OKLO

Oklo Inc at NRC

December 14, 2016

Outline of Meeting

- Oklo introduction (~15min)
- Brief introduction to EBR-II and IFR (~15min)
- ANL presentation on fast reactor metallic fuel experience set and database (~30min)
- Time for questions – can also be interspersed (~15min)

Oklo Intro

- Founded in 2013
- Awards
- Funded in 2015
- Growing team
- Press – overview/intentionally limited
- Designing compact fast reactor utilizing metallic fuel

Intro to EBR-II

- EBR-II was a 62.5MWth, 19 MWe sodium-cooled fast reactor with metallic fuel
- EBR-II:
  - operated for 30 years
  - sold power to the grid
  - had higher capacity factor than fleet at the time

Intro to EBR-II

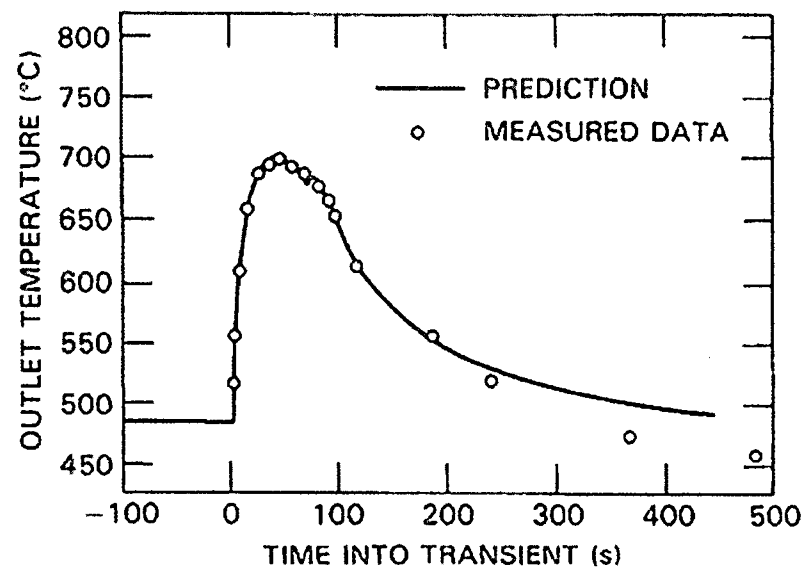
- Years of quality assured testing done with the EBR-II reactor
- Wealth of data on U-Zr fuel, various claddings
- Oklo currently working with ANL to compile relevant data

EBR-II Shutdown
Heat Removal Tests (SHRT)

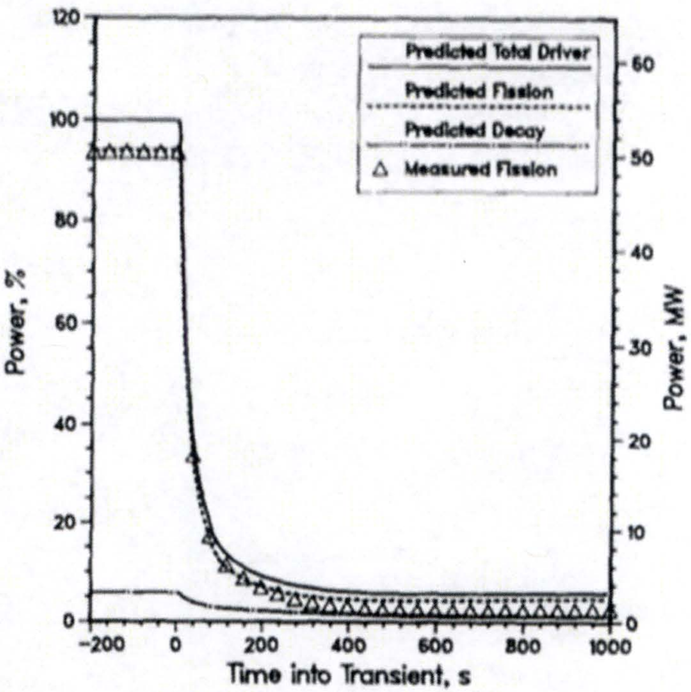
- Performed on the same day (April 3rd, 1986)
- Two types of unprotected loss-of-cooling accidents
  - Loss of Flow Without Scram
  - Loss of Heat Sink Without Scram
- Performed on the actual, operating reactor at full power!
- Started back up after both tests without damage

