbon Dioxide



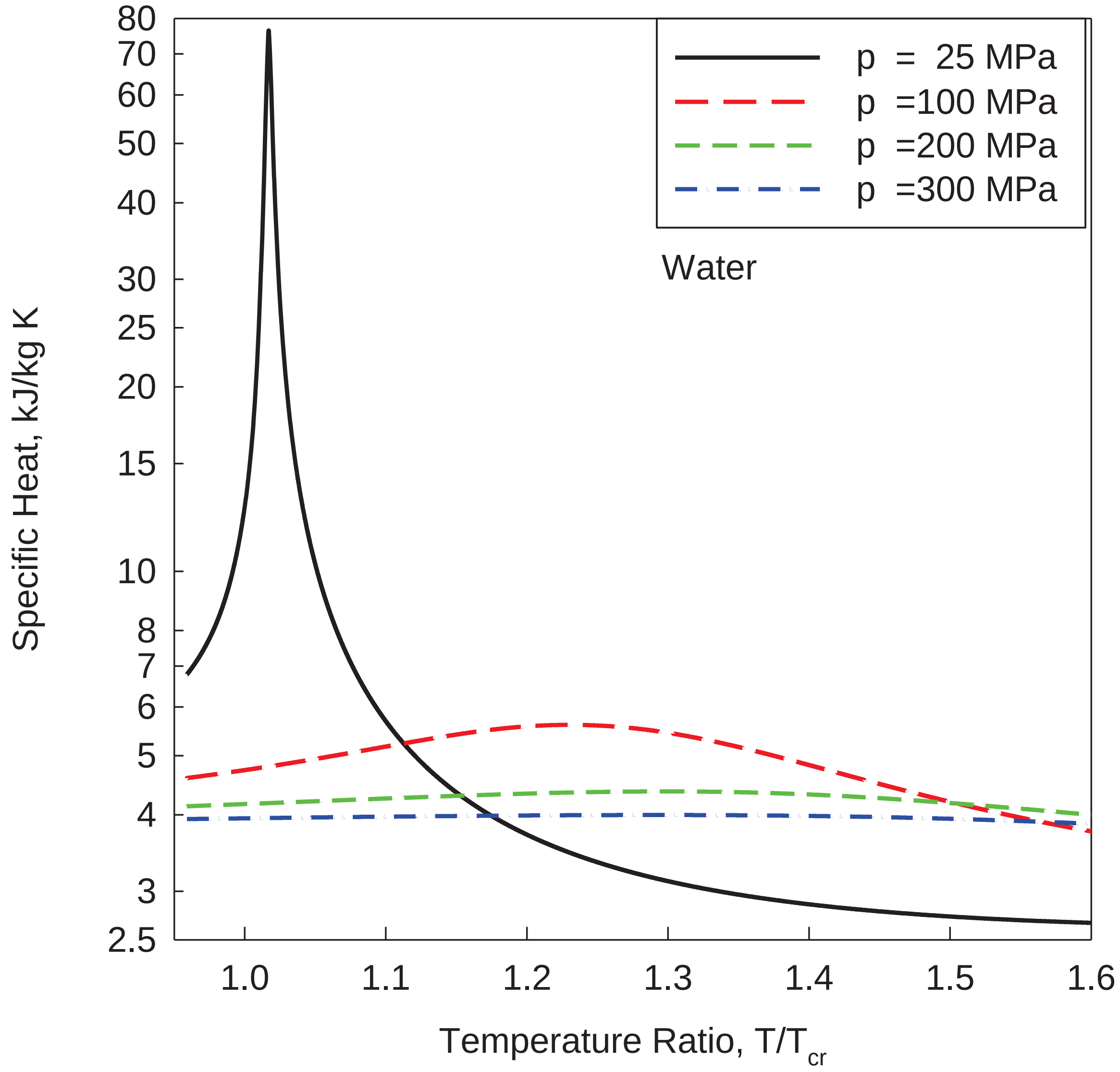
# Variations of Selected Thermophysical Properties of Water near Pseudocritical Point: Pseudocritical Region at 25 MPa is about ±25°C around Pseudocritical Point



# Specific Heat, Volume Expansivity and Thermal Conductivity vs. Temperature: Water, *P* = 24.5 MPa



# Specific Heat Variations at Various Pressures: Water



# Values of Pseudocritical Temperature and Corresponding Peak Values of Specific Heat within Wide Range of Pressure

| Pressure, MPa | Pseudocritical temperature, ºC | Peak value of specific heat, kJ/kg·K |
|---|---|---|
| **23** | 377.5 | 284.3 |
| **24** | 381.2 | 121.9 |
| **25** | 384.9 | 76.4 |
| **26** | 388.5 | 55.7 |
| **27** | 392.0 | 43.9 |
| **28** | 395.4 | 36.3 |
| **29** | 398.7 | 30.9 |
| **30** | 401.9 | 27.0 |
| **31** | 405.0 | 24.1 |
| **32** | 408.1 | 21.7 |
| **33** | 411.0 | 19.9 |
| **34** | 413.9 | 18.4 |
| **35** | 416.7 | 17.2 |

# Peak Values of Specific Heat, Volume Expansivity and Thermal Conductivity in Critical and near Pseudocritical Points

| Pressure, MPa | Pseudocritical temperature, ºC | Temperature, ºC | Specific heat, kJ/kg·K | Volume expansivity, 1/K | Thermal conductivity, W/m·K |
|---|---|---|---|---|---|
| $p_{cr}$=22.064 | $t_{cr}$=374.1 | – | ∞ | ∞ | ∞ |
| 22.5 | 375.6 | – | 690.6 | 1.252 | 0.711 |
| 23.0 | – | 377.4 | – | – | 0.538 |
| | 377.5 | – | 284.3 | 0.508 | – |
| 23.5 | – | 379.2 | – | – | 0.468 |
| | – | 379.3 | – | 0.304 | – |
| | 379.4 | – | 171.9 | – | – |
| 24.0 | – | 381.0 | – | – | 0.429 |
| | 381.2 | – | 121.9 | 0.212 | – |
| 24.5 | – | 382.6 | – | – | 0.405 |
| | – | 383.0 | – | 0.161 | – |
| | 383.1 | – | 93.98 | – | – |
| 25.0 | – | 384.0 | – | – | 0.389 |
| | 384.9 | – | 76.44 | – | – |
| | – | 385.0 | – | 0.128 | – |
| 25.5 | 386.7 | – | 64.44 | 0.107 | no peak |
| 26.0 | 388.5 | – | 55.73 | 0.090 | 0.355 |
| 27.0 | 392.0 | – | 43.93 | 0.069 | 0.340 |
| 28.0 | 395.4 | – | 36.29 | 0.056 | 0.329 |
| 29.0 | 398.7 | – | 30.95 | 0.046 | 0.321 |
| 30.0 | 401.9 | – | 27.03 | 0.039 | 0.316 |

# Conclusions to Part 1

**At critical and supercritical pressures a fluid is considered as a single-phase substance in spite of the fact that all thermophysical properties undergo significant changes within the critical and pseudocritical regions. Near the critical point, these changes are dramatic. In the vicinity of pseudocritical points, with an increase in pressure, these changes become less pronounced.**

**Also, it can be seen that properties such as density and dynamic viscosity undergo a significant drop (near the critical point this drop is almost vertical) within a very narrow temperature range, while the kinematic viscosity and specific enthalpy undergo a sharp increase.**

**The volume expansivity, specific heat, thermal conductivity and Prandtl number have peaks near the critical and pseudocritical points. The magnitude of these peaks decreases very quickly with an increase in pressure. Also, "peaks" transform into "humps" profiles at pressures beyond the critical pressure.**

**It should be noted that the dynamic viscosity, kinematic viscosity and thermal conductivity undergo through the minimum right after the critical and pseudocritical points**

# Part 2
# History of Supercritical Pressures Application in Power Industry

# INTRODUCTION

The use of supercritical fluids in different processes is not new and, actually, is not a human invention. Nature has been processing minerals in aqueous solutions at near or above the critical point of water for billions of years (Levelt Sengers 2000). In the late 1800s, scientists started to use this natural process in their labs for creating various crystals. During the last 50 – 60 years, this process, called hydrothermal processing (operating parameters: water pressure from 20 to 200 MPa and temperatures from 300 to 500ºC), has been widely used in the industrial production of high-quality single crystals (mainly gem stones).

The first works devoted to the problem of heat transfer at supercritical pressures started as early as the 1930s. E. Schmidt and his associates investigated free convection heat transfer of fluids at the near-critical point with the application to a new effective cooling system for turbine blades in jet engines. They found that the free convection heat transfer coefficient (HTC) at the near-critical state was quite high and decided to use this advantage in single-phase thermosyphons with an intermediate working fluid at the near-critical point (in general, thermosyphons are used to transfer heat flux from a heat source to a heat sink located at some distance.)

# INTRODUCTION

In the 1950s, the idea of using supercritical "steam"-water appeared to be rather attractive for "steam" generators. At supercritical pressures, there is no liquid-vapour phase transition; therefore, there is no such phenomenon as critical heat flux or dryout. Only within a certain range of parameters a deterioration of heat transfer may occur. The objective of operating "steam" generators at supercritical pressures was to increase the total efficiency of a power plant. Work in this area was mainly done in the USA and former USSR in the 1950s – 1980s.

At the end of the 1950s and the beginning of the 1960s, some studies were conducted to investigate the possibility of using supercritical fluids in nuclear reactors. Several designs of nuclear reactors using water as the coolant at supercritical pressures were developed in the USA and USSR. However, this idea was abandoned for almost 30 years and regained support in the 1990s.

Use of supercritical water in power-plant "steam" generators is the largest application of a fluid at supercritical pressures in industry. However, other areas exist where supercritical fluids are used or will be implemented in the near future.

