



U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

Fuel Cycle Research and Development

Fuel Development for Advanced
Reactors

Jon Carmack

National Technical Director

June 8, 2016

2nd DOE-NRC Workshop on non-LWR Reactors

Bethesda, MD



INL/MIS-16-38898

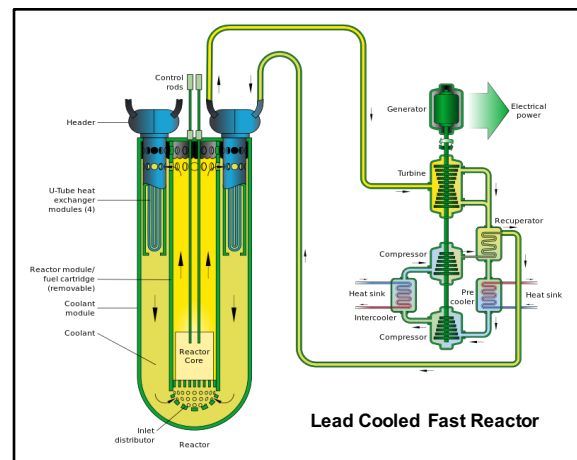
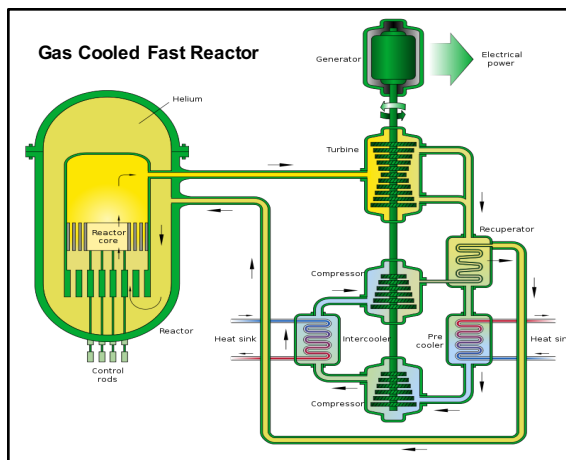
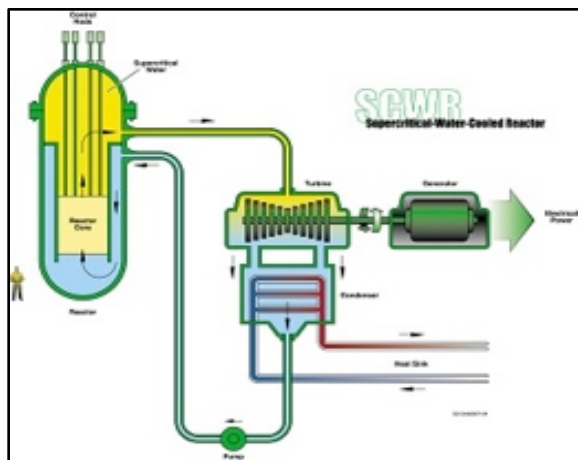
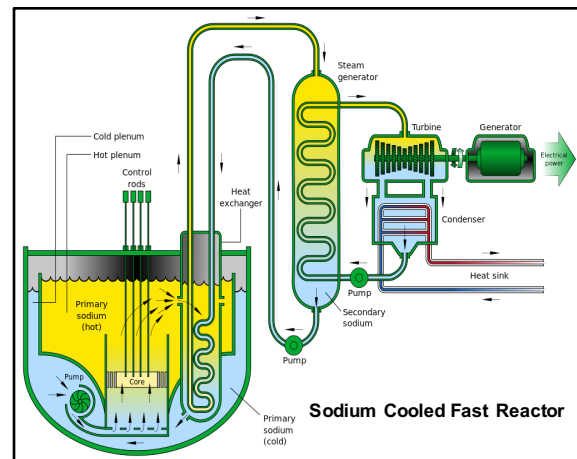
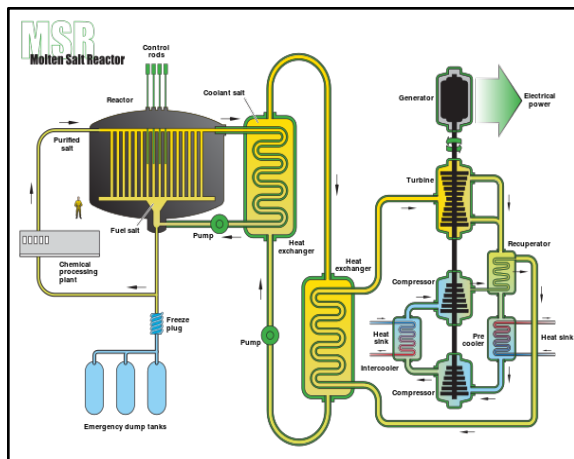
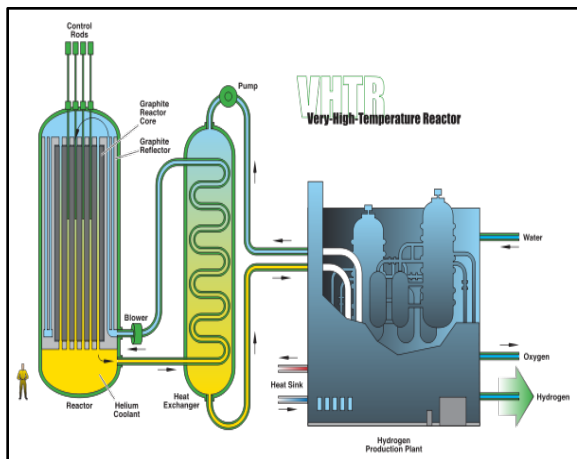


