Advanced Fuel Cycle Initiative (AFCI):
Fuels Development Overview

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U.S. DOE initiated a number of initiatives to promote the growth of nuclear energy.

2010 Initiative

- Explore new sites
- Develop business case
- Develop Generation III+ technologies
- Demonstrate new NRC process

Advanced Fuel Cycle Initiative (AFCI)

- Recovery of energy value from SNF
- Reduce the inventory of civilian Pu
- Reduce the toxicity & heat of waste
- More effective use of the repository

Nuclear Hydrogen Initiative (NHI)

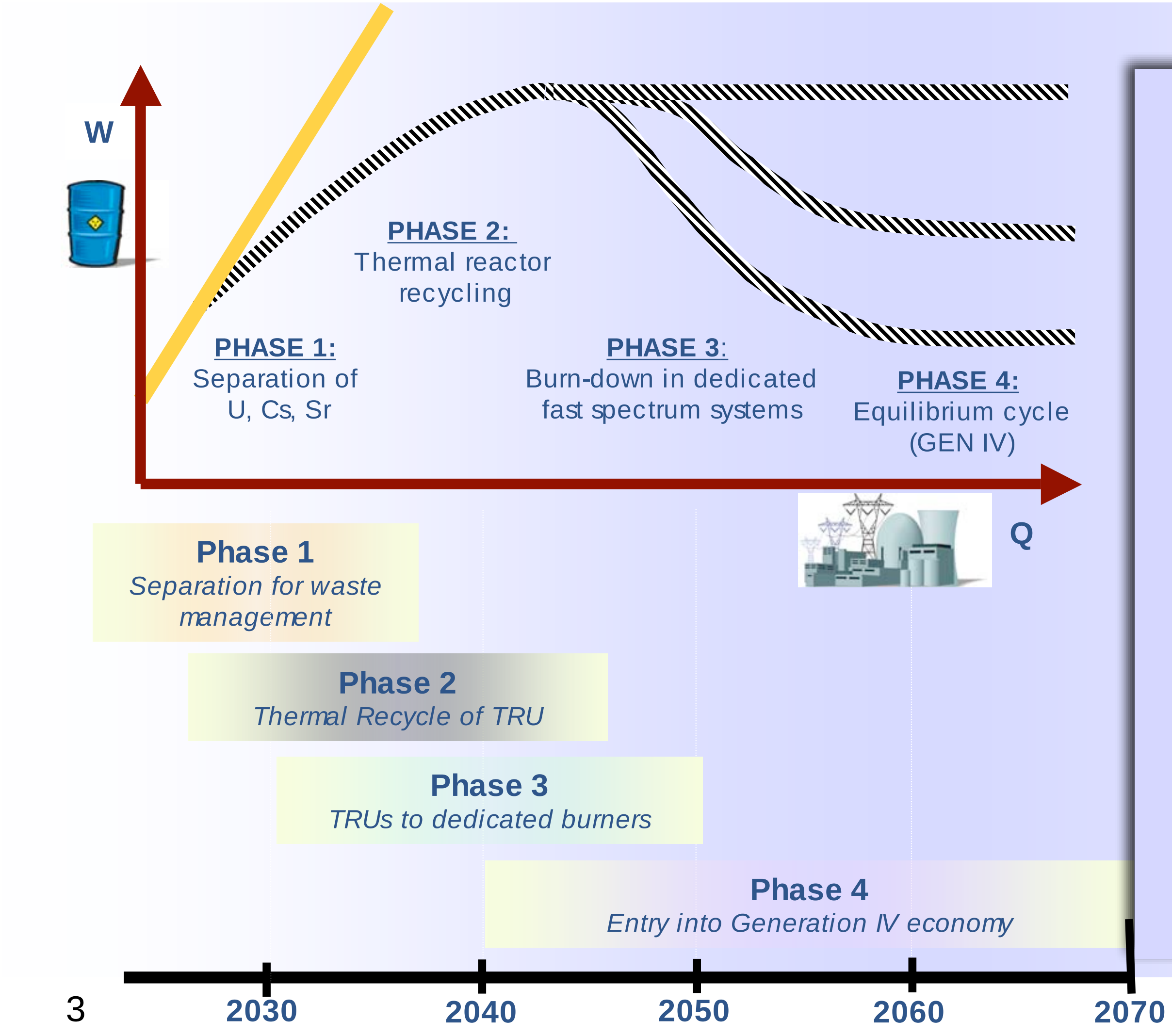
Develop technologies for economic, commercial-scale generation of hydrogen.

Generation IV (GEN IV)

Better, safer, more economic nuclear power plant with improvements in

- safety & reliability
- proliferation resistance & physical protection
- economic competitiveness
- sustainability

Advanced Fuel Cycle Initiative (AFCI) is focused on fuel cycle research on current and future systems with emphasis on waste management.



PHASE 1:
Separation of
U, Cs, Sr

PHASE 2:
Thermal reactor
recycling

PHASE 3:
Burn-down in dedicated
fast spectrum systems

PHASE 4:
Equilibrium cycle
(GEN IV)

Phase 1
Separation for waste management

Phase 2
Thermal Recycle of TRU

Phase 3
TRUs to dedicated burners

Phase 4
Entry into Generation IV economy

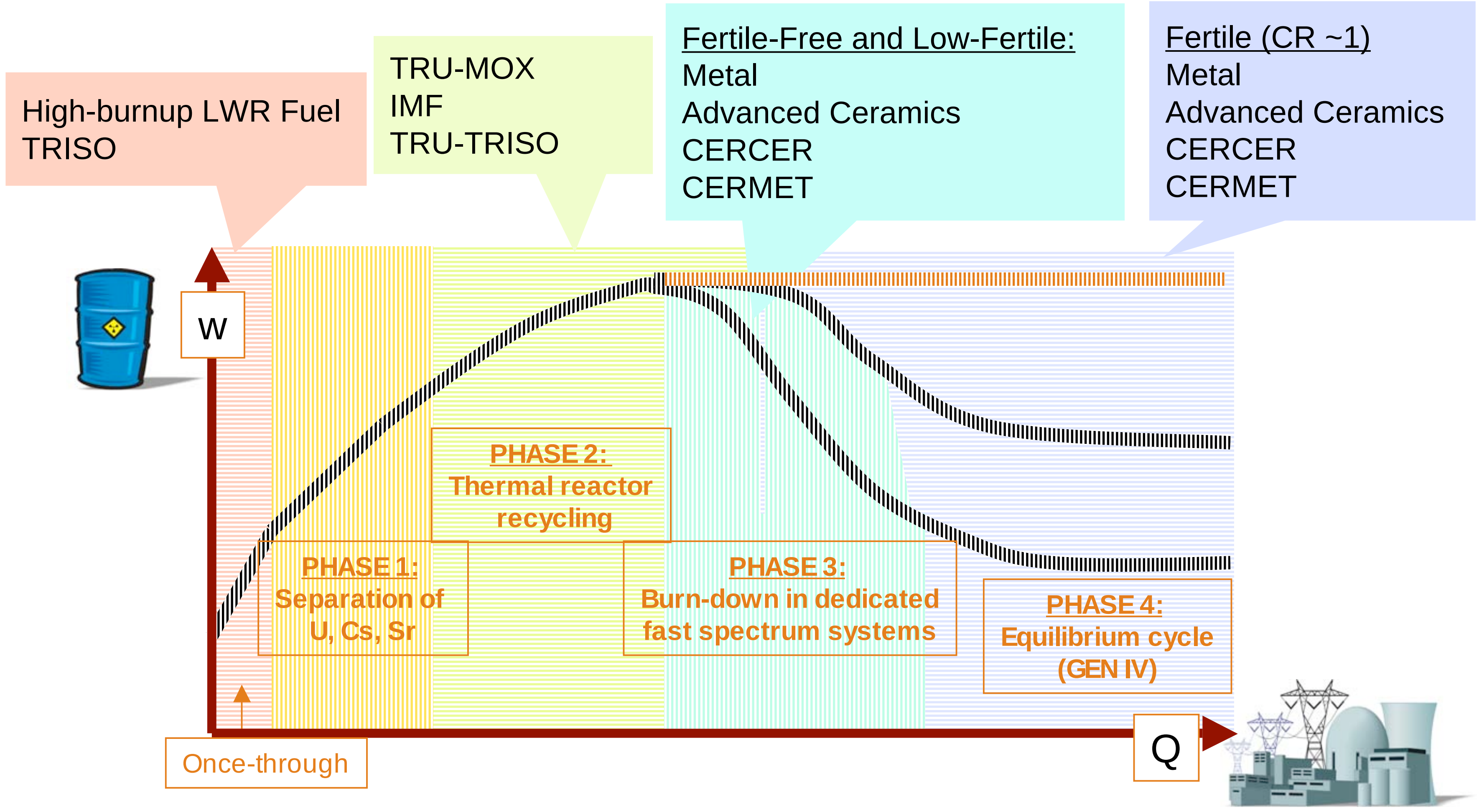
AFCI's mission is to develop and demonstrate technologies that enable the transition to a stable, long-term, environmentally, economically and politically acceptable fuel cycle.

Intermediate- and long-term

- separations,
- fuels, and
- transmutation

technologies for thermal and fast spectrum systems.

The fuel development covers the fuels needed in multiple phases of the fuel cycle evolution.