# SUPERCRITICAL THERMAL POWER PLANTS: REVIEW AND STATUS

## Russian Supercritical Units

# Parameters of Largest Russian SC Turbines

| Parameters | K-1200-240 | K-800-240 | K-800-240 |
|---|---|---|---|
| **Power, $MW_{el}$ (max power)** | 1200 (1380) | 800 (850) | **800 (835)** |
| **Main Steam** | | | |
| **Pressure, MPa** | 23.5 | 23.5 | **23.5** |
| **Temperature, °C** | 540 | 540 | **560** |
| **Max Flow Rate Through HP Turbine, t/h** | 3950 | 2650 | **2500** |
| **Reheat Steam** | | | |
| **Pressure, MPa** | 3.5 | 3.2 | **3.4** |
| **Temperature, °C** | 540 | 540 | **565** |
| **No. of Steam Extractions** | 9 | 8 | **8** |
| **Outlet Pressure, kPa** | 3.6 | 3.4 | **2.9** |
| **Cooling Water** | | | |
| **Temperature, °C** | 12 | 12 | **12** |
| **Flow Rate, $m^3/h$** | 108,000 | 73,000 | **85,000** |
| **Feedwater Temperature, °C** | 274 | 274 | **270** |
| **Turbine Layout** | | | |
| **No. of Cylinders** | 5 | 5 | **6** |
| **No. of HP Cylinders** | 1 | 1 | **-** |
| **No. of IP Cylinders** | 2 | 2 | **-** |
| **No. of LP Cylinders** | 2 | 2 | **-** |
| **Turbine Mass and Dimensions** | | | |
| **Total Mass, t** | 1900 | 1300 | **1600** |
| **Total Length, m** | 48 | 40 | **40** |
| **Total Length with Electrical Generator, m** | 72 | 60 | **46** |
| **Average Diameter of HP Turbine, m** | **3.0** | **2.5** | **2.5** |

# Supercritical "Steam" Generators Manufactured in Russia (based on 1995 data)

| Capacity MW | Manufacturer | | | | Total |
|---|---|---|---|---|---|
| | "ТКЗ" (Taganrog) | | "ЗиО" (Podol'sk) | | |
| | gas-oil | coal | gas-oil | coal | |
| **300** | 91 | 49 | 19 | 36 | 195 |
| **500** | – | – | – | 16 | 16 |
| **800** | 17 | 2 | – | 1 | 20 |
| **1200** | 1 | – | – | – | 1 |
| **In total** | 109 | 51 | 19 | 53 | – |
| | 160 | | 72 | | **232** |

# US Supercritical-Pressure Units

Power-plant “steam” generators put into operation at the “Emos” (1973) and “Gevin” (1974 – 1975) power plants (USA) (for 1130 MW units):

| | | |
|---|---|---|
| “steam” capacity, | t/h | 4438 |
| Pressure (primary “steam”), | MPa | 27.3 |
| Temperature (primary “steam”), | ºC | 543 |
| Steam capacity (secondary steam), | t/h | 3612 |
| Pressure (secondary steam), | MPa | 4.7 |
| Temperature (secondary steam), | ºC | 538 |
| Feed-water temperature, | ºC | 291 |
| Thermal efficiency, | % | 93 |

This thermal efficiency is related only to a “steam”-generator. The total or overall efficiency of a power plant will be significantly less (43 – 50%) due to a number of energy converting devices: $\eta_{total} = \eta_{steam\ gen.}\ \eta_{turbine}\ \eta_{el.gen.} \cdots$ In other words, the total or overall efficiency of a power plant is actually the ratio of net electrical power output to the rate of fuel energy input.

The largest supercritical units are rated up to 1300 MW with “steam” parameters of 25.2 MPa and 538ºC (Lee and Haller 1974).

# European Supercritical Units

In Germany, at the end of the nineties construction was started on Unit "K" of thermal power plant near Cologne. This power plant (output of 1000 MW and "steam" conditions of 27.5 MPa and 580/600ºC (main/reheat)) should be the most advanced lignite-fired power plant in the world with 45.2% planned overall thermal efficiency. At a later date, with new dry lignite technology introduced, a further increase in efficiency of 3 – 5% is expected.

In Denmark (Noer and Kjaer 1998), the first supercritical power plant started operation in 1984, and today a total of 7 supercritical units are in operation. Main parameters of these units are: output – 2 units 250 MW, the rest 350 – 390 MW, "steam" pressure 24.5 – 25 MPa, "steam" temperature 545 – 560ºC, reheat temperature 540 – 560ºC, feed-water temperature 260 – 280ºC and net efficiency 42 – 43.5%.

Main parameters of ultra-supercritical units: "steam" pressure 29 – 30 MPa, "steam" temperature 580ºC, steam reheat temperature 580 – 600ºC, feed-water temperature 300 – 310ºC and net efficiency 49 – 53%.

# Supercritical Units in Japan

In Japan, the first supercritical “steam” generator (600 MW) was commissioned in 1967 at the Anegasaki plant. Nowadays, many power plants are equipped with supercritical “steam” generators and turbines. Hitachi operating supercritical pressure “steam” turbines have the following average parameters (see also Table 2.4): output – 350 (1 unit), 450 (2 units), 500 (3 units), 600 (11 units), 700 (4 units) and 1000 MW (4 units), “steam” pressure about 24.1 MPa (one unit 24.5 MPa), “steam” temperature (main/reheat) – 538/566ºC (the latest units 600/600ºC (610°C)).

# Major Parameters of Selected Hitachi SC Plants (Turbines)

| First Year of Operation | Power Rating, $MW_{el}$ | Pressure, MPa(g) | $T_{main}/T_{reheat}$, °C |
|---|---|---|---|
| **2011** | 495 | 24.1 | **566/566** |
| **2010** | 809 | 25.4 | **579/579** |
| | 790 | 26.8 | **600/600** |
| **2009** | 1000 | 25.0 | **600/620** |
| | 1000 | 25.5 | **566/566** |
| | 677 | 25.5 | **566/566** |
| | 600 | 24.1 | **600/620** |
| **2008** | 1000 | 24.9 | **600/600** |
| | 887 | 24.1 | **566/593** |
| | 887 | 24.1 | **566/593** |
| | 677 | 25.5 | **566/566** |
| **2007** | 1000 | 24.9 | **600/600** |
| | 870 | 25.3 | **566/593** |
| **2006** | 600 | 24.1 | **566/566** |
| **2005** | 495 | 24.1 | **566/566** |
| **2004** | 700 | 24.1 | **538/566** |
| **2003** | 1000 | 24.5 | **600/600** |
| **2002** | 700 | 25.0 | **600/600** |
| **1998** | 1000 | 24.5 | **600/600** |
| **1994** | 1000 | 24.1 | **538/566** |
| **1992** | 700 | 24.1 | **538/566** |
| **1991** | 600 | 24.1 | **538/566** |
| **1989** | 1000 | 24.1 | **538/566** |
| | 700 | 24.1 | **538/566** |
| **1983** | 700 | 24.1 | **538/538** |
| | 600 | 24.1 | **538/566** |
| | 350 | 24.1 | **538/566** |
| **1981** | 500 | 24.1 | **538/538** |
| **1979** | 600 | 24.1 | **538/566** |
| **1977** | 1000 | 24.1 | **538/566** |
| | 600 | 24.1 | **538/566** |
| | 600 | 24.1 | **538/552/566** |
| **1974** | 500 | 24.1 | **538/566** |
| | 500 | 24.1 | **538/538** |
| **1973** | 600 | 24.1 | **538/552/566** |
| | 450 | 24.1 | **538/566** |
| **1972 & 1971** | **600** | **24.1** | **538/566** |

# World Supercritical Units

# Characteristics of Modern Supercritical "Steam" Generators (Smith 1999) (updated with recent data)

| Country | "STEAM" PARAMETERS | | | | | |
|---|---|---|---|---|---|---|
| | Capacity | Primary | | Reheat | | Feed water |
| | t/h | p, MPa | t, ºC | p, MPa | t, ºC | t, ºC |
| **China** | – | 25 | 538 | – | 566 | – |
| **Denmark** | – | 30 | 580 | 7.5 | 600 | 320 |
| **Germany** | 2420 | 26.8 | 547 | 5.2 | 562 | 270 |
| **Japan*** | 350–1000 | 24.1 | 538 | – | 566 | – |
| | | 25 | 600 | – | 610 | 300 |
| | | 31.1 | 566 | – | 566 | – |

On average, the usage of supercritical "steam" generators instead of subcritical ones increased overall power plant efficiency up to 45 – 50%

So-called "Ultra-supercritical boilers" are now being researched and deployed world wide, particularly in Japan, Korea and China. Using double steam reheat and advanced high temperature blade materials, the turbine inlet temperature is being extended to 625°C at pressures of up to 34 MPa, with overall efficiencies then approaching 51 – 53%.

# Conclusions to Part 2

**An analysis of SC-turbine data based on the current review and materials presented by Pioro and Duffey (2007) showed that:**

**The vast majority of the modern and upcoming SC turbines are single-reheat-cycle turbines;**

**Major "steam" inlet parameters of these turbines are:**
**The main or primary SC "steam" – $P$ = 24 – 25 MPa and $T$ = 540 – 600°C; and the reheat or secondary subcritical-pressure steam – $P$ = 3 – 5 MPa and $T$ = 540 – 620°C.**

**Usually, the main "steam" and reheat-steam temperatures are the same or very close (for example, 566/566°C; 579/579°C; 600/600°C; 566/593°C; 600/620°C).**

**Only very few double-reheat-cycle turbines were manufactured so far. The market demand for double-reheat turbines disappeared due to economic reasons after the first few units were built.**

# Part 3
# Supercritical Water-Cooled Nuclear-Reactor Concepts: Review and Status

Concepts of nuclear reactors cooled with water at supercritical pressure were studied as early as the 1950s and 1960s in the USA and former USSR. The main characteristics of the first concepts of SCWRs are listed in Table.

| **Parameters** | **Company / reactor acronym (year)** | | | |
|---|---|---|---|---|
| | Westinghouse | | GE, Hanford | B & W |
| | SCR (1957) | SCOTT-R (1962) | SCR (1959) | SCFBR (1967) |
| **Reactor type** | Thermal | Thermal | Thermal | Fast |
| **Pressure, MPa** | 27.6 | 24.1 | 37.9 | 25.3 |
| **Power, MW (thermal/electrical)** | 70/21.2 | 2300/1010 | 300/– | 2326/980 |
| **Thermal efficiency, %** | 30.3 | 43.5 | ~40 | 42.2 |
| **Coolant temperature at outlet, ºC** | 538 | 566 | 621 | 538 |
| **Primary coolant flow rate, kg/s** | 195 | 979 | 850 | 538 |
| **Core height / diameter, m/m** | 1.52/1.06 | 6.1/9.0 | 3.97/4.58 | – |
| **Fuel material** | $UO_2$ | $UO_2$ | $UO_2$ | MOX |
| **Cladding material** | SS | SS | Inconel-X | SS |
| **Rod diameter / pitch, mm/mm** | 7.62/8.38 | – | – | – |
| **Moderator** | $H_2O$ | Graphite | $D_2O$ | – |

**Explanations to the table:**
Acronyms: GE – General Electric; B & W – Babcock & Wilcox; SCR – SuperCritical Reactor; SCOTT-R – SuperCritical Once-Through Tube reactor; and SCFBR – SuperCritical Fast Breeder Reactor.

