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Integral Fast Reactor and Associated Fuel Cycle System

Part 2. Status of Metal fuel Development

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... for a brighter future

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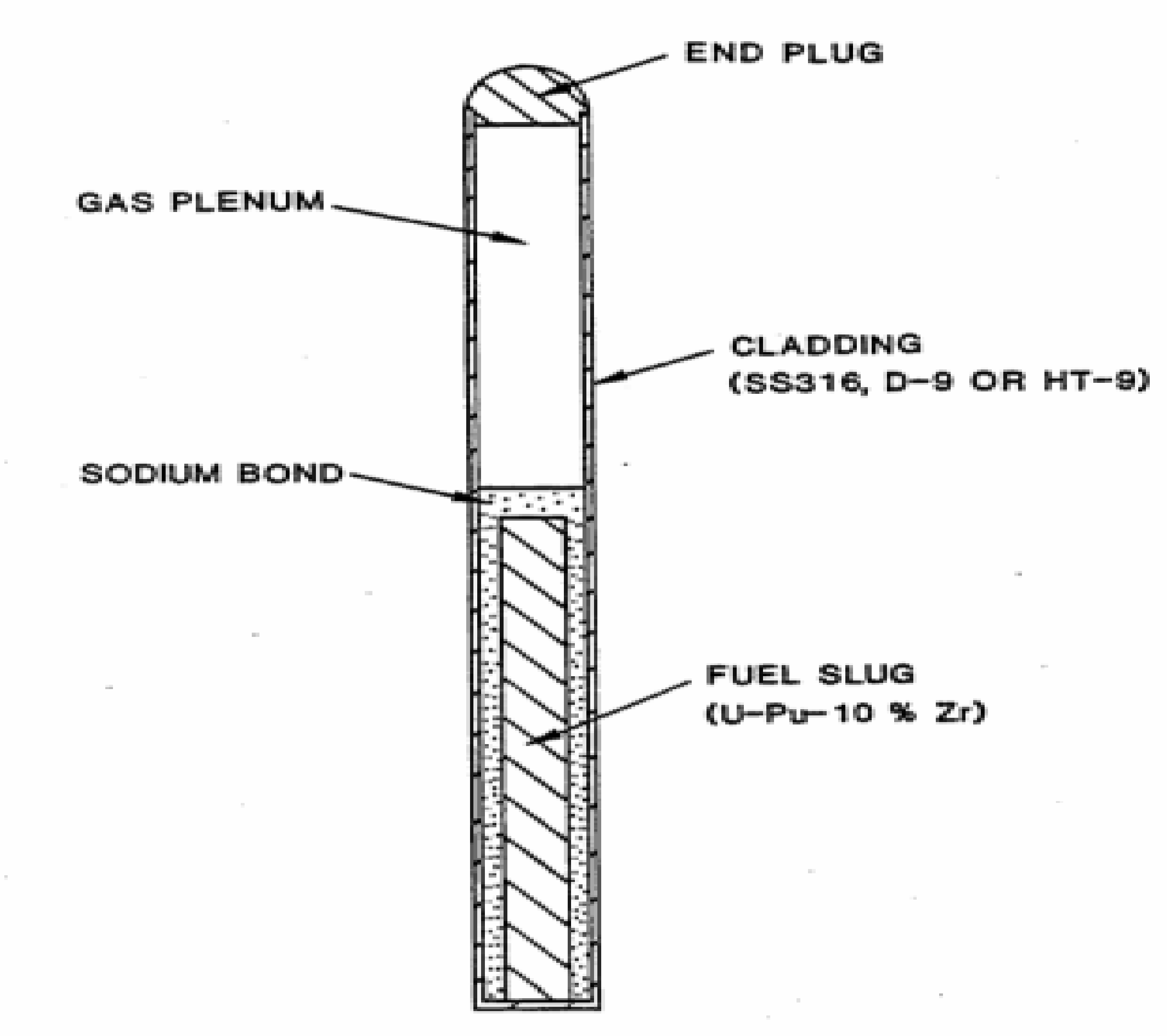
Historical Background of Metal Fuel

- Metal fuel was the original choice for all early fast reactors (EBR-1, Dounreay, EBR-II, and Fermi-1) due to its compatibility with the sodium coolant.
- The metal fuel development was abandoned in the late 1960's in favor of oxide fuel. It was perceived that metal fuel could not achieve high burnup because the irradiation swelling could not be constrained by cladding.
- However, EBR-II continued to use metal fuel as its driver fuel and its burnup capability was drastically improved through discoveries in the late 1960's and irradiation experience in the 1970's.