High-burnup LWR Fuel
TRISO

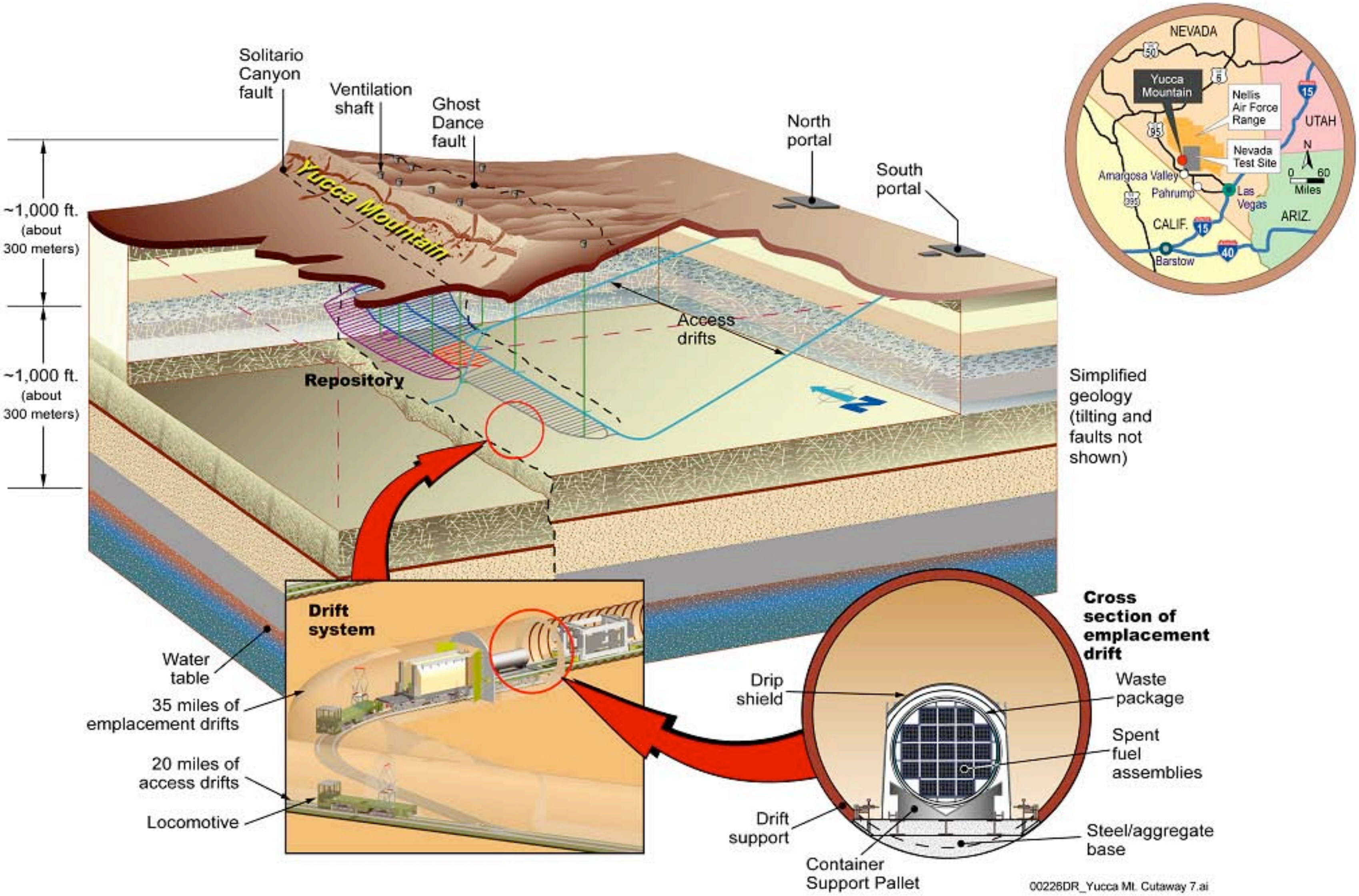
TRU-MOX
IMF
TRU-TRISO

Fertile-Free and Low-Fertile:
Metal
Advanced Ceramics
CERCER
CERMET

Fertile (CR ~1)
Metal
Advanced Ceramics
CERCER
CERMET

W = F(volume, radiological risk, short-term heat load, long-term heat load,plutonium mine)

Successful completion of the Yucca Mountain repository is essential for near term



Under nuclear growth scenarios, amount of SNF will reach very large quantities within this century.

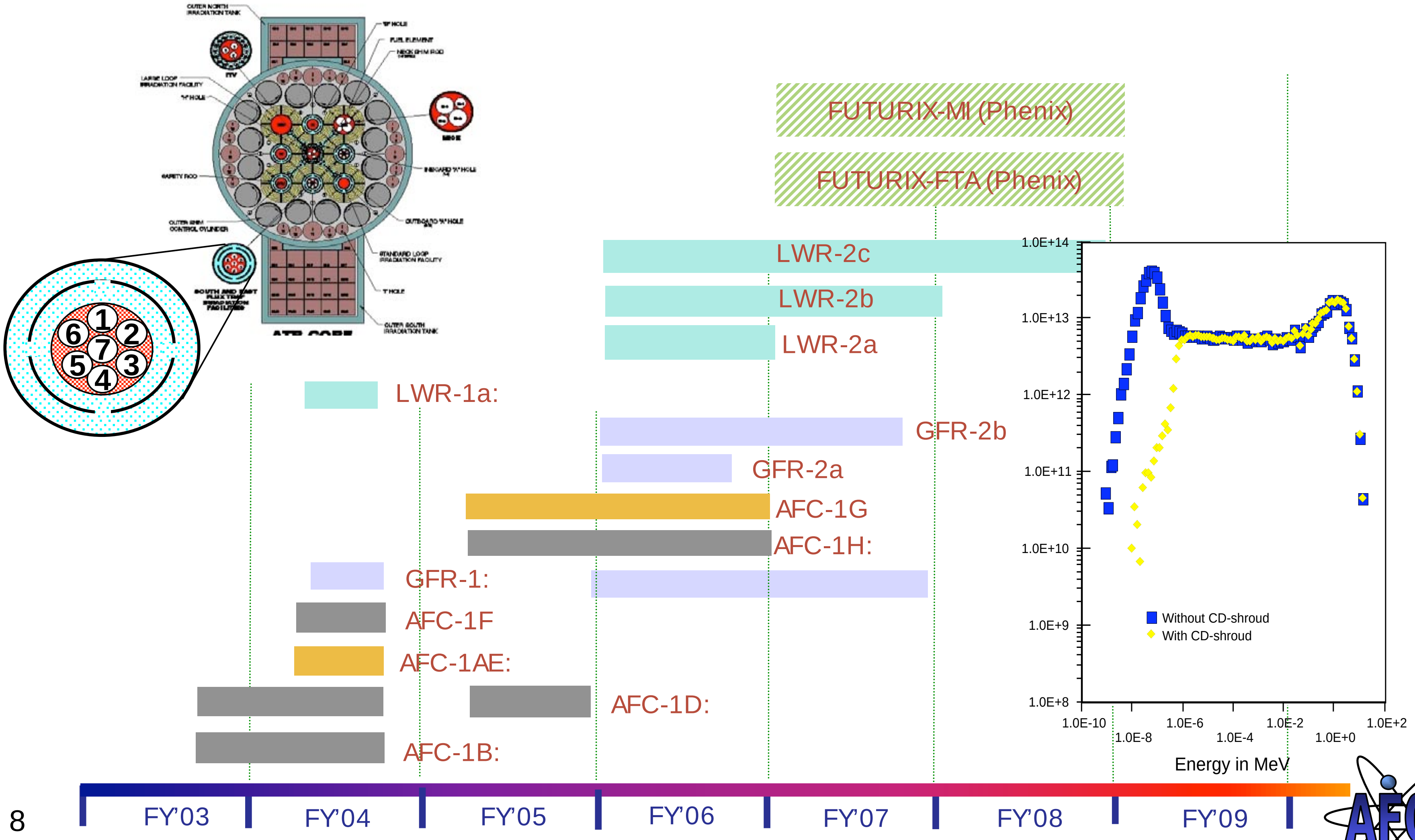
The table shows the number of Yucca Mountain equivalent repositories needed in the U.S. for various growth scenarios

Nuclear Futures	**Legislative Limit**	**Existing License Completion**	**Extended License Completion**	**Continuing Level Energy Generation**	**Continuing Market Share Generation**	**Growing Market Share Generation**
Cumulative Spent Fuel in 2100 (MTiHM)	63,000	86,000	118,000	240,000	600,000	1,300,000
	Number of Repositories Needed					
Current Management Approach		2	2	4	10	20
15 % Net Efficiency Improvement		2	2	4	9	18
Expand Repository Capacity		1	2	3	6	13
Efficiency Improvements + Capacity Improvements		1	~1	~2	~5	11
Separation of Pu, minor actinides. Longer cooling		1	1	1	2	~4
Separation of Pu, minor actinides, Cs, and Sr		1	1	1	1	1

The near-term major milestone is the “Transmutation and Fast Spectrum Fuel Feasibility” report in FY’10

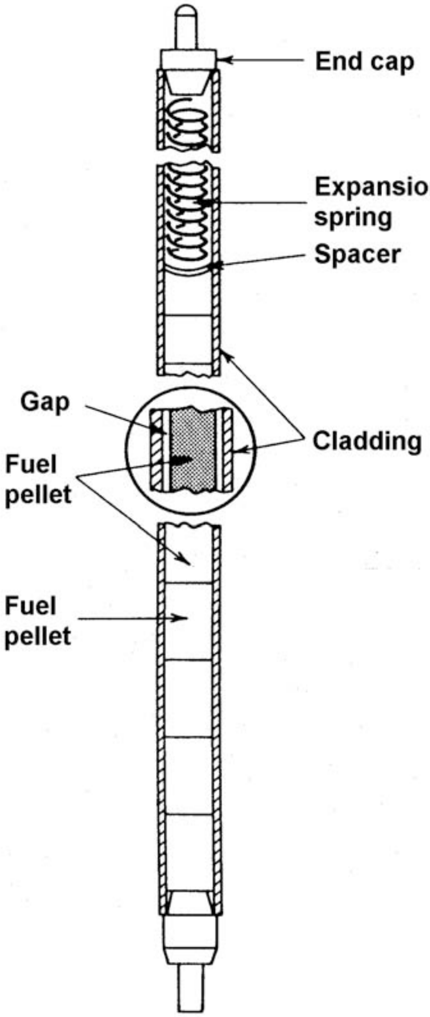
- **Fuel Types**
  - Mixed oxide, IMF, Am target
  - Metal, nitride, oxide, (cercer, cermet)
- **Fuel Fabrication**
  - Process development at laboratory scale
  - Process simulation model for full scale production
  - Pre-conceptual design of engineering-scale test and pilot plant
  - Cost estimate based on pre-conceptual design
  - Relative fabricability assessment of different types of fuels
- **Fuel Performance**
  - 50-100 samples (per fuel type) irradiated and examined (ATR, Phenix, JOYO)
  - Fuel performance model (as mechanistic as possible)
  - Estimation of transmutation performance
    - Impact of different sequences (LWR, FR, ADS combinations)
    - Relative performance assessment of different types of fuels

Transmutation fuel irradiation assessment is continuing through ATR irradiations



We are considering two types of transmutation fuel for potential use in LWRs & ALWRs: MOX & IMF

- IMF is attractive because it contains no fertile material.
  - High net transmutation rate per fuel pin.
- BUT, a full core IMF without substantial design changes is not possible.
  - Per core basis, net transmutation rate for IMF is comparable to MOX.
- The decision will be based on fuel performance, fabrication & licensing issues, cost and operator acceptability.
- The definition of “proliferation-resistance” and desired number of recycles also play a role on the choice.