- **GENIV Reactor Review**
- **2012/2014 Response to DOE Advanced Reactor RFI**
- **Current SMR and Venture Capital Efforts**
- **Summary of Current DOE Funded Advanced Fuel R&D**



GENIV Reactor Systems

https://www.gen-4.org/gif/jcms/c_40465/generation-iv-systems





GENIV – General Features

(https://www.gen-4.org/gif/jcms/c_9353/systems)

| System | Spectrum | Coolant | Outlet T (°C) | Fuel Cycle | Likely fuel system |
|--|--------------|-------------------------|---------------|-------------|--|
| VHTR (very-high-temperature reactor) | Thermal | Helium | 900-1000 | Open | TRISO Pebble or Prismatic |
| SFR (sodium cooled fast reactor) | Fast | Sodium | 500-550 | Closed | Metallic/Oxide/Nitride/Carbide |
| SCWR (super critical water reactor) | Thermal/fast | Water | 510-625 | Open/Closed | Oxide in high temp corrosion resistant steel |
| GFR (gas-cooled fast reactor) | Fast | Helium | 850 | Closed | Carbide in dispersion or pin SiC |
| LFR (lead-cooled fast reactor) | Fast | Lead | 480-570 | Closed | Metallic/Oxide/Nitride/Carbide |
| MSR (molten salt reactor) | Thermal/Fast | Fluoride/chloride salts | 700-800 | Closed | Liquid fuel or TRISO particle |



(8)-Advanced Reactor Concepts submitted to DOE 2012 Request for Information

Advanced Reactor Concepts, Technical Review Panel Report. Evaluation and Identification of future R&D on eight Advanced Reactor Concepts, conducted April – Sept. 2012. December 2012.

- General Atomics – Energy Multiplier Module, (EM2) [\[high temperature, gas-cooled fast reactor\]](#)
- Gen4 Energy Reactor Concept [\[lead-bismuth fast reactor\]](#)
- Westinghouse Electric Company - Thorium-fueled Advanced Recycling Fast Reactor for Transuranics Minimization [\[thorium-fueled sodium-cooled fast reactor\]](#)
- Westinghouse Electric Company Thorium-fueled Reduced Moderation Boiling Water Reactor for Transuranics Minimization [\[thorium fueled BWR\]](#)
- Flibe Energy- Liquid Fluoride Thorium Reactor (LFTR) [\[thorium-fueled liquid salt reactor\]](#)
- Hybrid Power Technologies, LLC – Hybrid Nuclear Advanced Reactor Concept [\[gas-cooled reactor / natural gas turbine combination\]](#)
- GE-Hitachi Nuclear Energy PRISM and Advanced Recycling Center [\[sodium fast reactor\]](#)
- Toshiba 4S Reactor [\[sodium fast reactor\]](#)



(7) - Advanced Reactor Concepts submitted to DOE 2014 Request for Information

Advanced Reactor Concepts, Technical Review Panel Report. Evaluation and Identification of future R&D on seven Advanced Reactor Concepts, conducted March – June 2014. October 2014.

- AREVA [prismatic, high temperature, gas cooled reactor]
- Hybrid Power Technologies, LLC – Hybrid Nuclear Advanced Reactor Concept [gas cooled reactor coupled with natural gas turbine]
- Gen4 Energy Reactor Concept [lead-bismuth fast reactor]
- LakeChime SSTAR [lead-cooled fast reactor]
- General Atomics [high temperature, gas-cooled fast reactor]
- X-Energy [pebble-bed, high temperature, gas-cooled reactor]
- GE-Hitachi Nuclear Energy PRISM and Advanced Recycling Center [sodium fast reactor]



Introducing the Advanced Nuclear Industry





GENIV - FUEL DEVELOPMENT

DOE activity can be traced back to early 2000's.
Experience on some concepts dates back to the early 1950's

- **NGNP:** **TRISO Fuel (VHTR/AGR), TRU-TRISO**
- **SWR:** Standard oxide (cladding corrosion is the issue)
- **MSR:** Liquid fuel, solid core w/TRISO
- **GFR:** Dispersion, pin
- **LFR:** Nitride, metal, oxide, dispersion
- **SFR:** Metal, oxide, nitride, dispersion