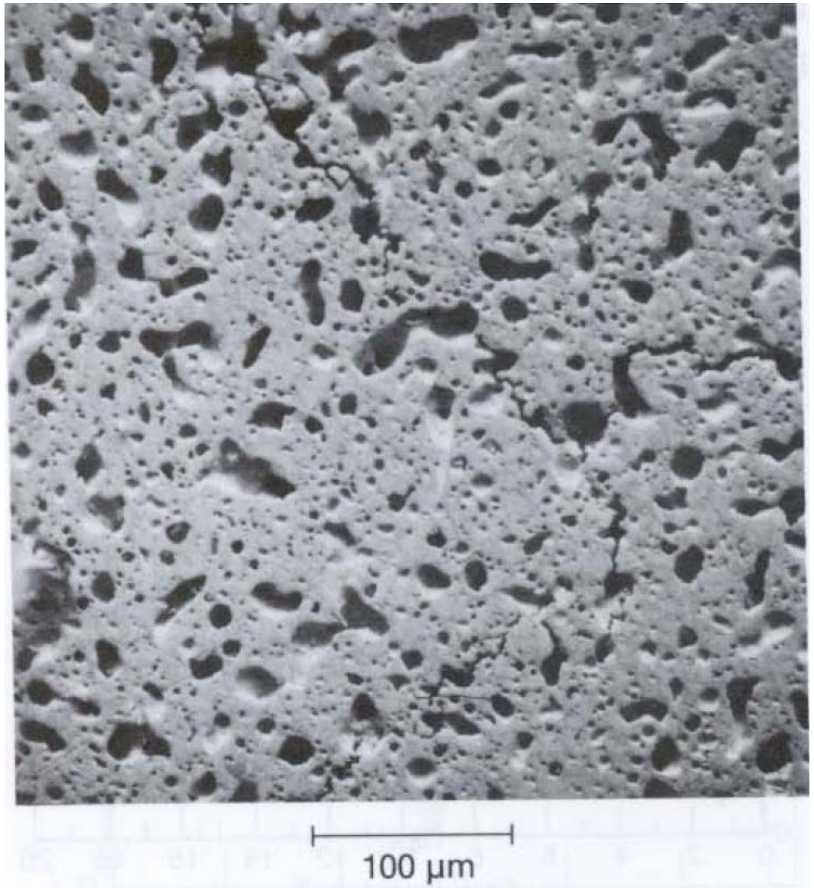
Schematic of Metal Fuel Pin



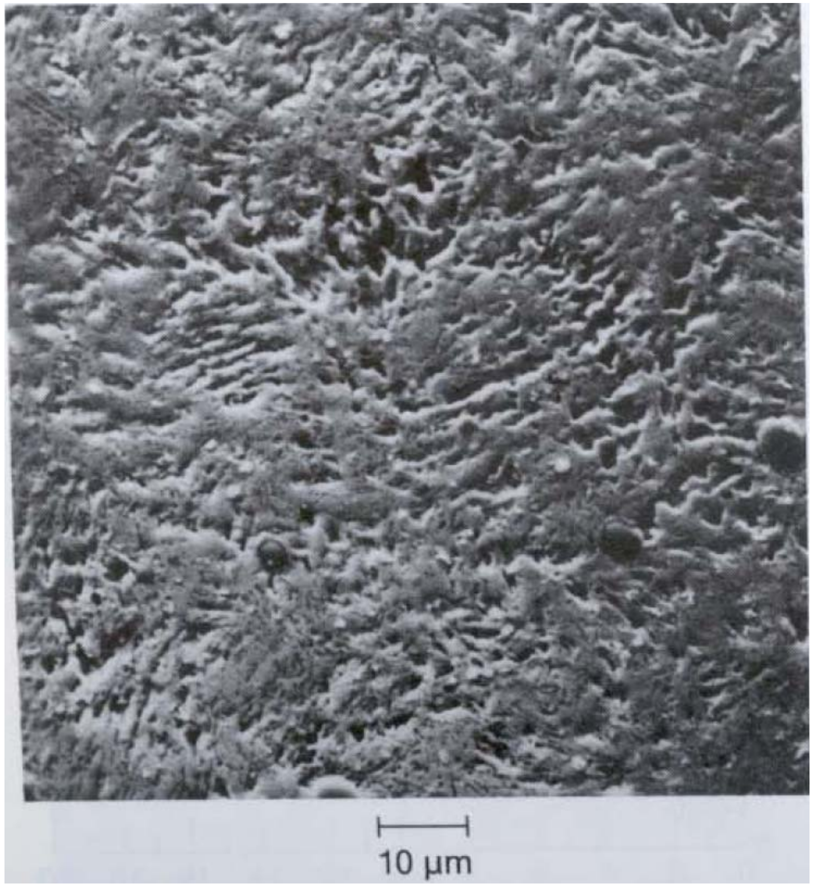
Key Discovery on Metal Fuel

- The fuel swelling is driven by the internal pressure of fission gas bubbles. Once fuel swells by about 30% in volume, then the fission gas bubbles interconnect and provide passage for fission gas release to plenum.
- By adequately sizing the plenum, the fuel swelling can easily be constrained by the cladding and a high burnup can be achieved.
- The porosity would also be available to accommodate the inexorable swelling from the accumulation of solid fission products, allowing ultimate burnup capability beyond 20% (200,000 MWD/T).

