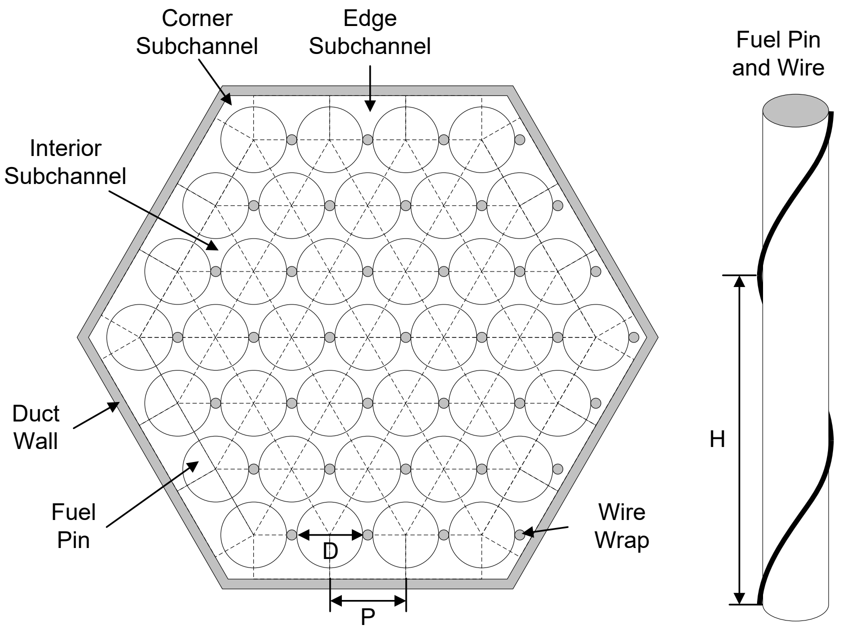
# FAST REACTOR FUELS




**TANJU SOFU**

**ARGONNE NATIONAL LABORATORY**

March 26, 2019
Fast Reactor Technology Training
U.S. Nuclear Regulatory Commission

# OUTLINE

- Fast reactor fuel types
- U.S. experience
- Fuel pin and assembly design
- Fuel design considerations and challenges
  - Oxide fuel
  - Metallic fuel
- Oxide and metallic fuel comparisons
- Fuel failure modes and consequences
- Metallic fuel irradiation and transient testing experience

# FAST REACTOR FUEL TYPES

- Fast reactor fuels can reach much higher burnup than LWR fuel
  - In LWRs, fuel kept in the core until the reactor loses its criticality
  - In FRs, theoretically fuel can be kept in the core indefinitely, imposing different restrictions on the fuel design and performance
    - Performance of same oxide fuel is significantly different in LWRs and FRs
- Decision on fuel type is based on many criteria (fabrication, performance, safety, and choice of fuel cycle)
  - Oxide fuel—$UO_2$, MOX
  - Metallic alloy fuel
    - Molybdenum experience (Dounreay and Fermi reactors)
    - Fissium and zirconium alloys (EBR-II)
  - Nitride fuel
  - Carbide fuel—UC
  - Other lesser known fuel types
    - Uranium sulphide (US)
    - $U_3Si$
    - Uranium phosphate (UP)

# MOST COMMON FAST REACTOR FUELS

## Often the choice is reduced to prior irradiation/testing experience

- Oxide fuel
  - Sintered pellet $UO_2$ or MOX fuel similar in design to a PWR oxide fuel pellet
  - Helium-filled gap between fuel and cladding
  - Large fission gas plenum (helium filled when manufactured)
- Metal fuel
  - Uranium-zirconium or uranium-plutonium-zirconium alloy rods
  - Sodium-filled gap between the fuel and cladding
  - Large fission gas plenum (argon filled when manufactured)
- Substantially different thermophysical properties of oxide and metal fuel forms play a significant role in their safety performance
  - Thermal conductivity, stored energy, melting point, failure mechanisms, …

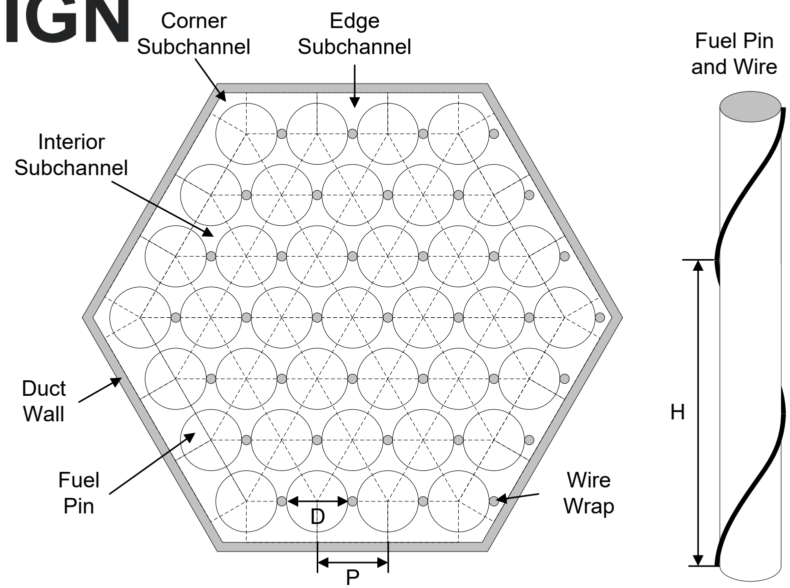
# U.S. SFR FUELS EXPERIENCE (1/2)

- SFRs have been extensively studied and operated by DOE and its predecessor, AEC
  - Experience with EBR-I, EBR-II, FFTF, and CRBR project
- Early U.S. SFR experience focused on metal-alloy fuel
  - EBR-II tests in late 1960's showed limited success achieving only low burnup
- Oxide fuel form was selected for further development in FFTF and CRBR project
  - Based on experience in commercial LWRs and naval reactors
- After CRBR project was canceled, DOE continued on with Advanced Liquid Metal Reactor (ALMR) and Integral Fast Reactor (IFR) programs
  - Emphasis back on a pool-type SFRs with metal alloy fuel to address regulatory concerns related to severe accidents
- Subsequent metallic fuel testing in 1980s (during IFR program) demonstrated that burnup limitation could be overcome by changing the fuel design
  - Larger fuel-cladding gap to accommodate irradiation induced swelling and achieve lower smeared density

# U.S. SFR FUELS EXPERIENCE (2/2)

- Under the ALMR program, PRISM (GE) and SAFR (Rockwell/WEC) concepts submitted their Preliminary Safety Information Document to NRC in 1986
  - NRC’s Pre-application Safety Evaluation Reports (NUREG-1368 and 1369) identified “*incomplete information on the proposed metallic fuel*” as one of the key regulatory issues
- IFR program (until its termination in 1994) as well as ongoing work under DOE's Advanced Reactor Technologies (ART) program and Advanced Fuels Campaign continued addressing this issue
  - PRISM, TWR, ARC-100 (and 4S, though not a U.S. design) all propose to use metallic fuel based on this experience