- **LWR/ALWR:** ATF, TRU-MOX, IMF, UHB UO₂, Metallic

◆ No recent DOE work

◆ Current DOE

◆ Work Curtailed under GNEP in 2008



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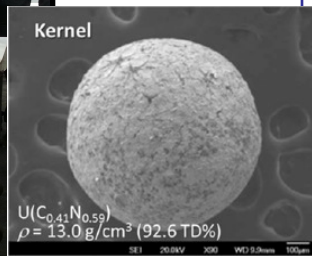
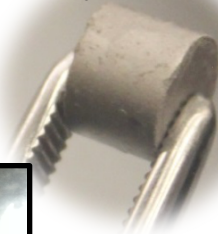
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DOE-NE advanced fuels research focuses on improved accident tolerance, high temperature operation, fuel cycle closure

High performance accident tolerant LWR fuels

- Accident tolerant
- Ceramic coated zircalloys
- Multi-layer ceramic claddings
- High density ceramics
- High thermal performance

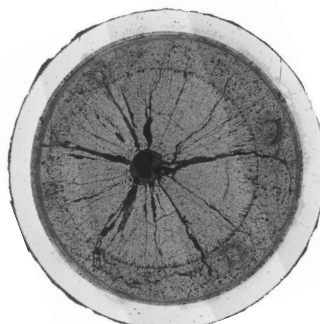
U_3Si_2 Pellet



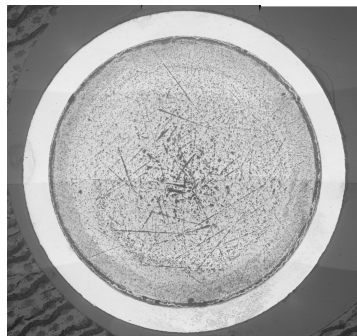
Transmutation fast reactor fuels

Actinide bearing

- Metallic
- Ceramic
- Cermets



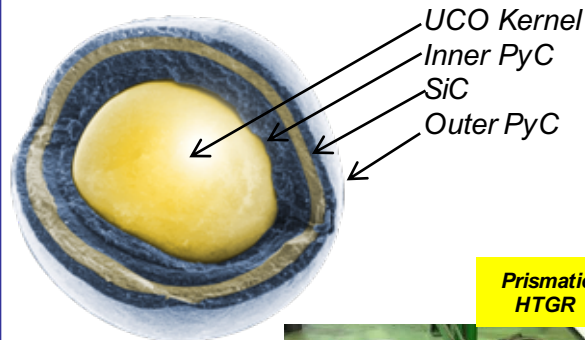
$(U_{0.75}, Pu_{0.20}, Am_{0.03}, Np_{0.02})O_{1.98}$
20.8 at% fissile burnup
($1.35E+21$ fiss/cm³)



$(U-29Pu-4Am-2Np-30Zr)$
33.2 at% fissile burnup
($3.91E+21$ fiss/cm³)

High temperature gas reactor fuels

- TRISO based fuel
- High burnup – high temperature operation (800° C) gas temperature
- Multi-layer fission production retention

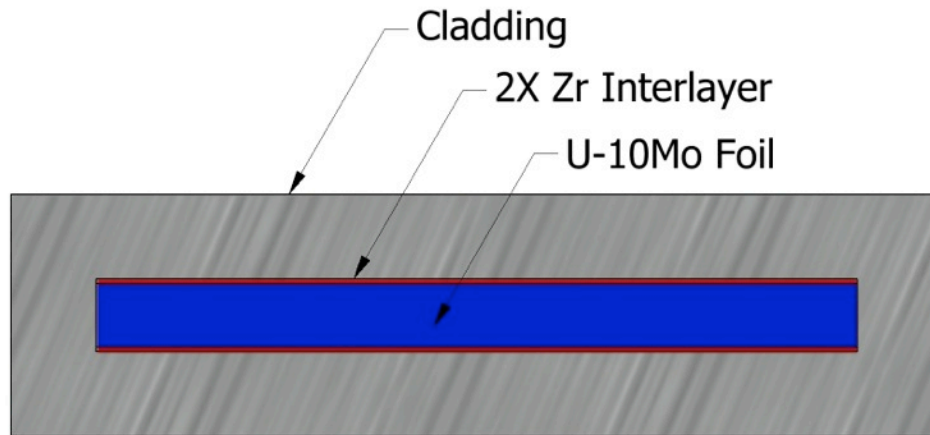


Prismatic HTGR



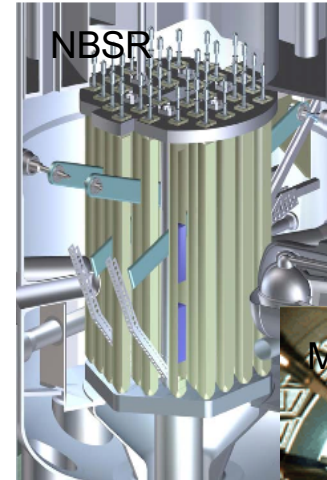


U-Mo Monolithic Fuel



U-Mo Monolithic Base Fuel Design

- Single 'base' fuel type that meets requirements for 4 U.S. High Performance Research Reactors and 1 critical facility (ATR-C)
- Application to HFIR requires additional fabrication development