After a 30-year interval, the idea of developing nuclear reactors cooled with supercritical water became attractive as the ultimate development path for water-cooling. Several countries (Canada, Germany, Japan, Korea, Russia, USA and others) have started R&D work in that direction. However, none of these concepts is expected to be implemented in practice before 2015 – 2020.

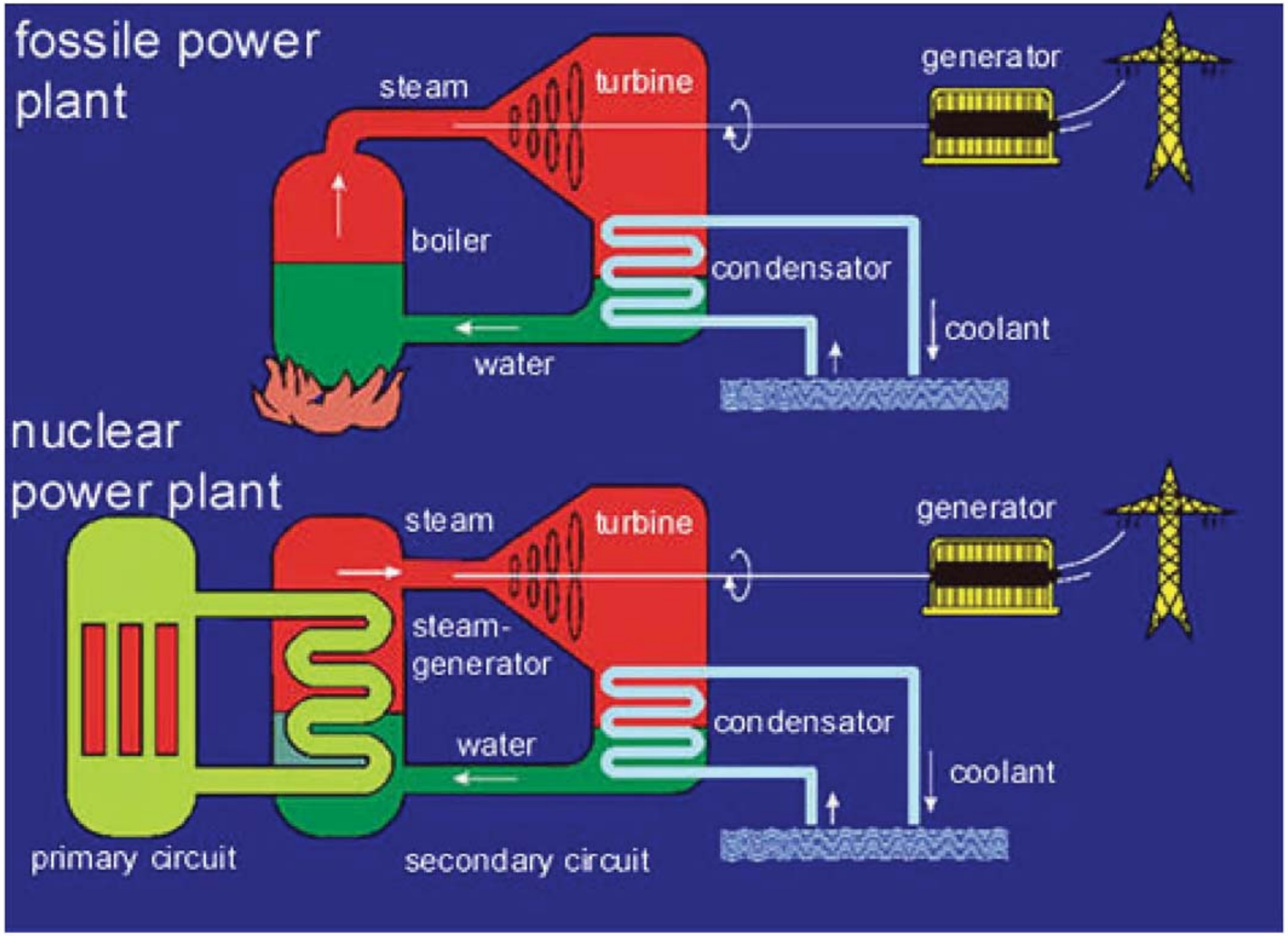
**The main objectives of using supercritical water in nuclear reactors are:**

**1) Increase the efficiency of modern nuclear power plants (NPPs) from 30 – 35% to about 45 – 50%*; and**

**2) Decrease capital and operational costs and hence decrease electrical energy costs.**

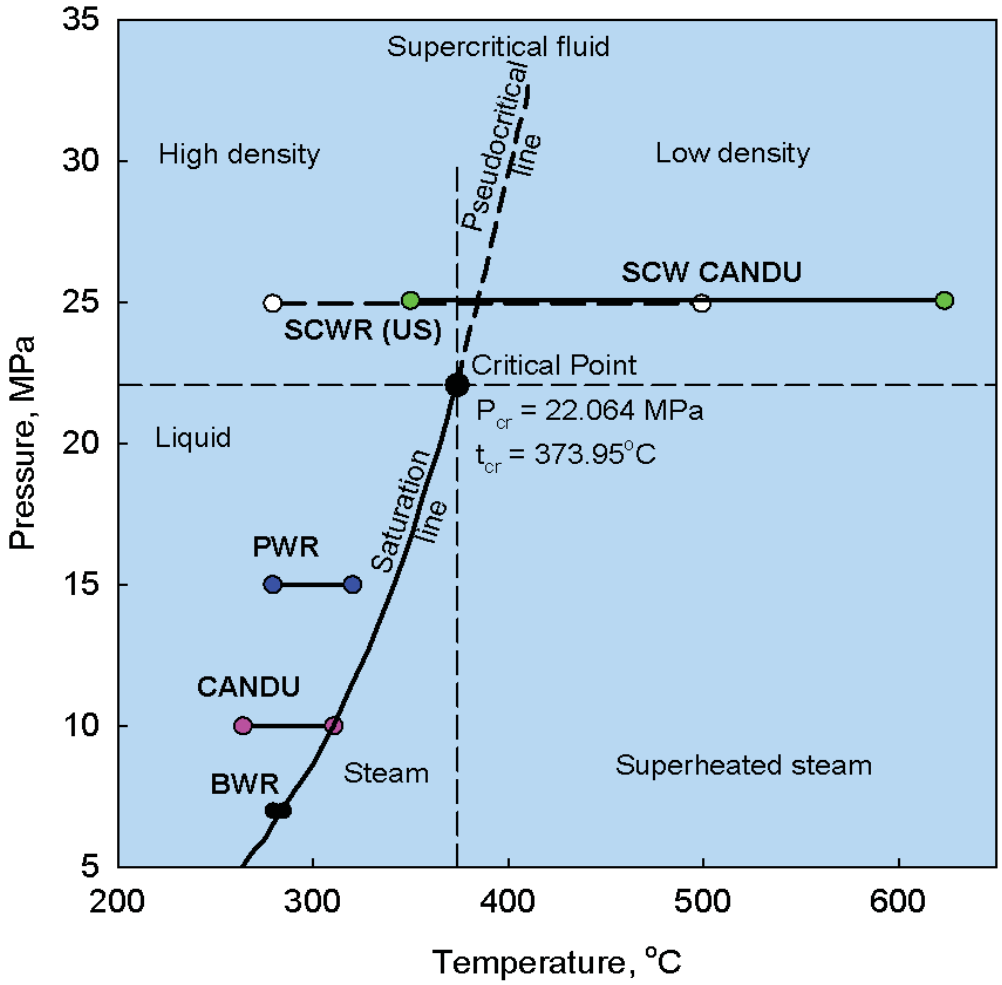
*** These values are the current level of thermal efficiencies of supercritical coal-fired thermal power plants. Combined cycle (gas turbine – subcritical pressure steam turbine) natural gas-fired thermal power plants – have reached highest thermal efficiencies in the power industry of 50 – 55%. Thermal efficiency is $MW_{electrical}$ / $MW_{thermal}$.**

# Nuclear-electric generation




**Courtesy of Professor G. Bereznai, UOIT**

# Pressure-temperature diagram of water with typical operating conditions of SCWRs, PWRs, CANDU-6 reactors and BWRs




Currently, USA does not develop SCWR concept. However, the shown parameters are typical to other SCWR concepts, for example, HPLWR or Super LWR.

