Core Design

Read: BWR – Section 3

PWR – Chapter 2

BWR and PWR UFSAR: Ch. 4.1 and 4.2

Fuel:

General Considerations for thermal reactor design can be divided into three broad categories:

1.) Nuclear Design:

Concerned with chain reaction behavior:

A) criticality and controllability

B) power distributions

C) fuel costs

2.) Thermal-Hydraulic Design:

Concerned with heat transfer and fluid flow forces:

A) fuel, coolant and moderator temperatures and phases

B) coolant pressure drops and forces exerted on fuel

3.) Mechanical / Material Design:

Concerned with structural performance of fuel:

A) material performance under irradiation, conditions in thermal and chemical environment of coolant

B) fuel costs

C) mechanical forces on fuel and dimensional stability, i.e. internal rod pressure, pellet-clad interaction, clad strain limit, etc.
## Basic Nuclear Reactor Core Design Requirements

Impact on Various Design Areas

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Nuclear</th>
<th>Thermal-Hydraulic</th>
<th>Material / Mechanical</th>
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</thead>
<tbody>
<tr>
<td>Energy Requirements Satisfied</td>
<td>Install Sufficient Reactivity</td>
<td>Coolant Properties to Minimize Material Degradation</td>
<td>Maximize Material Life in Core</td>
</tr>
<tr>
<td>Power Requirements Satisfied</td>
<td>Install Sufficient Reactivity &amp; Flatten Power Profile</td>
<td>Coolant Conditions Compatible With Entire Fluid Systems and Minimize Fuel Temperatures</td>
<td>Fuel Mechanically Capable of High Power Densities</td>
</tr>
<tr>
<td>Safety Criteria Satisfied</td>
<td>Flatten Power Profile Proper Reactivity Behavior During Transients</td>
<td>Fuel Temperatures &amp; Hydraulic Forces Acceptable</td>
<td>Fuel Maintains Integrity Under Transient Stress (temperature &amp; pressure effects)</td>
</tr>
<tr>
<td>Core Availability Maximized</td>
<td>Proper Reactivity Control to Override Fission Product Build-up Shutdown; Minimize Refueling Time</td>
<td>Maintain temperatures below level of excessive crud deposition on fuel rods</td>
<td>Conservative Design Basis to Assure Fuel Integrity</td>
</tr>
<tr>
<td>Load-Follow Capability Installed</td>
<td>Proper Reactivity (Fission Product + Reactivity Power Defect)</td>
<td>Capability to vary T/H conditions to improve load follow capability</td>
<td>Fuel Maintains Integrity Under Load-Follow Conditions</td>
</tr>
</tbody>
</table>
Material Selection

Evolution of Basic Nuclear Reactor Core Designs

Components Involved:

1) Fuel – Provide fissile isotope to sustain chain reaction and create power

2) Moderator – thermalize neutrons to improve neutron economy

3) Coolant – Transport heat from fuel to the rest of the fluid system.

4) Structural Materials – Hold Fuel, Moderator and Coolant in proper location and provide barriers between various components of reactor core, i.e. trap fission products in core, avoid chemical attack and corrosion.

**Fuel:** U\(^{235}\) only naturally occurring fissile isotope (low energy neutrons)

State of U:

A) Gas - Low density and unstable reactivity-wise

B) Liquid – Chemistry and radioactivity problems, Ex: Molten salt reactor

C) Solid – High density, stable reactivity-wise, radioactivity and chemistry problems can be overcome by cladding

What U solid to employ?

A) Metallic U –swells under irradiation and has low corrosion resistance.
   (Zr-U alloys avoid this problem and are used in Na fast reactors)

B) UC – Limits coolant and moderator to other than H\(_2\)O or D\(_2\)O due to strong reaction.

=> Use gas coolant and graphite moderator, easy to fabricate. – Ex: HTGR

C) UO\(_2\) – Ceramic
   1) ‘Acceptable’ thermal conductivity (due to high T\(_{\text{melt}}\))
   2) O has low capture cross-section
   3) Dimensionally stable, except cracks and voids develop with burnup and thermal cycling
   4) Weak reaction with H\(_2\)O or D\(_2\)O.
   5) Easy to fabricate as small pellets. Pressed into powder and baked => sintered

**Conclusion:** If reactor is to be water-cooled and/or moderated, use UO\(_2\) pellets placed in cladding for fission product barrier, structural support and isolation from water.
**Moderator:** Must be a light element to thermalize neutrons.

State of Moderator:
- **A)** Gas – Inefficient due to low density
- **B)** Liquid – high density and capable of being cooled by fluid flow (can also act as fuel coolant)
  - H₂O – cheap, well understood, can act as coolant also since good heat transfer properties, has higher absorption cross section than D₂O or C.
  - D₂O – expensive, has low absorption cross allowing natural U as fuel \( \Rightarrow \) No enrichment
  - Light and heavy water require pressurization to avoid vapor phase at low temperature. Introduces O, which is undesirable since causes oxidization
  - Organics – Chemical stability problems in high temperature and radiation environments

- **C)** Solid – high density and must be cooled. Graphite (C) – cheap, high melting temperature and good heat capacity, low neutron absorption, limited radiation damage [Wigner Energy]

**Coolant:** Must have good heat transfer characteristics,

State of Coolant:
- **A)** Gas – Low density so negligible effect on neutrons
  
  Requires high flow, relatively high pressure and large fuel heat transfer areas to cool adequately

  High pumping cost

  Potential for alternative energy conversion cycles (e.g. Brayton cycle)

  - CO₂: Adequate cooling properties, but introduces O into system (corrosion potential)
  - He: Inert and good cooling properties.