# FUEL PIN LAYOUT AND DESIGN

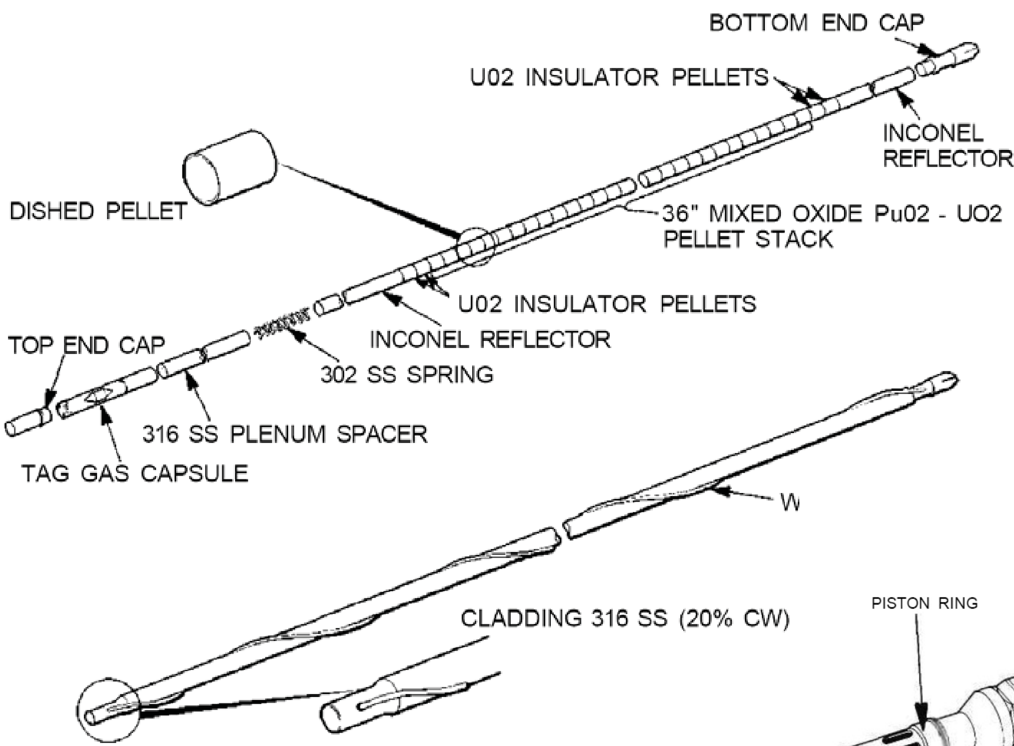


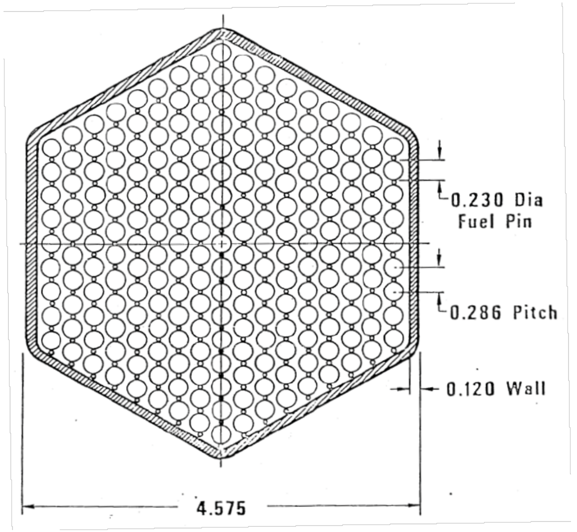

- Coolant moderation is not desired, so fuel is in most compact configuration: Triangular pitch, hexagonal fuel assembly
- Fuel assemblies contain tens to hundreds of pins inside a duct
  - Duct allows control of flow between fuel assemblies—unlike PWRs, which have an open core (BWRs have ducts for better control of boiling)
- Fuel pins are often spaced by wire-wrap, but spacer grids are also considered
- Fuel is clad in 316 stainless steel for CRBR or HT9 for newer designs
- In addition to axial reflector and shielding, breeder fuel pins may have top/bottom axial blankets
- Fuel pins have a large fission gas plenum above or below the fuel stack (top location has higher fission gas pressure)

