# OVERVIEW OF NUCLEAR REACTOR THERMAL HYDRAULIC


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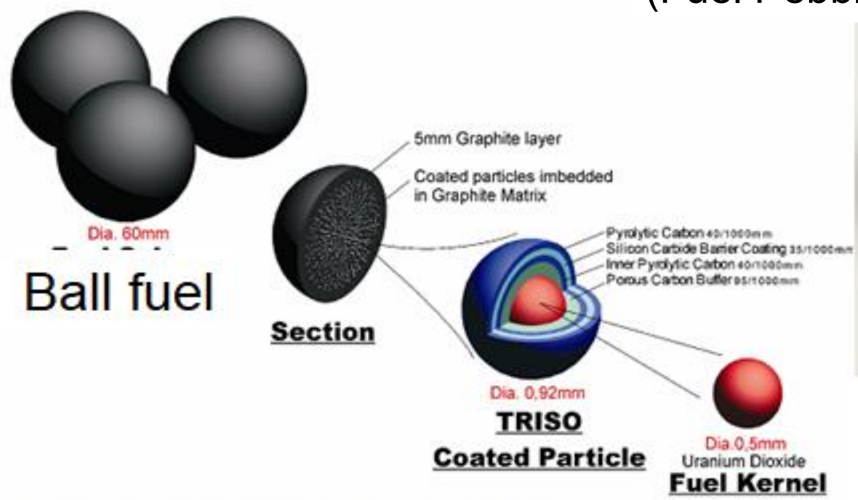
# Neutron Moderator, Coolant and Fuel for Reactor types

| Reactor Type | Coolant | Neutron Moderator | Fuel | Characteristics |
|---|---|---|---|---|
| PWR (Pressurized Water Reactor) | Light Water (non-boiling) | Light Water (LWR) | Low Enriched Uranium · Oxide | Tout= 300℃ Characteristics of Water is well known |
| BWR (Boiling Water Reactor) | Light Water (boiling) | | Low Enriched Uranium · Oxide | Tout= 300℃ Characteristics of Water is well known |
| CANDU (Canadian Deuterium Uranium Reactor) | Heavy Water (non-boiling) | Heavy Water (HWR) | Natural Uranium· Oxide | High grade of Pu can be produced |
| GCR (Gas-cooled Reactor) *Magnox Reactor | Gas ($CO_2$) | Graphite (Graphite Reactor) | Natural Uranium Metal | High grade of Pu can be produced. Power density is low. |
| HTGR (High Temperature Gas-cooled Reactor) | Helium | Graphite (Graphite Reactor | Low Enriched Uranium · Oxide | Tout= 1000℃ It is applicable for chemical industries such as $H_2$ production |
| FBR (Fast Breeder Reactor) | Liquid Metal | Non | Enriched Uranium/Plutonium · Mixed Oxide | Fuel Breeding is possible. U can be used for 2550 years |

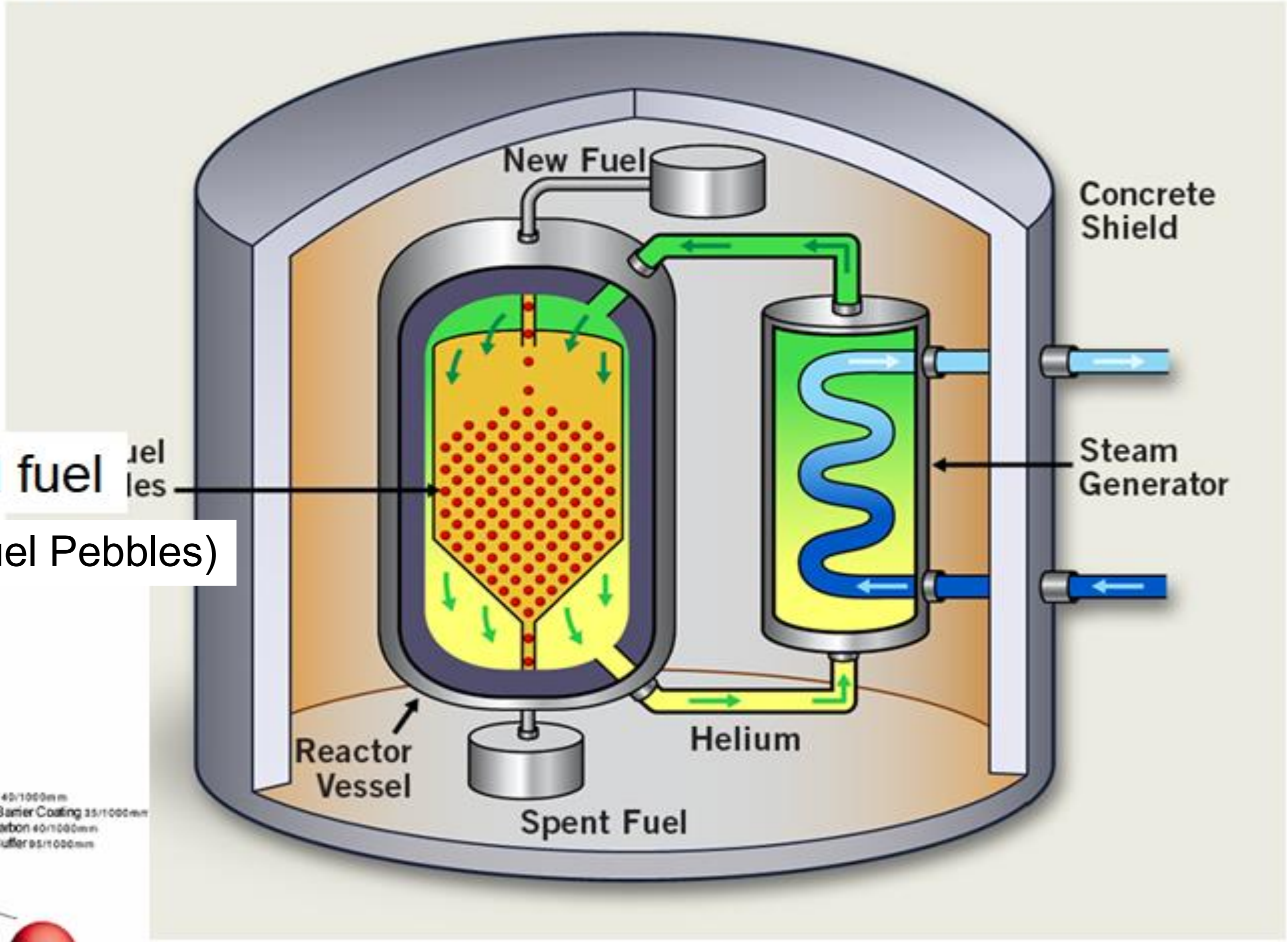
# Concept of  Pebble bed type HTGR

Ball fuel is refueled continuously

244x238-14.8kB-Idaho Samizdat: Nuke Notes: Pe...
http://djysrv.blogspot.com/2009/01/pebble-bed-fuel...




567x339-85.0kB-Nam's home page: 1. High-Tempe...
http://hoainamk3.blogspot.com/2010/11/high-tempera...




900x699-170.1kB-Cameco U101 - Types of Reactor...
http://www.cameco.com/uranium_101/electricity-gene...

# Outline of LWRs (PWR and BWR)

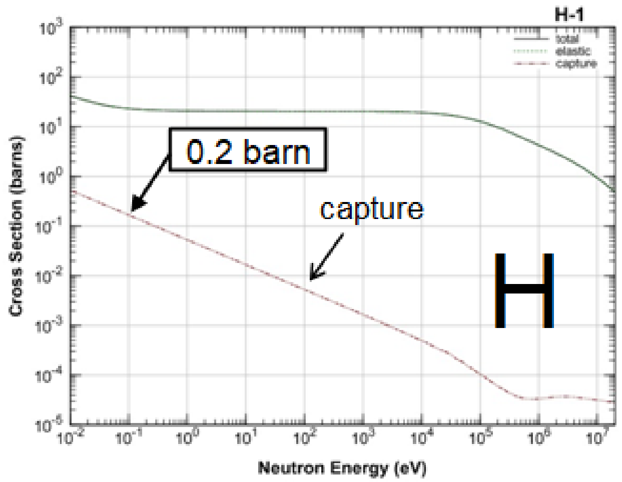
- Most usual and the cheapest coolant material; <u>light water</u>
- Biggest <u>slowing-down power</u> for achieving compact core
- Huge experiences of steam turbines since the industrial revolution period

On the other hand,

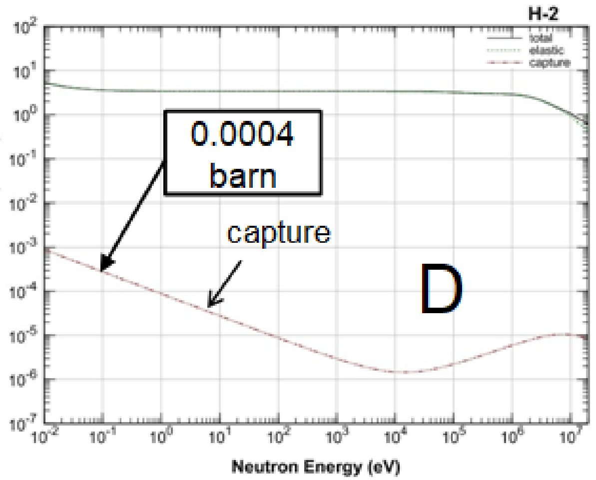
-<u>Uranium enrichment is necessary</u> for light water moderated reactors because of the relative <u>large neutron capture cross-section of hydrogen</u>.

-The enrichment technology was available in the USA in the early stage of development because of <u>military secret</u>.

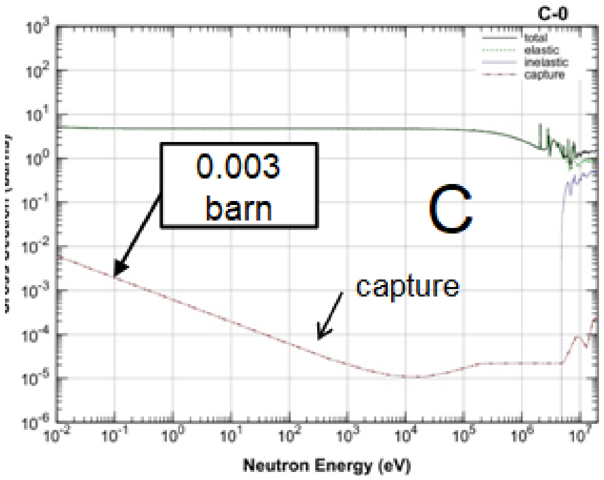
(So, the early power reactors used Natural uranium for the fuel in UK, France, Canada and used Graphite or Heavy water for the moderator.)



Cross-section of H



Cross-section of D

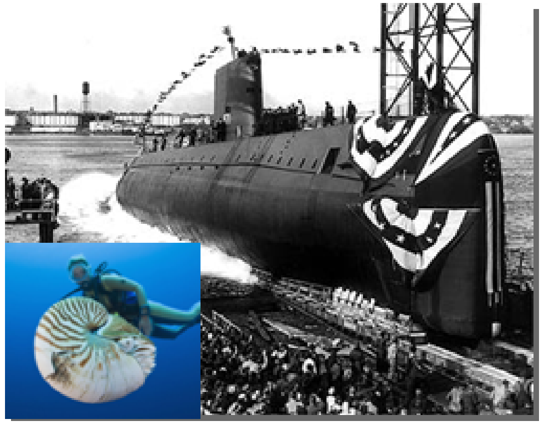


Cross-section of C

# Development of LWR (Light Water Reactor)

## Development of PWR

PWR was developed by Westinghouse (WH) for power source of a Nuclear Submarine "Nautilus" that started operation in Jan.,1955.



**First Commercial PWR in the World**

- Shippingport NPS Unit-1 (60MWe) started operation in Dec., 1957, USA

## Development of BWR

General Electric (GE) aimed at following WH and designed BWR based on the different concept.

**First Commercial BWR in the World**

- Dresden NPS Unit-1 (180MWe) started operation in June, 1960, USA

# NPPs in Operation or under Construction or Planned in the World

(As of Jan.1st, 2012)

| Country | In Operation | Under Construction | Planned | Total |
|---|---|---|---|---|
| **USA** | **104** | **1** | **9** | **114** |
| France | 58 | 1 | - | 59 |
| **Japan** | **50** | **1** | **(10)?** | **61** |
| Russia | 28 | 12 | 13 | 53 |
| Korea | 21 | 5 | 2 | 28 |
| Ukraine | 15 | 2 | - | 17 |
| Canada | 18 | - | - | 18 |
| Germany | 9 | - | - | 9 |
| **China** | **14** | **30** | **26** | **70** |
| England | 18 | - | - | 18 |
| Sweden | 10 | - | - | 10 |
| India | 20 | 7 | 4 | 31 |
| Vietnam | - | - | 4 | 4 |
| Bangladesh | - | - | 2 | 2 |
| Others | 62 | 13 | 31 | 106 |
| Total | **427** | 75 | 94 | **596** |

# Main Features of Core Thermalhydraulics

| Karakteristik | PWR | BWR | AGR | PHWR (Candu) | LWGR (RBMK) | FBR |
|---|---|---|---|---|---|---|
| Tinggi Teras, meter | 4,2 | 3,7 | 8,3 | 5,9 | 7,0 | 1,0 |
| Diameter Teras, meter | 3,4 | 4,7 | 9,3 | 6,0 | 11,8 | 3,7 |
| Bahan Bakar, Ton | 104 | 134 | 110 | 90 | 192 | 32 |
| Bentuk Containment | Bejana | Bejana | Bejana | *Tubes* | Bejana | n/a |
| Jenis bahan bakar | $UO_2$ diperkaya | $UO_2$ diperkaya | $UO_2$ diperkaya | $UO_2$ alam | $UO_2$ diperkaya | $UO_2/PuO_2$ diperkaya |
| **Pendingin** | $H_2O$ | $H_2O$ | $CO_2$ | $D_2O$ | $H_2O$ | Sodium |
| Sistem uap | *Indirect* | *Direct* | *Indirect* | *Indirect* | *Direct* | *Indirect* |
| Moderator | $H_2O$ | $H_2O$ | Grafit | $D_2O$ | Grafit | - |
| **Jumlah di Dunia** | 266 | 92 | 14 | 46 | 15 | 1 |

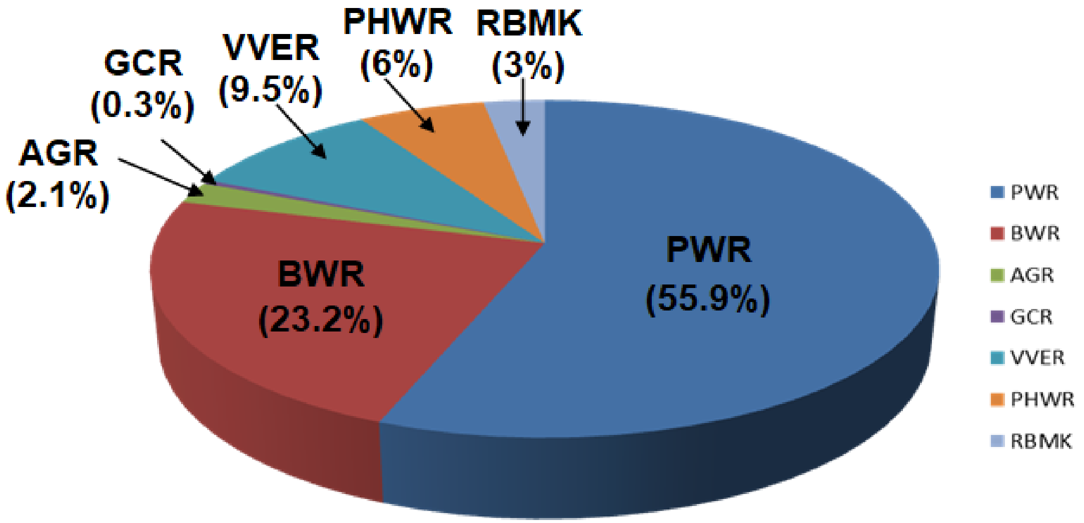
*PWR-Pressured Water Reactor, BWR-Boiling Water Reactor, AGR-Advanced Gas Cooled Reactor, PHWR-Pressurized Heavy Water Reactor, LWGR-Light Water Gas Cooled Reactor, FBR-Fast Breeder Reactor.*

# Share of BWR and PWR in the World

## Share of BWR and PWR in the World

| | | | |
|---|---|---|---|
| BWR | ~20% | PWR | Over 70% |

## Ratio of Electricity generated by Each Type Reactor in 2008

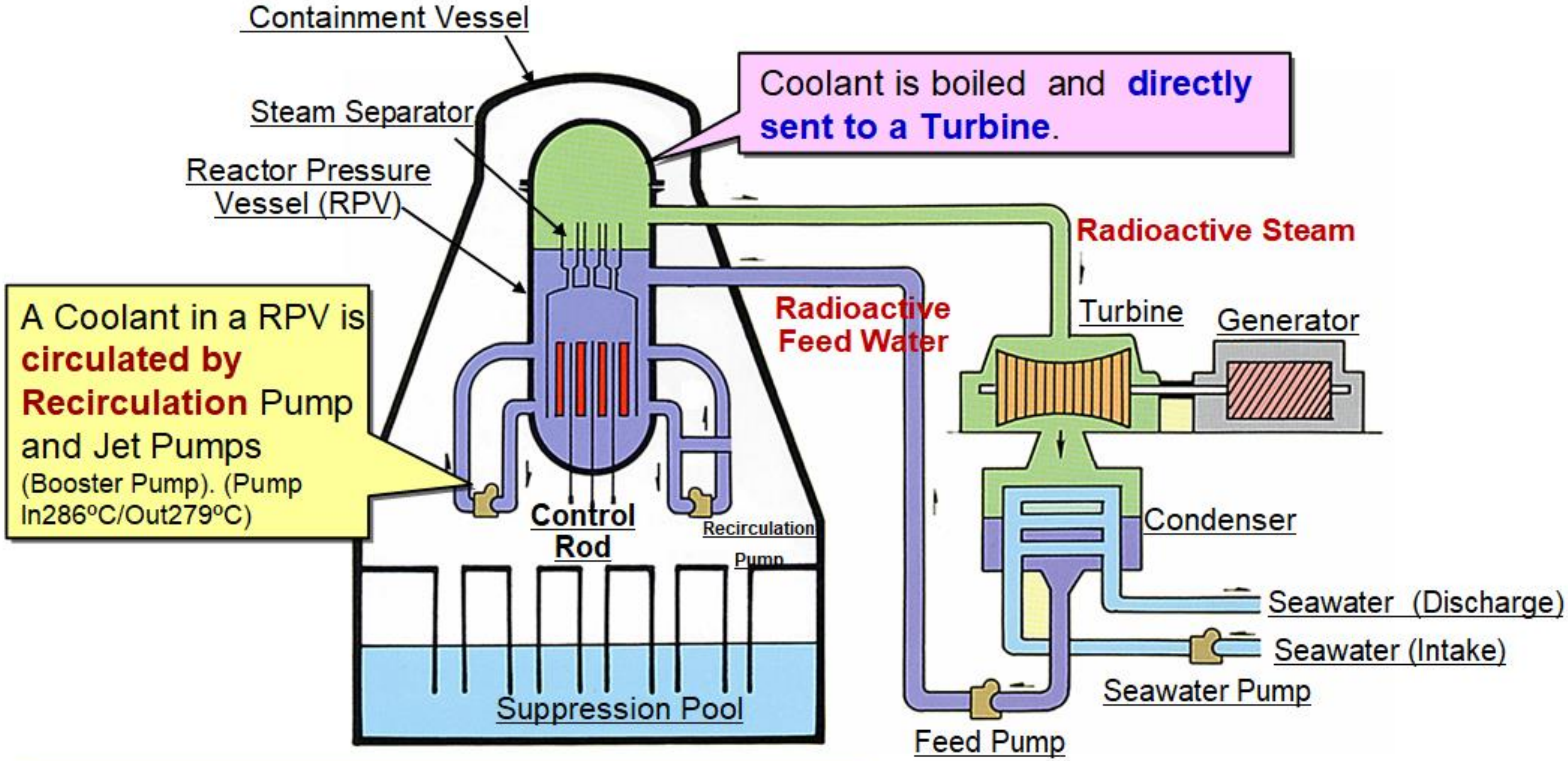



- AGR: Advance Gas-cooled Reactor
- GCR: Gas-cooled Reactor
- VVER: Russia Type PWR
- PHWR: Pressurized Heavy-Water Reactor (CANDU)
- RBMK: Pebble Bed Type High Temperature Gas-cooled Reactor