# Why SCWRs

**Because the vast majority of modern power nuclear reactors are water-cooled units; and moving from subcritical to supercritical conditions is considered to be a conventional way, which the thermal power industry has passed more than 50 years ago.**

**The following 17 slides are shown here just for reference purposes.**

# Operating nuclear power reactors (439 in total in 2010)

- Pressurized light-Water Reactors (PWRs) –

  262 (237 $GW_{el}$)
- Boiling light-Water Reactors (BWRs or ABWRs) –

  94 (83 $GW_{el}$)
- Gas-Cooled Reactors (GCRs or AGRs) – 22 (11 $GW_{el}$), UK
- Pressurized Heavy-Water Reactors (PHWRs) –

  44 (23 $Gw_{el}$), Argentina 2, Canada 22, China 2, India 12, Pakistan 1, Romania 2, S. Korea 4,
- Light-water, Graphite-moderated Reactors (LGRs) –

  15 (11 $Gw_{el}$), RBMK - Russia 15
- Liquid-Metal Fast-Breeder Reactors (LMFBRs) –

  2 (0.8 $GW_{el}$), Japan 1, Russia 1,

# Basis for Development SCWRs

1. Pressurized Water Reactor's technology (current pressures up to 16 MPa) (discussed in this lecture)
2. Boiling Water Reactor's once-through or direct cycle (discussed in this lecture)
3. Supercritical "steam" generator's technology and turbines from coal-fired power plants (will be discussed in another lecture)
4. Experience of nuclear steam superheating at several nuclear power plants (Russia and USA) (will be discussed in below)

# Types of SCWRs

**The SCWR concepts follow two main types, the use of either (a) a large reactor pressure vessel with a wall thickness of about 0.5 m to contain the reactor core (fuelled) heat source, analogous to conventional PWRs and BWRs, or (b) distributed pressure tubes or channels analogous to conventional CANDU® and RBMK nuclear reactors.**

**The pressure-vessel SCWR design is developed largely in the USA, EU, Japan (Oka et al. 2010), Korea and China and allows using a traditional high-pressure circuit layout.**

**The pressure-channel SCWR design is developed largely in Canada and in Russia to avoid a thick wall vessel.**

**The vast majority SCWR concepts are thermal spectrum reactors. However, a fast neutron spectrum core is also possible (Oka et al. 2010).**

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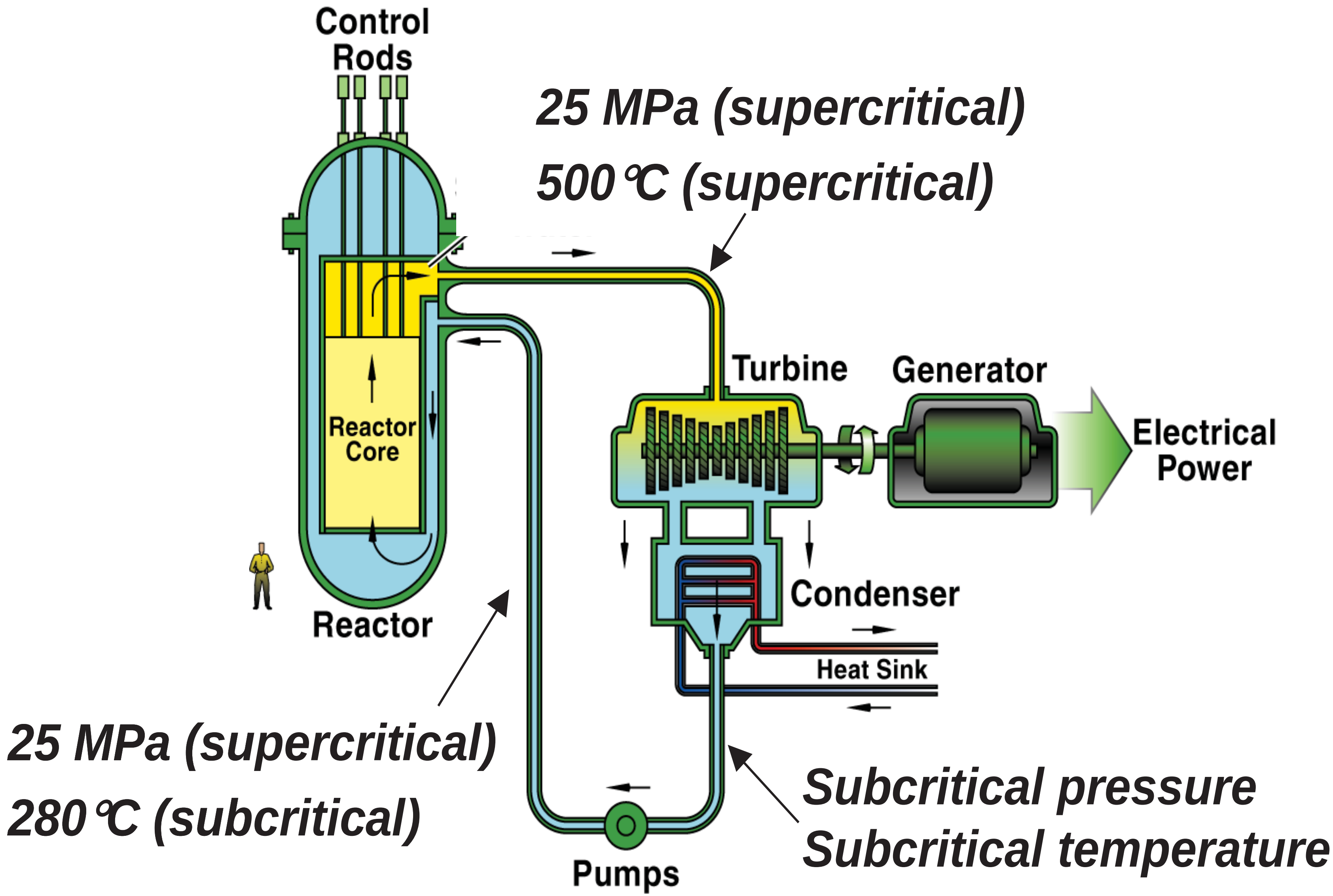
# Schematics of Pressure-Vessel SCWR



# Modern Concepts of Pressure-Vessel SCW Reactors

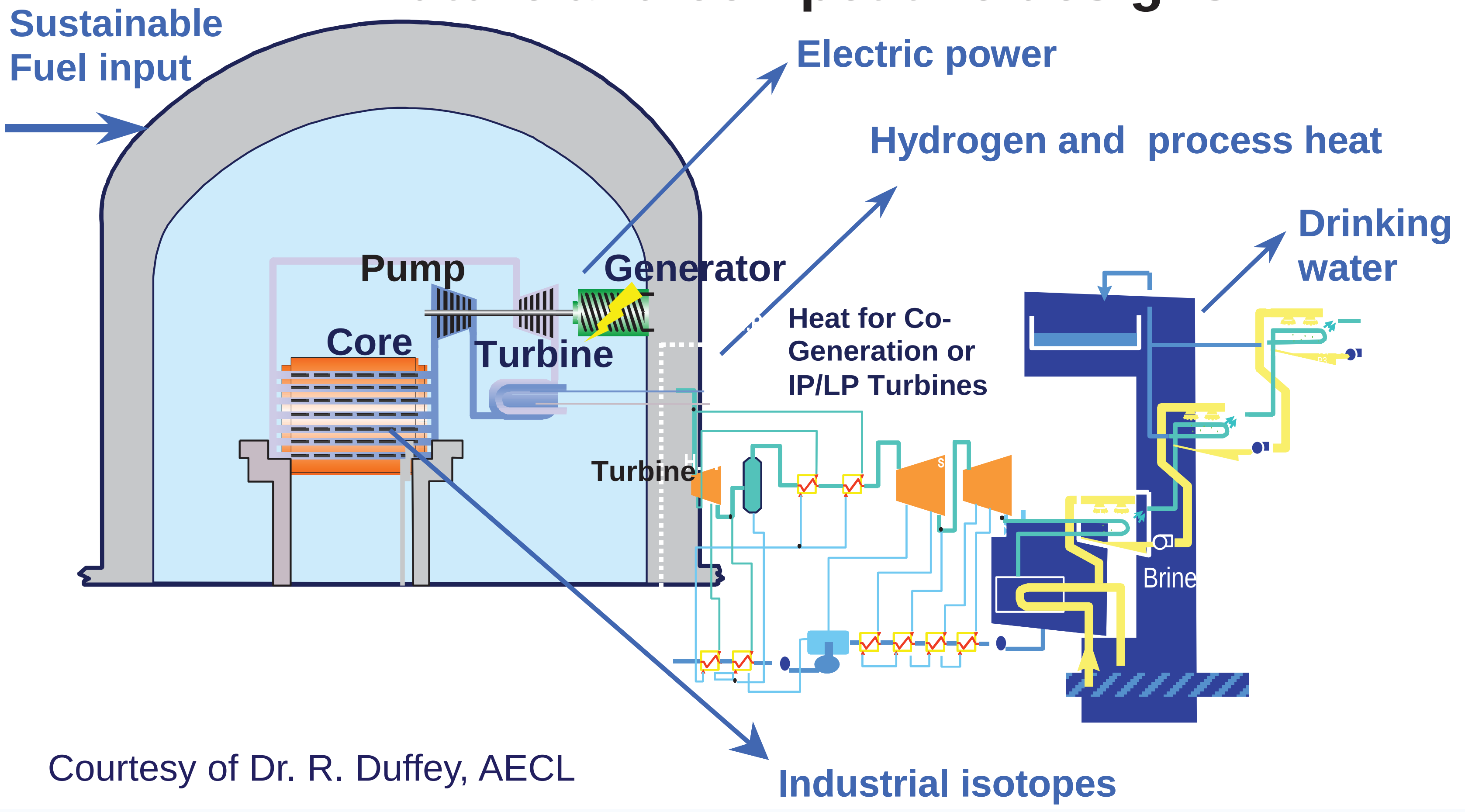
| Parameters | Unit | HPLWR | SCLWR | SCFBR | SCWR |
|---|---|---|---|---|---|
| Country | - | EU/Japan | Japan | | Korea |
| Spectrum | - | Thermal | Thermal | Fast | Thermal |
| Power el. | MW | 1000 | 1220 | 1730 | 1700 |
| Therm. eff. | % | 44 | 44 | 44 | 44 |
| Pressure | MPa | 25 | 25 | 25 | 25 |
| $T_{coolant}$ | C | 280-500 | 280-530 | 280-530 | 280-510 |
| Flow rate | kg/s | 1160 | 1340 | 1700 | 1860 |
| Core H/D | m/m | 4.2/- | 4.2/3.7 | 3.2/3.3 | 3.6/3.8 |
| Fuel | - | $UO_2$ or MOX | $UO_2$ | MOX | $UO_2$ |
| Enrichment | %wt. | <6 | 6 | - | 6 |
| $T_{max\ cladding}$ | C | 620 | 650 | 620 | 620 |
| Moderator | - | $H_2O$ | $H_2O$ | - | $ZrH_2$ |

