ENHANCING PROLIFERATION RESISTANCE FOR SMALL SFR

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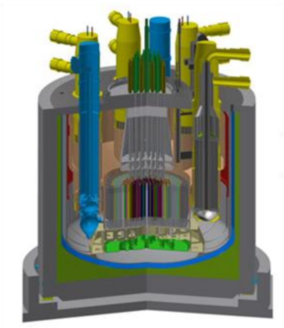
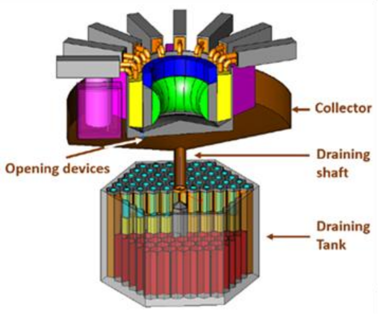
Studies of advanced reactors at KIT

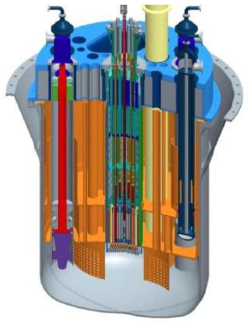
- Fuel cycle and safety studies, focus on severe accidents, mainly for EU projects
  - recently: more effort on small reactors
- Main fuel options: systems with MOX solid fuel, MSR with fluoride salts
  - now&planned: more effort on systems with metal and nitride solid fuels, chloride salts



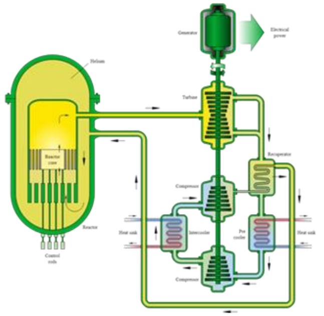
SFR



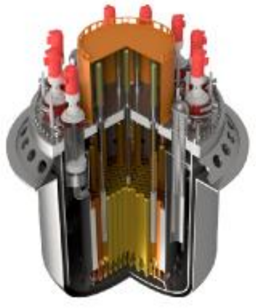
MSR



MYRRHA



GFR



LFR

EU projects on European Sodium Fast Reactor (ESFR)

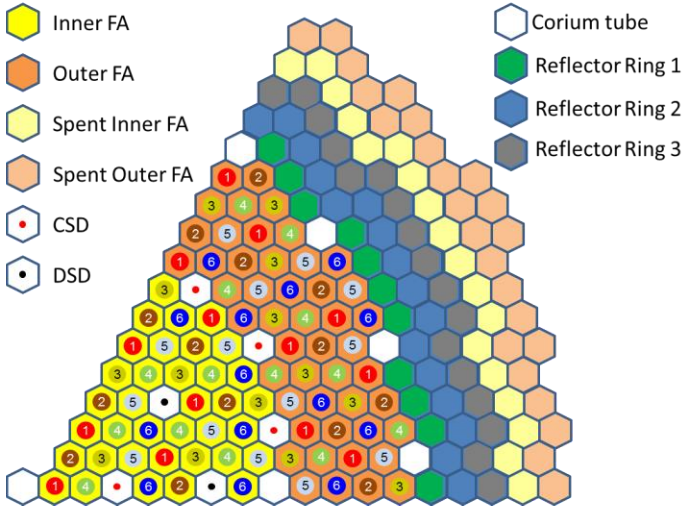
- CP-ESFR, 2008-2012, design and safety studies for a large 3600 MWth core with MOX
  - Design proposed by CEA, France, Pu238/Pu239/…/Pu240/Pu241/Pu242/Am241 vector is 3.7/48.6/28.0/8.4/10.5/0.8
  - No axial/radial fertile blanket, steel reflectors below, above, around the core
  - MOX enrichment about 14% in the inner core, about 17% in the outer core, near zero Pu balance
  - Sodium void/density effect: positive; multiple re-criticalities e.g. after unprotected loss of coolant flow (ULOF)

- ESFR-SMART, 2017-2022, continuation on design and safety studies for the large SFR with MOX
  - Optimized flatter core with more fuel subassemblies (SAs), sodium plenum above the core, lower fertile blanket, etc.
  - Sodium effect: close to zero; better safety behavior, core melting after ULOF under some pessimistic assumptions
  - Thicker axial blanket/shorter fissile in inner core, fuel enrichment about 18% in all SAs, near zero Pu balance