Source: Private communication with Mr. Mehmet Ceyhan in NFCMS/NFCW/IAEA

# Outline of Plant System Configuration of BWR and PWR

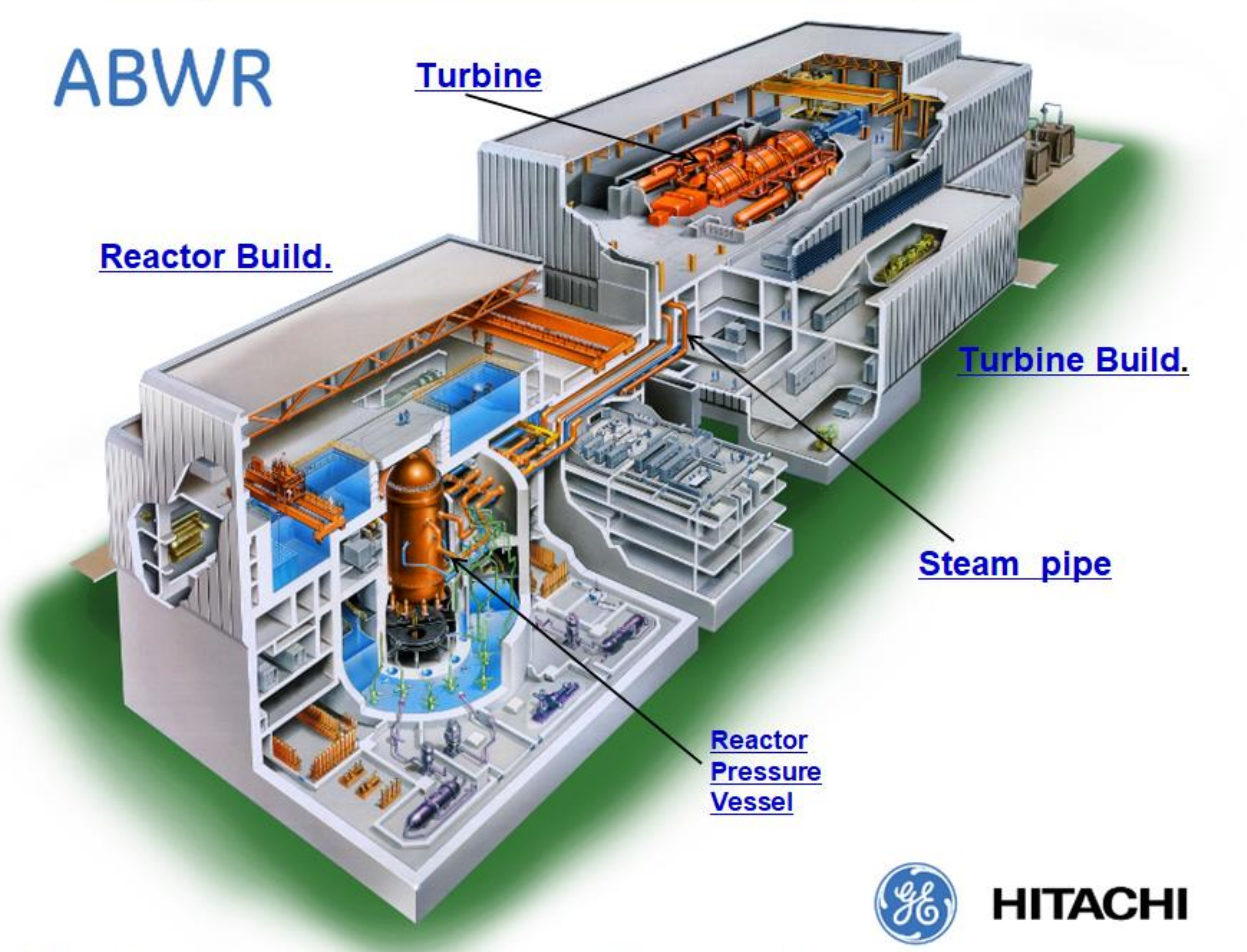
# BWR Main Plant System Configuration




## Main Plant Specifications of BWR (1,100MWe class)

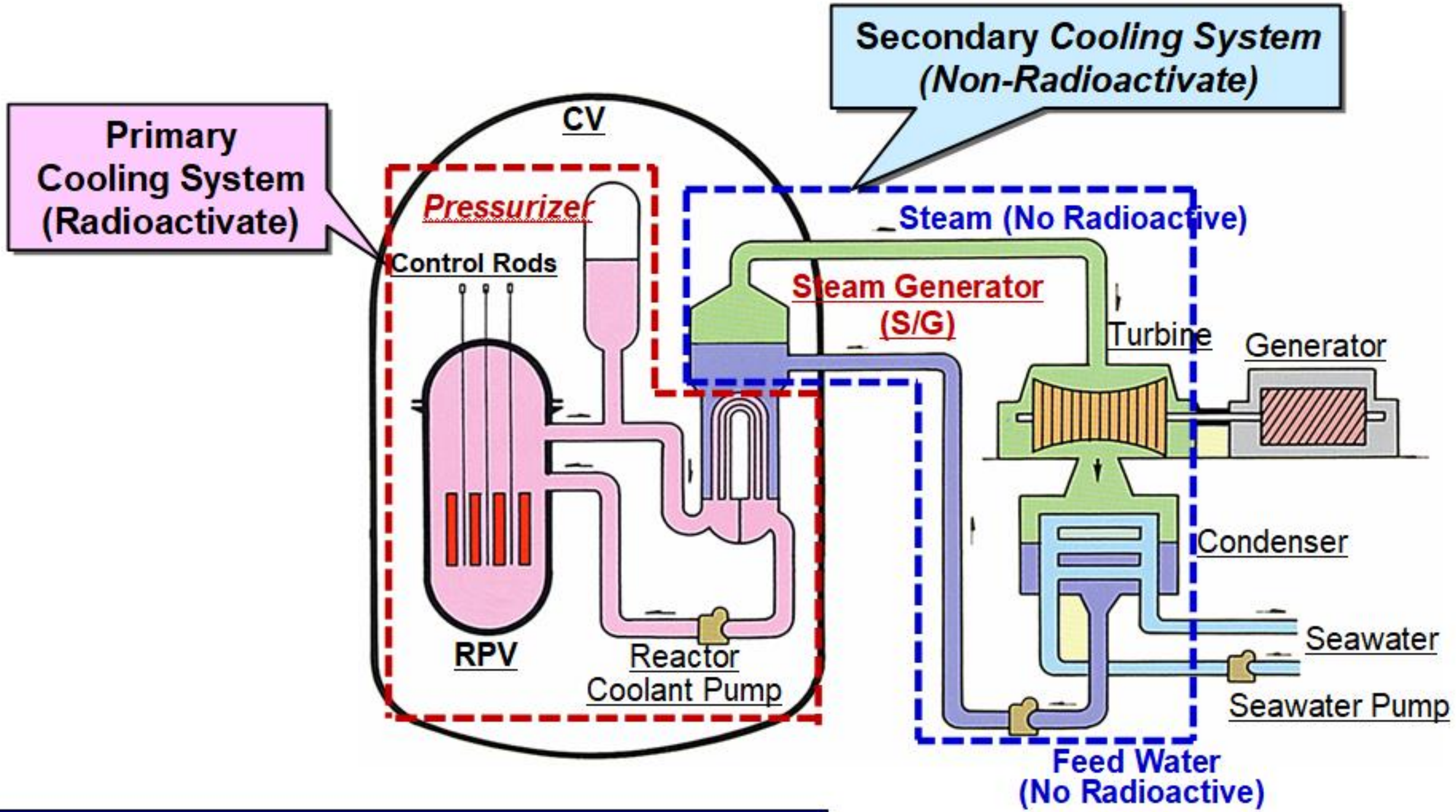
| RPV Pressure | Core Flow rate | Core Outlet Temp. | Core Inlet Temp. | Steam Flow Rate | Feed Water Temp. |
|---|---|---|---|---|---|
| *6.9MPa* | *48,300t/h* | *286°C* | *279°C* | *6,410t/h* | *216°C* |

# Bird's Eye View of ABWR NPP




http://www.ecomagination.com/portfolio/ge-hitachi-...

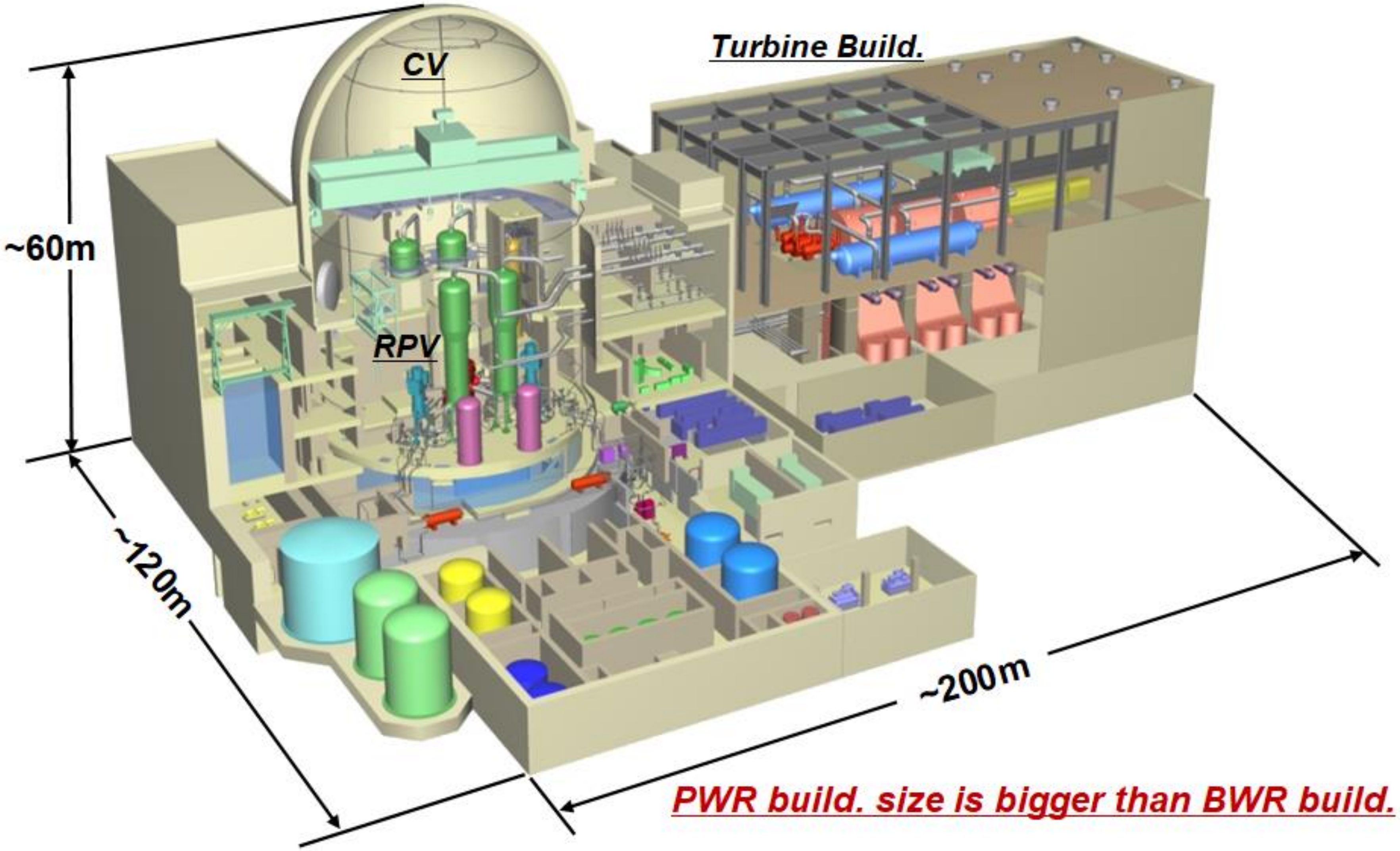
# PWR Main Plant System Configuration




## *Main Plant Specifications of PWR (1,100MWe class)*

| RPV Pressure | Core Flow rate | Core Outlet Temp. | Core Inlet Temp. | Steam Flow Rate | Feed Water Temp. |
|---|---|---|---|---|---|
| *15.4MPa* | *60,100t/h* | *325°C* | *289°C* | *6,760t/h* | *223°C* |

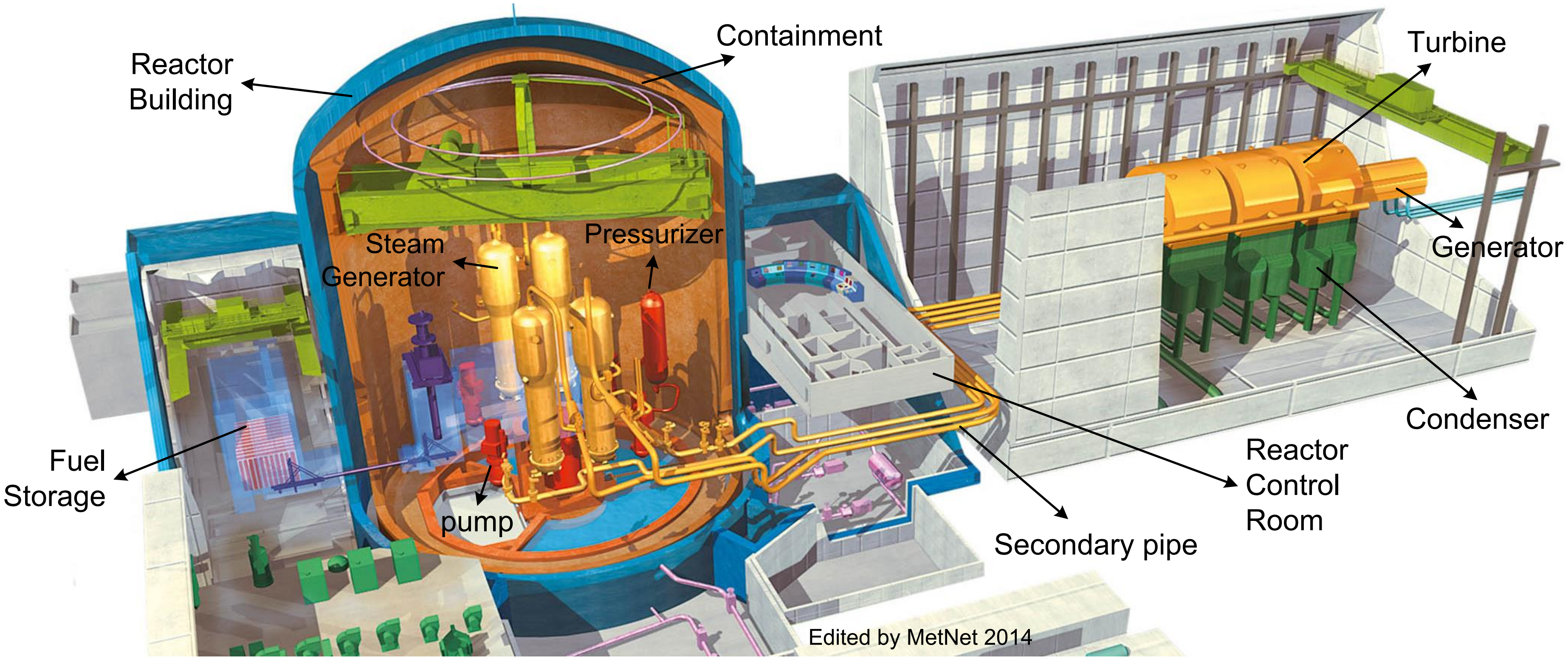
# Bird's Eye View of APWR (Facility Size Image)




PWR build. size is bigger than BWR build.

<4 Loops PWR Plant, 1,200MW Class>

# Bird’s Eye View of APWR (Facility Size Image)




**Primary system**

- Pressured vessel
- Steam generators
- Pressurizer
- Primary pumps

**Secondary system**

- Turbine
- Condenser
- Heater
- Secondary pump

# Power Generation and Thermal Efficiencies, Power Density

| | BWR | PWR |
|---|---|---|
| **Power Generation Efficiency ($P_{eff}$%)** | | |
| Electrical Output ($P_e$) | 1,100MWe | 1,100MWe |
| Thermal Output ($P_t$) | 3,293MWt | 3,411MWt |
| **$P_{eff} = P_e / P_t$ (%)** | **33.4% (ABWR:34.6%)** | **32.2% (APWR:34.4%)** |
| **Thermal Efficiency (η%)** | | |
| Steam Temperature ($T_H$) | 286ºC | 277ºC |
| Feed Water Temperature ($T_L$) | 216ºC | 223ºC |
| **Power Density (kW/ℓ)*** | | |
| Core Effective Length ($L_{eff}$) | 3.7m | 3.7m |
| Core Effective Diameter ($D_{eff}$) | 4.8m | 3.4m |
| **PD = ($P_t$/V) = $P_t$ / $\pi(D/2)^2$ x $L_{eff}$ (kW/ℓ)** | **~50kW/ℓ** | **~100kW/ℓ** |

# Main Features of PWR

| Perusahaan dan Negara Produsen | Nama Reaktor | Daya (MWe) | Kemajuan Sertifikasi Desain (April 2011) | Fitur Utama |
|---|---|---|---|---|
| Westinghouse (USA) | AP600<br>AP1000 | 600<br>1200 | AP600: disertifikasi oelh NRC 1999.<br>AP1000: disertifikasi oleh NRC 2005, beroperasi komersial di Cina tahun 2011. | • Operasi dan konstruksi lebih sederhana<br>• Konstruksi 3 tahun<br>• Operasi 60 tahun |
| AREVA (Prancis) | EPR<br>US-EPR | 1750 | Sedang dibangun di Finlandia, Prancis & Cina. Dalam proses sertifikasi oleh NRC, USA. | • Desain evolusi<br>• Efisiensi tinggi pada bahan bakar<br>• Operasi fleksibel |
| Mitsubishi (Jepang) | APWR<br>US-APWR<br>EU-APWR | 1530<br>1700<br>1700 | Dalam proses desain basis. | • Fitur keselamatan hibrit<br>• Operasi dan konstruksi lebih sederhana |
| KHNP (Korea Selatan) | APR-1400 | 1450 | Sertifikasi desain tahun 2003, operasi komersial tahun 2013 di Korea Selatan. Pemenang tender kontrak 4 PLTN di UAE. | • Desain evolusi.<br>• Peningkatan kehandalan<br>• Operasi dan konstruksi lebih sederhana |
| Gidropress (Russia) | VVER-1200 | 1290 | Dalam proses konstruksi di Leningrad dan Novovoronezh Rusia. | • Desain evolusi<br>• Efisiensi tinggi pada bahan bakar<br>• Operasi 50 tahun |

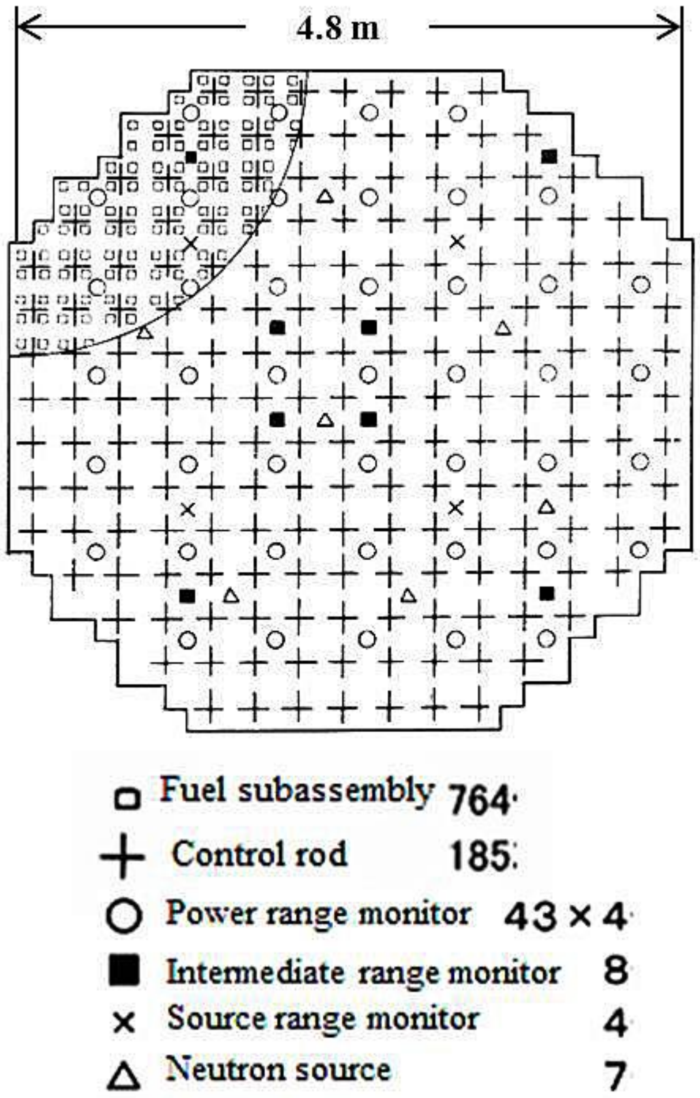
# Comparison of Main Components between BWR and PWR

1. Reactor Core ,Pressure vessel and internals
2. Fuel Assembly and Control Rod
3. Containment Vessel (CV)
4. Recirculation Pump of BWR
5. Steam Generator (S/G) of PWR
6. Pressurizer of  PWR

