Fuel Cycle Research and Development

Fuel Development for Advanced Reactors

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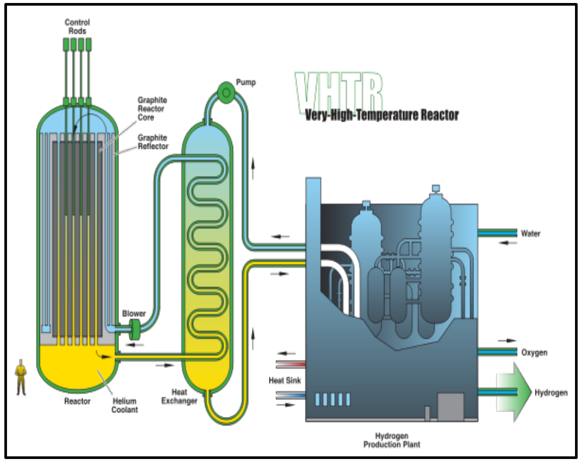
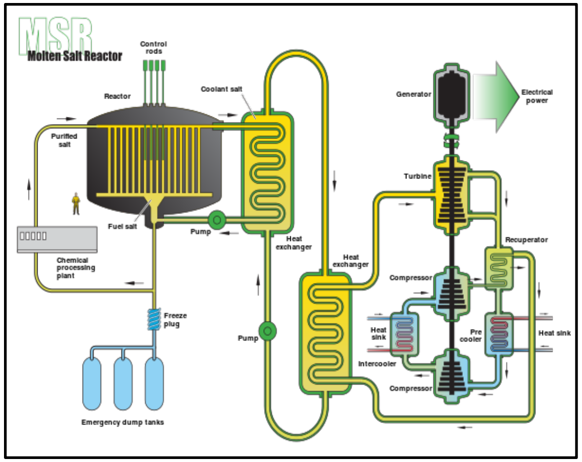
Contents

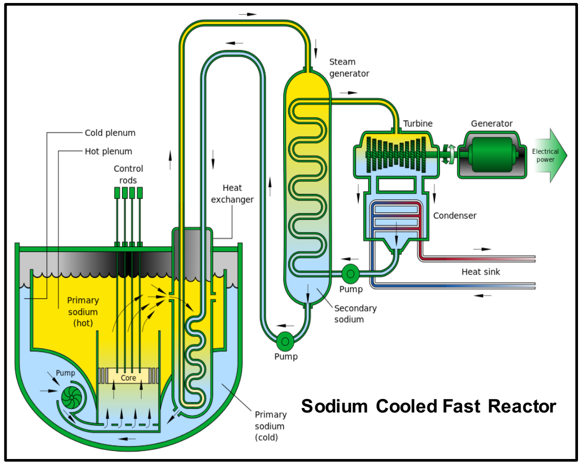
- GENIV Reactor Review
- 2012/2014 Response to DOE Advanced Reactor RFI
- Current SMR and Venture Capital Efforts
- Summary of Current DOE Funded Advanced Fuel R&D

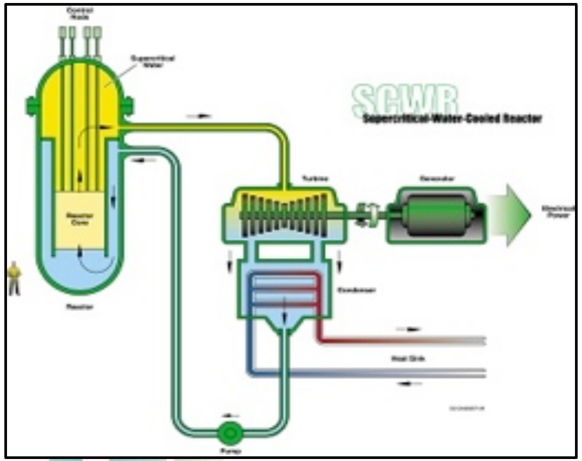
GENIV Reactor Systems

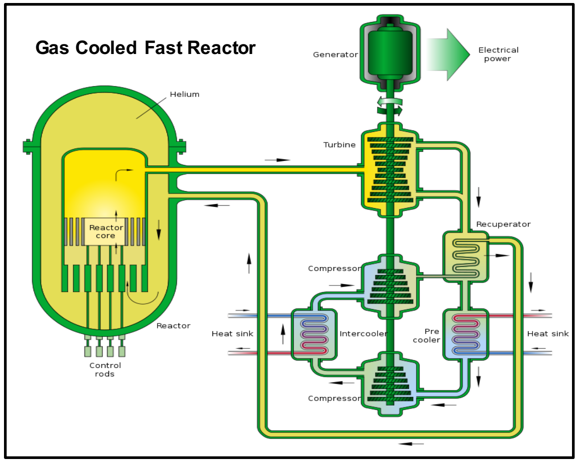
https://www.gen-4.org/gif/jcms/c_40465/generation-iv-systems

