Reactor core conceptual design: LUT Heating Experimental Reactor

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Nuclear Science and Technology Symposium 2019
Helsinki, 31 October 2019
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- LUTHER movable fuel assemblies
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Motivations

Finland district heating
• Space heating is a bigger CO2 emitter than electricity production!
• Annual supply of 37 TWh; ~50% from direct use of fossil fuels and peat

Need of emission-free & reliable energy
• EU’s climate and energy goals by 2030
• Finland’s goal to be a carbon-neutral society by 2050

Trend of de-centralized energy systems & small reactor units

LUT’s MOdular TEst Loop (MOTEL) - SMR testing facility capable

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1 Energiateollisuus ry, "District heating in Finland 2018", 2019
2 "Nordic heating and cooling-Nordic approach to EU’s Heating and Cooling Strategy," 2017
3 MOTEL inauguration, 2019: https://yle.fi/uutiset/3-11026726
Methodology

Literature review on the past and on-going low-temperature / pressure-channel reactor designs
• SECURE, DPR, and NHR\(^1\)
• CANDU, ACR, and SCWR\(^2\)

Fuel assembly reference (Westinghouse)

Trials & errors → Repeat

Basic thermal hydraulic heat transfer calculations

Serpent code for core simulation and reactor physics calculations

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\(^1\) Safe Environmentally Clean Urban Reactor, Deep Pool Reactor, and Nuclear Heating Reactor
\(^2\) CANadian Deuterium Uranium, Advanced CANDU Reactor, and Supercritical Water-Cooled Reactor
Overview of LUTHER\(^1\) core concept

Objectives:
- To develop a modular nuclear district heating reactor
- Simplified design & economical competitiveness
- Experiment and demonstration reactor

Design criteria:
- Light-water cooled and moderated pressure-channel reactor
- Use off-the-shelf reactor components as far as possible
- Utter simplicity for low cost, simple regulation, and highly enhanced safety

\(^1\) LUT Heating Experimental Reactor
Basic design of LUTHER

Energy efficiency near 100%

Below-grade siting

Unmanned (remote) operation possible

Scalable modular design, standard industrial components

Inherent safe, secure and proliferation resistant

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design thermal power</td>
<td>MWth</td>
<td>2</td>
</tr>
<tr>
<td>Primary coolant pressure</td>
<td>MPa</td>
<td>1.25</td>
</tr>
<tr>
<td>Primary coolant temperature</td>
<td>°C</td>
<td>150-180</td>
</tr>
<tr>
<td>Reactor moderator pressure</td>
<td>MPa</td>
<td>0.101325</td>
</tr>
<tr>
<td>Reactor moderator temperature</td>
<td>°C</td>
<td>40</td>
</tr>
<tr>
<td>Intermediate circuit temperature</td>
<td>°C</td>
<td>120-150</td>
</tr>
<tr>
<td>District heating network temperature</td>
<td>°C</td>
<td>90-120</td>
</tr>
</tbody>
</table>

1 Commercial sized thermal power
LUTHER fuel assembly / channel design

Features:
- Use off-the-shelf components
- Central tube for mechanical support and instrumentation
- Yttria-stabilized zirconia (YSZ) as a ceramic thermal insulator

<table>
<thead>
<tr>
<th>Fuel Assembly / Channel Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel rod lattice type</td>
<td>-</td>
<td>Triangular</td>
</tr>
<tr>
<td>Number of fuel rods</td>
<td>-</td>
<td>54</td>
</tr>
<tr>
<td>Fuel pellet diameter¹</td>
<td>mm</td>
<td>7.844</td>
</tr>
<tr>
<td>Fuel cladding thickness¹</td>
<td>mm</td>
<td>0.5715</td>
</tr>
<tr>
<td>Fuel rod outer diameter¹</td>
<td>mm</td>
<td>9.144</td>
</tr>
<tr>
<td>Fuel rod lattice pitch</td>
<td>cm</td>
<td>0.96</td>
</tr>
<tr>
<td>Enrichment of the UO2 fuel (95% TD)</td>
<td>%</td>
<td>4.95</td>
</tr>
<tr>
<td>Central tube material</td>
<td>-</td>
<td>ZIRLO™²</td>
</tr>
<tr>
<td>Central tube inner / outer diameter</td>
<td>mm</td>
<td>7.2 / 9.6</td>
</tr>
<tr>
<td>Pressure tube material</td>
<td>-</td>
<td>Zr-2.5 wt.% Nb</td>
</tr>
<tr>
<td>Pressure tube inner / outer diameter</td>
<td>cm</td>
<td>8.7 / 9.7</td>
</tr>
<tr>
<td>Thermal insulator material</td>
<td>-</td>
<td>YSR</td>
</tr>
<tr>
<td>Thermal insulator inner / outer diameter</td>
<td>cm</td>
<td>8.2 / 8.6</td>
</tr>
</tbody>
</table>

1 Parameters are referenced from VVER-1000 Robust Westinghouse Fuel Assembly (RWFA)
2 Zirconium low oxidation, also used as a fuel cladding material in LUTHER core
LUTHER 2 MWth core design