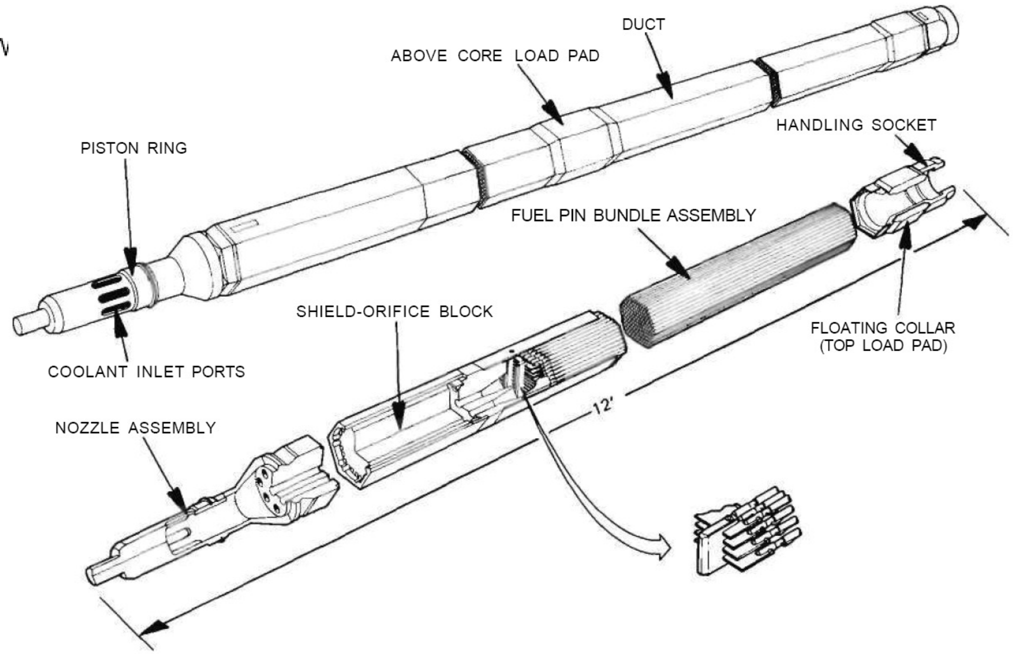

ABR-100 fuel pin design

# FFTF FUEL PIN AND ASSEMBLY DESIGN

## Oxide fuel

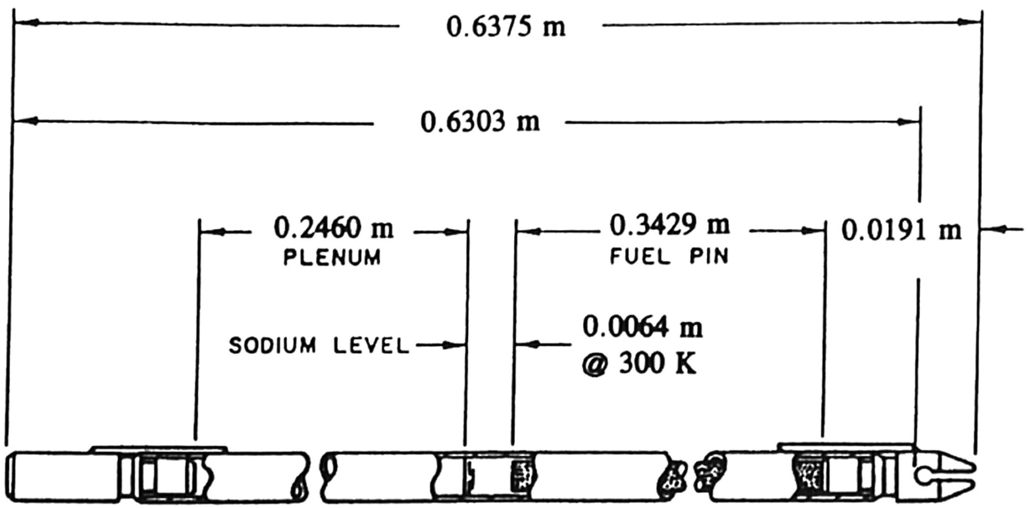


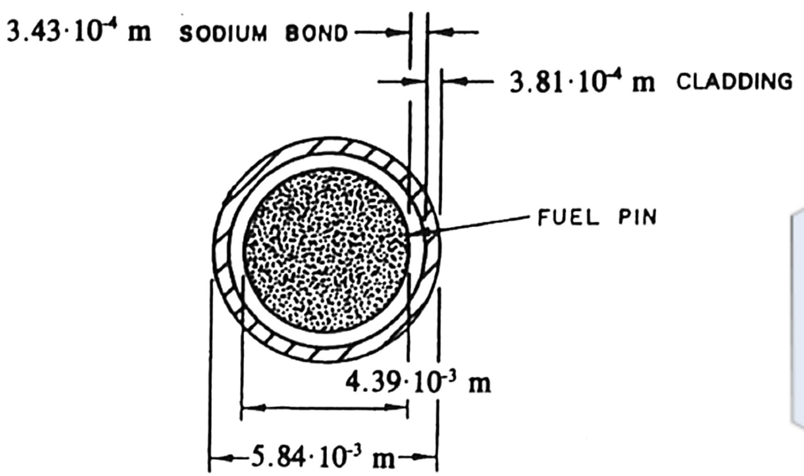



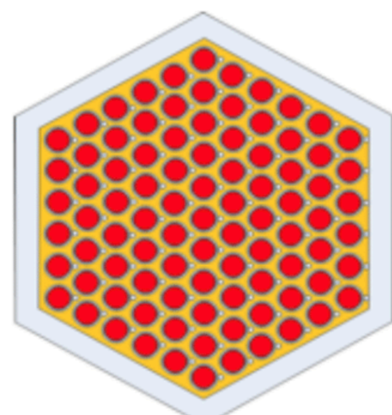



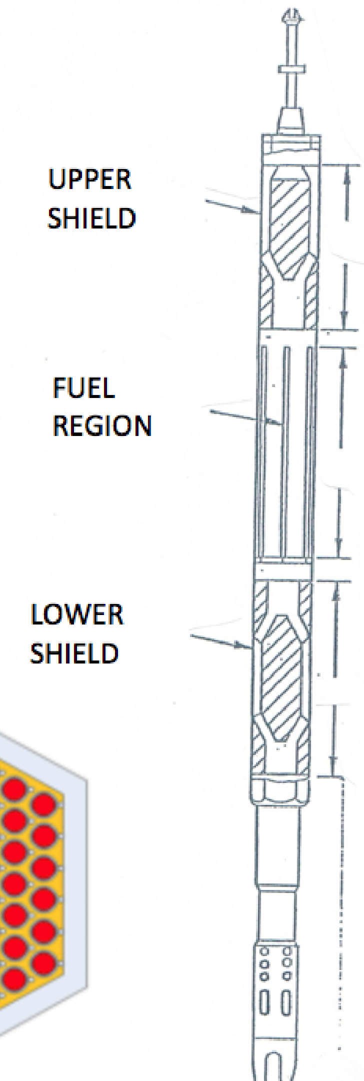
# EBR-II FUEL PIN AND ASSEMBLY DESIGN

## Metallic fuel





# FUEL PIN DESIGN CONSIDERATIONS

## Parameters that affect fuel performance

- Linear power
- Burnup
- Thermo-physical properties
- Gap conductance
- Temperature
- Strength

## Phenomena that affect fuel performance

- Creep
- Swelling
- Fuel restructuring
- Constituent migration
- Fission gas release and transport
- Fuel cracking
- Differential thermal expansion
- Irradiation damage
- Cladding attack by rare-earths
- Fuel alloy and cladding interdiffusion

# FAST REACTOR FUEL DESIGN CHALLENGES

- Higher burnup
  - Typical LWR fuel burnup is ~ 2–3%
  - SFR fuels typically reach burnup well in excess of 10% and that results in significant swelling and fission gas pressure inside the pin
- Greater fuel swelling
  - Both metallic and oxide fuel pin designs can accommodate it
- Fuel-Cladding Mechanical Interaction (FCMI)
  - Bigger challenge for hard, strong ceramic fuel forms and it can impose limits on maximum burnup
- Fuel-Cladding Chemical Interaction (FCCI)
  - Puts operational limit to coolant outlet temperature for a metallic fuel core
- Fuel-coolant compatibility
  - Oxide fuel chemically reacts with the sodium coolant imposing stricter limits on fuel pin failures to prevent potential flow blockages

# OXIDE FUEL (1/3)

## Fabrication

- High operating and manufacturing experience in part from LWRs
- Normally manufactured through powder metallurgy
  - Mixture is cold-compacted into a pellet
  - Pellets are sintered at ~1600°C to achieve desired densification level

## Physical properties

- Oxygen ions are arrayed in a simple cubic structure, and the heavy metal ions form a face-centered cubic sublattice
- Relatively brittle material at temperatures less than half the melting point

## Swelling

- Some porosity is intentionally incorporated to accommodate excessive fuel swelling in fast spectrum with high burnup
  - 85–90% of theoretical density (even lower smeared density)
- 0.15 to 0.45% per atom-% burnup of total swelling is due to solid fission products
- Substantially greater swelling results from fission gases

# OXIDE FUEL (2/3)

## Microstructure changes

- Steep radial temperature profiles cause columnar and equiaxed grains to develop after a few hours of irradiation
- Radial profile of oxygen to metal ratio also rapidly changes with impact on thermo-physical properties

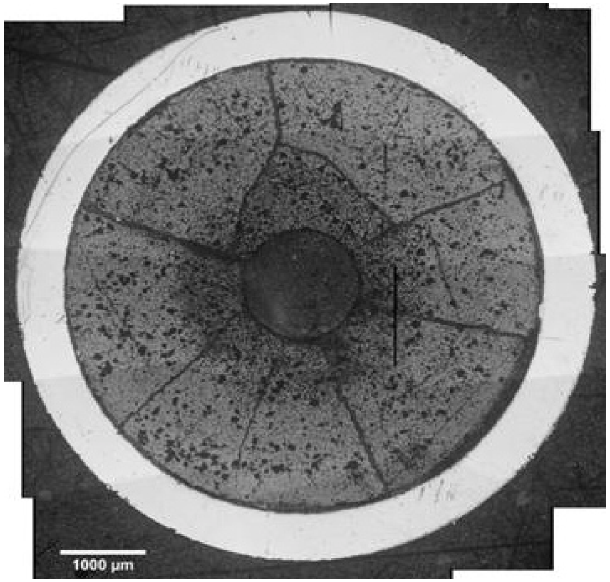
## Fission gas release

- Once released from the fuel matrix, fission gas is vented to collecting zones
  - Usually a fission gas plenum above or below the fuel stack
- Fuel temperature
  - For $T<1000^oC$, fission gas mobility is low and there is little gas escape
  - For $1000^oC<T<1600^oC$, atomic motion allows some diffusion, and some amount of gas can escape from fuel matrix
  - For $T>1600^oC$, thermal gradients can drive gas bubbles and closed pores over distances comparable to grain sizes