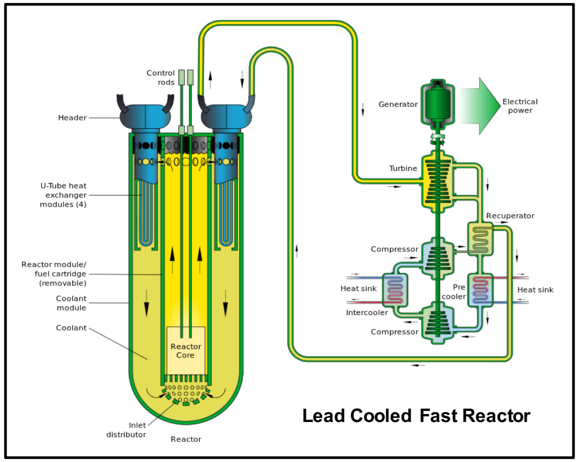












GENIV – General Features

(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

U.S. DEPARTMENT OF
ENERGY

Nuclear Energy

(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

Reactor Design Types

- ● Molten Salt Reactor
- ● Fluoride Salt-cooled High Temperature Reactor
- ● Liquid Metal-cooled Fast Reactor
- ● High Temperature Gas Reactor
- ● Pebble Bed Reactor
- ● Nuclear Battery Reactor
- ● Designs Advanced Nuclear Fuels
- ● Small Modular Reactor
- ● Fusion Reactor
- ● Super-Critical CO_2 Reactor

third way
fresh thinking

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 UO_2, Metallic

◆ *No recent DOE work*

◆ *Current DOE*

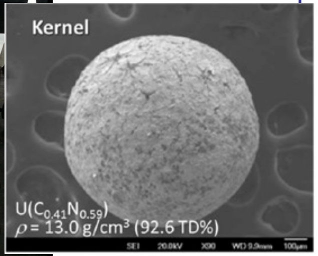
◆ *Work Curtailed under GNEP in 2008*

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 zircaloys*
- *Multi-layer ceramic claddings*
- *High density ceramics*
- *High thermal performance*

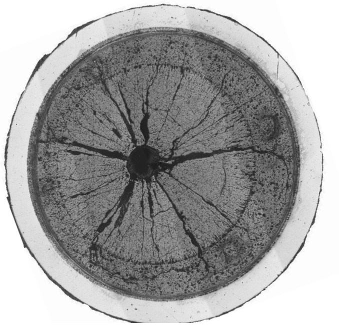
U_3Si_2 Pellet



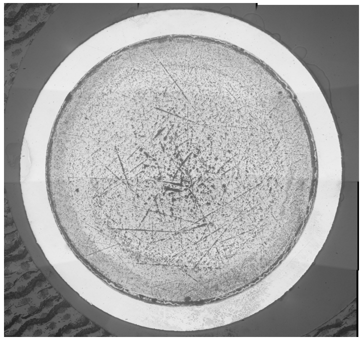
Transmutation fast reactor fuels

Actinide bearing

- *Metallic*
- *Ceramic*
- *Cermets*



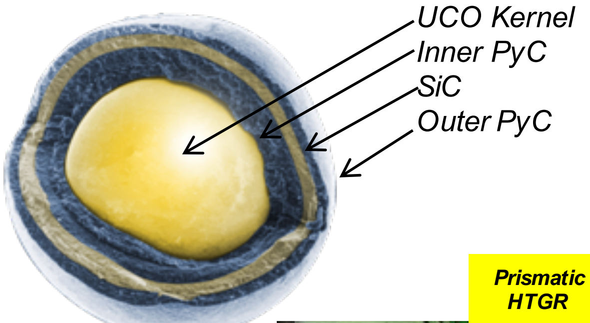
$(U_{0.75},Pu_{0.20},Am_{0.03},Np_{0.02})O_{1.98}$
20.8 at% fissile burnup
($1.35E+21$ fiss/cm^3)



(U-$29Pu$-$4Am$-$2Np$-$30Zr$)
33.2 at% fissile burnup
($3.91E+21$ fiss/cm^3)

