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Overview of LWR and Advanced Reactor Fuel Forms

February 2023

Changing the World's Energy Future

Sebastian Schunert

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Overview of LWR and Advanced Reactor Fuel Forms

02/28/2023

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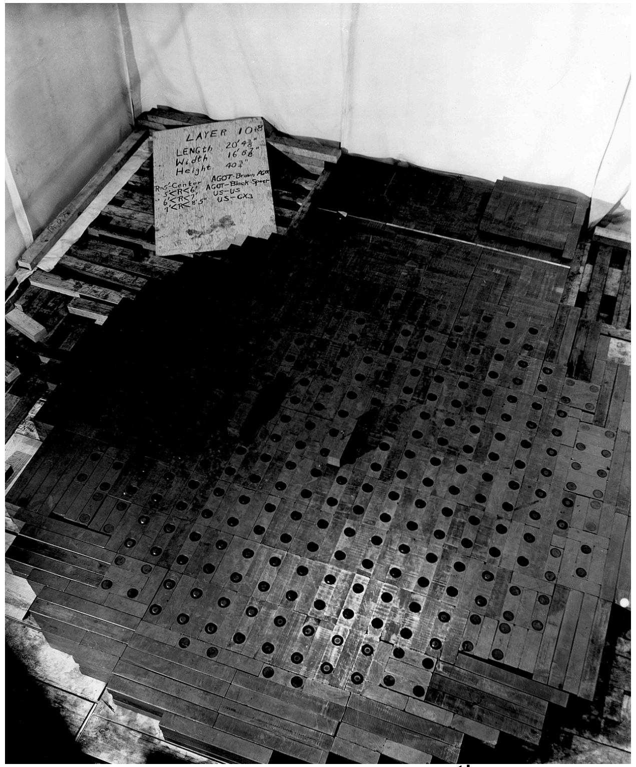
Requirements for Nuclear Fuel for Power Production

- **Neutronics**: Critical under operating conditions with margin for burnup & power level changes

  (excess reactivity * for PWRs 0.3 dk/k, 30,000 pcm)
- **Thermal-hydraulics**: fuel must be coolable
- **Fuel performance**: withstand harsh reactor conditions for reasonable duration & retain fission products
- **Chemistry**: Chemical compatibility with moderator, coolant, structural materials



Chicago pile 10th layer [1]

Does CP1 make the cut?

*

Fuel – Moderator – Coolant: Mix & Match

Thermal reactors

Fast reactors

Geometry: homogeneous, dissolved, dispersed, plate, rods, pebbles

Fuels
U, Pu, Th
Enrichment
Metal, Ceramic,
Dissolved, TRISO

Moderator
Graphite, Beryllium,
H_20, D_20, Hydrites (ZrH),
Flibe

Coolant
Liquid metals, Molten salts,
Water, Gas, Heat pipes

Fluoride salt-cooled high-temperature reactor (FHR)
TRISO fuel in pebbles HALEU (<20% enriched)
Molten salt coolant (Flibe)
Graphite moderator [some moderation from Flibe]

Light water reactor
5% enriched UO_2 rods
H_20 coolant & Moderator

Fast Molten Salt Reactor (MSFR)
U-Pu-Th dissolved in molten LiF:
$LiF\text{-}(U,Pu)F_3\text{-}ThF_4$

Mix & Match

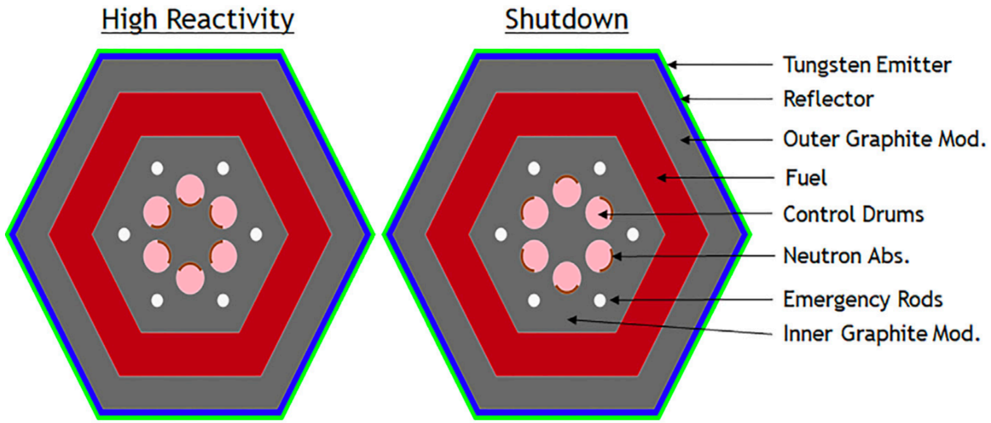
RBMK (graphite moderated BWRs)
1.8% enriched UO_2
Graphite moderated
H_20 cooled

Positive power coefficients of reactivity

Met
Met
H_20

Water oxidizes metallic fuel
Cladding failure is severe!

