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Reactor core conceptual design: LUT Heating Experimental Reactor

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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[1]

Need of emission-free & reliable energy

- EU's climate and energy goals by 2030[2]
- Finland's goal to be a carbon-neutral society by 2050[2]

Trend of de-centralized energy systems & small reactor units

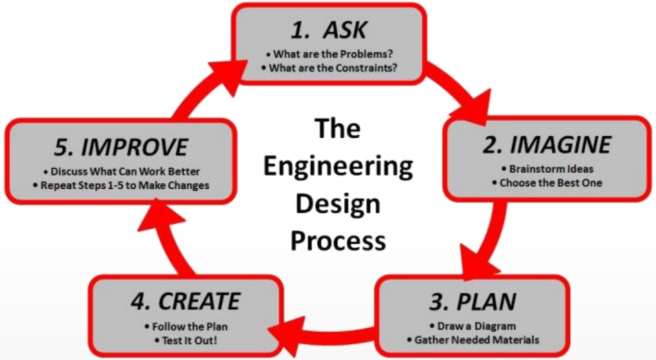
LUT's MOdular TEst Loop (MOTEL) - SMR testing facility capable[3]

[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

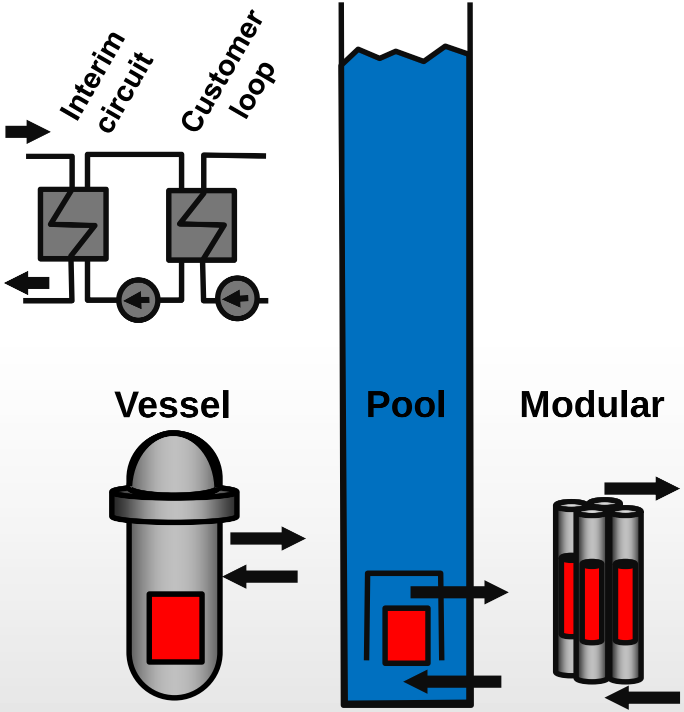
Overview of LUTHER[1] core concept

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



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[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

Design Parameter	Unit	Value
Design thermal power	MWth	2 | 24[1] | 120[1]
Primary coolant pressure	MPa	1.25
Primary coolant temperature	ºC	150-180
Reactor moderator pressure	MPa	0.101325
Reactor moderator temperature	ºC	40
Intermediate circuit temperature	ºC	120-150
District heating network temperature	ºC	90-120

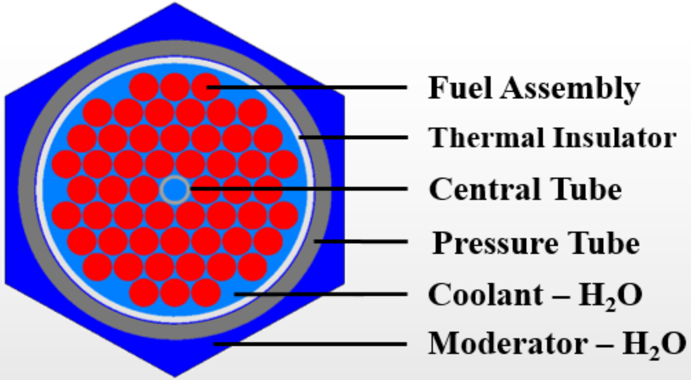
[1] Commercial sized thermal power

LUTHER fuel assembly / channel design

Fuel Assembly / Channel Parameter	Unit	Value
Fuel rod lattice type	-	Triangular
Number of fuel rods	-	54
Fuel pellet diameter[1]	mm	7.844
Fuel cladding thickness[1]	mm	0.5715
Fuel rod outer diameter[1]	mm	9.144
Fuel rod lattice pitch	cm	0.96
Enrichment of the UO2 fuel (95% TD)	%	4.95
Central tube material	-	ZIRLO™[2]
Central tube inner / outer diameter	mm	7.2 / 9.6
Pressure tube material	-	Zr-2.5 wt.% Nb
Pressure tube inner / outer diameter	cm	8.7 / 9.7
Thermal insulator material	-	YSR
Thermal insulator inner / outer diameter	cm	8.2 / 8.6

