SFR Fuel Performance and Approach to Qualification

Steven L. Hayes and Douglas L. Porter
Fuels & Materials Performance Department
Idaho National Laboratory

November 27-28, 2007

Idaho National Laboratory

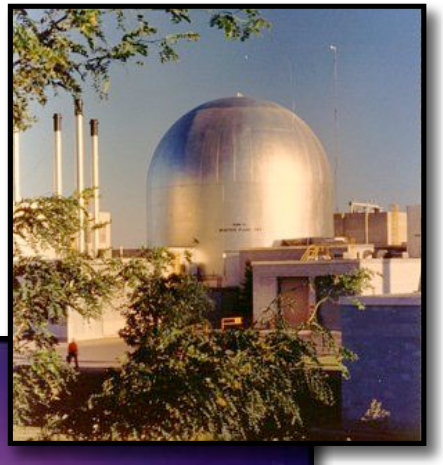
Outline of Presentation

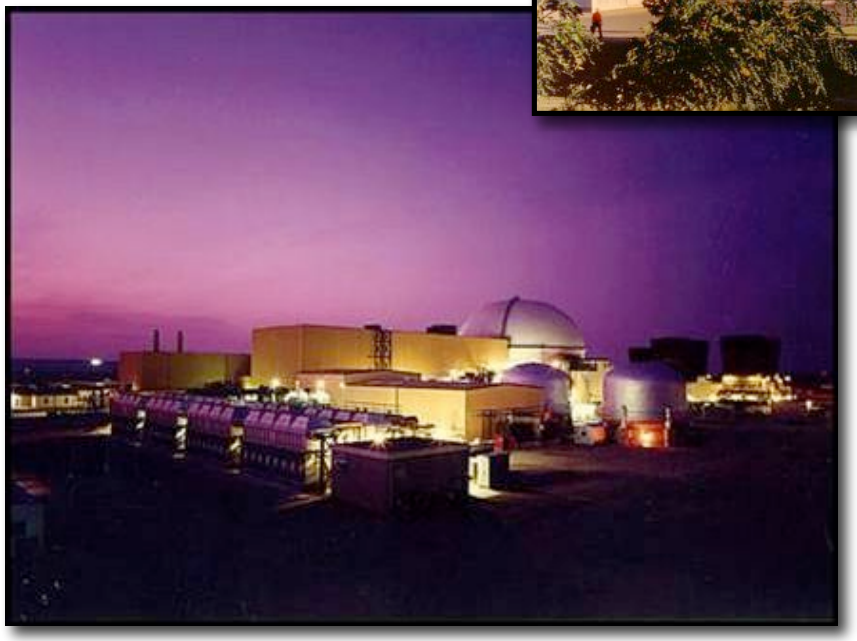
- **SFR Fuels Experience in the US**
  - Fuel Types
  - Fuel Performance Issues
  - Experience/Testing
- **Fuel Test Plan (1994) for PRISM Prototype**
- **Fuel Specification**
- **Experience with Fuels Containing Minor Actinides (AFCI/GNEP)**
- **Approach to Fuel Development and Qualification**

SFR Fuels Experience in the US

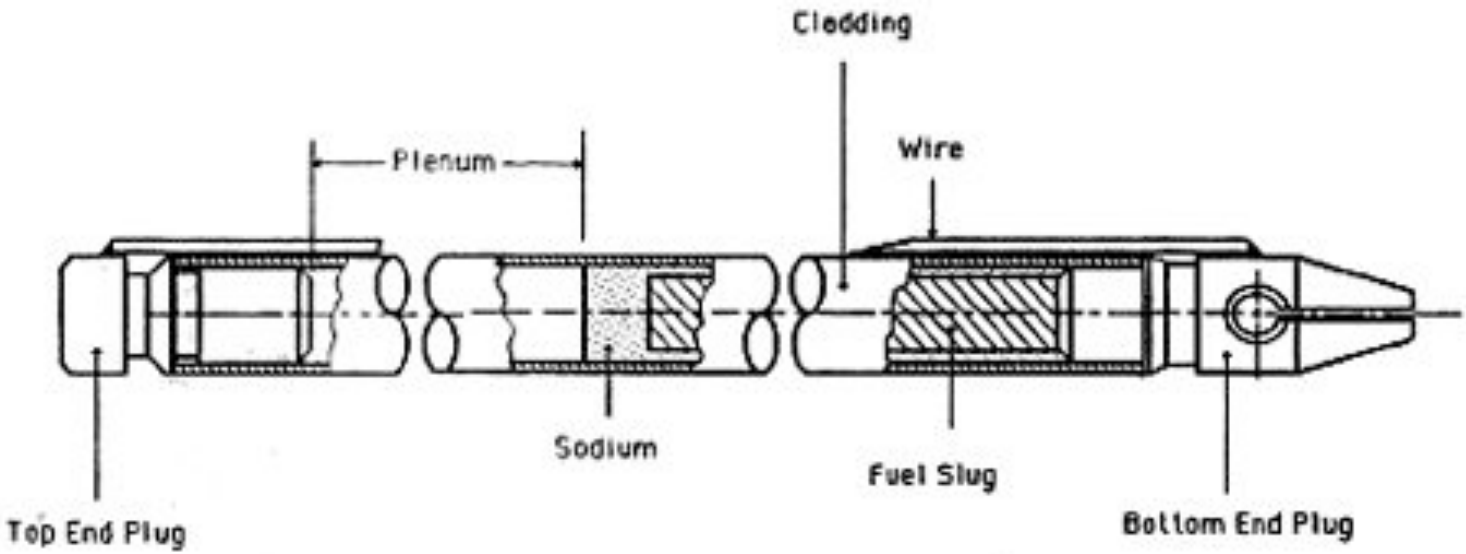
SFR Fuels Experience in the US

- **Metallic Fuels**
  - EBR-I, Fermi-1, EBR-II, FFTF
  - U-Fs, U-Mo, U-Zr, U-Pu-Fs U-Pu-Zr, others
- **Mixed Oxide Fuels (MOX)**
  - EBR-II, FFTF
  - $(U,Pu_{0.2\text{-}0.3})O_2$
- **Mixed Carbide Fuels (MC)**
  - EBR-II, FFTF
  - (U,Pu)C w/15% $(U,Pu)_2C_3$
  - No current interest



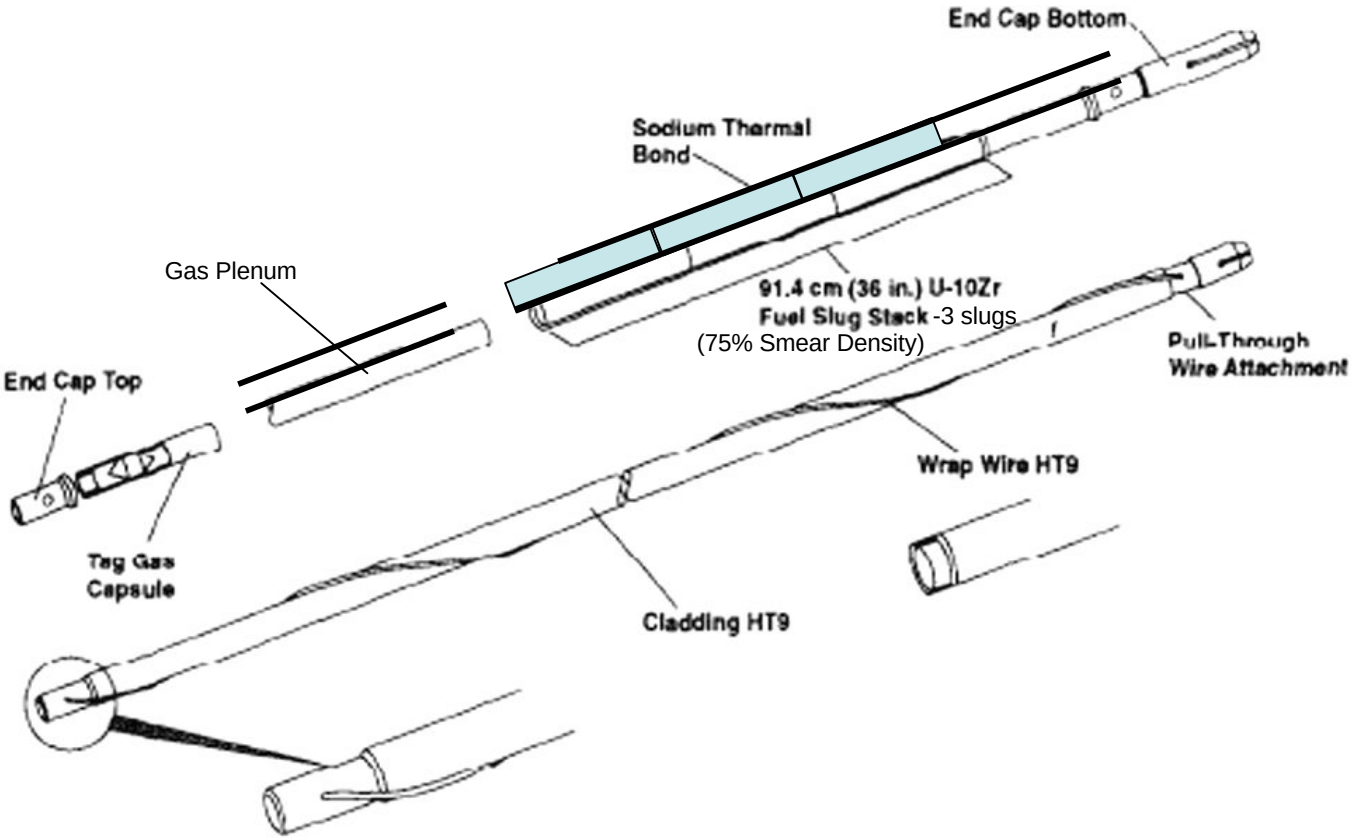


Metallic Fuel Design (EBR-II)



Features of a Metallic Fuel Pin (from Pahl, et al, 1990)

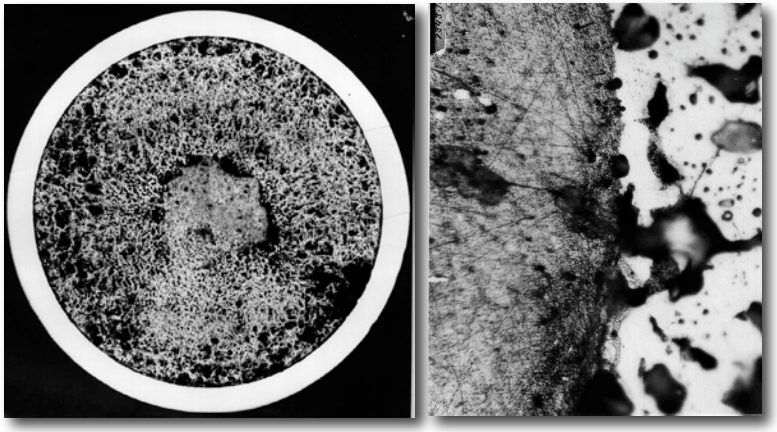
Metallic Fuel Design (FFTF)

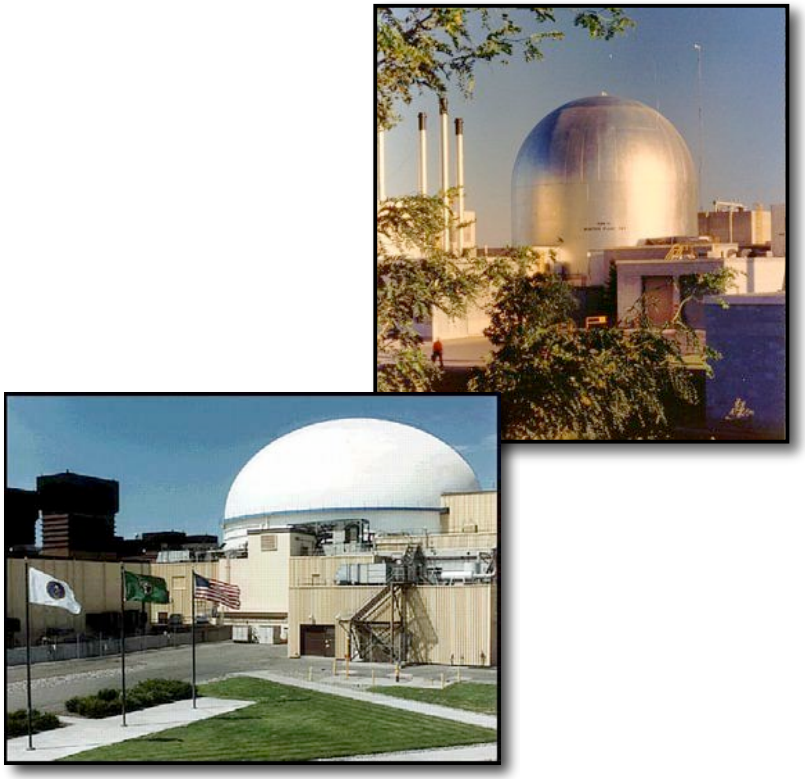


FFTF Series III.b Metallic Driver Fuel Design (from Pitner and Baker, 1993)

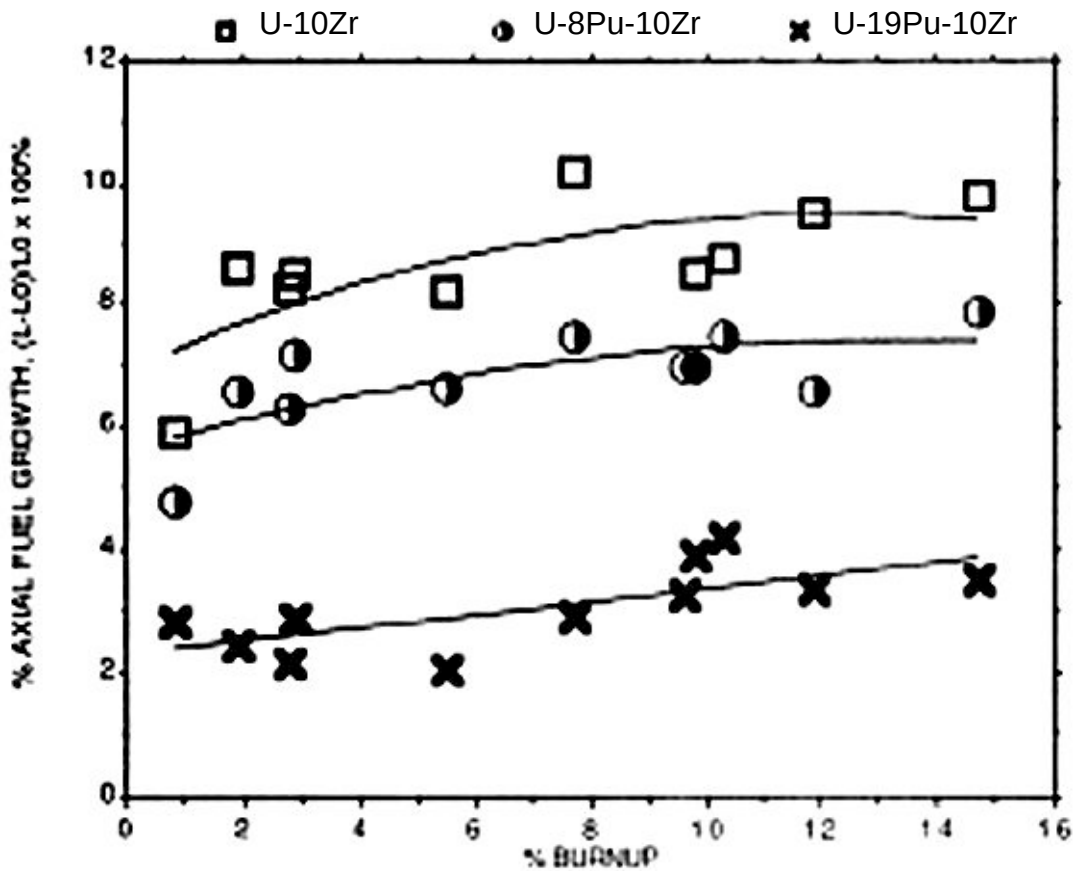
Important Metallic Fuel Performance Phenomena

- **Irradiation growth**
- **Fuel swelling and fuel-cladding mechanical interaction (FCMI)**
- **Gas release**
- **Fuel constituent redistribution**
- **Fuel-cladding chemical interaction (FCCI)**