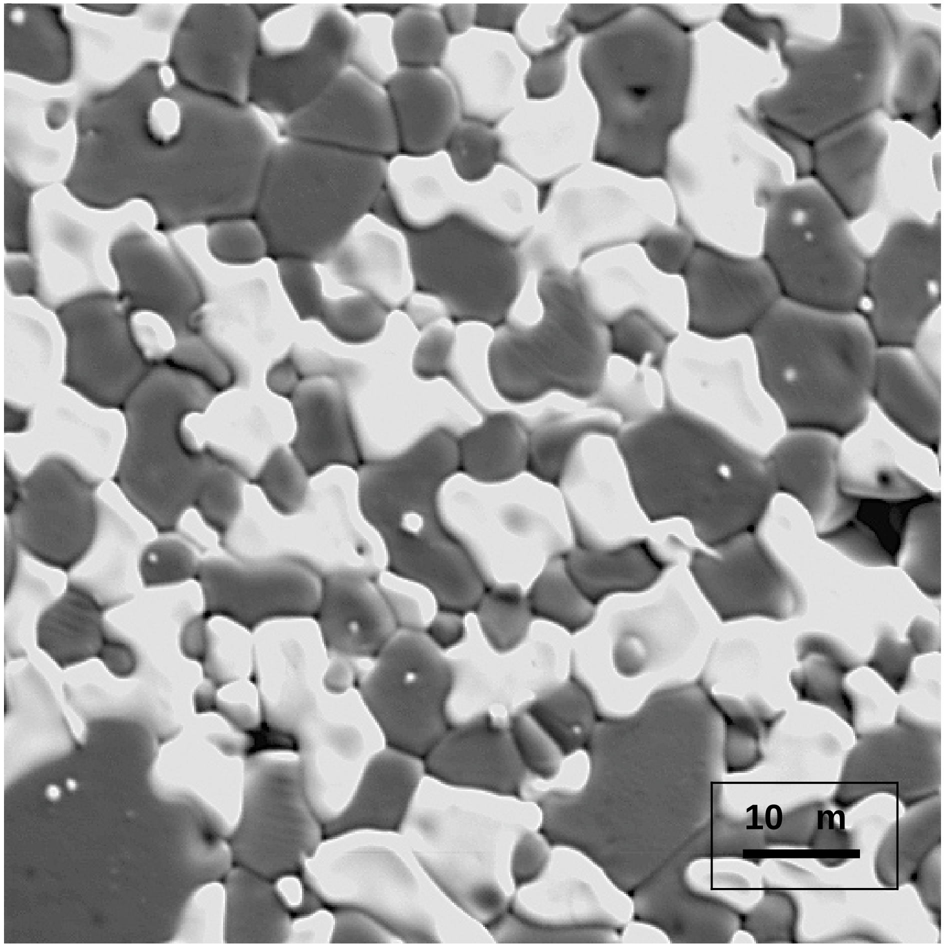
For IMF, YSZ (Yttria stabilized Zirconia) is the #1 matrix material that is being looked at in Europe

- We are primarily looking at fuels that look and act like UO_2 fuel
  - Oxides dispersed or dissolved in oxide matrix
  - $(Pu,Er,Y,Zr)O_{2-x}$ highest state of development
  - Other matrix materials will be looked in a new U-NERI project.
- Two issues with YSZ matrix $(Pu,Er,Y,Zr)O_{2-x}$
  - Low thermal conductivity (high-fuel centerline temperature)
  - Difficulty in recycling
    - Attractive for proliferation-resistance in once-through applications
- For liquid metal cooled fast systems, magnesia (MgO) also is a good choice for matrix material
  - MgO amenable for recycling using standard techniques
  - But, hot water is very corrosive for MgO
    - Clad breach accidents are a problem.

We are looking at a $MgO\text{-}ZrO_2$ matrix for improved performance

MgO pellet after 3 hr in boiling water

Microstructure evaluation shows a distinc MgO phase and a MgO-ZrO_2 solid solution



50/50

- Bright phase: $Mg_{0.160}Zr_{0.840}O_{1.840}$
- Dark phase: MgO
- Grain size 10-20 µm

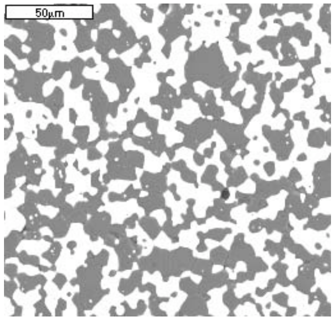
Experimental investigation of hydration resistance is performed

- Performed in de-ionized and borated (13000ppm H_3BO_3) water
- Parr pressure vessel
- Up to 700 hours, T=300°C, saturation pressure
- Post-exposure examination: microscopy and x-ray diffraction
- Monitored pellet mass as a function of time
- Used mass loss rate per cm^2 sample surface area to quantify hydration resistance

MgO pellet
after 3 hr in boiling water

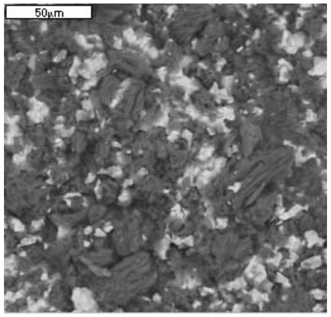
$MgO-ZrO_2$ pellet after 700 hr
in de-ionized water at 300°C

As-fabricated, polished and etched surface

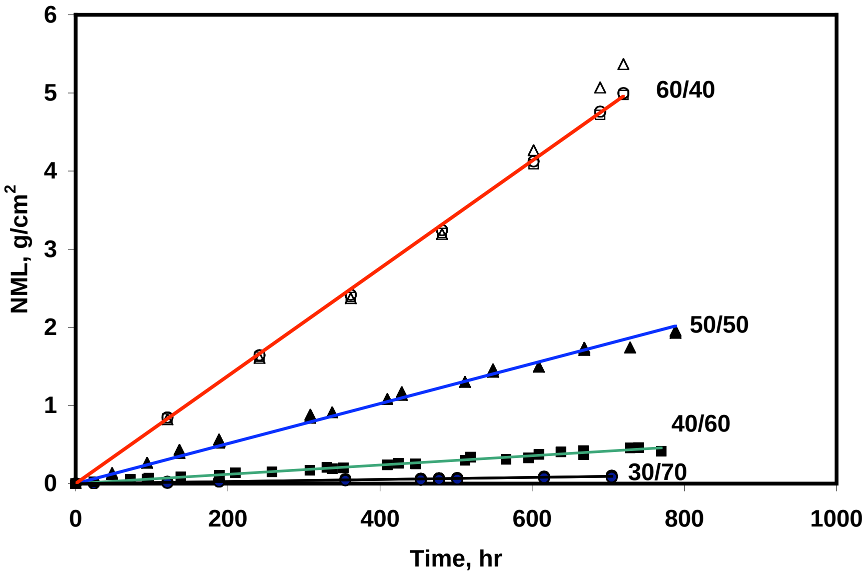


White phase: ZrO_2-MgO(ss);
grey phase: MgO

Surface after 700 hr in deionized water at 300°C

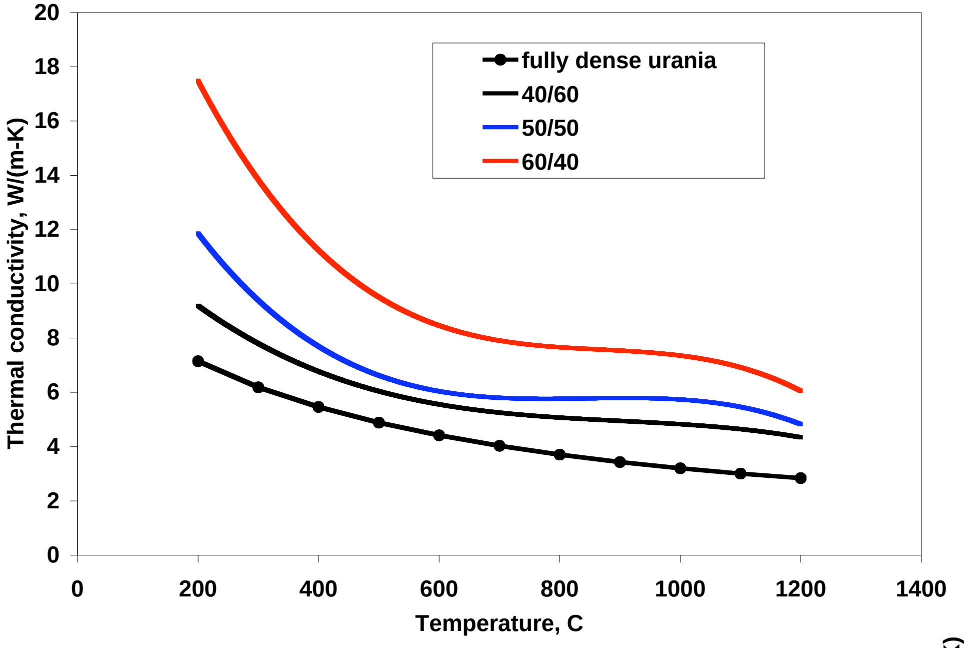


White phase: ZrO_2-MgO(ss);
grey phase: $Mg(OH)_2$+MgO

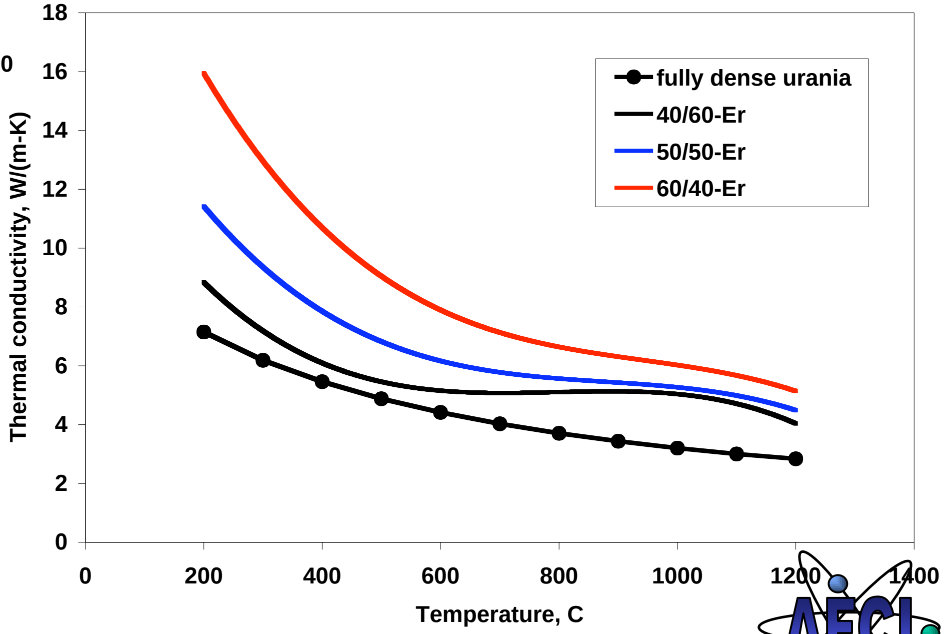


Hydration reaction is confined to the surface layer
Bulk of the MgO is encapsulated by ZrO_2

