Research of the safety concept and systems design of the Generation IV reactor ALLEGRO

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Outline

• Description of ALLEGRO MOX core model creation in SERPENT and calculation of $k_{eff}$.

• Analysis of the control devices impact and other operating parameters to the fuel assemblies power distribution and the fission products and transuranus increase in the fuel.

• Analysis of the ALLEGRO reactor breeding capabilities and transmutation possibilities of long lived fission products and transuranus.
ALLEGRO

- an experimental fast reactor designed by CEA
- aim to test the technology for the power reactor GFR
- MOX fuel and carbide fuel
- cooled by helium under the pressure of 7 MPa
- boron carbide ($B_4C$) enriched to 70% by B-10 isotope
- operating temperature of ALLEGRO reactor – 530°C for MOX core and 850°C for core loaded by ceramic fuel
- power of the ALLEGRO reactor will be $75 MW_{th}$
- two systems of control assemblies to control reactivity and to shutdown reactor: 6 CSD and 4 DSD rods
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ALLEGRO reactor MOXcore:

- 6 experimental assemblies
- 81 MOX fuel assemblies
- 6 Control and Shutdown Devices (CSD)
- 4 Diverse Shutdown Devices (DSD)
- 174 reflector assemblies
- 198 shielding assemblies

Background document:
TEMESVÁRI, E. (CER): ALLEGRO Core Specification, ESNII plus, 15/10/2014, D6.6.1-2, revision 0
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### Material composition of non-fuel core regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Composition (vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOX</td>
<td>25.5 % PuO$_2$</td>
</tr>
<tr>
<td>ABSR</td>
<td>B$_4$C enriched to the 70 % by B-10</td>
</tr>
<tr>
<td>ARFL</td>
<td>75.00 % AIM1 + 25.00 % COOL</td>
</tr>
<tr>
<td>RRFL</td>
<td>80.00 % AIM1 + 20.00 % COOL</td>
</tr>
<tr>
<td>ASHLD</td>
<td>10.00 % AIM1 + 50.00 % NATB4C + 40.00 % COOL</td>
</tr>
<tr>
<td>RSHLD</td>
<td>10.00 % AIM1 + 70.00 % NATB4C + 20.00 % COOL</td>
</tr>
<tr>
<td>FLWCSD</td>
<td>13.69 % AIM1 + 86.31 % COOL</td>
</tr>
<tr>
<td>FLWDSD</td>
<td>13.69 % AIM1 + 86.31 % COOL</td>
</tr>
</tbody>
</table>

**Axial composition of core assemblies:**
- a) fuel assembly,
- b) DSD assembly,
- c) CSD assembly,
- d) experiment assembly,
- e) radial reflector assembly,
- f) radial shielding assembly
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Plot of xy - cut (top) of ALLEGRO MOX core model at the level of fuel rod lattice, $z = 121$ cm

Plot of xy - cut (top) of ALLEGRO MOX core model at the level of ABSR rod lattice, $z = 218$ cm
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Plot of xz - cut (front view) of ALLEGRO MOX core model, y = 0 cm

Plot of yz - cut (side view) of ALLEGRO MOX core model, x = 0 cm
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Calculation of $k_{\text{eff}}$:
Neutron – reaction library: ENDF/B –VII.0

Neutron population:
5 millions neutrons per cycle
500 active cycles, 50 inactive cycles

$$k_{\text{eff}} = 1.02573 \quad \sigma = 1.70 \times 10^{-5}$$
Comparison of power distribution in MOX core model of ALLEGRO and modified model, without impact of control devices at burnup of 0 MWd/kg\textsubscript{HM}

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\[ k_{\text{eff}} = 1.02573E+00 \pm 1.7E\ 05 \]

\[ k_{\text{eff}} = 1.06748E+00 \pm 1.7E\ 05 \]
Further modification of previous MOX core model of ALLEGRO reactor:
1) Experimental positions were filled by MOX fuel assemblies and a zone than contains 87 fuel assemblies.
2) The fuel part of the zone was divided into the 5 axial nodes.
3) The fuel part was divided by 120° symmetry and each fuel assembly in the third of zone was monitored separately.
4) Entering the 75 MW heating power and burn steps.