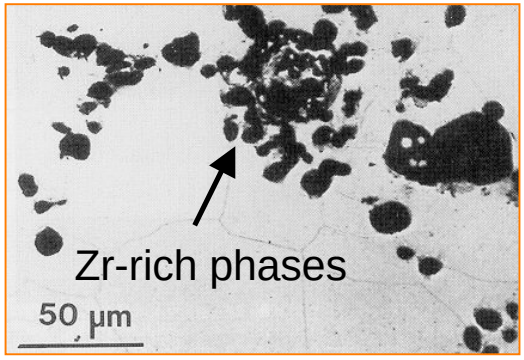


Metallic Fuel Behavior—Axial Growth



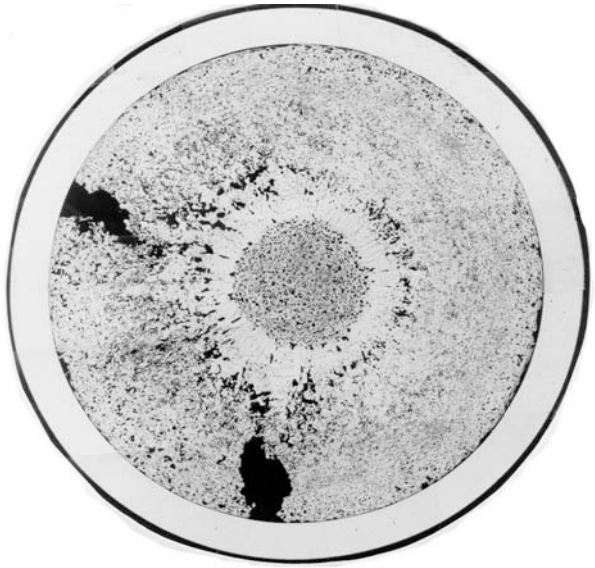
Axial Fuel Growth, from Pahl et al, 1990

Metallic Fuel Behavior—Swelling & Restructuring

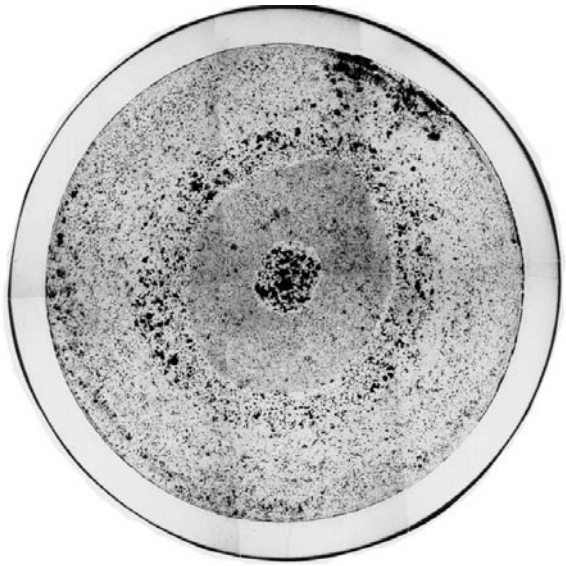


As fabricated U-20Pu-10Zr

X423A at 0.9% BU



X419 at 3% BU

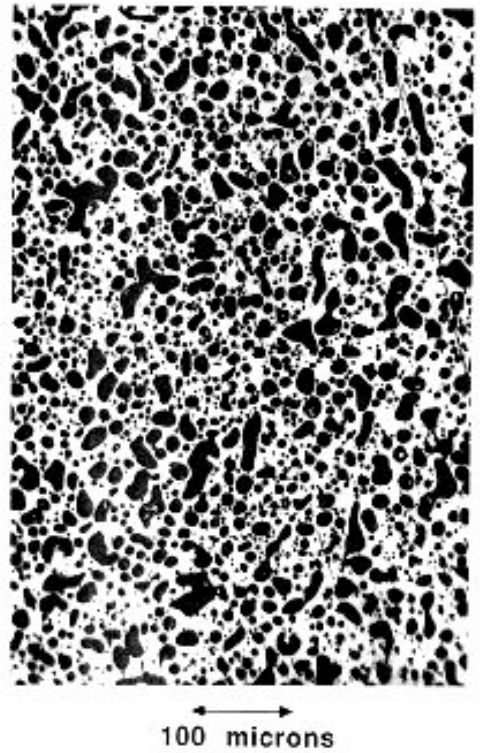


X420B at 17% BU

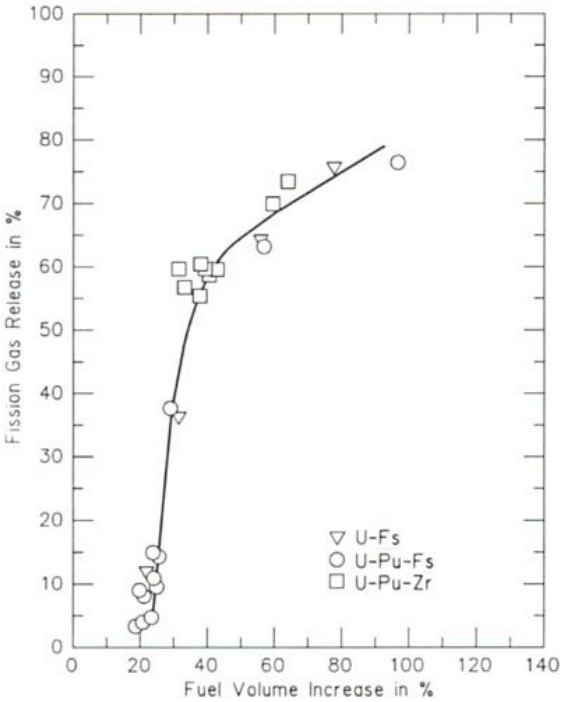
- Redistribution of U and Zr occurs early
- Inhomogeneity doesn't affect fuel life

Metallic Fuel Behavior—Swelling & Gas Release

- **Swelling**
  - Low smear density fuels
  - Rapid swelling to 33 vol% at ~2 at.% burnup
- **Gas Release**
  - Inter-linkage of porosity at 33 vol% swelling results in large gas release fraction
  - Decreases driving force for continued swelling

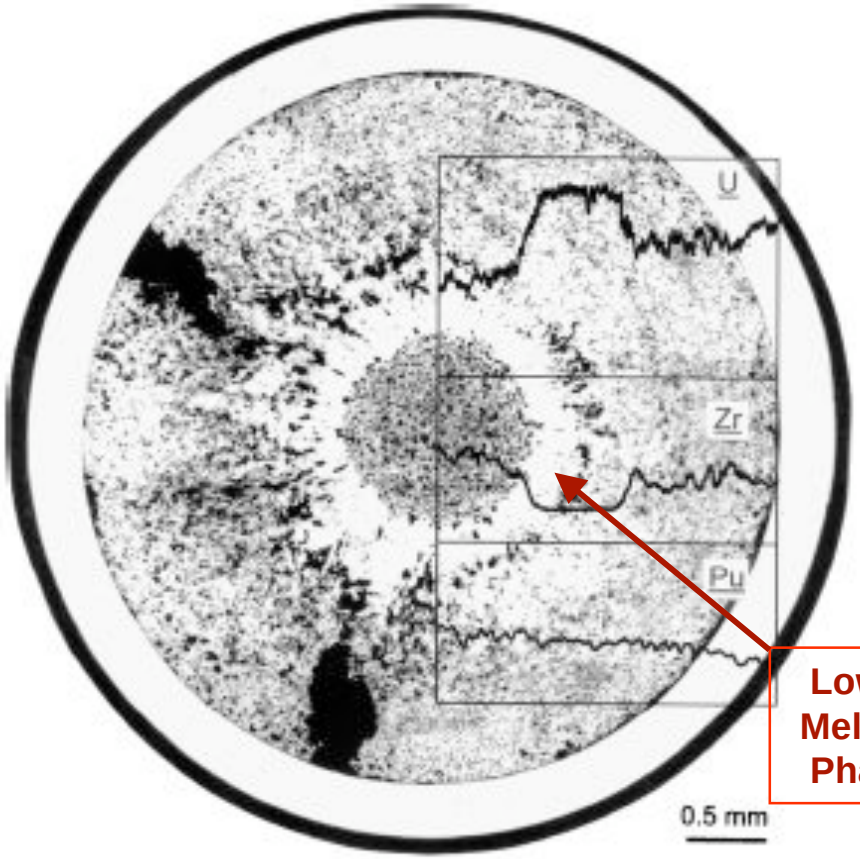


U-19Pu-10Zr (γ-phase) at 2 at.% burnup

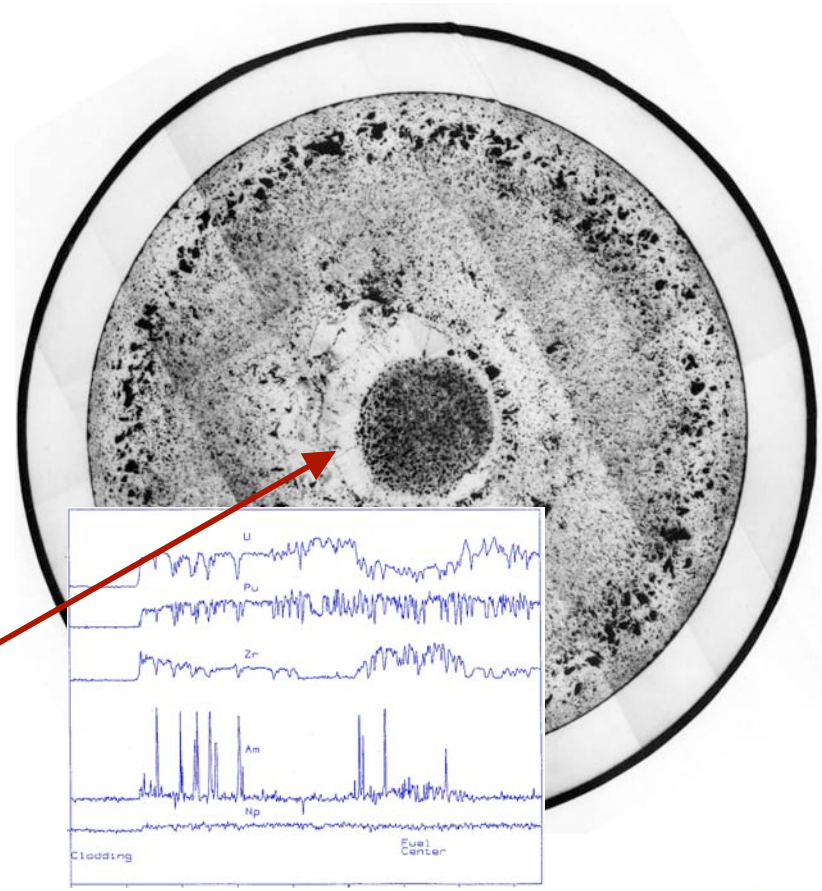


Metallic Fuel Behavior—Fuel Constituent Redistribution

U-Pu-Zr



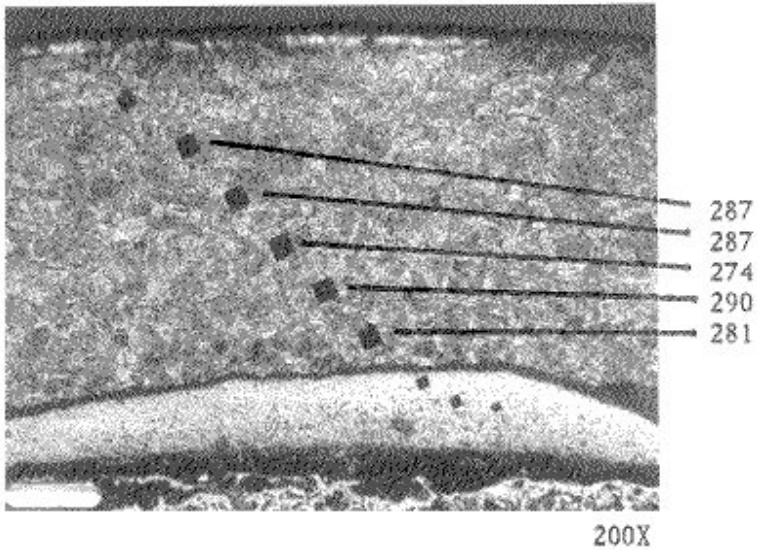
U-Pu-Am-Np-Zr



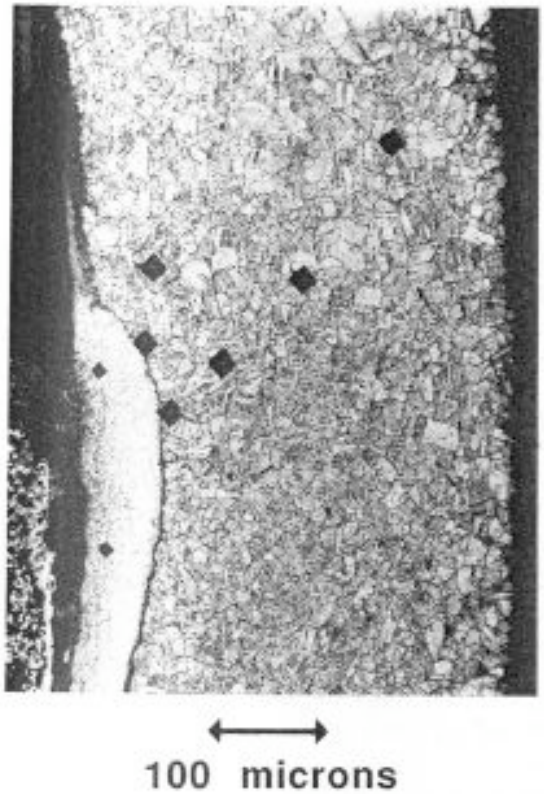
Lower Melting Phase

Metallic Fuel Behavior—Steady-state FCCI

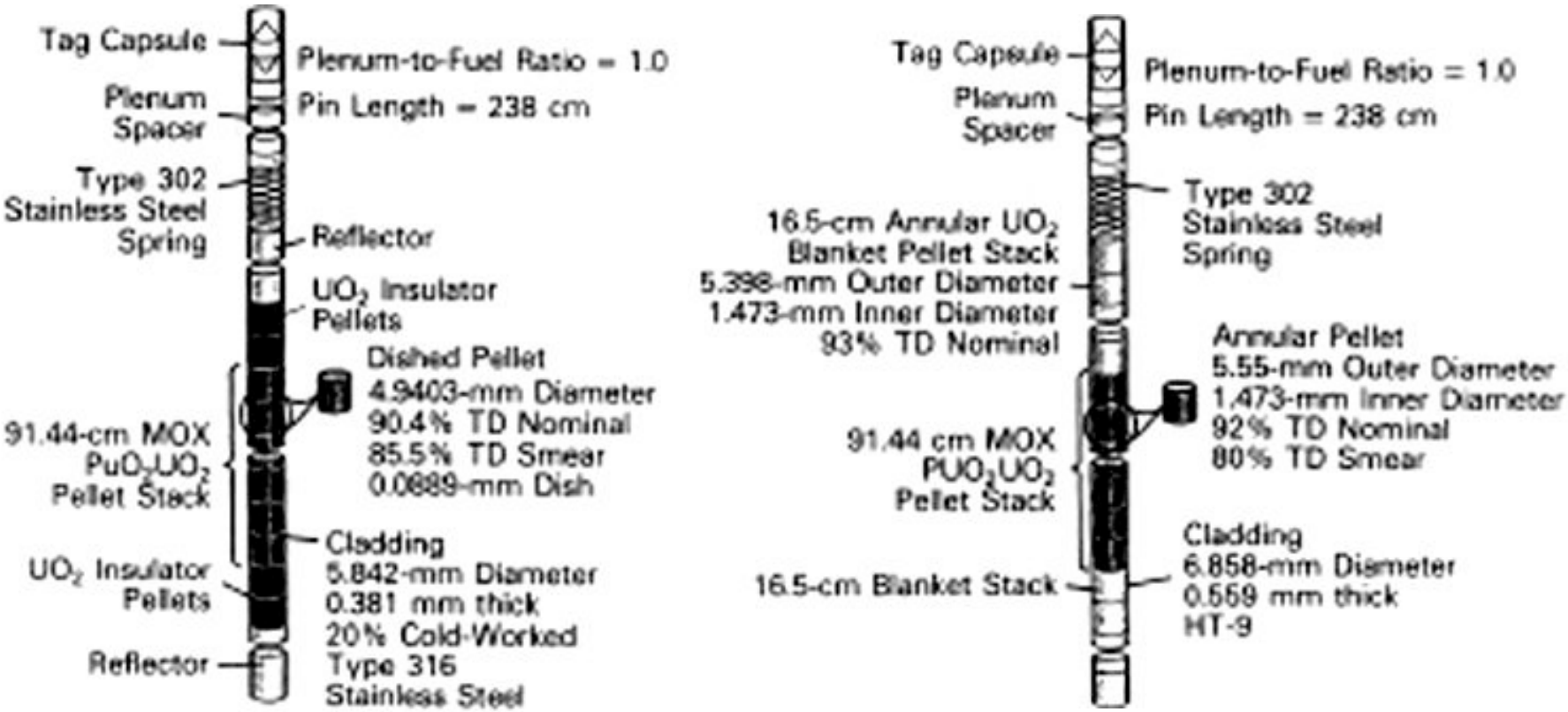
- **Fuel-Cladding Inter-diffusion**
  - RE fission products (La, Ce, Pr, Nd) and some Pu reacts with SS cladding
  - Interaction product brittle
  - Considered as cladding wastage