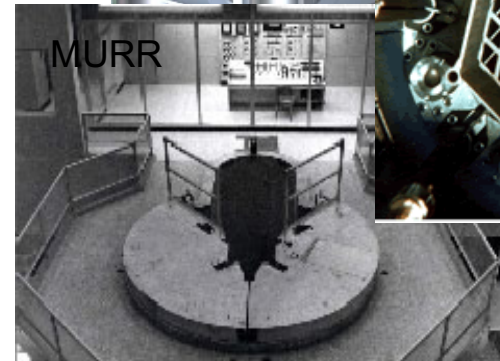
NBSR



HFIR



MITR



MURR

ATR

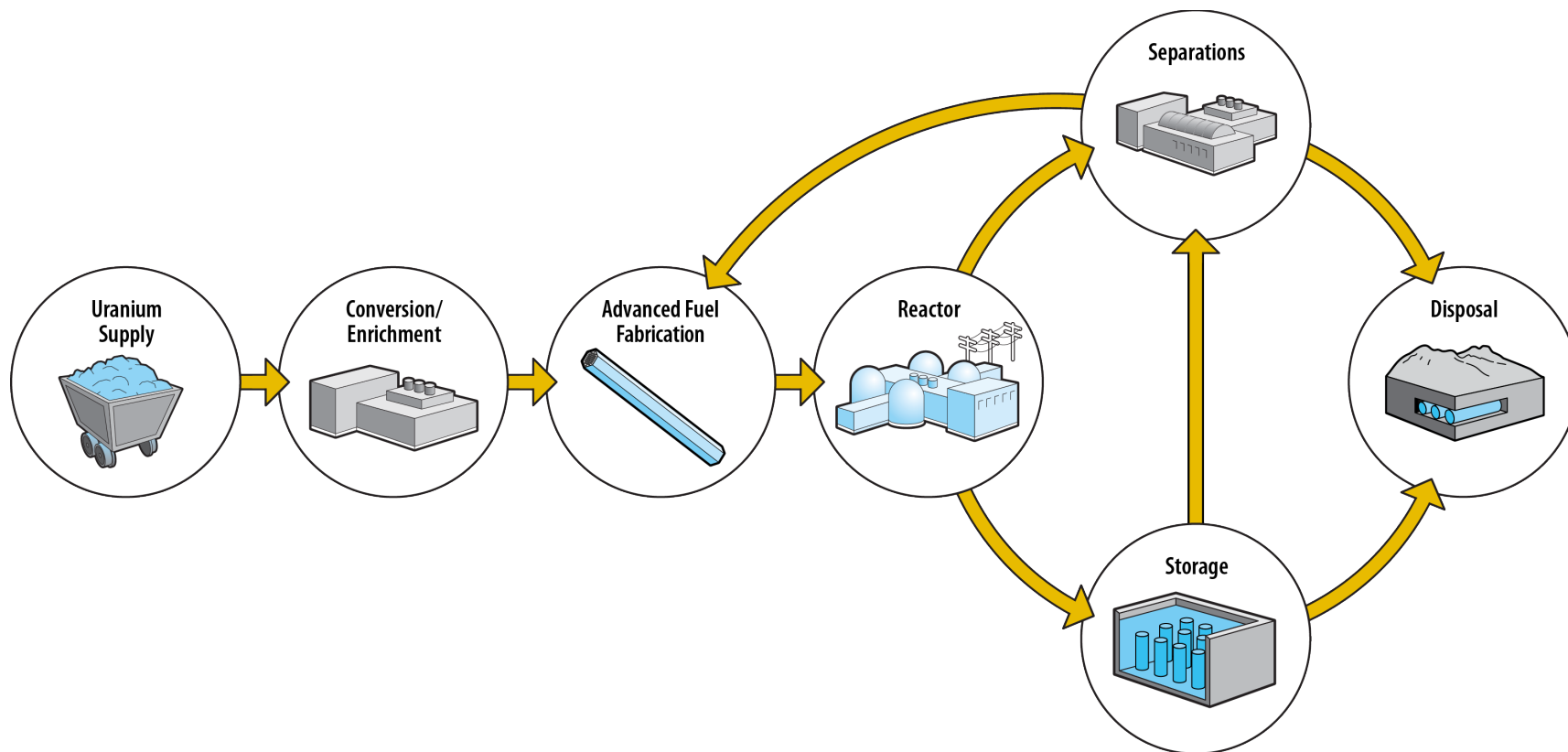




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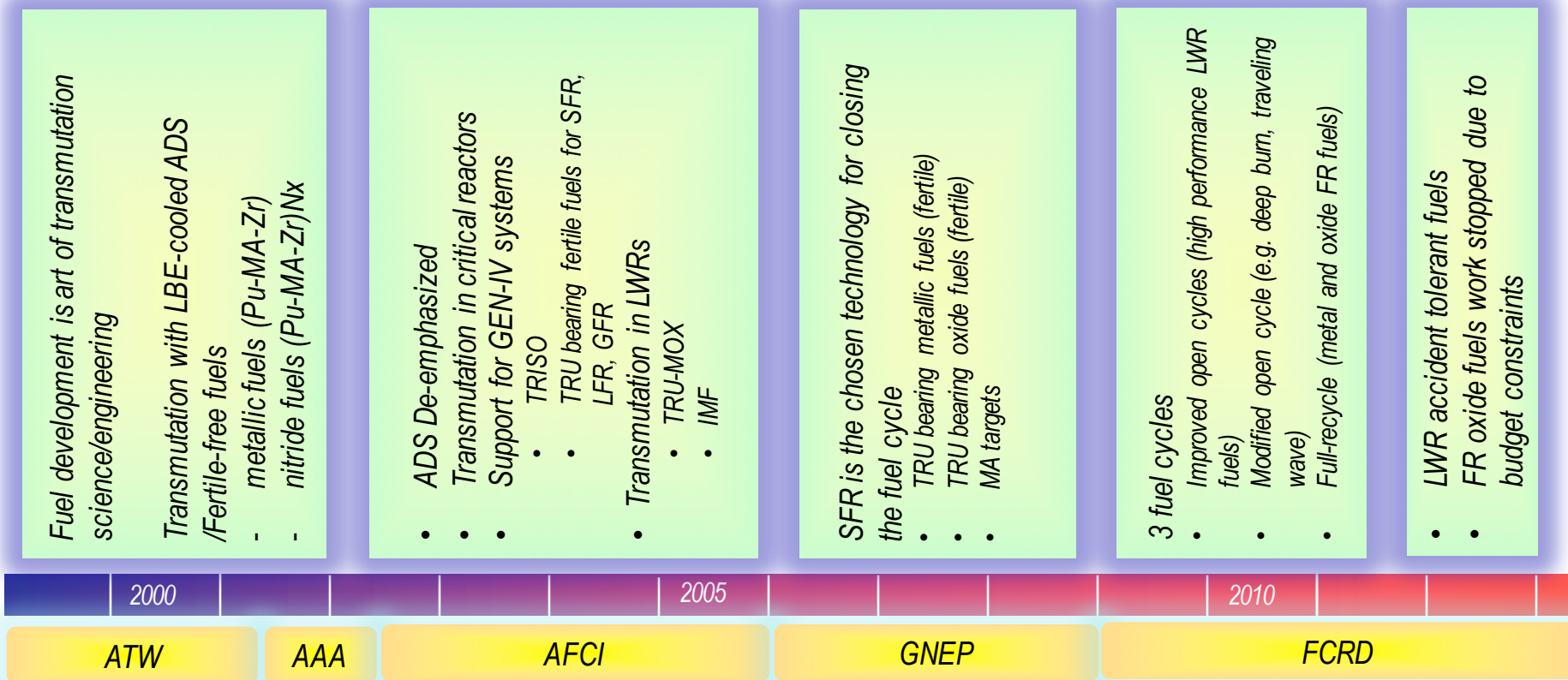
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Fuel Cycle as a System: Towards a closed fuel cycle





Over the last 16 years, DOE advanced fuels campaign has gone through multiple changes in name and scope



▲ ATW Roadmap

▲ Fuels campaign established – separate from transmutation engineering

▲ Basic TRISO fuel development moved to NGNP

DOE-NE Roadmap

Goal-oriented science based approach defined for fuel development

FUKUSHIMA accident happened



Base SFR/LFR Fuel Technology: US Experience

Crawford, Porter, Hayes, Journal of Nuclear Materials, 371: 202-231 (2007).

| | Metallic | Mixed Oxide | Mixed Carbide |
|--|--|--|---|
| Driver Fuel Operation | ≥ 120,000 U-Fs rods in 304LSS/316SS 1-8 at.% bu ~13,000 U-Zr rods in 316SS 10 at.% bu | >48,000 MOX rods in 316SS (Series I&II) 8 at.% bu; | None applicable |