Thermal conductivity measurements show improvements over urania

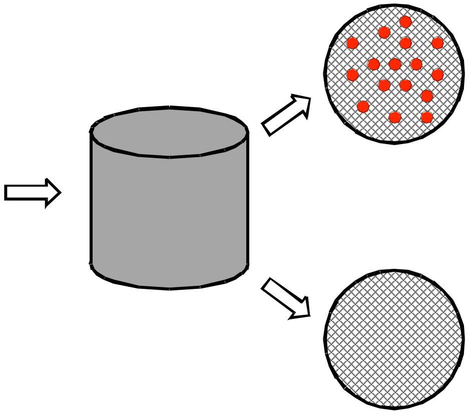


784°C-1040°C margin between T_{cl} and $T_{melting}$
Current Westinghouse PWR: 1068°C
(T_{cl} = 1788°C and $T_{melting}$ =2878°C)



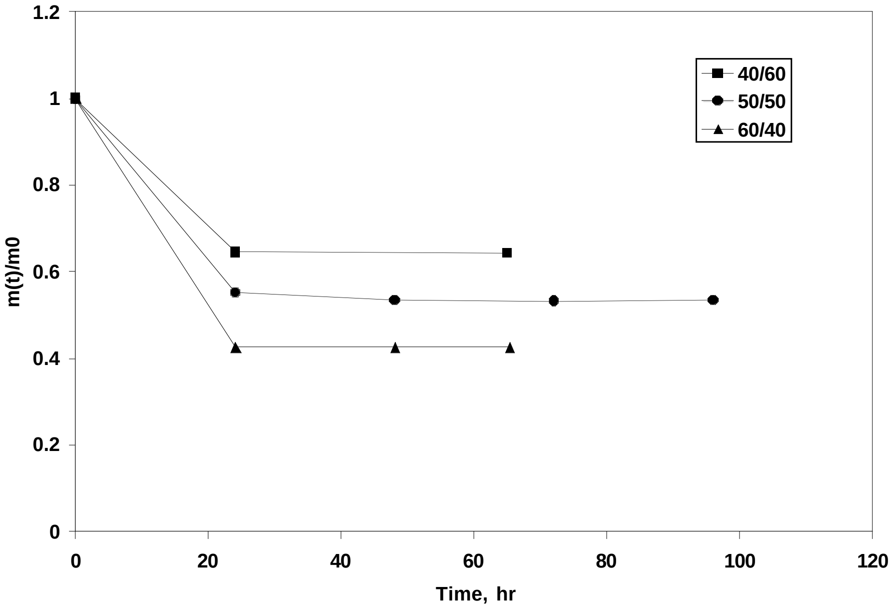
Dissolution of the matrix in Nitric Acid also is investigated

- Samples exposed to concentrated HNO_3 at ~55ºC
- Sample mass monitored as a function of time
- Samples appeared intact despite mass loss
- Mass lost equaled mass of the MgO phase present in samples
- XRD confirmed dissolution of MgO phase



Macrodispersion: Inert matrix and dispersed plutonium inclusions 0.1- 1.0 mm diameter

Microdispersion: Inert matrix and plutonium intimately mixed

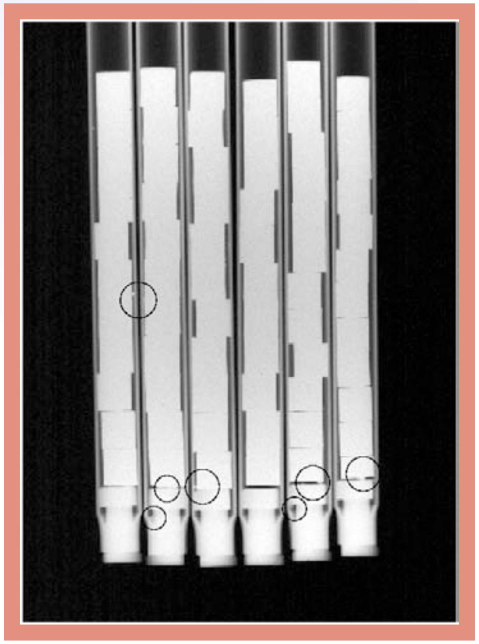


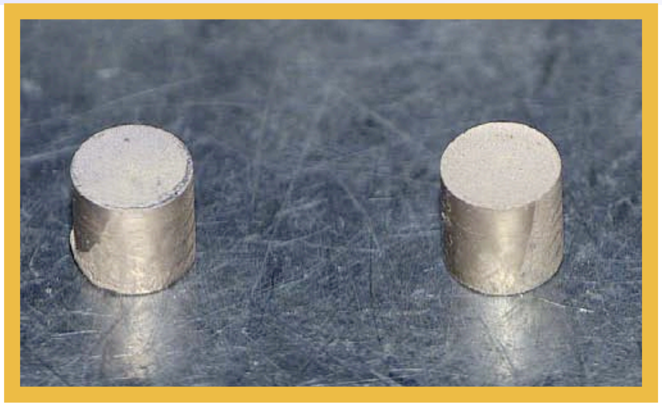
- Dissolution of MgO allows penetration of the HNO_3 into the matrix, leaving ZrO_2 behind
- The structure appears intact after dissolution
- It is not clear if we can dissolve Pu this way
  - Pu in ZrO_2 versus in MgO
  - Different pellet design

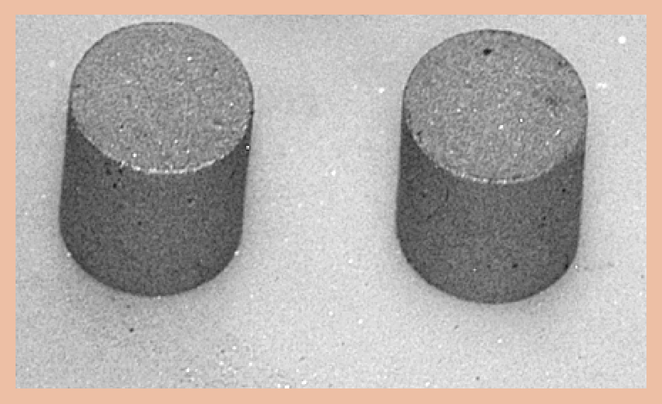
Considerable progress is made in understanding the nitride fabrication process

Status

- Problems with carbothermic reduction have been resolved
  - Carbon & oxygen content in the fuel is reduced to acceptable levels.
- Structural and low-density issues have been resolved
  - Process parameters better understood and more robust
- Americium loss still appreciable during sintering
  - Requires additional improvements
- Sodium-bonding process for nitride fuels is being assessed
  - Not as robust as the process for metal fuels



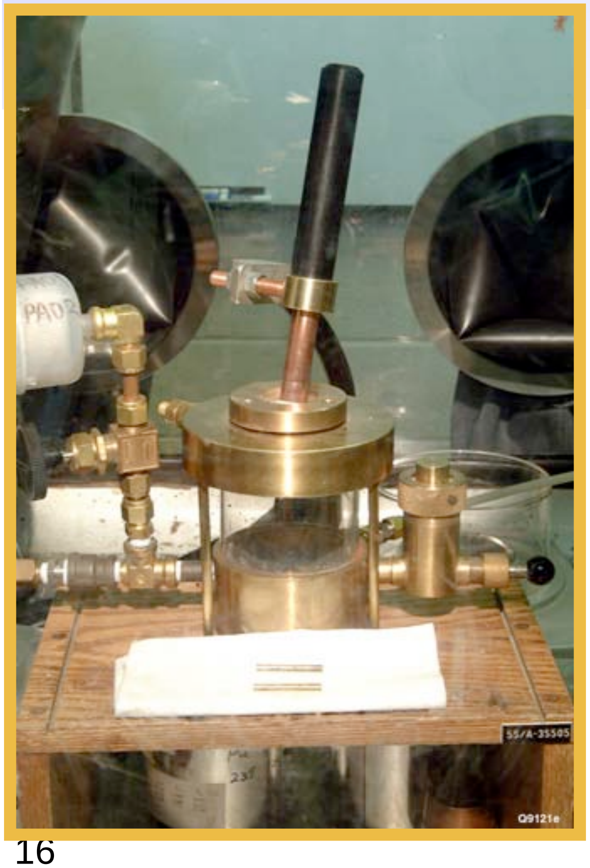


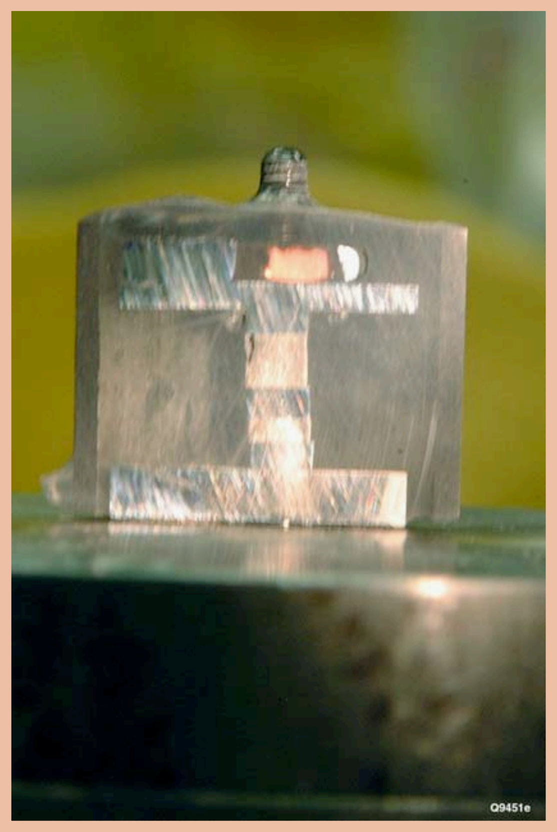


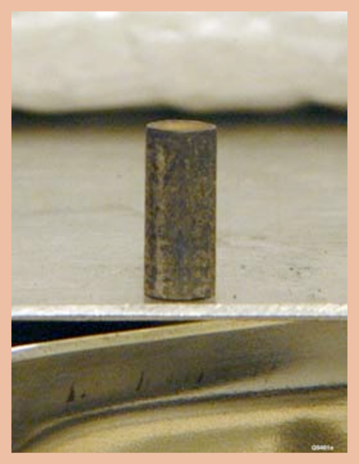
Metal fuel development progressed without any glitch so far