U-19Pu-10Zr with D9; 12 at.% burnup (from Pahl, et al, 1990)



MOX Fuel Design (FFTF)

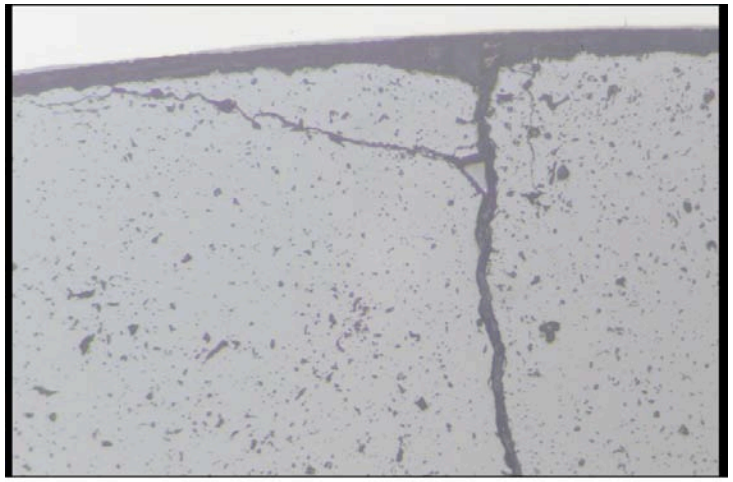


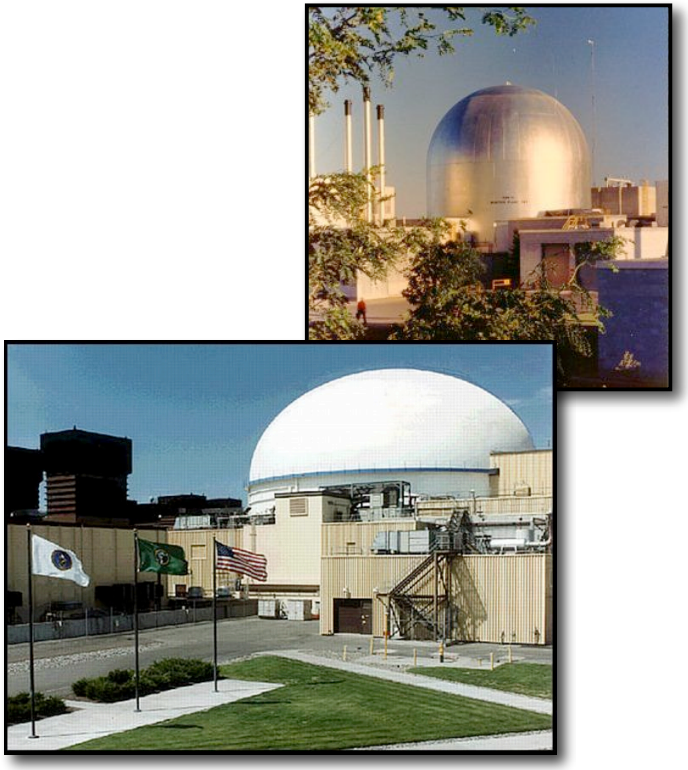
a) b)

FFTF He-bonded MOX Fuel: a) Driver Fuel and b) Core Demonstration Experiment Fuel
(from Bridges et al, 1993)

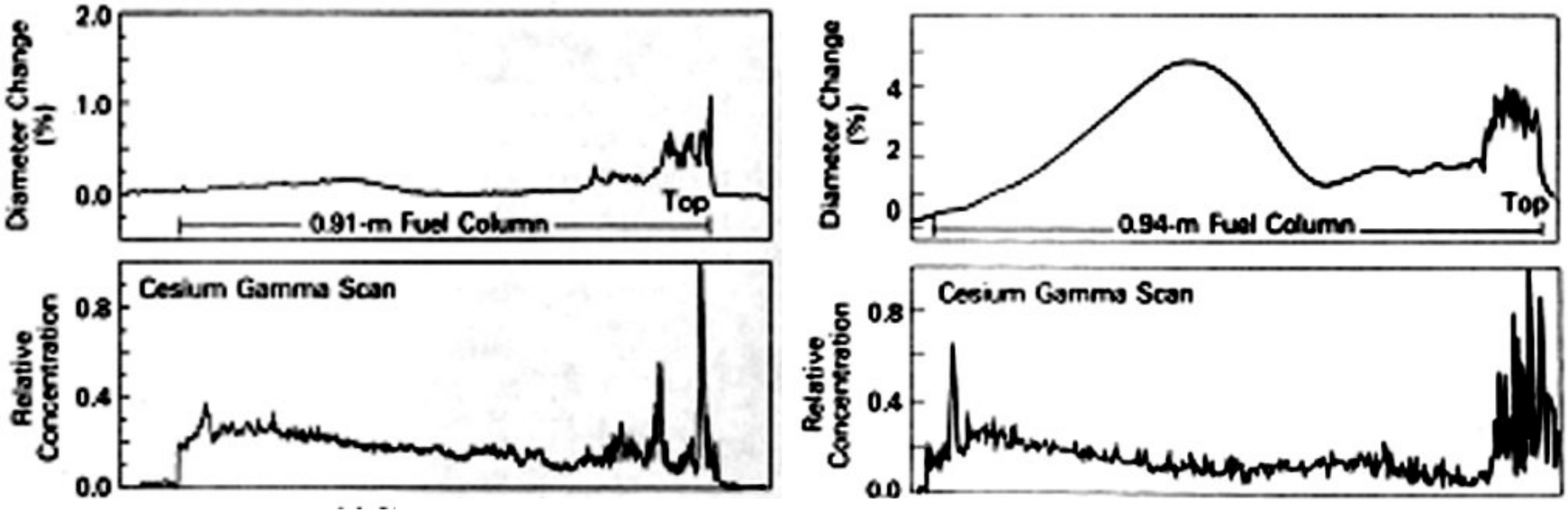
Important MOX Fuel Performance Phenomena

- **Fuel swelling and FCMI**
- **Fuel restructuring**
- **Gas release**
- **FCCI**
- **Fuel-coolant compatibility**





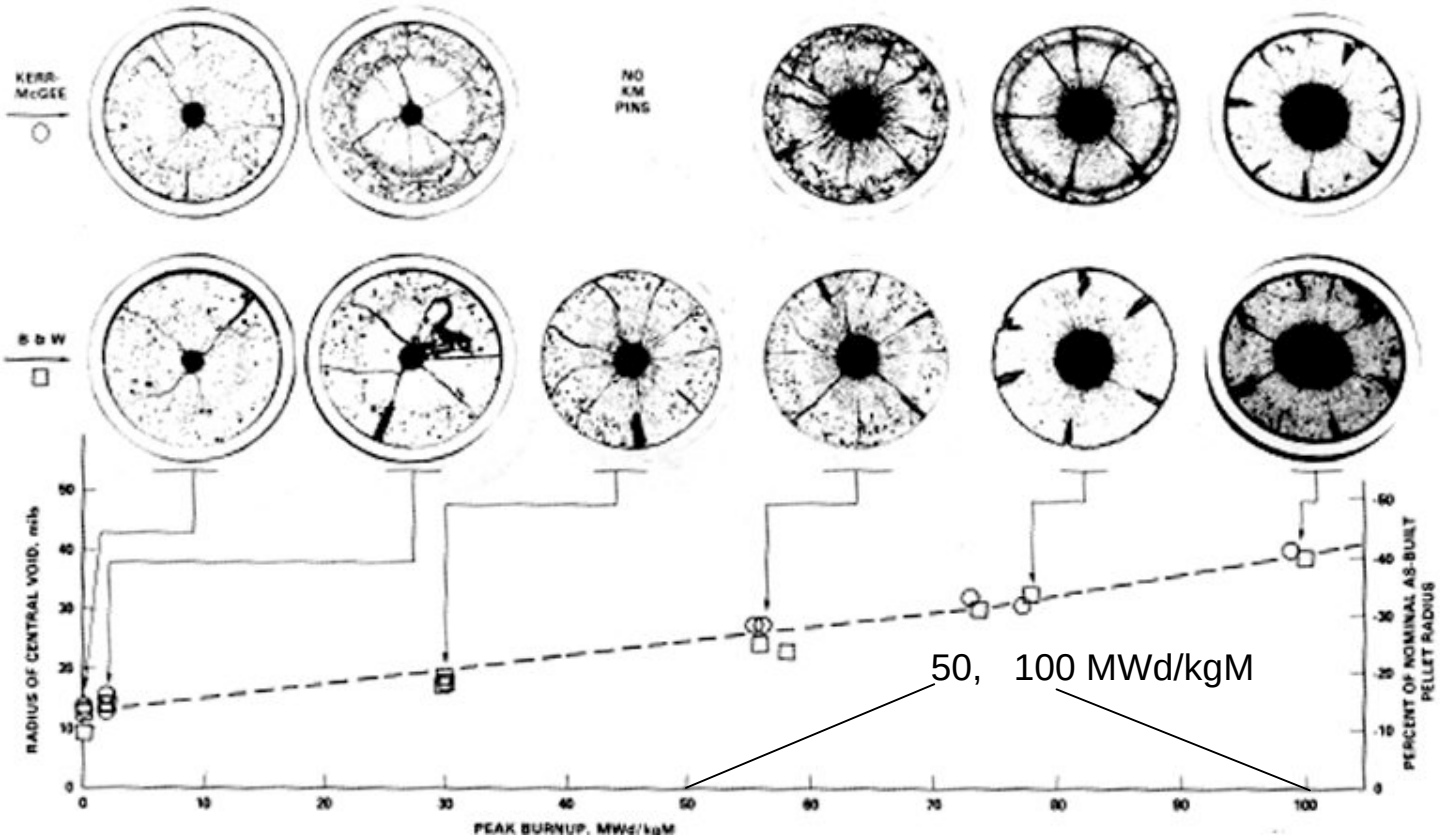
MOX Fuel Behavior—Fuel Swelling and FCMI



(a) (b)

Diameter and cesium fission product accumulation in high-temperature MOX pins, HT9-clad (a) and D9-clad (b). Cs interacted with MOX fuel causing FCMI.
(from Bridges, et al ,1993)

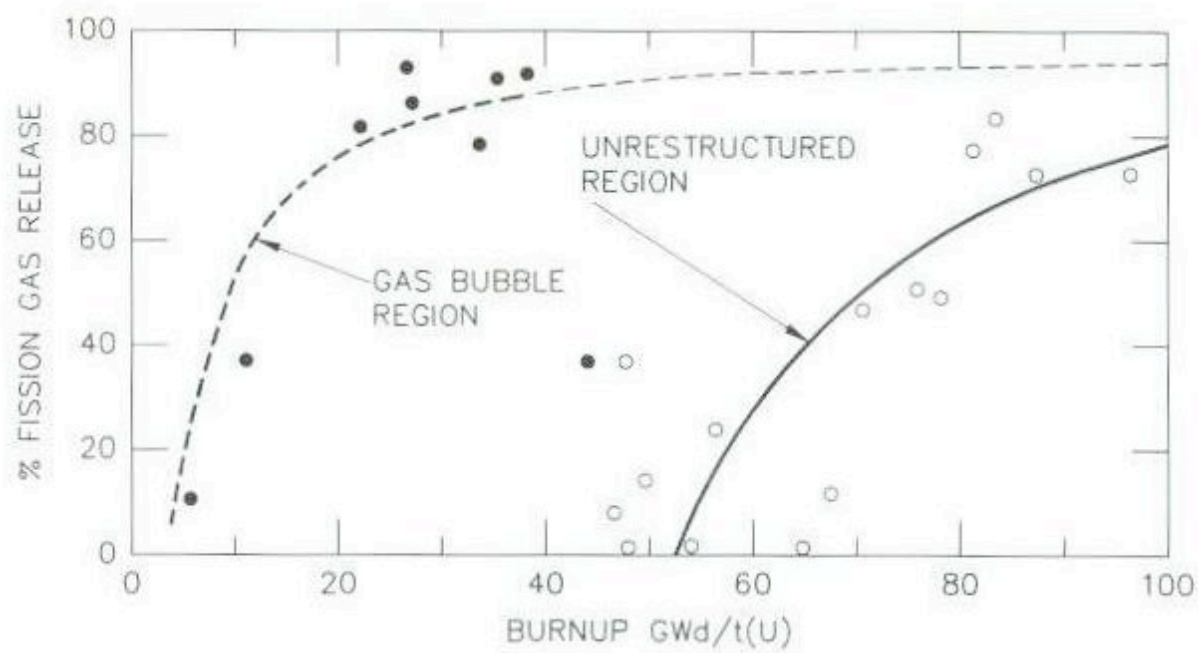
MOX Fuel Behavior—Restructuring



MOX fuel ceramography of FFTF driver fuel produced by Kerr-McGee and Babcock and Wilcox, showing restructuring as a function of burnup. (from Hales, et al, 1986)

MOX Fuel Behavior—Gas Release

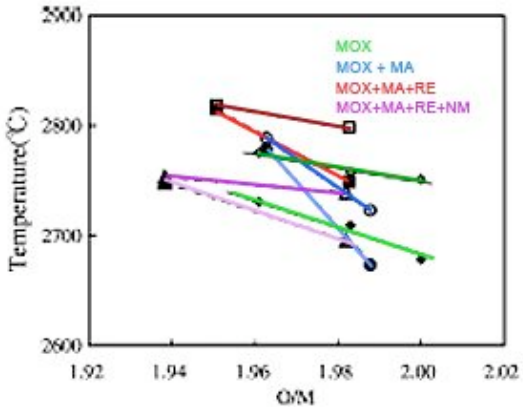
- **MOX fuel operated at high temperature and undergoing restructuring exhibits high gas release.**



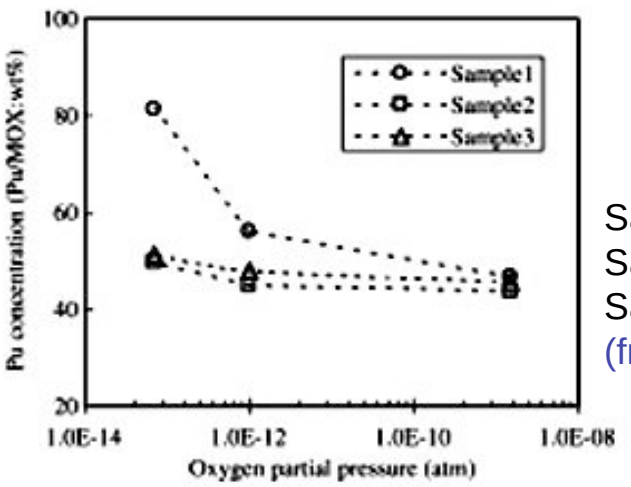
(from Lambert, et al, 1994)

MOX Fuel Behavior—FCCI

- **Hypostoichiometric MOX for SFRs**
  - As-fabricated O/M < 2.00 to suppress free oxygen at high burnup, mitigate FCCI
  - O/M ratio affects fabrication
  - O/M ratio affects properties



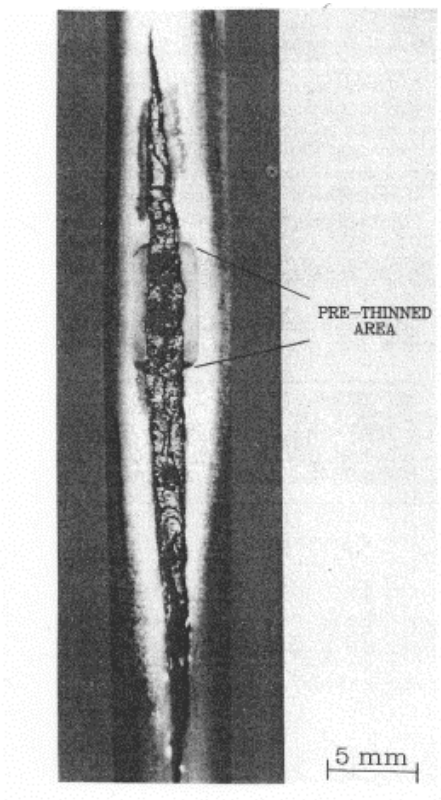
Melting T vs O/M
(from Morimoto, et al, 2005)



Sample 1 – MOX + MAs
Sample 2 – MOX+MAs+REs
Sample 3 – MOX+MAs+REs+NMs
(from Morimoto, et al, 2005)