Power reactor without



Ref [2]

High temperature ultra-small modular reactor: Pre-conceptual design

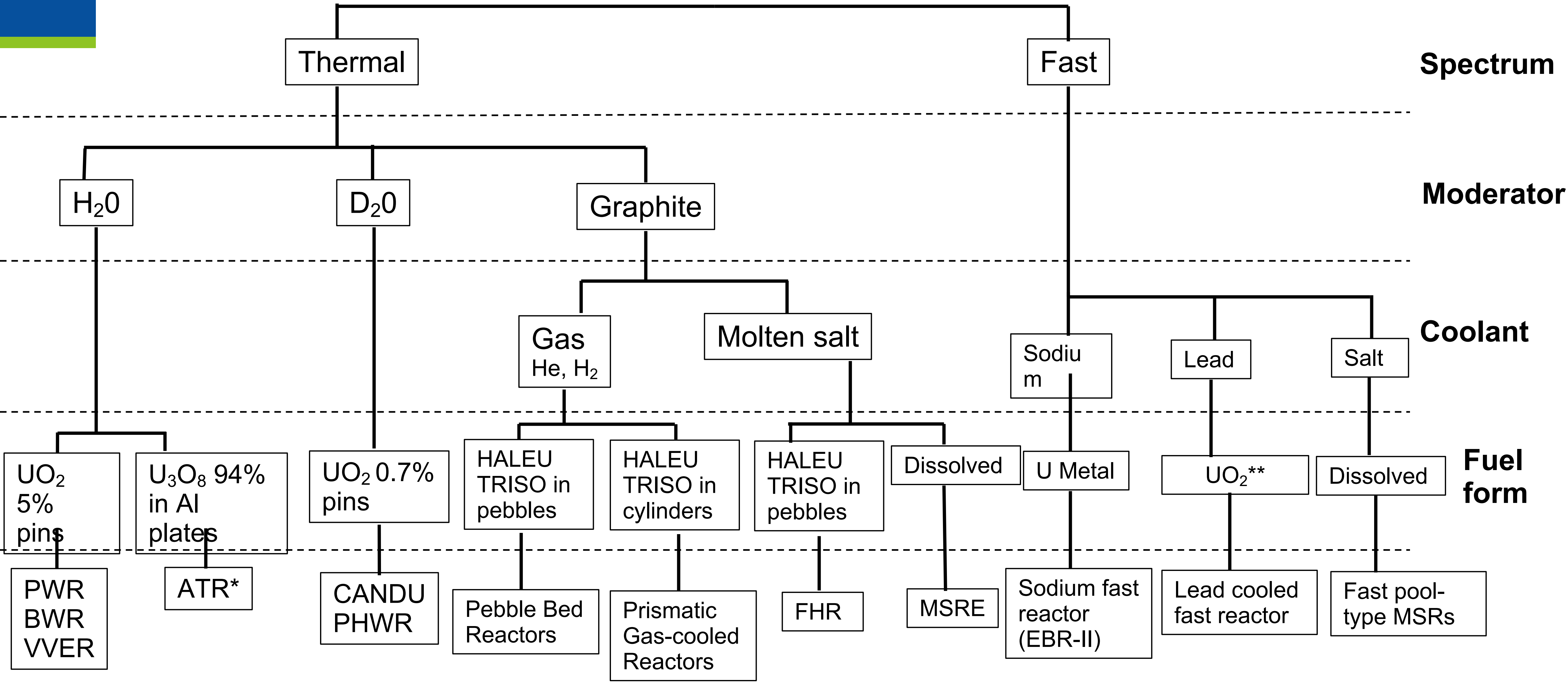
Naiki Kaffezakis, Stefano Terlizzi, Corey Smith, Anna S. Erickson, Shannon K. Yee, Dan Kotlyar*

Georgia Institute of Technology, 770 State St NW, Atlanta, GA 30313, Georgia

Ultrasmall high-temperature
UC or UN CERMET fuel
Graphite moderated
Conduction + radiation + PV

Genealogy of Nuclear Reactors

Not an exhaustive list!