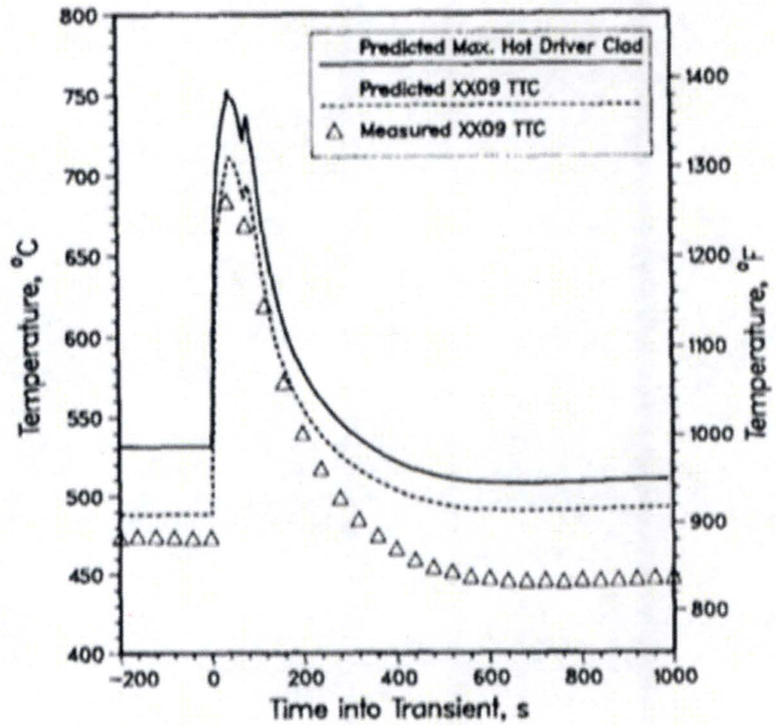
EBR-II Loss of Flow Without Scram

- Loss of Flow Without Scram (LOFWS): Primary coolant pumps turned off while operating at full power
- Reactor shut down due to fuel thermal expansion feedbacks
- No damage to fuel or otherwise



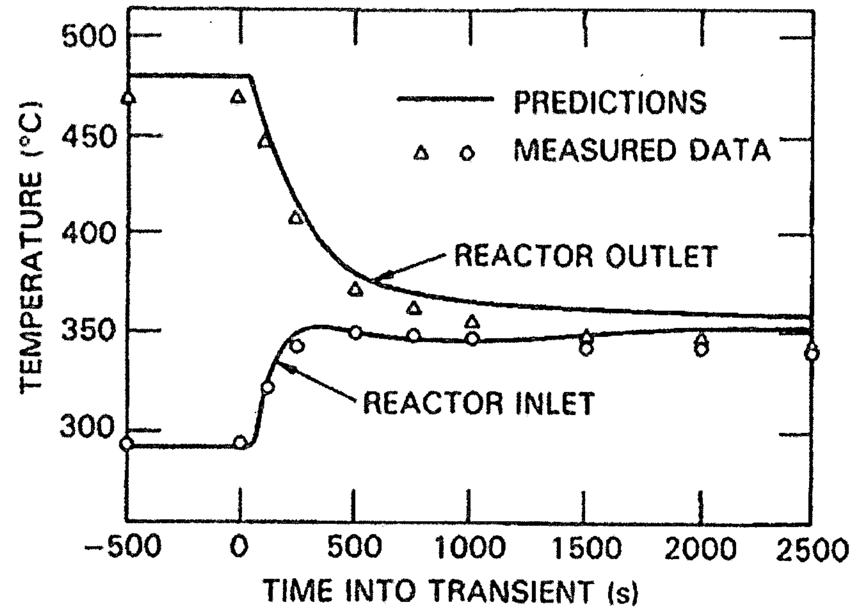
EBR-II LOFWS Plots





EBR-II Loss of Heat Sink Without Scram

- Loss of Heat Sink Without Scram (LOHSWS): Intermediate coolant pumps turned off while operating at full power
- Again, reactor shuts down without scram due to thermal expansion feedbacks
- No damage to fuel or otherwise



EBR-II Safety Test Takeaways

"These are sensational results. Two of the most severe accidents that can threaten nuclear power systems have been shown to be of no consequence to safety or even operation of EBR-II. The reactor was inherently protected without requiring emergency power, safety systems, or operator intervention."

-J.I. Sackett

"OPERATING AND TEST EXPERIENCE WITH EBR-II, THE IFR PROTOTYPE", Progress in Nuclear Energy 31, 1-2, pp. 111-129, 1997.