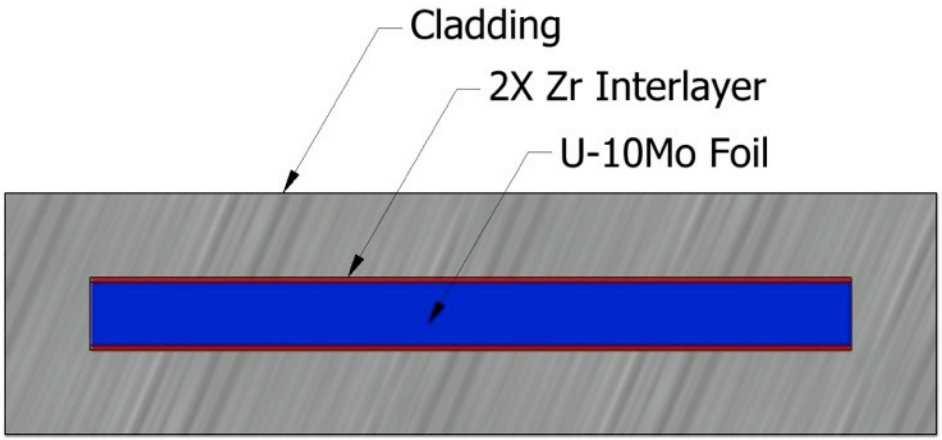
High temperature gas reactor fuels

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



Prismatic HTGR

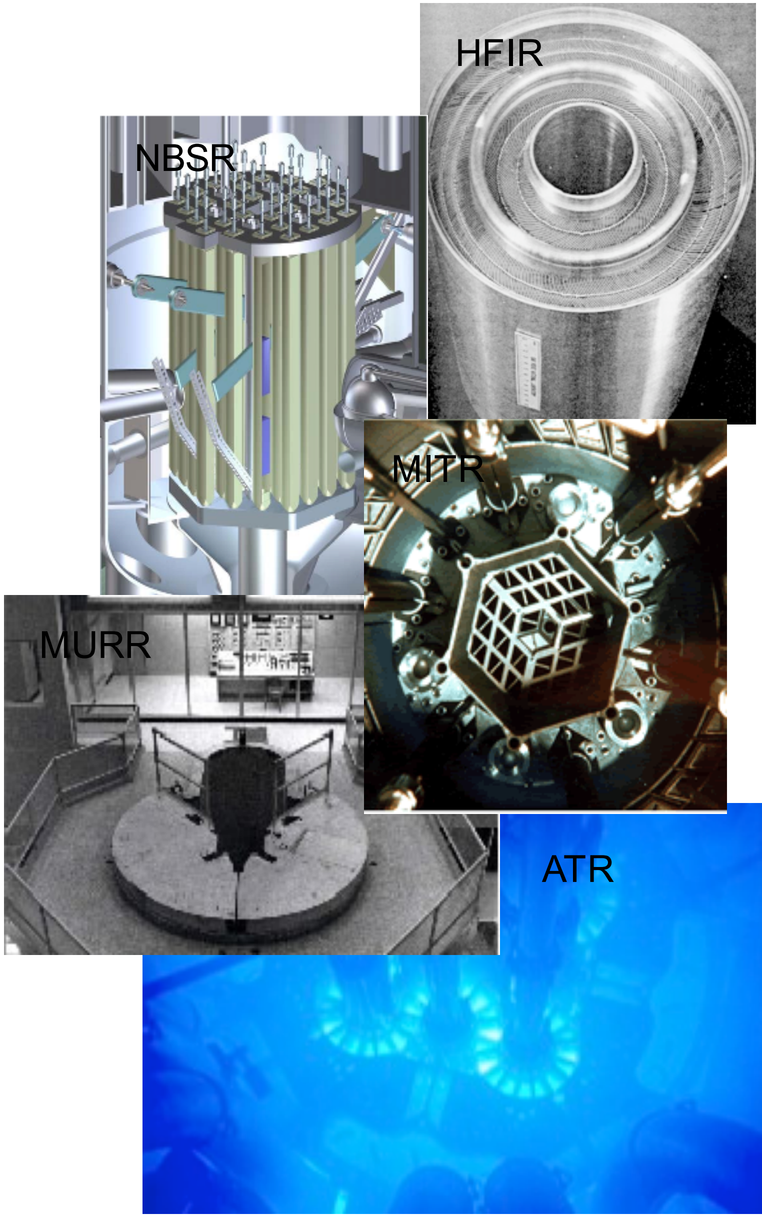
U-Mo Monolithic Fuel