MOX Fuel Behavior—Fuel-coolant Compatibility

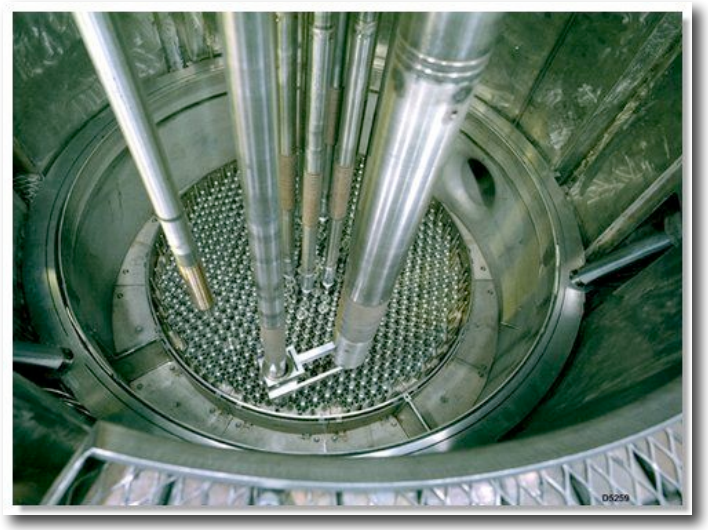
- **Run-beyond-cladding-breach (RBCB) of MOX accompanied by fuel/Na reaction and initial crack extension**
- **Fuel loss can be related to degree of interaction.**
- **Reactant layer becomes coherent and inhibits further reaction with coolant.**

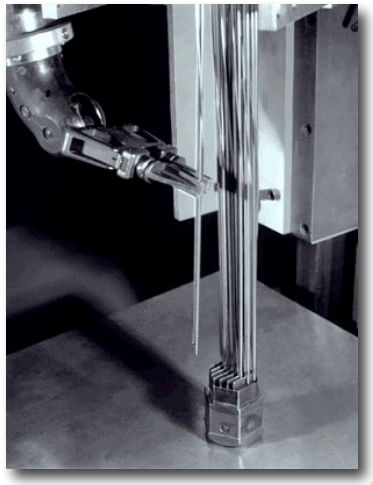


Typical breach extension in induced midlife failure, EBR-II K2B test.
(from Lambert, et al, 1990)

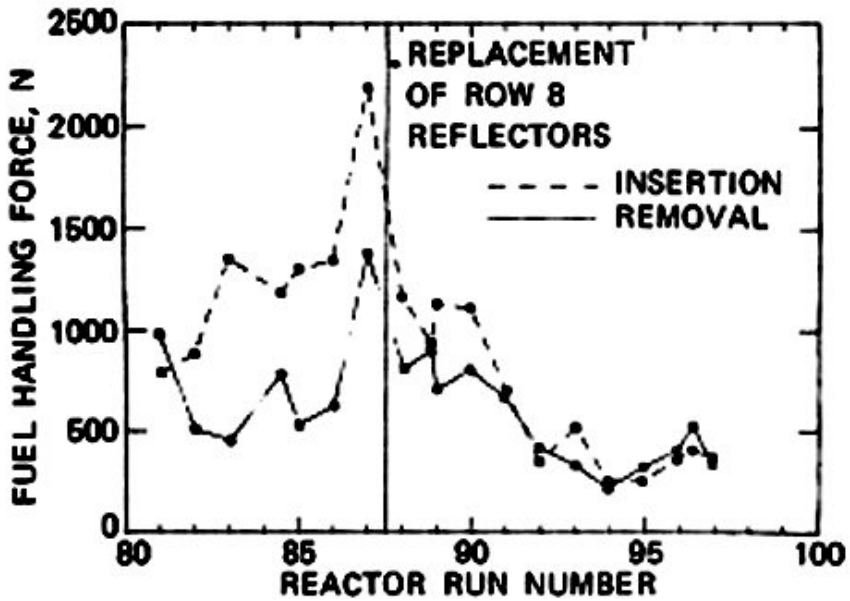
Stainless-Steel Cladding & Duct Performance

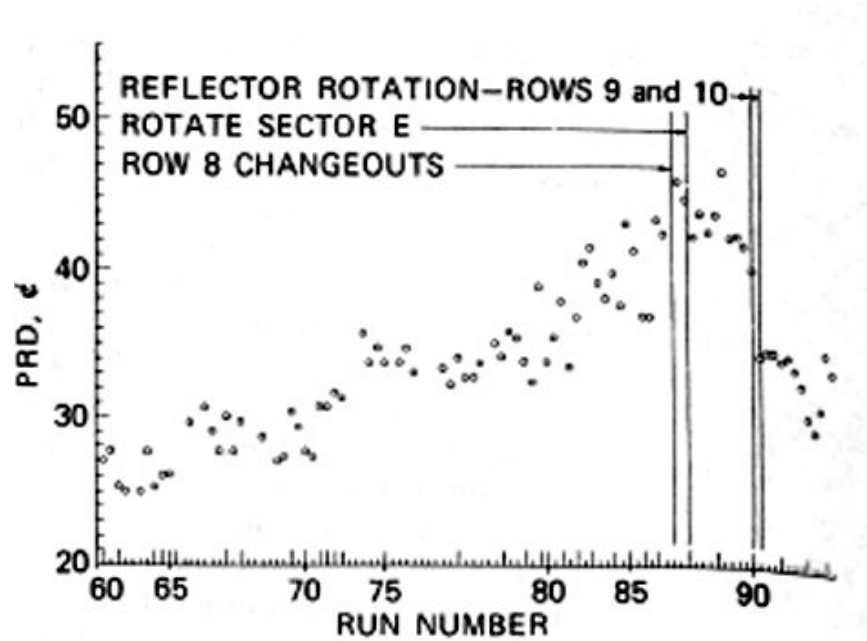
- **Performance Issues**
  - Cladding dilation
  - Duct dilation, bowing, or twisting
- **Irradiation Behavior**
  - Void swelling (AS)
  - Irradiation creep (AS & FMS)
  - Irradiation embrittlement (AS & FMS)
- **Alloys to Address Issues**
  - Advanced austenitic stainless steels
  - Ferritic & tempered-martensitic stainless steels
  - Oxide-dispersion strengthened steel alloys





Duct Performance—Bowing & Dilation





Effects on fuel handling forces and the Power Reactivity Decrement (PRD) to get to 62.5 MWt versus EBR-II run number. Anomalies were caused by assembly hex-duct bowing and dilation. (from Shields, 1981)

Duct Performance—Length Change

R.D. Leggett, L.C. Walters / Status LMR fuel development in the USA

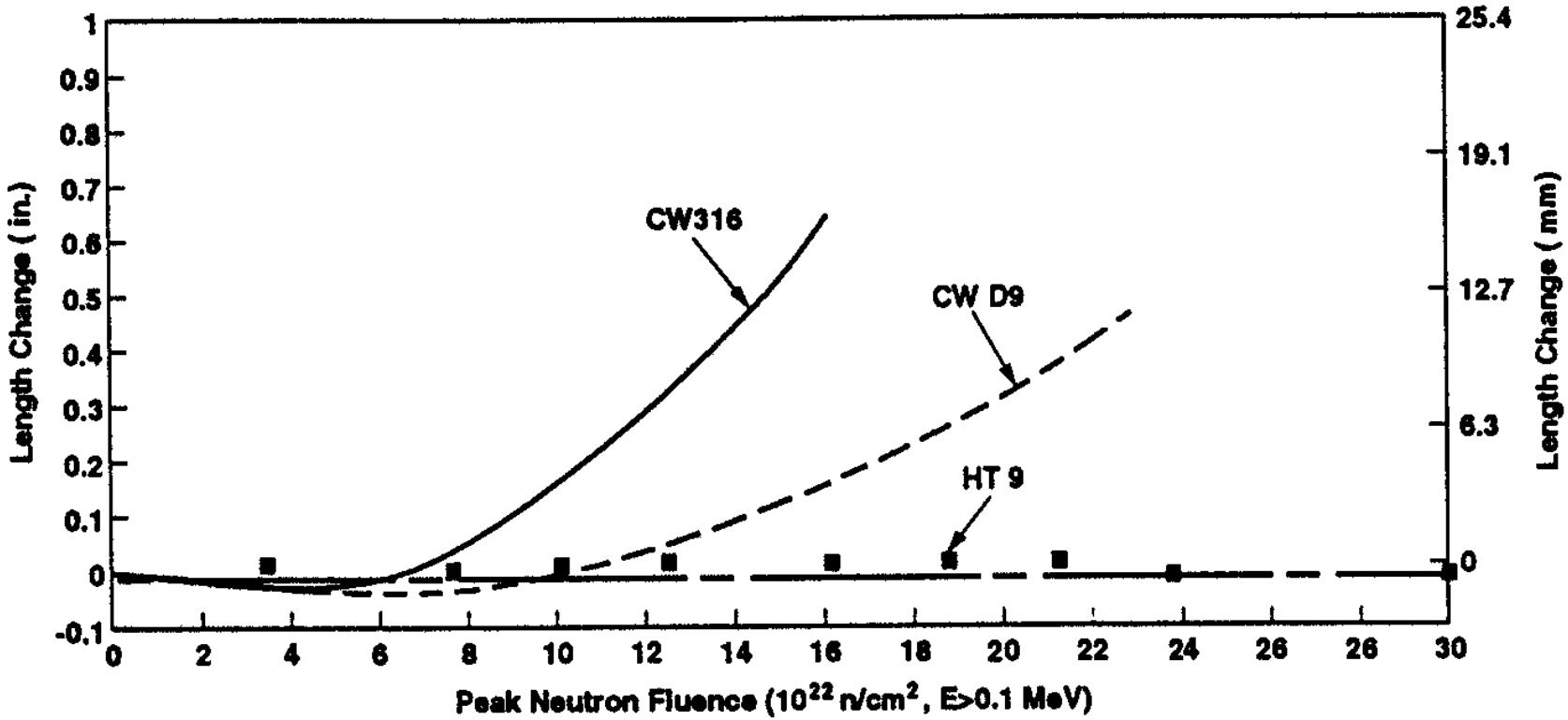
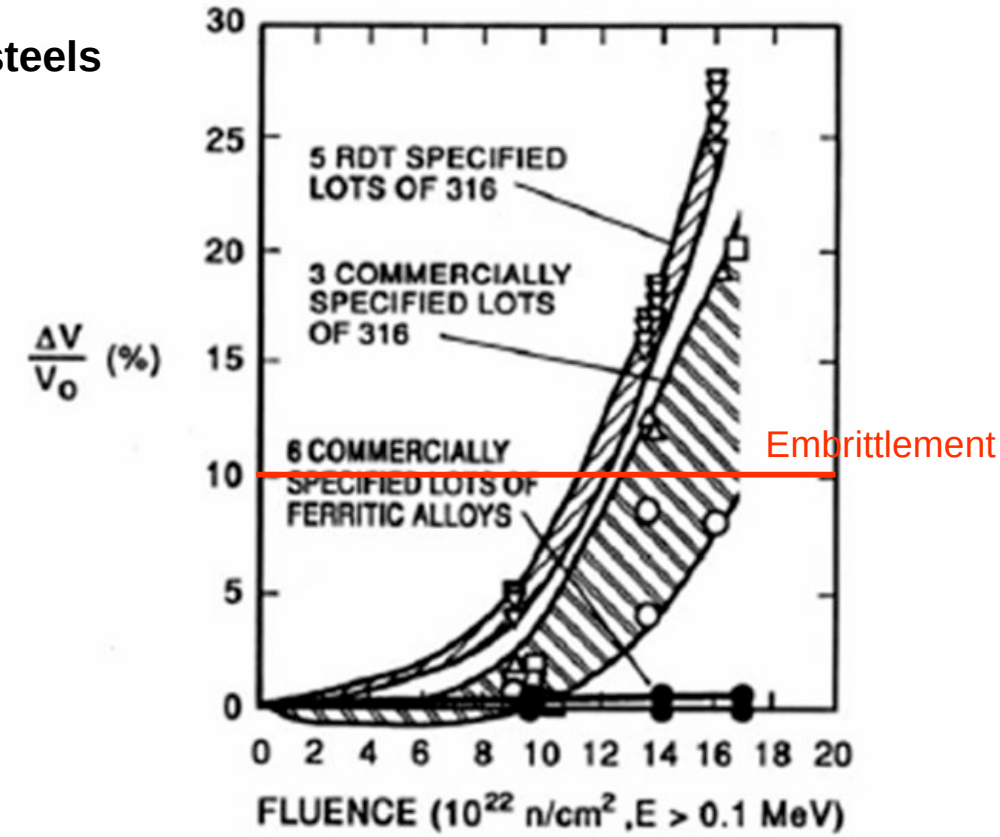


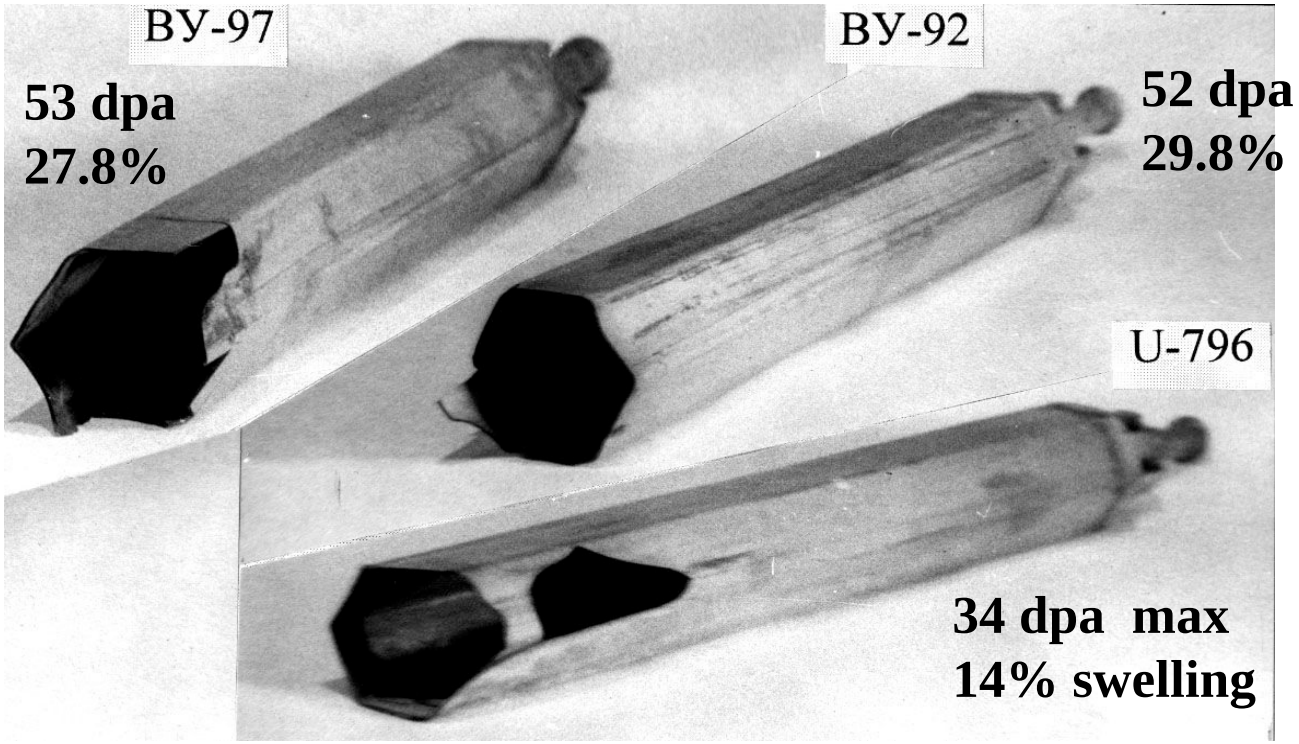
Fig. 4. FFTF subassembly length change with various duct materials.