| Through Qualification | U-Zr in 316SS, D9, HT9 ≥ 10at.% bu in EBR-II & FFTF | MOX in HT9 to 15-20 at.% bu (CDE) MOX in 316SS to 10 at.% bu | None applicable |
| Burnup Capability & Experiments | 600 U-Pu-Zr rods; D9 & HT9 to > 10 - 19 at.% in EBR-II & FFTF | 4300 MOX rods in 316SS to 10 at.%; fab var' s; CL melt 3000 MOX rods in EBR-II; peak at 17.5at.% bu 2377 MOX rods in D9 to 10-12 at.% bu; some at 19 at.% bu | 18 EBR-II tests with 472 rods in 316SS cladding; 10 rods up to 20 at.% w/o breach 5 of which experienced 15% TOP at 12 at.% 219 rods in FFTF, incl 91 in D9, 91 with pellet & sphere-pac fuel |
| Safety & Operability | 6 RBCB tests U-Fs & U-Pu-Zr/U-Zr(5) 6 TREAT tests U-Fs in 316SS (9rods) & U-Zr/U-Pu-Zr in D9/HT9 (6 rods) | 18 RBCB tests; 30 breached rods 4 slow ramp tests 9 TREAT tests MOX in 316SS (14 rods) & HT9 (5 rods) | 10 TREAT tests (10 rods; Na or He bond); ≤ 3-6 times TOP margins to breach Loss-of-Na bond test; RBCB for 100 EFPD; Centerline melting test |