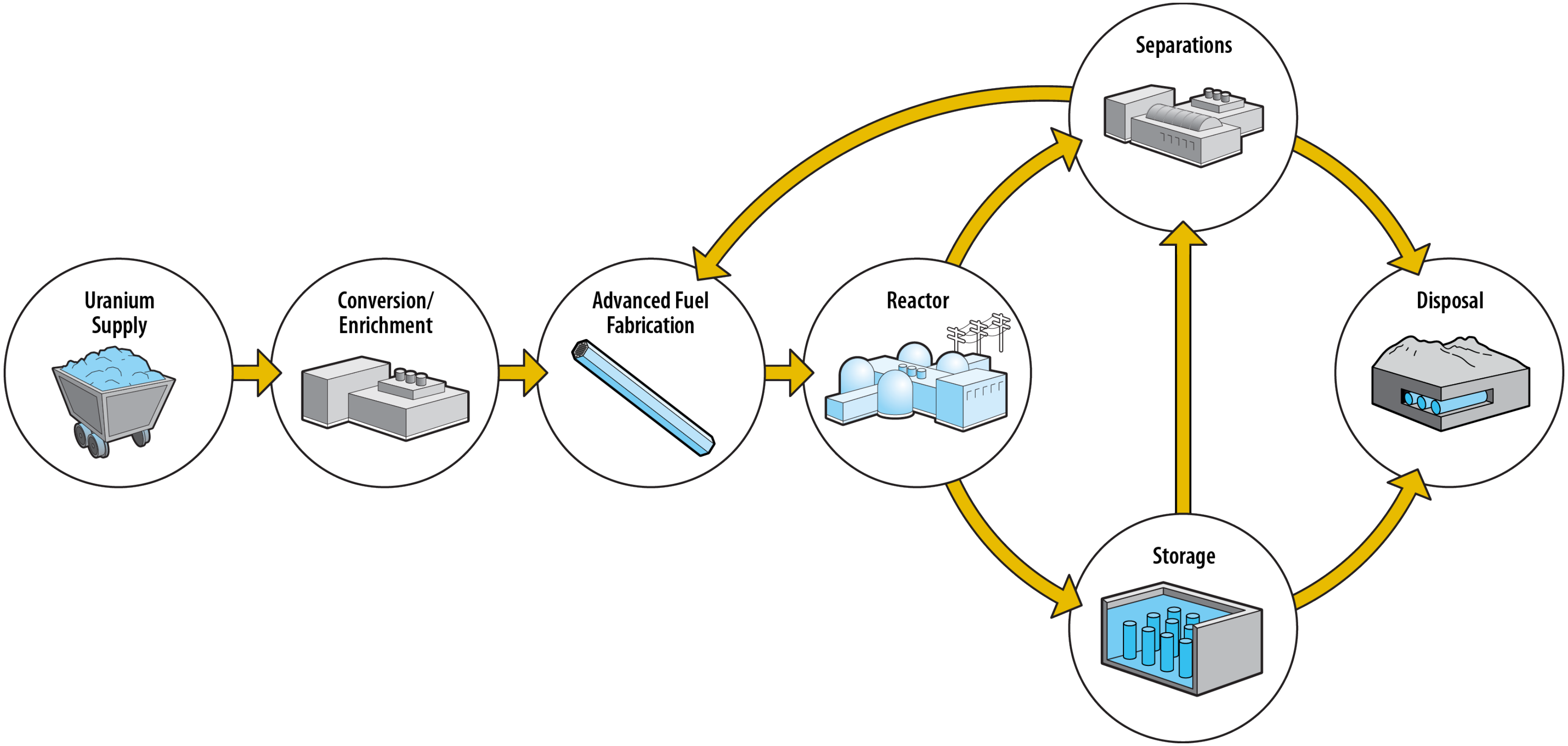
U-Mo Monolithic Base Fuel Design

- Single ‘base’ fuel type that meets requirements for 4 U.S. High Performance Research Reactors and 1 critical facility (ATR-C)