Fission Gas Porosity in Metal Fuel

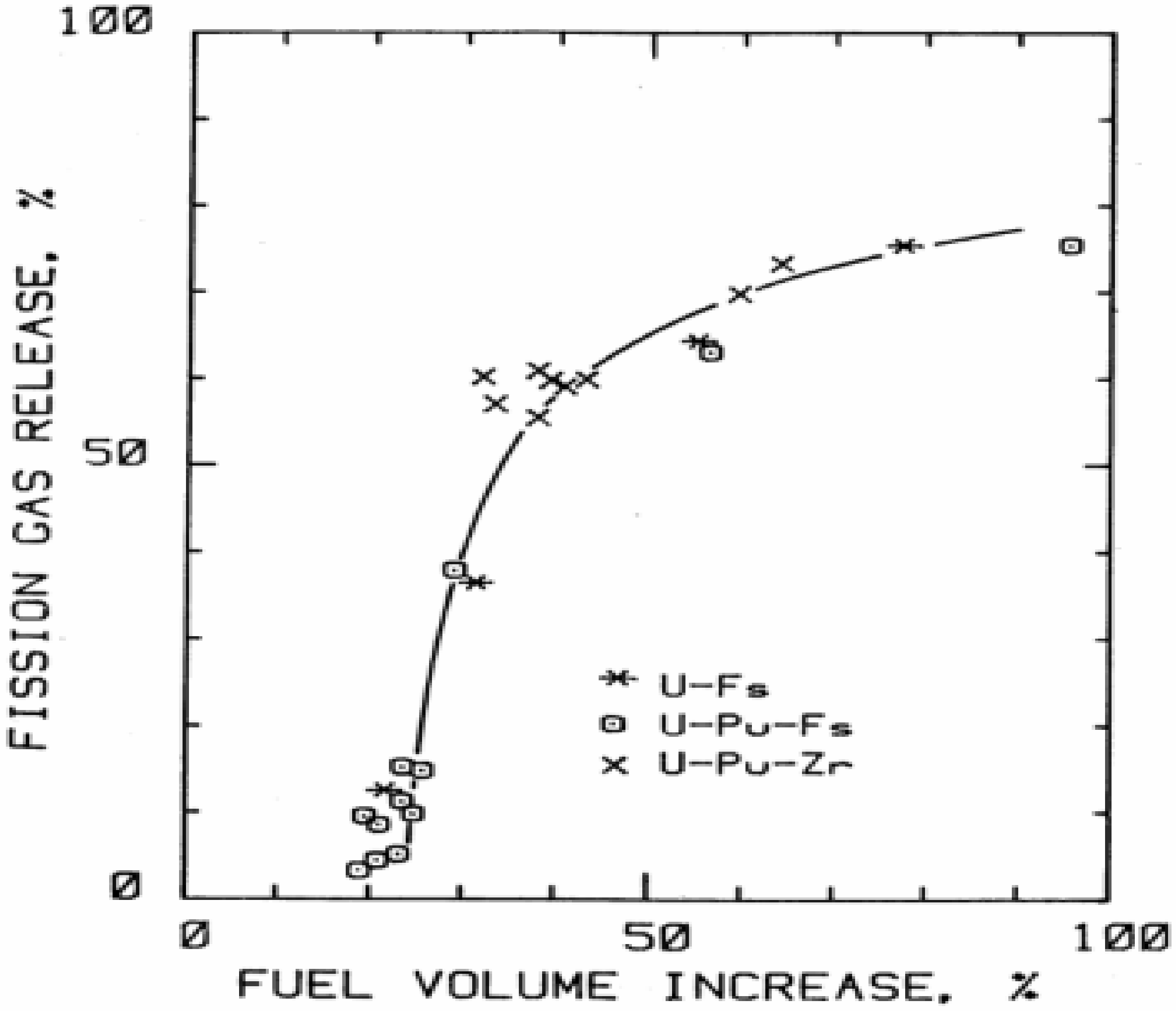


Pore morphology of irradiated
U-10Zr (dominantly γ-phase)
Fuel center

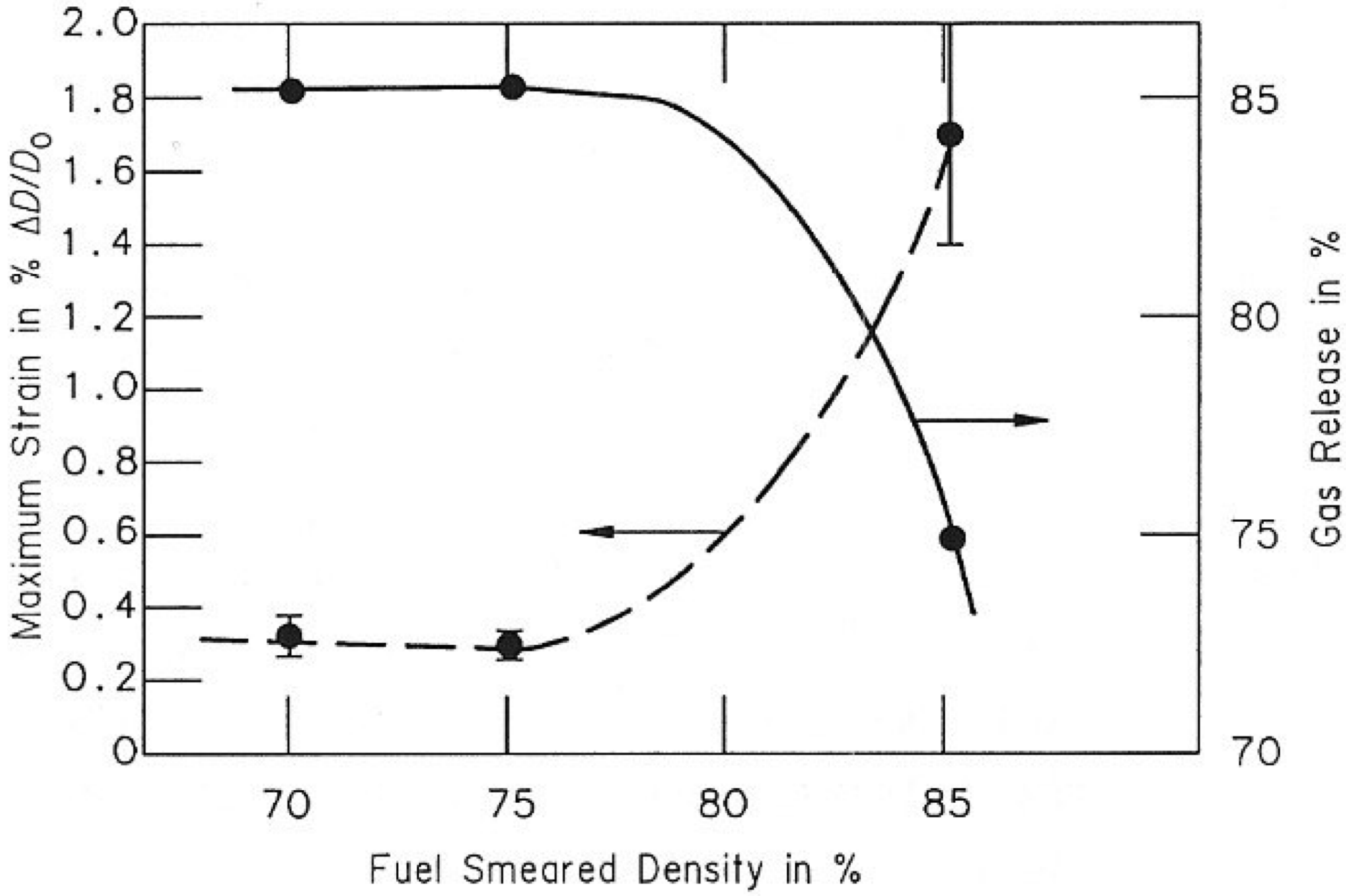


Pore morphology of irradiated
U-10Zr (dominantly α-phase)
Fuel periphery

Fission Gas Release Rate vs. Swelling



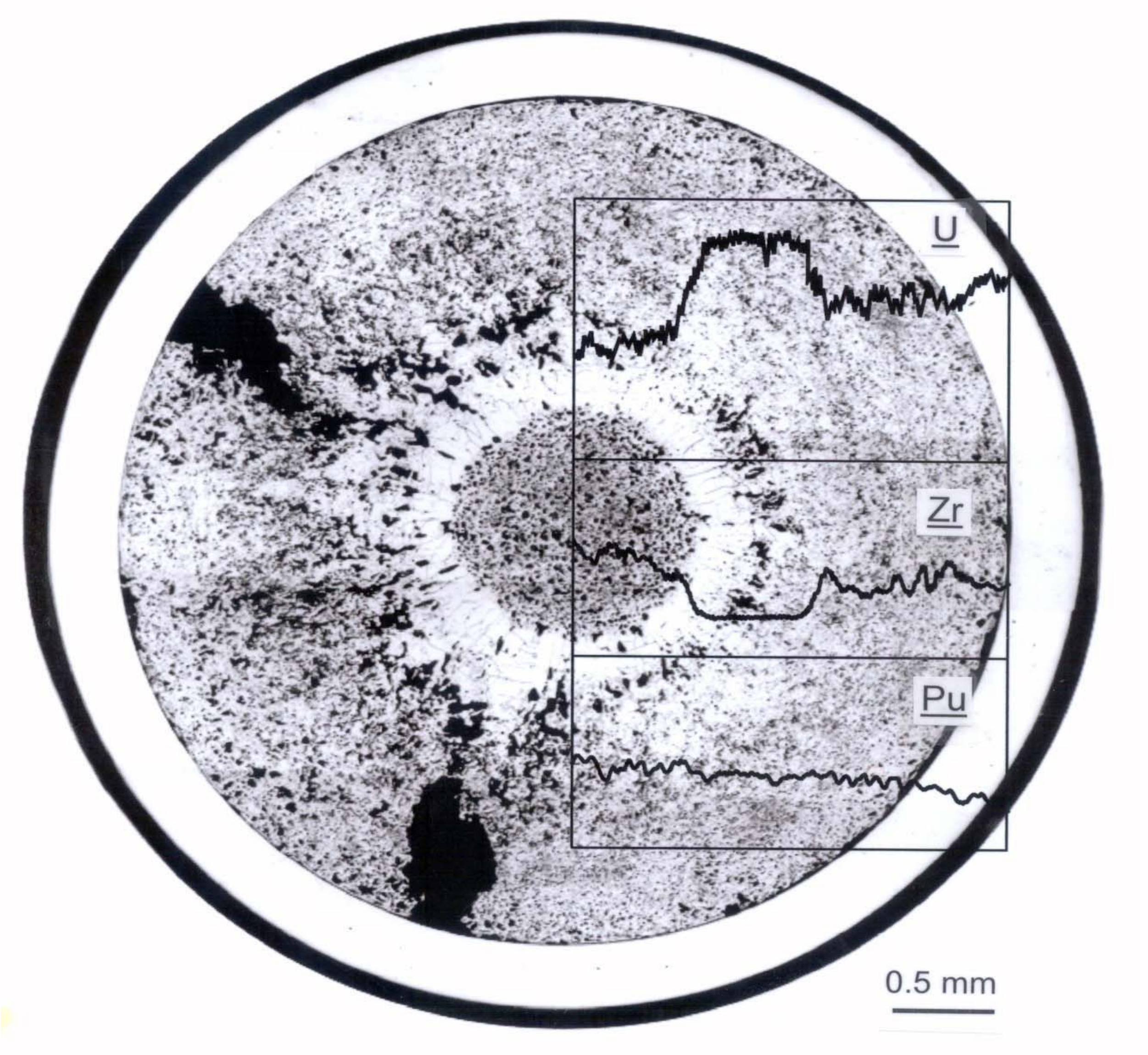
Fuel Cladding Mechanical Interaction



Excellent Steady-State Irradiation Performance

- Over 40,000 EBR-II Mark-II (75% smear density U-Fs) driver fuel pins have been successfully irradiated through early 1980's.
- When IFR Program was initiated in 1984, 10% Zr replaced 5% fissium, and a total of 16,800 U-Zr and 660 U-Pu-Zr fuel pins have been irradiated in the next 10 years. U-Pu-Zr fuel reached peak burnup of ~20%.
- In addition, 7 full metal fuel assemblies have been irradiated in FFTF. Lead test achieved peak burnup of 16%. One assembly contained U-Pu-Zr, which achieved peak burnup of 10%.

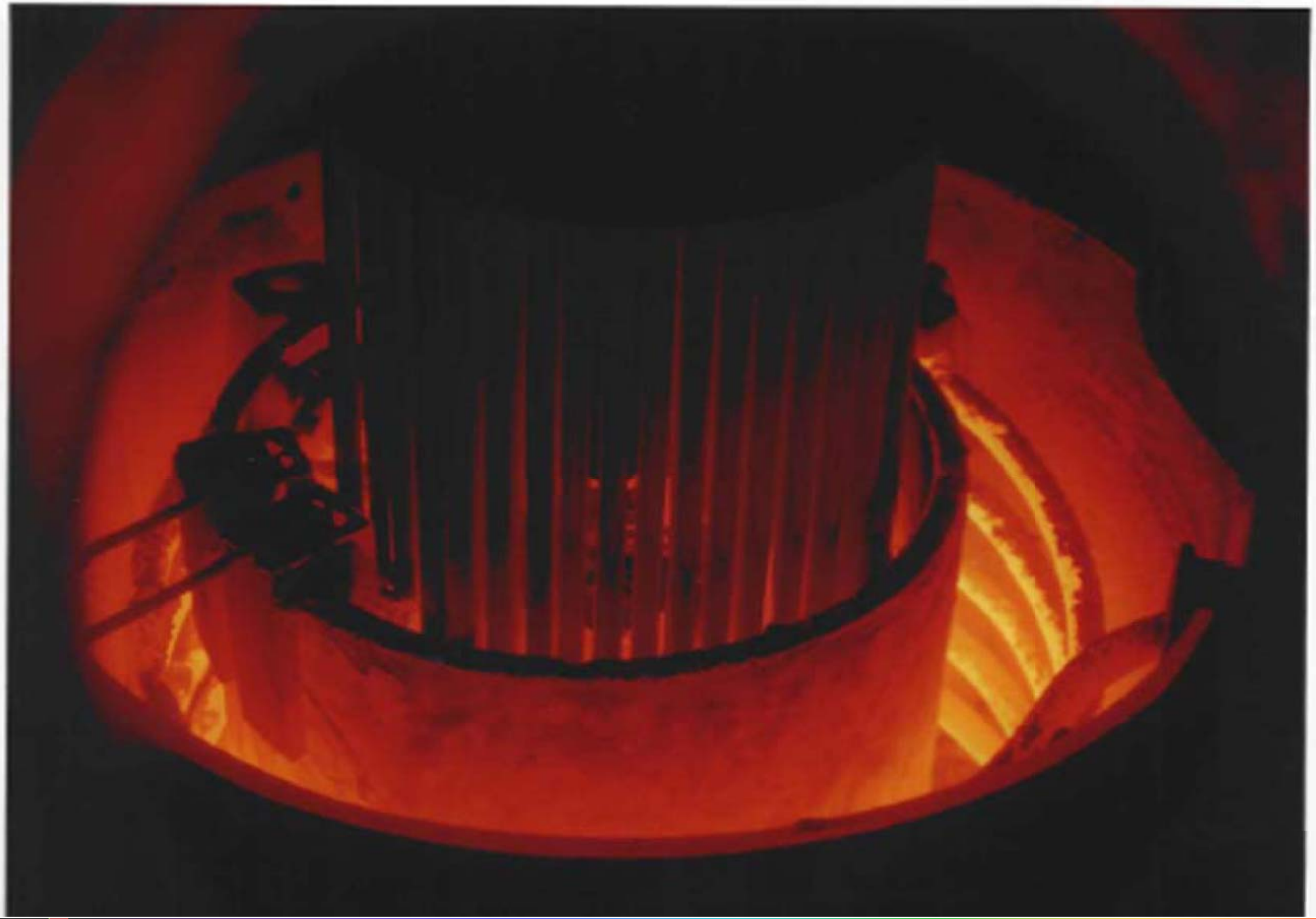
U-Pu-Zr Fuel Restructuring under Irradiation