- ESFR-SIMPLE, since 2022: several directions, including a small SFR with MOX
- The number of subassemblies reduced by factor of 6 (same as 1 batch for the large core)
  - 217 instead of 271 pin per SA, smaller SA size, HEX pitch 18.66 cm instead of 20.985 cm
  - Similar pin radial dimensions and fresh fuel isotopic composition as in previous studies, negative Pu balance
  - As in ESFR-SMART: axial fertile subregions to reduce reactivity variation per cycle and improve sodium void effect
  - Sodium void effect negative, no core melting after ULOF (preliminary)

Large ESFR core with MOX (ESFR-SMART project)

- Power: 3600 MWth
- Design in plane fixed first, considering design limits from previous projects
- Axial design obtained after optimization studies. Inner/outer fissile heights: 75/95 cm. Fuel enrichment ca. 18% in all SAs
- SAs in yellow for inner core, in red for the outer core, also storage at core periphery is shown (60-degree sector)
- Fuel management, 6 batches of ca. 367 days (2170 days in total)
- Homogeneous design: Fertile plate touches Fertile blanket



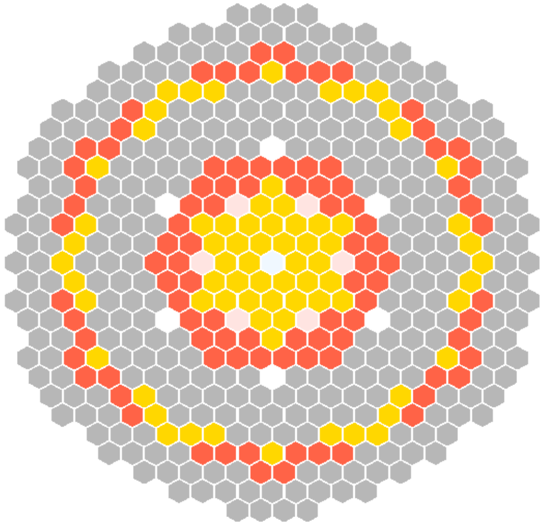
Large SFR: plane layout for the 60-degree sector

Inner Core	Outer core
Sodium plenum	Sodium plenum
Upper Gas Plenum and Plug	Upper Gas Plenum and Plug
Fissile region	Fissile region
Fissile region	Fissile region
Fissile region	Fissile region
Fertile plate	Fissile region
Fertile blanket	Fertile blanket

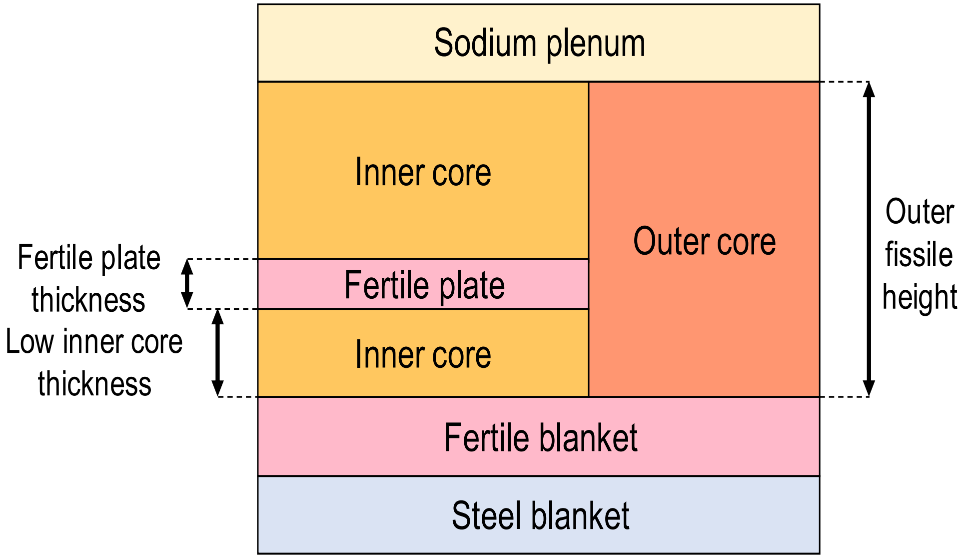
Large SFR: axial layout

Small ESFR core with MOX (ESFR-SIMPLE Project)