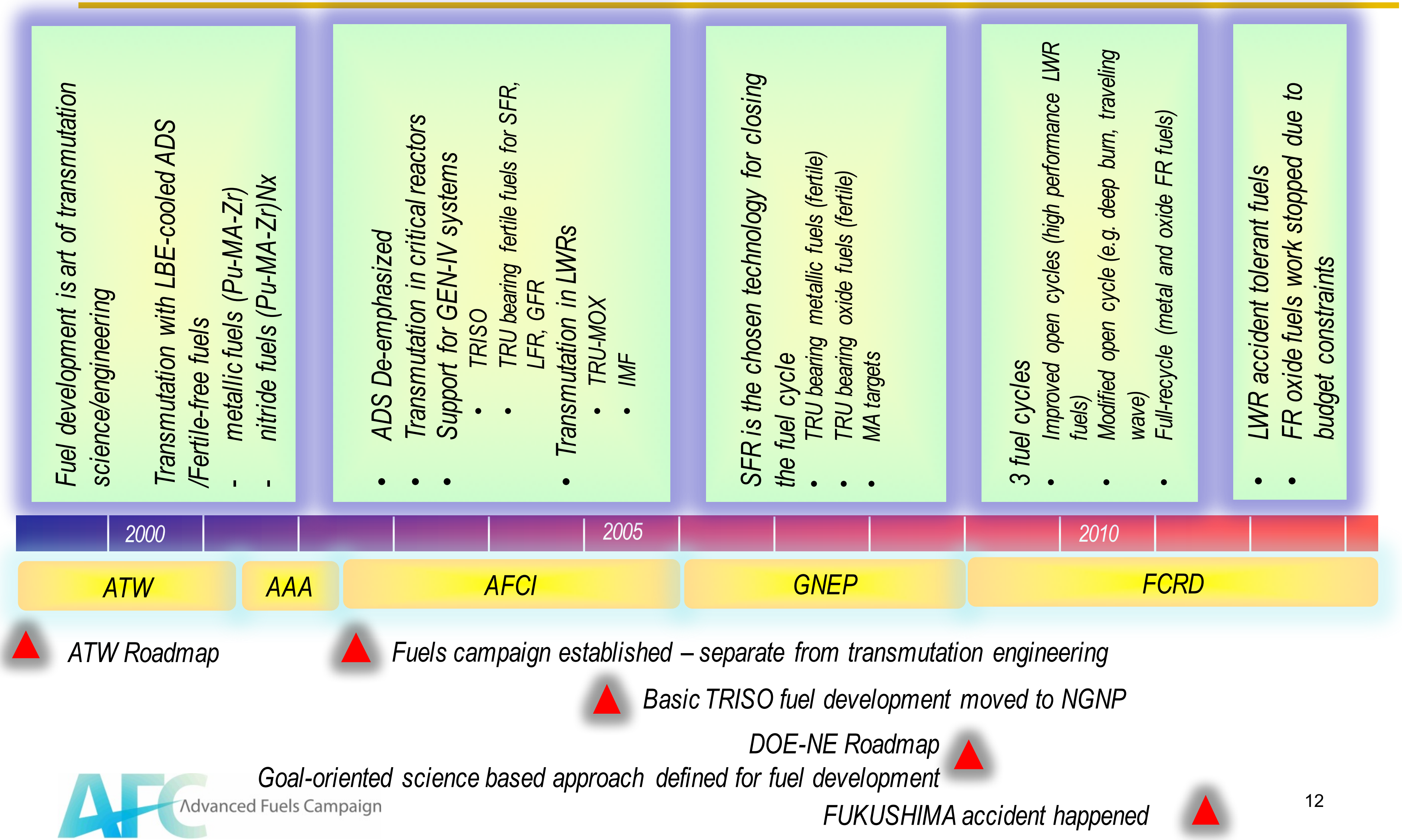
- Application to HFIR requires additional fabrication development



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



- *Fuel development is art of transmutation science/engineering*
- *Transmutation with LBE-cooled ADS /Fertile-free fuels*
  - *metallic fuels (Pu-MA-Zr)*
  - *nitride fuels (Pu-MA-Zr)Nx*

- *ADS De-emphasized*
- *Transmutation in critical reactors*
- *Support for GEN-IV systems*
  - *TRISO*
  - *TRU bearing fertile fuels for SFR, LFR, GFR*
- *Transmutation in LWRs*
  - *TRU-MOX*
  - *IMF*

- *SFR is the chosen technology for closing the fuel cycle*
  - *TRU bearing metallic fuels (fertile)*
  - *TRU bearing oxide fuels (fertile)*
  - *MA targets*

- *3 fuel cycles*
  - *Improved open cycles (high performance LWR fuels)*
  - *Modified open cycle (e.g. deep burn, traveling wave)*
  - *Full-recycle (metal and oxide FR fuels)*

- *LWR accident tolerant fuels*
- *FR oxide fuels work stopped due to budget constraints*

▲ *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

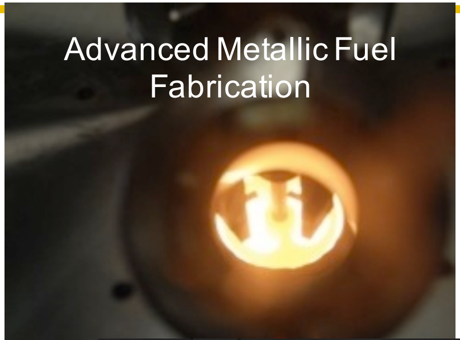
Crawford, Porter, Hayes, **Journal of Nuclear Materials**, **371**: 202-231 (2007).

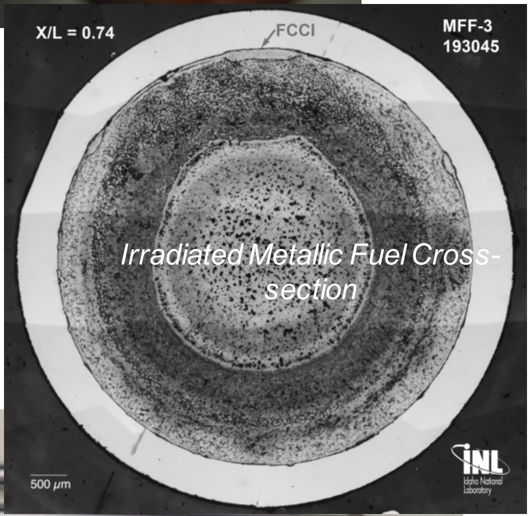
	Metallic	Mixed Oxide	Mixed Carbide
Driver Fuel Operation	≥ 120,000 U-Fs rods in 304LSS/316SS 1-8 at.% bu ~13,000 U-Zr rods in 316SS 10 at.% bu	>48,000 MOX rods in 316SS (Series I&II) 8 at.% bu;	None applicable
Through Qualification	U-Zr in 316SS, D9, HT9 ≥ 10at.% bu in EBR-II & FFTF	MOX in HT9 to 15-20 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