*Advanced Test Reactor

**UN [Westinghouse design], MOX or metallic fuels possible

Why so many reactor concepts?

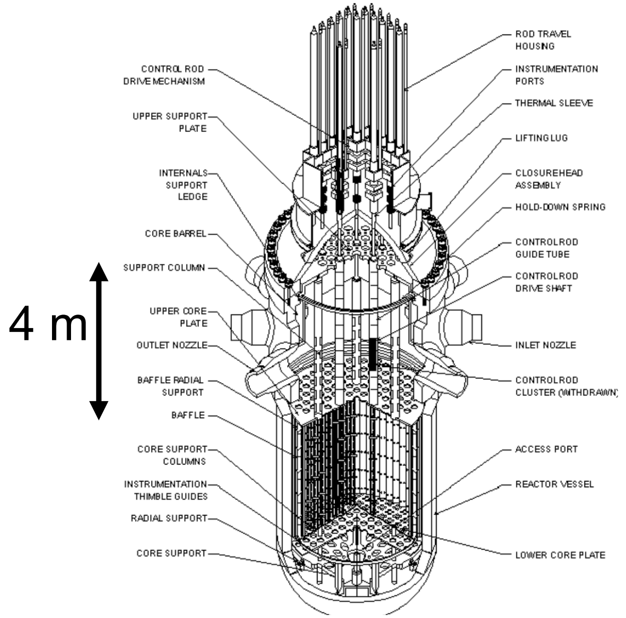
Reactor types have advantages and disadvantages and no one reactor is perfect for every need!

- PWR
  - High power density, relatively low fuel enrichment, economy of scale, water is not toxic, transparent, liquid at room temperature & pressure
  - Require active safety systems, pressurized, low outlet temperatures (330ºC), difficult fuel reprocessing, relatively small discharge burnup, small margin to boiling, generates H_2 from cladding
- Gas cooled pebble bed reactors
  - Passively safe, deployable at moderate powers (100 MW), high outlet temperatures (750ºC), high discharge burnup, continuous refueling and low excess reactivity
  - HALEU is required, Low power density, pressurized, no fuel reprocessing, create dust during operation
- Sodium fast reactors
  - Passively safe, supports fuel reprocessing, decent outlet temperature (550ºC), atmospheric or near atmospheric pressure, high discharge burnup, high power density
  - HALEU is required, sodium reacts with air & water, metal fuel poses fuel performance issues

Example 1: Pressurized water reactor (Gen II)

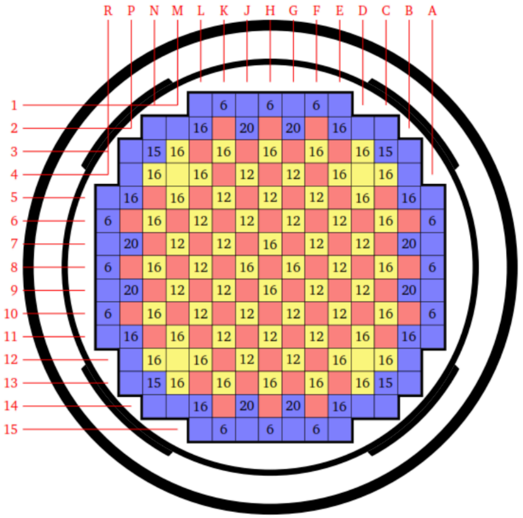
Quantity	Value
Spectrum	Thermal
Power	~3,000 MWth
Average core power density	~100 MW/m3
Maximum burnup	62.5 MWd/kg
Fuel	5% enriched UO_2

- Ceramic UO_2 fueled, light water moderated
- Square assemblies (20 cm across), 17x17 pins (D = 0.94 cm)
- High pressure (15.5 MPa) keeps most water from boiling (yet some channels boil!)
- LWRs are mostly used for grid scale electricity production with once-through fuel cycles