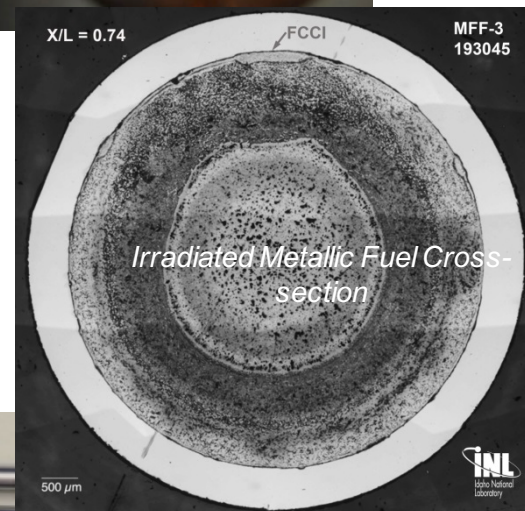
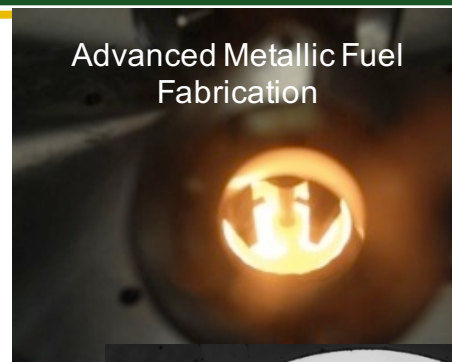
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Adv. Reactor Fuel Technology Development for Actinide Management

Focus Priority on Metallic Fuels

- *Advanced fabrication techniques*
- *Characterization of material properties of minor actinide bearing fuels*
- *Irradiation behavior of actinide bearing fuel compositions*
- *Development of advanced claddings having high burnup capability*



MSR Fuels: Liquid Fluoride/Chloride Salt or TRISO fueled solid core

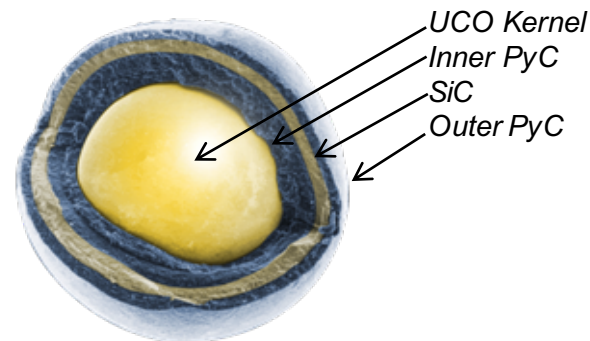
Reference: R.J.M. Konings ed. Comprehensive Nuclear Materials, Vol 5: Material Performance and Corrosion/Waste Materials. Elsevier. 2012. pp. 221-250.

Liquid salt fuel options are varied and can include U, Pu, and TRU

Table 2 Molar compositions, melting temperatures (°C),²⁷ and solubility of plutonium trifluoride (mol%) at 600 °C in different molten fluoride salts considered as candidates for the fuel and the coolant circuits in MSR concepts