# OXIDE FUEL (3/3)

## Irradiation experience

- Large FR irradiation experience in FFTF and international reactors in France, Russia, and Japan
- Acceptable performance and reliability demonstrated at 10 at.% burnup, with capability established up to 20 at.% burnup
- Robust overpower capability established in TREAT tests: ~ 3 to 4x's nominal power
  - Well above primary and secondary FFTF trips
  - Pre-failure axial molten fuel motion
  - Clad failures near core mid-plane
- Performance issues typically related to creep rupture of cladding at high burnup, primarily due to fission gas pressure, and perhaps FCMI

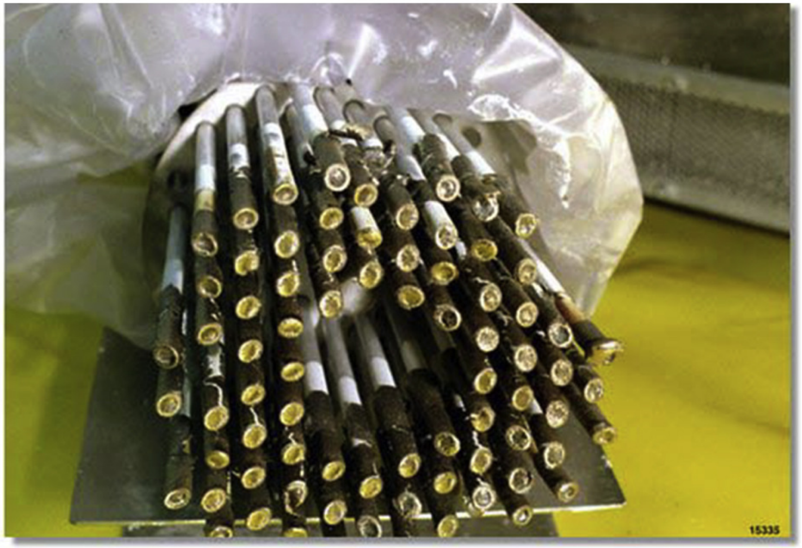



High Burnup Oxide Fuel

# METALLIC FUEL (1/4)

## Fabrication

- Developed at Argonne based on experience gained through 20+ years operation of EBR-II
- Injection cast as cylindrical slugs and placed inside the cladding tubes
- Liquid-metal sodium is used inside the pin to thermally bond the fuel/cladding
  – Increased gap conductance is a factor for fresh fuel
  – Along with the high fuel thermal conductivity, maintains significantly lower fuel operating temperatures compared to oxide fuel



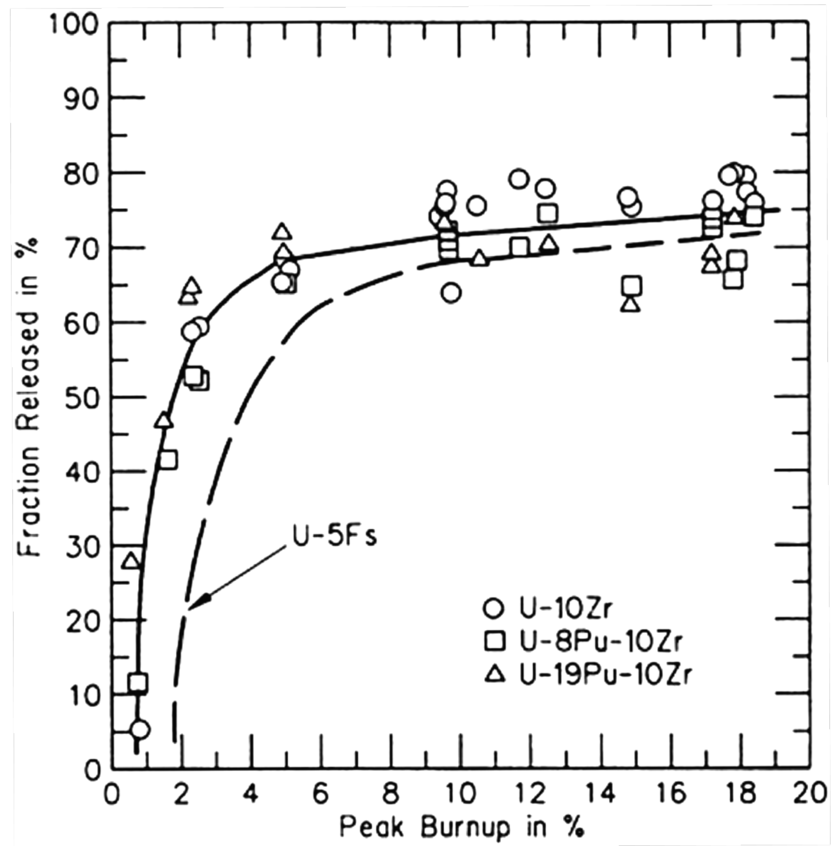
# METALLIC FUEL (2/4)

## Physical properties

- Metallic fuel hardened by alloying with zirconium
- Nonbrittle material with relatively soft matrix

## Swelling

- The fuel-cladding gap is sized for a low smear density to accommodate fuel swelling and achieve a high burn-up
- Interconnected porosity that forms after initial few atom-% burnup allows fission gases to escape to pin plenum
- No significant swelling thereafter

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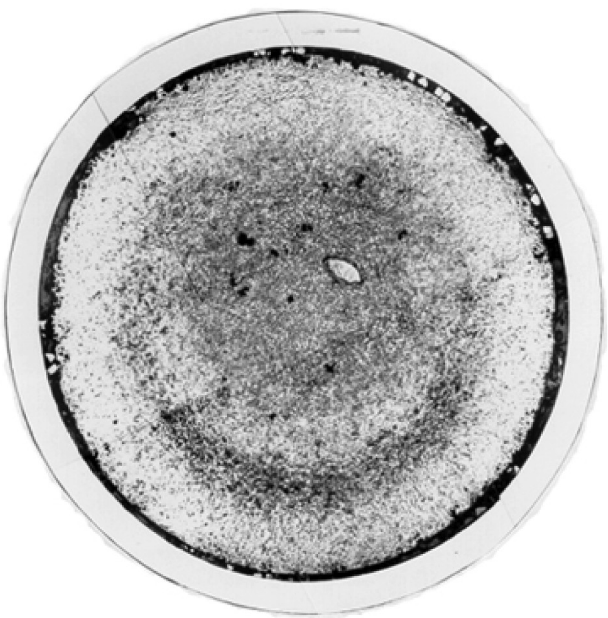
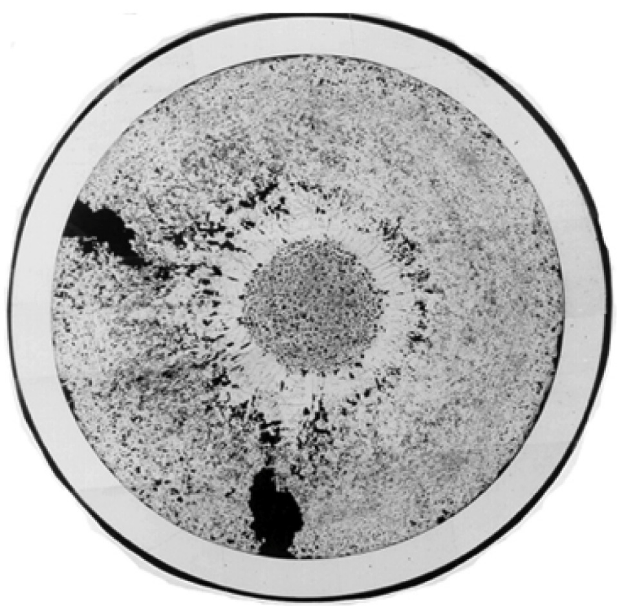
# METALLIC FUEL (3/4)

