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

27 June - 1 July, 2011

SCWR CORE DESIGN 2: LWR TYPE

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SCWR Core Design 2: LWR Type

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Objectives

• Contrast and compare with existing LWR designs
• Introduce various SCWR designs based on LWR technology
• Compare a thermal-, fast-, and mixed-neutron spectra cores
Supercritical water character

Density (kg/m³)

Temperature (°C)

Specific heat (kJ/kg-°C)

p = 25 MPa

Specific heat (kJ/kg-°C)

Critical Point

25.0 MPa

15.0 MPa

7.0 MPa

SCWR

PWR

BWR

Critical Point

S

V

P (MPa)

T (°C)

280

285

320

374

450

T (°C)
Comparing to the current LWR

PWR

BWR/6

ABWR

SCWR

A boiling water reactor ...without the boiling.

ESBWR
**Advantage: Lower Costs**

**Comparison of Containment Size**

- same scale -

**AP1000**

- 1117 MW\(_e\)
- 83 m

**BWR**

- 1284 MW\(_e\)
- 49 m

**SCWR**

- 1000 MW\(_e\)
- 25 m
Comparing to the current LWR

- Simple & compact plant systems
- No water/steam separation
- Low flow rate (1/10), high enthalpy coolant
- High temperature & thermal efficiency (510°C, ~44%)
- Flexibility of the neutron spectrum, increase the utilization of the fuel
- Utilizations of current LWR and Supercritical FPP technologies
- Major components are used within the temperature range of past experiences
## Comparing to the current LWR(FA)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>AP1000</th>
<th>EPR</th>
<th>ESBWR</th>
<th>SCWR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel diameter (mm)</td>
<td></td>
<td>9.5</td>
<td>9.5</td>
<td>10.26</td>
<td>10.2</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td></td>
<td>10.8</td>
<td>12.6</td>
<td>12.95</td>
<td>11.2</td>
</tr>
<tr>
<td>Cladding thickness (mm)</td>
<td></td>
<td>0.57</td>
<td>0.625</td>
<td>3.2</td>
<td>0.63</td>
</tr>
<tr>
<td>Cladding material</td>
<td></td>
<td>ZIRLO™</td>
<td>Zircaloy</td>
<td>Zircaloy-2</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Fuel arrangement</td>
<td></td>
<td>17\times17 square</td>
<td>17\times17 square</td>
<td>10\times10 square</td>
<td>25\times25 square</td>
</tr>
<tr>
<td>Fuel rod No./ FA</td>
<td></td>
<td>264</td>
<td>264</td>
<td>92</td>
<td>300</td>
</tr>
<tr>
<td>Average linear heat (w/cm)</td>
<td></td>
<td>188</td>
<td>154.9</td>
<td>151</td>
<td>180</td>
</tr>
<tr>
<td>FA assembly size (mm)</td>
<td></td>
<td>210</td>
<td>215.04</td>
<td>-</td>
<td>292.2</td>
</tr>
<tr>
<td>Fuel enrichment (%)</td>
<td></td>
<td>0.74-4.235</td>
<td>-5%:UO2</td>
<td>-5%:UO2</td>
<td>4.0-6.2</td>
</tr>
<tr>
<td>Active height (m)</td>
<td></td>
<td>4.27</td>
<td>4.2</td>
<td>3.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Comparing to the current LWR (Core)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AP1000</th>
<th>EPR</th>
<th>ESBWR</th>
<th>SCWR*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel bundle number</td>
<td>157</td>
<td>241</td>
<td>1132</td>
<td>121</td>
</tr>
<tr>
<td>Core diameter (m)</td>
<td>3.04</td>
<td>3.767</td>
<td>5.883</td>
<td>3.73</td>
</tr>
<tr>
<td>Thermal power (MW)</td>
<td>3400</td>
<td>4250</td>
<td>4500</td>
<td>2744</td>
</tr>
<tr>
<td>Electricity power (MW)</td>
<td>1090</td>
<td>1500</td>
<td>1600</td>
<td>1200</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>15.51</td>
<td>15.5</td>
<td>8.62</td>
<td>25</td>
</tr>
<tr>
<td>Coolant flow rate (t/h)</td>
<td>48488</td>
<td>75347</td>
<td>34453</td>
<td>5104.8</td>
</tr>
<tr>
<td>Coolant inlet temp. (C)</td>
<td>279.4</td>
<td>295.3</td>
<td>269-272</td>
<td>280</td>
</tr>
<tr>
<td>Coolant outlet temp. (C)</td>
<td>322.3</td>
<td>328.2</td>
<td>288</td>
<td>500</td>
</tr>
</tbody>
</table>