| Alkali-metal fluorides | ZrF ₄ -containing | BeF ₂ containing | ThF ₄ containing | Fluoroborates |
|---|--|---|---|--|
| LiF-PuF ₃ (80–20) 743 °C ²⁸ | | | | |
| LiF-KF (50–50) 492 °C | LiF-ZrF ₄ (51–49) 509 °C | LiF-BeF ₂ (73–27) 530 °C | LiF-ThF ₄ (78–22) 565 °C | KF-KBF ₄ (25–75) 460 °C |
| – | – | 2.0 ³² | 4.2 ²⁹ | – |
| LiF-RbF (44–56) 470 °C | NaF-ZrF ₄ (59.5–40.5) 500 °C | LiF-NaF-BeF ₂ (15–58–27) 479 °C | LiF-BeF ₂ -ThF ₄ (75–5–20) 560 °C | RbF-RbBF ₄ (31–69) 442 °C |
| – | 1.8 ³¹ | 2.0 ^{32,33} | 3.1 ²⁹ | – |
| LiF-NaF-KF (46.5–11.5–42) 454 °C | LiF-NaF-ZrF ₄ (42–29–29) 460 °C | LiF-BeF ₂ (66–34) 458 °C | LiF-BeF ₂ -ThF ₄ (71–16–13) 499 °C | NaF-NaBF ₄ (8–92) 384 °C |
| 19.3 ⁵ | – | 0.5 ^{32,33} | 1.5 ³⁰ | – |
| LiF-NaF-RbF (42–6–52) 435 °C | LiF-NaF-ZrF ₄ (26–37–37) 436 °C | LiF-BeF ₂ -ZrF ₄ (64.5–30.5–5) 428 °C | LiF-BeF ₂ -ThF ₄ (64–20–16) 460 °C | |
| – | – | – | 1.2 ²⁹ | |
| | NaF-RbF-ZrF ₄ (33–24–43) 420 °C | NaF-BeF ₂ (57–43) 340 °C | LiF-BeF ₂ -ThF ₄ (47–51.5–1.5) 360 °C | |
| | – | 0.3 ³² | – | |
| | NaF-KF-ZF ₄ (10–48–42) 385 °C | LiF-NaF-BeF ₂ (31–31–38) 315 °C | | |
| | – | 0.4 ³² | | |
| | KF-ZrF ₄ (58–42) 390 °C | | | |

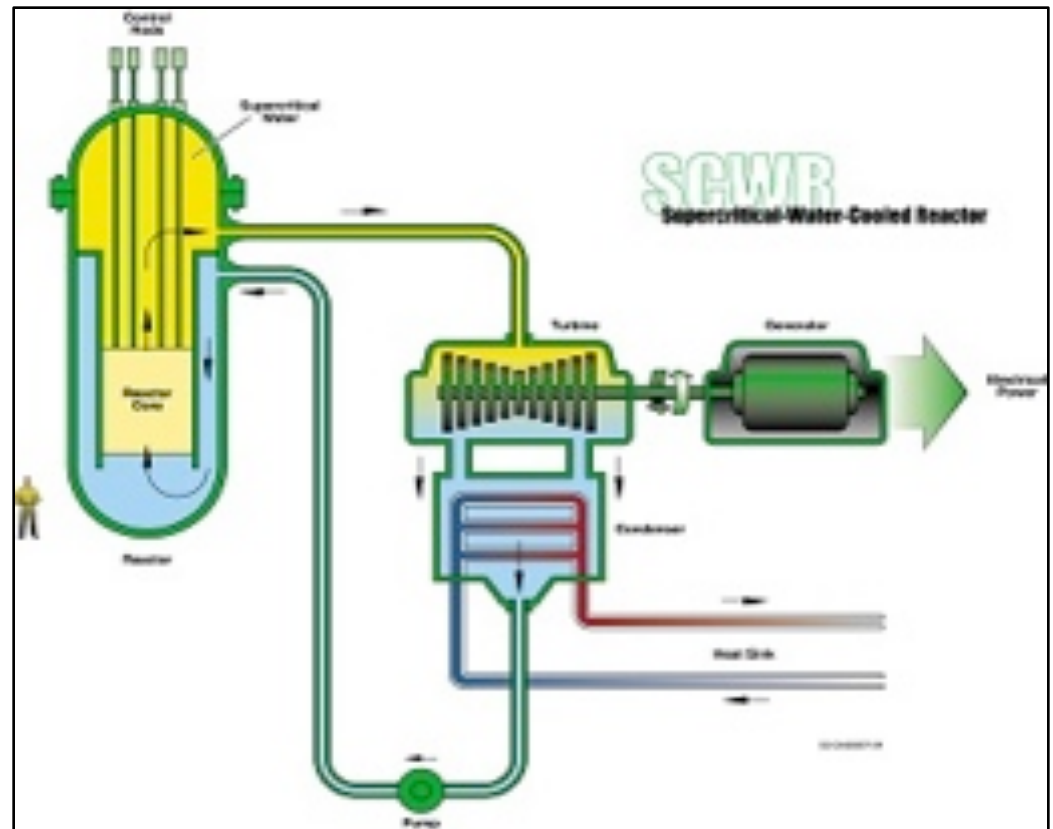
Solid fuel options typically based on TRISO technology



SCWR Fuels

UO₂ pellet in Corrosion Resistant Steel

- Fuel: UO₂ (ThO₂)
- Cladding material
 - Inconel or Stainless steel
- Coolant: Water



GFR Fuel Options

Carbide in SiC pin or dispersion matrix

Rouault and Wei. The GENIV Gas Cooled Fast Reactor: Status of Studies. Presentation.
Feb 2005.