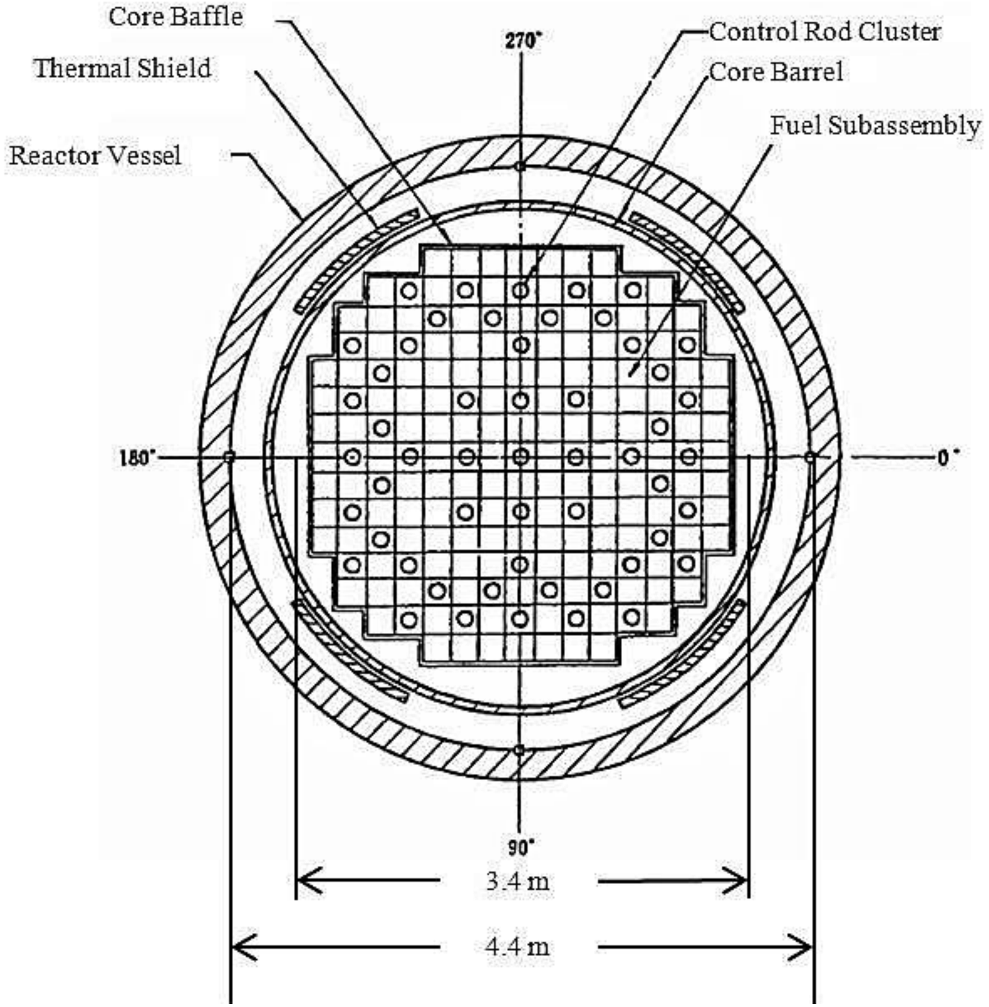
# 1)-1 Reactor Core and internals

| | BWR | PWR |
|---|---|---|
| Equivalent Diameter | 4.8m | 3.4m |
| Equivalent Core Height | 3.7m | 3.7m |
| No. of Fuel Assemblies (Fuel Rods in a Fuel assemblies) | 764<br>( Fuel rods 8x8) = 45,840 fuel rods | 193<br>(Fuel rods: 17x17) = 50,952 fuel rods |
| **Average Fuel U Enrichment (Reloading)** | **~3.5%** | **~3.4%** |
| Reactivity control | Control rod +burnable poison | Chemical shim +control rod +burnable poison |
| No. of Control Rods | 185 | 53 |
| Power Density | 50W/cc | 105W/cc |
| Burnup (Gwd/t) | 39.5 | - |
| Moderator/Fuel Volume Ratio | 2.91 | - |

# 1)-2 Comparison of Core Map




**BWR**




**PWR**

# 1)-3 Comparison of RPV Specification

| BWR (1,100MWe Class) | | PWR (1,100MWe Class) | |
|---|---|---|---|
| Designed Pressure | 86.2MPa | Max. Allowable Working Pressure | 171.6MPa |
| Designed Temperature | 302ºC | Max. Allowable Working Temperature | 343ºC |
| **Operating Pressure** | **6.93MPa** | **Operating Pressure** | **15.4MPa** |
| **Operating Temperature** | **286ºC** | **R/V Outlet Temperature** | **325ºC** |
| | | **R/V Inlet Temperature** | **289ºC** |
| **Overall Height** | **~22m** | **Overall Height** | **~13m** |
| **Shroud Inner Diameter** | **~6.4m** | **Inner Diameter** | **~4.4m** |
| Thickness | ~16cm | Min. Thickness | 20~25cm |
| Total Weight | ~750t | Total Weight | ~400t |
| Material | Ferrite Steel | Material | Ferrite Steel |

Since BWR has Steam Separator and Steam Dryer, **BWR RPV is larger than PWR** one.

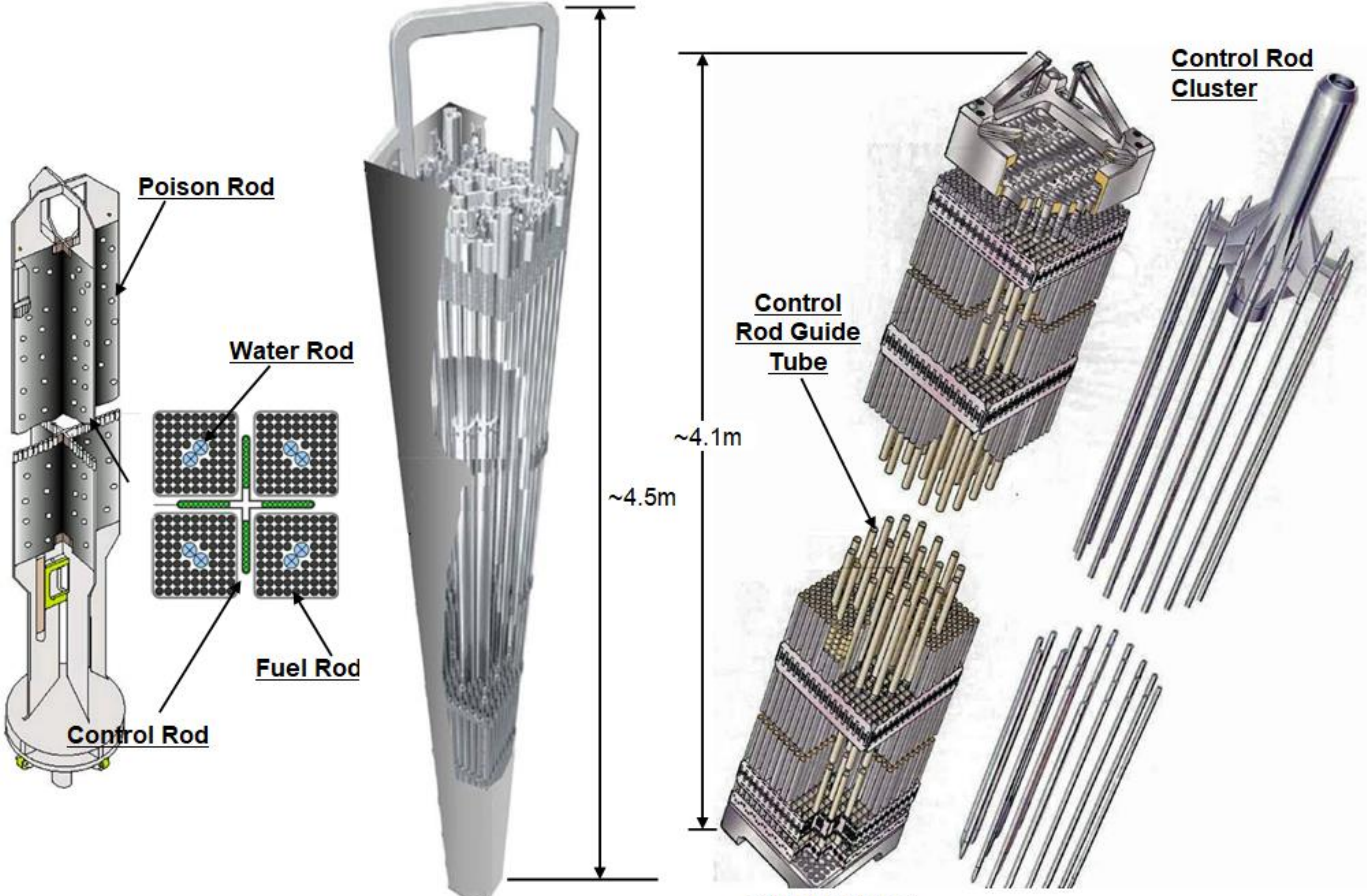
# 2)-1 Comparison of Fuel/Control Rod Assembly

| Specification | | BWR | PWR |
|---|---|---|---|
| **Fuel Assembly** | **No. of Fuel Assemblies in core** | **764** | **193** |
| | **Fuel Placement** | **8x8 Square Lattice** | **17x17 Square Lattice** |
| | **No. of Fuel Rod** | **60** | **264** |
| | Max. Linear Power Density | 440W/cm | 420W/cm |
| | **Max. Burn-up** | **50,000MWD/t** | **48,000MWD/t** |

| Specification | | ***BWR*** | ***PWR*** |
|---|---|---|---|
| **Fuel Rod** | Outer Diameter | 12.3mm | 9.5mm |
| | $UO_2$ Pellet Diameter/Height | 10.4mm/10mm | 8.2mm/5mm |
| | Cladding Tube Thickness | 0.86mm | 0.6mm |
| | Cladding Material | Zry-2 | Zry-4 |
| | He Gas Pressure | 0.5MPa | 3.2MPa |

| Specification | | ***BWR*** | ***PWR*** |
|---|---|---|---|
| **Control Rod** | **No. of Control Rod** | **185** | 53 |
| | Absorber | Absorber<br>●Hafnium<br>●Born carbide ($B_4C$) | Ag-In-Cd Alloy<br>(Cadmium Alloy) |

# 2)-2 Comparison of Control Rod between BWR and PWR

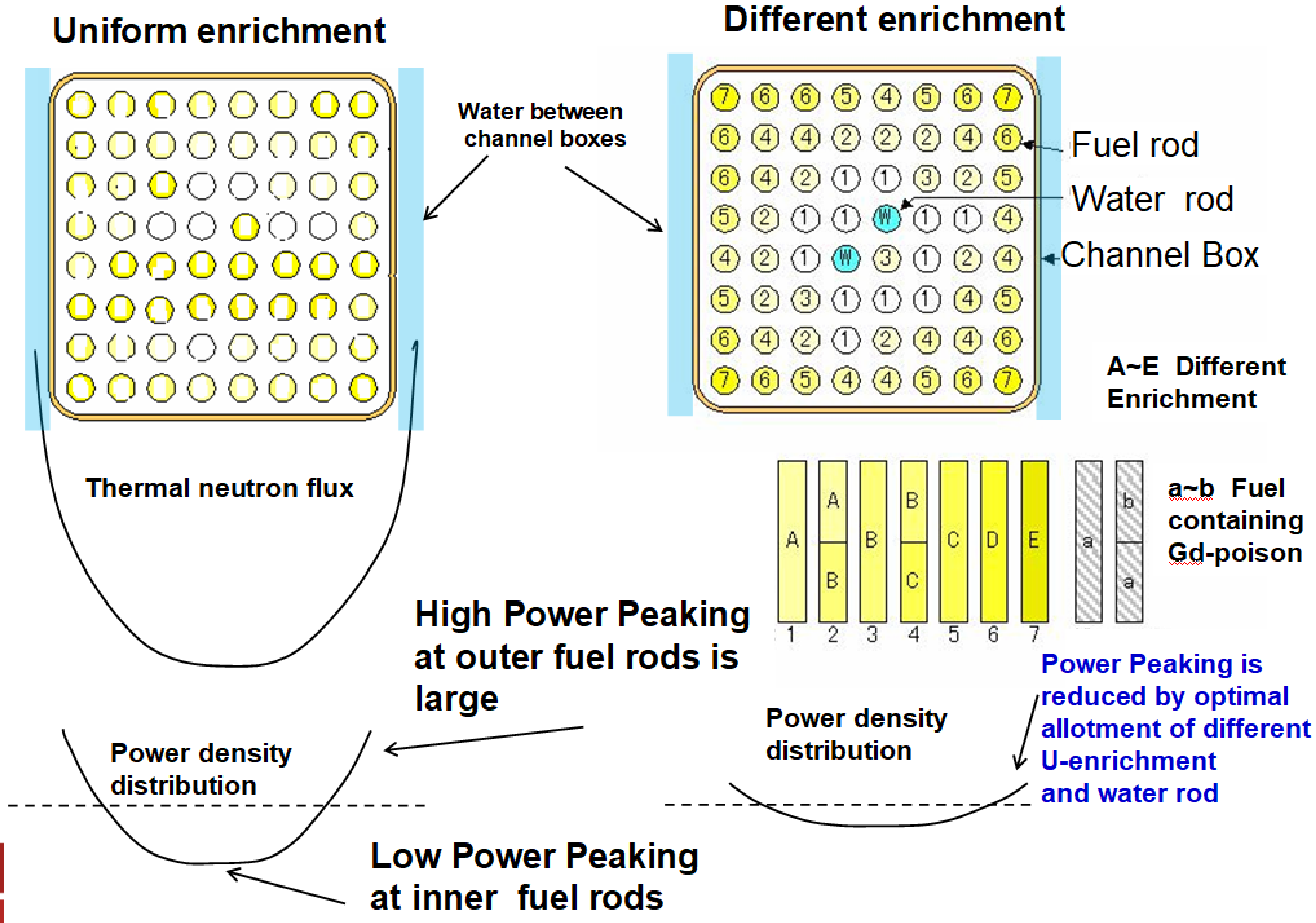



<17x17 Type>

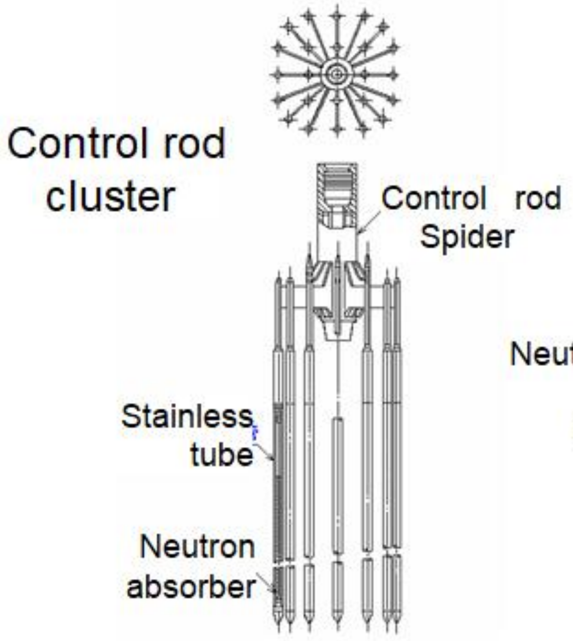
<BWR>

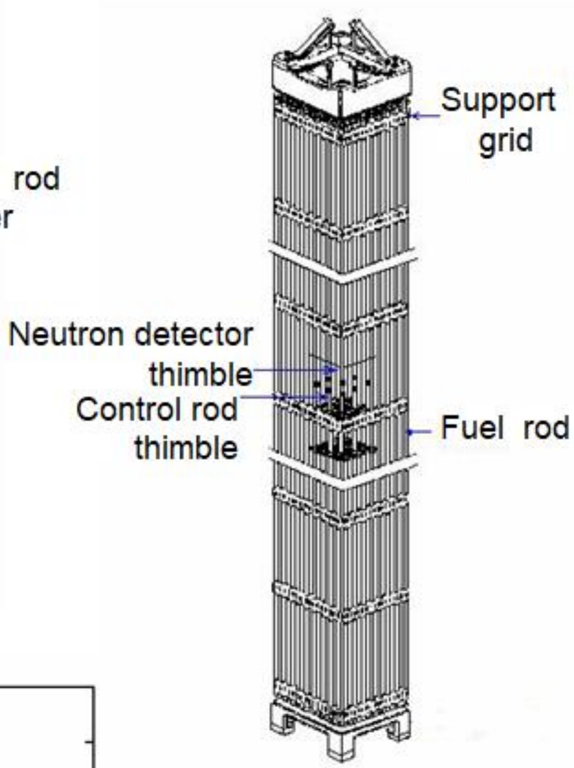
<PWR>

# 2)-3Uranium enrichment Allotment in BWR Fuel Assembly

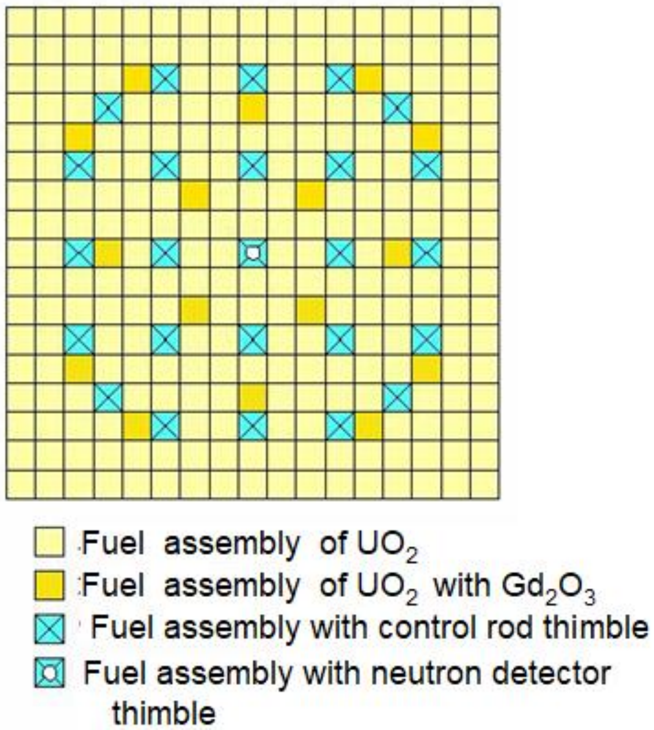


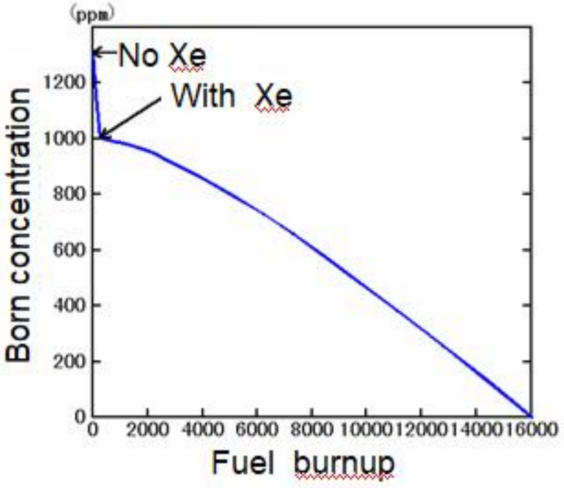
## 2)-4 Core, Fuel assembly, control rod shim control PWR




Fuel assembly



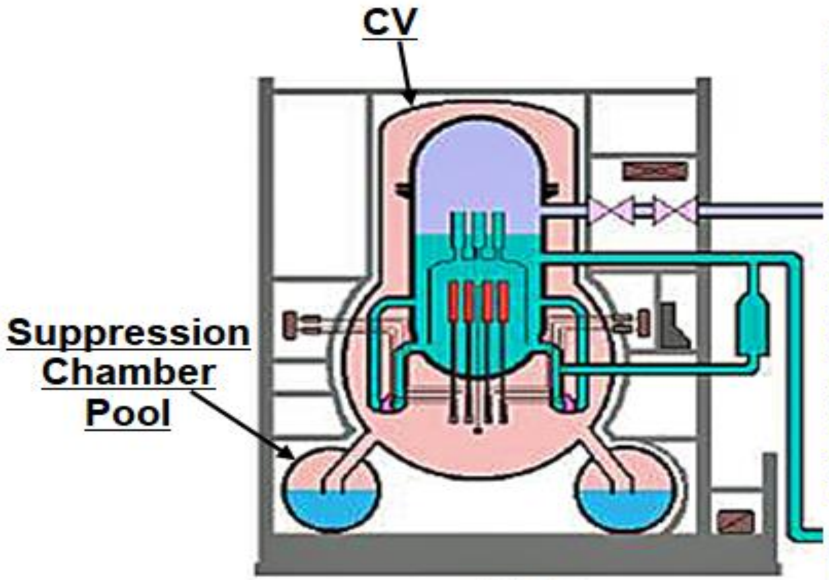

Chemical shim control

**Uranium enrichment in a fuel assembly is uniform.**

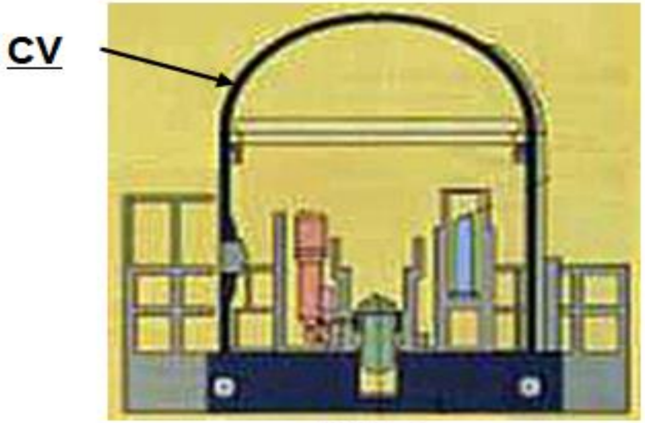
**Reactivity is controlled with control rod shim control (boron concentration in coolant) and burnable poison $Gd_2O_3$ in PWR**

# 3) Comparison of CV between BWR and PWR

## How to Control Rising of CV Inside Pressure in the Accident?



<BWR>



<PWR>

**BWR CV**

- The **mixture of steam and water** produced in CV is **dumped into a Suppression Chamber Pool**.
- Rising of CV-Inside Pressure is restrained by **Condensing of Steam by Spray System**.

