Energy Well: Conceptual Design of a Molten Salt Cooled Small Modular Reactor
Content

- Task and Status
- Reactor Pre-Concept
- Secondary and Tertiary Circuits and Heat Balance
- Logistics and Operation
- Next Steps
Task and Status

Why-What-How
The Task (What)

- SMR cooled with molten salt
- High passive safety
- Long operation period with minimal staff
- Modularization and transportability by standard transportation means
- Independent on existing local infrastructure
- 20 MWt
- LEU fuel
## FHR main features

<table>
<thead>
<tr>
<th>Features</th>
<th>Phenomenological Impact</th>
<th>Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High primary coolant volumetric heat capacity</strong></td>
<td>Low fluid pumping requirements</td>
<td>Compact coolant and heat transport loops (small pipes, pumps, heat exchangers)</td>
</tr>
<tr>
<td></td>
<td>Near-constant-temperature energy transport</td>
<td></td>
</tr>
<tr>
<td>Low primary system pressure</td>
<td></td>
<td>Thin-walled reactor vessel and piping</td>
</tr>
<tr>
<td><strong>High primary system temperatures</strong></td>
<td>High power conversion efficiencies</td>
<td>High efficiency</td>
</tr>
<tr>
<td></td>
<td>High temperature fluid – materials corrosion and strength performance</td>
<td></td>
</tr>
<tr>
<td>TRISO fuels</td>
<td>Large fuel temperature margins</td>
<td>Robust operating margins and safety case</td>
</tr>
<tr>
<td></td>
<td>Good fission product attention</td>
<td></td>
</tr>
</tbody>
</table>
Reactor Pre-Concept
The current status

Fuel

- Fission products remain inside irradiated TRISO up to 1800°C
- TRISO particles are in the graphite matrix
- Fuel elements form a rhomb with two fuel plates sandwiching a central carbon slab
- This fuel is the same as the HTGR fuel developed under DOE-NE sponsorship
Reactor core

- Core HM (UOC): 0.82 t.
- Core weight without reflector: 18.3 t. (28.2 t. including reflector)
- Core average neutron flux: 3-5 E+13 n/cm/s
- Control rods are both for reactivity control and compensation of excess reactivity
- Passive reactor shut down system (capsule)
- Coolant: FLiBe // NaFNaB
Core parameters

- Packing Fraction
- Reactor thermal power
- Plutonium vector
- Campaign length
- Fuel enrichment
- Reactivity control means

The Plutonium vector requirements are: Pu-239 < 70% and Pu-240 > 19%. The configuration meets the requirements (GREEN).

20 MWth power system with a 15% enrichment and 25% fraction (PF) was selected as a reference, which reaches a cycle length of up to 7 years at 69.8 MWd / kg burn-up.
Reactivity control

Keff, 15% enrichment

- Criticality
- No Gd in fuel
- B4C inserted rods
- 1% Gd in fuel + fully inserted rods

Burnup (GWD/MTU)
FLiBe as a coolant

- 2LiF-BeF$_2$
- Melting point: 459 °C
- Boiling point: 1430 °C
- Operating temperature
  - 650 - 700 °C
- 10+ years of experience with FLiBe
Thermal-hydraulics

- High operation temperature: 650 / 700 °C / Δ T = 50 °C
- Atmospheric pressure in the system.
- Coolable geometry with high passive safety.
- Natural circulation in case of Loss of flow scenario verified.
- Temperature control during salt freezing in the primary circuit.
# Heat exchanger and pumps

## Type of heat exchanger - Shell & Tube

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Shell side</th>
<th>Tube side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td>FLiBe</td>
<td>NaFNaB</td>
</tr>
<tr>
<td>Mass Flow Rate [kg/s]</td>
<td>170</td>
<td>100</td>
</tr>
<tr>
<td>Temperature inlet/outlet [°C]</td>
<td>700/650</td>
<td>500/635</td>
</tr>
<tr>
<td>Operational Pressure [bar]</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Construction Type</td>
<td>TEMA class E</td>
<td>U-tube</td>
</tr>
</tbody>
</table>

## Pumps

- Circuit pressure drop: 200 kPa
- All 6 pumps power consumption: 24 kW
- Total coolant flow through the reactor: 186 kg/s
Thermal-hydraulics – Loss of flow - Temperatures

Entering new steady state
Thermal-hydraulics – Loss of flow – Mass flows

~ 3.5 kg/s
Reactor vessel = transport container

Reactor vessel
- transport container allows to store container at the site until the salt solidifies and container will be prepared for the transportation.
- Estimation of doses was done for CASTOR-like container
- Container weight: $\approx 130 \text{ t.}$
- Container outer diameter: $\approx 4 \text{ m}$ transportable on railways
- On site handling simplifications necessary (infrastructure)
- 1 year after shutdown we are below radiation limits for container transportation
- Prescreening showed feasibility of this solution