Metallic Fuel Experience in Fast Reactors

Oklo Inc. Public Meeting with the NRC

Presented by:

Abdellatif M. Yacout

Argonne National Laboratory

December 14, 2016

Presentation Overview

- Presentation Purpose
- Metallic Fuel Experience
- Steady State Performance
- Transient Behavior
- GAIN Program Activities with Oklo Inc
- Summary

Presentation Purpose

- Familiarize the NRC with the performance of metallic fuel
- Present current GAIN program related activity to support licensing of Oklo design

Metallic Fuel Experience

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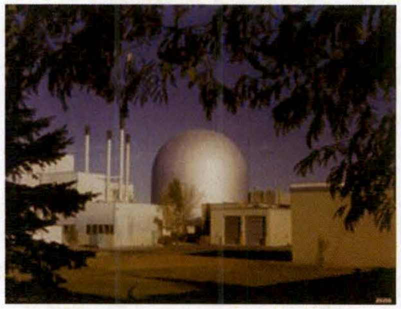
Metallic Fuel History

- Over 30 years of irradiation experience
- EBR-I, Fermi-1, EBR-II, FFTF
- U-Fs*, U-Mo, U-Pu-Fs*, U-Zr, U-Pu-Zr, others
- EBR-II
  - > 40,000 U-Fs* pins, **> 16,000 U-Zr pins** & > 600 U-Pu-Zr pins irradiated, clad in 316 stainless steel, D9 & **HT9**
- FFTF
  - **> 1000 U-Zr pins**, mostly in HT9
  - Vast experience with HT9 cladding

EBR-II



FFTF

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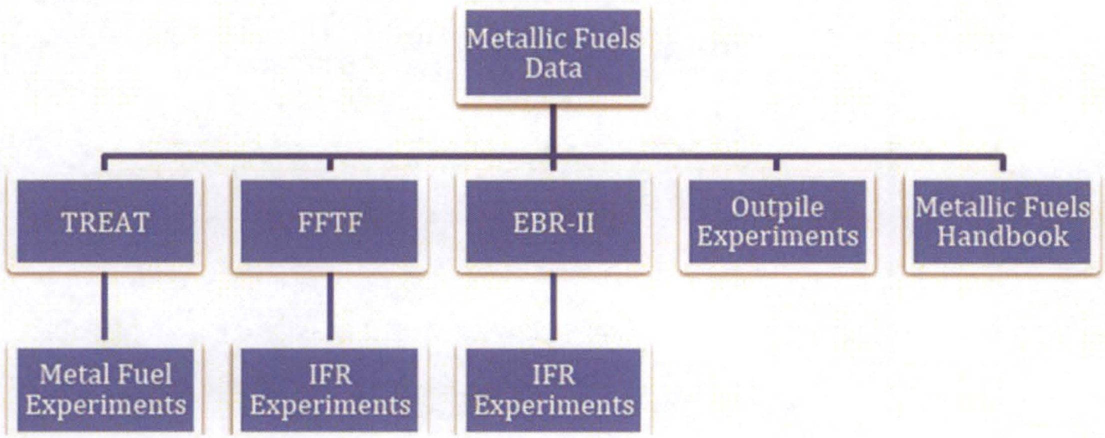
*Fs – Simulated Fission Products

Sources of Metallic Fuel Data



Metallic Fuel Experimental Database (Steady State)

- EBR-II experiments to look at parameters and phenomena of interest to fuel performance
  - Prototype fuel behavior
  - RBCB* and failure mode
  - Fuel swelling and restructuring
  - Lead IFR** fuel test
  - Fabrication
  - Design parameters
  - High clad temperature
  - Large fuel diameter
  - Blanket safety
  - Fuel qualification
  - Fuel impurities

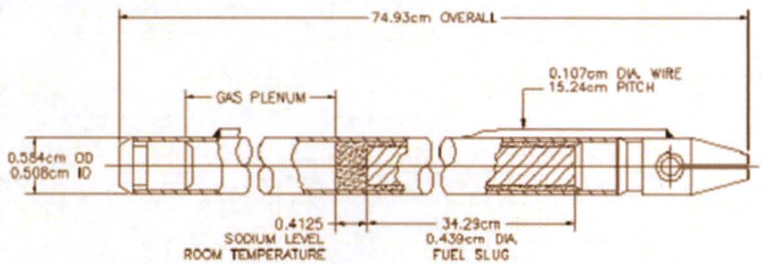
*RBCB – Run Beyond Cladding Breach
**IFR – Integral Fast Reactor