Critical state:
- DSD rods in the top position over the core
- CSD rods inserted $55.7 \text{ cm}$ to the core from the top position

Total life of starting MOX core is to the burnup of 18.8 MWd/kg$_{HM}$ which is represented by 660 efpd at the power of 75 MWt.
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Distribution of assemblies relative power in the core at burnup of 18.8 MWd/kg_{HM} and critical position of CSD rods

Average power of node: 1.72414E+05 W
Average power of assembly: 8.62069E+05 W
Power of zone: 7.50000E+07 W
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Distribution of relative power at pins of assemblies around the CSD rod at burnup of 18.8 MWD/kg_{HM} and critical position of CSD rods
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Concentration and distribution change of U-235 and U-238 in the core

Distribution of nuclide U-235 in core [$10^{21}$gtHM] at burnup of 18.8 MWd/kgHM

Distribution of nuclide U-238 in core [$10^{21}$gtHM] at burnup of 18.8 MWd/kgHM
Concentration and distribution change of Pu-239 in the core

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Concentration and distribution change of Pu-241 and Pu-242 in the core

Distribution of nuclides Pu-241 in core [10^4 g/t\text{HM}] at burnup of 18.8 MWd/kg\text{HM}

Distribution of nuclides Pu-242 in core [10^4 g/t\text{HM}] at burnup of 18.8 MWd/kg\text{HM}

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Concentration and distribution change of Cm-244 in the core

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Distribution of some fission products at burnup of 18.8 MWd/kgHM

Distribution of nuclide Tc-99 in core [10^2 g/tHM] at burnup of 18.8 MWd/kgHM

Distribution of nuclide Cs-134 in core [10^2 g/tHM] at burnup of 18.8 MWd/kgHM
Scenarios for monitoring the fertile properties of ALLEGRO reactor

1. **first scenario**: Fresh MOX fuel was identical to the fuel specified in the international benchmark ESNII+ with the PuO$_2$ content 26.374 % by mass and the matrix of UO$_2$ composed of natural uranium.

2. **second scenario**: Zone divided into two areas, assemblies in the central area with the original PuO$_2$ content (26.374 % by mass), other assemblies with increased PuO$_2$ content by 5 % to the 31.374 %.

3. **third scenario**: Zone divided into two areas, assemblies in the central area with decreased PuO$_2$ content by 5% to the 21.374 %, other assemblies with original PuO$_2$ content (26,374 % by mass).

4. **fourth scenario**: All 87 fuel assemblies in the zone had the same chemical composition, mixture of UO$_2$ enriched to the 5.652 % by U-235 isotope and reduced content of PuO$_2$ to the 20.1 %.

5. **fifth scenario**: All 87 fuel assemblies in the zone had the same chemical composition, mixture of UO$_2$ enriched to the 15 % by U-235 isotope and reduced content of PuO$_2$ to the 4.78 %.
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Evaluation of fertile properties of the ALLEGRO reactor

Dependence of conversion factor from burnup

Dependence of effective multiplication coefficient from burnup
Monitoring the transmutation properties of the ALLEGRO reactor

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction</th>
<th>Nucleus</th>
<th>Mass fraction</th>
<th>Half-life</th>
<th>Decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>0.20829</td>
<td>Am-241</td>
<td>0.30884</td>
<td>432.2 roka</td>
<td>100% α</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Am-243</td>
<td>0.69116</td>
<td>7370 roka</td>
<td>100% α</td>
</tr>
<tr>
<td>Np</td>
<td>0.72030</td>
<td>Np-237</td>
<td>1.00000</td>
<td>2,144 E+6 roka</td>
<td>100% α</td>
</tr>
<tr>
<td>Cm</td>
<td>0.07141</td>
<td>Cm-242</td>
<td>0.26844</td>
<td>162,8 dňa</td>
<td>100% α</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cm-243</td>
<td>0.00637</td>
<td>29.1 roka</td>
<td>100% α</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cm-244</td>
<td>0.67247</td>
<td>18.1 roka</td>
<td>100% α</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cm-245</td>
<td>0.04930</td>
<td>8500 roka</td>
<td>100% α</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cm-246</td>
<td>0.00342</td>
<td>4730 roka</td>
<td>99.973 α, 0.0263 SF</td>
</tr>
</tbody>
</table>