Role of Zirconium

- Raises melting temperature of U-Pu.
- Improves fuel cladding compatibility by suppressing inter-diffusion of fuel and cladding components.

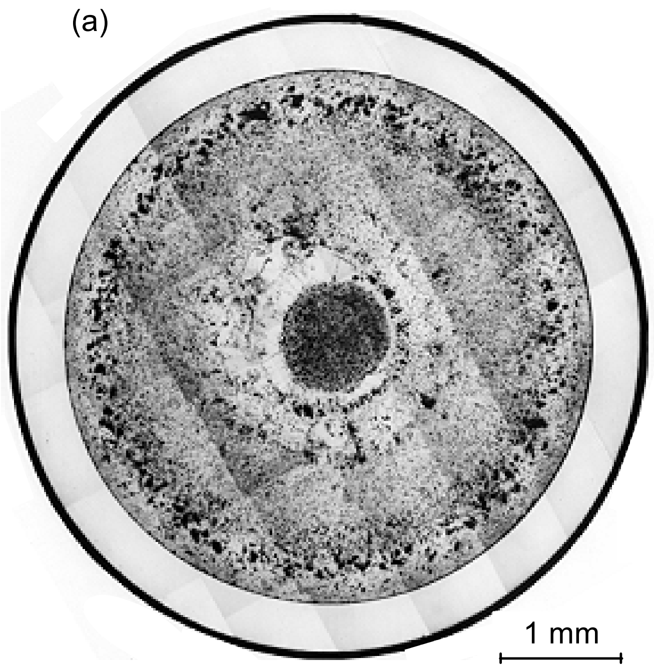
Injection Casting of Metal Fuel Rods

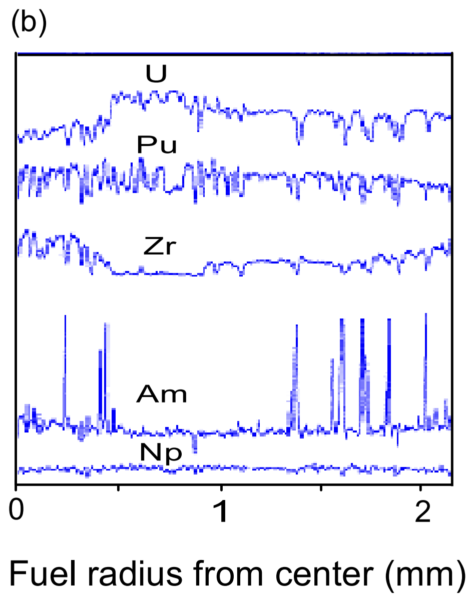


Minor Actinide Fuel is Straight-forward

- Three full length pins containing minor actinides were successfully fabricated and irradiated to 6% burnup.
- As-fabricated composition was: 68.2%U, 20.2%Pu, 9.1%Zr, 1.2%Am, and 1.3%Np.
- Approximately 40% of the initial Am was lost during casting due primarily to volatile impurities of Pu-Am feedstock (3 at% Ca and 2,000 ppm Mg).
- Judicious selection of the cover gas pressure during the melt preparation and the mold vacuum level during casting is expected reduce the Am loss by ~200 times.

Post-irradiation Examination of Minor Actinide Fuel at 6% Burnup





Observations

- The similar trends for U, Pu, Zr as in U-Pu-Zr fuel.
- Am follows Zr, and precipitates in pores.
- Am tends to migrate more in porous fuel.

→ Vapor-phase diffusion?

- Np is sessile.

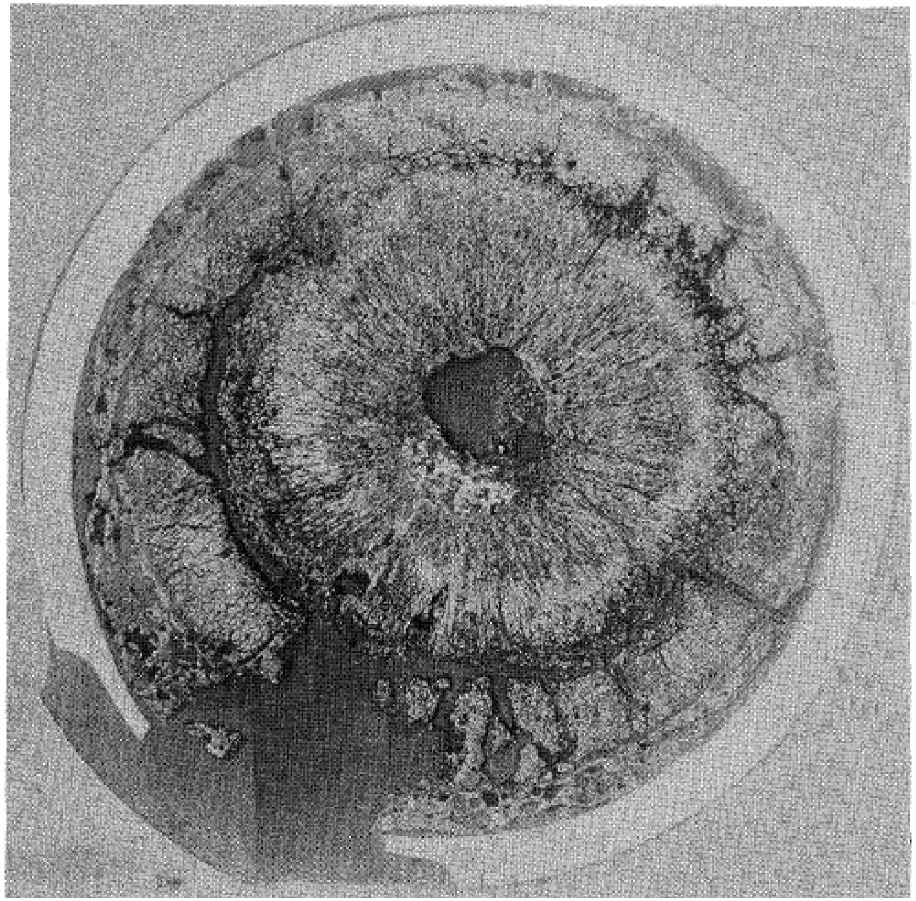
Excellent Off-Normal Performance Characteristics

- Transient Capabilities
- Run-beyond-cladding-breach performance
- Transient overpower failure margins
- Pre-failure axial extrusion behavior