Duct Performance—Void Swelling

Void swelling of commercial steels irradiated in EBR-II at ~420°C.
(from Gelles, 2004)

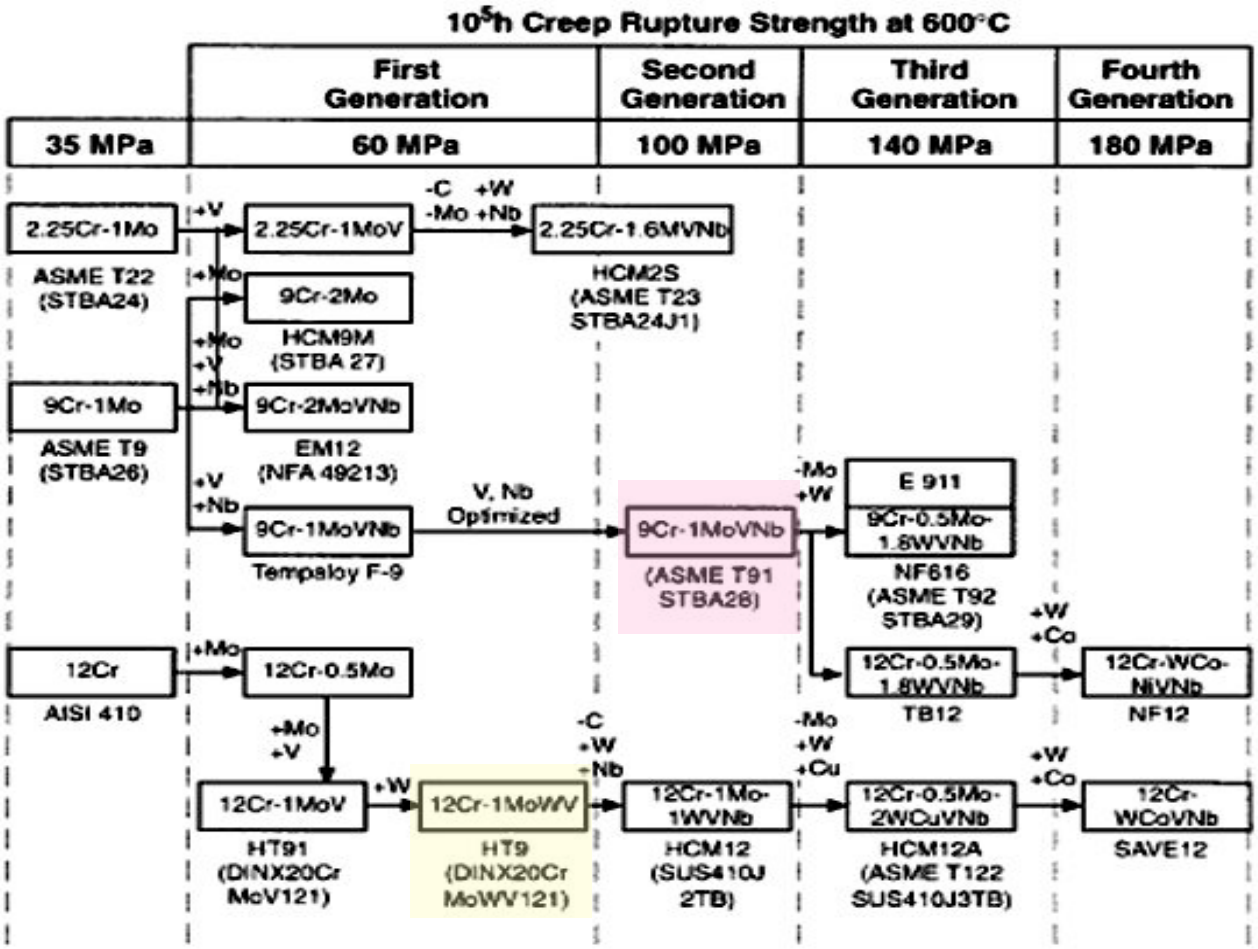


Duct Performance—Void-induced Embrittlement



Severe void-induced embrittlement in X18H10T (304ss-like) hexagonal assemblies from core and reflector regions of BOR-60. **(from Garner, 2000)**

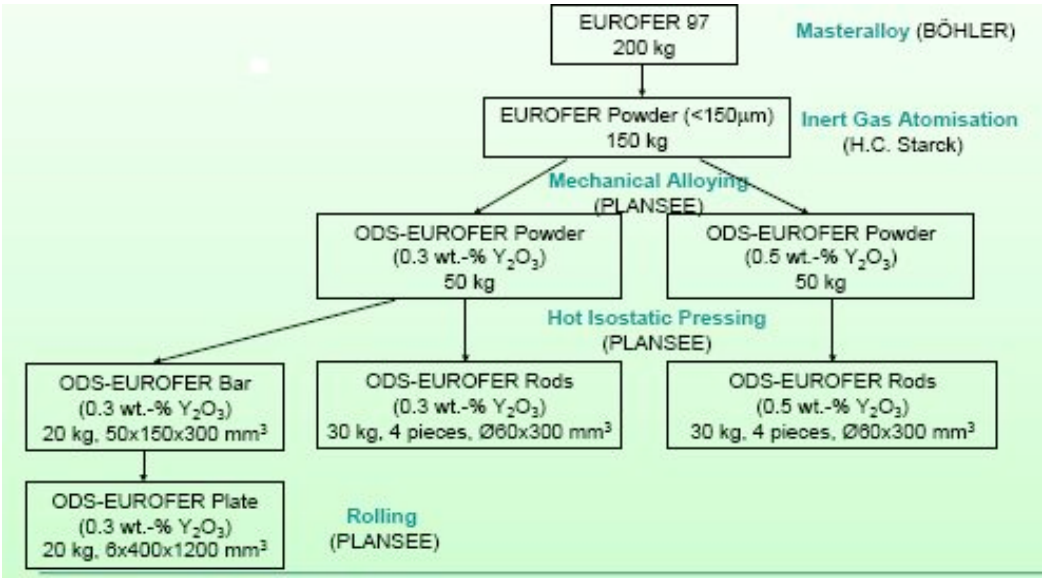
Ferritic/Martensitic Stainless Steel Development



Development of ferritic/martensitic alloys for high-temperature applications. (from Allen, 2004)

Oxide Dispersion Strengthened (ODS) Ferritic/Martensitic Alloys

- **Ferritic/martensitic alloy use limited by high temperature stress rupture properties.**
- **Further strengthening achieved by addition of very small oxide particles (usually Y_2O_3).**

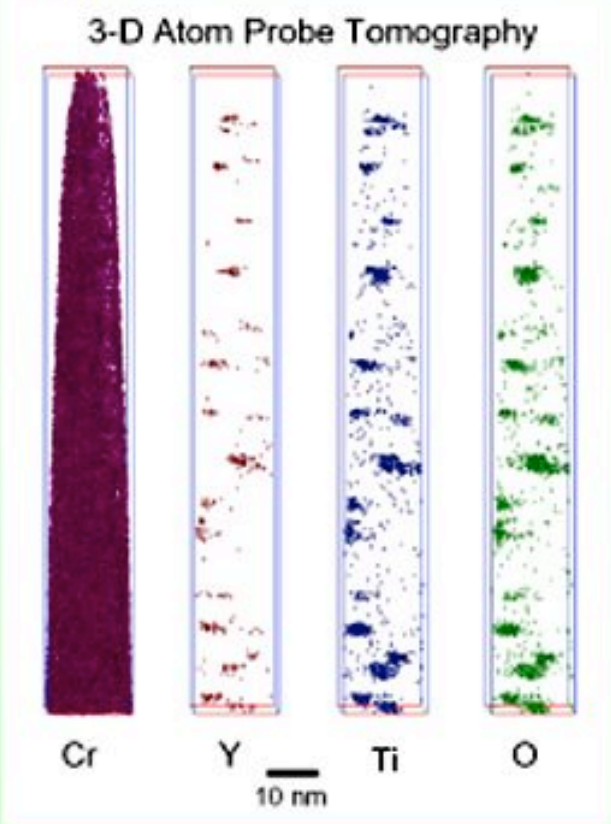


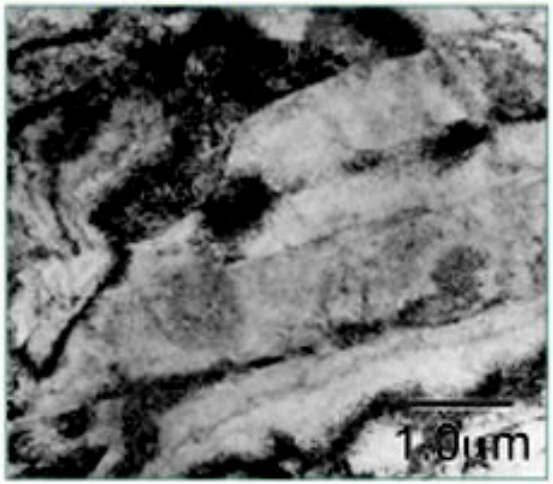
European ODS ferritic/martensitic alloy fabrication.
(from Lindau et al, 2005)

Oxide Dispersion Strengthened Ferritic/Martensitic Alloys

Nanocomposited Ferritic (NCF) Steel

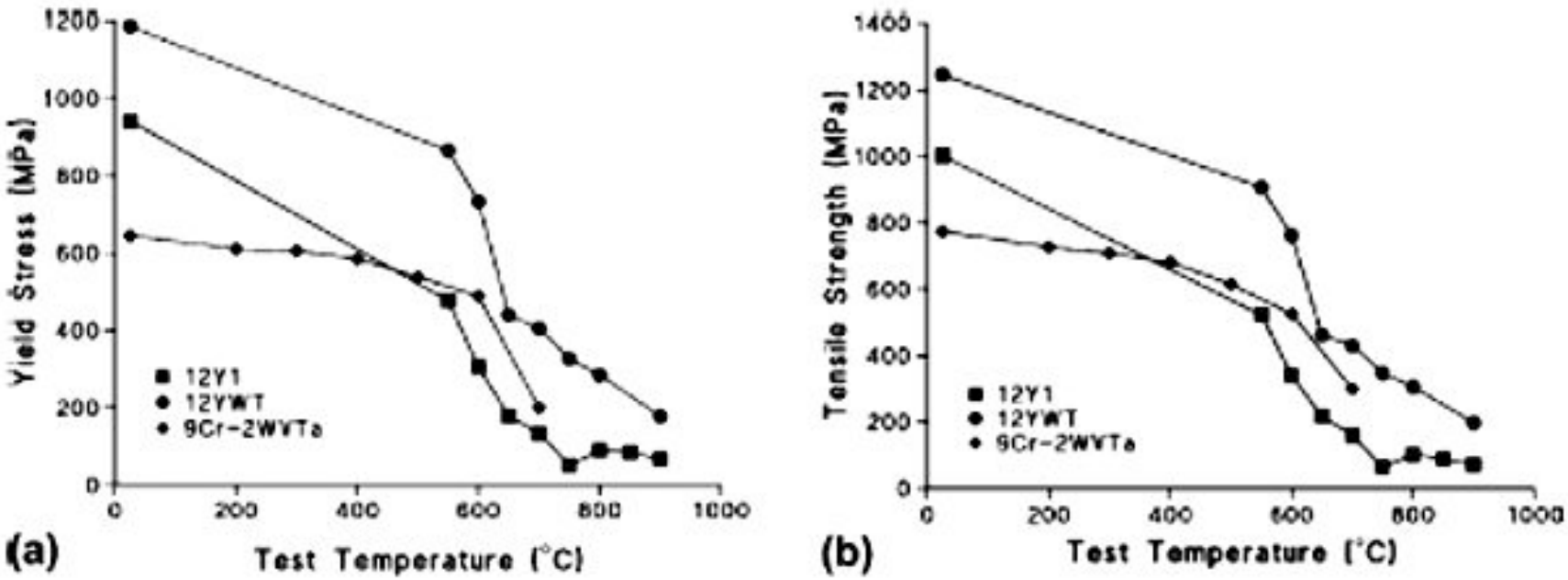
(MA Fe-12Cr-3W-0.4Ti + 0.25Y_2O_3 : 12YWT) Miller, Hoelzer, Zinkle ORNL





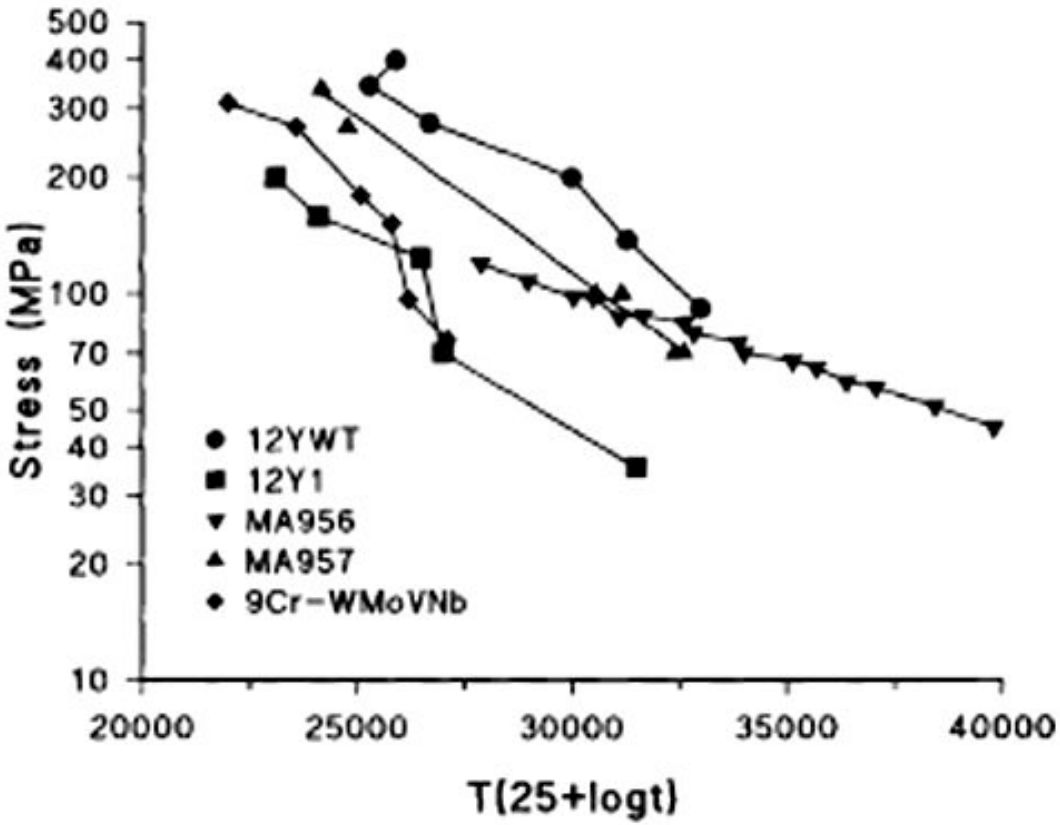
- very high number density of ~10^{24}/m of uniformly distributed nanoclusters
  - site occupancy on bcc Fe lattice
  - average size r_g = 2.0 (+/- 0.8) nm
- elongated grains containing high dislocation number density (TEM)

Strength of ODS Ferritic/Martensitic Steels



Yield (a) and tensile (b) strength of ODS alloys compared to a non-ODS Ferritic/ Martensitic steel. (from Klueh, et al 2005)

Stress Rupture of ODS Ferritic/Martensitic Steels



Stress rupture properties of ODS alloys compared to a non-ODS Ferritic/ Martensitic steel. **(from Klueh, et al 2005)**

Limitations to Use of Ferritic/Martensitic Steels

- **Ferritic/martensitic stainless steels (e.g., HT9, Mod 9Cr-1Mo, HCM12, etc.) are expected to be applicable to 200 dpa peak dose (~140 MWd/kg burnup), 650°C peak cladding temperature.**

- **ODS ferritic-martensitic stainless steels (FMS S/A duct) is expected applicable to 250 dpa peak dose (~ 180 MWd/kg burnup) and 700°C peak cladding temperature.**

- **Major issues are accumulation of high burnup demonstration data and establishment of mass-production technology.**

Base 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

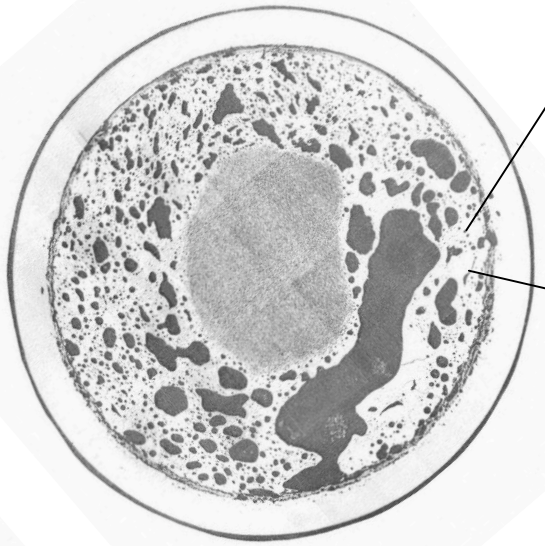
Transient Phenomena—Metallic Fuels

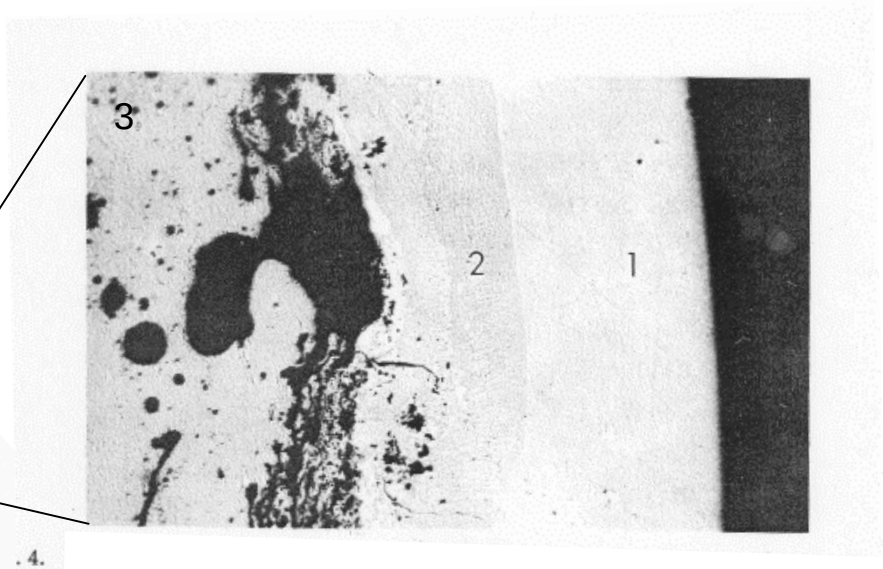
- **Pre-failure Behavior**
  - Axial expansion
  - Cladding strain due to gas pressure
  - Possible fuel-cladding liquefaction
- **Failure Behavior**
  - Failure generally near top of fuel column
  - Stress rupture due to gas pressure in cladding thinned by eutectic-like penetration and weakened at high temperature
- **Post-failure Behavior**
  - Fuel injection into coolant
  - Low stored energy, no reaction with coolant, local sodium voiding
- **Overpower capability 4.0 to 4.4 times nominal power**

Transient Phenomena—Metallic Fuels
Fuel/Cladding 'Eutectic' Formation

U-10Zr / HT9 at 800°C, 1 hr

(from H. Tsai, et al, 1990)





1 - Unaffected cladding
2 - Fuel/cladding solid-state interaction
3 - Fuel/cladding liquid phase

Transient Phenomena—MOX Fuels

- **Pre-failure Behavior**
  - Axial relocation (apparently, upward axial motion)
  - Cladding strain due to FCMI and gas pressure
- **Failure Behavior**
  - Failure generally in upper 1/3 of fuel column
  - Cladding melt-through with gas pressure and FCMI, cladding weakened at high temperature
- **Post-failure Behavior**
  - Fuel dispersal into coolant
  - Relatively high stored energy, reaction with coolant, local sodium voiding
- **Overpower capability 3.0 to 4.5 times nominal power**

Metallic and MOX Fuels Well Developed

- **Metallic Fuels (U-Zr or U-Pu-Zr)**
  - Acceptable performance and reliability demonstrated up to 10 at.% burnup, with capability demonstrated to 20 at.% burnup
  - Robust overpower capability demonstrated in TREAT tests: ~ 4 to 5x's nominal power; failures near top of fuel column; pre-failure axial expansion
  - Performance issues typically creep rupture at high burnup, accelerated due to FCCI.
  - Performance phenomena with U-Fs, U-Zr & U-Pu-Zr are the same. Burnup, temperature and cladding performance are key variables
- **MOX Fuels**
  - Acceptable performance and reliability demonstrated up to 10 at.% burnup, with capability demonstrated to 20 at.% burnup
  - Robust overpower capability demonstrated in TREAT tests: ~ 3 to 4x's nominal power; well above primary and secondary FFTF trips; failures near core mid-plane; pre-failure axial fuel motion
  - Performance issues typically creep rupture at high burnup, accelerated due to FCMI (and FCCI if O/M not controlled).