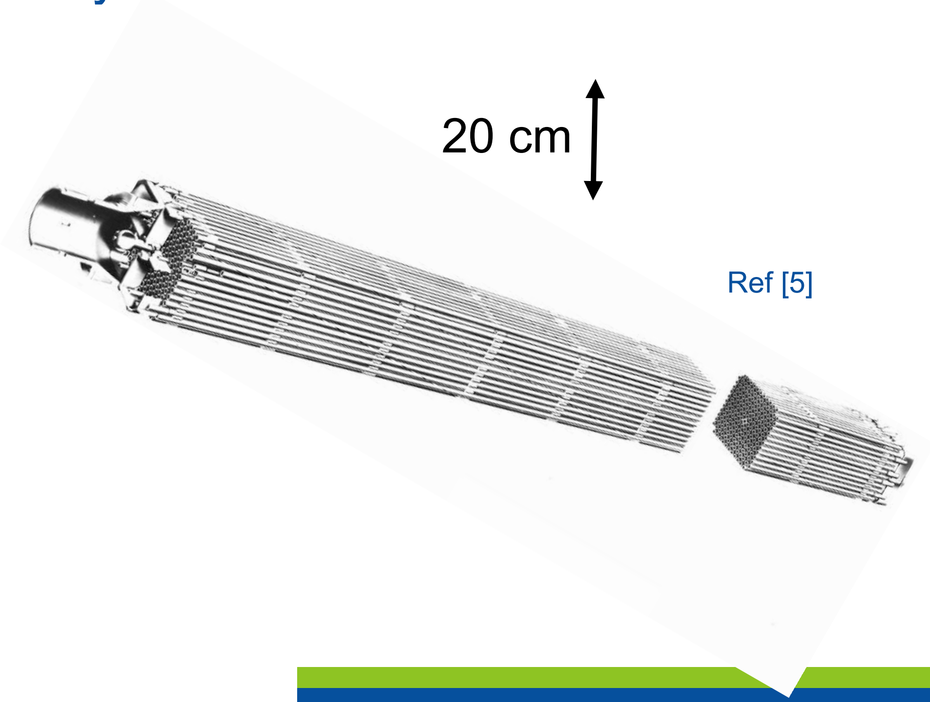


Ref [3]

x-y view of the core



Ref [4]

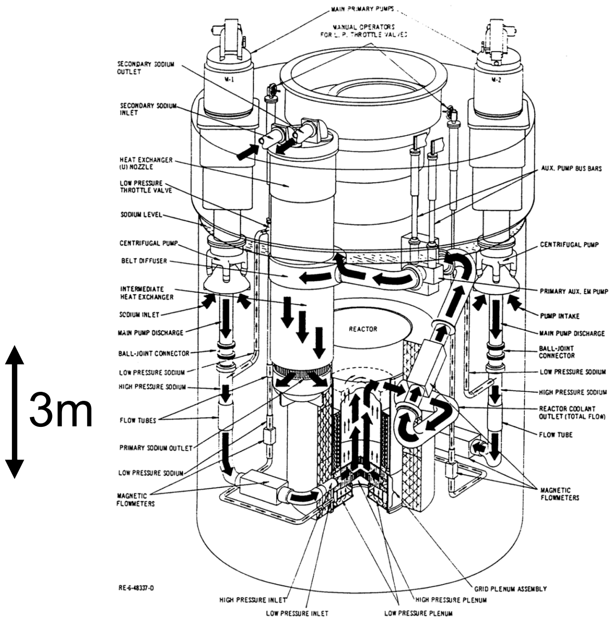


Ref [5]

Example 2: Sodium Cooled Fast Reactor – EBR-II

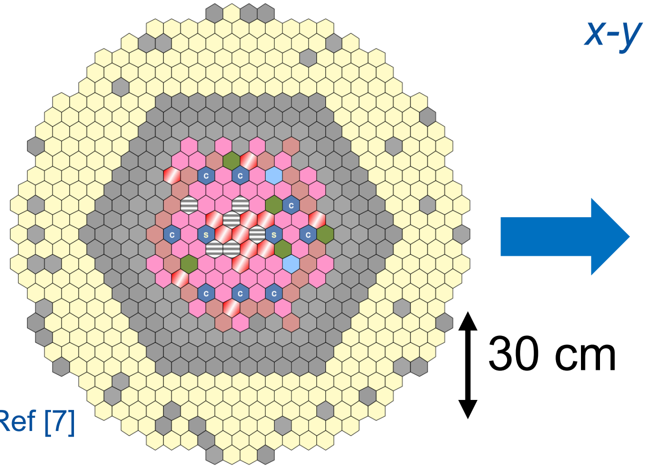
Quantity	Value
Spectrum	Fast
Power	~60 MWth
Driver fuel power density	~400 MW/m3
Typical burnup	100 MWd/kg
Driver fuel	95 wt% U (62.5% enriched) + 5% Fissium*