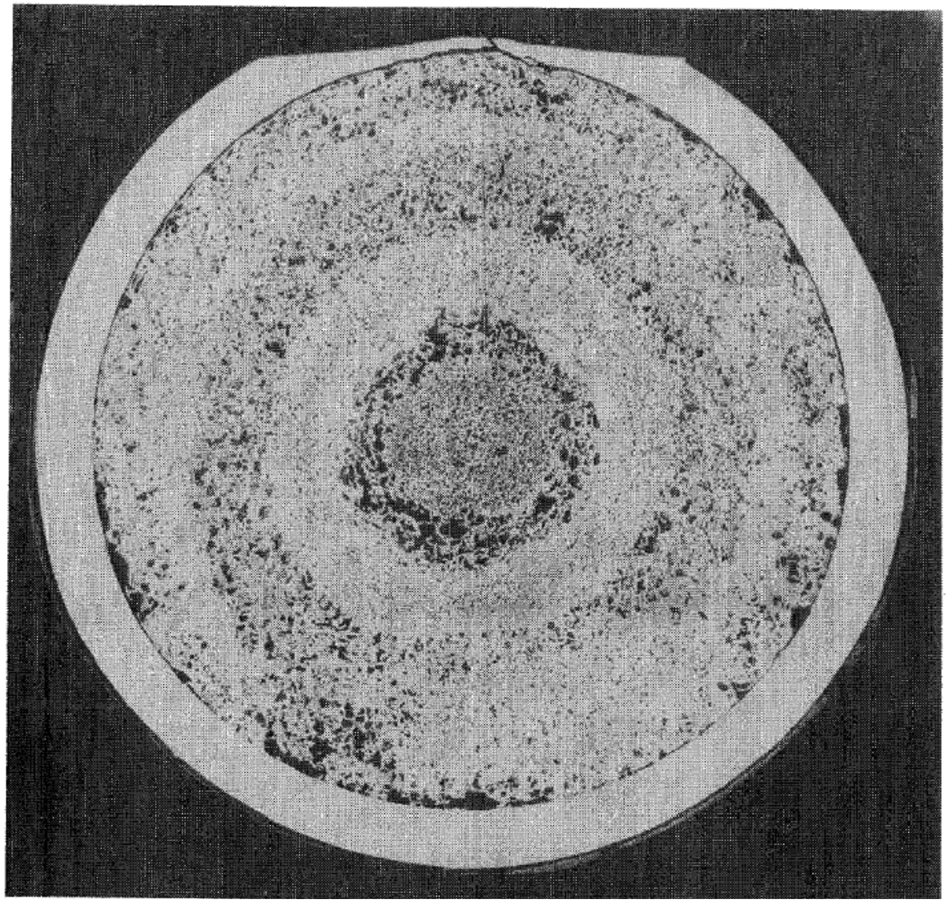
Transient Capabilities of Metal Fuel

- Sample history of a typical driver fuel in EBR-II:
  - 40 start-ups and shutdowns
  - 5 15% overpower transients
  - 3 60% overpower transients
  - 45 loss-of-flow and loss-of-heat-sink tests