*Japan thermal design Kamei, et al., ICAPP’05, Paper 5527
Challenges of SCWR

- Extreme operating conditions
  - High pressure
  - High temperature
  - High heat flux
  - Neutron irradiation

- Challenges in core/fuel assembly design
  - Large property variation
  - Non-uniformity of moderation
  - Sensitive to hot channel factor
  - Non-uniformity of local heat transfer
  - Upper limit of cladding temperature

Large number of FA and Core designs
FA design summary

We discuss in this lecture
SCWR FA design examples

Thermal design

Fast design
**SCWR core design examples FA design**

<table>
<thead>
<tr>
<th>Design requirements</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flow rate per unit power (&lt; 1/8 of LWR) due to large $\Delta T$ of once-through system</td>
<td>Narrow gap between fuel rods to keep high mass flux</td>
</tr>
<tr>
<td>Thermal spectrum core</td>
<td>Many/Large water rods</td>
</tr>
<tr>
<td>Moderator temperature below pseudo-critical</td>
<td>Insulation of water rod wall</td>
</tr>
<tr>
<td>Reduction of thermal stress in water rod wall</td>
<td>Uniform fuel rod arrangement</td>
</tr>
<tr>
<td>Uniform moderation</td>
<td></td>
</tr>
</tbody>
</table>

- **Control rod guide tube**
- **UO$_2$ fuel rod**
- **UO$_2$ + Gd$_2$O$_3$ fuel rod**
- **Water rod**
- **ZrO$_2$**
- **Stainless Steel**
SCWR core design examples Coolant flow scheme

Flow directions

<table>
<thead>
<tr>
<th></th>
<th>Coolant</th>
<th>Moderator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner FA</td>
<td>Upward</td>
<td>Downward</td>
</tr>
<tr>
<td>Outer FA</td>
<td>Downward</td>
<td>Downward</td>
</tr>
</tbody>
</table>

To keep high average coolant outlet temperature
SCWR core design examples

SCWR Design Concepts in Europe:

The High Performance Light Water Reactor (HPLWR)

Assembly design

- Thermal neutron spectrum
- Three heat-up steps
Coupled neutronic / thermal-hydraulic analyses of
- Core power distribution
- Burn-up analyses
- Optimization of fuel shuffling
- Effect of control rods and burnable poisons
- Coolant mixing inside assemblies
- Uncertainties
- Single fuel rod predictions

Rel. power in ¼ core at beginning of an equilibrium cycle

C. Maráczy, KFKI
Analyses of Coolant and Moderator Flow

Twisted streamlines caused by wire wrap spacers

CFD-Analysis

CFD and system code analyses of

- Heat transfer and flow inside assemblies
- Mixing in plenums above and below the core
- Feedwater flow and heat transfer inside the pressure vessel
SCWR Core Design Concepts: The Super Fast Reactor, Japan

- Two heat-up steps
- Fast neutron spectrum

Y. Oka and Y. Ishiwatari
Reduce void reactivity and the local power peaking
## Proposal of SCWR-M Core

<table>
<thead>
<tr>
<th></th>
<th>Thermal core</th>
<th>Fast core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core &amp; FA design (mechanical)</td>
<td>X</td>
<td>√</td>
</tr>
<tr>
<td>Cladding temperature</td>
<td>X</td>
<td>√</td>
</tr>
<tr>
<td>Heterogeneity (hot channel factor)</td>
<td>X</td>
<td>√</td>
</tr>
<tr>
<td>Void reactivity feedback (safety)</td>
<td>√</td>
<td>X</td>
</tr>
<tr>
<td>Water storage in RPV (safety)</td>
<td>√</td>
<td>X</td>
</tr>
<tr>
<td>Enrichment</td>
<td>√</td>
<td>X</td>
</tr>
<tr>
<td>Conversion ratio (sustainability)</td>
<td>X</td>
<td>√</td>
</tr>
<tr>
<td>Power density</td>
<td>X</td>
<td>√</td>
</tr>
</tbody>
</table>

**Mixed core**
SCWR-M Core Structures (SJTU)
FA optimization

- P/d
- Diameter
- Wall clearance

- Thermal FA two-row fuel assembly design (uniform moderation)
- Axial multilayer fuel assembly to flat the power profile and increase the conversion ratio
FA Structures