- Metal fuel – sodium cooled breeder reactor
- Integral (no direct pipes out of vessel) pool type concept
- Hexagonal assemblies (6 cm across), fuel pins (D = 0.37 cm)
- Phase 1: technological demonstration of complete breeder power plant + reprocessing of metallic fuel
- Phase 2: demonstrate the integral fast reactor with a focus on material's testing & safety transients



Ref [6]

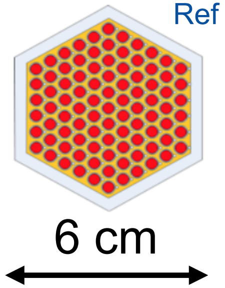
x-y view of the core + blanket



Ref [7]

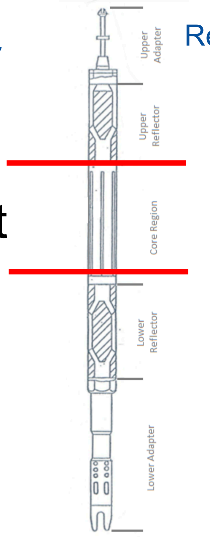
x-y view of driver assembly

Ref [7]



axial view of driver assembly

Ref [7]



* Fissium: metal fuel + small amount of fission products

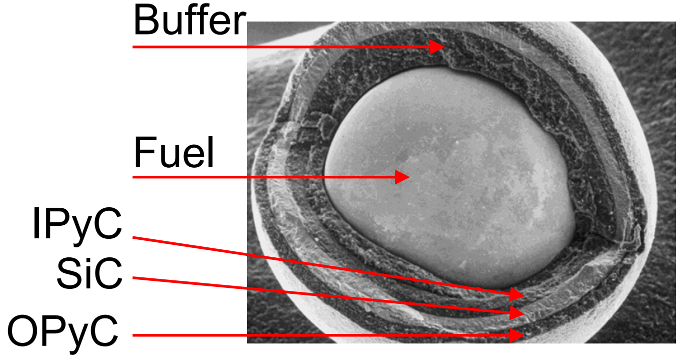
Example 3: Pebble Bed Reactor – XE-100

- XE-100 is X-energies ARDP design
- 200 MWth Helium cooled pebble bed reactor
- Special feature of PBRs is online refueling, pebbles move through the core while being irradiated
- Fuel:
  - Several 100,000 pebbles in the core
  - Pebble contains thousands of tristructural isotropic particles (TRISO)
  - TRISOs are extremely robust: retain fission products for longer than 300 h at 1800C

Quantity	Value
Spectrum	Thermal
Power	~200 MWth
Average core power density	~4 MW/m3
Typical burnup	160 MWd/kg
Fuel	15.5% enriched UCO TRISO in graphite pebbles

Ref [8]

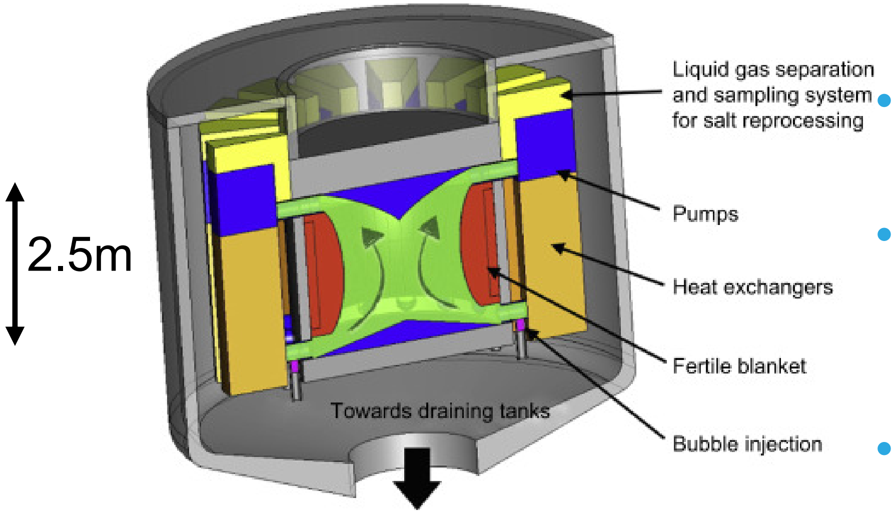
Ref [9]



*Note: fuel enrichment and fuel type (UO2 vs. UCO) varies between designs and operational phase