Run Beyond Cladding Breach Tests

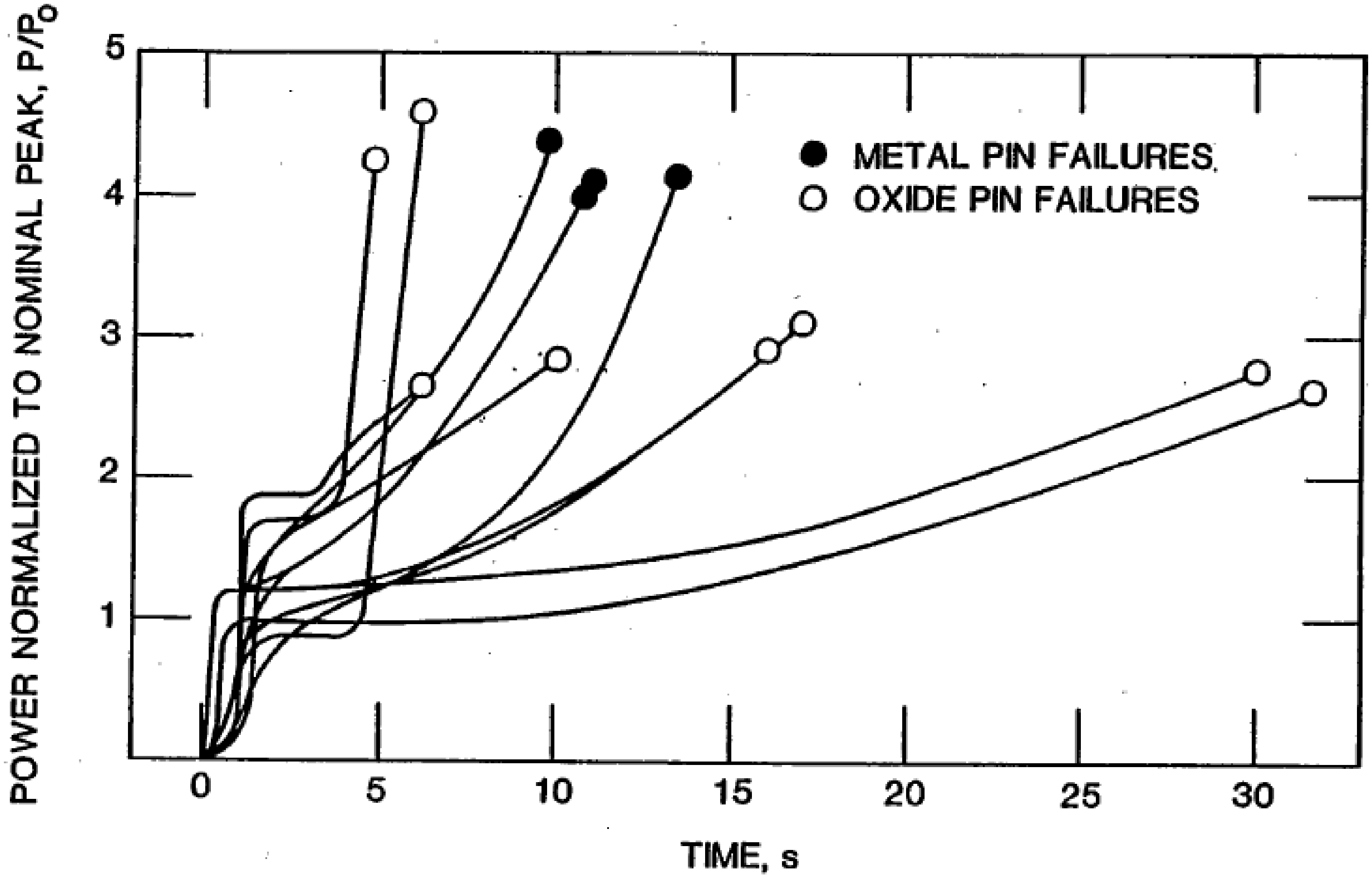


9% burnup Oxide RBCB Test

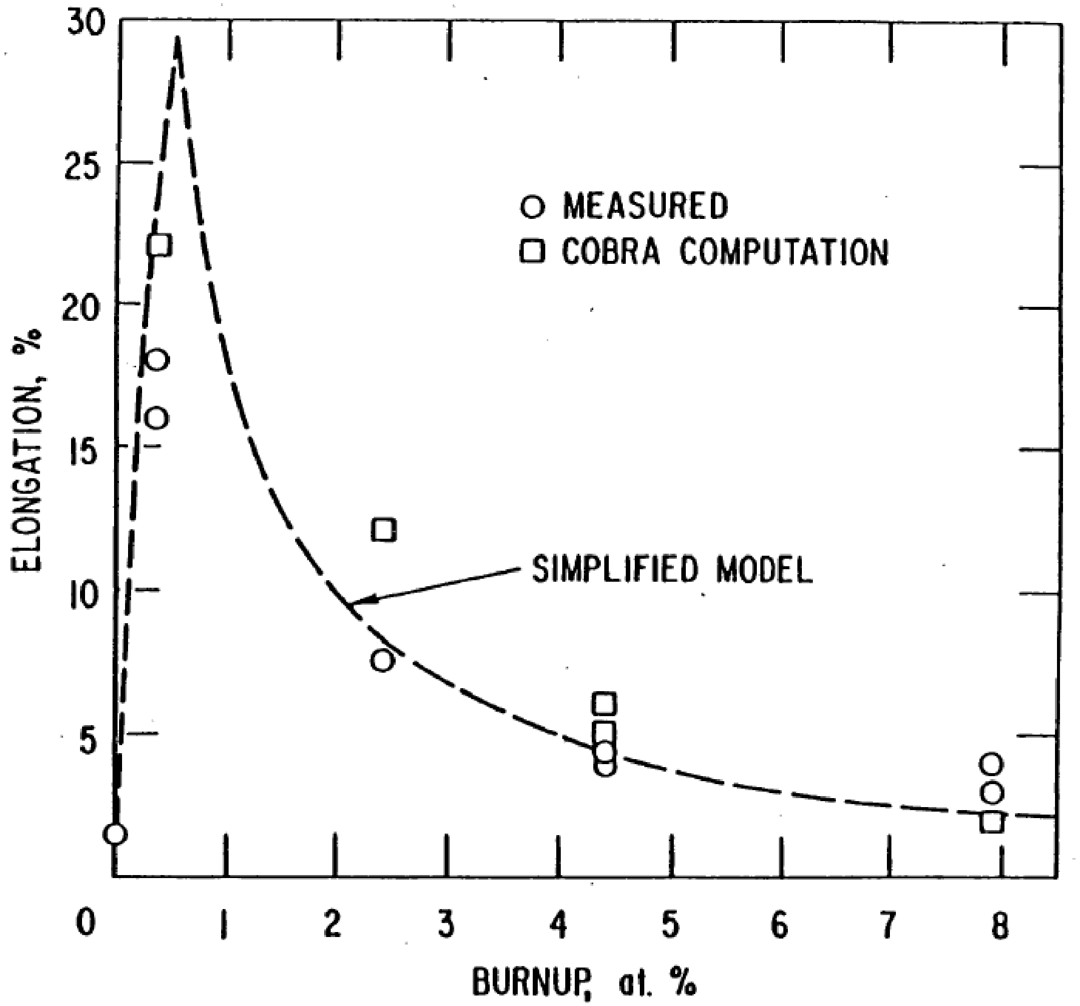


12% Burnup Metal RBCB Test
(Operated 169 days after breach)

Transient Overpower Failure Tests in TREAT



Pre-failure Axial Fuel Extrusion Behavior



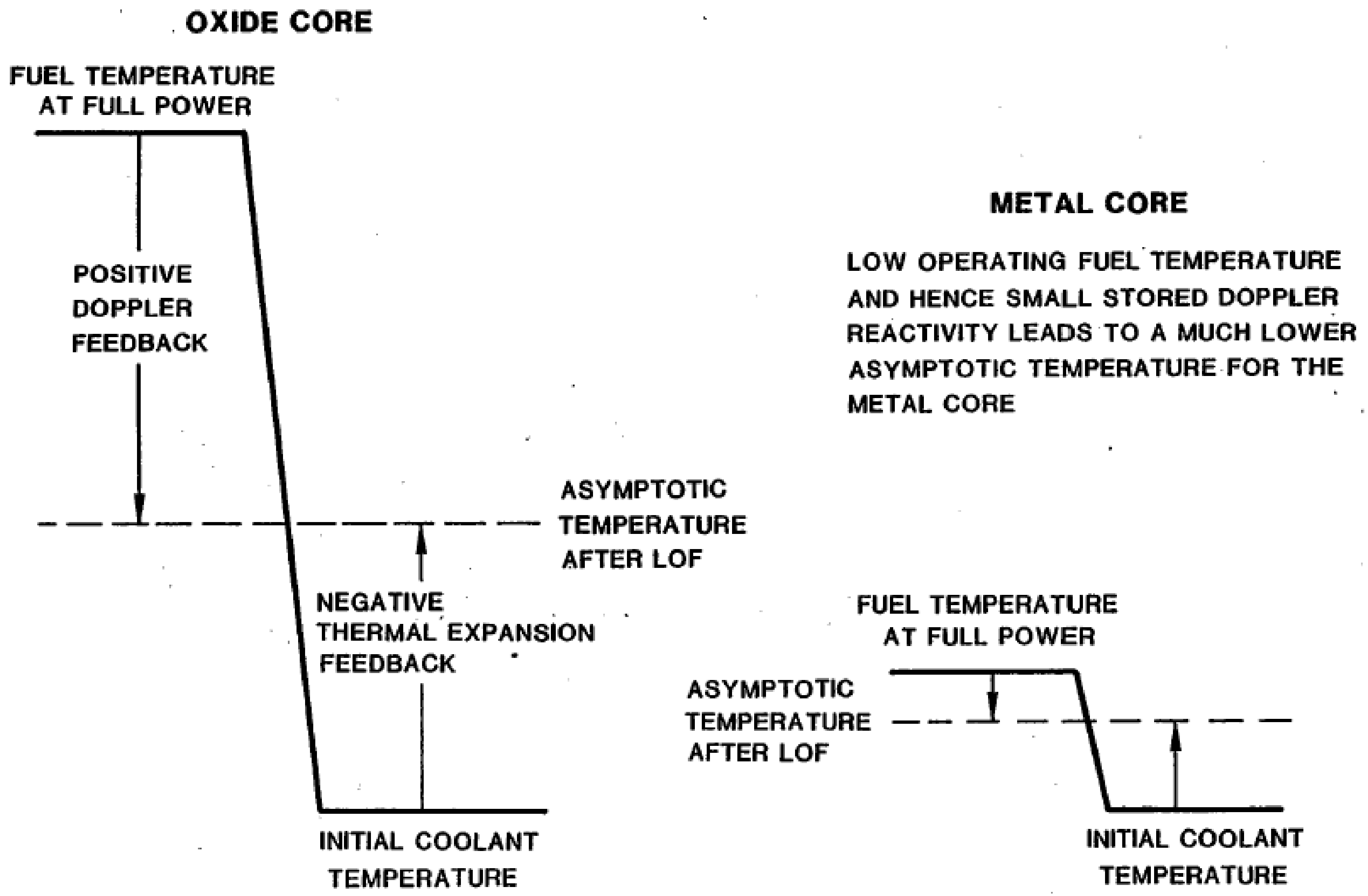
Fuel-Cladding Eutectic Formation

- The onset of fuel-cladding eutectic formation starts at 700-725^{o}C, depending on the fuel alloy and cladding types.
- At the onset temperature, the interaction is benign. Even at 100^{o}C above the eutectic temperature, the eutectic formation is minimal in one hour.
- Only at much higher temperatures, close to fuel melting point, the eutectic formation becomes rapid.
- Therefore, the eutectic formation is not a primary safety concern during transient overpower conditions.