Features:

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



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[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

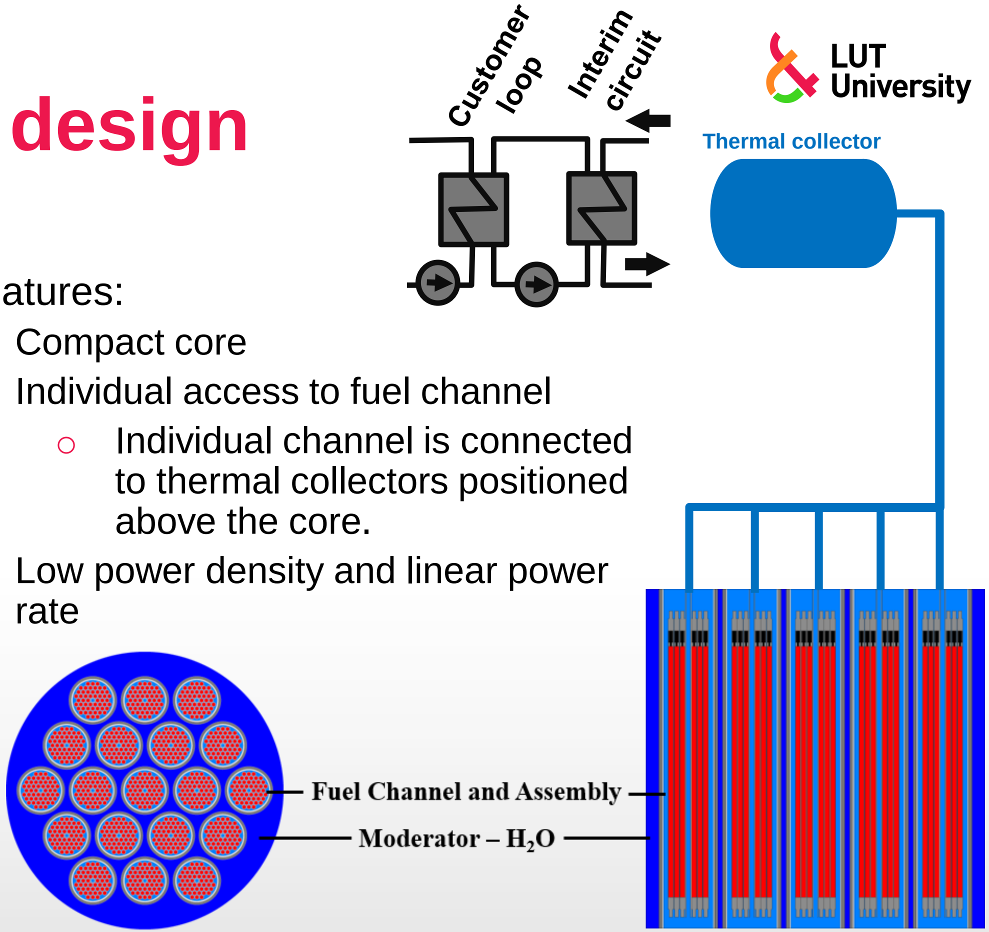
Core Parameter	Unit	Value
Fuel assembly lattice type	-	Triangular
Number of fuel assemblies[1]	-	19
Fuel channel lattice pitch	cm	10.5
Equivalent core diameter	m	0.48
Active core height	m	0.48
Thermal power output per assembly[2]	kW	105.3
Linear power rate[2]	kW/m	3.853
Core power density[2]	kW/l	22.94
Mass inventory of UO2 fuels	tons	0.25
Single channel coolant flow rate[2]	kg/s	1.58