Technical Readiness Levels for SFR Fuels

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 (~100 gram batches). Irradiation testing of small-samples (rodlets) in relevant environment. Design parameters and features establsihed. Basic properties compiled.
5		Fabrication of pins using prototypic feedstock materials at laboratory-scale (10 kg). Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified.
6		Fabrication of pins using prototypic feedstock materials at laboratory-scale (1 kg) and using prototypic fabrication process. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Safety basis establis
7	Proof-of-performance	Fabrication of test assemblies using prototypic feedstock materials at engineering-scale (100 kg) and using prototypic fabrication process. Assembly-scale irradiation testing at prototypic environment. Safety basis established for full-core operations.
8		Fabrication of a few core-loads of fuel (tons) and operation of a prototype reactor with such fuel.
9		Routine commercial-scale operations. Multiple reactors operating

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

Driver Fuel/ Analog Transmutation Fuel
Metal (U-Pu-Zr)
- Not formally qualified
- Not used in industrial-scale

Driver Fuel Analog Transmutation Fuel
Metal (U-Zr)
Oxide (U,Pu)
- Qualified for reactor operations
- Successful mission operations
- Operational database wider for MOX, especially considering International experience

Metallic and MOX Fuels—Summary

- **Metallic and MOX fuel performance in SFRs are both well known, with good experience in the US**
- **MOX fuel is particularly well developed in France and Japan**
- **GNEP application of these fuel forms to an actinide transmutation mission will bring significant new challenges**

Fuel Test Plan for PRISM Prototype

Fuel Test Plan (Energy Policy Act of 1992)

- **Created by Argonne National Laboratory, GE and Westinghouse for metallic fuels:**
  - "In response to the Energy Policy Act of 1992… complete R&D activities by the end of 1996 for U-Pu-Zr driver fuel and U-Zr blanket fuel in order to initiate Title II design activities for the Prototype ALMR, and, by the end of 1998, to extend the database to include U-Pu-Zr fuel which contains minor actinides (Am, Np) in quantities representative of light water reactor spent-fuel recycle."
- **The <u>Fuel Test Plan</u> (June 1994) outlined the remaining issues and schedules for achieving these goals. It also responded to all of the questions concerning fuel performance raised by the NRC in:**
  - "Pre-application Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor, Final Report," U.S. Nuclear Regulatory Commission, NUREG-1368, January 1994.

Fuel Test Plan (1994)—Issues Identified for U-Pu-Zr Fuels

- **Steady-State Performance**
  - Fuel Swelling—well characterized; no expectation that MAs and higher concentrations of REs would have an effect
  - Constituent Redistribution, FCMI, and FCCI—*effects of MAs not well characterized; effect of higher RE concentrations needs to be assessed* (*also true for MOX*)
  - Fuel Pin Length (i.e., evaluation of experimental database to longer pin designs)—well characterized; no expectation that MAs and REs would have an effect
  - Fission Gas Release—well characterized; no expectation that MAs and REs would have an effect

Fuel Test Plan (1994)—Issues Identified for U-Pu-Zr Fuels

- **Transient Performance**
  - Fuel/Cladding Compatibility—*effect of MAs not well characterized; effects of REs needs to be assessed*. (MOX—*O/M modifications may be needed*)
  - FCMI—well characterized; no expectation that MAs and REs would have an effect
  - Fuel Melting—unusual compositions may need characterization. (MOX—*O/M modifications may be needed*)
- **Post Failure Performance (Run-Beyond-Cladding-Breach)**
  - Fuel Loss, Fuel/Coolant Interaction—well characterized; no expectation that MAs and REs would have an effect. (MOX—*confirmatory testing may be required depending on O/M modifications*)

Fuel Test Plan (1994)—General Issues Identified

- **Fuel Reliability**
  - Statistical evaluation of fuel lifetime—fuel element reliability for recent designs has been controlled by cladding and duct properties (e.g., creep rupture for cladding, swelling for ducts). Expected lack of influence from MAs and REs on fuel reliability needs to be demonstrated in LTAs.
- **Fuel Modeling**
  - Semi-empirical models (LIFE4, SIEX, FRAPCON?) seem adequate to predict MOX lifetime.
  - Incorporation of 'first principles' or 'atomistic' models may be used to short-cut design to demonstration scope.
  - LIFE-METAL needs more mechanistic models.

Fuel Test Plan (1994)—General Issues Identified

- **<u>Fabrication</u> (i.e., do modifications in fabrication methods affect fuel performance?)**
  - Metallic Fuel: The simplicity of metallic fuel fabrication well suited for transfer to a remote setting. Waste from molds and crucibles, potential losses of Am (due to high vapor pressure) needs to be reduced/eliminated by modification of casting process; replace injection casting with bottom pour (no vacuum, reusable molds, etc.).
  - MOX Fuel: Proven fabrication methods in glovebox setting. Hot cell/remote setting may create challenges. O/M control with the inclusion of MAs and REs unproven.

Fuel Test Plan (1994)—General Issues Identified

- **Cladding and Duct Performance**
  - Ferritic/martensitic steels expected applicable to 200 dpa dose (~140 MWd/kg fuel burnup), 650°C peak temperature; should be applicable for ducts to higher exposures.
  - ODS ferritic stainless steel cladding expected applicable to 250 dpa dose (~180 MWd/kg fuel burnup) and 700°C peak temperature.
  - Major issues
    - *Accumulation of high burnup/dose demonstration data*
    - *Establish industrial production base*

Fuel Test Plan (1994)—Conclusions

- **Most fuel performance issues are well understood and adequately tested**
  - U-Pu-Zr metallic fuel
  - $(U,Pu)O_2$
- **Variations in fuel compositions to include MAs and possible carry-over of RE fission products will require additional testing**
- **Fuel modeling and code development needs additional effort, especially for metallic fuels**

Fuel Specification

Metallic Fuel Specification—Historical Trend

- **EBR-II experience showed that early specifications contained too much 'process control' information**
  - Chemistry over-specified (i.e., concern for potential minor contaminants that would not affect fuel performance)
  - Dimensional control of fuel slug over-specified (i.e., to ensure the fuel and Na bond height would be as expected, but these did not critically influence thermal hydraulics)
  - The last fuel specification (Mark-V) written reflected much-relaxed tolerances and was largely based upon delivering a homogeneous fuel with a known/controlled reactivity.

Metallic Fuel Specification—Example

- **EBR-II Mark-V Fuel Specification**
  - Recycled metallic fuel (U-Pu-Zr in HT9 cladding) containing carry-over RE fission products and actinide isotopes characteristic of recycled EBR-II fuel
  - Written to exclude process control information.
  - Chemistry
    - *Slug top & bottom sampled for homogeneity.*
    - *C, O, N, and Si impurity analysis to ensure Zr in solution (Zr important to FCCI and these impurities tie-up Zr and render it ineffective); all other impurity elements analyzed for information only.*
    - *Actinide tolerances relaxed (e.g., Pu = 20 ± 1 wt.%); isotopics measured for use in determining acceptable slug weight*

Fuel Specification (Example)

- **EBR-II Mark-V Fuel Specification**
  - Fuel slug dimension and weight
    - *Dimensional guidelines relaxed (e.g., ±0.003 in. on diameter, ±0.1 in on length)*
    - *Fuel slug mass (tolerances set by physics analysis for EBR-II):*

      $1.23 * {}^{239}Pu + {}^{235}U + 0.51 * {}^{240}Pu + 0.10 * {}^{238}U = 45.4 \pm 2.3$ *grams per slug*
    - *Na bond height (0.50 ± 0.25 in.)*
  - Radiography to measure Na bond height used for bond quality.
  - Closure welds qualified and 100% visual inspection, 100 % leak check (unless qualification showed this could be eliminated).

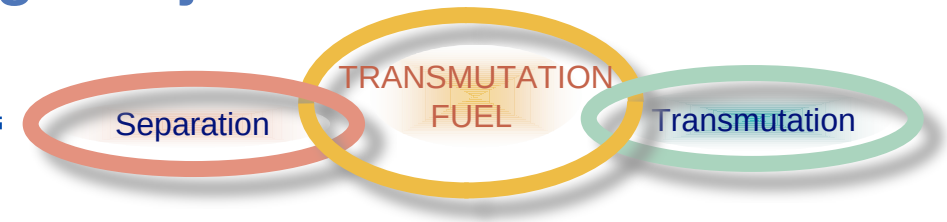
Fuel Specification

- **Draft metallic fuel specification for PRISM (by GE with ANL input) based upon Mark-V approach (GE 23A3912, Rev.B, 2-28-92).**

- **MOX fuel specification should utilize same approach, but performance issues will require some dimensional tolerances to remain tight due to He bond. Control of starting O/M, etc. may require additional chemistry control.**

Experience with Fuels Containing Minor Actinides

GNEP Fuels Campaign Objective



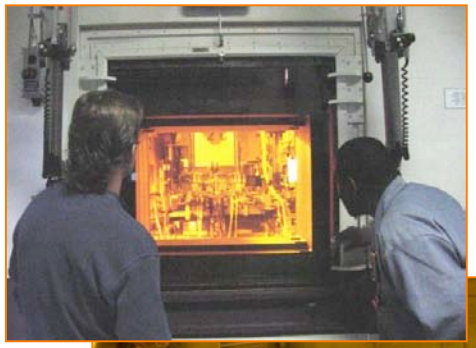
- The ultimate objective of the fuel development campaign is to develop and qualify the initial transmutation fuel/target for use in fast burner reactors over the entire range of compositions:
  - obtain closure of the fuel cycle,
  - maintain the commercial competitiveness for nuclear energy
- If a step-wise approach is adopted by DOE in closing the fuel cycle, develop and qualify fuels to support the intermediate steps.
- Maintain a long-term R&D program
  - risk mitigation
  - capabilities and long-term competitiveness

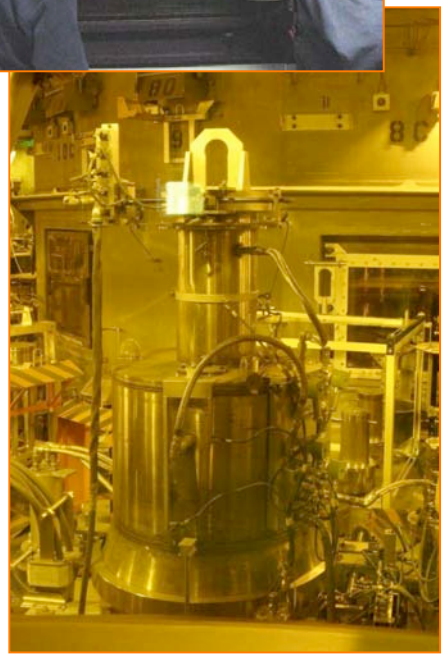
Qualification means "demonstration that the fuel will perform predictably and acceptably under normal and accident conditions". This is achieved by

- *Rigorous testing for a limited number of fuel compositions, fabrication processes and cladding materials up to the level of lead-test assemblies*
- *An extensive modeling and simulation approach to quickly extend the empirical database to the entire range of variables that are needed to meet the GNEP objectives.*

SFR Transmutation Fuels with Minor Actinides (MAs) and Rare Earth (RE) Fission Products

- **Unique Features of SFR Transmutation Fuels**
  - Pu content, which depending on CR selected my be higher than historic database (with corresponding decrease in U content)
  - Minor actinides (Am, Np, Cm) present in significant quantities
  - Rare earth fission product (La, Ce, Pr, Nd) carry-over from recycle step may be non-trivial
- **Gives Rise to Challenges and Unknowns**
  - Need for remote fuel fabrication
  - Likely need for new fabrication methods (e.g., due to Am volatility; waste minimization, etc.)
  - Effects on fuel performance must be determined





AFC Test Series in the Advanced Test Reactor

	AFC-1	AFC-2	AFC-3	AFC-4
Test Strategy	Scoping – Many compositions	Scoping – Focused compositions	Focused compositions	Focused compositions
	Nominal conditions	Nominal conditions	Nominal & limiting conditions	Nominal conditions
Capsule Type	Drop-in	Drop-in	Instrumented lead	Drop-in
Fuel Types	Metals Nitrides	Metals Oxides	Metals Oxides	Metals Oxides
Key Features	Baseline + MA	Baseline + MA + RE	Temperature control	Recycle feed Remote fabrication
Time Frame	FY 2003 – FY 2008	FY 2008 – FY 2013 +	FY **2009** – FY 2013	FY **2010** – FY 2014

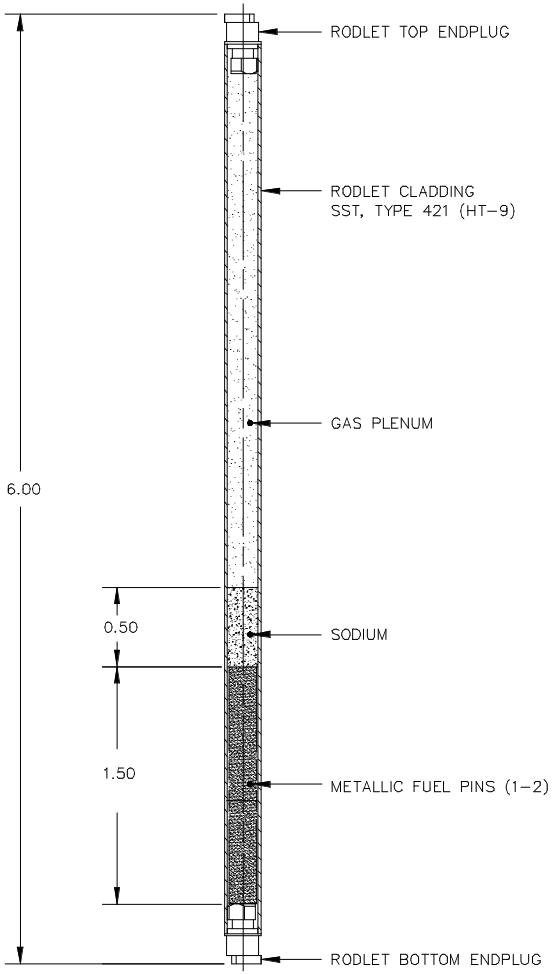
☐ Test series in progress.
☐ Future test series.