Status

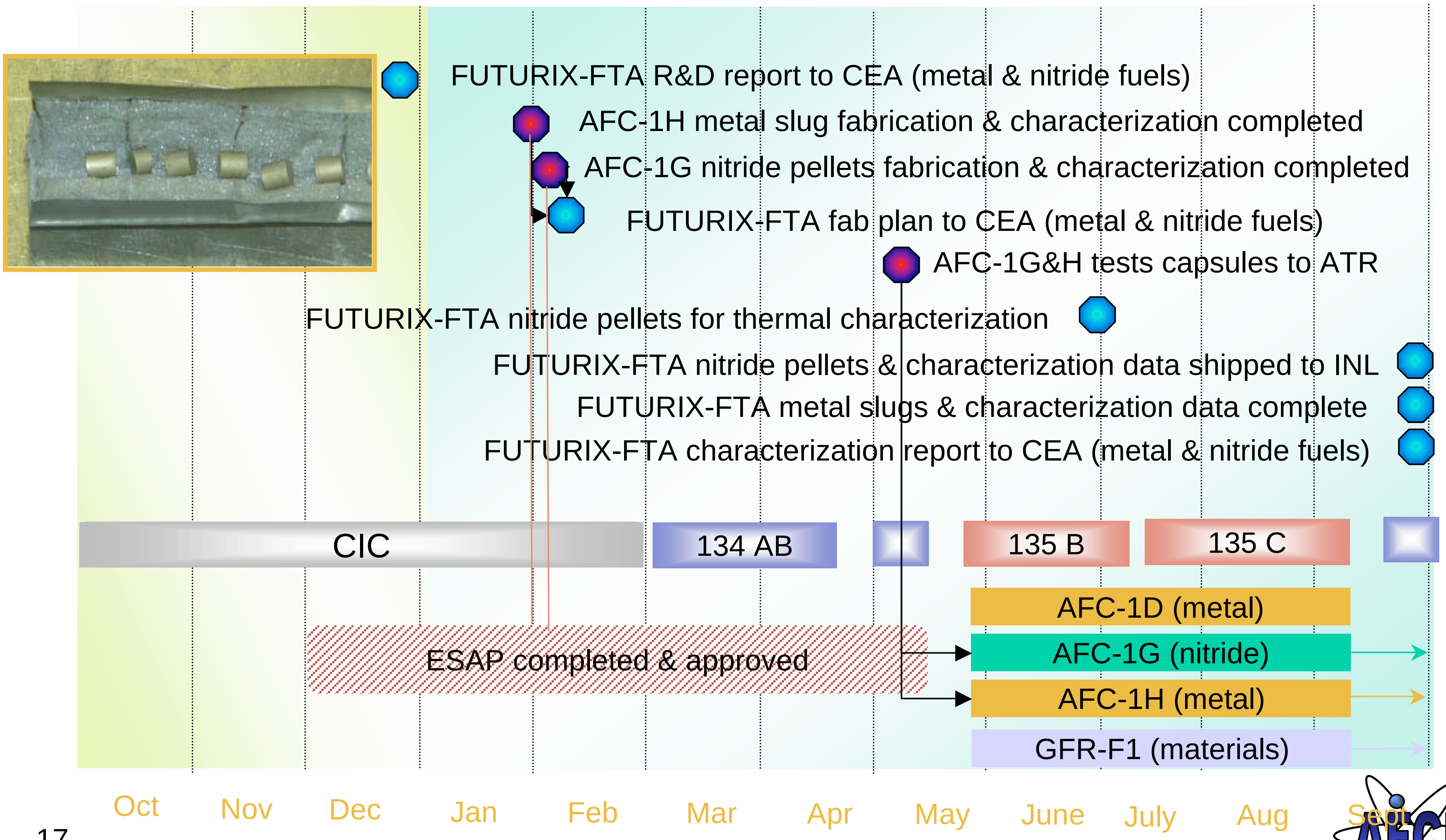
- Considerable amount of fuel with MA have been fabricated and characterized
- No surprises
- Still need to develop a fabrication process amenable to large-scale fabrication







Nitride and metal development is progressing according to plan



FUTURIX-FTA R&D report to CEA (metal & nitride fuels)

AFC-1H metal slug fabrication & characterization completed

AFC-1G nitride pellets fabrication & characterization completed

FUTURIX-FTA fab plan to CEA (metal & nitride fuels)

AFC-1G&H tests capsules to ATR

FUTURIX-FTA nitride pellets for thermal characterization

FUTURIX-FTA nitride pellets & characterization data shipped to INL

FUTURIX-FTA metal slugs & characterization data complete

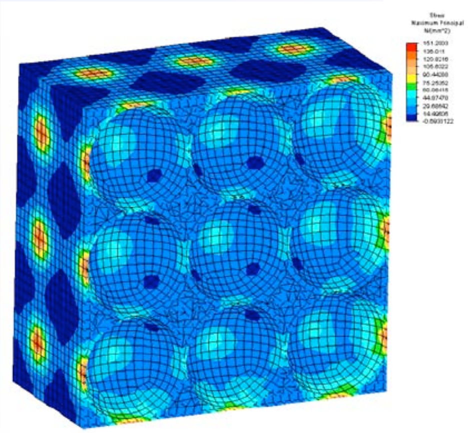
FUTURIX-FTA characterization report to CEA (metal & nitride fuels)

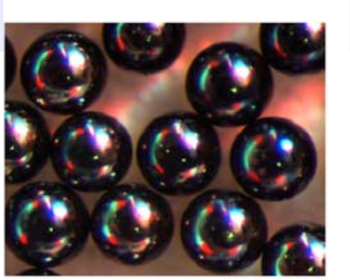
Development of dispersion fuels for GFR started last year

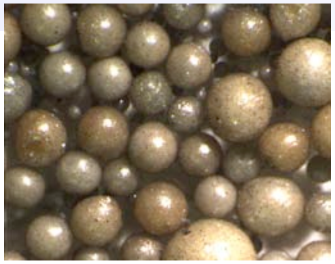
- Basic elements of GFR fuel fabrication R&D progressing
  - UC particle fabrication
  - Matrix consolidation
  - Coating (Powder coating at ANL, ORNL INERI for CVD)

- Feasibility of GFR fuels assessed for MA transmutation [pins (vented) > 20% ^{241}Am, dispersions ~ 5 % ^{241}Am, pins (sealed) ~ 5 % ^{241}Am]
  - particle bed – marginal with no ^{241}Am

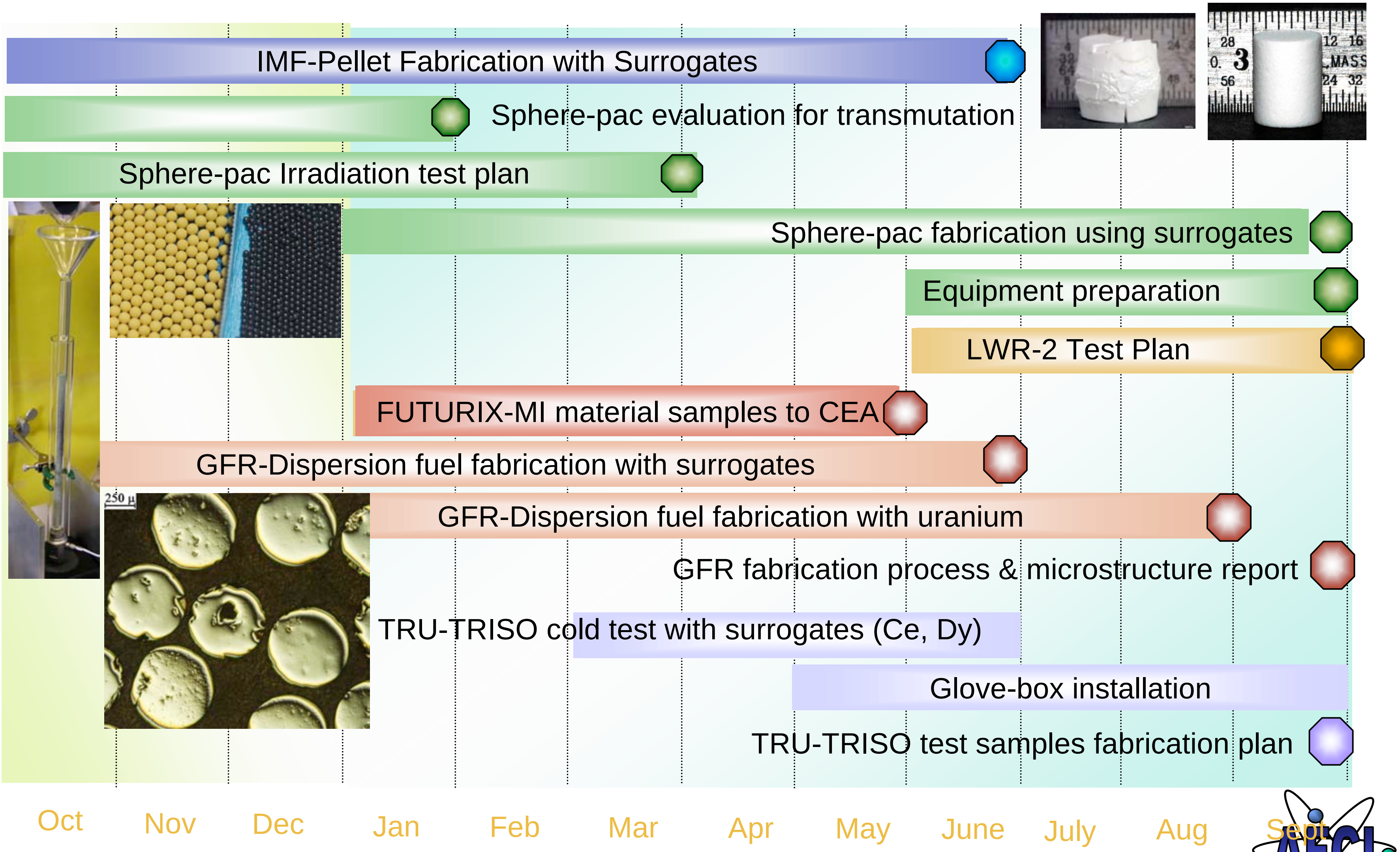
- Materials testing in ATR and Phenix







Preparatory scoping work continues for IMF, GFR-dispersion, sphere-pac and TRU-TRISO.