Adv. Reactor Fuel Technology Development for Actinide Management

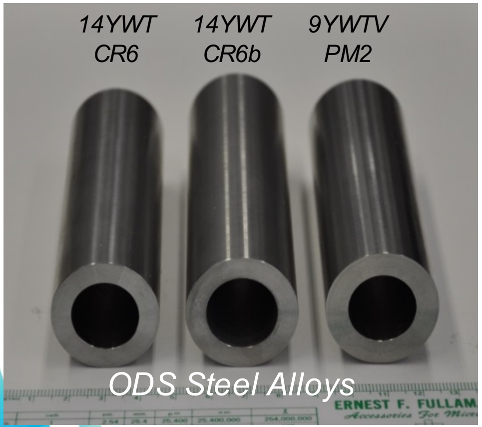
Focus Priority on Metallic Fuels

- ***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***


Advanced Metallic Fuel Fabrication



Irradiated Metallic Fuel Cross-section



ODS Steel Alloys

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

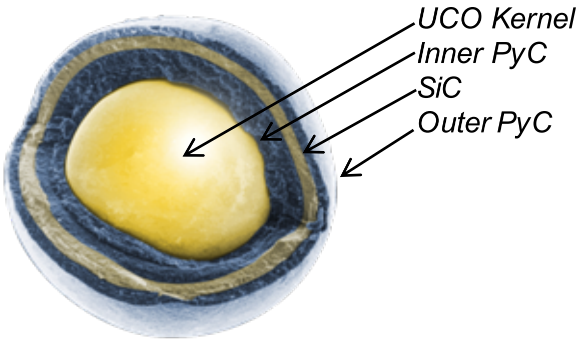
Reference: R.J.M. Konings ed. Comprehensive Nuclear Materials, Vol 5: Material Performance and Corrosion/Waste Materials. Elsevier. 2012. pp. 221-250.

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

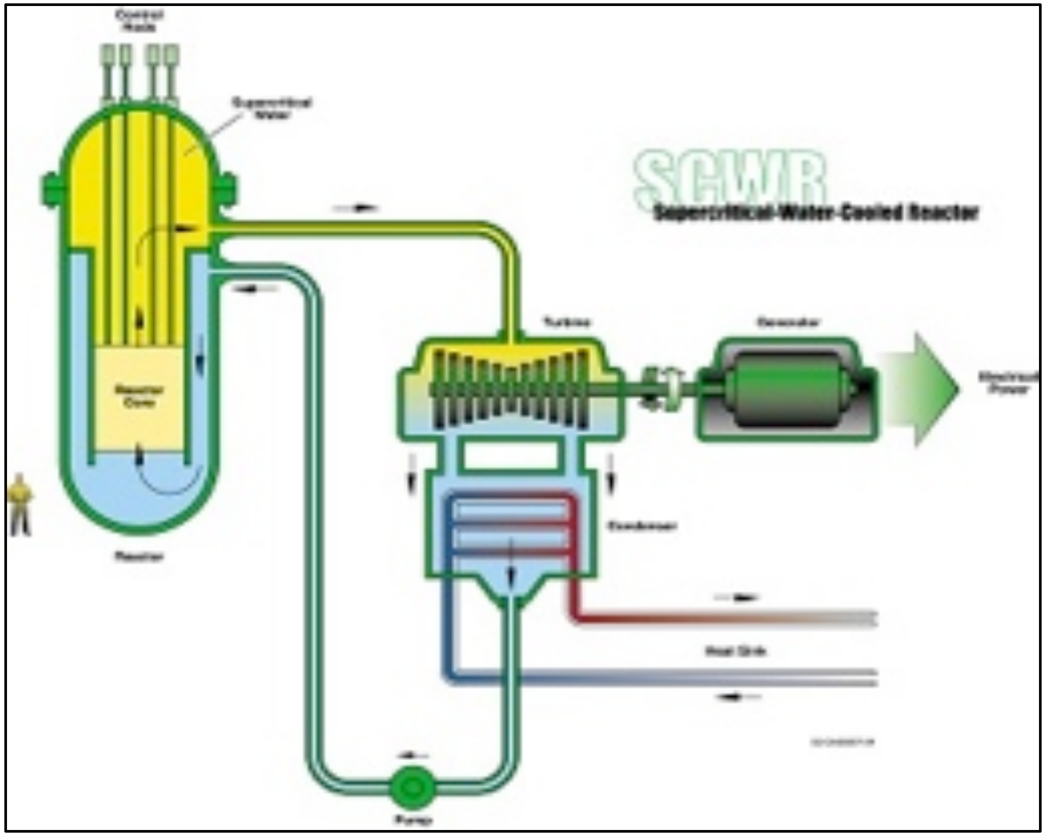
Alkali-metal fluorides	*ZrF_4-containing*	*BeF_2 containing*	*ThF_4 containing*	*Fluoroborates*
$LiF–PuF_3$ (80–20) 743 °C[28]				
LiF–KF (50–50) 492 °C –	$LiF–ZrF_4$ (51–49) 509 °C –	$LiF–BeF_2$ (73–27) 530 °C 2.0[32]	$LiF–ThF_4$ (78–22) 565 °C 4.2[29]	$KF–KBF_4$ (25–75) 460 °C –
LiF–RbF (44–56) 470 °C –	$NaF–ZrF_4$ (59.5–40.5) 500 °C 1.8[31]	$LiF–NaF–BeF_2$ (15–58–27) 479 °C 2.0[32,33]	$LiF–BeF_2–ThF_4$ (75–5–20) 560 °C 3.1[29]	$RbF–RbBF_4$ (31–69) 442 °C –
LiF–NaF–KF (46.5–11.5–42) 454 °C 19.3[5]	$LiF–NaF–ZrF_4$ (42–29–29) 460 °C –	$LiF–BeF_2$ (66–34) 458 °C 0.5[32,33]	$LiF–BeF_2–ThF_4$ (71–16–13) 499 °C 1.5[30]	$NaF–NaBF_4$ (8–92) 384 °C –
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 0.3[32]	$LiF–BeF_2–ThF_4$ (47–51.5–1.5) 360 °C –	
	$NaF–KF–ZF_4$ (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%*

