Modelling Long Term Performance of Minor Actinide Fuel Targets in the Experimental ADS MYRRHA

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1.1. Introduction

- Subcritical ADS can provide effective and safe solution for MA transmutation and Pu burning.

- The Belgian nuclear research Centre SCK·CEN, in collaboration with other countries, works on design of an experimental ADS to study MA transmutation in innovative dedicated fuels.

- A new fuel performance code MACROS-II devoted to modelling of the behaviour of the dedicated fuels in ADS is under development and testing.
1.2. Introduction:

**ADS MYRRHA**

**Proton beam line**

**Proton accelerator**

**Main performances:**

- Proton source: $E_p \sim 350$ MeV, $I_p \sim 5$ mA
- Liquid Pb-Bi spallation source and coolant
- Highly enriched MOX in the sub-critical core
- $k_{eff}$ limited to $\sim 0.95$
- Total power $\sim 50$ MW(th)
- Fast neutron flux $\sim 10^{15}$ n cm$^{-2}$s$^{-1}$
1.3. Introduction: Option of the core

![Diagram of core with labeled zones: Reflector zone, Active zone, Spallation target, Experimental channels, Tested fuel segment.]

- Reflector zone
- Active zone
- Spallation target
- Experimental channels
- Tested fuel segment
2.1. Irradiation conditions:

Neutron spectrum

![Graph showing neutron spectrum with different energy ranges and relative flux per unit lethargy.]
2.2. Irradiation conditions:

A-assembly position

Neutron spectrum:
- mean neutron flux \(3.17 \times 10^{15}\) neutron/(cm\(^2\)·s)
- thermal (En < 0.5 eV) \(6.0 \times 10^{-5}\) %
- epithermal + resonance (0.5 eV < En < 20 keV) 10.97 %
- fast (20 keV < En < 1 MeV) 74.24 %
- Very fast (En > 1 MeV) 14.79 %

LM coolant:
- max. velocity in sub-channel 2.0 m/s
- input temperature 200-250 °C

Operation time-table:
- irradiation cycle duration 90 days
- cold period between the cycles 30 or 90 days
2.3. Irradiation conditions:

Neutron flux regime

- Neutron flux regime
- Constant flux regime
- Constant beam current
- Constant LHGR regime
3.1. Fuel pin pre-design

- Fuel column: MOX or IMF
- Reflector segments: MgO or ZrO₂
- Gas plenum (bottom + top): He: 1-5 bar (STP)
- Cladding: FMS T91
3.2. Fuel pin pre-design: Driver zone pellets

- Diameter/height: 5.35 x 6 mm
- Composition: $(\text{Pu}_{0.3}\text{U}_{0.7})\text{O}_{2-x}$ MOX: 30 wt.% Pu in HM
- Density 95 % TD
- Initial fuel isotopic vectors: PWR spent fuel, burnup 33 MWd/kg HM, 10 years of storage.

<table>
<thead>
<tr>
<th>PLUTONIUM</th>
<th>URANIUM</th>
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<tbody>
<tr>
<td>Isotope</td>
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<td>$^{238}\text{Pu}$</td>
<td>1.27</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>61.88</td>
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<tr>
<td>$^{240}\text{Pu}$</td>
<td>23.50</td>
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<td>$^{241}\text{Pu}$</td>
<td>8.95</td>
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<tr>
<td>$^{242}\text{Pu}$</td>
<td>4.40</td>
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</table>
3.3. Fuel pin pre-design: IMF target pellets

- Diameter/height: 5.85 x 6 mm
- Composition:
  - 40 vol.% \((Cm_{0.1}Am_{0.5}Pu_{0.4})O_{2-x}\) + 60 vol.% ZrO\(_2\)
  - 40 vol.% \((Cm_{0.1}Am_{0.5}Pu_{0.4})O_{2-x}\) + 60 vol.% MgO
- Density 90% TD
- Initial fuel isotopic vectors: 2nd strata (FUTURE).

### Plutonium

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<td>(^{239})Pu</td>
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<td>(^{242})Pu</td>
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### Americium

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<td>(^{241})Am</td>
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<td>(^{243})Am</td>
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### Curium

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<tr>
<td>(^{245})Cm</td>
<td>10.00</td>
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</table>
3.4. Fuel pin pre-design: 
Thermal conductivity (BOL)
4. Code MACROS-II

  - MACROS = PLUTON + ASFAD
  - UO₂, UO₂+Gd₂O₃
  - LWR and Halden HBWR

- **MACROS-II (2004)**
  - New burnup/depletion module (PLUTON 2MG)
  - Mechanistic modelling
  - He production and release
  - Effects of heterogeneity
  - Fuels: UO₂, MOX, IMF with MA
  - Spectra: LWR, FR, ADS, ...
  - Successfully validated with:
    - FUMEX-II IAEA benchmark (high burnup LWR fuels)
    - OECD benchmark (MOX behaviour in HRP experiment)
    - DOMO irradiation experiment (UO₂, MOX)
    - To be validated with EFFTRA data (IMF with MA)
5.1. Results of modeling: Flux and burnup evolution

- IMF(MgO) average
- IMF(ZrO2) average
- MOX(30Pu) average
- Neutron flux
5.2. Results of modelling: Linear heating rate

![Graph showing linear heating rate over time for different materials: Driver MOX, IMF(MgO), IMF(ZrO2).]
5.3. Results of modelling: Initial temperature

\[ T_{\text{melt MOX}} = 2685 \, ^\circ\text{C}; \quad T_{\text{unstable IMF(MgO)}} \sim 2000 \, ^\circ\text{C}; \quad T_{\text{melt IMF(ZrO}_2\text{)}} \sim 2500 \, ^\circ\text{C} \]
5.4. Results of modelling: 
“Pellet-clad” gap at start
5.5. Results of modeling:

Fuel temperature evolution

- IMF(ZrO2)
- IMF(MgO)
- driver MOX

Fuel centreline temperature, °C.

Time, d
5.6. Results of modeling:

**Fuel swelling**

- IMF(MgO), max
- IMF(ZrO2), max
- Driver MOX
5.7. Results of modeling: Pellet-clad gap closing
5.8. Results of modeling: Xe, Kr and He production in MOX

Production of He, Xe or Kr, g-at/cm³.

MOX (30Pu)

- He
- Xe
- Kr
5.9. Results of modeling: Xe, Kr and He production in IMF

- **Xe, Kr and He production in IMF**

![Graph showing the production of He, Xe, and Kr over time in IMF(MgO)](image)
5.10. Results of modeling: Release of noble gases

![Graph showing release of noble gases over time for IMF(ZrO2), IMF(MgO), and Driver MOX.](image-url)
5.11. Results of modeling: Gas pressure in the rods

- IMF(MgO)
- IMF(ZrO2)
- Driver MOX
6. Conclusions

- The fuel performance code MACROS-II developed for modelling of IMF fuel behaviour in ADS is under validation and testing at the SCK·CEN.

- Prognosis of the behaviour of two CERCER IMF pins with \((\text{Am, Cm, Pu})_2\text{O}_{2-x}\) fuel and MgO and ZrO\(_2\) matrices in the sub-critical core of ADS MYRRHA was performed with this code.

- It was shown that both can withstand at least six cycles (540 EFPD) of operation without serious problems, reaching the representative burnup of 11 % FIMA. IMF with MgO matrix can operate at higher fission rates and has better safety margins.
Future steps

- Validation of the MACROS code with the data of EFTTRA and other irradiation experiments performed with MA containing fuels.

- Application in IP EUROTRANS for fuel design and modelling.