AFC-2A,B Currently Under Irradiation in the ATR

AFC-2A,B Test Matrix

Rodlet	AFC-2A&B
1	U-20Pu-3Am-2Np-15Zr
2	U-20Pu-3Am-2Np-1.0RE-15Zr
3	U-20Pu-3Am-2Np-1.5RE-15Zr
4	U-30Pu-5Am-3Np-1.5RE-20Zr
5	U-30Pu-5Am-3Np-1.0RE-20Zr
6	U-30Pu-5Am-3Np-20Zr

RE=6% La, 16% Pr, 25% Ce, 53% Nd



AFC-2A,B Test Objectives

- LHGR = 350 W/cm; PICT = 550°C
- Burnups of 10 at.% (2A) and 25 at.% (2B)
- Group recovery of 30 year-cooled PWR TRU
- Effect of RE fission product carry-over on FCCI

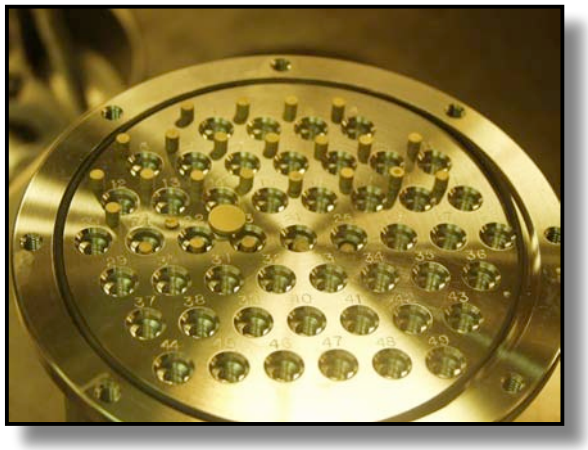
AFC-2C,D Currently in Fabrication

- **AFC-2C,D Test Matrix**

Rodlet	AFC-2C&D
1	$(U_{0.75},Pu_{0.20},Am_{0.03},Np_{0.02})O_{1.95}$
2	$(U_{0.80},Pu_{0.20})O_{1.98}$
3	$(U_{0.75},Pu_{0.20},Am_{0.03},Np_{0.02})O_{1.98}$
4	$(U_{0.75},Pu_{0.20},Am_{0.03},Np_{0.02})O_{1.95}$
5	$(U_{0.80},Pu_{0.20})O_{1.98}$
6	$(U_{0.75},Pu_{0.20},Am_{0.03},Np_{0.02})O_{1.98}$

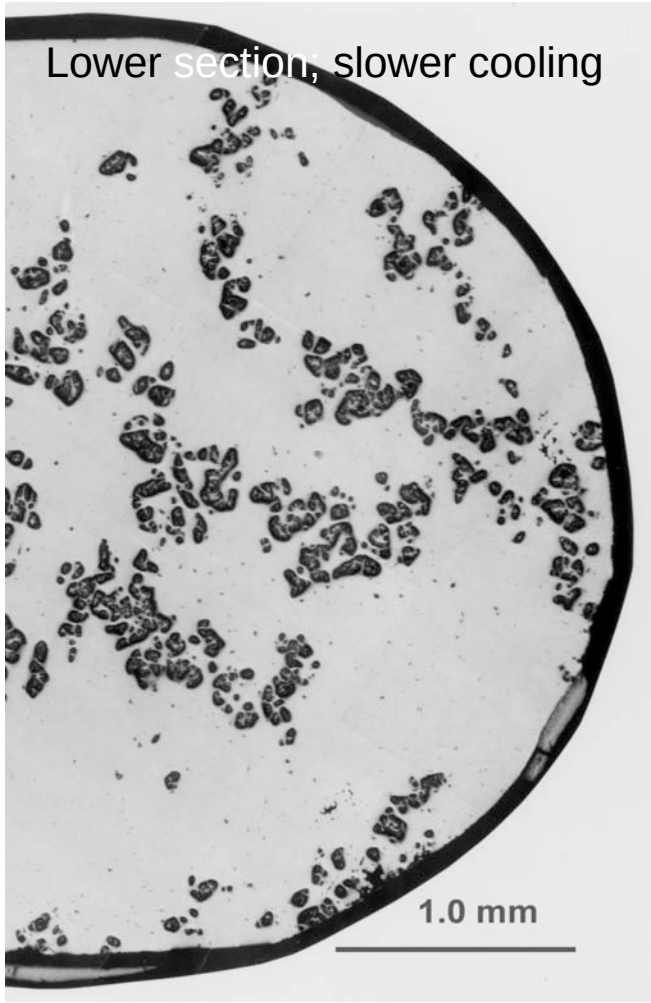
Los Alamos NATIONAL LABORATORY

- Fuel specification in refinement
- Fuel pellets in fabrication

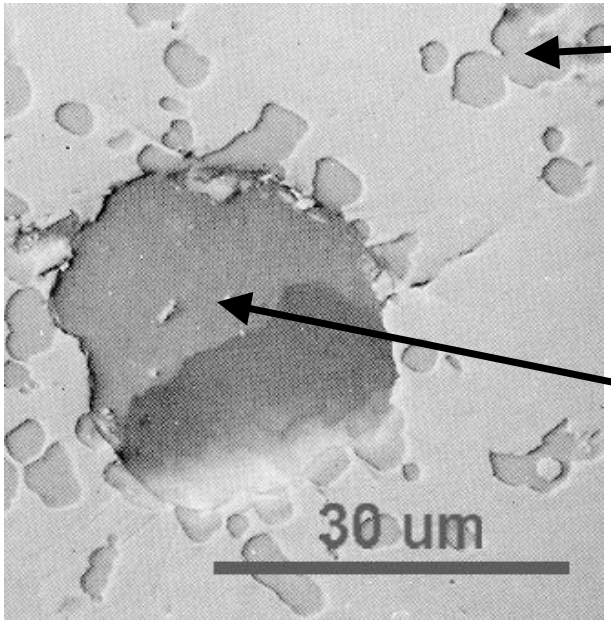


- **AFC-2C,D Test Objectives**
  - LHGR = 350 W/cm; PICT = 550°C
  - Burnups of 10 at.% (2A) and 25 at.% (2B)
  - Group recovery of 30 year-cooled PWR TRU
  - Effect of O/M on FCCI

Metallic Fuel with MA—X501 Fabrication



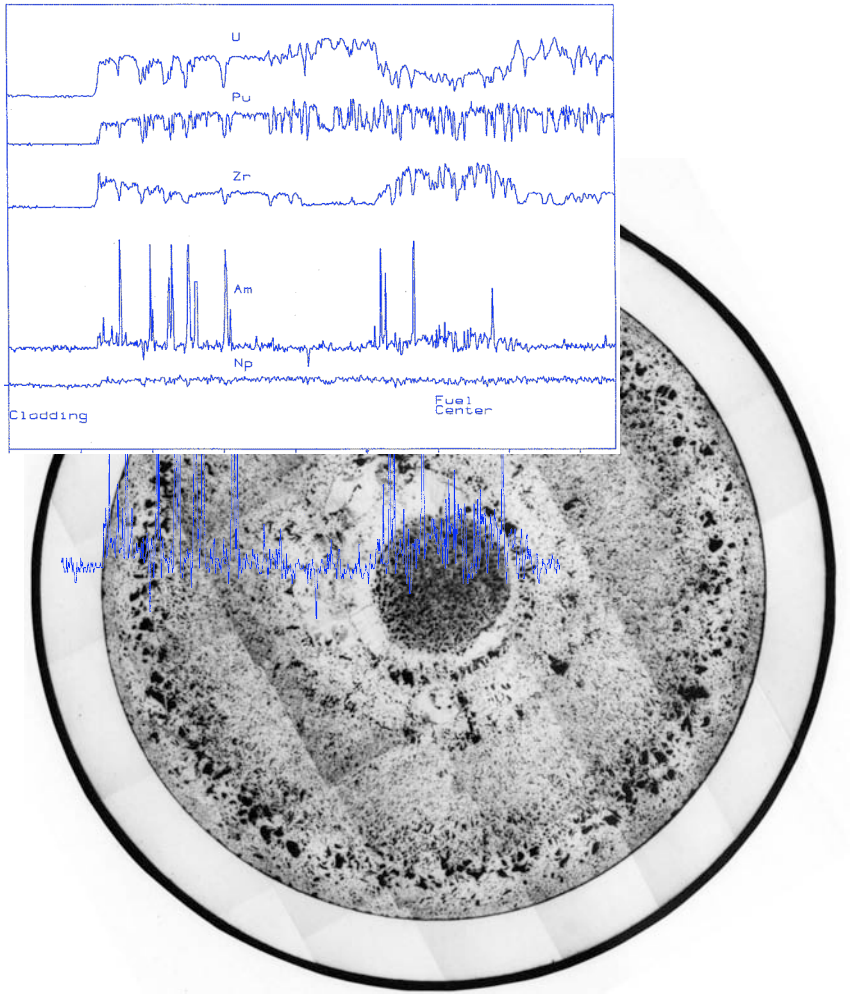
- U-20.2Pu-9.1Zr-1.2Am-1.2Np
- Injection cast at 1450°C
- Inhomogeneous microstructure
- Am and Np segregate to phases with variable composition

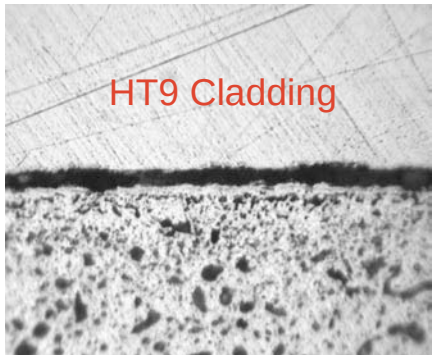


6 U
3 Pu
6 Np
86 Zr

21-47 U
14-49 Pu
9-19 Zr
0-25 Am
0-18 Np
Impurities

Metallic Fuel with MA—X501 Irradiation

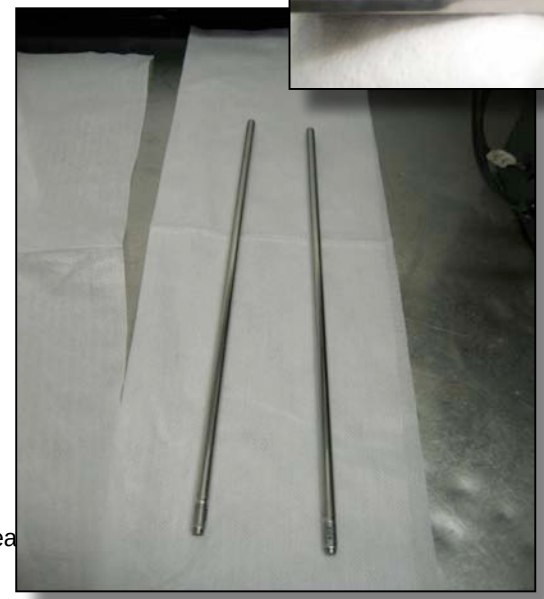




- LHGR = 450 W/cm
- PICT = 540°C
- Burnup = 7.6%
- ^{241}Am transmutation = 9.1%
- Gas Release
  - Fission gas = 79%
  - Helium = 90%

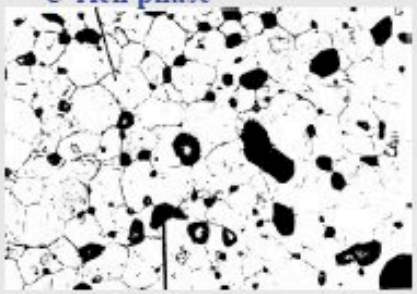
Metallic Fuel with MA—FUTURIX-FTA

- **U-29Pu-4Am-2Np-30Zr and Pu-12Am-40Zr Fuel Pins**
  - ✔ Pins received at Phénix, Sept06
  - ✔ Safety Report Completed, Jan07
  - ✔ Approval granted by Phénix Safety Committee, Feb07
  - ✔ Assembly Fabrication Complete, Mar07
  - ✔ Approval by French National Safety Authority, Apr07
  - ✔ Insertion into Phénix Reactor, Apr07
  - ✔ Phénix startup for Cycle 55-1, May 5, 2007
  - ✔ Irradiation currently underway
  - – Irradiation complete at 240 EFPDs, Jan09



Metallic Fuel with MA+RE—METAPHIX

- Joint research with ITU
- Fabrication MA-Metal slug by arc-melting
- Property measurements of MA-Metal slug
  - # Melting temperature
  - # Thermal conductivity
  - # Mechanical property
  - # Microstructure
  - # Compatibility with cladding material
- Irradiation tests at Phenix (Jan. 2004~) (METAPHIX-1-2-3)
  - ✓ Reference Metal (U-Pu-Zr) fuel
  - ✓ 5%MA-Metal fuel
  - ✓ 2%MA/2%RE-Metal fuel
  - ✓ 5%MA/5%RE-Metal fuel (Burnup, 1at.%, 5at.%, 10at.%)



Microstructure of 5%MA/5%RE-U-Pu-Zr metal fuel

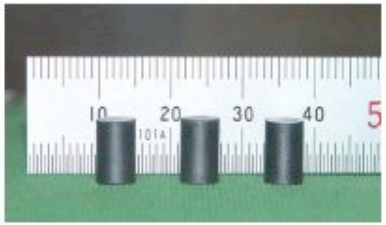
(From Arai and Pillon, 2004)

MOX Fuel with MA+RE—Fabrication

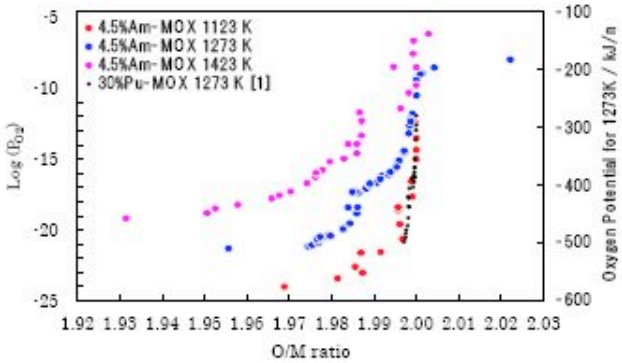
MA-bearing MOX Fuel

Fabrication and Characterization

- Simplified pelletizing method
  - » Die wall lubrication pelletizing, Sintering, O/M adjustment
    - – Good accuracy of Pu content adjustment by solution mixing
    - – Pellet fabrication with die wall lubrication
    - – Good Sintering of Am/Np/simulated FP pellet with low O/M ratio
- Property measurements
  - » MA and simulated FP bearing MOX fuel
    - – Melting point
    - – Thermal conductivity
    - – Oxygen potential, etc.



5%Am-MOX fuel pellets for JOYO irradiation test



(From Minato, et al., 2006)

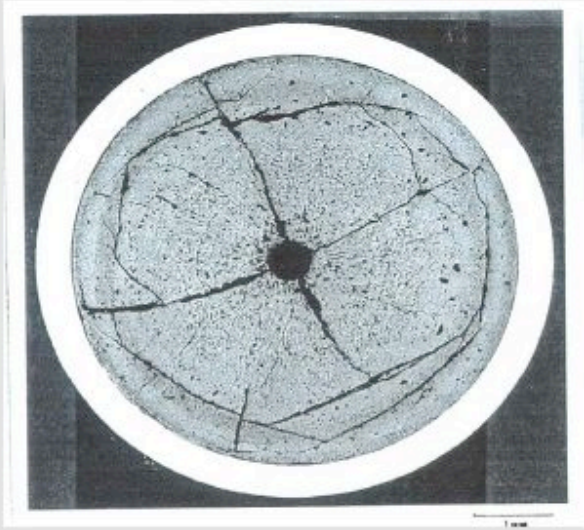
MOX Fuel with MAs—Irradiation Performance

MA-MOX Fuel Development in Europe (2)
CEA/ITU Collaboration (1984-1992)