Example 4: Pool-type Fast Molten Salt Reactor

Quantity	Value
Spectrum	Fast
Power	~3,000 MWth
Average core power density (per salt volume)	~350 MW/m3 (167 MW/m3)
Typical burnup	Very high
Fuel	LiF-ThF$_4$-(^{233}U or ^{enr}U)F$_4$ or LiF-ThF$_4$-(Pu-MA)F$_3$ with 77.5 mol% LiF



Pictures are all from Ref [13]

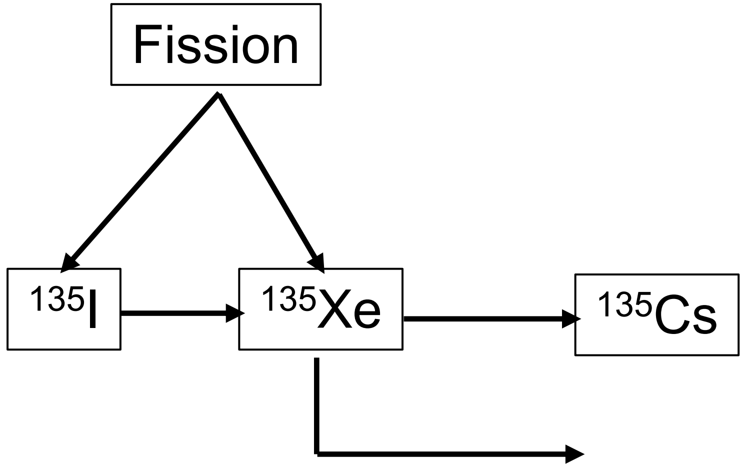
- Design based on the molten salt fast reactor (MSFR) concept initially developed at CNRS (European conceptual design)
- MSFR is a very big machine compared to other MSRs
- Very simple design:
  - Pool of molten salt with dissolved fuel
  - Molten salt flows into reactor cavity most of the power is created
  - 16 pump & heat exchanger legs around the core
  - Online reprocessing of fission products
- Fast pool-type MSRs can be designed as breeders (Th and U) or for burning transuranics
- Salt can be fluoride or chloride based
  - LiF: fluoride is chemically reactive, Li creates Tritium
  - UCl$_3$ – NaCl, Cl is a neutron absorber
- **Big R&D need: Corrosion & material compatibility!**

Where do fission products matter for reactor engineering?

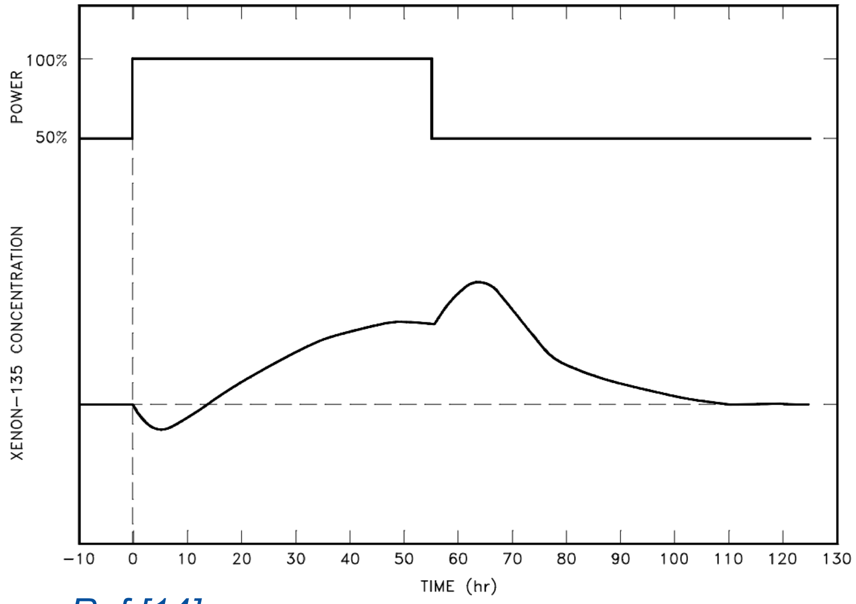
- Example 1: Reactivity effects when reactor power changes - Xenon pit
- Example 2: Fission products' chemical interaction with the clad after going into contact (fuel-cladding-chemical-interaction, FCCI)
- Example 3: Source term in TRISO fuel – diffusion of fission products through TRISO layers
- Honorable mention: **Decay heat** (important but unfortunately not enough time)