## Microstructure changes

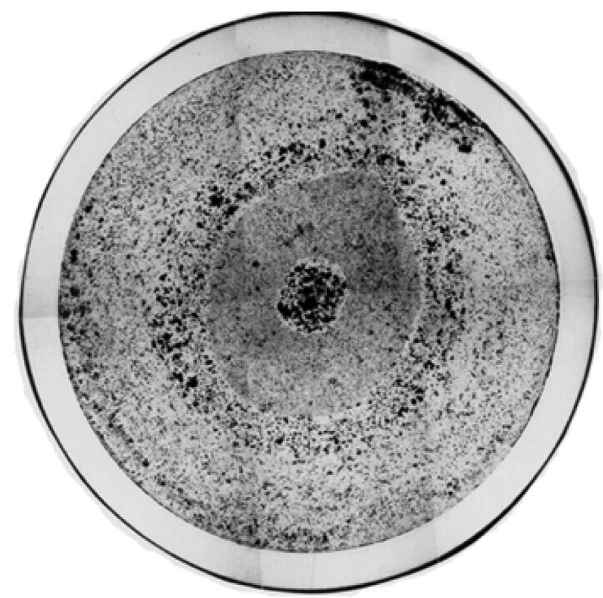
- Small radial temperature gradient
- But significant fuel constituent redistribution at high burnup
- Low melting-point eutectic potential between fuel and cladding



X423A at 0.9% BU



X419 at 3% BU



X420B at 17% BU

# METALLIC FUEL (4/4)

## Irradiation experience

- Large database with metal fuel from EBR-II and FFTF irradiation tests
- Acceptable performance and reliability demonstrated at 10 at.% burnup, with capability established up to 20 at.% burnup
- Robust overpower capability established in TREAT tests: ~4-5x nominal power
  - Axial fuel expansion prior to melting
  - Pre-failure axial molten fuel motion
  - Failures near top of fuel column

<table>
<tr><th>Reactor</th><th>Fuel Type</th><th># of Pins</th><th>Clad</th><th>Peak burnup</th></tr>
<tr><td rowspan="4">EBR-II</td><td>Mark-I/IA (U-5Fs)</td><td>~90,000</td><td rowspan="4">316SS, D9, HT9</td><td>~2.5%</td></tr>
<tr><td>Mark-II (U-5Fs)</td><td>~40,000</td><td>~8%</td></tr>
<tr><td>Mark-IIC/IICS/III/IIIA/IV (U-10Zr)</td><td>~16,000</td><td>~10%</td></tr>
<tr><td>U-Pu-Zr</td><td>>600</td><td>~15-20%</td></tr>
<tr><td rowspan="2">FFTF</td><td>U-10Zr</td><td>>1050</td><td rowspan="2">HT9</td><td>~14%</td></tr>
<tr><td>U-Pu-Zr</td><td>37</td><td>~9%</td></tr>
</table>

# OXIDE AND METALLIC FUEL COMPARISONS (1/4)

| | | Oxide ($UO_2$-20$PuO_2$) | Metal (U-20Pu-10Zr) |
|---|---|---|---|
| Heavy Metal Density, $g/cm^3$ | | 9.3 | 14.1 |
| Melting Temperature ($T_{melt}$), K | | 3000 | 1400 |
| Thermal Conductivity, W/cm-K | | 0.023 | 0.16 |
| Operating Centerline Temp. at 40 kW/m, K | | 2360 | 1060 |
| Margin to melting | $T/T_{melt}$ | 0.79 | 0.76 |
| | $\Delta T/T_{melt}$ | 0.21 | 0.24 |
| Fuel-Cladding Solidus, K | | 1675 | 1000 (eutectic) |
| Thermal Expansion, 1/K | | $12\times 10^{-6}$ | $17\times 10^{-6}$ |
| Heat Capacity | $c_p$, J/g-K | 0.34 | 0.17 |
| | $\rho c_p$, $J/cm^3$-K | 3.2 | 2.4 |

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# OXIDE AND METALLIC FUEL COMPARISONS (2/4)

## Impact of neutron spectrum

| | Oxide fuel | Metal Fuel | Reason |
|---|---|---|---|
| **Spectrum** | Softer | Harder | Oxygen moderation |
| **Effective heavy metal density** | Lower | Higher | |
| **Neutron yield** | Lower | Higher | Yield is higher in harder spectrum and for larger heavy-metal density |
| **Conversion rate** | Lower | Higher | Due to all of the above |
| **Burnup reactivity swing** | Higher | Lower | Due to conversion rate difference |
| **Excess external reactivity needed** | Larger | Smaller | Due to burnup reactivity swing difference |
| **Available reactivity for accidental insertion** | Larger | Smaller | Due to above |
| **Mean free path** | Shorter | Longer | Spectrum difference (greater sensitivity to axial/radial expansion for metal fuel) |

# OXIDE AND METALLIC FUEL COMPARISONS (3/4)

## Impact of operating temperature and Doppler feedback

| | Oxide fuel | Metal Fuel | Reason |
|---|---|---|---|
| **Operating temperature** | Higher | Lower | Thermal conductivity and gap conductance difference |
| **Radial temperature gradient** | Higher | Lower | Thermal conductivity difference |
| **Heat capacity** | Higher | Lower | |
| **Stored heat** | Higher | Lower | Fuel temperature, density and heat capacity difference |
| **Grace period needed to tackle cooling deficiencies** | Longer | Shorter | Stored heat difference |
| **Doppler feedback** | Larger | Smaller | Neutron spectrum and operating temperature difference |
| **Zero- to full-power Doppler reactivity swing** | Larger | Smaller | Also due to radial temperature gradient difference |
| **Reactivity control requirement** | Larger | Smaller | Due to all of the above |
| **External reactivity available for accidental insertion** | Larger | Smaller | Due to all of the above |