☞ **CV Type: "Pressure Suppression Type"**

**PWR CV**

- Rising of CV-Inside Pressure is **restricted by Huge Volume of CV** and **Condensing of Steam by Spray System**.

☞ **CV Type: "Dry Container Type"**

*Large Size of Dry TypeCV: >70,000m$^3$

**To raise strength of CV**

⇨ **Prestressed Concrete Containment Vessel (PCCV)**

# 4) Recirculation of coolant flow in core of BWR

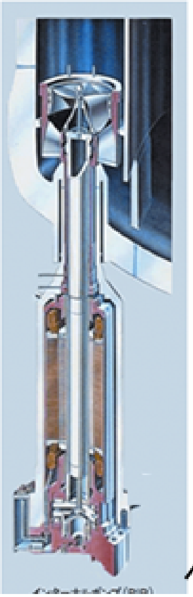
To **Distribute the Coolant Boiling to the Fuel Assemblies Uniformly**, ABWR has **internal Pumps** .

| 1350MWe ABWR | |
|---|---|
| No. of Circulation Pumps | 10 |
| Core Flow Rate | Approx. 8300m³/h |

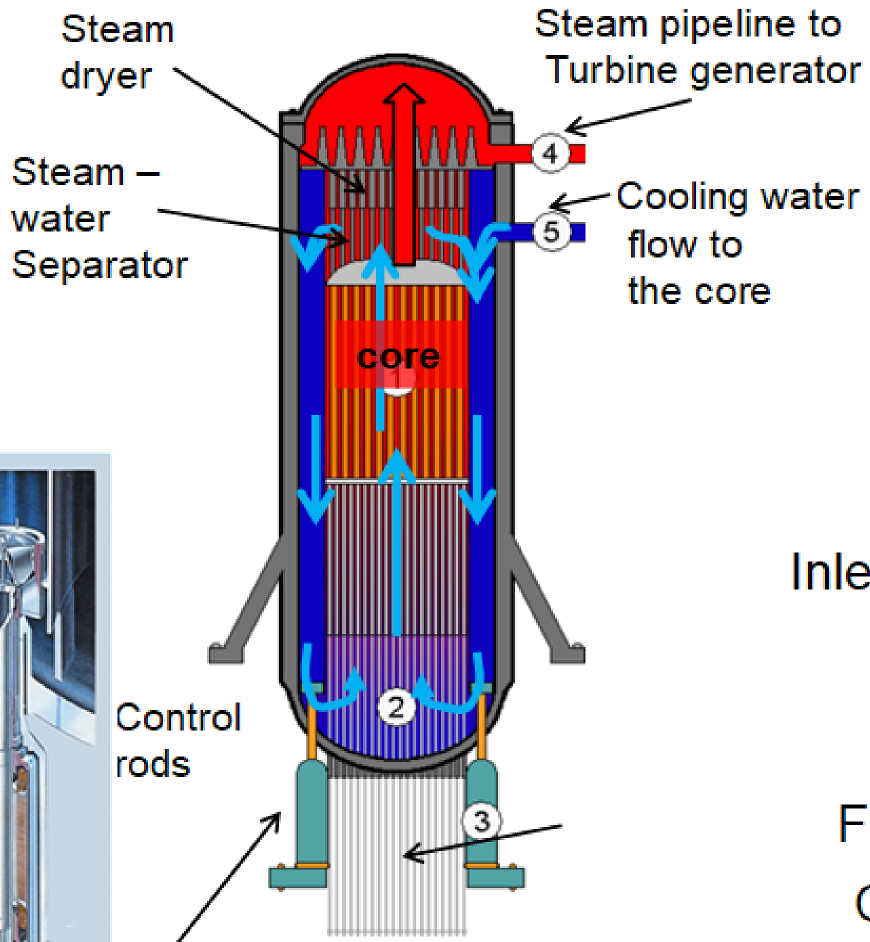
**Coolant –water flown from core is mixed with feed-water.**

**They are recalculated with internal Pumps.**

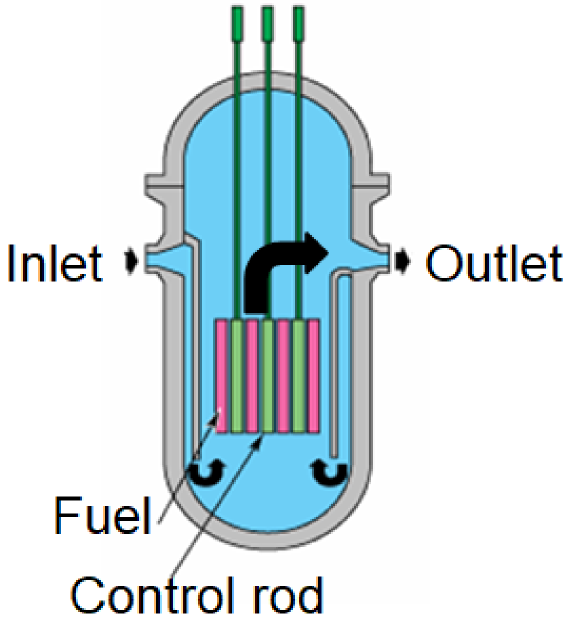
**Thermal power can be controlled by internal pump with the recirculation**



Internal Water Pump




Reactor pressure vessel

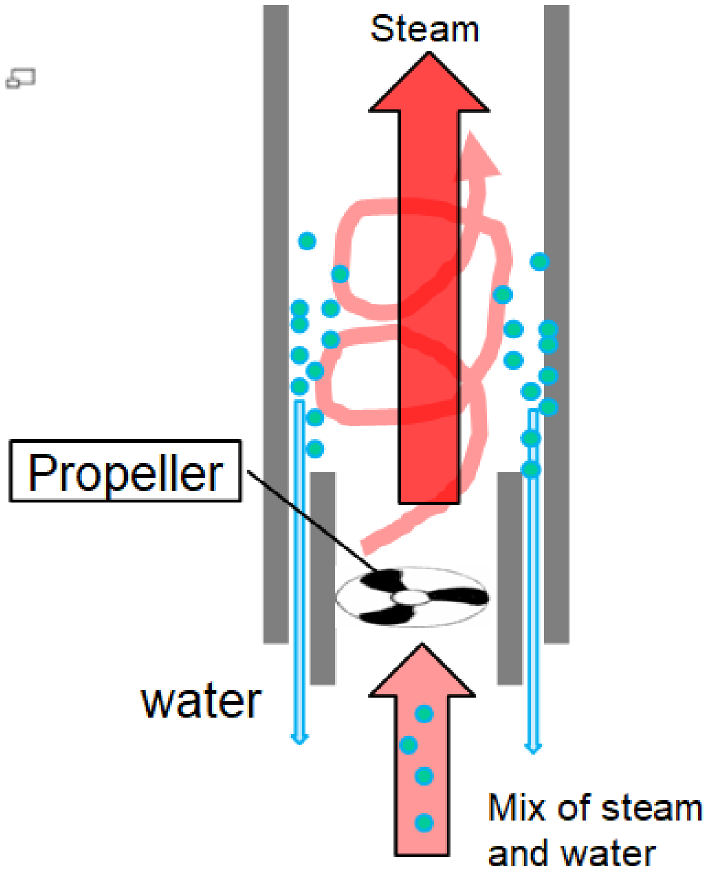



PWR

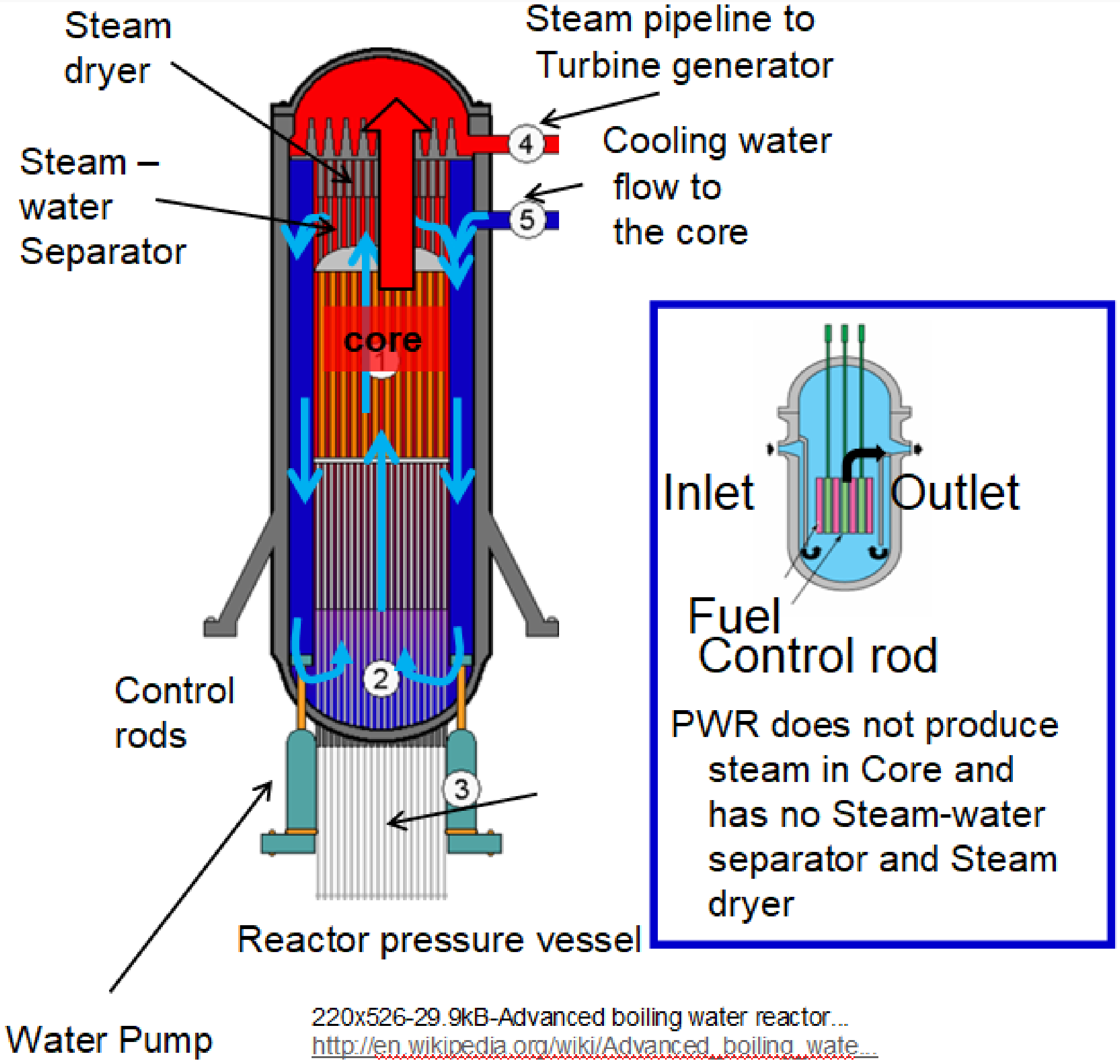
220x526-29.9kB-Advanced boiling water reactor...
http://en.wikipedia.org/wiki/Advanced_boiling_wate...

# 4) -2 Steam – Water separator of BWR

Mix of steam and water are produced in core. Steam is separated from the mix to increase the quality of steam. Centrifugal force is applied for the separation

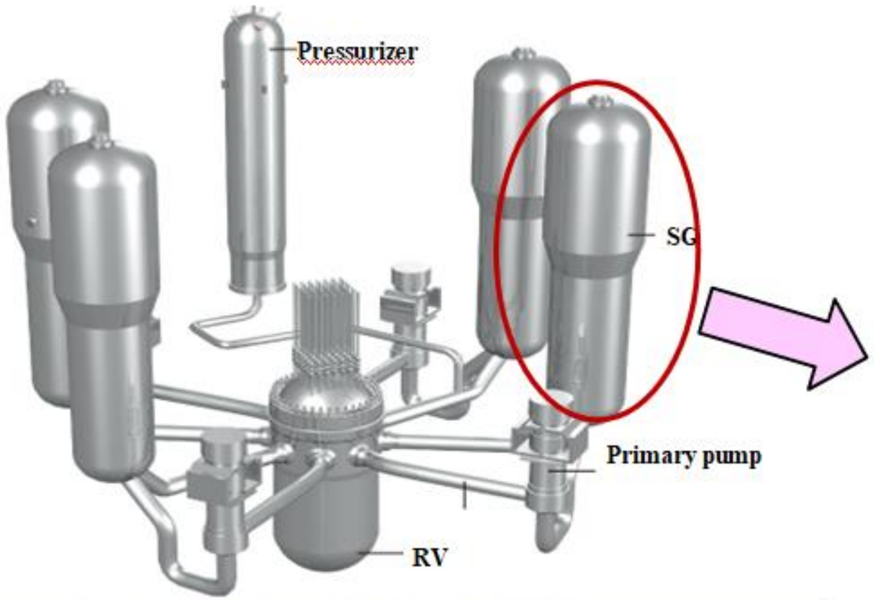



Principal of Steam – water Separator

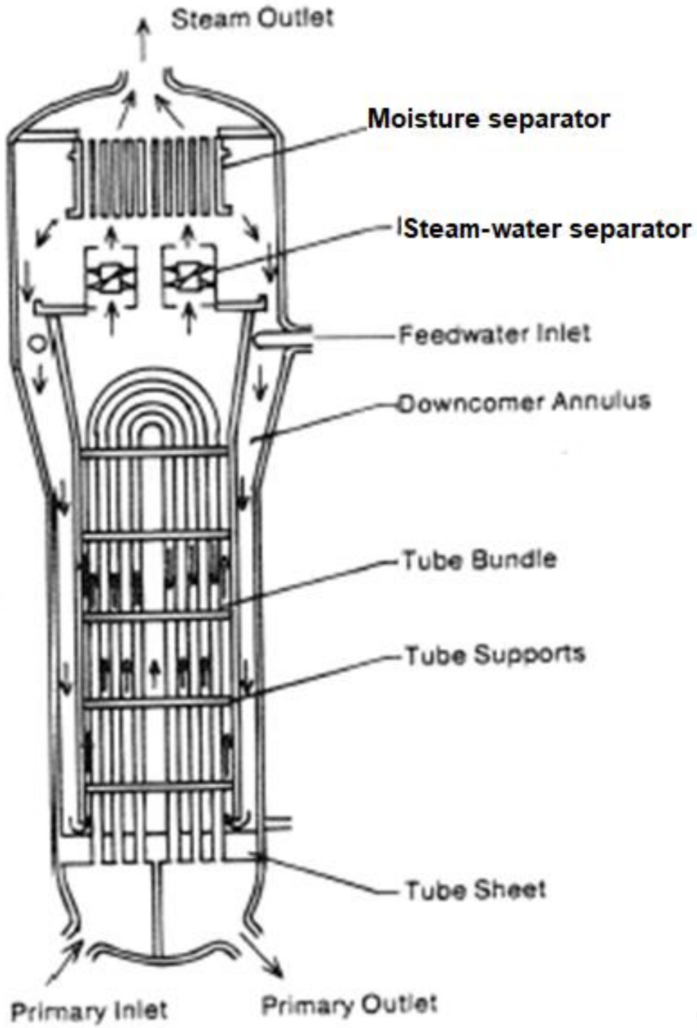



220x526-29.9kB-Advanced boiling water reactor...
http://en.wikipedia.org/wiki/Advanced_boiling_wate...

# 5) Steam Generator (S/G) of PWR




| Specification of S/G (4 S/G Types) | |
|---|---|
| Height | ~20m |
| Diameter | ~5m |
| Design Pressure | ~8.2MPa |
| Shape | U Shape Transfer Tube |
| Primary Side (Inside) | 325°C, 15.4MPa |
| Secondary Side (Outside) | 277°C, 6.0MPa |
| Material | TTI Inconel 690 (High Corrosion Resistant) |
| No. of Tubes | ~3,300 |
| Tube Diameter | ~2cm |
| Tube Thickness | ~1.3mm |



# 6) Pressurizer of PWR

◆***Provided Equipment***:

-Electric Heater

-Water-spray Nozzle

-Safety Valve

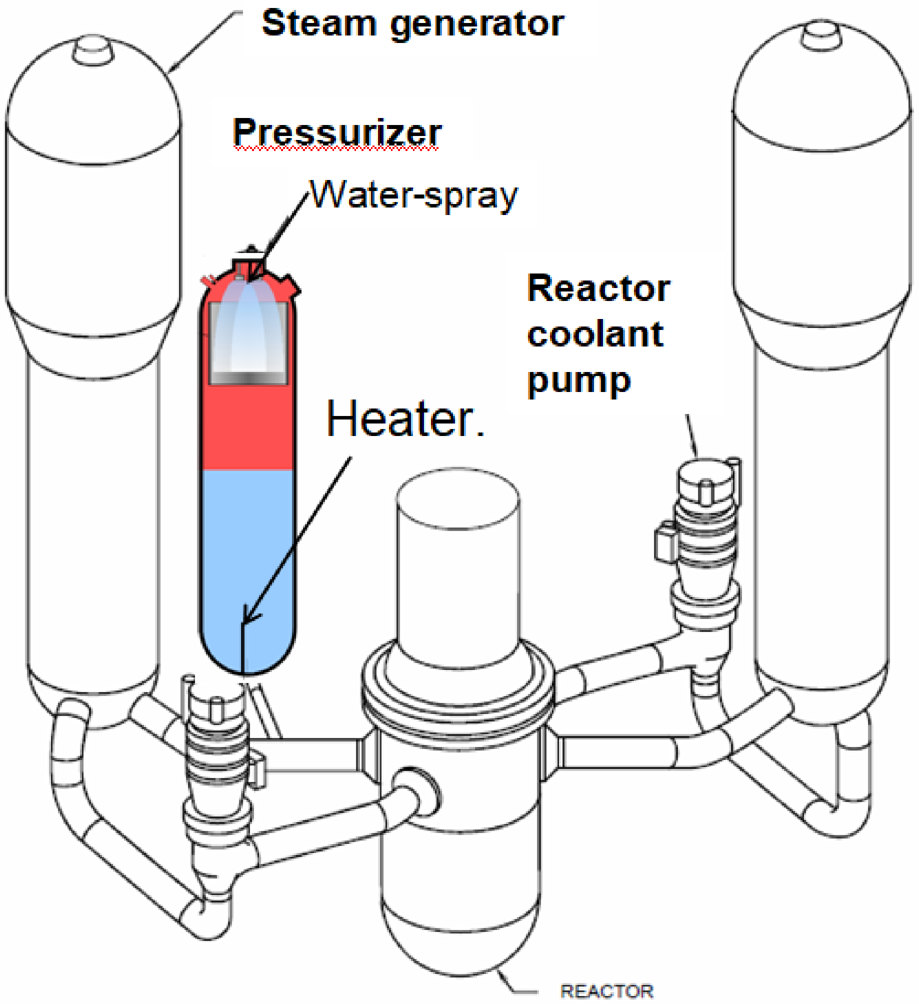
◆***Operation Method:***

-Water level is maintained at 60% of the vessel capacity

-Pressurizing by generating steam by using

◆If pressure becomes excessive, low-temperature water will be supplied from the primary cold leg piping.

◆Consequently, the operation pressure is able to be kept constantly by decreasing pressure by condensation of steam.



# Comparison of Each Feature between BWR and PWR

1) Feature related to Feedback Reactivity (Self Regulating Characteristics)

2) Feature related to Structural Design

3) Feature related to Power and reactivity Control

# 1) Comparison of Feedback Reactivity in BWR and PWR

## Concept of "Self Regulating Characteristic"

Unexpected Disturbance
(Increasing Nuclear Fission)

Reactor Power Up

Rising of Fuel Temp.

Rising of Coolant Temp.