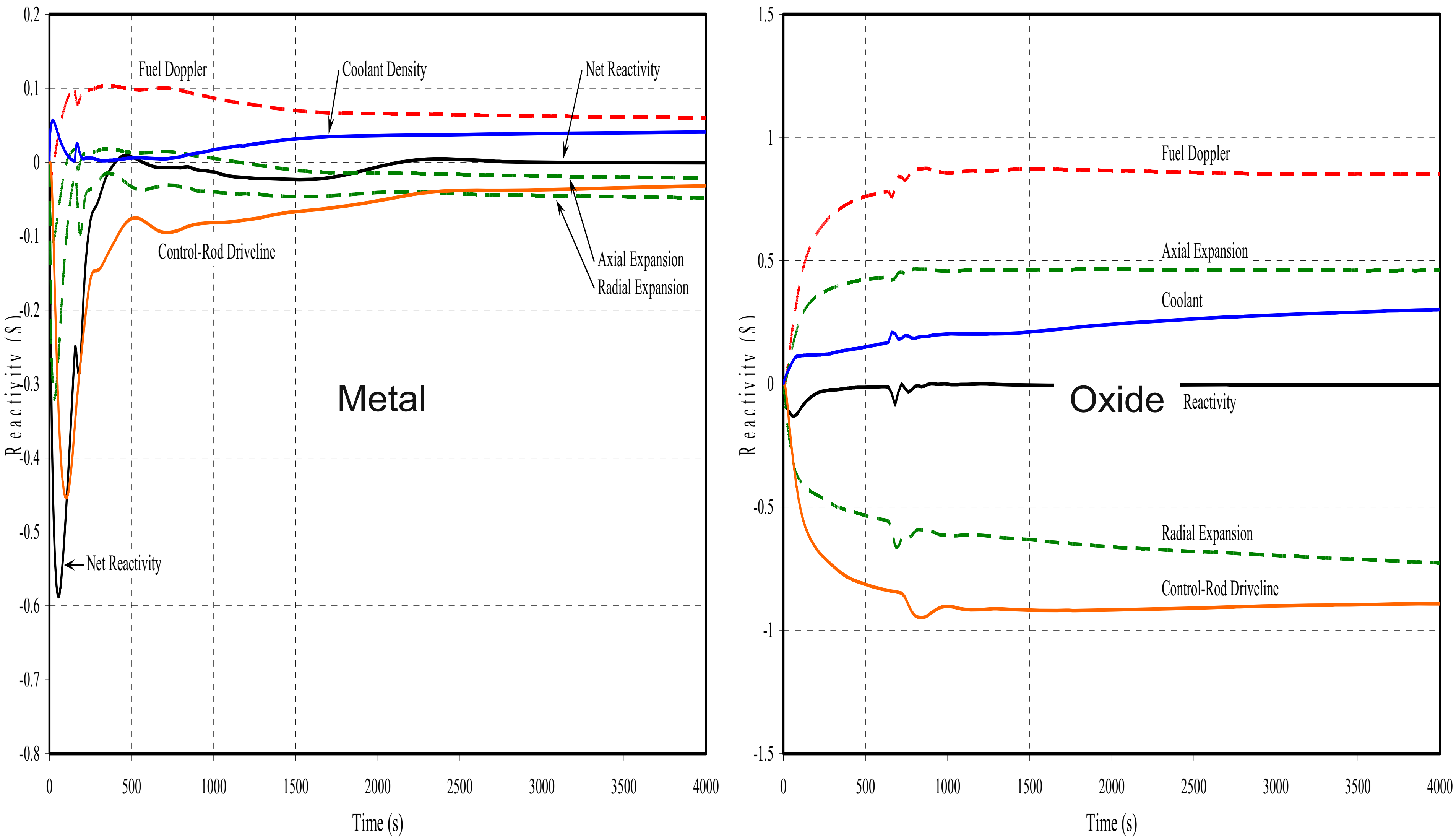
Inherent Passive Safety Demonstrated

- The landmark tests conducted on EBR-II in April 1986 demonstrated the ultimate passive safety characteristics of sodium cooled fast reactors, if properly designed.
- Two major accident initiators simulated:
  - Loss-of-flow without scram from full power
  - Loss-of-heat-sink without scram from full power

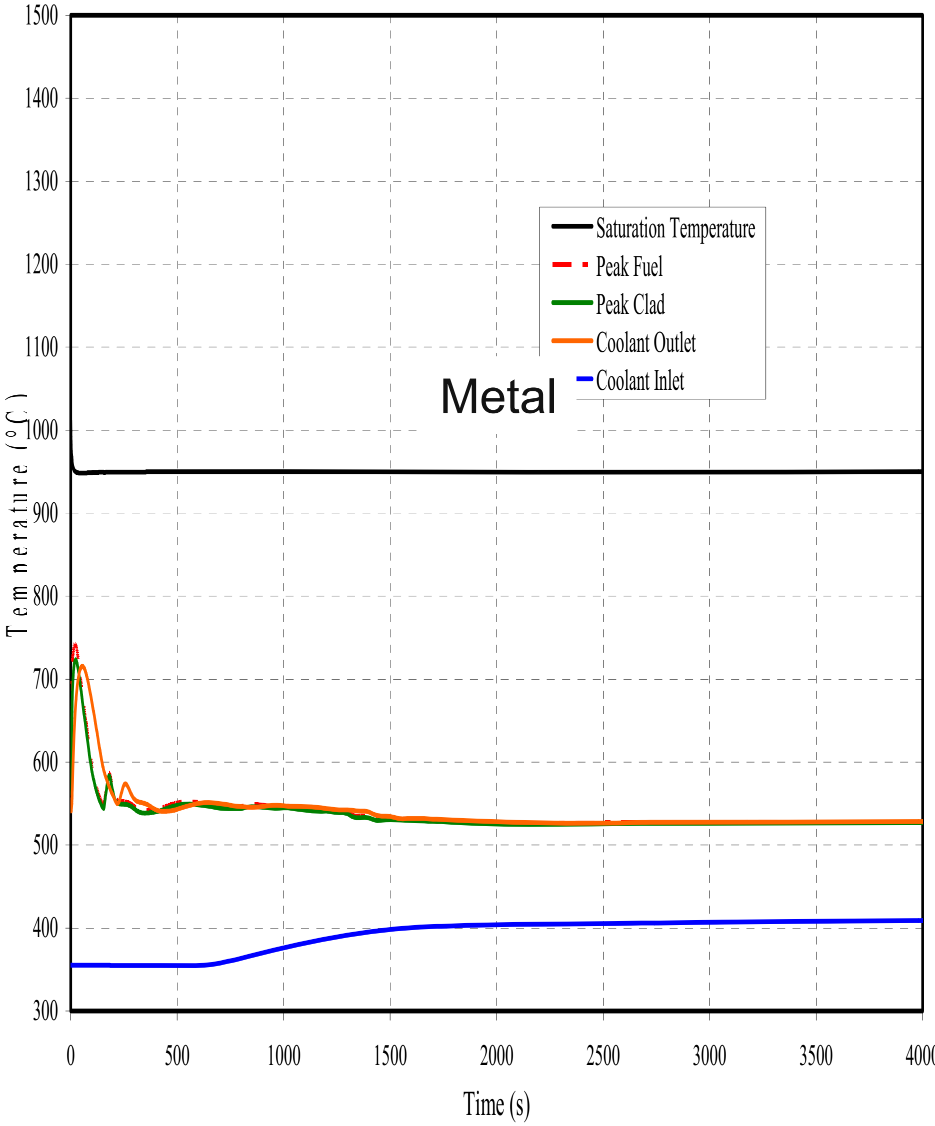
Schematic Comparison of Oxide and Metal Cores