# Modern Concepts of Pressure-Vessel SCW Reactors

| Parameters | Unit | PVWR | WWPR-SCP | SCWR-US |
|---|---|---|---|---|
| Country | - | Russia | | USA |
| Spectrum | - | Thermal | Fast | Thermal |
| Power el. | MW | 1500 | 1700 | 1600 |
| Therm. eff. | % | 34 | 44 | 45 |
| Pressure | MPa | 25 | 25 | 25 |
| $T_{coolant}$ | C | 280-550 | 280-530 | 280-500 |
| Flow rate | kg/s | 1600 | 1860 | 1840 |
| Core H/D | m/m | 3.5/2.9 | 4.1/3.4 | 4.9/3.9 |
| Fuel | - | $UO_2$ | MOX | $UO_2$ |
| Enrichment | %wt. | - | - | 5 |
| $T_{max\ cladding}$ | C | 630 | 630 | - |
| Moderator | - | $H_2O$ | - | $H_2O$ |

# Pressure-Channel SCW CANDU Reactor Concept

**Multiple products are key to sustainable future and competitive designs**




Courtesy of Dr. R. Duffey, AECL

# Modern Concepts of Pressure-Channel SCW Reactors

| Parameters | Unit | CANDU | ChUWR | | KP-SKD |
|---|---|---|---|---|---|
| Country | - | Canada | Russia (RDIPE) | | |
| Spectrum | - | Thermal | Thermal | Fast | Thermal |
| Power electr. | MW | 1220 | 1200 | 1200 | 850 |
| Thermal eff. | % | 48 | 44 | 43 | 42 |
| Pressure | MPa | 25 | 24.5 | 25 | 25 |
| $T_{coolant}$ | C | 350-625 | 270-545 | 400-550 | 270-545 |
| Flow rate | kg/s | 1320 | 1020 | - | 922 |
| Core H/D | m/m | -/4 | 6/12 | 3.5/11 | 5/6.5 |
| Fuel | - | $UO_2$/Th | UCG | MOX | $UO_2$ |
| Enrichment | %.wt. | 4 | 4.4 | - | 6 |
| $T_{max\ cladding}$ | C | 850 | 630 | 650 | 700 |
| Moderator | - | $D_2O$ | Graphite | - | $D_2O$ |

# Conclusions to Part 3

**Concepts of nuclear reactors cooled with water at supercritical pressure were studied as early as the 1950s and 1960s in the USA and former USSR.**

**The main objectives of using supercritical water in nuclear reactors are:**
**1) Increase the efficiency of modern nuclear power plants (NPPs) from 30 – 35% to about 45 – 50%;**
**2) Decrease capital and operational costs and hence decrease electrical energy costs.**

**The design of SCWRs is seen as the natural and ultimate evolution of today's conventional water-cooled nuclear reactors. SCWR designs are based on:**
**1. Modern Pressurized Water Reactors (PWRs), which operate at pressures of 15 − 16 MPa.**
**2. Boiling Water Reactors (BWRs) with the once-through or direct-cycle design, i.e., steam from a nuclear reactor is forwarded directly into a turbine.**
**3. Some experimental reactors, which have used nuclear steam reheat with outlet steam temperatures well beyond the critical temperature, but at pressures below the critical pressure. And**
**4. Modern supercritical turbines, which operate successfully at thermal coal-fired power plants for more than 50 years at pressures of about 25 MPa and inlet temperatures up to 600ºC.**

**The SCWR concepts follow two main types, the use of either (a) a large reactor pressure vessel with wall thickness of about 0.5 m to contain the reactor core (fuelled) heat source, analogous to conventional PWRs and BWRs, or (b) distributed pressure tubes or channels analogous to conventional CANDU and RBMK nuclear reactors.**

**The pressure-vessel SCWR design is developed largely in the EU, Japan (Oka et al. 2010), China and some other countries and allows using a traditional high-pressure circuit layout.**

**The pressure-channel SCWR design is developed largely in Canada and Russia to avoid a thick-wall vessel.**

# References


1. Pioro, I.L. and Duffey, R.B., Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications, ASME Press, New York, NY, USA, 2007, 334 pages.
2. Oka, Yo., Koshizuka, S., Ishiwatari, Y. and Yamaji, A., 2010. Super Light Water Reactors and Super Fast Reactors, Springer, 416 pages and 200 figures.
3. Shultis, J.K. and Faw, R.E., 2008. Fundamentals of Nuclear Science and Engineering, 2nd ed., CRC Press, Boca Raton, FL, USA, 591 pages.
4. Hewitt, G.F. and Collier, J.G., 2000. Introduction to Nuclear Power, 2nd ed., Taylor & Francis, New York, NY, USA, 304 pages.
5. Some slides for the current lecture, which used here only for educational purposes, are courtesy of DOE, NRC, ROSENERGOATOM, AECL and other organizations and companies.

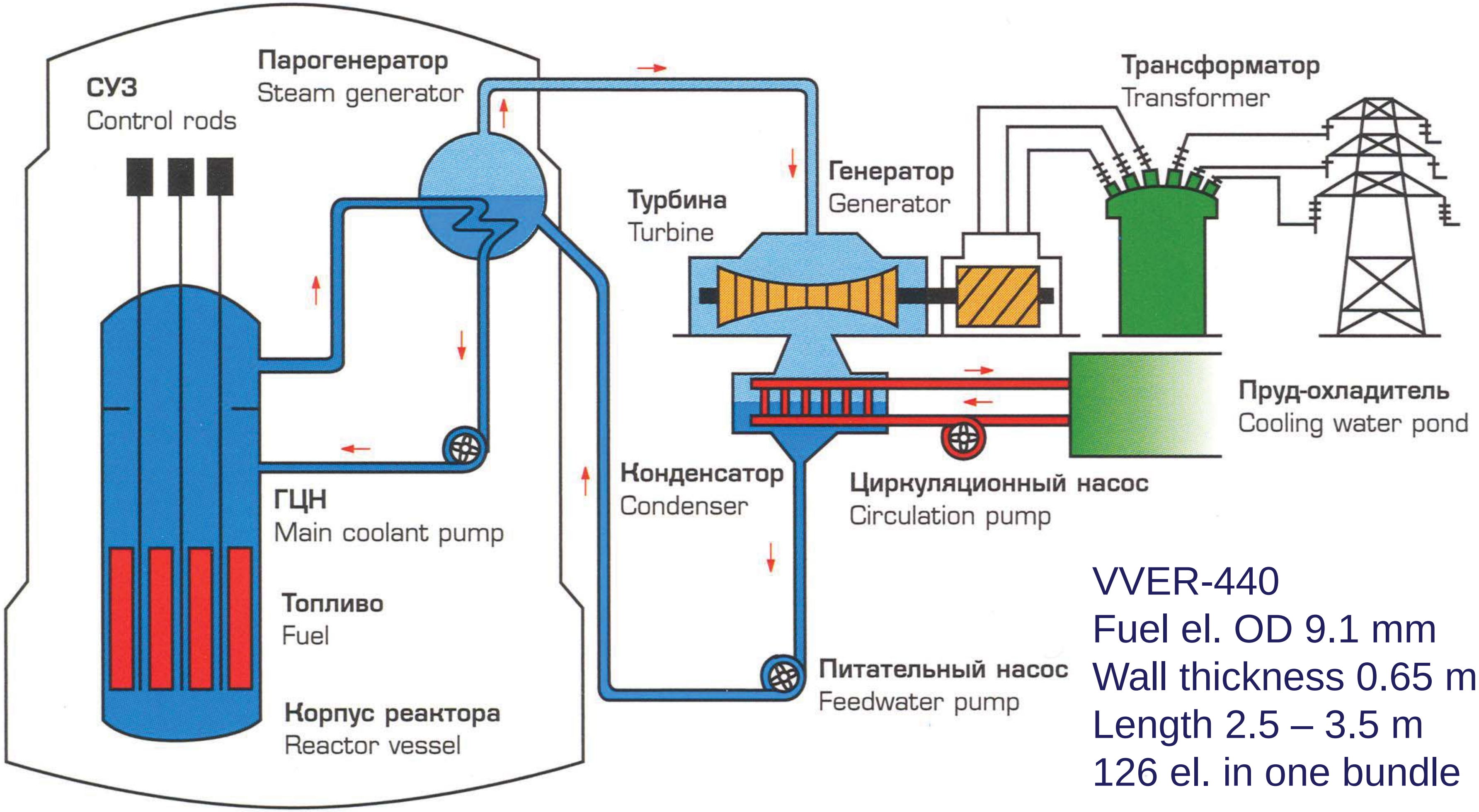
# Appendix
# Current Power Nuclear Reactors

# Current Nuclear Power Units by Nation in 2010

| No. | Nation | # Units | Net $MW_{el}$ |
|---|---|---|---|
| 1. | USA | 104 | 100,460 |
| 2. | France | 59 | 63,363 |
| 3. | Japan | 53 | 45,218 |
| 4. | Russia | 31 | 20,843 |
| 5. | Germany | 18 | 20,643 |
| 6. | Canada | 22 | 15,222 |
| 7. | S. Korea | 19 | 15,850 |
| 8. | Ukraine | 15 | 13,200 |
| 9. | UK | 23 | 11,852 |