[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



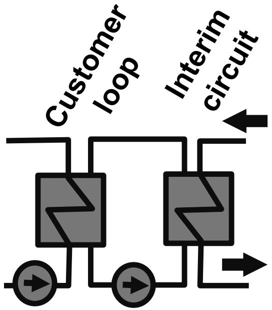
LUTHER 2 MWth comparisons

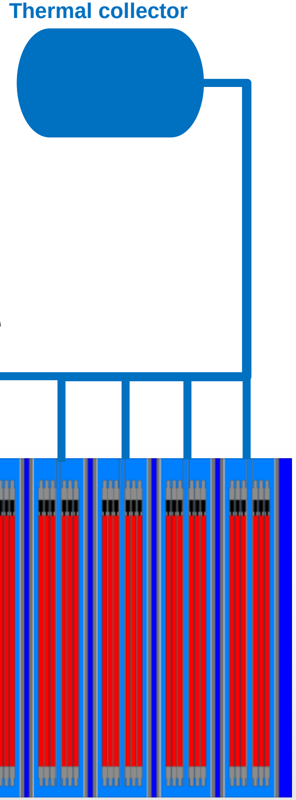
Reactor Core Parameter	Unit	LUTHER	EPR[2]	AES-2006[3]
Design thermal power	MWth	2	4300	3200
Number of fuel assemblies	-	19	241	163
Enrichment of the UO2 fuel	%	4.95	1.9-4.9	4.79
Active core height	m	0.48	4.2	3.75
Equivalent core diameter	m	0.48	3.77	3.16
Operating pressure	MPa	1.25	15.5	16.2
Operating temperatures	ºC	150-180	296-329	298-329
Linear power rate[1]	kW/m	3.853	15.61	16.78
Core power density[1]	kW/l	22.94	~103	108.5

[1] Average value of the design parameter

[2] Okiluoto 3 (EPR), https://www.tvo.fi/uploads/julkaisut/tiedostot/ydinvoimalayks_OL3_ENG.pdf

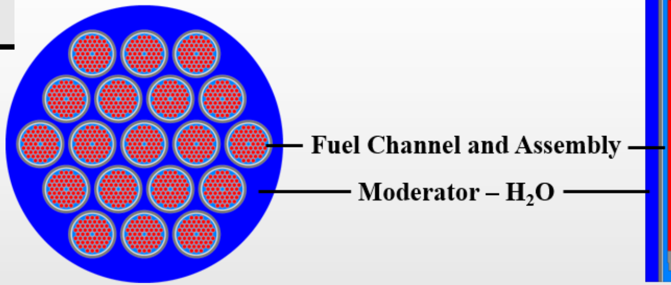
[3] VVER-1200 (V-491), https://aris.iaea.org/PDF/VVER-1200(V-491).pdf





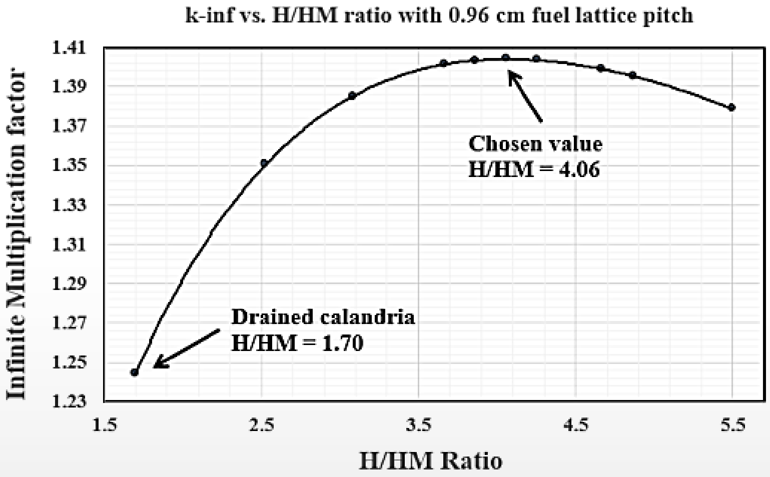
Features:

- Inherent high safety margins!
- Low temperature and low pressure
- ~4x smaller in power density and linear power rate