Fission Product Impact 1: Xenon pit

- Xenon-135 is a strong neutron absorber
- It is created by fission & decay from I-135
- During reactor steady-state its level remains constant
- What happens when power/flux levels change (say drop)?
  - If power drops, both direct creation and destruction reduce, but indirect reduction reduces slower
  - Initial buildup and then slump of Xe-135
  - This has significant reactivity consequences
- Xe pit occurred before Chernobyl accident and led the operator to remove all control rods
- Relevant during power changes in reactors – not important for base load but very important for load following
- Issue for all thermal reactors



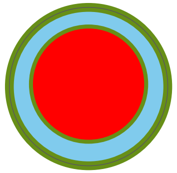
Simplified Xe decay scheme

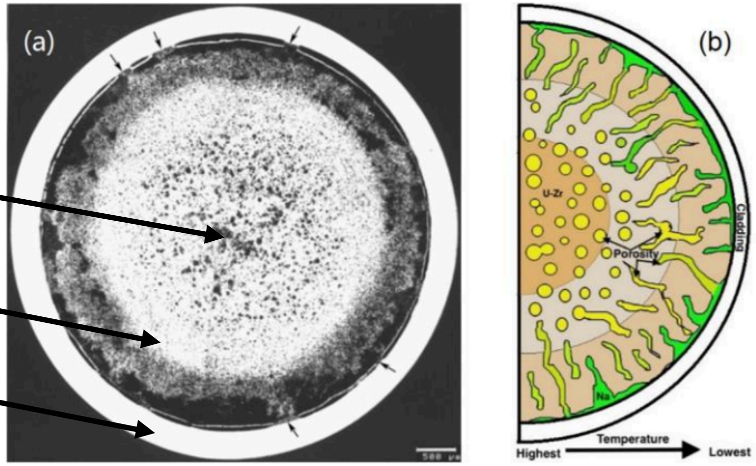


Ref [14]

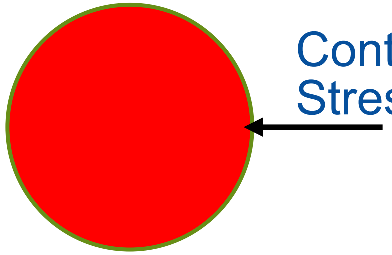
Fission Product Impact 2: Fuel-Cladding-Chemical-Interaction

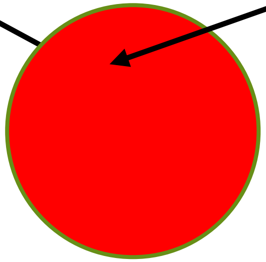
- SFR fuel: Metallic U-Fis with stainless-steel cladding & sodium bond
- Metallic fuel swells significantly under irradiation => cladding failure if fuel contacts clad before fission gas release (FCMI)
- Reduce smear density to release fission gases before cladding contact
- This creates Lanthanide fission product pathways
- Lanthanides form low melting eutectics at the pellet cladding interface => cladding failure





Ref [10]



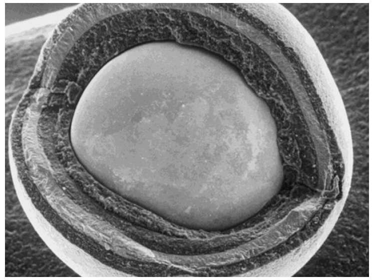


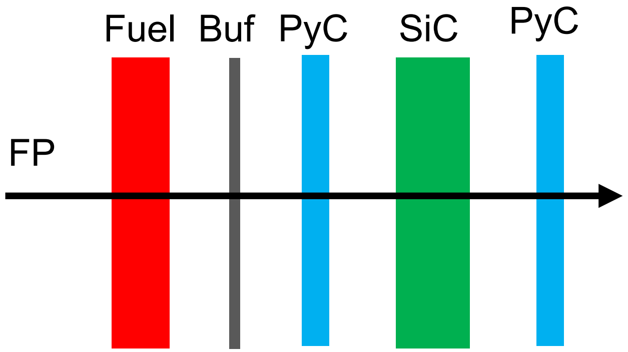
Fission Product Impact 3: TRISO Fission Product Retention