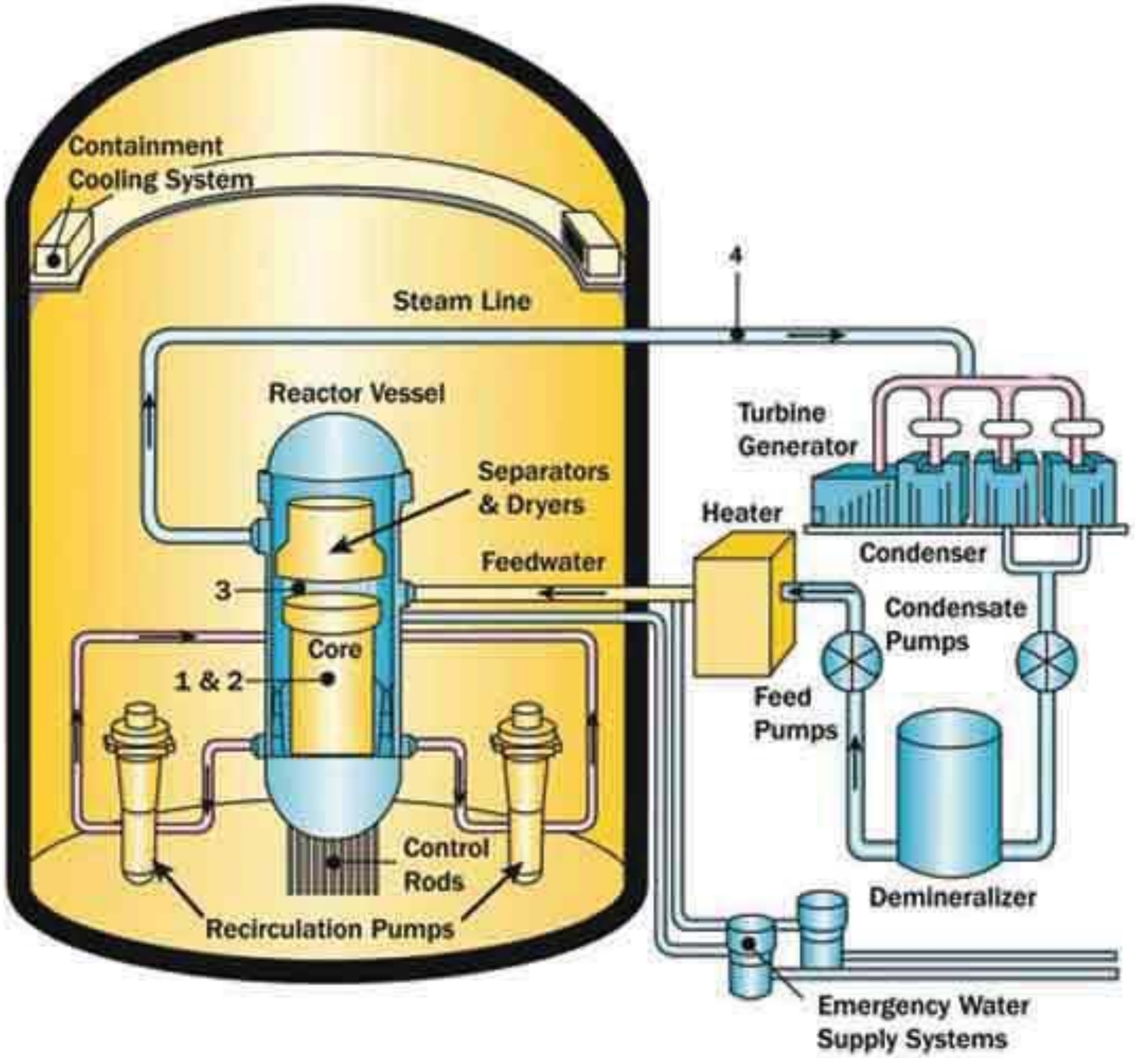
# Реактор ВВЭР – отпуск электроэнергии потребителю
## Reactor VVER – Electricity to the consumer

## PWR-type reactor

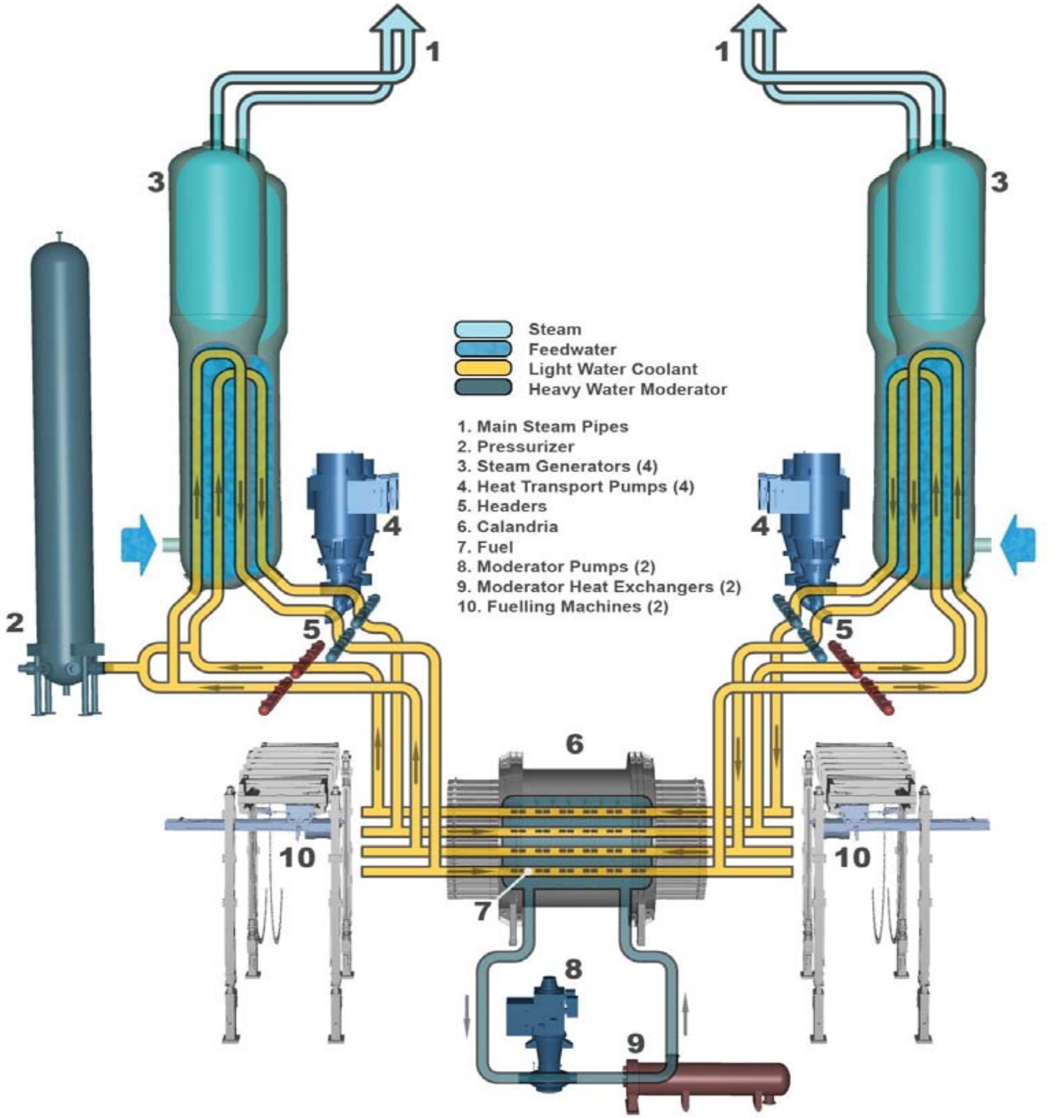



VVER-440
Fuel el. OD 9.1 mm
Wall thickness 0.65 mm
Length 2.5 – 3.5 m
126 el. in one bundle

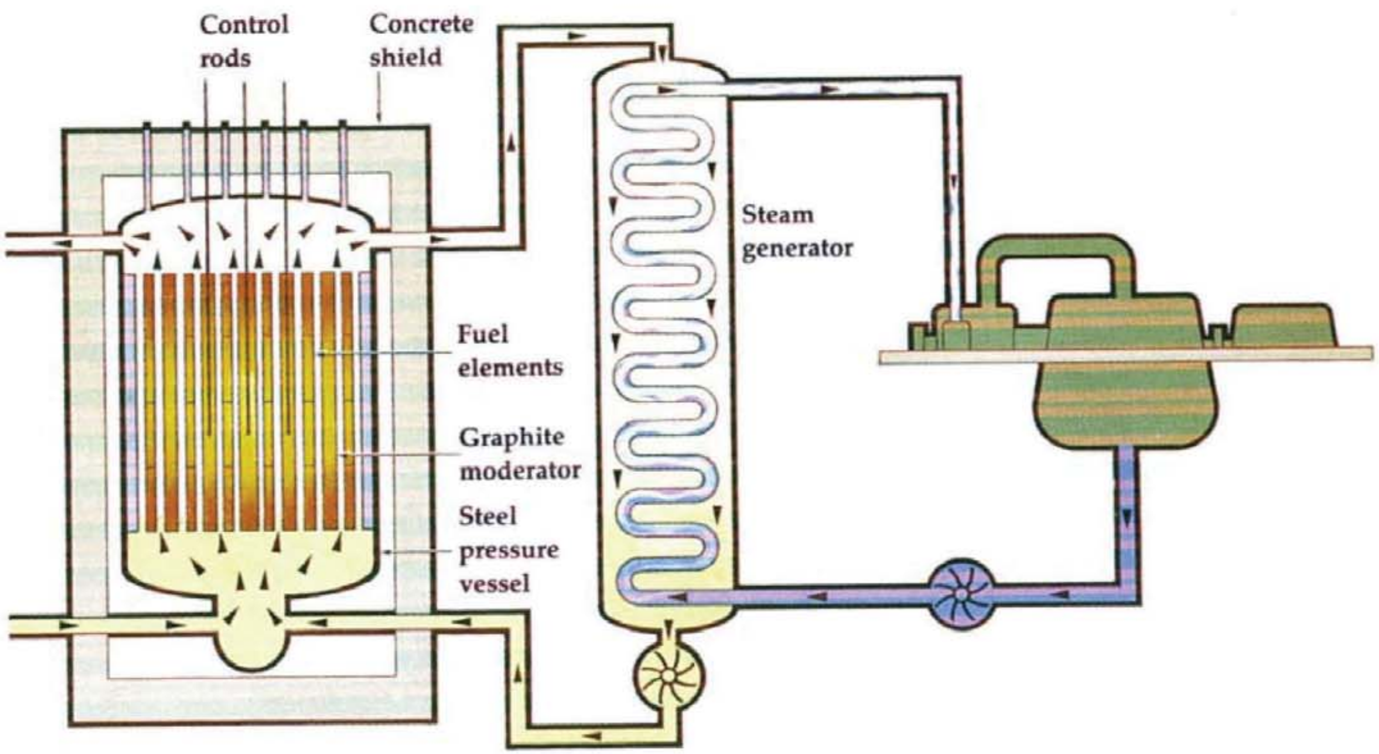
# Boiling Water Reactor (BWR)