- FFTF experiments to look at
  - Fuel column length effects
  - Lead metal fuel tests
  - Metal fuel prototype
  - Metal fuel qualification

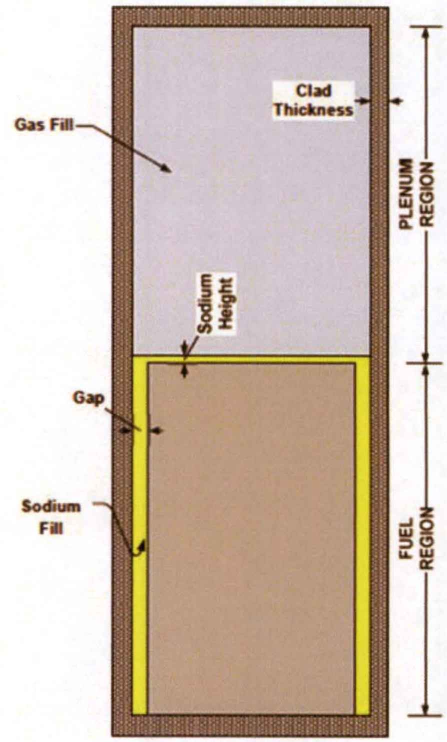
Metallic Fuel Experimental Database (Transient)

- In-Pile
  - Run Beyond Cladding Breach (RBCB) experiments:
    6 RBCB tests U-Fs &
    U-Pu-Zr/U-Zr
  - 6 TREAT tests:
    U-Fs in 316SS&
    U-Zr/U-Pu-Zr in D9/HT9
- Out-Pile
  - Whole Pin Furnace Tests (WPF)
  - Fuel Behavior Test Apparatus (FBTA)
  - Diffusion compatibility tests

Typical Metallic Fuel Design



Typical EBR-II Metallic Fuel Pin (Pahl, et al., 1990)



Design Parameters (nominal) of EBR-II Fuel

Item	Mark-IA	Mark-II	Mark-IIC	Mark-IICS	Mark-III	Mark-IIIA	Mark-IV
Fuel alloy, wt %	U-5Fs	U-5Fs	U-10Zr	U-10Zr	U-10Zr	U-10Zr	U-10Zr
Enrichment weight, % ^{235}U	52	67	78	78	66.9	66.9	69.6
Fuel-slug mass, g	64	52	47	47	83	83	78
Fuel smeared density, %	85	75	75	75	75	75	75
Cladding-wall thickness, cm	0.023	0.030	0.030	0.030	0.038	0.038	0.046
Cladding-wall OD, cm	0.442	0.442	0.442	0.442	0.584	0.584	0.584
Length, cm	46.0	61.2	63.0	53.6	74.9	74.9	74.9
Cladding material	304L	316	316	316	CW D9	CW316	HT9
Spacer-wire diameter, cm	0.124	0.124	0.124	0.124	0.107	0.107	0.107

C. E. Lahm, et al., "Experience with Advanced Driver Fuels in EBR-II," 1993.

Historical Fuel Design Parameters

Key Parameter	EBR-II/FFTF
Peak Burnup, 10^4MWd/t	5.0 – 20
Max. linear power, kW/m	33 – 50
Cladding hotspot temp., °C	650
Peak center line temp., °C	<700
Peak radial fuel temp. difference, °C	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 Material of Interest

- Fuel Alloy: U-10Zr
  - High thermal conductivity
  - Compatible with sodium coolant
  - Sufficiently high melting temperature for safety considerations
  - Large experimental database
  - Used as **driver fuel** in EBR-II where over 16,000 pins were irradiated (Mark-III & Mark-IIIA)
  - **Qualified** as driver fuel in both EBR-II and FFTF
  - Previous comments from **NRC review of PRISM** **(NUREG-1368)** fuel qualification plan were related to U-Pu-Zr fuel and U-Pu-MA-Zr fuel.