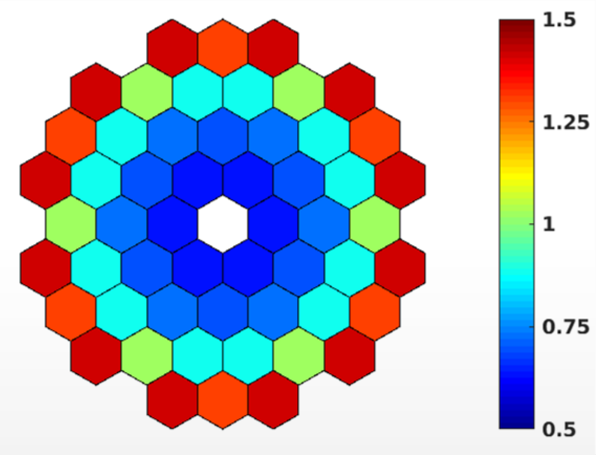
Characteristics of LUTHER design

k_∞ vs. H/HM ratio



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

Assembly power distribution



Normalized power distribution in a fuel assembly

*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 moving

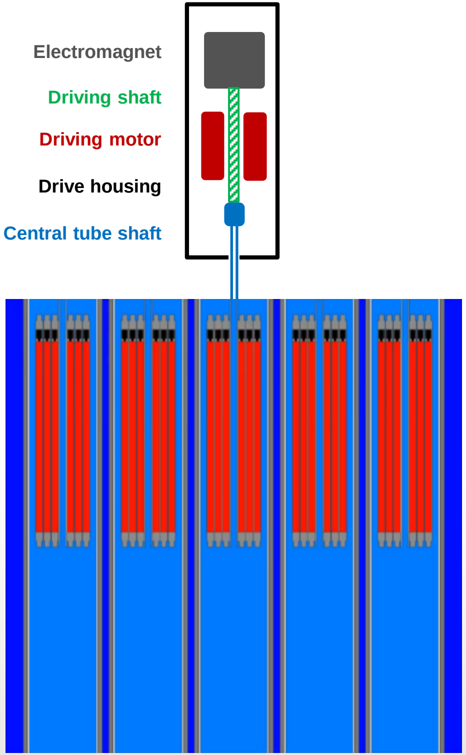
Driven by conventional control rod drive mechanisms

- e.g., electromagnetic control rod drive

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

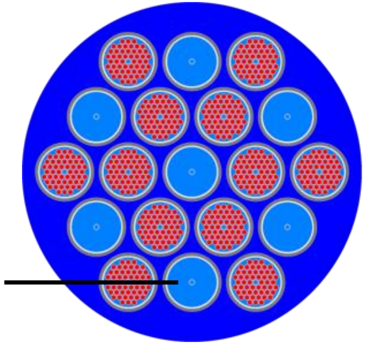
Eliminating control rods

Soluble boron free in coolant and moderator



Fuel assembly reactivity worth

Configuration A →



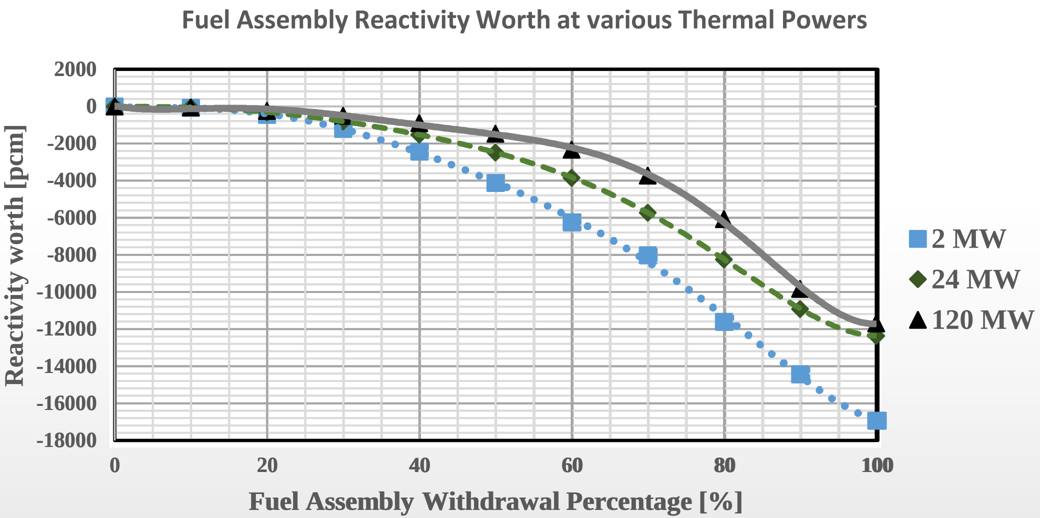
Moving selected fuel assemblies

- 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:



*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)

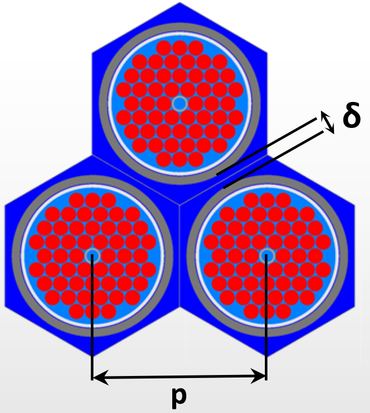
Limited options to choose for an optimal lattice pitch for fuel channels

- p = 10.5 cm

Tight space clearance between fuel channels

- δ = 8 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

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Thank you!

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