- **B)** Liquid – High density, so must have low absorption cross section. Can be chosen to have good heat transfer characteristics.
  - D₂O: expensive
  - H₂O: same comments as under moderator description
  - Na: excellent heat transfer characteristics, but interacts exothermically with D₂O or H₂O
**Structural Material:** Material selection depends on strength requirements and neutron absorption characteristics

Materials Employed:

- **Inconel:** High strength/moderate thermal neutron absorption. Can be used in limited amounts where strength is required.

- **Zirc:** Moderate strength/lowest thermal neutron absorption. Can be used in considerable amounts where moderate strength is required.

- **Stainless Steel:** Good strength/low-moderate thermal neutron absorption. Seems good compromise, but experiences ductility problems after irradiation and stress-corrosion cracking under boiling conditions.

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**Component Pairing In a Thermal Reactor Core**

<table>
<thead>
<tr>
<th>Moderator</th>
<th>Coolant</th>
<th>Fuel</th>
<th>Structural Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>H\textsubscript{2}O</td>
<td>H\textsubscript{2}O</td>
<td>UO\textsubscript{2} (≈4-5 w/o U\textsuperscript{235})</td>
<td>Cladding-Zirc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>In-Core Support of Clad &amp; Fuel – Zirc &amp; Inconel</td>
</tr>
<tr>
<td>D\textsubscript{2}O</td>
<td>D\textsubscript{2}O/H\textsubscript{2}O</td>
<td>UO\textsubscript{2} (≈ 0.71-2 w/o U\textsuperscript{235})</td>
<td>Zirc</td>
</tr>
<tr>
<td>Graphite</td>
<td>He</td>
<td>UC or UO\textsubscript{2} (8-20 w/o U\textsuperscript{235})</td>
<td>Nothing much – just stack graphite blocks containing fuel or pebbles</td>
</tr>
</tbody>
</table>
Mechanical Description of a Light Water Reactor (LWR) Core

- The LWR concept will be employed to illustrate the design process, due to dominance in the market.

- Many of the design considerations presented are applicable to Gas Cooled/Graphite Moderated Reactors.

- First present the basic physical components of the core, then discuss the details of the core design.

1. Pellet

Basic Fuel Structure: 4-5 w/o enriched UO₂ sintered pellets.

Density: ≈95% of theoretical density

Provides space (voids) within the fuel material to accommodate fission product gasses.

Dimension: PWR - radius ≈ 0.16”-0.18”
- length ≈ 0.6”

BWR - radius ≈ 0.17”-0.24”

Length reflects fabrication considerations.
(2) Cladding – thin tube containing the fuel pellets, affixed with end plugs and top spring => fuel rod.

Upper plenum provides space to accumulate and retain Fission Products

Adds structure

Material selection to minimize corrosion and neutron absorption

Clad thickness sufficient to prevent clad collapse during normal operation.

Material: Zirc II-IV, Zirloy, M3, etc.

<table>
<thead>
<tr>
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<th>PWR</th>
<th>BWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>≈ 0.19”-0.21”</td>
<td>0.20-0.28”</td>
</tr>
<tr>
<td>Thickness</td>
<td>≈ 22-24 mils</td>
<td>≈ 26-32 mils</td>
</tr>
<tr>
<td>Length</td>
<td>≈ 12 ft</td>
<td>≈ 12 ft</td>
</tr>
</tbody>
</table>
Fuel Rod Schematic
(3) Grid or Spacer – egg crate type structure designed to hold 90-200 fuel rods together for strength
- mixing vanes to promote turbulence

Figure 2-6. Portion of Spring Clip Grid Assembly

(4) Fuel Assembly or Bundle – grouping of fuel rods held together by grids are affixed to top and bottom nozzles, which adds strength and allows handling.

*Zirc clad is free to lengthen, which occurs from radiation damage and thermal expansion.

Fuel Rod Array/Assembly Size:

<table>
<thead>
<tr>
<th></th>
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<th>BWR</th>
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<tr>
<td>14x14-17x17</td>
<td>7x7-10x10</td>
<td></td>
</tr>
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</table>
Basic Fuel Assembly Structure:

**PWR**: Several fuel rod locations (5-25) are replaced with hollow tubes, which are force-fitted or brazed on grids and bolted onto top and bottom nozzles (water rods).

These tubes can be used for instrumentation, burnable poison rods, or control rods.

*Figure 2-3. Cutaway of 17 x 17 Optimized Fuel Assembly with RCC*
PWR 17 x 17 Fuel Assembly Cross Section
**BWR:** Fuel rods are attached to top and bottom tie plates => (1 or 2) hollow tubes, to which grids are affixed.

Entire assembly canned in Zirc, allows flow orficing and increases flow stability.
BWR Typical Core Cell
(5) Core Loading: Assemblies are placed side by side, supported by the core lower support plate and held stationary by the core upper support plate.

The arrangement of assemblies of different enrichments establishes the core loading pattern.

As plant power rating increases, the number of assemblies increases, holding average power density nearly constant.

<table>
<thead>
<tr>
<th># Assemblies</th>
<th>PWR</th>
<th>BWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>120-240</td>
<td>400-780</td>
</tr>
</tbody>
</table>

=> Fuel Weight = 150,000 – 260,000 # UO₂

**Optimum Core Shapes**

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Optimum Dimensions</th>
<th>Minimum Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallelepiped</td>
<td>a = b = c</td>
<td>161/B³</td>
</tr>
<tr>
<td>Cylinder</td>
<td>R = 0.55 H</td>
<td>148/B³</td>
</tr>
<tr>
<td>Sphere</td>
<td>R</td>
<td>130/B³</td>
</tr>
</tbody>
</table>

The “square” cylinder is the optimum “practical” power reactor design.