Conclusion on homogeneous recycling

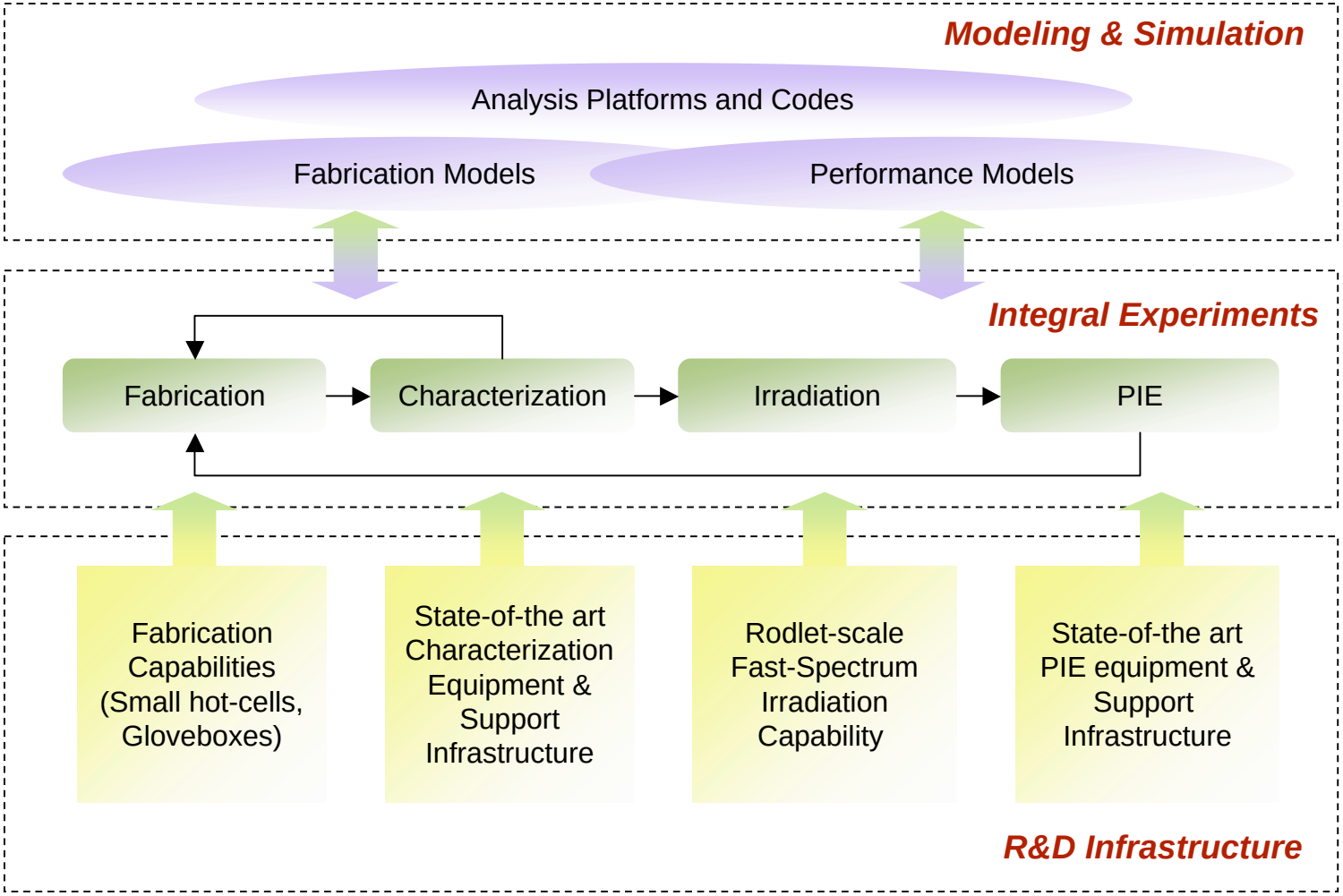
- –No significant impact on the fuel properties and fuel behaviour proved at least up to 6.4 % of BU
  - •Formation of a central hole, equivalent to what is observed on standard fuel irradiated under similar condition
  - •No signal of inner corrosion, no accelerated corrosion
  - •Normal FP and Pu redistribution
  - •Behaviour of FG similar to that of standard pins
- –But higher helium production (x4)
  - –100% released during irradiation
  - –58% released during cooling time

2% Am



(From Arai and Pillon, 2004)

Modeling & Simulation Fully Integrated with Fuel Development and Qualification



Modeling and Simulation Strategy

(LIFE4, SIEX, LIFE-METAL, FRAPCON)

Legacy Codes:
- *Sensitivity studies*
- *Design support for fuels*
- *Empirical model support*

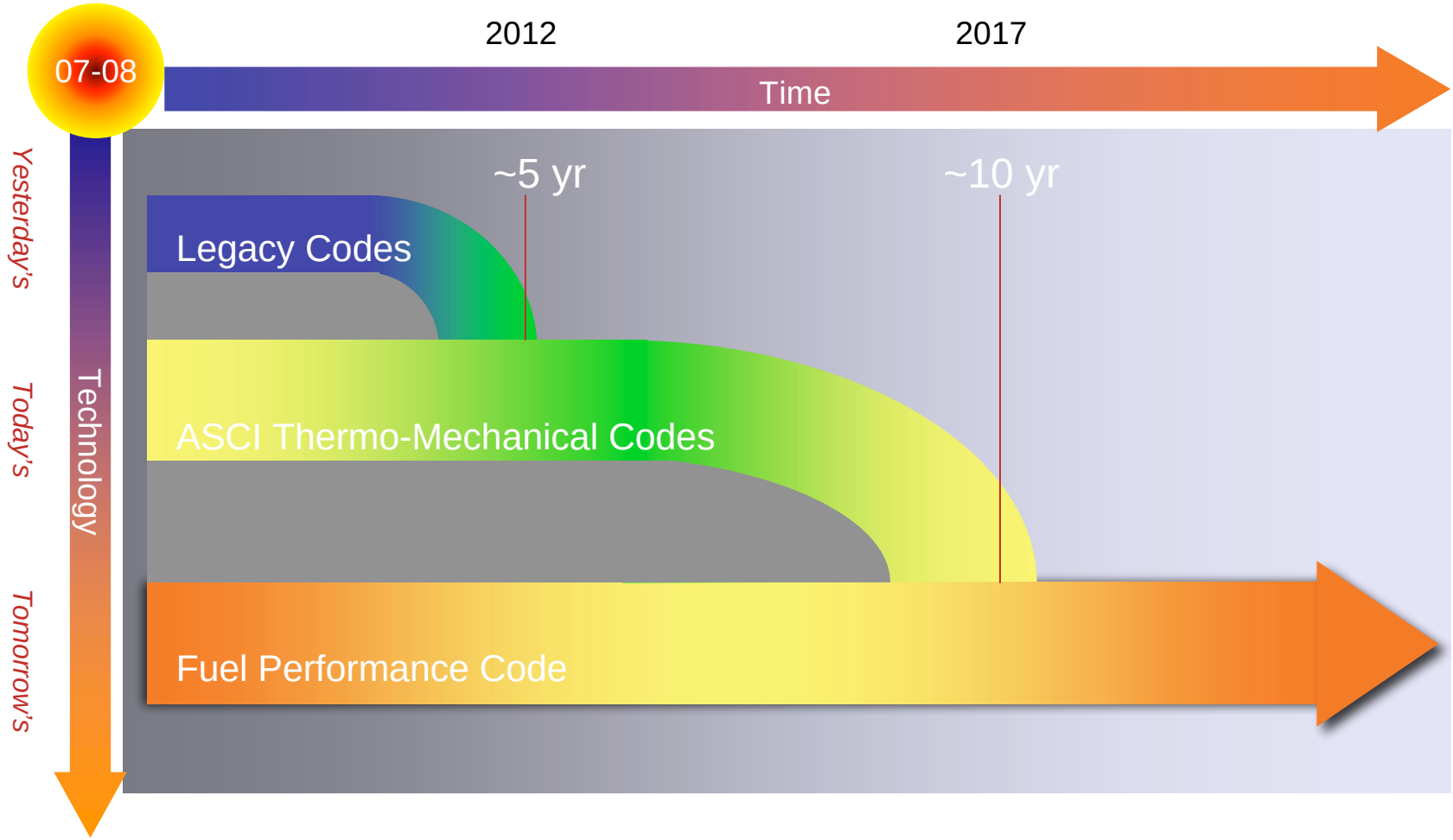
ASCI Thermo-Mechanical Codes:
- *Intermediate-term results*
- *Test bed and feasibility assessment*
- *Import ASCI technology to NE needs*

Lower length-scale Modeling:
- *Fundamental understanding*
- *Reduced reliance on empirical data*
- *Collaborations with Office of Science*

Basic Experiments
- *Fundamental properties*
- *Phenomenological tests for model development*

Next Generation Fuel Performance Code:
- *Long-term qualification code*
- *Includes all important phenomenology*
- *Specifically tailored to fuel physics*
- *State-of-the art numerical models*

Modeling and Simulation Forecast



Approach to Fuel Development and Qualification

Fuel Development & Safety Testing

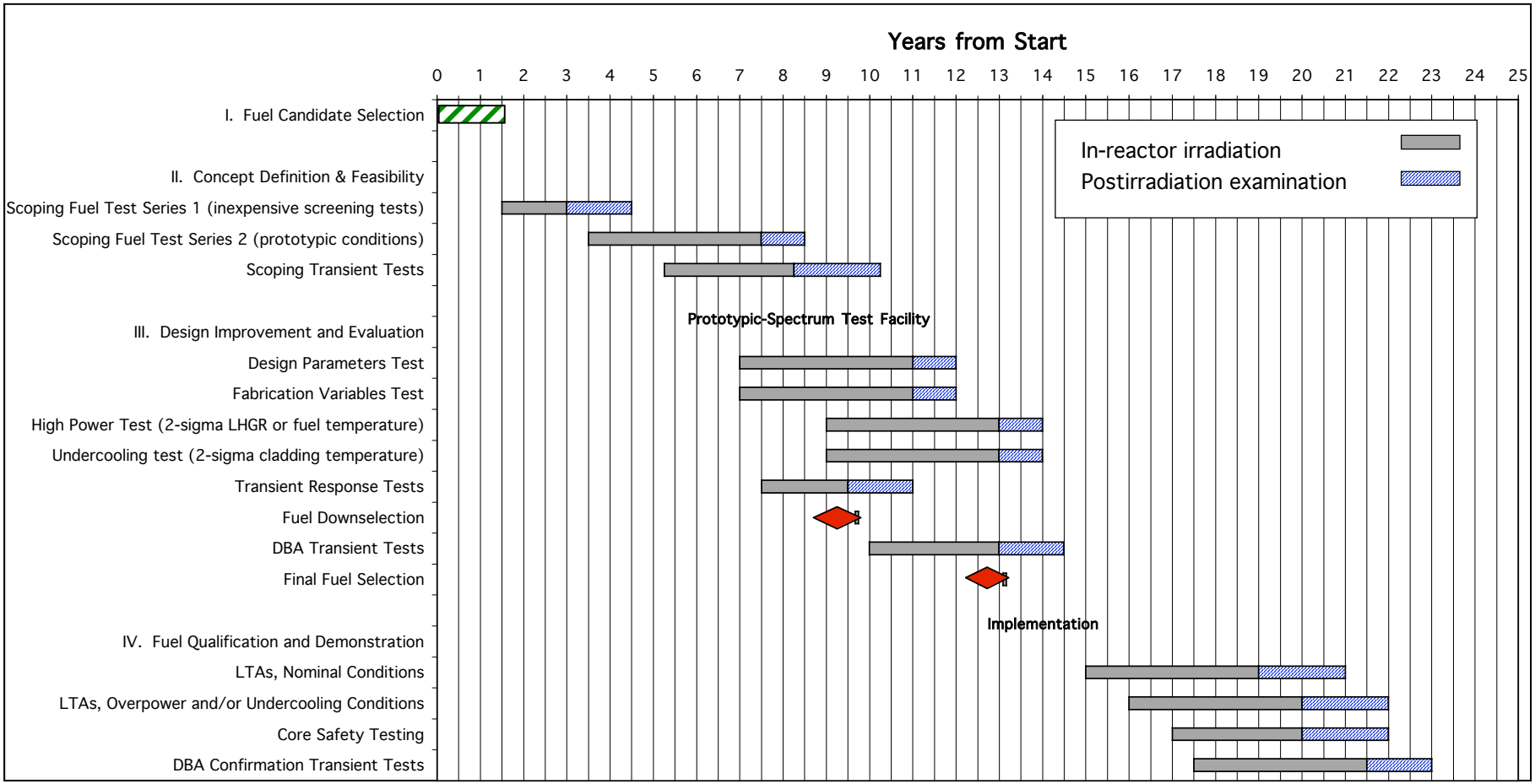
Crawford, et al., **Journal of Nuclear Materials**, **371**: 232-242 (2007).

- **Review of 4 phases of fuel development process**
  - 1. Fuel candidate selection
  - 2. Concept definition and feasibility
  - 3. Design improvement and evaluation
  - 4. Fuel qualification and demonstration
- **Example of EBR-II & FFTF experience with fuel qualification/confirmation testing**

TRL Objective in Fuel Qualification

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 (~100 gram batches). Irradiation testing of small-samples (rodlets) in relevant environment. Design parameters and features establsihed. Basic properties compiled.
5		Fabrication of pins using prototypic feedstock materials at laboratory-scale (10 kg). Pin-scale irradiation testing at relevant environment. Primary performance parameters with representative compositions under normal operating conditions quantified.
6		Fabrication of pins using prototypic feedstock materials at laboratory-scale (1 kg) and using prototypic fabrication process. Pin-scale irradiation testing at relevant and prototypic environment (steady-state and transient testing). Safety basis establis
7	Proof-of-performance	Fabrication of test assemblies using prototypic feedstock materials at engineering-scale (100 kg) and using prototypic fabrication process. Assembly-scale irradiation testing at prototypic environment. Safety basis established for full-core operations.
8		Fabrication of a few core-loads of fuel (tons) and operation of a prototype reactor with such fuel.
9		Routine commercial-scale operations. Multiple reactors operating

Conceptual Fuel Development Schedule



Fuel Development Phase 1: Fuel Candidate Selection

- **Objective: Based on previous experience, identify candidate fuel forms/concepts that appear capable of meeting mission needs.**
- **Selection criteria might include:**
  - Ability to accommodate desired fuel compositions
  - Experience with similar fuel types or analogues
  - Suitability of established fabrication techniques, or the potential for successful innovative techniques
  - Anticipated performance capabilities (e.g., temperature, burnup, or fluence)
  - Anticipated safety-related behavior (which may be quite speculative at an early stage)
  - Suitability of design, considering issues such as fuel-cladding compatibility, fuel-coolant compatibility, and fuel properties
  - Compatibility with envisioned back-end fuel cycle technology
  - Expected cost of fabrication
- **Achieves TRL 2**

Fuel Development Phase 2: Concept Definition and Feasibility

- **Objective: Establish a reference concept/design**
- **Determine how the fuel can be fabricated**
  - Process scoping & feasibility
  - Fabricate characterization and test samples
- **Determine and assess key properties**
  - Feasibility issues for irradiation testing
- **Use scoping irradiation tests to assess phenomena envisioned to impact feasibility and fuel lifetime**
  - Simple experiments
  - Prototypic conditions as possible
- **Achieves TRL 4**

Fuel Development Phase 3: Design Improvement and Evaluation

- **Objectives:**
  - Optimize the fuel design for economics, performance and safety
  - Produce a Fuel Specification and a Fuel Safety Case for a core of fuel
  - Establish predictive fuel performance code (or codes)
- **Develop engineering-scale fabrication processes and equipment**
- **Assess fuel properties vs. composition or processing variations**
- **Irradiation testing to:**
  - Determine sensitivity of performance to fuel design and fabrication variables and to operating conditions
  - Establish burnup limits and safety margins for various operating conditions (normal and off-normal)
- **Develop fuel behavior models and predictive codes**
- **Achieves TRL 6**

Fuel Development Phase 4: Fuel Qualification and Demonstration

- **Objectives:**
  - Qualify production-line fuel as the driver fuel for a demonstration reactor
  - Demonstrate the safety and reliability of a core of fuel through successful operation of the demonstration reactor
  - Validate predictive fuel performance code (or codes)
- **Demonstrate production of fuel in conformance with Fuel Specification**
- **Demonstrate through LTA irradiation that fuel/fuel assembly behavior is within the bounds of the Fuel Safety Case**
- **Accumulate reactor performance data and operating experience with a core of fuel to support licensing of first-of-a-kind unit**
- **Achieves TRL 7 or 8**

Fuel Development Phase 4: Fuel Qualification and Demonstration

- **Example for Metallic Fuels in EBR-II**
  - Confirmation Testing (Mark-III, IIIA, and IV)
    - *Performance phenomena limiting useful lifetime of a fuel assembly (breach, hardware dimensional change, etc.) are known. Limits can be predicted and pre-set.*
    - *Use of modeling [Cumulative Damage Fraction (CDF) or other].*
    - *Run a set of assemblies representing the range of possible operating conditions to an exposure (burnup, neutron fluence, etc.) in excess of the limiting exposure to prove capability is as predicted.*
    - *The tests lead the remaining core in exposure.*
    - *Four assemblies used [1 inner core, 1 outer core (normal flow), 1 outer core (high flow), 1 orificed to nominally achieve 2-σ peak cladding temperatures]*

Fuel Development Phase 4: Fuel Qualification and Demonstration

- **Example for Oxide and Metallic Fuels in FFTF**

Confirmation Tests in FFTF to Support Exposure Limits
(from Baker, et al, 1990)

Type	Fuel	Duct & Cladding Material	Number of FFTF Tests*	Transient Testing	Driver Cores Produced
Series I	$(U,Pu)O_2$	316	17F	Yes	2 cores
Series II	$(U,Pu)O_2$	316	--	--	2 cores
Series III.a	$(U,Pu)O_2$	D9	1F, 4R	No	--
Series III.b	U-10Zr	HT9	2P, 6F	No	--
Series IV	UO_2	D9	1P	No	--

*F=full assembly, P=partial assembly, R=related test

Summary

- **SFR Fuels Experience in the US**
  - Fuel Types
  - Fuel Performance Issues
  - Experience/Testing
- **Fuel Test Plan (1994) for PRISM Prototype**
- **Experience with Fuels Containing Minor Actinides**
- **Fuel Specification**
- **Fuel Development and Qualification**