# OXIDE AND METALLIC FUEL COMPARISONS (4/4)

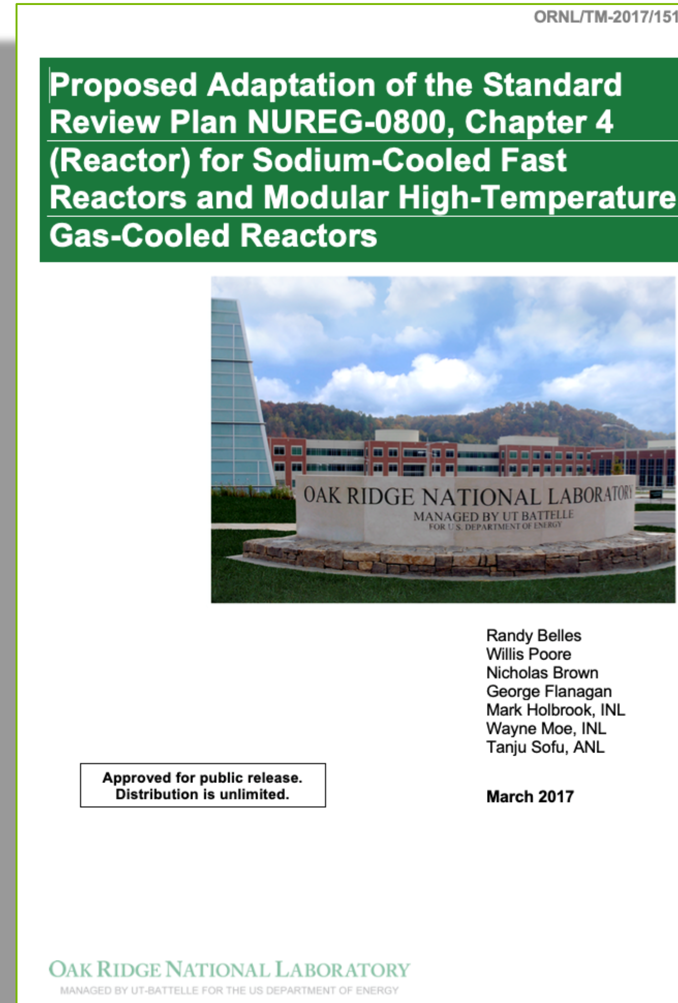
- Overall, oxide fuel offers a very robust and chemically stable fuel form with significant manufacturing and irradiation experience from past LWR and international SFR operations
  - Metallic fuel has a softer matrix, can experience significant constituent migration at high burnup, and can chemically interact with iron in cladding
- High thermal conductivity and gap conductance is an advantage for metallic fuel
  - Low steady-state and transient temperatures, and flat temperature profile
- Since metal fuel cladding generally fails below the coolant boiling point, damaged metal fuel pins remain coolable
- Despite big difference in melting point, both oxide and metal fuels have similar margin to melting during accidents
- Phenomena depending on diffusional rate processes, such as creep and fission gas release, are also similar
- Fuel-coolant compatibility
  - Oxide fuel chemically reacts with sodium coolant
  - Metal fuel is compatible with sodium coolant and minor clad failures ca be tolerated

# GAPS IN SRP FOR FAST REACTOR FUELS

## Proposed adaptation of NUREG-0800 Chapter 4 for SFR and HTGR: ORNL/TM-2017/151

Sodium Fast Reactor Review Plan Section 4.2: Fuel System Design

- Areas of review
- Acceptance criteria
  - Fuel system damage (stress/strain, vibration, corrosion, dimension change)
  - Fuel rod failure modes (overheating, fuel/cladding interactions)
  - Fuel coolability (clad failure, molten fuel motion, clad melting, ballooning, structural deformation)
  - Design Evaluation (operating experience, prototype testing, analytical predictions)
  - Testing, Inspection, and Surveillance Plans
- Review procedures, evaluation findings, implementation
- Appendix: Acceptance criteria and guidance for the fuel system design during postulated accidents


ORNL/TM-2017/151

**Proposed Adaptation of the Standard Review Plan NUREG-0800, Chapter 4 (Reactor) for Sodium-Cooled Fast Reactors and Modular High-Temperature Gas-Cooled Reactors**



Randy Belles
Willis Poore
Nicholas Brown
George Flanagan
Mark Holbrook, INL
Wayne Moe, INL
Tanju Sofu, ANL

Approved for public release.
Distribution is unlimited.

March 2017

OAK RIDGE NATIONAL LABORATORY
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# FUEL FAILURE MODES

## Fuel failures are anticipated only during multiple-failure events

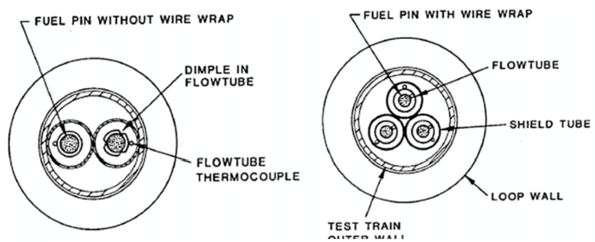
- FCMI: Can be a contributor to fuel failure for both high-smeared density oxide and metal fuel forms
  - Not a significant factor for low smeared fuels (larger fuel cladding radial gap leaves room for early fuel swelling and allows development of inter-connected porosity in fuel matrix for release of fission gas to pin plenum)
- FCCI: Major contributor to metallic fuel pin failure due to formation of low melting-point intermetallic eutectic between the uranium and iron at the fuel-cladding interface
  - When zirconium is used in the metal fuel alloy (also with some coated cladding options), this eutectic penetration is delayed and reduced
  - If, however, transient temperatures are sufficiently high for an extended period, the potential for significant cladding thinning and subsequent breach exists
  - Not a contributor for oxide fuel form
- Fission-gas pressure induced cladding strain leading to thermal creep, accelerated due to FCCI, is the dominant failure mode for metallic fuel

# METAL-FUEL FAILURE CONSEQUENCES

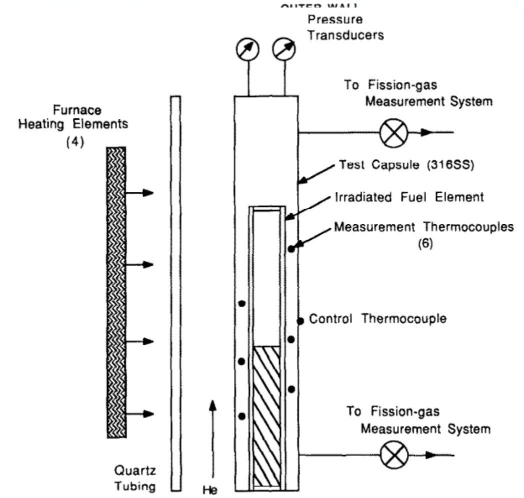
- Due to the high conductivity, peak fuel temperatures during normal operation and accidents are well the axial mid-plane
- Peak cladding temperature is consistently near the top of the fuel column
  – Mimics the rise in coolant temperature
- Therefore, failure locations are predictably near the top of active core where upward ex-pin molten fuel relocation reduces core reactivity
  – Propagation of molten fuel cavity through the top of the fuel column may also lead to molten fuel extrusion to pin plenum prior to cladding breach
- When cladding fails, metallic fuel compatibility with sodium coolant offers an advantage
  – Significantly different from the chemical reaction with oxide fuel and sodium
- Molten metal fuel and cladding eutectic mix disperses in the sodium coolant and gets entrained out of the core
  – Instead of freezing and creating a blockage that can propagate the damage
- Cladding damage typically occurs at temperatures below sodium boiling point
  – Damaged configurations are usually coolable

# METALLIC FUEL TRANSIENT TEST EXPERIENCE

- EBR-II passive and inherent safety tests
  - ~80 integral experiments from comprehensive shutdown heat removal, BOP, and inherent plant control testing program
    - Including several unprotected (without scram) LOF and LOHS tests
  - No challenge to fuel integrity during entire testing program
- TREAT M-series tests
  - Rapid transient overpower tests to examine margin to cladding failure, fuel melting and relocation
  - Whole irradiated EBR-II pins in flowing Na loops
  - U-5Fs/SS, U-10Zr/HT9, U-19Pu-10Zr/D9 fuel types