Steady State Metallic Fuel Performance

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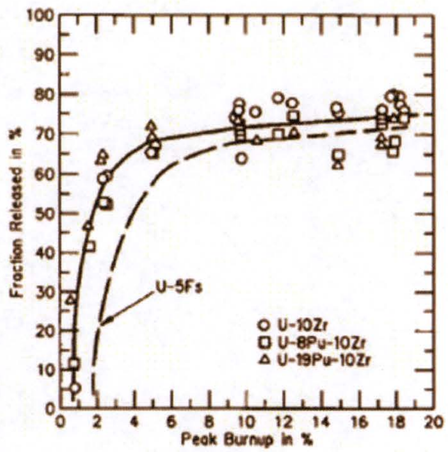
Steady State Performance Topics

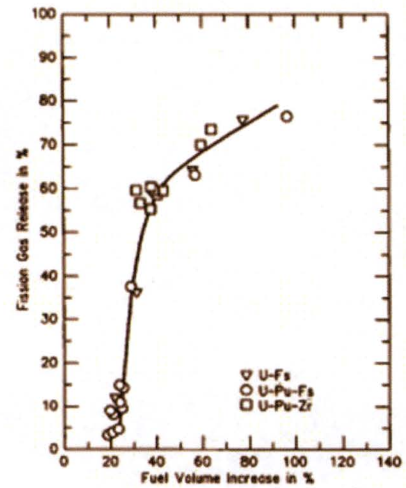
- Fission Gas Release (FGR)
- Fuel Swelling
- Constituent Redistribution and Zone Formation
- Fuel-Cladding Chemical Interaction (FCCI) & Rare Earth Migration
- Fuel-Cladding Mechanical Interaction (FCMI)
- Cladding Material Performance

Fission Gas Release (FGR)

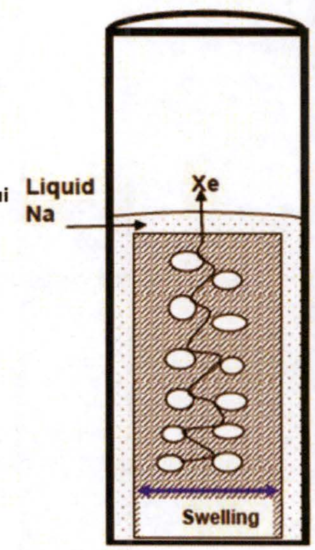
- Insoluble fission gases, Xe and Kr, accumulate in fuel until inter-linkage of porosity at sufficient burnup leads to release of large fraction of gas.
- The fission gases accumulate in plenum region and constitute the primary clad loading mechanism.



FGR vs. Burnup (Hofman & Walter, 1994): U-5Fs slightly lower because of beneficial effect of Si inclusion

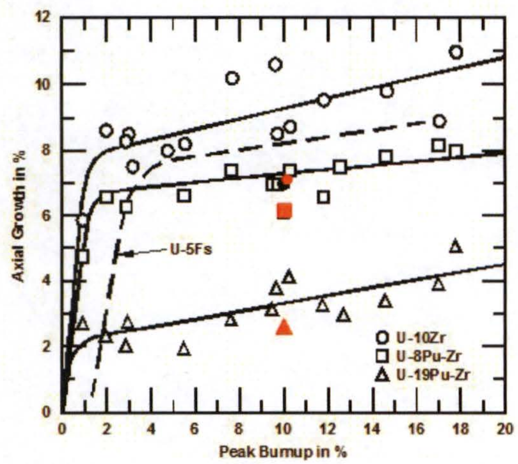


FGR vs. Fuel Swelling (Hofman & Walter, 1994): Independent of metal-fuel type



Fuel Swelling

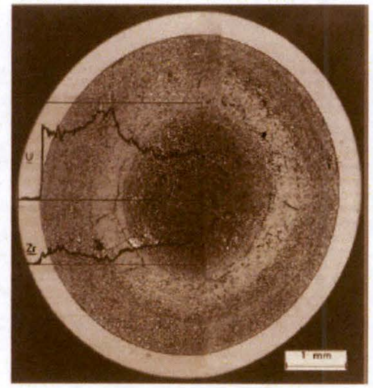
- Driven by nucleation and growth of immobile fission-gas bubbles
- Low fuel smeared density (~75%) combined with high swelling rate allow rapid swelling to ~33 vol% at ~2 at.% burnup where inter-linkage of porosity results in large gas release fraction which decreases the driving force for continued swelling



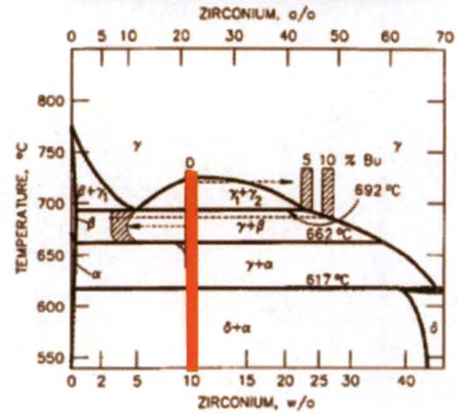
EBR-II fuel length increase in various metallic fuels as a function of burnup where closed symbols correspond to FFTF data (ANL-AFCI-211)

Constituent Redistribution & Zone Formation

- Fuel melting temp. decrease in Zr-depleted region (this zone happens off the fuel center).
- Local fission rate change.
- Changes in swelling characteristics.
- Reliable predictive model has been developed.