Cycle of Pu and MA recycling from LWR spent nuclear fuel and fabrication of fuel and MA mixture for ALLEGRO reactor

Representation of separated MA from spent nuclear fuel after five years in spent fuel storage and their half-lives and decay modes

Scenario of homogeneous transmutation

- **first transmutation scenario**: Homogeneous distribution of Pu and MA in the core. Representation of separated MA is shown in Table.

  The fresh fuel is composed from UO₂ enriched to the 5.652 % by U-235 isotope, content of PuO₂ was 19.698 % by mass and MA was 2.0 % by mass.
Evaluation of transmutation properties of the ALLEGRO reactor (homogeneous dispersion of MA with content of 2% in the fuel)

Concentration of americium isotopes at burnup of 0, 18.8 and 150 MWd/kgHM

Concentration of curium isotopes at burnup of 0, 18.8 and 150 MWd/kgHM
Cycle of Pu and MA recycation from LWR spent nuclear fuel and fabrication of heterogeneous fuel and MA mixture for ALLEGRO reactor

Scenario of heterogeneous transmutation where mixture was placed in the central pins (pink pins) of the assemblies at first orbit in experimental position (assemblies with yellow pins).

- **second transmutation scenario**: Separation of the Am and its integration to the inert MgAl$_2$O$_4$ matrix. The mixture contained 11 % of AmO$_2$ by mass.
- **third transmutation scenario**: Separation of the Am and Np separation and their integration to the depleted UO$_2$ with 0.25 % content of U-235 isotope. The mixture of oxides (UO$_2$, AmO$_2$, NpO$_2$) contained 20 % by mass of MA.
- **fourth transmutation scenario**: Separation of the Am, Np and Cm separation and their integration to the depleted UO$_2$ with the U-235 isotope content of 0.25 %. The mixture of oxides (UO$_2$, AmO$_2$, NpO$_2$, CmO$_2$) contained 20 % by mass of MA.
Evaluation of transmutation properties of the ALLEGRO reactor (Am in the MgAl$_2$O$_4$ matrix)

Concentration of americium isotopes at burnup of 0, 18.8 and 150 MWd/kgHM
Evaluation of transmutation properties of the ALLEGRO reactor (Am and Np in the matrix from depleted UO$_2$)

Concentration of americium isotopes at burnup of 0, 18.8 and 150 MWd/kg$_{HM}$

Concentration of neptunium at burnup of 0, 18.8 and 150 MWd/kg$_{HM}$
Evaluation of transmutation properties of the ALLEGRO reactor (Am, Np and Cm in the matrix from depleted UO₂)

Concentration of americium and neptunium isotopes at burnup of 0, 18.8 and 150 MWd/kgHM

Concentration of curium isotopes at burnup of 0, 18.8 and 150 MWd/kgHM
Conclusion

• At the locations with high power can be observed decrease of fissile nuclides concentration as U-235, Pu-239 and Pu-241, while higher actinides like Cm and fissile products were accumulated mainly at locations with high power.
• Breeding properties of ALLEGRO reactor were achieved only by reducing the PuO$_2$ content at the expanse of increasing UO$_2$ content, which results to the increasing amount of fertile U-238.
• In terms of fertile characteristics of the ALLEGRO reactor, is not appropriate zone with high PuO$_2$ content.
• By comparing of homogeneous and heterogeneous transmutation of MA, transmutation occurs better in the case of heterogeneous transmutation for the americium as well as curium isotopes.
• In terms of transmutation characteristics appears promising only the possibility of heterogeneous placement of MA in the core of ALLEGRO reactor.
Thank you for your attention

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