- Out-of-pile tests in radiant furnaces
  - Fuel Behavior Test Apparatus (FBTA)
    - Irradiated U-10Zr, U-Pu-Zr pin segments
    - Examined liquid phase formation and FCCI rate
  - Whole Pin Furnace (WPF) Tests
    - Irradiated whole U-Zr, U-Pu-Zr pins
    - Examined margin to cladding failure



# BACKUP PAGES

# ACRONYMS

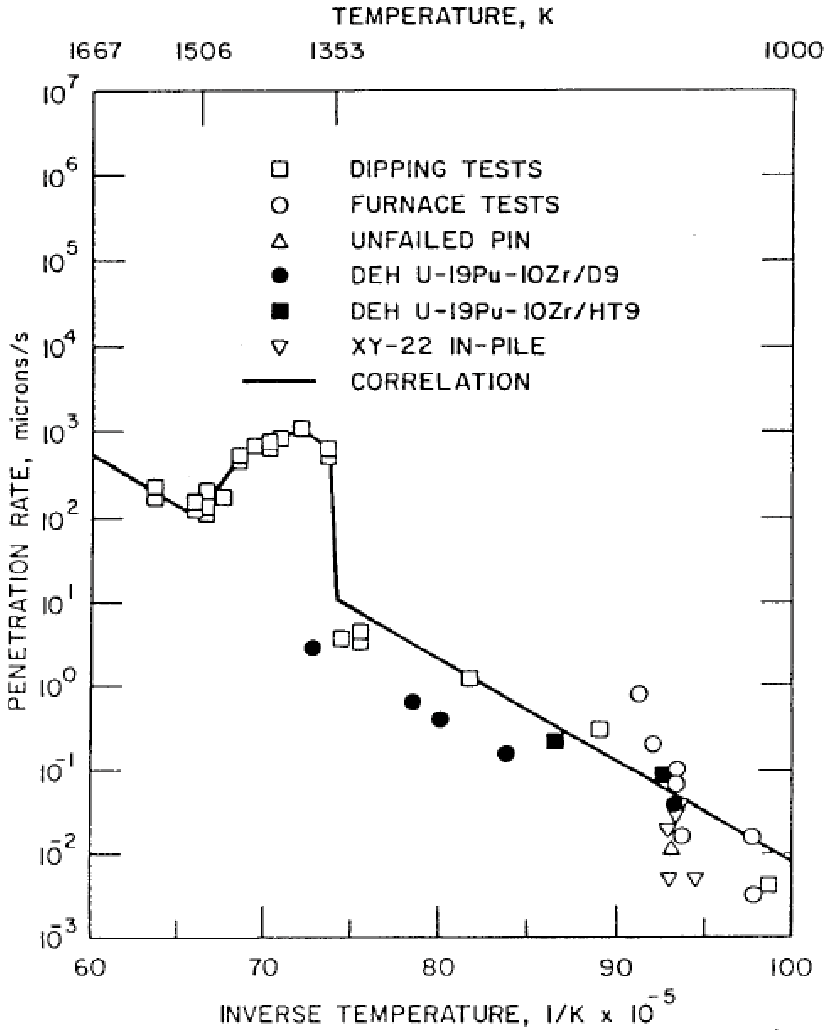
- AFR-100: Advanced Fast Reactor (100 MWe)
- ALMR: Advanced Liquid Metal Reactor program
- BU: Burnup
- CRBR: Clinch River Breeder Reactor
- EBR: Experimental Breeder Reactor
- FBTA: Fuel Behavior Test Apparatus
- FCCI: Fuel-Cladding Chemical Interaction
- FCMI: Fuel-Cladding Mechanical Interaction
- FFTF: Fast Flux Test Facility
- FR: Fast Reactor
- IFR: Integral Fast Reactor program
- LWR: Light Water Reactor
- MOX: Mixed-OXide fuel form
- PWR: Pressurized Water Reactor
- SFR: Sodium-cooled Fast Reactor
- TREAT: TRansient REactor Test facility
- WPF: Whole Pin Furnace

# FUEL PIN DESIGN CONSIDERATIONS

- Burnup is defined in terms of energy yield (MWd/kg) or as the fraction of heavy atoms fissioned (atom-% burned)
- Creep is time-dependent strain under applied stress over a period of time
- Most fission products lodge within both oxide and metal fuel matrix and contribute to overall volumetric increase known as fission product swelling
  - But not all the fission product gases remain confined within the fuel
    - Some can diffuse to the grain boundaries and escape to the pin plenum via interconnected porosity and cracks
  - Net swelling of the fuel is derived from the balance between fission gas retention vs. its release from the fuel into the fuel cladding gap and plenum
  - Grain structure, porosity distribution, temperature, and temperature gradients are important factors influencing swelling
  - Released fission gas pressurizes the fuel pin and applies stress to cladding
    - Could result in cladding liftoff concern for oxide fuel, but not metallic fuel due to presence of bond sodium inside the cladding
- Material mechanical properties such as hardness, yield, and ultimate strength are less important parameters in fuel selection

# METAL FUEL-CLADDING EUTECTIC FORMATION

- Temperature limit depends on fuel/cladding compositions and the irradiation history, but measurable cladding thinning starts around 725°C (1000K)
- Penetration rate is slow until the fuel melting begins
- As the molten fuel eventually comes into contact with the cladding, the eutectic penetration rate becomes very fast



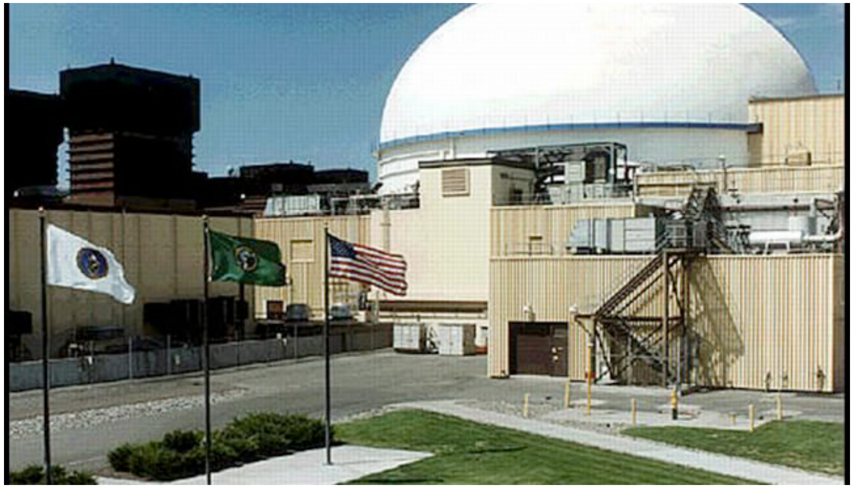
# METALLIC FUEL EXPERIENCE (1/2)

## Focal points for performance assessments

EBR-II

- Fuel fabrication and design impacts
- Prototype fuel behavior
- Swelling and restructuring vs. burnup
- Influence of high temperatures
- Fuel failure mode
- Impact of fuel impurities
- Run beyond cladding breach tests

FFTF



- Fuel column length effects
- Lead metal fuel tests with HT9 cladding
- Commercial metal fuel prototype
- Metal fuel qualification