<table>
<thead>
<tr>
<th>Core Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel assembly lattice type</td>
<td>-</td>
<td>Triangular</td>
</tr>
<tr>
<td>Number of fuel assemblies¹</td>
<td>-</td>
<td>19</td>
</tr>
<tr>
<td>Fuel channel lattice pitch</td>
<td>cm</td>
<td>10.5</td>
</tr>
<tr>
<td>Equivalent core diameter</td>
<td>m</td>
<td>0.48</td>
</tr>
<tr>
<td>Active core height</td>
<td>m</td>
<td>0.48</td>
</tr>
<tr>
<td>Thermal power output per assembly²</td>
<td>kW</td>
<td>105.3</td>
</tr>
<tr>
<td>Linear power rate²</td>
<td>kW/m</td>
<td>3.853</td>
</tr>
<tr>
<td>Core power density²</td>
<td>kW/l</td>
<td>22.94</td>
</tr>
<tr>
<td>Mass inventory of UO2 fuels</td>
<td>tons</td>
<td>0.25</td>
</tr>
<tr>
<td>Single channel coolant flow rate²</td>
<td>kg/s</td>
<td>1.58</td>
</tr>
</tbody>
</table>

¹ 91 fuel assemblies in a 24 MWth reactor and 271 fuel assemblies in a 120 MWth reactor
² Average value of the design parameter

Features:
• Compact core
• Individual access to fuel channel
  • Individual channel is connected to thermal collectors positioned above the core.
• Low power density and linear power rate
LUTHER 2 MWth comparisons

<table>
<thead>
<tr>
<th>Reactor Core Parameter</th>
<th>Unit</th>
<th>LUTHER</th>
<th>EPR²</th>
<th>AES-2006³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design thermal power</td>
<td>MWth</td>
<td>2</td>
<td>4300</td>
<td>3200</td>
</tr>
<tr>
<td>Number of fuel assemblies</td>
<td>-</td>
<td>19</td>
<td>241</td>
<td>163</td>
</tr>
<tr>
<td>Enrichment of the UO2 fuel</td>
<td>%</td>
<td>4.95</td>
<td>1.9-4.9</td>
<td>4.79</td>
</tr>
<tr>
<td>Active core height</td>
<td>m</td>
<td>0.48</td>
<td>4.2</td>
<td>3.75</td>
</tr>
<tr>
<td>Equivalent core diameter</td>
<td>m</td>
<td>0.48</td>
<td>3.77</td>
<td>3.16</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>MPa</td>
<td>1.25</td>
<td>15.5</td>
<td>16.2</td>
</tr>
<tr>
<td>Operating temperatures</td>
<td>ºC</td>
<td>150-180</td>
<td>296-329</td>
<td>298-329</td>
</tr>
<tr>
<td>Linear power rate¹</td>
<td>kW/m</td>
<td>3.853</td>
<td>15.61</td>
<td>16.78</td>
</tr>
<tr>
<td>Core power density¹</td>
<td>kW/l</td>
<td>22.94</td>
<td>~103</td>
<td>108.5</td>
</tr>
</tbody>
</table>

1 Average value of the design parameter

Features:
- Inherent high safety margins!
- Low temperature and low pressure
- ~4x smaller in power density and linear power rate
Characteristics of LUTHER design

$k_\infty$ vs. H/HM ratio

Assembly power distribution

*The fuel channel lattice pitch is varied which corresponds to H/HM ratio.
**Average relative statistical error is ±3.0 E-5.

*The assembly consists of identical 4.95% U-enriched fuel pins.
**Average relative statistical error is ±2.19 E-4.
LUTHER movable fuel assemblies

Use for reactivity control & fuel burnup compensation

Individual or cluster of fuel assemblies capable of moving

Driven by conventional control rod drive mechanisms
  • e.g., electromagnetic control rod drive

Inherent passive safety feature (e.g., gravity)

Eliminating control rods

Soluble boron free in coolant and moderator
Fuel assembly reactivity worth

Configuration A →

Moving fuel assembly

Moving selected fuel assemblies
- Every 3rd assembly, started in the center
- Highlighted by light-blue color

Total reactivity worth (2/24/120 MWth)
- 17 000 / 12 500 / 12 000 pcm

Reactivity worth:

Fuel Assembly Reactivity Worth at various Thermal Powers

*Average relative statistical error is ±5.25 E-5.
Challenges of LUTHER core concept

Light water used as a coolant and moderator
• Highly dense at low temperatures (150-180°C / 40°C)

Limited options to choose for an optimal lattice pitch for fuel channels
• \( p = 10.5 \text{ cm} \)

Tight space clearance between fuel channels
• \( \delta = 8 \text{ mm} \)

Reaching / maintaining criticality of LUTHER 2 MWth core
Conclusions & future works

LUTHER core concept is feasible!
• Pressure-channel district heating reactor
• Scalable and modular design (commercial size 24 / 120 MWth)
• Unique feature of moving fuel assemblies
• Finland's own design (i.e., FinReactor) and in-house manufacture feasible

Future works include:
• Flattening power distributions (fuel assembly & reactor core)
• Optimizing the fuel assembly and fuel channel design (e.g., lattice configuration and design dimensions)
• Reactivity feedbacks and core criticality analyses
• Reactivity control systems & shutdown mechanisms
• Completing thermal-hydraulic system design
Special thanks to …

Prof. Juhani Hyvärinen & D.Sc. Heikki Suikkanen

LUT University

SYP2019 committee
Thank you!

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