# EC-6 (Enhanced CANDU) Nuclear Reactor Systems Schematic

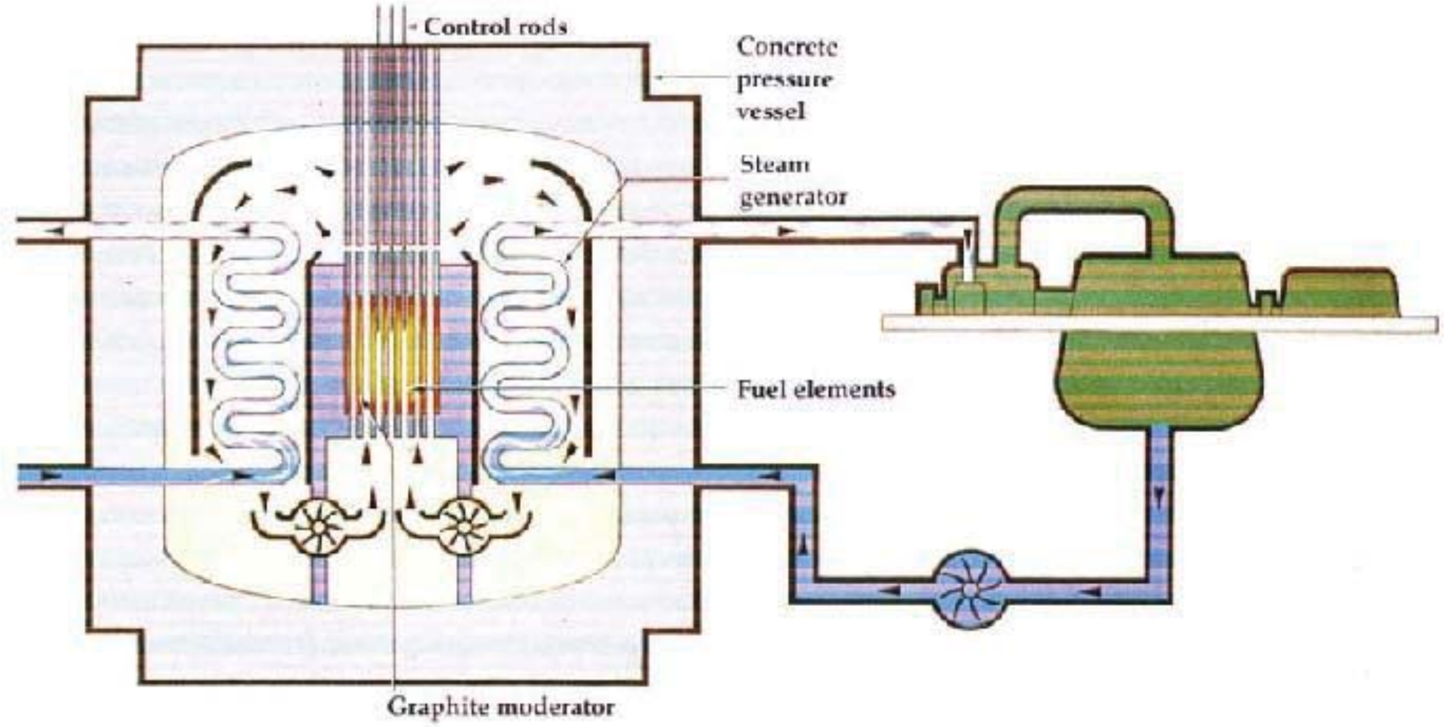


# Gas Cooled Reactor (MAGNOX)

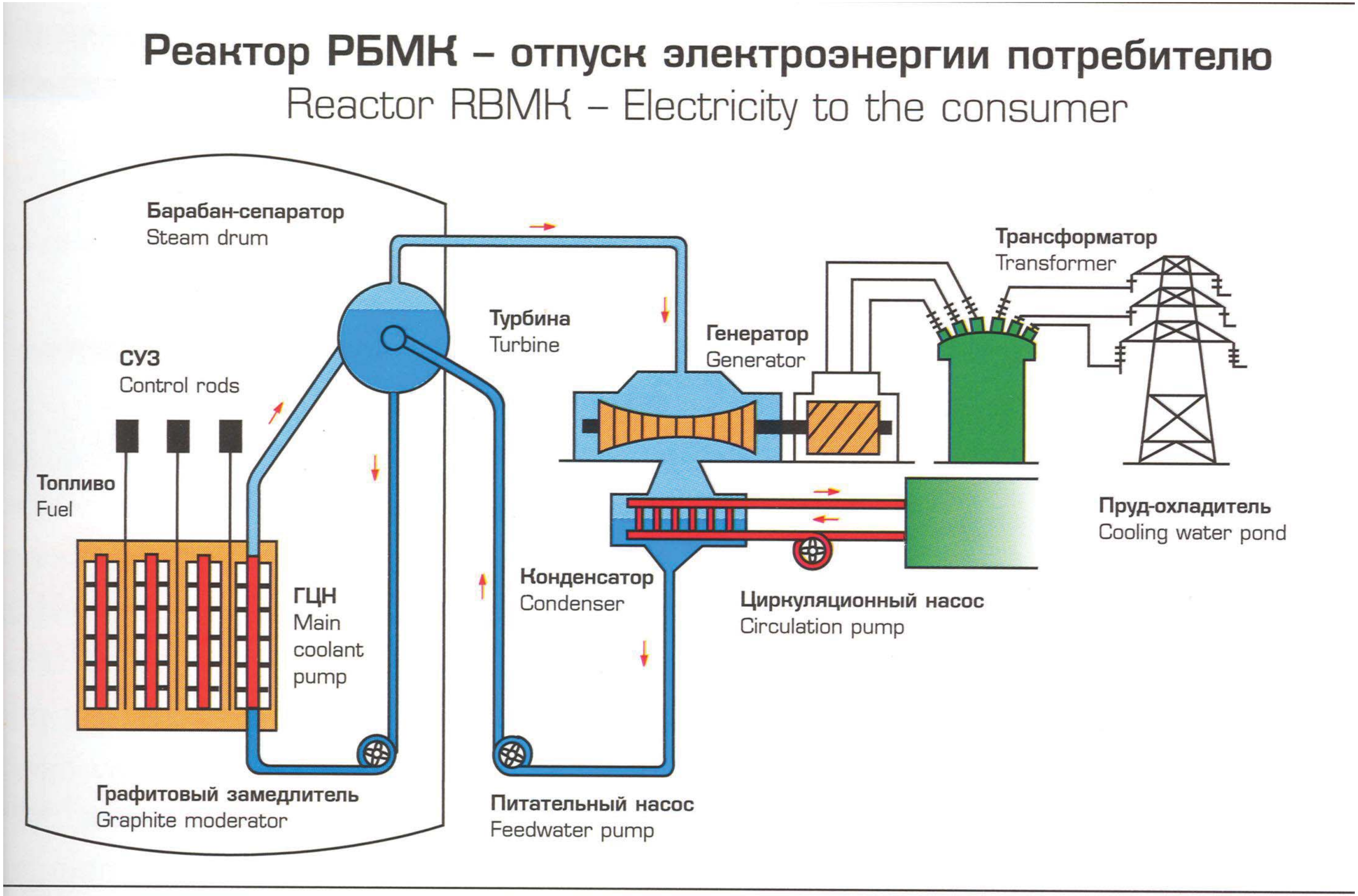



**Courtesy of Professor G. Bereznai, UOIT**

# Advanced Gas Reactor (AGR)



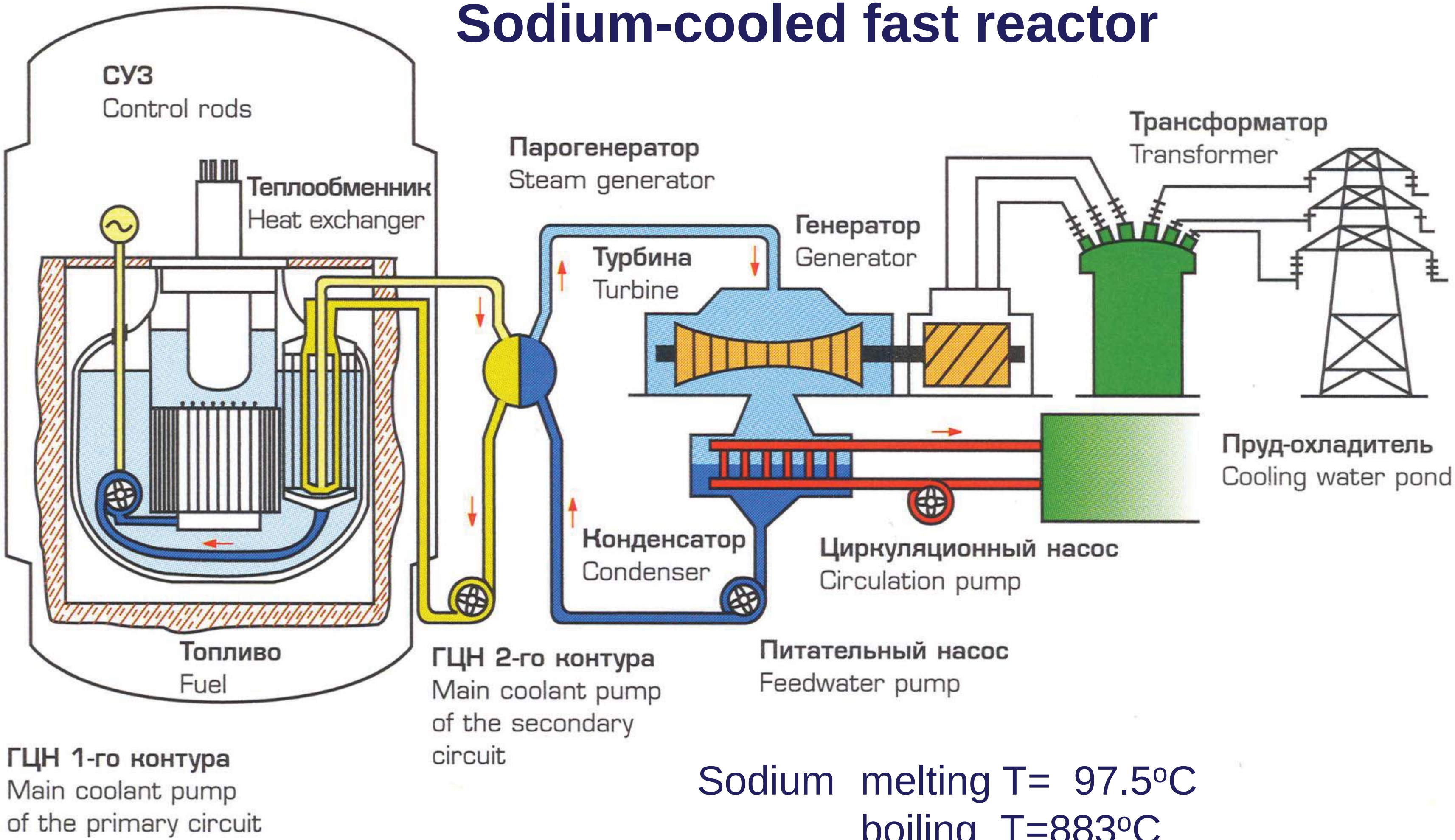

**Courtesy of Professor G. Bereznai, UOIT**




# RBMK – Reactor of Large Capacity Channel type (boiling)

# Реактор БН-600 – отпуск электроэнергии потребителю
## Reactor BN-600 – Electricity to the consumer

## Sodium-cooled fast reactor




Sodium melting T= 97.5°C
boiling T=883°C

# Major Parameters of Russian Power Reactors

| Parameter | VVER-440 | VVER-1000 | RBMK-1000 | RBMK-1500 | BN-600 |
|---|---|---|---|---|---|
| Thermal power, MW | 1375 | 3000 | 3200 | 4800 | 1500 |
| Electrical power, MW | 440 | 1000 | 1000 | 1500 | 600 |
| Thermal efficiency, % | 32.0 | 33.3 | 31.3 | 31.3 | 40.0 |
| Coolant P, MPa | 12.3 | 15.7 | 6.9 | 6.9 | ~0.1 |
| Coolant flow, t/h | 40,800 | 84,800 | 32,000 | 48,000 | 25,000 |
| Coolant T, $^{o}$C | 270/298 | 290/322 | 284 | 284 | 380/550 |
| Steam flow rate, t/h | 2700 | 5880 | 5600 | 8400 | 660 |
| Steam pressure, MPa | 4.3 | 5.9 | 6.6 | 6.6 | 14.0 |
| Steam T, $^{o}$C | 256 | 276 | 280 | 280 | 505 |
| Core: D/H m/m | 3.8/11.8 | 4.5/10.9 | 11.8/7 | 11.8/7 | 2.1/0.75 |
| Fuel enrichment, % | 3.6 | 4.3 | 2.0-2.4 | 2.0 | 17-33 |
| No. fuel assemblies | 349 | 163 | 1580 | 1661 | 369 |

VVERs are PWRs; RBMKs are pressure-channel boiling reactors (outlet fuel-channel steam quality is 14% (maximum 30%) (in BWRs - about 10%); BNs are sodium-cooled fast reactors.

# Typical parameters of US PWR (Shultis, J.K. and Faw, R.E., 2007)

| Power | | Steam generators | |
|---|---|---|---|
| Thermal output, $MW_{th}$ | 3800 | No. | 4 |
| Electrical output, $MW_e$ | 1300 | $P_{out}$, MPa | 6.9 |
| Thermal efficiency, % | 34 | $T_{out}$, °C | 284 |
| Specific power, kW/kg(U) | 33 | m, kg/s | 528 |
| Power density, kW/L | 102 | **Reactor PV** | |
| Ave. linear heat flux, kW/m | 17.5 | OD, m | 4.4 |
| Rod heat flux ave/max, $MW/m^2$ | 0.584/1.46 | Height, m | 13.6 |
| **Core** | | Wall thickness, m | 0.22 |
| Length, m | 4.17 | **Fuel** | |
| OD, m | 3.37 | Fuel pellets | $UO_2$ |
| **Reactor coolant system** | | Pellet OD, mm | 8.19 |
| P, MPa | 15.5 | Rod OD, mm | 9.5 |
| $T_{in}$, °C | 292 | Zircaloy clad thickness, mm | 0.57 |
| $T_{out}$, °C | 329 | Rods per bundle (17x17) | 264 |
| Mass flow rate (m), kg/s | 531 | Bundles in core | 193 |

# Typical parameters of US PWR (Shultis, J.K. and Faw, R.E., 2007)

| Fuel | |
|---|---|
| Fuel loading, ton | 115 |
| Enrichment, % | 3.2 |
| **Reactivity control** | |
| No. control assemblies | 68 |
| Shape | Rod clusters |
| Absorber rods per assembly | 24 |
| Neutron absorber | Ag-In-Cd and/or $B_4C$ |
| Soluble poison shim | Boric acid $H_3BO_3$ |

# Typical parameters of US BWR (Shultis, J.K. and Faw, R.E., 2007)

| **Power** | | **Reactor coolant system** | |
|---|---|---|---|
| Thermal output, $MW_{th}$ | 3830 | Core flow rate, kg/s | 14,167 |
| Electrical output, $MW_e$ | 1330 | Core void fraction ave/max | 0.37/0.75 |
| Thermal efficiency, % | 34 | | |
| Specific power, kW/kg(U) | 26 | | |
| Power density, kW/L | 56 | **Reactor PV** | |