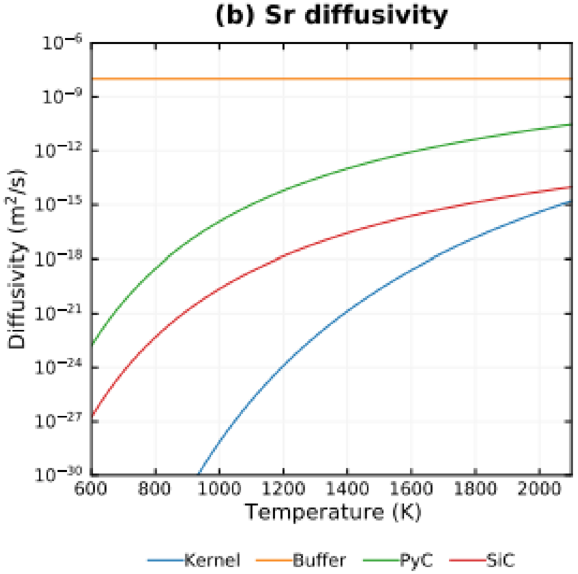
- Nuclear fuel should retain fission products from entering the coolant as much as possible
- Traditionally, fuel matrix + cladding serve that purpose
- For TRISO fuel, the TRISO layers provide that function
- Fission products: Sr-90, Ag-110, Cs-137 & 134

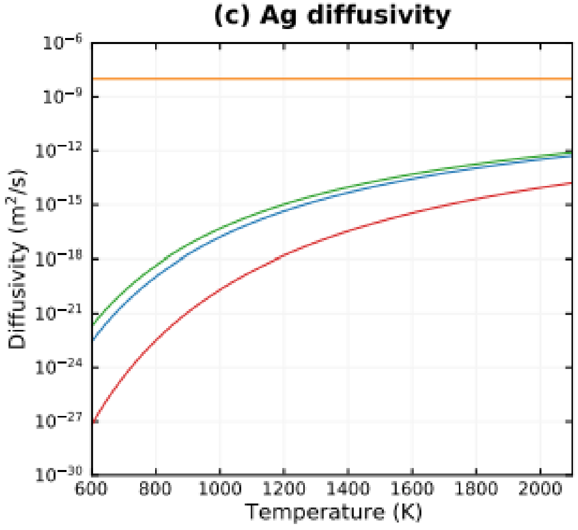
How well do TRISOs retain fission products?

- AGR-1 reported 0 TRISO failures out of 300,000 TRISOs

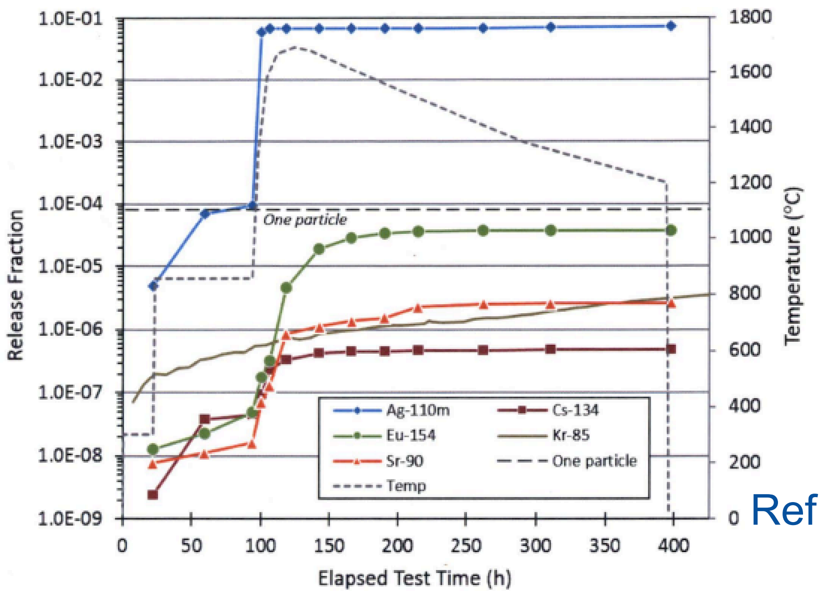








Ref [12]



Ref [11]

T>1600C!!
Large Ag release
Everything else is retained

Sr is retained by SiC & Kernel but Ag is only retained by the SiC => need to avoid SiC failure!

Summary and Conclusion

- Power reactors come in a variety of shapes and sizes because no single concept fits all needs
- A variety of fuel forms is used: ceramic, metallic, TRISO, dissolved in molten salts
- With different fuel forms come different challenges to handle fission products – think FCCI in metallic fuel & retention in TRISOs
- Some challenges stemming from fission products are common to many reactors: Xenon pit is an example for all thermal reactors
- Data needs in the future will not just require fission product yields but also uncertainties as we include uncertainties in our designs

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