*Temperature Effect*
*(Self Regulating Characteristics)*

Doppler Effect
(BWR and PWR)

Void Effect
(BWR)

Density Effect
(PWR)

Negative Reactivity Feedback

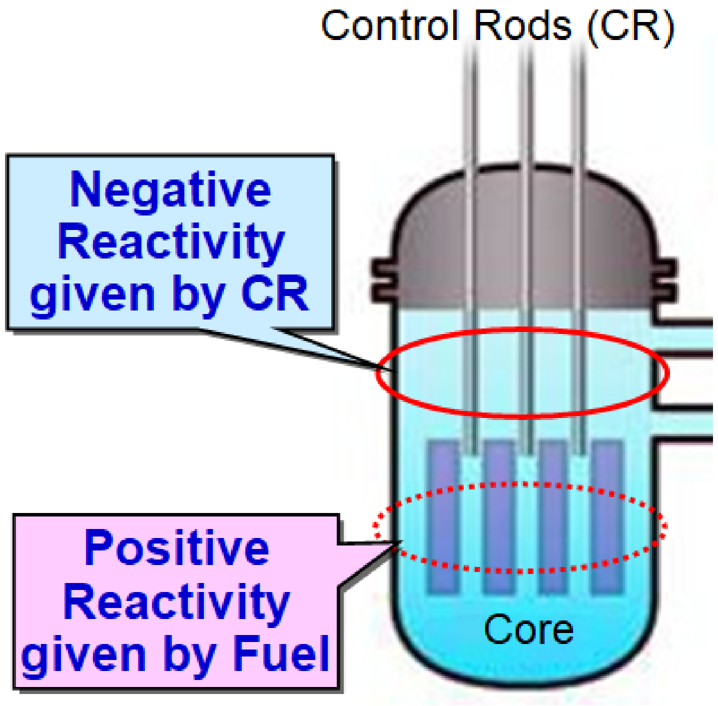
Decreasing of Nuclear Fission

Reactor Power Down

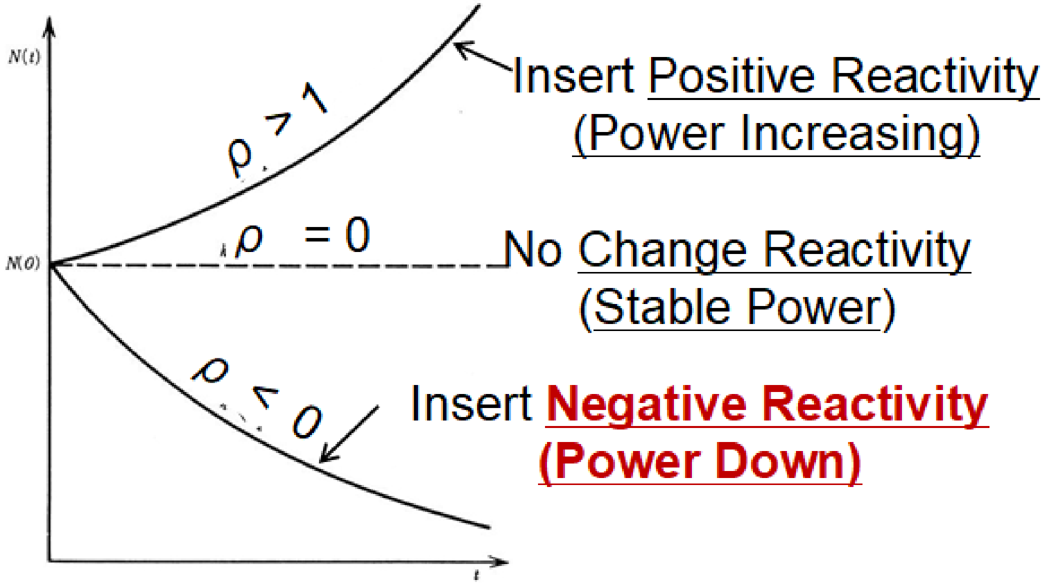
Even if Temp. in a core rises, Reactor Power **automatically goes down** by negative reactivity feedback.

# Reference: Image of "Reactivity"

- Reactivity expresses the degree of **Nuclear Fission Numbers**.
- **Positive Reactivity**: Increasing of Fission Number
  - ☞ **Given by Fuel**
- **Negative Reactivity**: Decreasing of Fission Number
  - ☞ Given by CR or **Self Regulating Characteristics**




$\rho = (k-1)/k$ definition of reactivity

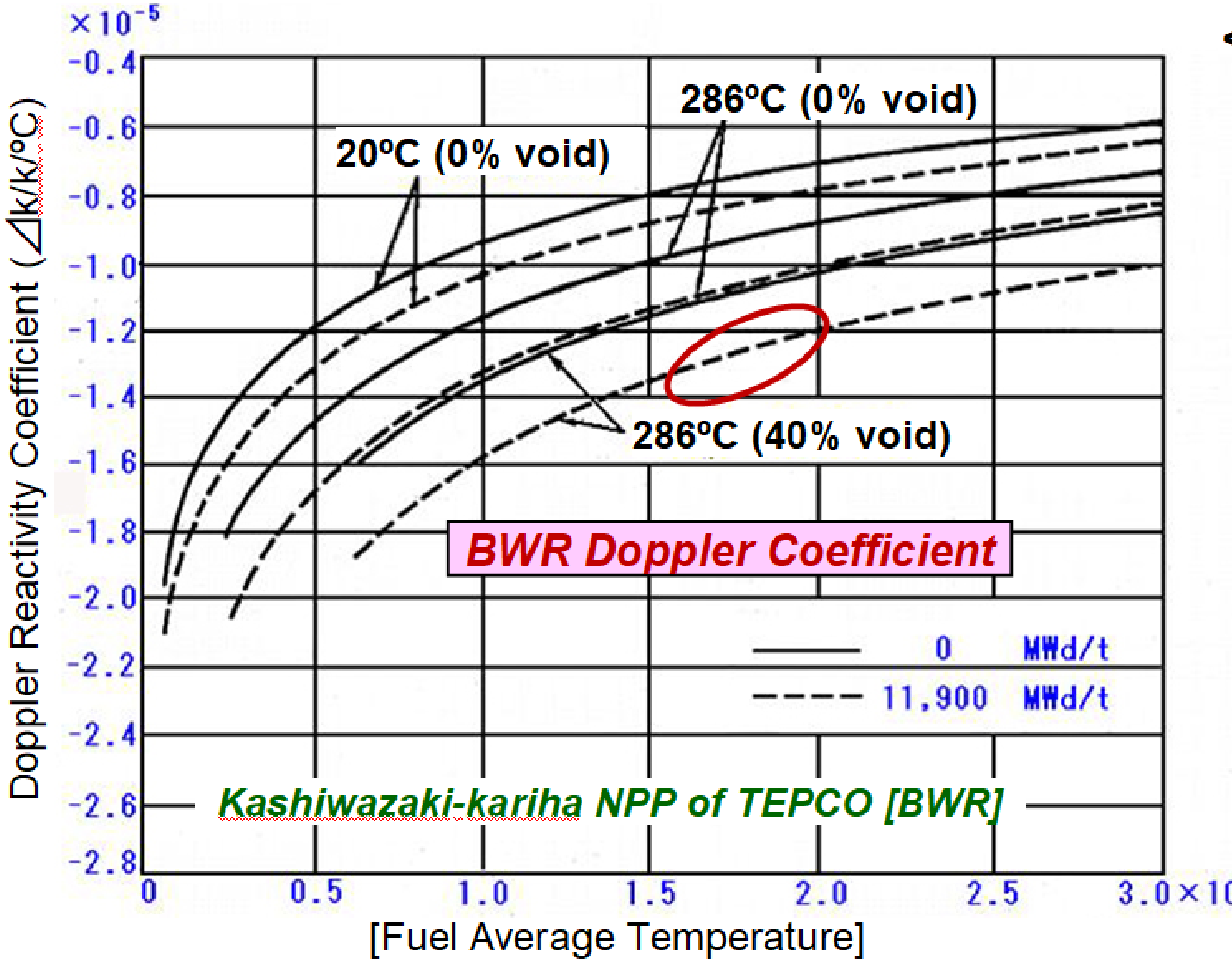



$P = P_0 \ \mathrm{Exp}\,(c\ \rho\ t)$ :(simplified Eq.)

# Comparison of Doppler Coefficient in BWR and PWR

- Figure shows Doppler reactivity coefficient of BWR as a sample.
- The coefficient per unit temperature in **PWR** is about **$-3$ to $-5\times10^{-5}\Delta k/k/^{o}C$*** which is ***larger than BWR***.

*Source: 原子力百科事典ATOMICA、軽水炉(PWR型)原子力発電所、炉心・遮蔽設計、PWRの炉心設計




***<Fuel Rod Numbers>***

| BWR | PWR |
|---|---|
| 45,840 (8x8 x764S/A) | 50,952 (17x17 x193S.A |

***<Doppler Coefficient>***

| BWR | PWR |
|---|---|
| $\sim-1.2$ to $-1.4\times10^{-5}$ | $\sim-3$ to $-5\times10^{-5}$ |

($\Delta k/k/^{o}C$)

***PWR has larger Negative reactivity feed back than BWR***

# Void Effect in BWR

## Inherent Safety

Reactor Power Up

⇩

Rise of Coolant Temperature

⇩

*Increase of Void Amount*

⇩

Hardening of Neutron Spectrum

⇩

*Decrease of Slowdown Effect*

⇩

Decrease of Nuclear Fission

⇩

*Reactor Power Down*

## Weak Point of BWR

*Rise of Inner Pressure of Core*

⇩

*Crushing of Void*

⇩

*Increase of Moderator (Coolant) Amount*

⇩

*Increase of Slowdown Effect*

⇩

Increase of Nuclear Fission

⇩

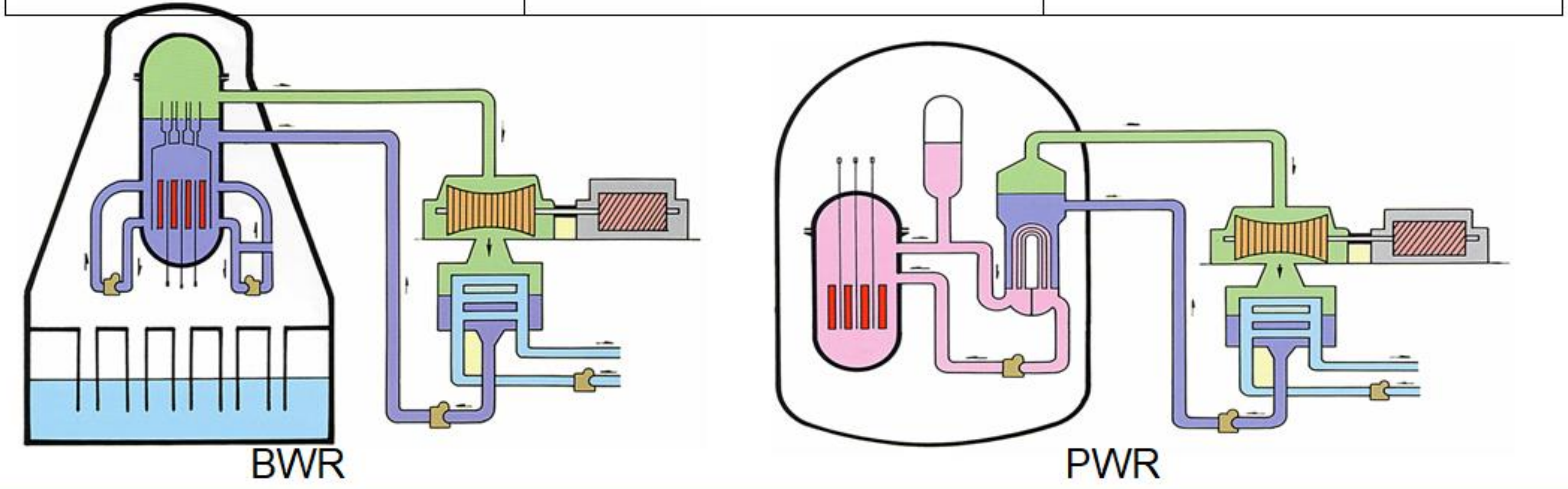
*Rise of Reactor Power*

*Positive reactivity feed back*

# 2)-2 Steam Condition between BWR and PWR

The ***steam condition of BWR is superior to PWR*** because BWR can directly use the ***steam produced in a core***. While, PWR's steam is generated via S/G (secondary).

| | BWR | PWR |
|---|---|---|
| Steam Pressure | 6.9MPa | 6.0MPa |
| Steam Temperature ($T_H$) | 286ºC | 277ºC |
| Feed Water Temperature ($T_L$) | 216ºC | 223ºC |
| Steam Flow Rate | $6.41 \times 10^6$kg/h | $6.76 \times 10^6$kg/h |
| **$P_{eff} = P_e / P_t$ (%)** | **33.4% (ABWR:34.6%)** | **32.2% (APWR:34.4%)** |



# 2)-4 Refueling Work

**RPV and CV of BWR**

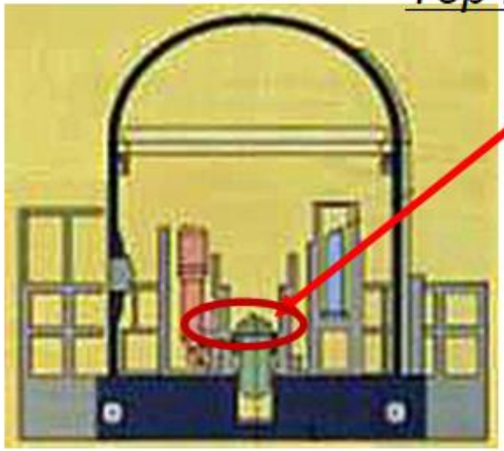
For Refueling Work, **Top Flanges of RPV and CV are opened**.

**CV of BWR**

- CV of PWR has no Flange. **Top Flanges of RPV is opened**.
- Refueling Work is performed inside of CV.

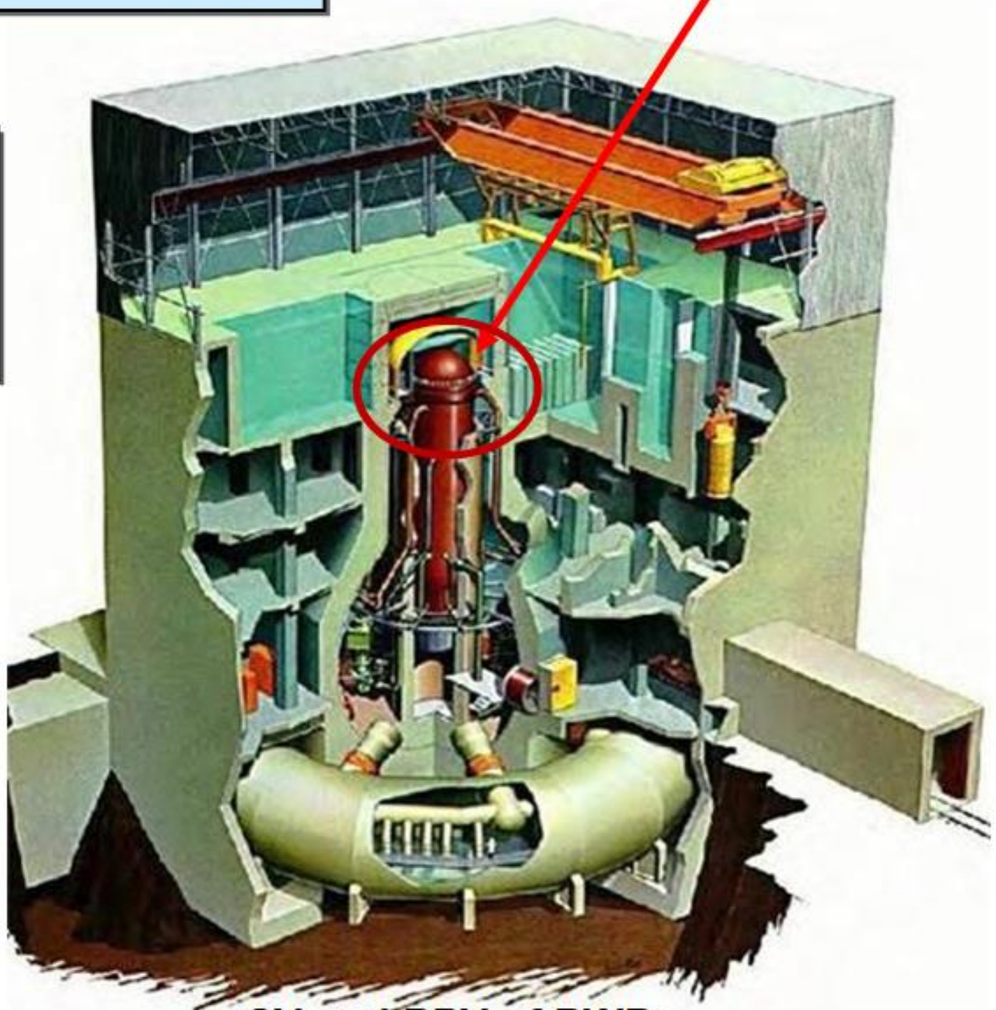
***Refueling prosees of PWR may be simpler than BWR***

*Top Flanges of RPV*



<CV of PWR>

*Top Flanges of RPV and CV*

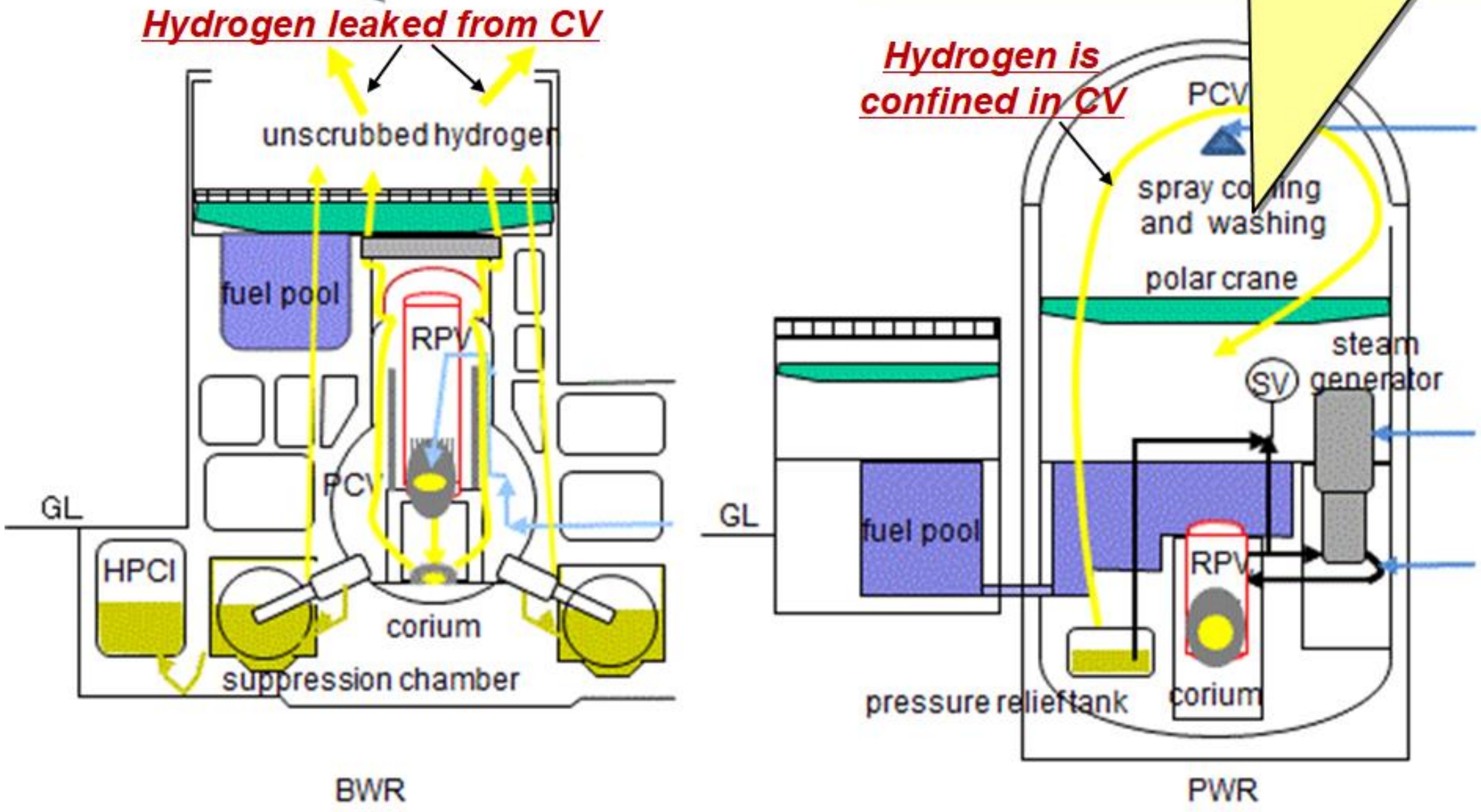


<CV and RPV of BWR>

# Comparison of Airtightness between BWR and PWR during Severe Accident

The **Airtightness** of the penetration parts of CV and Suppression Chamber of **BWR** is **Low**.