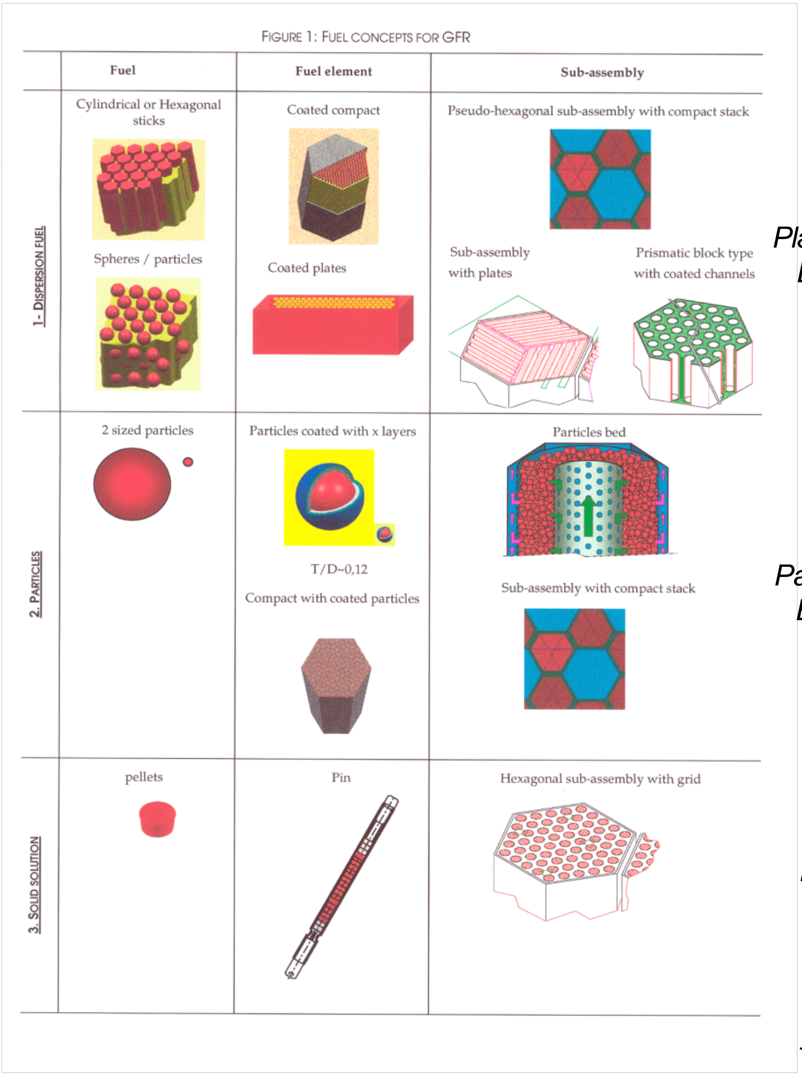


FIGURE 1: FUEL CONCEPTS FOR GFR

	Fuel	Fuel element	Sub-assembly
1- DISPERSION FUEL	Cylindrical or Hexagonal sticks Spheres / particles	Coated compact Coated plates	Pseudo-hexagonal sub-assembly with compact stack 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
3. SOLID SOLUTION	pellets	Pin	Hexagonal sub-assembly with grid

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.

