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—\( \text{UO}_2 \), 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)
    - \( \text{U}_3\text{Si} \)
    - 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).
FFTF FUEL PIN AND ASSEMBLY DESIGN

Oxide fuel

- Bottom End Cap
- UO2 Insulator Pellets
- Inconel Reflector
- Dish Pellet
- Top End Cap
- UO2 Insulator Pellets
- Inconel Reflector
- 316 SS Plenum Spacer
- Tag Gas Capsule
- Cladding 316 SS (20% CW)
- 36” Mixed Oxide PuO2 - UO2 Pellet Stack
- 0.230 Dia Fuel Pin
- 0.286 Pitch
- 0.120 Wall
- Above Core Load Pad
- Duct
- Handling Socket
- Fuel Pin Bundle Assembly
- Coolant Inlet Ports
- Nozzle Assembly
- Shield-Orifice Block
- Floating Collar (Top Load Pad)
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°C, fission gas mobility is low and there is little gas escape
  - For 1000°C<T<1600°C, atomic motion allows some diffusion, and some amount of gas can escape from fuel matrix
  - For T>1600°C, 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
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
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>
<thead>
<tr>
<th>Reactor</th>
<th>Fuel Type</th>
<th># of Pins</th>
<th>Clad</th>
<th>Peak burnup</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBR-II</td>
<td>Mark-I/IA (U-5Fs)</td>
<td>~90,000</td>
<td>316SS, D9, HT9</td>
<td>~2.5%</td>
</tr>
<tr>
<td></td>
<td>Mark-II (U-5Fs)</td>
<td>~40,000</td>
<td></td>
<td>~8%</td>
</tr>
<tr>
<td></td>
<td>Mark-IIIC/IICS/III/IIIA/IV (U-10Zr)</td>
<td>~16,000</td>
<td></td>
<td>~10%</td>
</tr>
<tr>
<td></td>
<td>U-Pu-Zr</td>
<td>&gt;600</td>
<td>HT9</td>
<td>~15-20%</td>
</tr>
<tr>
<td>FFTF</td>
<td>U-10Zr</td>
<td>&gt;1050</td>
<td></td>
<td>~14%</td>
</tr>
<tr>
<td></td>
<td>U-Pu-Zr</td>
<td>37</td>
<td></td>
<td>~9%</td>
</tr>
</tbody>
</table>
**OXIDE AND METALLIC FUEL COMPARISONS (1/4)**

<table>
<thead>
<tr>
<th></th>
<th>Oxide (UO₂-20PuO₂)</th>
<th>Metal (U-20Pu-10Zr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Metal Density, g/cm³</td>
<td>9.3</td>
<td>14.1</td>
</tr>
<tr>
<td>Melting Temperature (Tₘ₀ₐ₅), K</td>
<td>3000</td>
<td>1400</td>
</tr>
<tr>
<td>Thermal Conductivity, W/cm-K</td>
<td>0.023</td>
<td>0.16</td>
</tr>
<tr>
<td>Operating Centerline Temp. at 40 kW/m, K</td>
<td>2360</td>
<td>1060</td>
</tr>
<tr>
<td>Margin to melting</td>
<td>T/Tₘₐ₅</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>ΔT/Tₘₐ₅</td>
<td>0.21</td>
</tr>
<tr>
<td>Fuel-Cladding Solidus, K</td>
<td>1675</td>
<td>1000 (eutectic)</td>
</tr>
<tr>
<td>Thermal Expansion, 1/K</td>
<td>12× 10⁻⁶</td>
<td>17× 10⁻⁶</td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>cₚ, J/g-K</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>ρcₚ, J/cm³-K</td>
<td>3.2</td>
</tr>
</tbody>
</table>
## OXIDE AND METALLIC FUEL COMPARISONS (2/4)

**Impact of neutron spectrum**

<table>
<thead>
<tr>
<th></th>
<th>Oxide fuel</th>
<th>Metal Fuel</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrum</strong></td>
<td>Softer</td>
<td>Harder</td>
<td>Oxygen moderation</td>
</tr>
<tr>
<td><strong>Effective heavy metal density</strong></td>
<td>Lower</td>
<td>Higher</td>
<td></td>
</tr>
<tr>
<td><strong>Neutron yield</strong></td>
<td>Lower</td>
<td>Higher</td>
<td>Yield is higher in harder spectrum and for larger heavy-metal density</td>
</tr>
<tr>
<td><strong>Conversion rate</strong></td>
<td>Lower</td>
<td>Higher</td>
<td>Due to all of the above</td>
</tr>
<tr>
<td><strong>Burnup reactivity swing</strong></td>
<td>Higher</td>
<td>Lower</td>
<td>Due to conversion rate difference</td>
</tr>
<tr>
<td><strong>Excess external reactivity needed</strong></td>
<td>Larger</td>
<td>Smaller</td>
<td>Due to burnup reactivity swing difference</td>
</tr>
<tr>
<td><strong>Available reactivity for accidental insertion</strong></td>
<td>Larger</td>
<td>Smaller</td>
<td>Due to above</td>
</tr>
<tr>
<td><strong>Mean free path</strong></td>
<td>Shorter</td>
<td>Longer</td>
<td>Spectrum difference (greater sensitivity to axial/radial expansion for metal fuel)</td>
</tr>
</tbody>
</table>
### OXIDE AND METALLIC FUEL COMPARISONS (3/4)

Impact of operating temperature and Doppler feedback

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

<table>
<thead>
<tr>
<th>Key Parameter</th>
<th>EBR-II/FFTF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Burnup, $10^4$MWd/t</td>
<td>5.0 – 20</td>
</tr>
<tr>
<td>Max. linear power, kW/m</td>
<td>33 – 50</td>
</tr>
<tr>
<td>Cladding hotspot temp., °C</td>
<td>650</td>
</tr>
<tr>
<td>Peak center line temp., °C</td>
<td>&lt;700</td>
</tr>
<tr>
<td>Peak radial fuel temp. difference, °C</td>
<td>100 - 250</td>
</tr>
<tr>
<td>Cladding fast fluence, n/cm²</td>
<td>up to $4 \times 10^{23}$</td>
</tr>
<tr>
<td>Cladding outer diameter, mm</td>
<td>4.4 - 6.9</td>
</tr>
<tr>
<td>Cladding thickness, mm</td>
<td>0.38 – 0.56</td>
</tr>
<tr>
<td>Fuel slug diameter, mm</td>
<td>3.33 – 4.98</td>
</tr>
<tr>
<td>Fuel length, m</td>
<td>0.3 (0.9 in FFTF)</td>
</tr>
<tr>
<td>Plenum/fuel volume ratio</td>
<td>0.84 to 1.45</td>
</tr>
<tr>
<td>Fuel residence time, years</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Smeared density, %</td>
<td>75</td>
</tr>
</tbody>
</table>
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…
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