IMF-Pellet Fabrication with Surrogates

Sphere-pac evaluation for transmutation

Sphere-pac Irradiation test plan

Sphere-pac fabrication using surrogates

Equipment preparation

LWR-2 Test Plan

FUTURIX-MI material samples to CEA

GFR-Dispersion fuel fabrication with surrogates

GFR-Dispersion fuel fabrication with uranium

GFR fabrication process & microstructure report

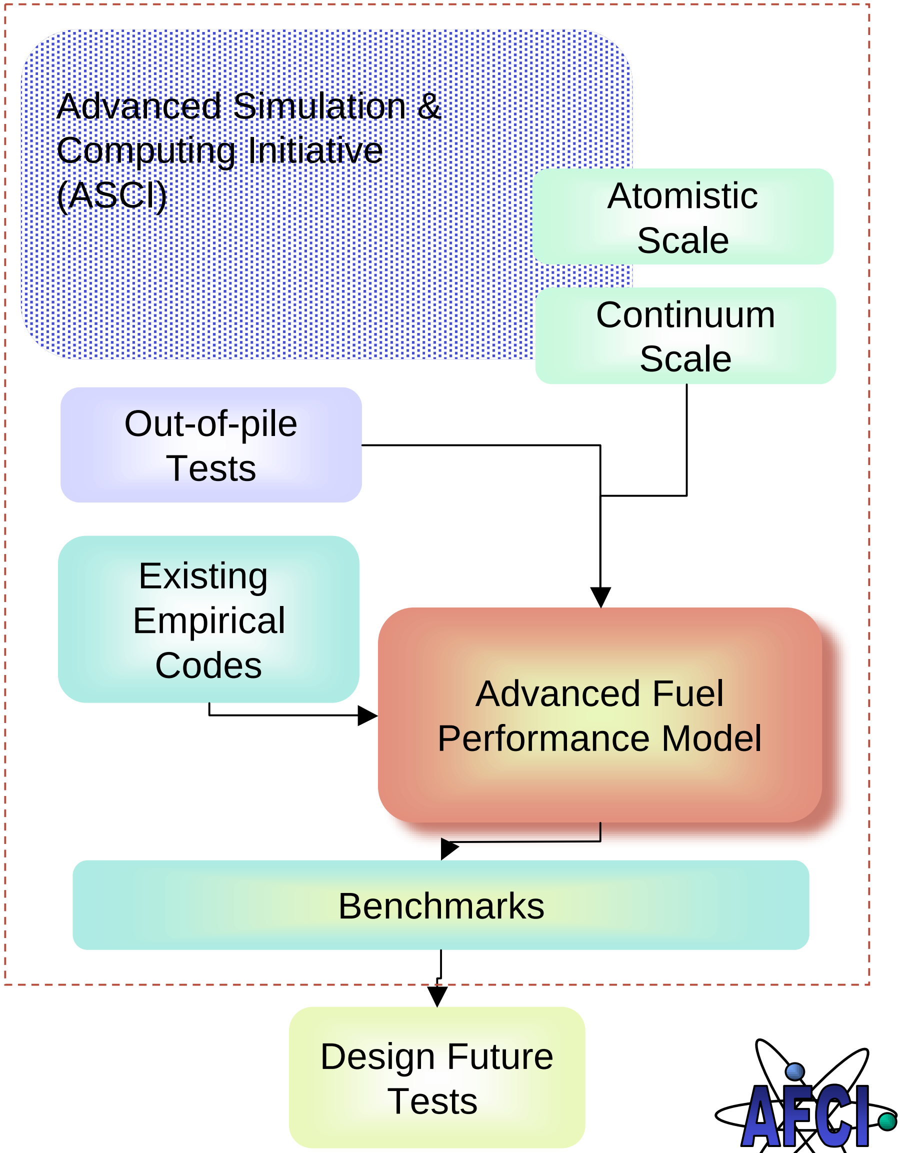
TRU-TRISO cold test with surrogates (Ce, Dy)

Glove-box installation

TRU-TRISO test samples fabrication plan

Modeling and simulation is being emphasized

- 10-year objective is a first-principle based fuel performance code.
- Multiple programs abroad and at the universities are being reviewed for a common framework
  - To be established this year
- 3 International workshops are held
- Phenomenological models are being developed and assessed for oxide fuels.



Advanced Simulation & Computing Initiative (ASCI)

Atomistic Scale

Continuum Scale

Out-of-pile Tests

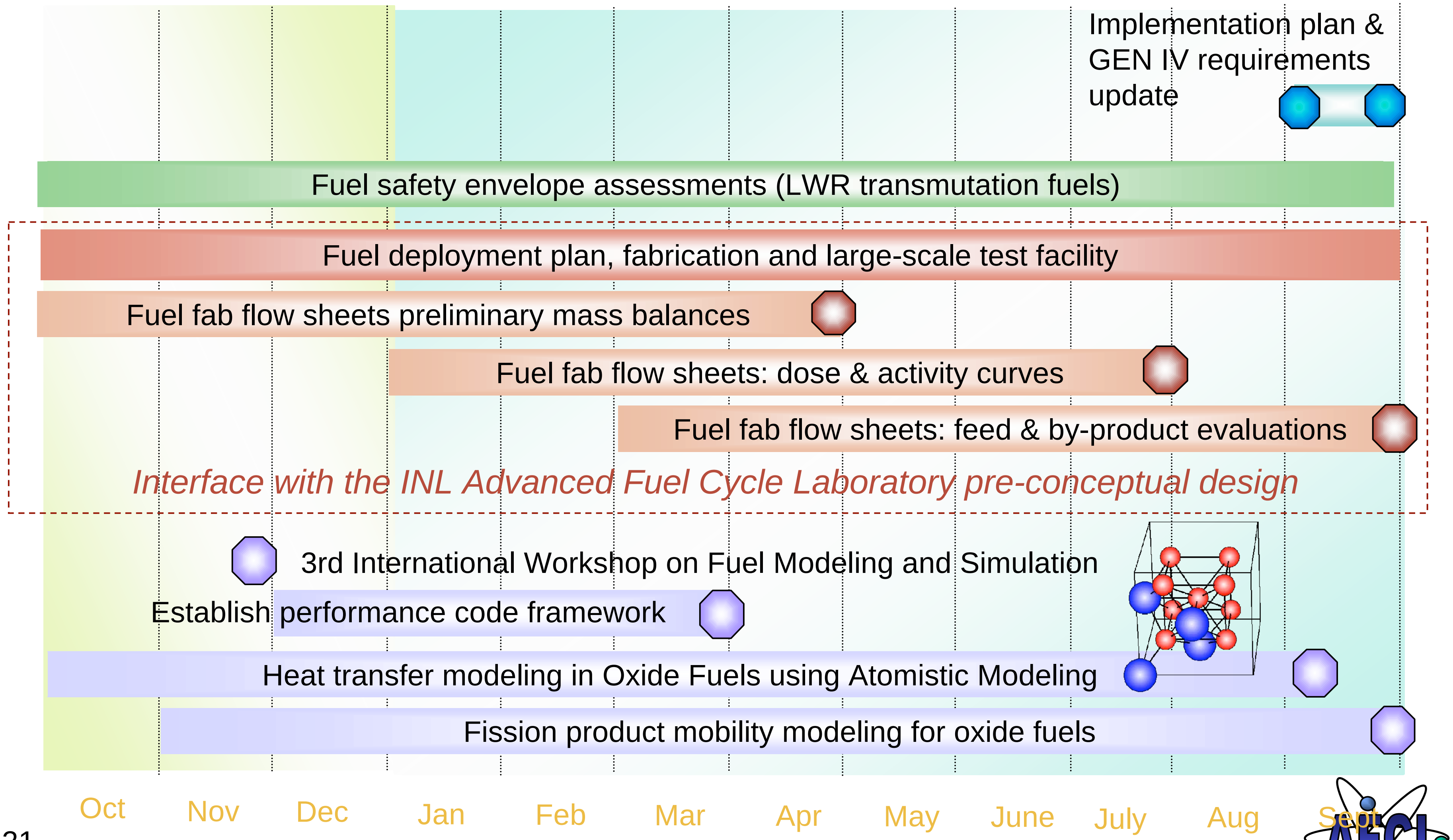
Existing Empirical Codes

Advanced Fuel Performance Model

Benchmarks

Design Future Tests

Analytic support tasks include facility assessments and fuel performance & safety envelopes



Implementation plan & GEN IV requirements update

Fuel safety envelope assessments (LWR transmutation fuels)