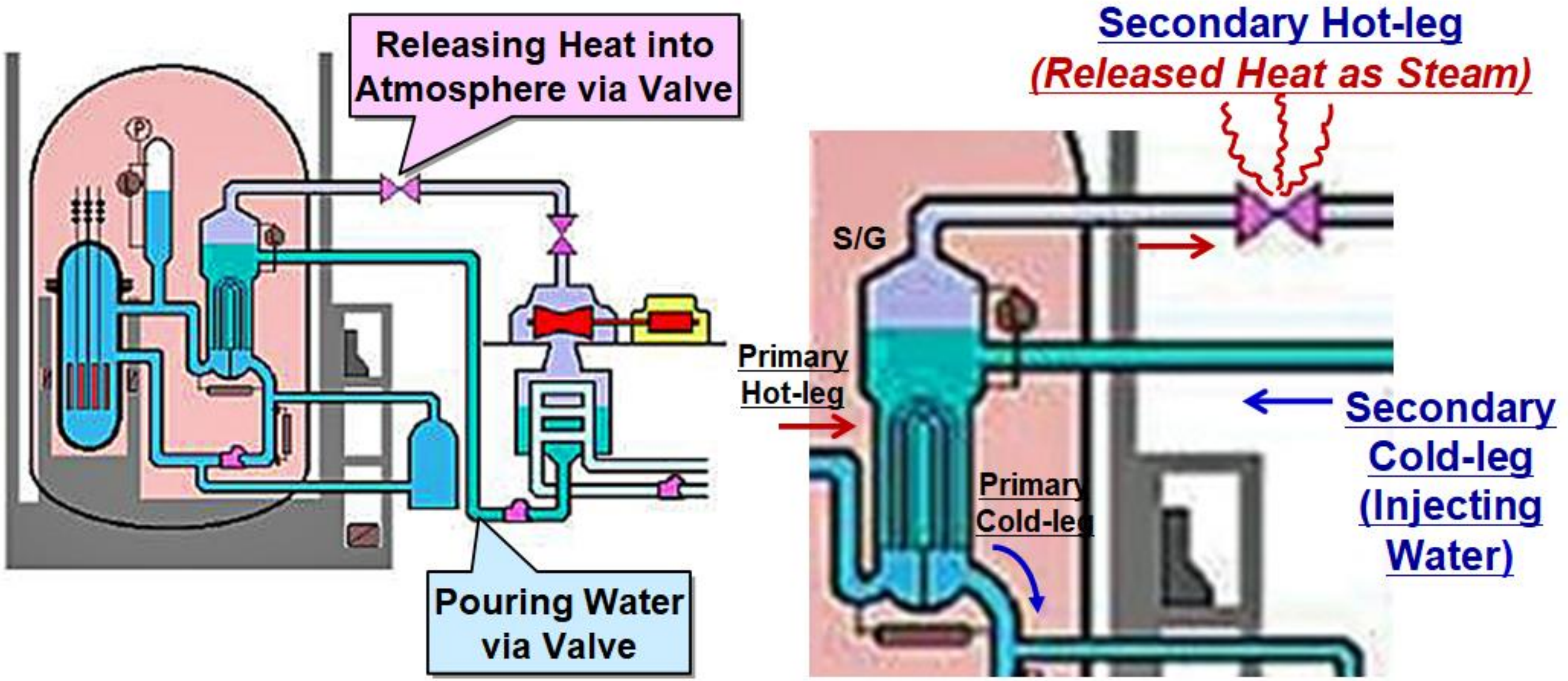
Since the ***CV volume of PWR is larege***, the temperature increase in CV is lower. Therefore, ***Airtightness of PWR may be High***.



# 2)-5 Cooling Function under Total Loss of Power in PWR

## Cooling Reactor Core by Natural Convection via S/G (PWR)

Reactor core of PWR can be cooled by ***Natural Convection*** through a Steam Generator (S/G) even if loss of all powers occurs.




☞ ***Pump is not necessary!!***

**Basic Principle of Natural Convection**

Driving Force = Difference of Coolant Density x Difference of Gravity

# Reference: Fundamental Equation of Natural Circulation Driving Force

◆The natural convection force is dominated by the following two main factors:

**1) Density Difference (Coolant Temperature Difference)**

✓This factor is the most important source which influences buoyancy.

✓Since sodium is able to maintain a liquid state in the wide range due to its high boiling point of 880 ℃, sodium can easily obtain a big density difference compared with the complicated water system accompanied with boil.

**2) Elevation Difference between Components**

✓ An elevation difference between coolant components is proportional to buoyancy.

◆The formula of buoyancy is as follows:

$$f = \Delta\rho \cdot g \cdot H$$

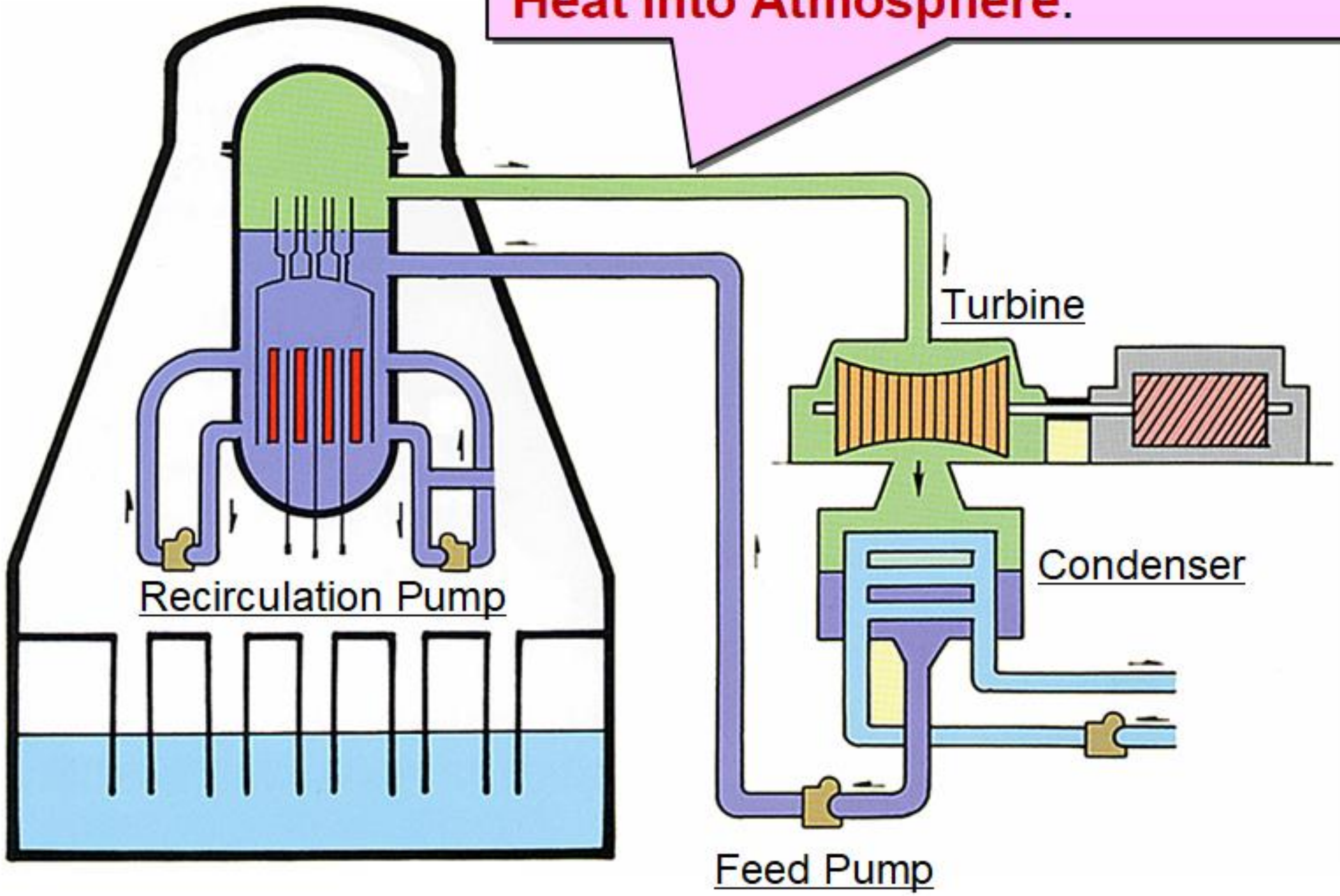
◆ While, flow is determined by a balance between buoyancy mentioned above and flow resistance as shown in the following:

$$K\frac{1}{2}\rho \cdot v^2 = \Delta\rho \cdot g \cdot H$$

Here, $\rho$ : Density of Fluid, $\Delta\rho$ :Difference of Density, g: Gravity Acceleration, $H$: High of Region existing Difference density, v: Representative Flow Velocity, $K$: Pressure Loss Coefficient

# 2)-5: Cooling Function under All Loss of Power in BWR

Since **Hot leg of BWR is Contaminated**, it **cannot open the Boundary for Releasing Heat into Atmosphere**.



# 2)-6 Influence of Decomposed Hydrogen

During under operation, **Hydrogen** is produced by **Decomposition of Water** due to Strong Radiation in a core.

**PWR**

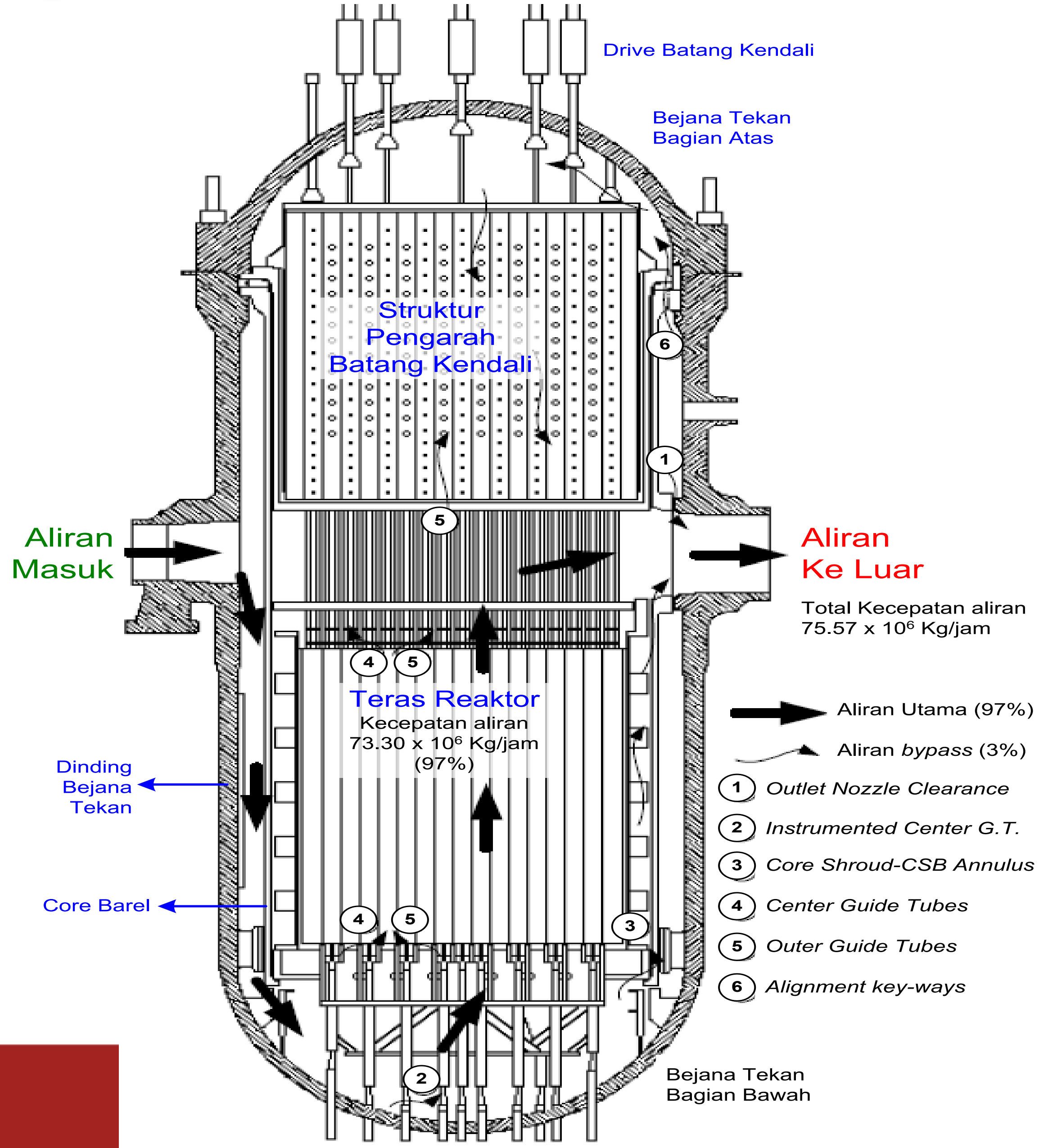
- Even **Hydrogen is generated** by Decomposition **of Water**, it will be quickly **Return Back to Water by Recombine Catalyst added in the Primary Cooling System**.

- **Recombine Catalyst cannot be used in the Steam Line**.
- Consequently, **Hydrogen influenced** to the **Piping Strength and inspection of pipes become important** during maintenance work.

**PWR is less influenced by decomposed Hydrogen.**

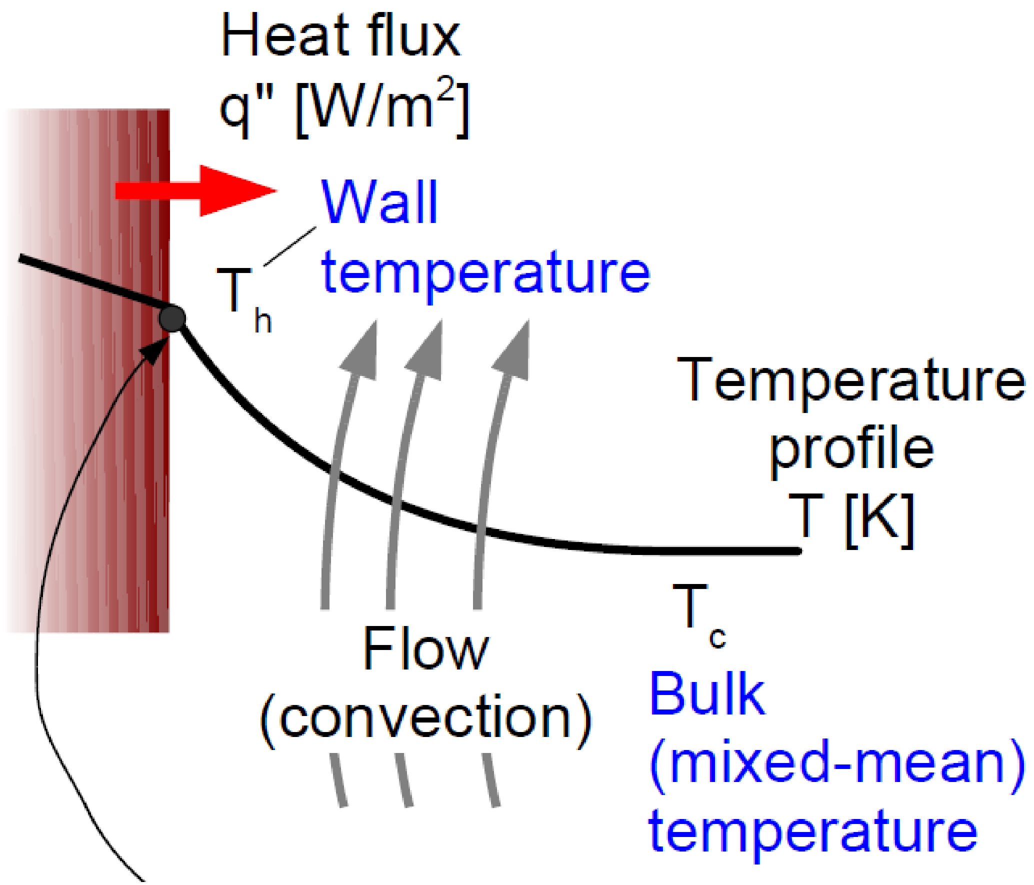
- Reactor Cooling System (Hydraulics)
  - Overview
  - Forced Convection
  - Natural Convection
  - Burnout

# Flow Rate Pattern in PWR Core




- Inlet
- Down through Narrow Channel
- Mixing in Downcomer
- Reactor Core
- Outlet

# Reactor Cooling System




Heat transfer

$$q = hA(t_w - t_f)$$

Where

h = heat transfer coefficient by convection [W/m²K]

A = heat flow area [m²]

$t_w$ , $t_f$ = wall – surface and fluid bulk temperatures [°C]

- Nusselt Number
  - Means enhancement ratio compared with heat conduction

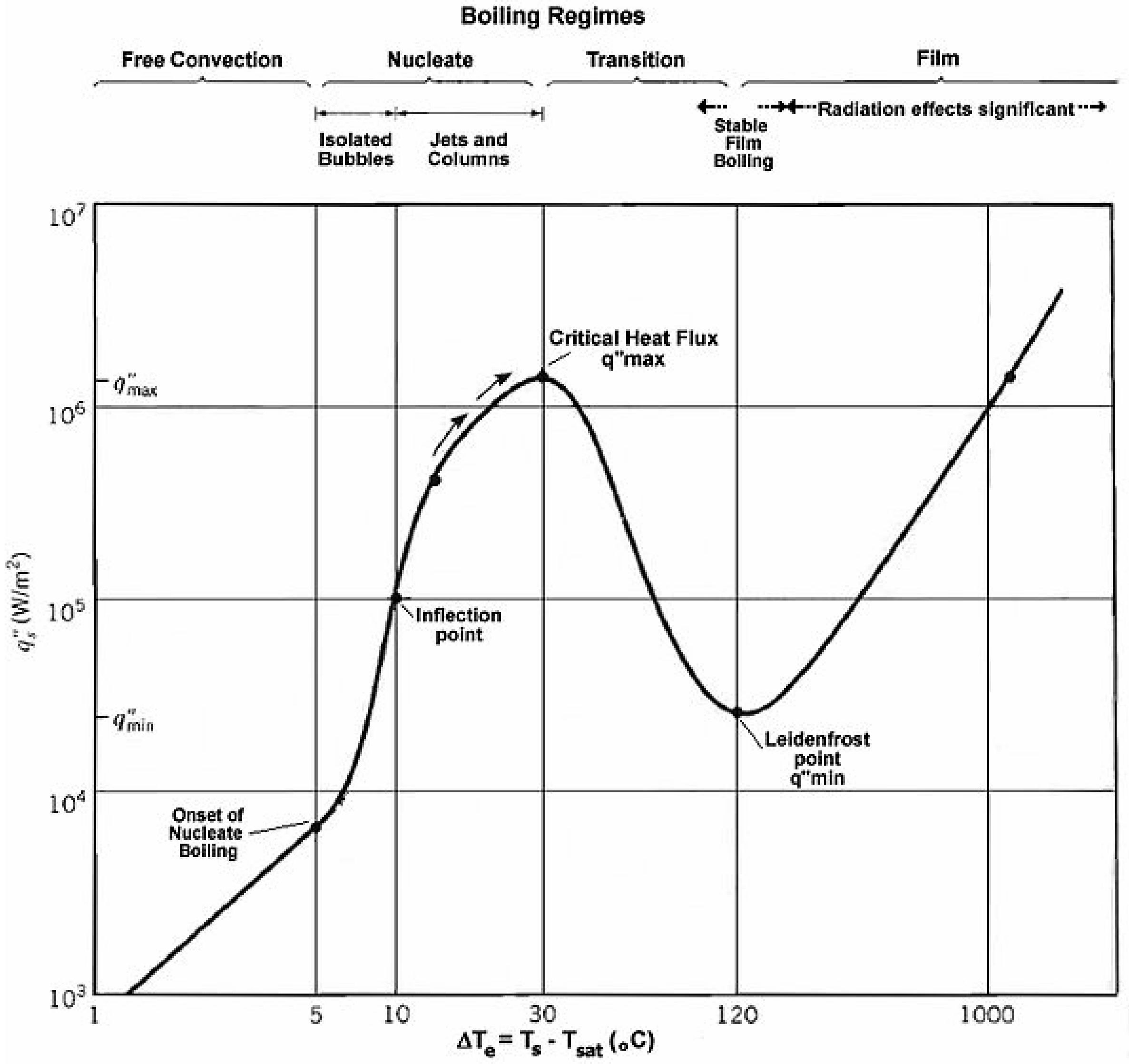
$$Nu = \frac{\alpha D}{k}$$

α : Heat transfer coeff. [W/m²K]
D : Characteristic length [m]（Diameter of pipe, etc.; length scale of the temperature profile）
k : Heat conductivity [W/mK]