- Power: 360 MWth
- Design in plane was fixed first, considering transportation
- Axial design was obtained after optimization studies, a bit shorter core than in large SFR
- Fuel management, 6 batches of 305 days (1830 days in total)
- In the figure below: SAs in yellow for inner core, in red for the outer core
- Heterogeneous design: Fertile plate does not touch Fertile blanket, reducing reactivity loss per cycle



Small SFR: plane layout



Small SFR: axial layout and optimized values

Isotopic composition of spent fuel

In spent fuel

- in fissile subregions, Pu is of similar grade as in the fresh fuel, with low Pu239 content
- in fertile subregions, high content of Pu239 in Pu

- In the following, studies are presented which follow the approach proposed by G. Kessler, former director of KIT/INR

- Proliferation-resistant materials:
  - LEU
  - Pu with high content of Pu238 (above 6% or 8%): because of high decay heat produced by Pu238
  - Am
  - Cm
- Np is not considered as proliferation-resistant

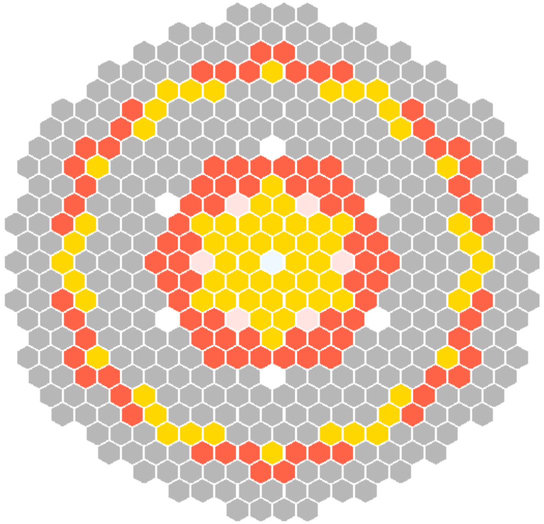
- Option to increase Pu238 content in Pu: to add material with Am241 to the fresh fuel
- Because of the Am241 -> Am242(m) -> Cm242 -> Pu238 chain

- Addition of Am to the fissile domain:
  - Decreases the core reactivity, may reduce reactivity variation per cycle
  - Increases the sodium void effect
  - Decreases the Doppler effect

- Introduction of Am241 in the fertile region only is studied in the following: for a small SFR with MOX

Small SFR with/without Am in Fertile Region (1)

- Same configuration in plane as for SMR of ESFR-SIMPLE
- Homogeneous axial layout, same as for the large SFR
  - In view of reactivity reduction after adding Am241 close to core center
- Power of 400 MWth due to higher core
- Pu content in MOX: ca. 21.5%



Inner Core	Outer core
Sodium plenum	Sodium plenum
Upper Gas Plenum and Plug	Upper Gas Plenum and Plug
Fissile region	Fissile region
Fissile region	Fissile region
Fissile region	Fissile region
Fertile plate	Fissile region
Fertile blanket	Fertile blanket

Small SFR 400 MWth, with and without Am in Fertile Region (2)

	Am, 0%	Am, 4%
Pu238 fraction in Pu of Fertile at EOL, %	0.04	15.1
Pu239 fraction in Pu of Fertile at EOL, %	93.4	77.0
Initial core reactivity vs. Am 0% option	0	-100 pcm
Sodium void effect vs. Am 0% option	0	-20 pcm
Reactivity loss BOC to EOC, pcm	1515	1522
Burn-up, MWd/kg	65.5	65.5
Am mass BOL/EOL, kg	15/73	103/137
Decay heat Total/FP 84 core SAs 5y cooling, kW	74/24	90/24

Introduction of Am in the fertile region:

- Strong increase of Pu238 content, reduction of Pu239 content, making Pu less attractive
- No appreciable effect on criticality, sodium void effect, reactivity loss per cycle
- Lower production of Am (34 kg instead of 58 kg), slightly higher decay heat after cooling for 5 y.

Conclusive remarks

Fertile blankets around the core: approach applied since the beginning of SFR development

- Augments Pu balance in the system
- Reduces reactivity variation per cycle
- Increases leakage from the core to the blanket, thus reducing the sodium void effect

Modern reactor designs

- Upper fertile blankets: removed in modern designs with MOX because of installation of the sodium plenum above the core
- Radial fertile blankets: removed to avoid Pu production there
- Lower blankets/internal fertile: remain in ESFR designs

Introduction of Am in fertile

- Produced Pu is less attractive
- No appreciable deterioration or minor improvement of major reactor characteristics
- Makes fuel fabrication more difficult