Fuel deployment plan, fabrication and large-scale test facility

Fuel fab flow sheets preliminary mass balances

Fuel fab flow sheets: dose & activity curves

Fuel fab flow sheets: feed & by-product evaluations

Interface with the INL Advanced Fuel Cycle Laboratory pre-conceptual design

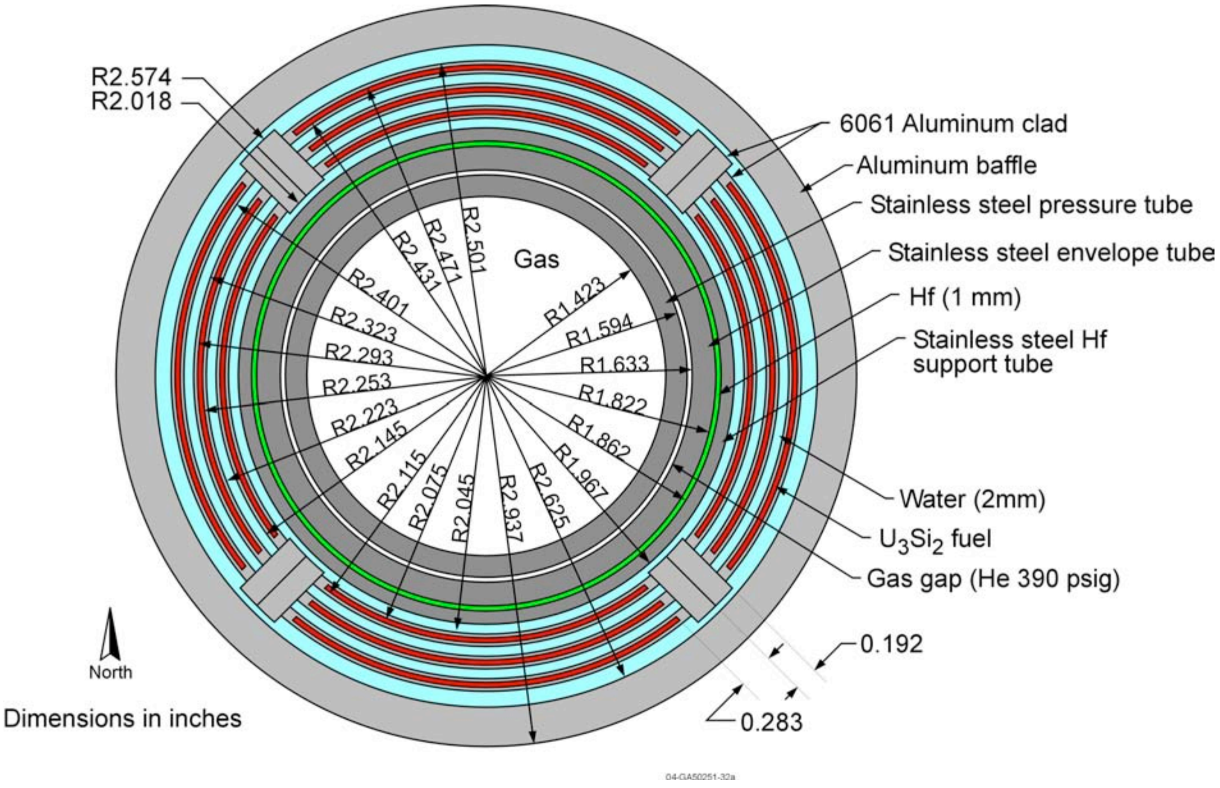
3rd International Workshop on Fuel Modeling and Simulation

Establish performance code framework

Heat transfer modeling in Oxide Fuels using Atomistic Modeling

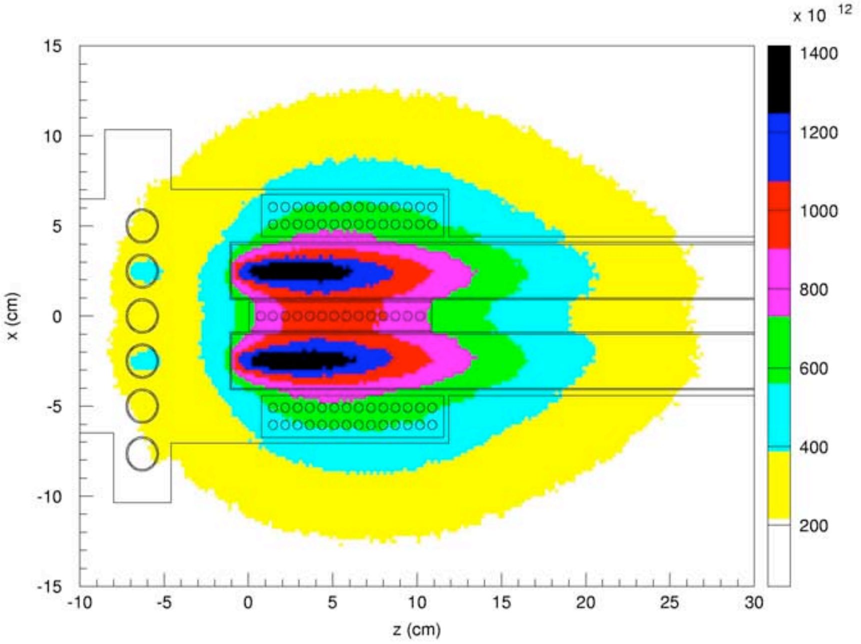
Fission product mobility modeling for oxide fuels

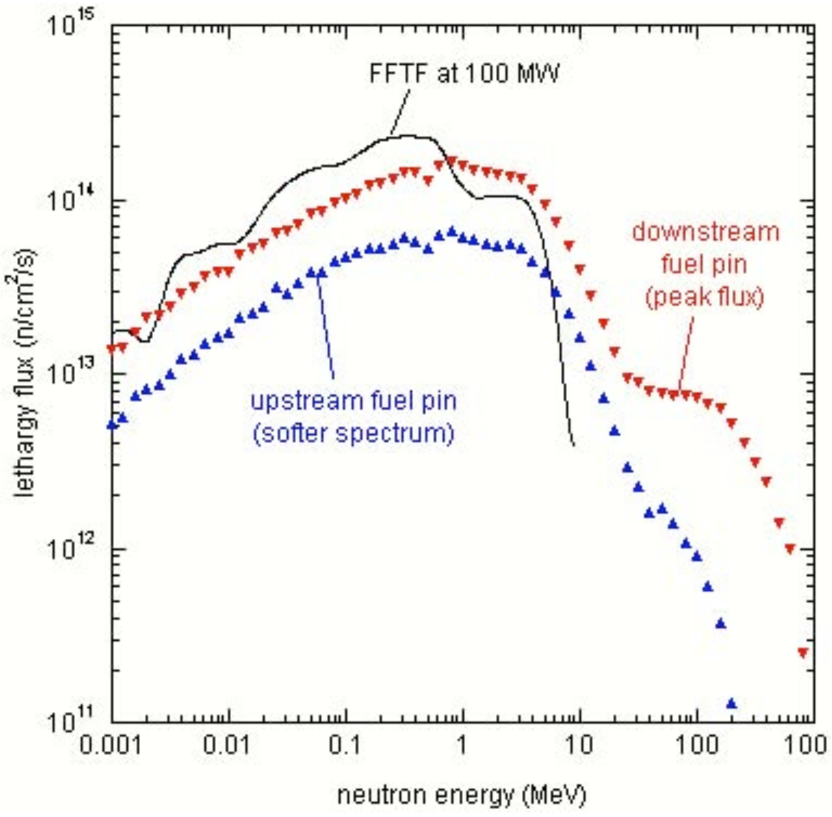
We are considering a fast flux booster (gas loop) in ATR.

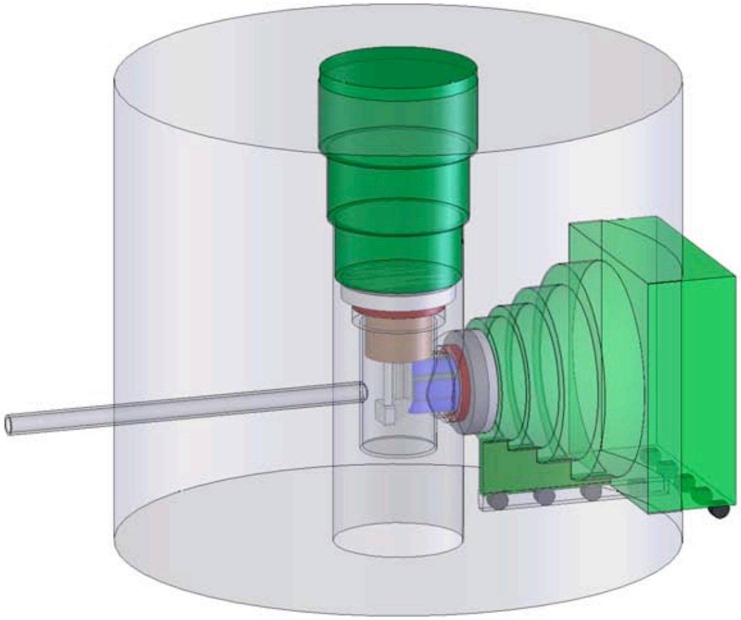


To achieve 10^{15} n/cm^{2}-s fast neutron flux, the lobe power for the reactor is > 40 MW