Multilayer FA (thermal)  Multilayer FA (fast)
## FA Parameters

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Thermal FA</th>
<th>Fast FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of fuel pins, mm</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Pitch-to-diameter ratio, -</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>Assembly side, mm</td>
<td>177.2</td>
<td>177.2</td>
</tr>
<tr>
<td>Fuel composition, -</td>
<td>$\text{UO}_2$</td>
<td>MOX</td>
</tr>
<tr>
<td>Fuel enrichment, %</td>
<td>5.0; 6.0; 7.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Conversion ratio, -</td>
<td>0.6</td>
<td>1.01</td>
</tr>
<tr>
<td>Fuel temperature reactivity coefficient, $10^{-5}/\text{K}$</td>
<td>-1.72</td>
<td>-2.65</td>
</tr>
<tr>
<td>Coolant reactivity coefficient*, $10^{-5}/\text{K}$</td>
<td>-27.9</td>
<td>-5.20</td>
</tr>
<tr>
<td>Moderator reactivity coefficient, $10^{-5}/\text{K}$</td>
<td>-100.0</td>
<td>--</td>
</tr>
</tbody>
</table>

* Change the water temperature in the coolant and moderator channel respectively to get the reactivity coefficient.
# SCWR-M Core Parameters

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Thermal</th>
<th>Fast</th>
<th>Whole core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power (MW)</td>
<td>2400.0</td>
<td>1400.0</td>
<td>3800.0</td>
</tr>
<tr>
<td>Electrical power (MW)</td>
<td>—</td>
<td>—</td>
<td>1650.0</td>
</tr>
<tr>
<td>Core height (m)</td>
<td>4.5</td>
<td>2</td>
<td>—</td>
</tr>
<tr>
<td>Equivalent diameter (m)</td>
<td>3.4</td>
<td>2.14</td>
<td>3.4</td>
</tr>
<tr>
<td>No. of fuel assembly (-)</td>
<td>164</td>
<td>120</td>
<td>284</td>
</tr>
<tr>
<td>Power density (MW/m$^3$)</td>
<td>100.89</td>
<td>75.74</td>
<td>90.26</td>
</tr>
<tr>
<td>Moderator fraction (%)</td>
<td>20.0</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Coupling Analysis Method

- Set of design parameters
- New burn-up distribution
  - Core calculation
  - Pin power construction
    - Sub-channel analysis
  - Burn-up calculation
    - EOC?
      - Y: Design criteria meet?
        - Y: End
        - N: Design criteria meet?
      - N: TH-N coupling
        - SKETCH-N
          - Power distribution
            - COBRA-SC
              - TH distribution
                - Converged?
                  - N: Feedback of macro cross-section
                  - Y: End
Measures to improve the SCWR-M

- The fast and thermal zones are divided into 2 parts with different enrichment.
- Increase the mass flow rate in the fuel assemblies, which have higher power density and non-uniform pin-power distributions.
- Reduce the moderator mass fraction from 25% to 20%, to provide a higher coolant mass flux to reduce the peak cladding temperature.
- Enlarge the clearance of the peripheral fuel rod to 1.5mm, to provide a better coolability of the fuel rods near the assembly wall.
SCWR-M Core Optimization Results

radial distribution

axial distribution
FA Power and Flow Distribution

Power distribution

Flow distribution
## Sub channel scale results

<table>
<thead>
<tr>
<th>Results</th>
<th>Thernal (FA56)</th>
<th>Fast (FA32)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. linear heat rate (kW/m)</td>
<td>36.18</td>
<td>42.09</td>
</tr>
<tr>
<td>Max. coolant temperature (°C)</td>
<td>614.43</td>
<td>542.44</td>
</tr>
<tr>
<td>Hot channel factor (-)</td>
<td>1.264</td>
<td>1.563</td>
</tr>
<tr>
<td>Max. moderator temperature (°C)</td>
<td>368.10</td>
<td>—</td>
</tr>
<tr>
<td>Max. cladding temperature (°C)</td>
<td>725.12</td>
<td>708.90</td>
</tr>
<tr>
<td>Max. fuel temperature (°C)</td>
<td>1688.08</td>
<td>2089.93</td>
</tr>
</tbody>
</table>
Conclusions

• Big potential advantage of SCWR comparing to LWR

• A technical review of the LWR-SCWR: Japan and Europe, Thermal and fast spectrum

• The development and character of the SCWR-M
References


9. AP1000 Design Control Document
...Thank you for your attention!

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