GFR Fuel Requirements

■ High heavy metal density

- High coolant volume fraction in core
- Limit on Pu content
 - Non-proliferation (artificial)
 - Conversion ratio ≈ 1

■ High temperature capability

- 900° -1200°C – peak cladding temperature during normal operation
- 1600°C – minimal fission product release
- 2000°C – no core disruption

■ Low parasitic absorption

- Rules out refractory metal-based cermets

■ Amenable to recycle

■ High burnup potential (?)

- Current target 5%

FIGURE 1: FUEL CONCEPTS FOR GFR

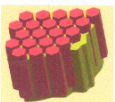
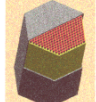
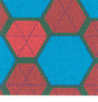
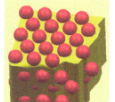

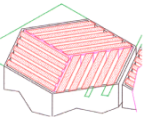
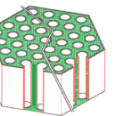
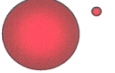
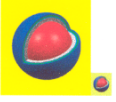
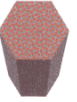
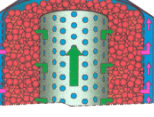
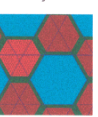


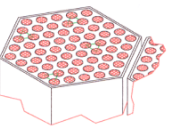
| | Fuel | Fuel element | Sub-assembly |
|--------------------|--|--|---|
| 1- DISPERSION FUEL | Cylindrical or Hexagonal sticks  | Coated compact  | Pseudo-hexagonal sub-assembly with compact stack  |
| | Spheres / particles  | Coated plates  | Sub-assembly with plates  Prismatic block type with coated channels  |
| 2- PARTICLES | 2 sized particles  | Particles coated with x layers  T/D=0,12 Compact with coated particles  | Particles bed  Sub-assembly with compact stack  |
| | pellets  | Pin  | Hexagonal sub-assembly with grid  |
| 3- SOLID SOLUTION | | | |

Plate and Block

Particle Bed

Pin

Thorium: DOE and the U.S. have experience and history but no recent experimental activity

Performance: ThO_2 is a robust material that has similar performance to UO_2 but Th is a breeding isotope with U-233 as the fissile component. Still need for initial supporting enrichment.

Proliferation Th-Based Fuels can significantly reduce total Pu production. HOWEVER, U-233 may be of proliferation concern and concepts with U-238 denaturing may be proposed.

Waste Th-Based Fuels are chemically more stable, and have higher radiation resistance than UOX ☹️ higher burnup potential; attractive option for once-through cycle (reduced production of transuranics can benefit repository performance; more durable and stable waste form, reduced waste per GWe, etc.)

Reactor/Fuel Systems Proposing Thorium:

Molten Salt

Lead Fast

BWR

Sodium Fast

GCFR

VHTR

LWR

Although the U.S. has a large Thorium resource the large infrastructure and supply of Uranium makes Thorium a low priority for DOE R&D.

Designing a sustainable system that takes full advantage of Thorium is challenging:

Generally requires driver/blanket

May require reduced power density

Pa-233 production complicates U-233 utilization in MSR.

Most GENIV fuels rank at TRL 4 or less at this time (Significant scale up needed for TRL 5 and 6 and transient testing needed for TRL 7

| TRL Function | | Definition | |
|--------------|----------------------|--|--|
| 1 | Proof-of-Concept | A new concept is proposed. Technical options for the concept are identified and relevant literature data reviewed. Criteria developed. | LWR Accident Tolerant Fuels |
| 2 | | Technical options are ranked. Performance range and fabrication process parametric ranges defined based on analyses. | |
| 3 | | Concepts are verified through laboratory-scale experiments and characterization. Fabrication process verified using surrogates. | |
| 4 | Proof-of-Principle | Fabrication of samples using stockpile materials at bench-scale irradiation testing of small-samples (rodlets) in relevant environment. Design parameters and features established. Basic properties compiled. | Transmutation Fuel TRU-metal, TRU-oxide (roughly same TRL) Metal experience: mostly U.S. Oxide experience: mostly international (France and Japan) |
| 5 | | Fabrication of pins using prototypic feedstock materials at laboratory-scale. Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified. Fuel behavior models developed for use in fuel performance code(s). | |
| 6 | | Fabrication of pins using prototypic feedstock materials at laboratory-scale and using prototypic fabrication processes. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Predictive fuel performance code(s) and safety basis establishment. | |
| 7 | Proof-of-Performance | Fabrication of test assemblies using prototypic feedstock materials at engineering-scale and using prototypic fabrication processes. Assembly-scale irradiation testing in prototypic environment. Predictive fuel performance code(s) validated. Safety basis established for full-core operations. | Fast Reactor Metallic (U-Zr), Oxide (U,Pu) • Licensed for reactor operations • Successful mission operations • Operational database wider for MOX, especially considering international experience |
| 8 | | Fabrication of a few core-loads of fuel and operation of a prototype reactor with such fuel. | |
| 9 | | Routine commercial-scale operations. Multiple reactors operating. | LWR UO ₂ -Zr Fuels |

Thank you



<https://nuclearfuel.inl.gov>