We are considering a test station at the end of the LANSCE accelerator





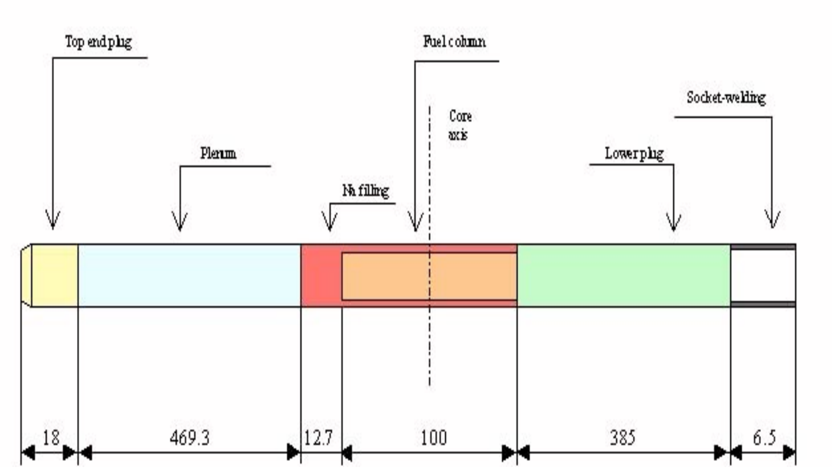


FUTURIX-FTA

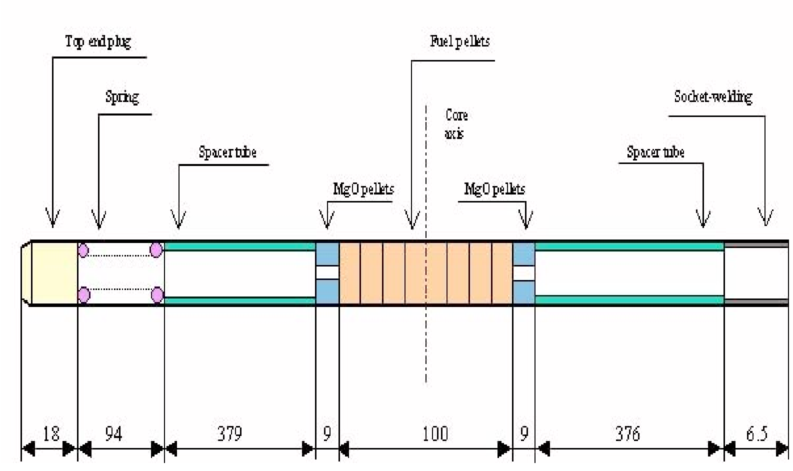
Non-Fertile Fuels	Bond	Fabricator
(48)Pu-12Am-40Zr	Na	ANL
$(Pu_{0.50}, Am_{0.50})N$ + 36-wt%ZrN	Na	LANL
$(Pu_{0.20}, Am_{0.80})O_2$ + 65-vol%MgO	He	CEA
$(Pu_{0.50}, Am_{0.50})O_2$ + 70-vol%MgO	He	CEA
$(Pu_{0.23}, Am_{0.25}, Zr_{0.52})O_2$ + 60-vol%Mo^{92}	He	ITU
$(Pu_{0.50}, Am_{0.50})O_2$ + 60-vol% Mo^{92}	He	ITU
Low-Fertile Fuels		
(35)U-29Pu-4Am-2Np-30Zr	Na	ANL
$(U_{0.50}, Pu_{0.25}, Am_{0.15}, Np_{0.10})N$	Na	LANL

19-pin experimental subassembly to be used
- 8 experimental pins
- 11 standard Phénix driver pins or dummies

Irradiation in Phénix ring 3 or 4
- Satisfies LHGR limit of 350 W/cm



Na-bonded fuels



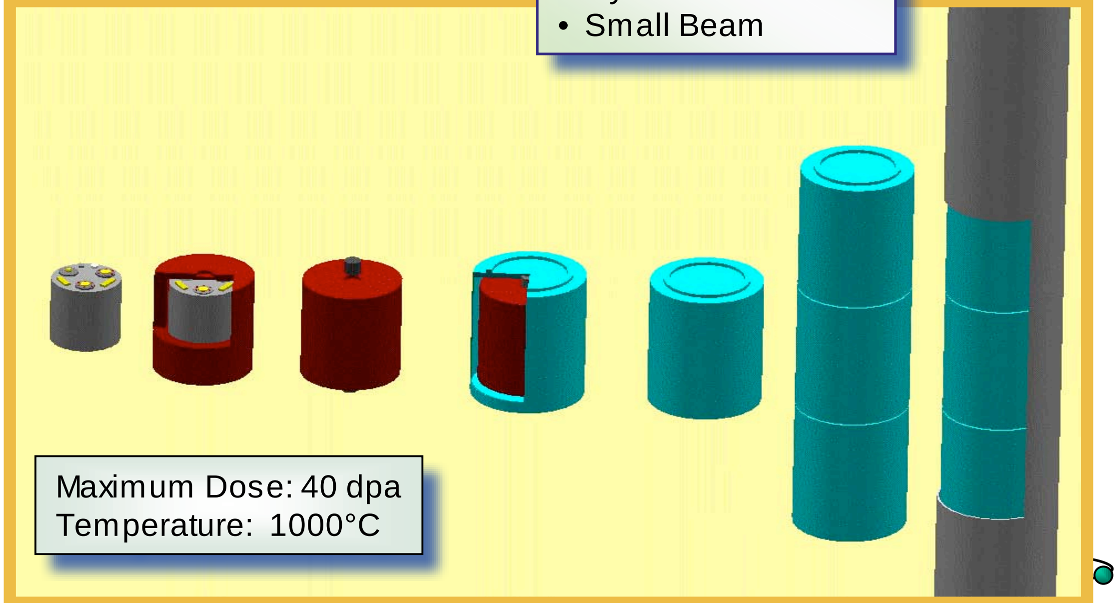
He-bonded fuels

FUTURIX-MI

EFFECT OF IRRADIATION ON PHYSICAL AND CHEMICAL PROPERTIES
- DENSITY (SWELLING)
- MICROSTRUCTURE
- COMPOSITION - CRYSTALLOGRAPHIC PHASES
- ACTIVATION
- THERMAL PROPERTIES : Thermal Conductivity,Thermal Diffusivity, Heat Capacity, Linear Expansion
- MECHANICAL PROPERTIES : Young Modulus, Poisson ration, Hardness, Strength
- ELECTRICAL RESISTIVITY

INERT MATERIALS
α-SiC : 2 types (mono and polycrystal)
β-SiC: 2 types (mono and polycrystal)
ZrC : 2 types (micro and sub-micro.)
TiC
TiN
ZrN
Mo (Alloy)
SiC_f/SiC : 2D **SiC_f/SiC : 3D**
2 materials to be defined : TiN,SiC (other composition) NbZrC ?

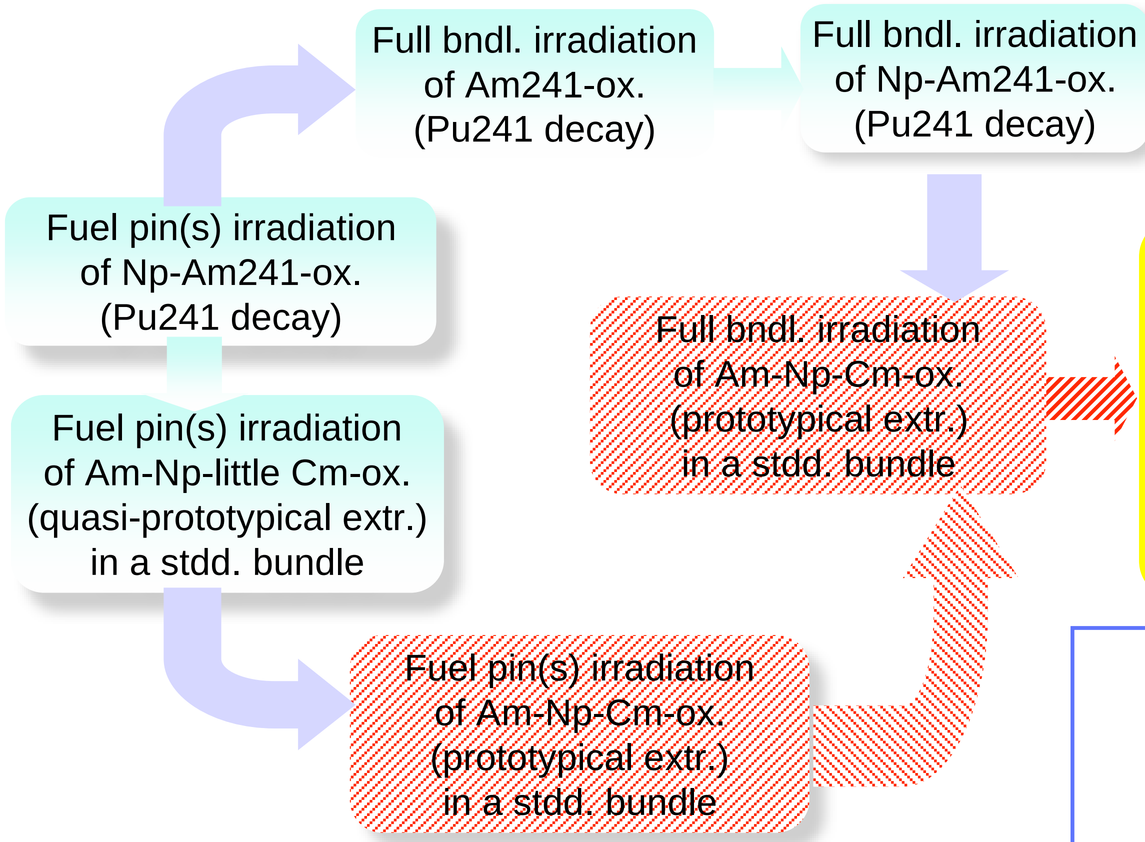
SAMPLES
- Small Disk
- TEM Specimen
- Cylinder
- Small Beam



Maximum Dose: 40 dpa
Temperature: 1000°C

DOE-CEA-JNC: Global Actinide Management

- *Joyo future tests data*
- *Phenix-SF1*
- *ATR future data*



Fuel pin(s) irradiation of Np-Am241-ox. (Pu241 decay)

Full bndl. irradiation of Am241-ox. (Pu241 decay)

Full bndl. irradiation of Np-Am241-ox. (Pu241 decay)

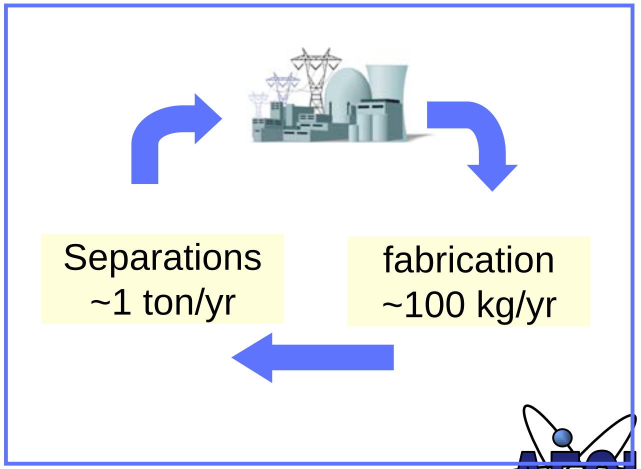
Fuel pin(s) irradiation of Am-Np-little Cm-ox. (quasi-prototypical extr.) in a stdd. bundle

Fuel pin(s) irradiation of Am-Np-Cm-ox. (prototypical extr.) in a stdd. bundle

Full bndl. irradiation of Am-Np-Cm-ox. (prototypical extr.) in a stdd. bundle

Demonstration

- Full bundles
- FR-recycle fuel as well as LWR-SF recycle fuel
- TRU homogeneous extraction technology
- Remote fabrication
- Significant MA consumption



Separations ~1 ton/yr

fabrication ~100 kg/yr