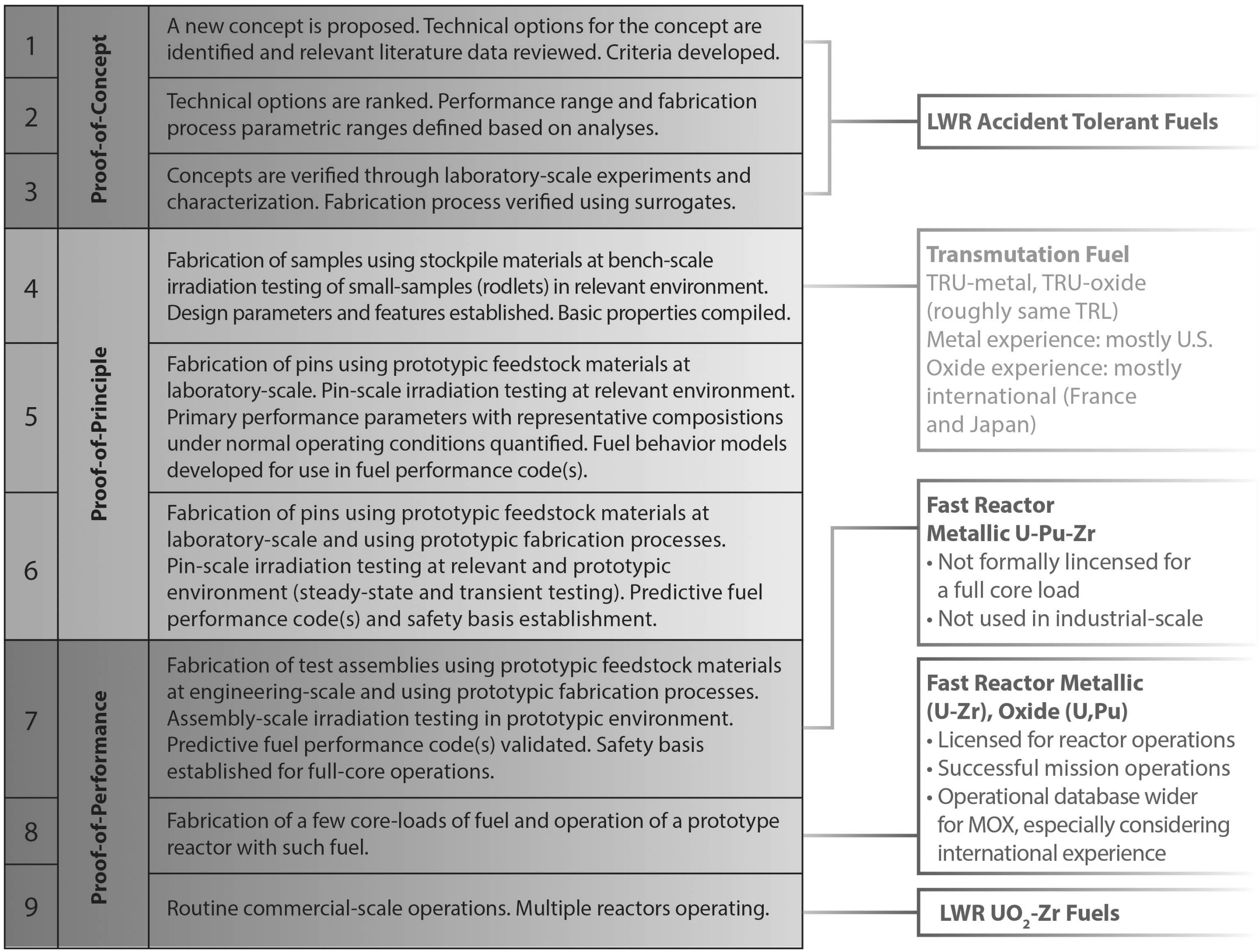
Designing a sustainable system that takes full advantage of Thorium is challenging:

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.
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.
5		Fabrication of pins using prototypic feedstock materials at laboratory-scale. Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative composistions 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.
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 Accident Tolerant Fuels

Transmutation Fuel
TRU-metal, TRU-oxide
(roughly same TRL)
Metal experience: mostly U.S.
Oxide experience: mostly international (France and Japan)

Fast Reactor Metallic U-Pu-Zr
- Not formally lincensed for a full core load
- Not used in industrial-scale

Fast Reactor Metallic (U-Zr), Oxide (U,Pu)
- Licensed for reactor operations
- Successful mission operations
- Operational database wider for MOX, especially considering international experience

LWR UO_2-Zr Fuels

Thank you

Advanced Fuels Campaign

https://nuclearfuel.inl.gov