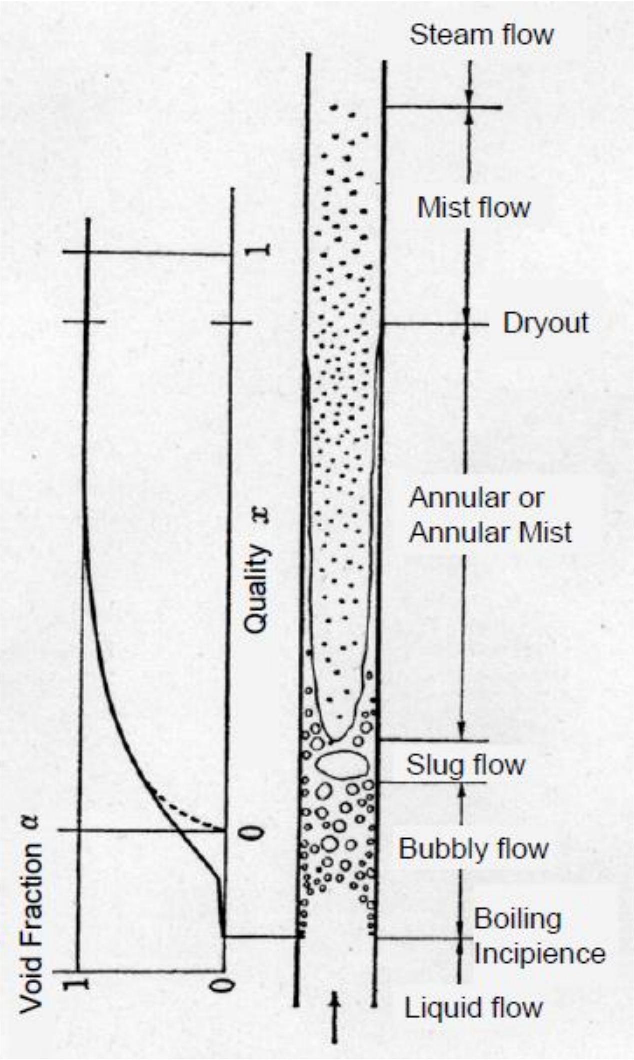
- Reynold Number
  - determine flow characteristics: laminar or turbulence
  - Controling factor of the forced convection

$$Re = \frac{\rho U D}{\mu} = \frac{UD}{\nu}$$

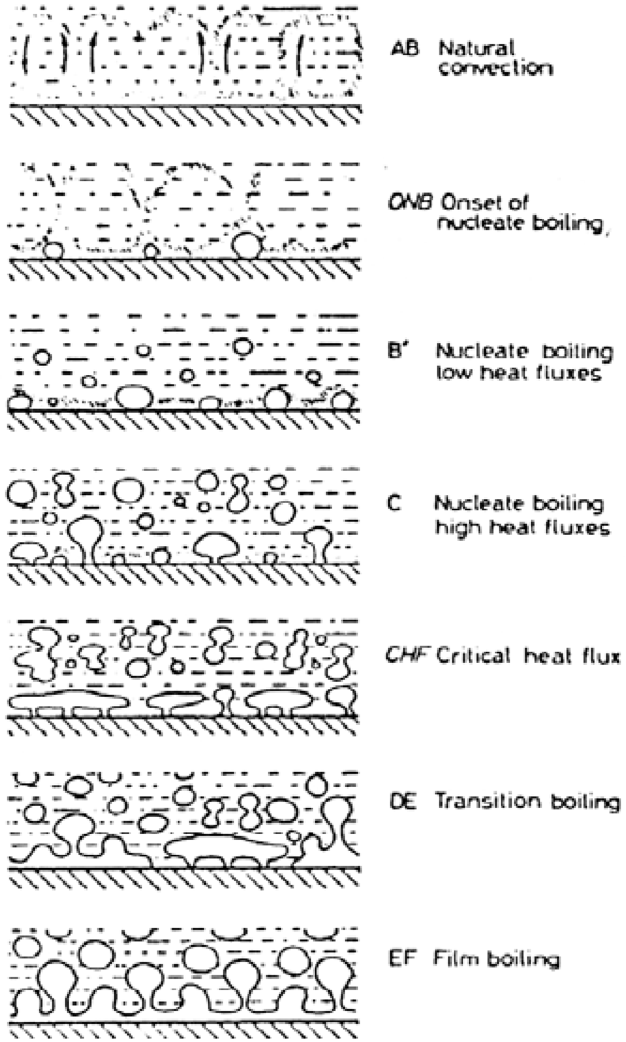
U :Flow velocity [W/m²K]
D : Characteristic length (Pipe diameter, heater length, etc.) [m]
ρ: Density [kg/m³]
μ: Viscosity [Pa s]
ν: Kinetic viscosity [m²/s] (=μ/ρ)




Boiling Curve for water at 1 atm.
Surface heat flux q" as a function of excess temperature $\Delta T_e = T_s - T_{sat}$



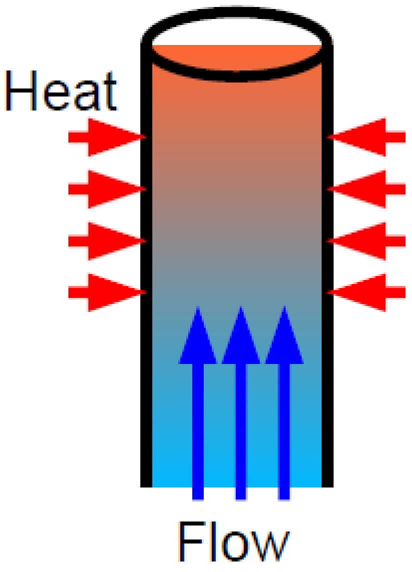
Steam flow
Mist flow
Dryout
Annular or Annular Mist
Slug flow
Bubbly flow
Boiling Incipience
Liquid flow
Void Fraction α
Quality x
1
0
1
0

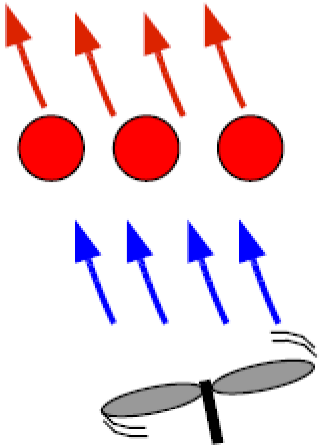



AB Natural convection
ONB Onset of nucleate boiling
B' Nucleate boiling low heat fluxes
C Nucleate boiling high heat fluxes
CHF Critical heat flux
DE Transition boiling
EF Film boiling

# Forced Convection

- Flow driven externally, by pump, blower, etc.
- The flow controls heat transfer coefficient



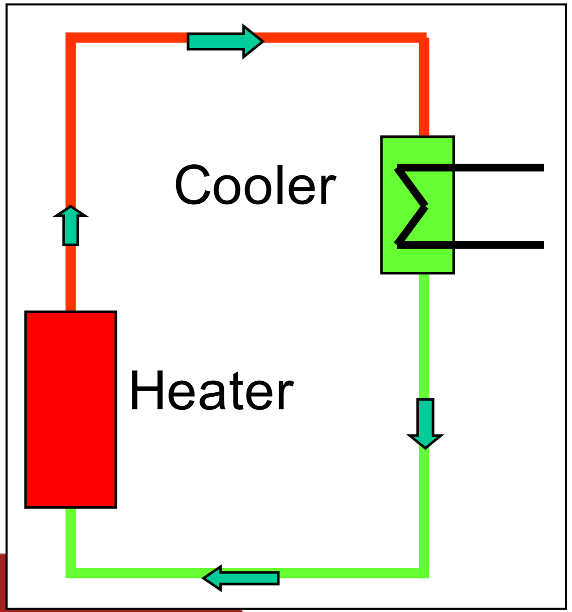
- Dittus-Boelter Correlation

$$Nu_D = 0.023 Re_D^{0.8} Pr^{0.3}$$

$$Nu_D = 0.023 Re_D^{0.8} Pr^{0.4}$$

# Natural Convection

- Mode of heat transfer where fluid flows only due to the presence of boutancy forces
- Flow naturally induced by temperature gradient (density change) and gravity (bouyancy)
- The flow is developed by heat transfer



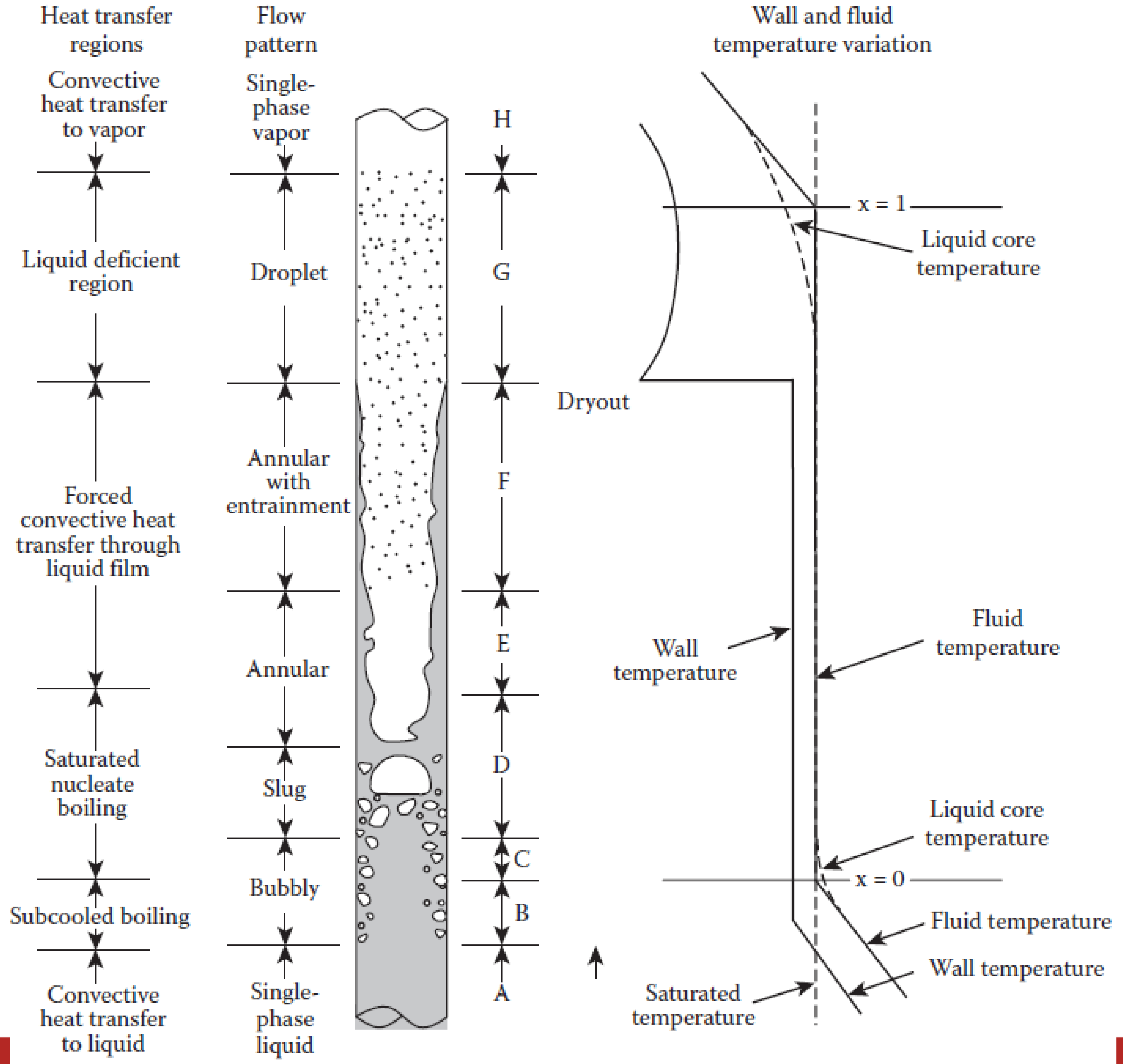

NCS

$$Nu_L = 0.59 Ra_L^{1/4} \text{ for } Ra_L = 10^4 \sim 10^9 \text{ (laminar)}$$

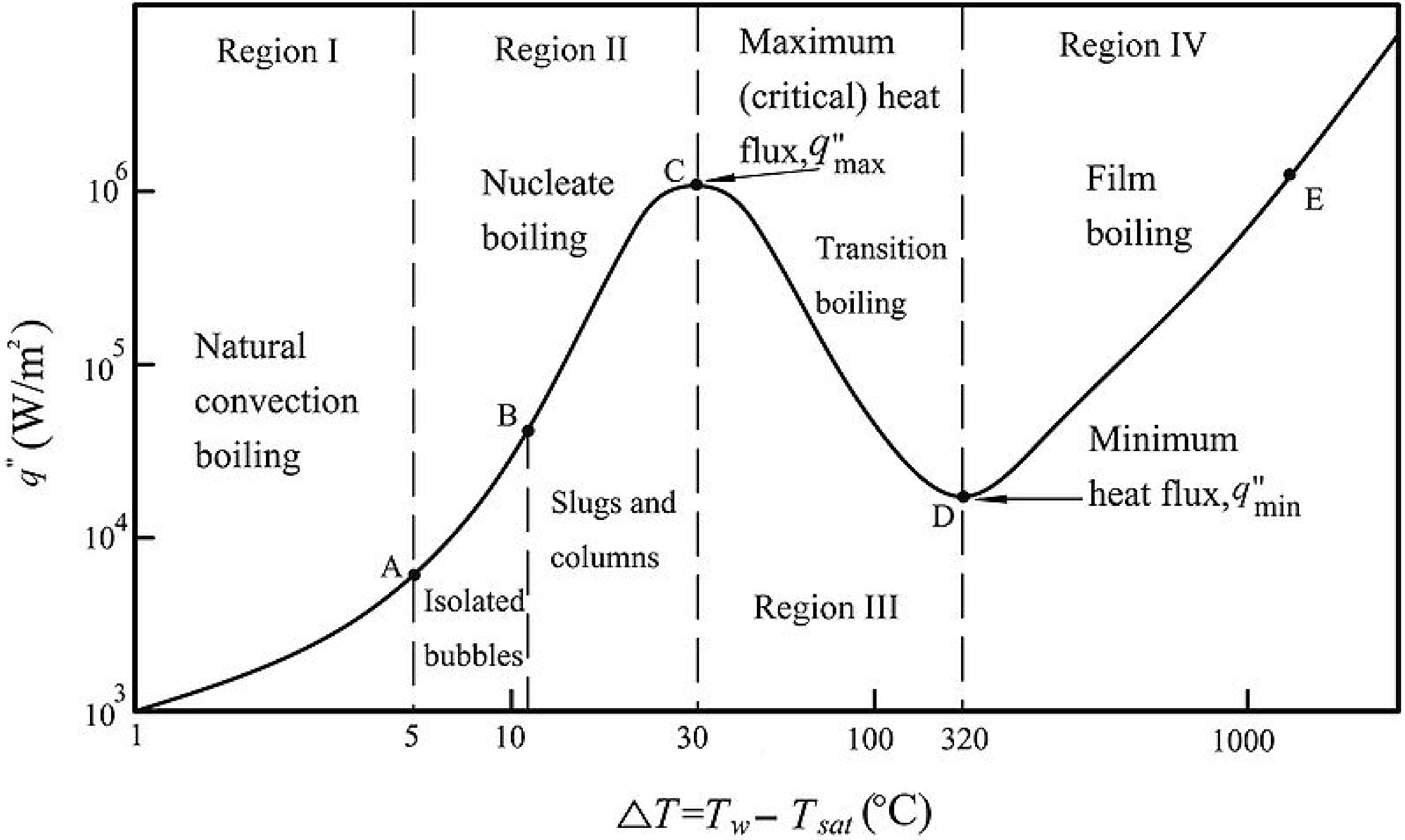
$$Nu_L = 0.10 Ra_L^{1/3} \text{ for } Ra_L = 10^9 \sim 10^{13} \text{ (turbulent)}$$

# Burnout

## Flow Pattern



# Burnout: Transition boiling



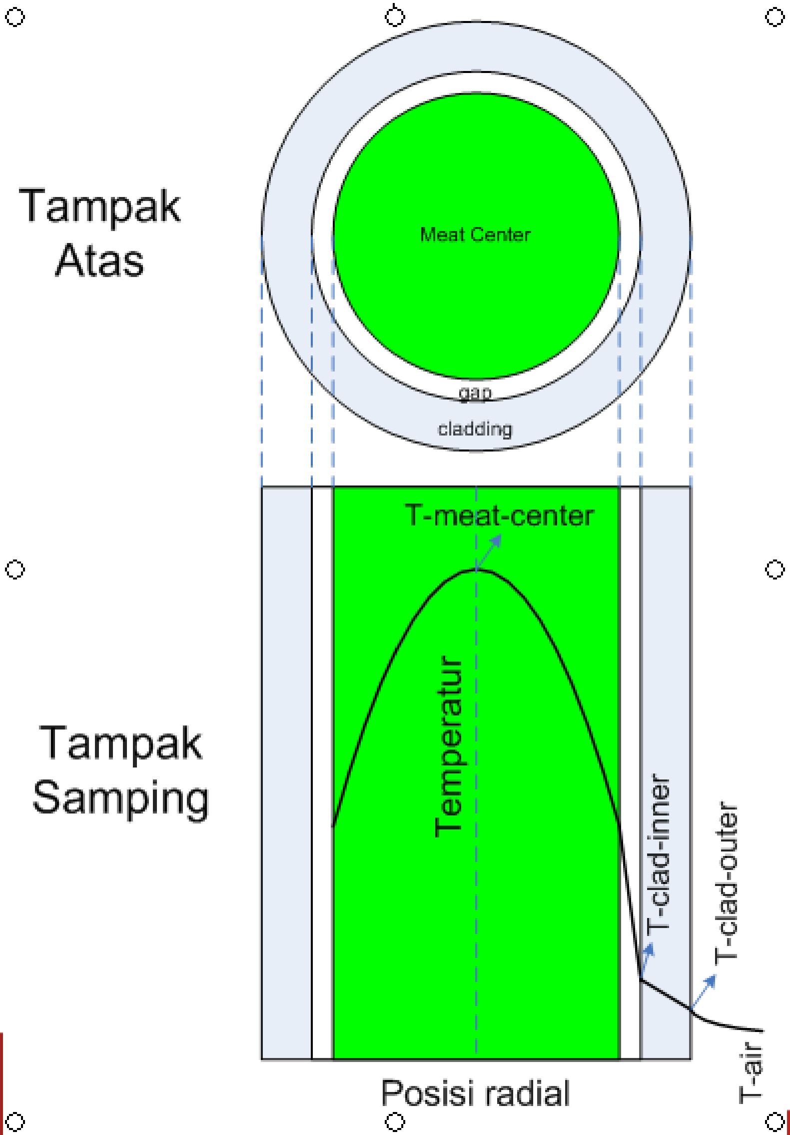
# Burnout: PWR Boiling limit

| Regime | Correlation | Remarks |
|---|---|---|
| DNB<br>For PWR | Westinghouse W-3, Tong (1967, 1972)<br>$q''_{cr,n} = q''_{cr} / F, \quad F = \dfrac{C\int_0^l q''(z')e^{-C(l-z')}dz'}{q''(l)[1-e^{-Cl}]}$<br>$C = \dfrac{4.23\times10^6[1-x_e(l)]^{7.9}}{G^{1.72}} \quad m^{-1}$<br>$q''_{cr} = [(2.022-0.06238p)+(0.1722-0.001427p)$<br>$e^{18.177-0.5987p}x_e][(0.1484-1.596x_e+0.1729x_e\lvert\mathbf{x}_e\rvert)$<br>$2.326G+3271][1.157-0.869x_e][0.2664+0.837e^{-124D_h}]$<br>$[0.8258+0.0003413(h_f-h_{in})]$<br>$q''_{cr,n} =$ $q''$ (kW/m²) local at DNB position for axially non-uniform heat flux, $l$(m) = distance to DNB, $x_e$ = local steam thermodynamic quality, | For circular, rectangle and rod bundle geometry.<br>Range:<br>$p = 5.5$–$13.8$ MPa<br>$G = 1350$–$6789 kg/m^2s$<br>$D_h = 0.005$–$0.0178$ m<br>$x_e = -0.15$–$0.15$<br>$L = 0.254$–$3.658$ m |

- Introduction
- Main Features of PWR Core Thermal-hydraulics
- Core Desain
- Core Thermalhydraulics Desain
  - Temperature Distribution in Fuel
  - Technical Thermal-hydraulics Data
  - Material Thermal-hydraulics Property
- Steady State Thernalhydraulics Analysis