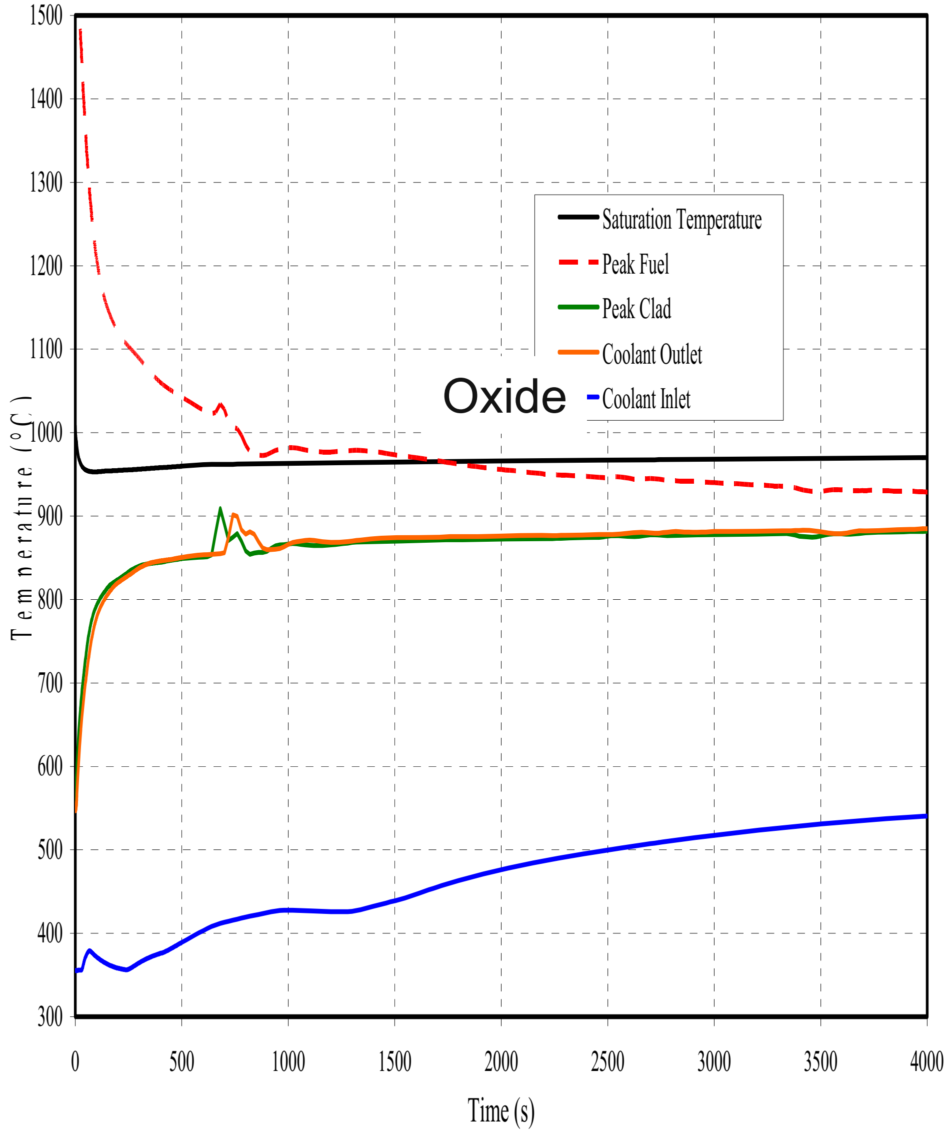


ULOF Transient: Reactivity Feedback comparison Metal vs. Oxide



ULOF Transient: Peak Channel Temperatures - Metal vs. Oxide

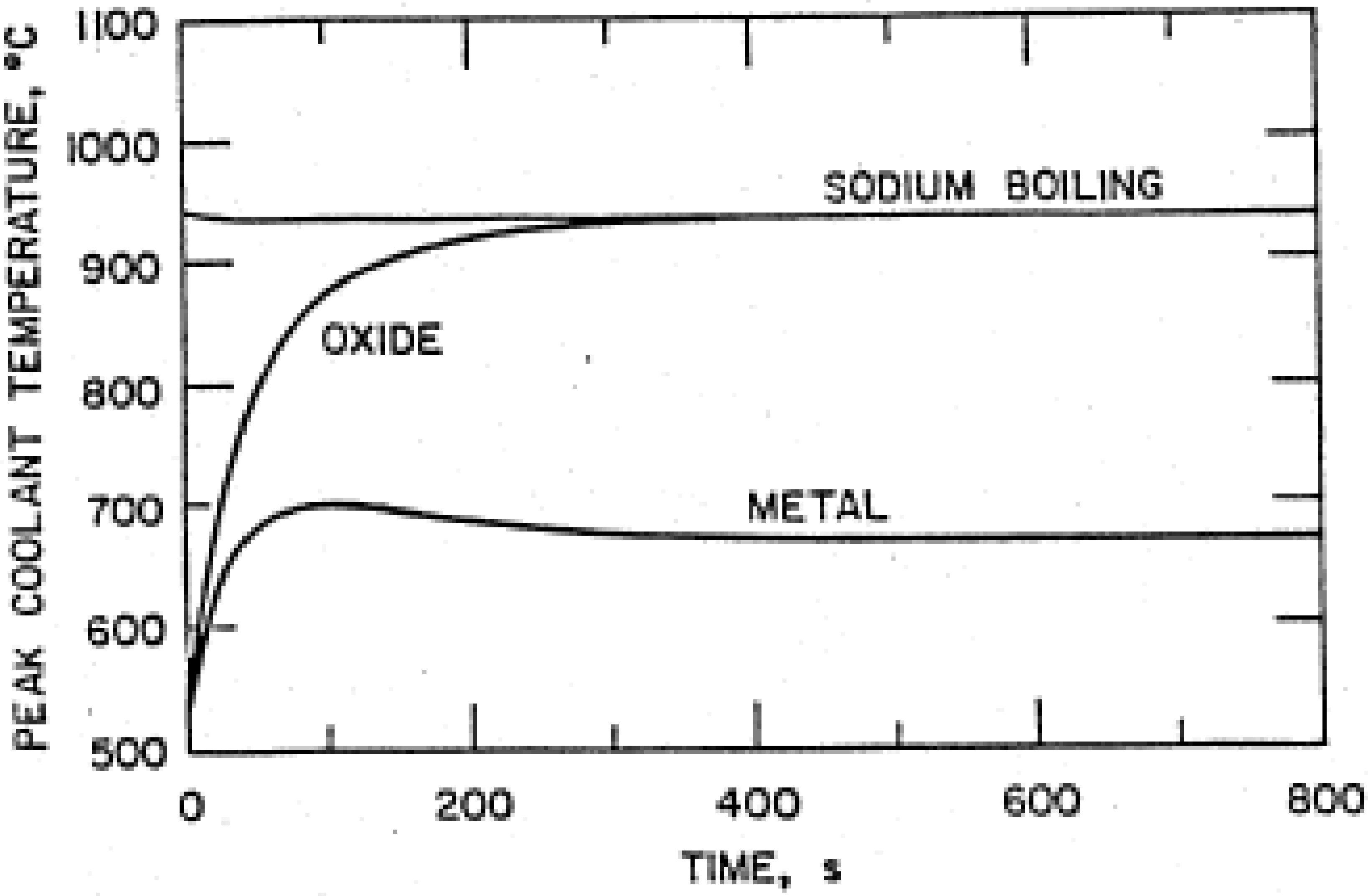




Inherent Properties of Fast Reactor

- Take advantage of inherent properties of sodium and metal fuel in the safety design approach to achieve:
  - Inherent passive means to eliminate pathways to severe accidents, such as anticipated transients without scram
  - Simplified safety systems
  - Tolerance to operator errors and safety system malfunctions
- Such inherent safety characteristics can be achieved independent of size.

Low-of-Flow without Scram for Large Reactors



Margin to Coolant Boiling for Metal Fueled Cores, °C

Reactor size, MWth	**471**	**900**	**3500**
Loss-of-flow w/o scram	170	160	130
Loss-of-heat-sink w/o scram	340	310	360

Licensing Implications

- Prescriptive design criteria in 10CFR50 was used with modification for FFTF and CRBR.
- It is not clear how to take credit for inherent safety characteristics in the traditional approach.
- NRC is now developing a risk-informed, performance based alternative to 10CFR50 for future advanced reactors: draft 10CFR53.
- Under the new regulatory framework, a probabilistic risk assessment will be an integral part of the design process and safety assessment as well as in the licensing process, and the benefits of inherent passive safety can be quantified in a concrete way.

Design Goals for Future Fast Reactors

- Too much emphasis in cost reduction (commodities reduction) may compromise the inherent passive safety potential.
- If the design is optimized for inherent passive safety, the economic competitiveness will be achieved naturally through longevity, reliability, operability, public acceptance, etc.
- The Generation III advanced LWR designs have evolved toward increased thermal margins, passive activation of makeup coolant, natural circulation cooling, etc.

Sodium-Water Reaction

- Sodium reacts exothermically with water, producing caustic sodium hydroxide and hydrogen gas.
- Therefore, it is highly desirable to avoid potential contact of sodium with water/steam in steam generator design.
- One conservative approach is double-wall tube steam generator: EBR-II SG operated without a single tube leak for the entire 30-year life.
- Although early fast reactors experienced some isolated SG problems primarily associated with welding techniques used for dissimilar metals, in general fast reactor SGs have been highly reliable.

Design Solutions

- A secondary sodium loop is always added to isolate primary sodium system from BOP. Steam generator tube leaks will not impact the primary system.
- Steam generator relief and dump system is also employed to relieve pressures in the secondary sodium system in the event of a major steam/water leak into sodium. Rupture disc is located in the SG and sodium-water reactor products are collected in a separator tank.

Sodium Fire

- Liquid sodium reacts readily with air and oxidation reaction can occur in a runaway manner leading to sodium fire.
- Sodium burning is accompanied by production of dense sodium oxide smoke.
- The heat itself is much less than that of conventional hydrocarbon fires. Sodium flame height is also an order of magnitude lower, allowing a close approach for fire fighting.

Design Solutions

- Sodium in the primary system is blanketed with inert gas and is maintained in double containment.
  - Reactor vessel sodium free surface is covered with inert gas, and the gap between reactor vessel and guard vessel as well as the gap between sodium pipe and guard pipe around it are also filled with inert gas.
- A variety of techniques are available for sodium leak detection. The principal technique relies on the detection of sodium aerosols in the annulus gap, produced by oxygen and water impurities in inert gas atmosphere.
- In the secondary sodium system, a gap between the pipe and its insulation enable leak detection, but no preventive measures are deployed.

Metal Fuel Summary

- Steady-state irradiation performance and high burnup potential are as good or better.
- Off-normal performance characteristics are superior.
- Enables inherent passive safety characteristics, which can help the licensing process and simplify the plant design.
- Enables simple fabrication techniques, leading to easy remotization and better economics.
- Enables pyroprocessing, leading to major improvements in economics, actinide recycling, waste management, and proliferation-resistance.
- Major drawback: Already established programs cannot abandon existing infrastructure on oxide fuel and switch.