Natural circulation is sufficient for decay heat removal
Secondary and Tertiary Circuits and Heat Balance
Main Features for designing of Secondary and Tertiary circuit

- **Safety**
  - Different pressure levels between I.C and II.C
  - Medium type of II.C (NaFNaB) used for stop of nuclear fission chain reaction

- **Simply**
  - III.C is designed as closed Ericson-Bryton with heat regeneration
    - Lower efficiency than “advanced” EB cycles (ie recompression), but consist of less components -> lower risk of failure
    - Increasing of efficiency up to 42% (recompression cycle) is another step for optimization

- **Small and Compact**
  - II.C covered by standard 6 m (20´) container
  - III.C covered by standard 12 m (40´) container
Cycles schematic drawing

- Air / water
- CO₂
- NaFNaB
- FLiBe

Cooler

40°C

Compressor

HE II/III

500°C

HE - regeneration

Turbine

Water (steam)

HE - bypass

Core

Pump

700°C

500°C

635°C

635°C

650°C

Reactor

500°C
Assumptions and design parameters of tertiary circuit

**Assumptions:**
- Simple concept
- Thermal power input 20 MWt
- Primary salt temperature 700/650°C (HEI/II in/out)
- Secondary circuit with salt
- Tertiary circuit cooler – two options
  - Air cooled
  - Water cooled

**Design input parameters:**
- Thermal input 20 MW
- Input temperature 621°C
- Input pressure 21.5 MPa
- Output temperature 505 °C
- Output pressure 7.9 MPa

**Design output parameters:**
- Recompression cycle 42 % and 8.4 MWe
- Electrical power output 6.95 MWe
  - Cycle efficiency 34.75 %
- Possible “waste” heat utilization
  - Cooler and turbine bypass
Power plant layout

Tertiary Circuit

Secondary Circuit

Primary Circuit

Nuclear reactor
Arrangement of secondary and tertiary circuit

- Regeneration HE
- Salt/CO₂ HE
- Salt purification
- Salt pump
- Generator
- Cooler
- Turbine and Compressor
HBD – simple E-B with regeneration

Thermal input: 20 MWt
El. output: 6.95 MWe
Efficiency (el.): 34.75%
HBD – recompression E-B - preliminary

Thermal input 20 MWt
El. output 8.4 MWe
Efficiency (el.) 42 %
Logistics and Operation
Life cycle

- Fuel
- FLiBe Container
- II Circuit
- III Circuit

3 years of cooldown

Construction
Fabrication

7 y

Operating site

Maintenance
Refueling

Shipment
Logistics and Operation

- Transport to the site:
  - Vessel dimensions: 8 - 10 m height, 3.5 – 4 m diameter
  - Total weight: below 190t

Source: www.ensi.ch
Logistics and Operation – End of Cycle

- Reactor vessel will be qualified for spent nuclear fuel transport
- At the end of fuel life, the whole reactor module will be replaced by the new one containing fresh fuel and coolant
- The reactor module is not refuelled on-site, its transport will be subjected to the same regulations as the transport of the spent fuel cask
- Elimination of the on-site refuelling enables simple power plant design
- Reactor module with spent fuel and salt will be kept for the definite time to cool down by natural circulation and activity drop
Logistics and Operation

Decay heat [W]

Dose rate (in 2 m distance) [mSv/h]

Time

1 second                          1 hour 1 day                         1 year

Decay heat

Dose rate

UJV Group
Logistics and Operation

- Number of transport casks design exists (see TECDOC-1532) which can contain load with residual power between 20 – 30 kW

- Our reactor vessel-transport cask design will aim into this class

- Dose limit for spent fuel transport
  - < 2 mSv/h on the surface
  - < 0.1 mSv/h in the distance of 2 m

- Indicative results for reference design show that the on-site cooling time necessary for transport will be less than one year, due to the dose rate limit
Next Steps
Summary

- The team is up and running
- Patent applied (Cz and US)
- Financing of the next steps partially secured
- Involvement of the industry is under discussion
- Further detailing ongoing
Ongoing activities

- TAČR FHR – Material compatibility research
- Material and thermal-hydraulic experiment on the FLiBe loop
- Spectra measurements in LR-0 reactor with the FLiBe salt
- Economic feasibility study
- Manufacturing feasibility
- Security concept
Thank you for your attention!

Energy Well