# METALLIC FUEL DESIGN PARAMETERS

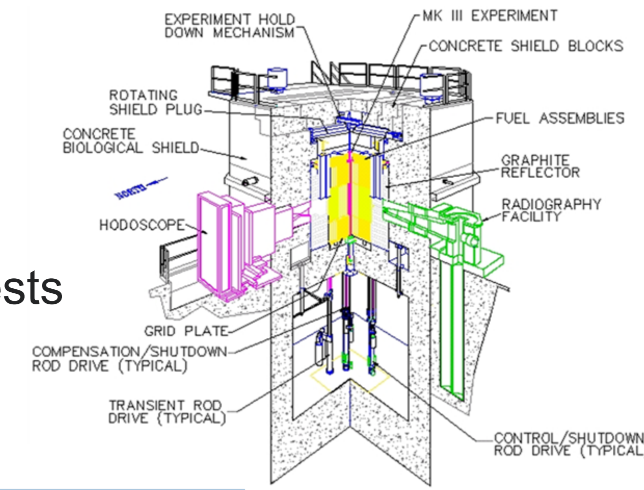
| **Key Parameter** | **EBR-II/FFTF** |
|---|---|
| Peak Burnup, $10^4$MWd/t | 5.0 – 20 |
| Max. linear power, kW/m | 33 – 50 |
| Cladding hotspot temp., $^oC$ | 650 |
| Peak center line temp., $^oC$ | <700 |
| Peak radial fuel temp. difference, $^oC$ | 100 - 250 |
| Cladding fast fluence, n/cm$^2$ | up to 4 x $10^{23}$ |
| Cladding outer diameter, mm | 4.4 - 6.9 |
| Cladding thickness, mm | 0.38 – 0.56 |
| Fuel slug diameter, mm | 3.33 – 4.98 |
| Fuel length, m | 0.3 (0.9 in FFTF) |
| Plenum/fuel volume ratio | 0.84 to 1.45 |
| Fuel residence time, years | 1 - 3 |
| Smeared density, % | 75 |

# FUEL RESPONSE DURING UNPROTECTED ACCIDENTS

- Some multiple-fault accident initiators can lead to fuel failures (typical cases involve unprotected accidents)
  - When PPS fails to scram the reactor, key early measure is to maintain the coolant temperature below its boiling point
  - Net negative reactivity feedback eventually brings the reactor power into equilibrium with the available heat rejection rate as the system approaches an asymptotic temperature distribution
  - In the long term, goal is to keep the asymptotic cladding, vessel, support structure temperatures below creep limits
- Avoiding core damage therefore depends on:
  - Providing sufficient negative reactivity feedback to overcome the initial power-to-cooling mismatch, and
  - Reducing the reactivity feedback components (mainly Doppler) that resist the return of the system to equilibrium

# TREAT EXPERIMENTS RELATIONAL DATABASE

- Searchable collection of transient tests conducted in TREAT (1959-1994)
  - ~900 tests & categories w/ parametric information (e.g. fuel, transient info, results)
  - ~6000 searchable PDFs with links to referenced tests
- Metallic Fuel Transient Overpower Tests
  - Test specifications, test plans, digital data…




| | objectives or outcomes | | | | | | | fuel | | B/U | | | clad | | transient type | | transient meas. | | post-test analyses | | | | | | posttest examinations & measurements | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Limited fuel damage, no clad breach | Pre-failure in-pin fuel motion | Cladding failure threshold | Mild cladding failure | Fission product release | Fuel-coolant interaction | Post-failure fuel and cladding disruption & dispersal | U-Zr | U-Pu-Zr | Zero (fresh fuel) | Low (up to 5 at.%) | Medium (5 to 10 at.%) | D9 | HT9 | Overpower | Heat balance | Fast Neutron Hodoscope | Thermal-hüdraulic (Press, Temp, Flow) | Thermal-hydraulics | Cladding failure | Fuel motion | Severe-accident behavior, interaction of multiple Phenomena | Microstructural and mm-scale changes | Fuel-cladding interface or gap behavior | Examinations of irradiated sibling samples | Non-destructive examination of test remains | Destructive examination of test remains | Micro-examination of fuel & cladding remains |
| **M5** | ✓ | ✓ | | | | | | | ✓ | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **M6** | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **M7** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

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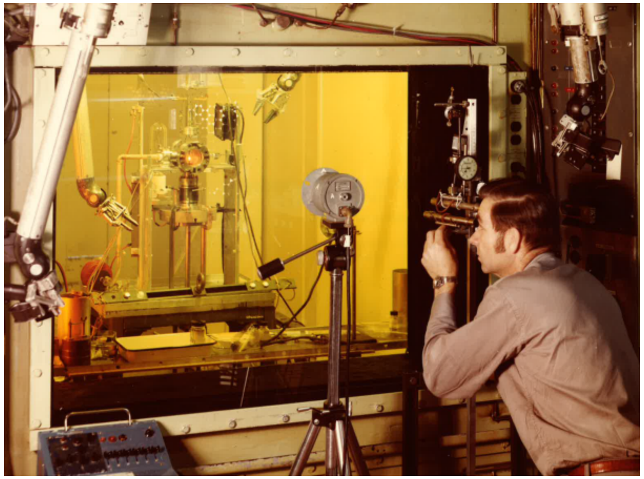
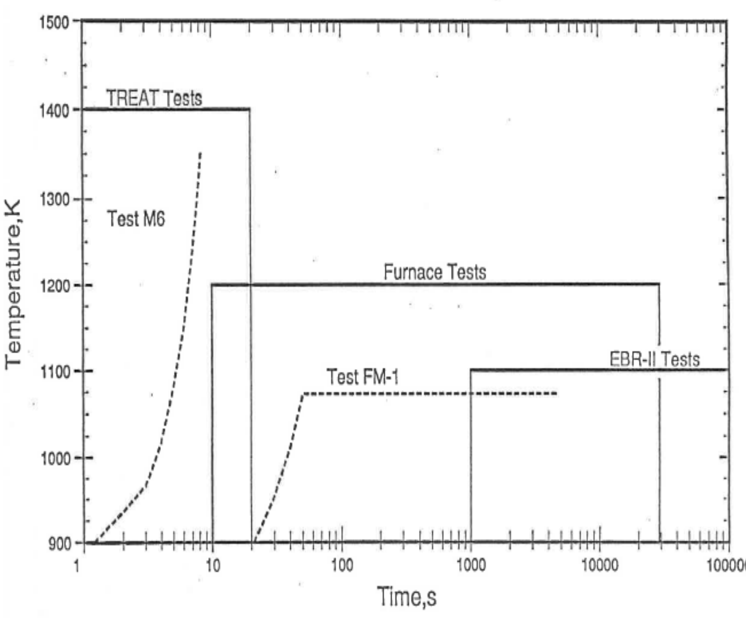
# DATABASE FOR OUT OF PILE EXPERIMENTS

## Transient furnace tests in hot cells



- Chopped irradiated pin segments in Fuel Pin Test Apparatus (FBTA)
- Full length irradiated pins in Whole Pin Furnace (WPF)
- Simulated reactor accidents, varying ramp rates and peak temperatures
- Showed significant safety margin for selected transient conditions
- U-(0-26)Pu-10Zr pins in D9, HT9, 316SS clad
  - Burnup: 2-3 a/o in WPF, 6-12 a/o in FBTA
  - Fuel compatibility tests on clad fuel segments
  - Fission gas retention examinations
  - Cladding penetration depth measurements
- Results being archived in an online database:
  - Metallurgical examination of tested materials
  - Fission product release measurements

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