# Core Thermalhydraulics Desain

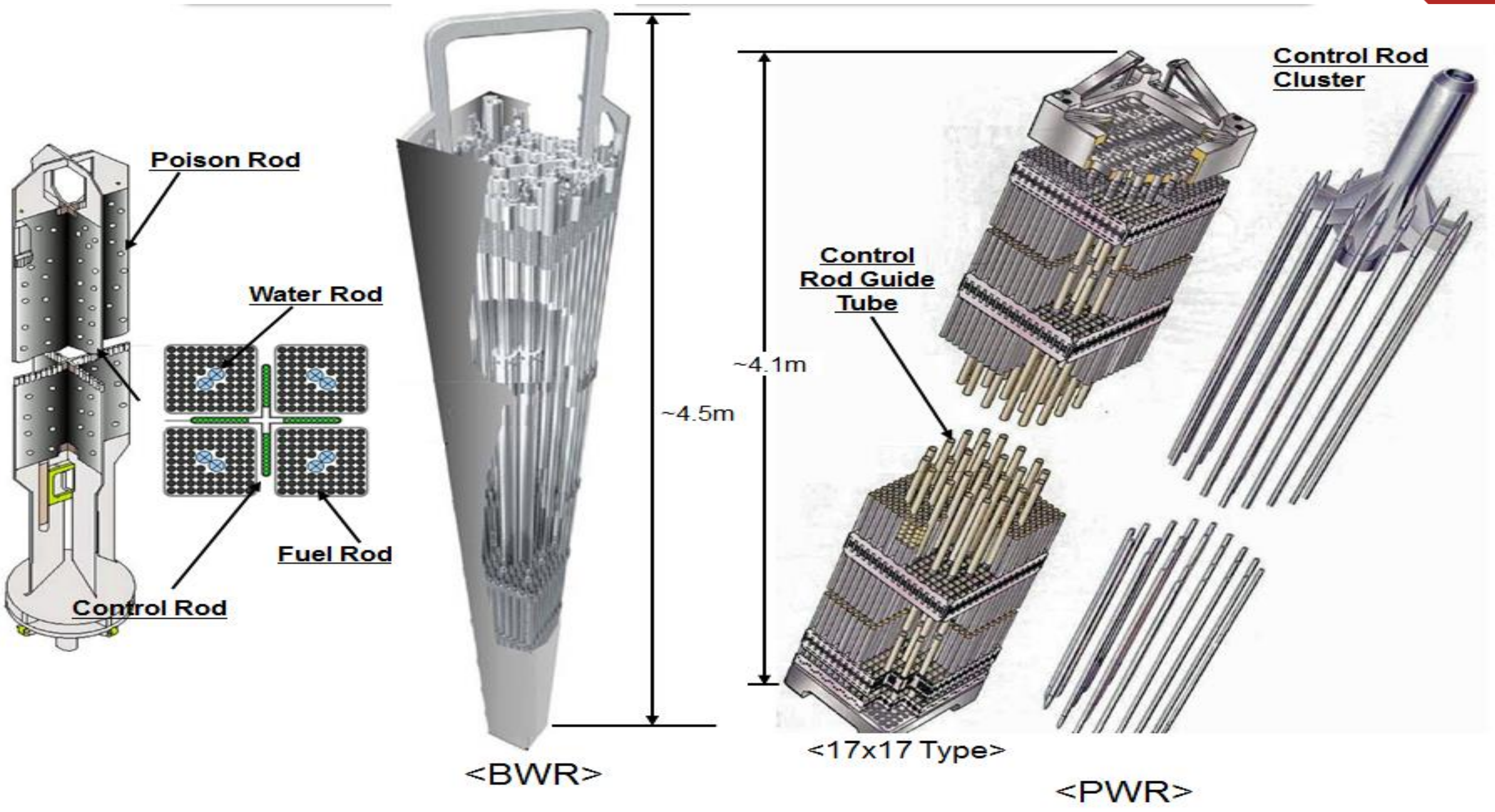
## Temperature Distribution in Fuel

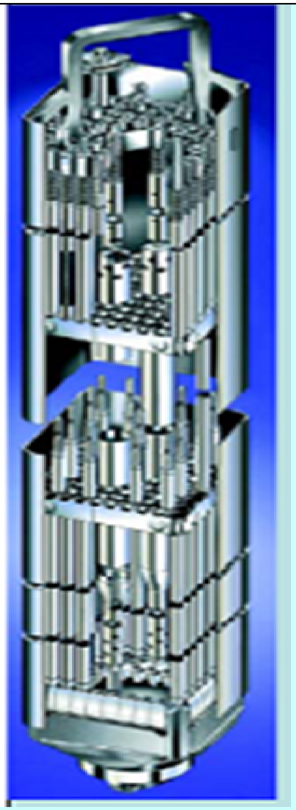



| Posisi | Persamaan |
|---|---|
| *Meat center* | $\Delta T_f = T_c - T_f = \dfrac{q'}{4\pi k_f}$ |
| *Fuel wall* | $\Delta T_g = \dfrac{q'}{2\pi r_f}\left(\dfrac{t_G}{k_G}\right)$ |
| *Inner cladding* | $\Delta T_c = \dfrac{q'}{2\pi(r_f + t_G)}\left(\dfrac{t_G + t_c}{k_c}\right)$ |
| *Outer cladding* | $\Delta T_{bulk} = \dfrac{q'}{2\pi h_s(r_f + t_G + t_c)}$ |

# Heat Conduction in Fuel Elements

# 1. Comparison of Fuel Assembly between BWR and PWR

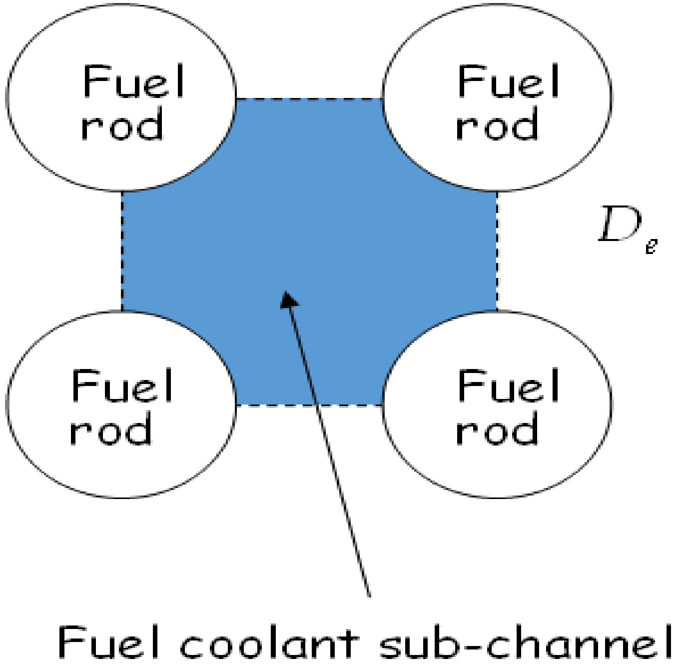




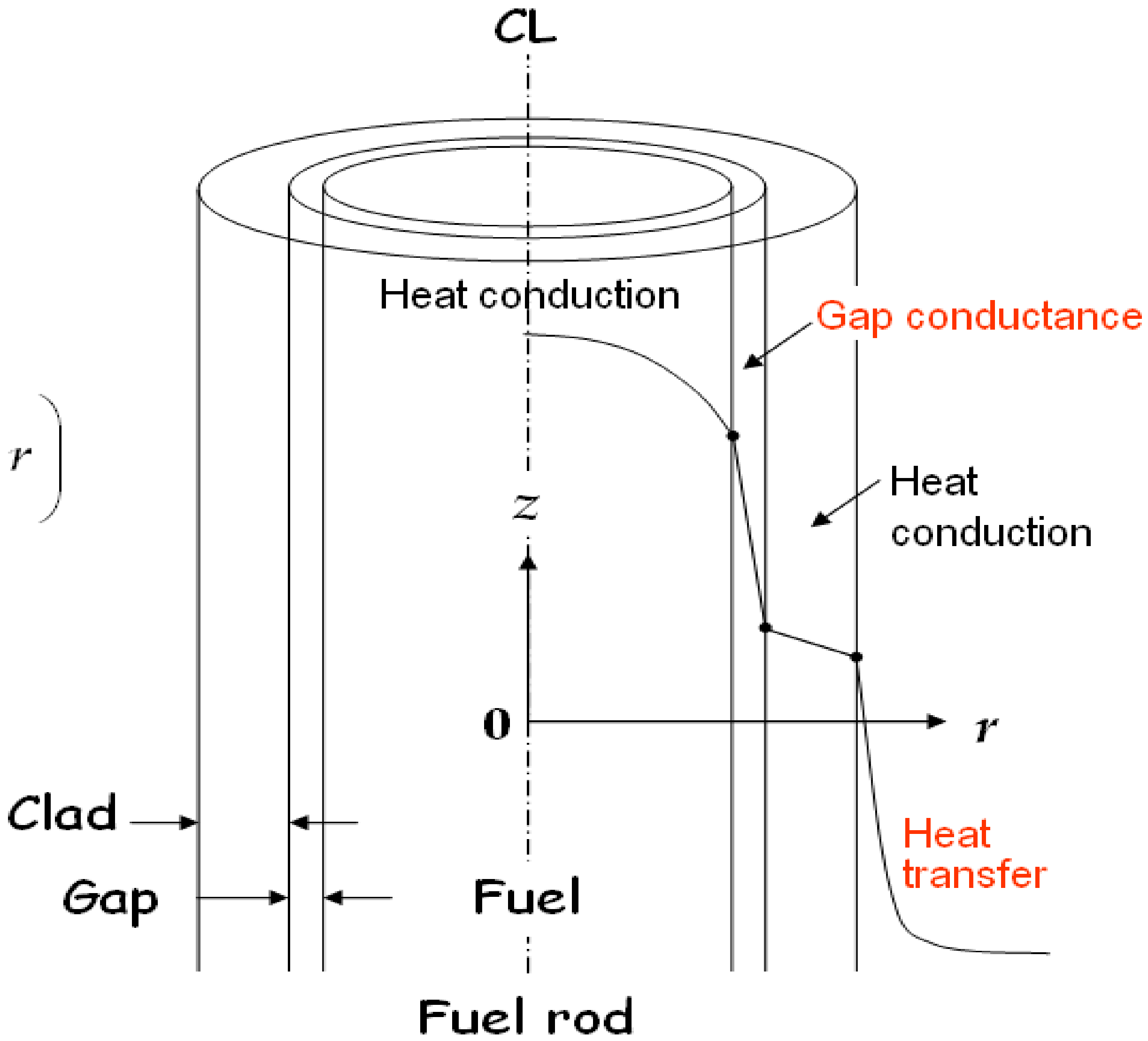
| | BWR | PWR |
|---|---|---|
| Fuel type | 10 × 10 | 17 × 17 |
| Overall dimensions (cm) | ~13.5 | ~21.4 |
| Active fuel length (m) | 3.66 | 3.66 |
| Rod Pitch (mm) | 13.0 | 12.6 |
| Cladding OD (mm) | 10.0 | 9.4 |
| Cladding thickness (mm) | 0.66 | 0.61 |
| Gap thickness (mm) | 0.089 | 0.084 |
| Fuel pellet diameter (mm) | 8.5 | 8.0 |
| Pellet length (mm) | 11.4 | 11.4 |
| Number of Fuel rods | 92 | 264 |
| Fuel | $UO_2$/MOX | $UO_2$/MOX |
| Cladding | Zr2 | Zr4/Zirlo/M5 |
| Fuel mass (kg U) | ~180 | ~600 |
| System Pressure (MPa) | 7.14 | 15.5 |
| Coolant flow rate ($\times 10^6$ kg/m$^2$.hr) | 5.13 | 12.47 |

(Ref: NUREG 1754, p. 2-7)

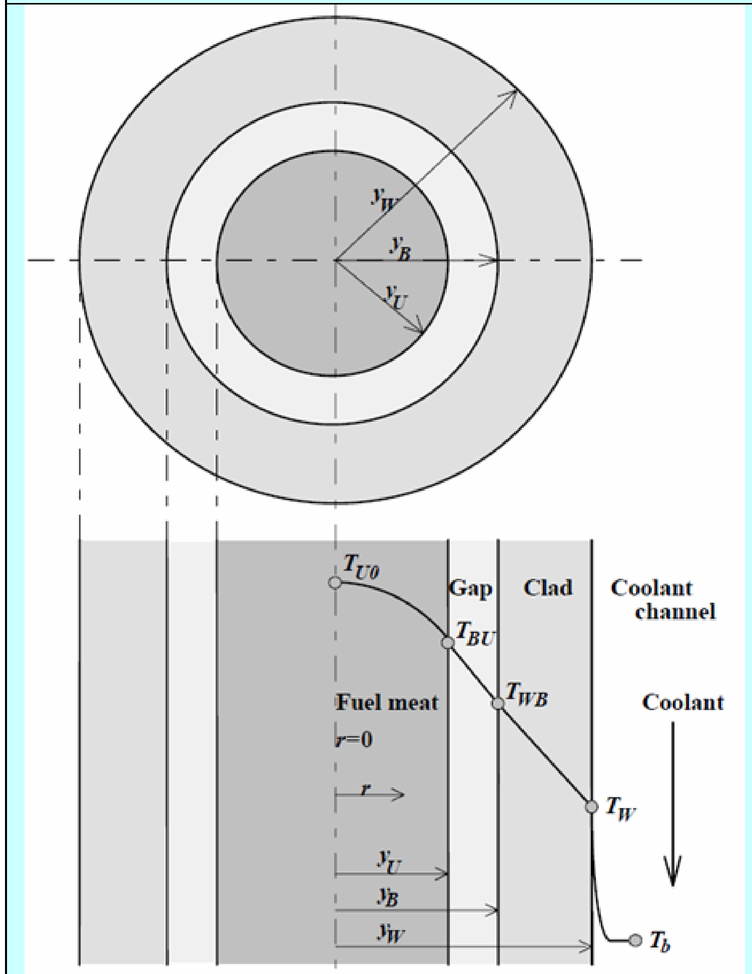
# Heat Conduction in a Fuel Rod




$$D_e = 2\left(\frac{l^2}{\pi r} - r\right)$$



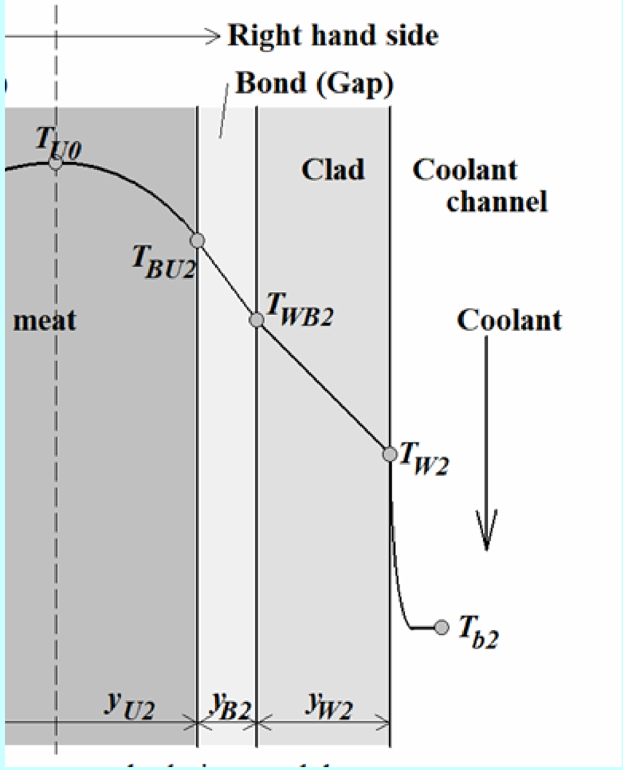
# Heat Conduction in a Cylindrical Fuel rod




| Written in COBRA-EN, p.97-99 | Written in "Nuclear Heat Transport" El Wakil, p.123-124 |
|---|---|
| (1) Clad outer surface temperature : $T_g$ <br> $(T_g - T_f) = q/h_f$ | $T_c = T_f + \dfrac{q''' R^2}{2h_f(R+c)}$ |
| (2) Clad inner surface temperature : $T_{ig}$ <br> $\Delta T_{clad} = (T_{ig} - T_g) = q\dfrac{D_g}{2k_g}\log\dfrac{D_g}{D_{ig}}$ | $T_{ic} = T_c + \dfrac{q''' R^2}{2k_c}\ln\dfrac{R+c}{R}$ |
| (3) Fuel meat surface temperature : $T_{sp}$ <br> $\Delta T_{gap} = (T_{sp} - T_{ig}) = \dfrac{q}{h_{gap}}$ | $T_s = T_{ic} + \dfrac{q''' R^2}{h_{gap}}$ |
| (4) Fuel meat maximum temperature : $T_{cp}$ | $T_m = T_s + \dfrac{q'''}{4k_f}R^2$ |

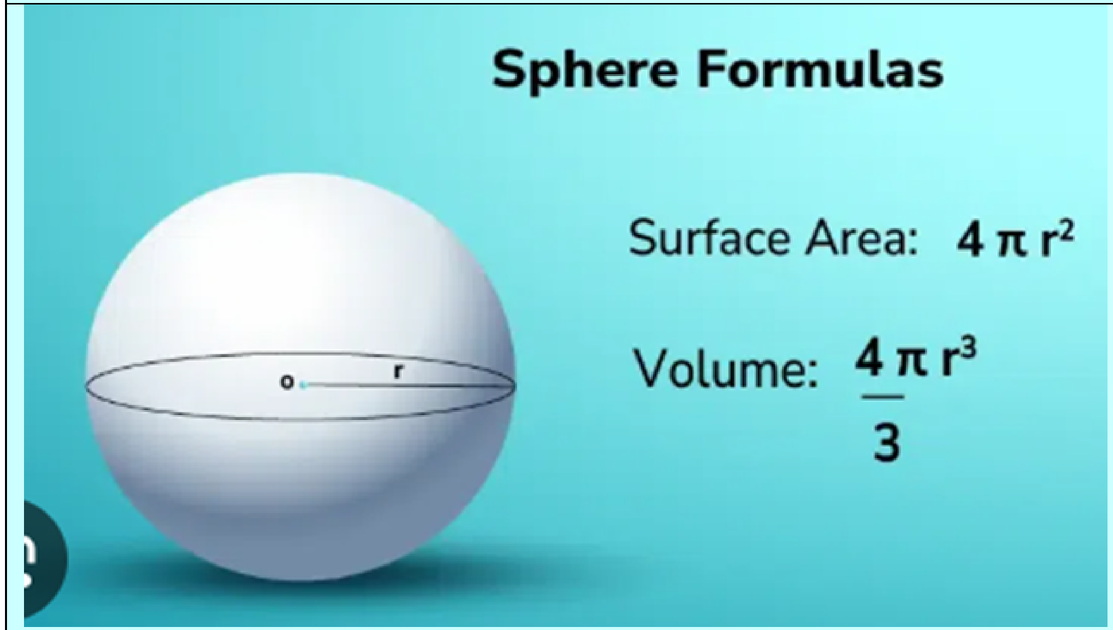
# Tambahan info

# Heat Conduction in a Fuel Plate

| | Written in COOLOD-N2, p.2-3 | Written in "Nuclear Heat Transport" El Wakil, p.115-117 |
|---|---|---|
|  | (1) Coolant bulk temperature : $T_b$ $$T_b = T_{in} + F_b \frac{1}{G\,A\,Cp} \int_0^L Q(Z)dZ$$ | |
| | (2) Clad outer surface temperature : $T_W$ $$T_W = T_b + F_f \frac{q_W}{h_W}$$ $$q_W = q_U$$ | $$T_c = T_f + \frac{q'''s}{h}$$ |
| | (3) Clad inner surface temperature : $T_{WB}$ $$T_{WB} = T_W + F_W \frac{q_U\, y_W}{k_W}$$ | $$T_s = T_c + \frac{q'''s_c}{k_c}$$ |
| | (4) Fuel meat surface temperature : $T_{BU}$ $$T_{BU} = T_{WB} + F_B \frac{q_U\, y_B}{k_B}$$ | |
| | (5) Fuel meat maximum temperature : $T_{U0}$ $$T_{U0} = T_{BU} + F_U \frac{\dot{q}_U}{2k_U} {y_U}^2$$ $$q_U = \dot{q}_U\, y_U$$ | $$T_m = T_s + \frac{q'''}{2k_f} s^2$$ |

# Heat Conduction in a Spherically Shaped Fuel

Written in "Nuclear Heat Transport"
El Wakil, p.128-129




Clad outer surface temperature : $T_S$

$$T_m - T_s = \frac{q''' R^2}{6k_f}$$

Total heat generation, $q_s = \frac{4}{3}\pi R^3 q'''$

Combining 2 equations above

$$q_s = 8\pi R k_f (T_m - T_s)$$

$4\pi R^2 = A_s$ , total area of spherical element

$$q_s = 2k_f A_s \frac{(T_m - T_s)}{R}$$

Wikipedia :

The conduction through a spherical shell with internal radius, $r_1$, and external radius, $r_2$, can be calculated in a similar manner as for a cylindrical shell

Solving:

$$\dot{Q} = 4k\pi \frac{T_1 - T_2}{1/r_1 - 1/r_2} = 4k\pi \frac{(T_1 - T_2) r_1 r_2}{r_2 - r_1}$$

# -Conclusion-

- Around 80% of NPP in the world is LWR.
- Among them, over 70% of LWR is PWR.
- BWR generates power by using directly the steam generated in a core, while PWR uses the steam generator, which provides steam that is not radioactive.
- Radiation control area in PWR is limited only to the primary cooling system located in CV.
- CRDM is installed at top of RPV for PWR.
- Reactor core of PWR can be cooled by natural circulation in case of loss of all electricity power for cooling.
- Safety of the Advanced LWR (ABWR and APWR) has improved by adopting the various kinds of advanced technologies.

# Thank you