| Ave. linear heat flux, kW/m | 20.7 | ID, m | 6.4 |
| Rod heat flux ave/max, $MW/m^2$ | 0.51/1.12 | Height, m | 22.1 |
| **Core** | | Wall thickness, m | 0.15 |
| Length, m | 3.76 | **Fuel** | |
| OD, m | 4.8 | Fuel pellets | $UO_2$ |
| **Reactor coolant system** | | Pellet OD, mm | 10.6 |
| P, MPa | 7.17 | Rod OD, mm | 12.5 |
| $T_{feedwater}$, $^{o}C$ | 216 | Zircaloy clad thickness, mm | 0.86 |
| $T_{out\ steam}$, $^{o}C$ | 290 | Rods per bundle (8 x 8) | 62 |
| Outlet steam flow rate, kg/s | 2083 | Bundles in core | 760 |

# Typical parameters of US BWR (Shultis, J.K. and Faw, R.E., 2007)

| Fuel | |
|---|---|
| Fuel loading, ton | 168 |
| Enrichment, % | 1.9 |
| **Reactivity control** | |
| No. control assemblies | 193 |
| Shape | Cruciform |
| Overall length, m | 4.42 |
| Length of poison section, m | 3.66 |
| Neutron absorber | Boron carbide |
| Soluble poison shim | Gadolinium |

## Table 2-1 Heat Transport System Design Data

| | CANDU 6 | Darlington | ACR-1000 |
|---|---|---|---|
| Reactor outlet header pressure [MPa (g)] | 9.9 | 9.9 | 11.1 |
| Reactor outlet header temperature [°C] | 310 | 310 | 319 |
| Reactor inlet header pressure [MPa (g)] | 11.2 | 11.3 | 12.5 |
| Reactor inlet header temperature [°C] | 260 | 267 | 275 |
| Single channel flow (maximum) [kg/s] | 28 | 27.4 | 28 |

## Table 2-2 Heat Transport Pump Data

| | CANDU 6 | Darlington | ACR-1000 |
|---|---|---|---|
| Number | 4 | 4 | 4 |
| Rated flow [L/s] | 2228 | 3240 | 4300 |
| Motor rating [MWe] | 6.7 | 9.6 | 10.0 |

Darlington – CANDU-9 reactor; ACR – Advanced CANDU Reactor; CANDU is CANnada Deuterium Uranium

## Table 2-3 Steam Generator Design Data

| Steam Generators | CANDU 6 | Darlington | ACR-1000 |
|---|---|---|---|
| Number | 4 | 4 | 4 |
| Type | Vertical U-tube / integral pre-heater | Vertical U-tube / integral pre-heater | Vertical U-tube / integral pre-heater |
| Nominal tube diameter [mm] | 15.9 (5/8") | 15.9 (5/8") | 17.5 (11/16") |
| Steam temperature (nominal) [°C] | 260 | 265 | 275.5 |
| Steam quality | 0.9975 | 0.9975 | 0.999 |
| Steam pressure [MPa (g)] | 4.6 | 5.0 | 5.9 |

## Table 2–4 Heavy Water Inventory Design Data

| | CANDU 6 | Darlington | ACR-1000 |
|---|---|---|---|
| Moderator System [Mg $D_2O$] | 265 | 312 | 250 |
| Heat Transport System [Mg $D_2O$] | 192 | 280 | 0 |
| Total [Mg $D_2O$] | 457 | 592 | 250 |

# Selected parameters of gas-cooled reactors (UK)

## Natural Uranium Graphite-Moderated (Magnox) Reactors

**Coolant – carbon dioxide; pressure - 2 MPa; outlet/inlet temperature – 414/250°C; core diameter – up to 14 m; height – up to 8 m; natural uranium fuel; magnesium alloy sheath with fins; thermal efficiency – 31.5%.**

## Advanced Gas-cooled Reactors (AGRs)

## (design similar to Magnox reactors)

**Coolant – carbon dioxide; pressure - 4 MPa; outlet/inlet temperature – 650/292°C; steam – 17 MPa and 560°C; stainless steel sheath with ribs; hollow fuel pellet; enriched fuel 2.3%; thermal efficiency – 41.6% (the highest in nuclear power industry).**

**Hewitt, G.F. and Collier, J.G., 2000. Introduction to Nuclear Power, 2nd ed., Taylor & Francis, New York, NY, USA, 304 pages.**

# …Thank you for your attention!

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