Metallographic cross section with superimposed radial microprobe scans at top of U-10Zr pin DP-81, experiment X447 (Hofman, et al., 1995)



U-Zr Phase Diagram

Fuel Cladding Chemical Interaction (FCCI) & Fission Product Migration

- At steady state FCCI is characterized by solid state interdiffusion
- Interdiffusion forms U/Fe alloys with lower eutectic temperature
- Decarburized zone at fuel-clad interface is expected in HT-9 cladding
- RE fission products (La, Ce, Pr, Nd) form a cladding brittle layer
- Penetration depth data are available from
  in and out-of-pile measurements

FCCI of U-10Zr/HT-9 due to inter-diffusion of fuel/cladding constituents after 6 at% burnup at 620°C (Hofman & Walter 1994)

Fuel Cladding Mechanical Interaction (FCMI)

- Due to accumulation of solid fission products at high burnups
- Low fuel smeared density (~75%) allows for a large amount of fuel swelling (~30%) and gas release which reduces FCMI
- Porous fuel at low burnups (<5 at.%) does not exert significant force on cladding

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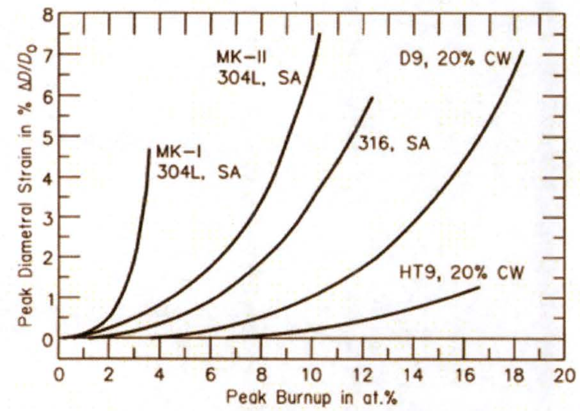
Cladding Material Performance

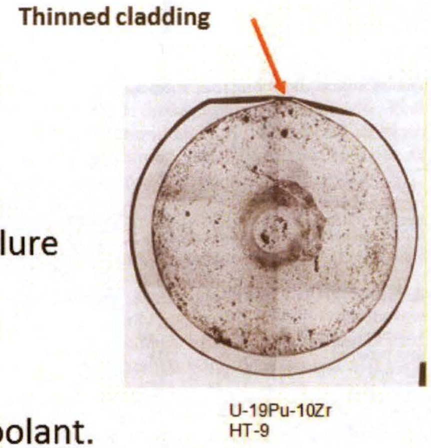
- Experience with different types of steel cladding: 304, 316, CW-316, D9, & HT9.
- **CW-316 steel (Mark-IIIA) and D9 (Mark-III)** with U10Zr were qualified in EBR-II (over 16000) to 10at% BU.
- EBR-II core was converted to Mark-III and Mark-IIIA fuel during IFR program.
- **Limited failure** of Mark-III&IIIA fuel during operations (5 pins, where most failures attributed to fabrication defects that were corrected later)
- HT9 ferritic-Martensitic alloy with adequate swelling resistance, toughness, strength, and ductility.
- 100s of HT9 clad pins were irradiated in EBR-II & 1000s were irradiated in FFTF



Void swelling behavior of HT9 cladding compared to other steels (Pahl, et al., 1992).

Run Beyond Cladding Breach (RBCB)

- EBR-II RBCB experiments
  - An area of cladding was machined down to 25-50 μm (<10% of cladding thickness is left).
  - After a short period of irradiation, cladding failure occurred at the machined spot.
- Test Results
  - **No chemical interactions** between fuel and coolant.
  - **No fuel loss into coolant** (under normal conditions).
  - **No significant liquid or solid FP** escape.
  - Only release of **fission gas and Cs** retained in the bond sodium was **detected.**



Metallographic cross-section through cladding breach of a metallic fuel element after RBCB operation (Batte' and Hofman, 1990)

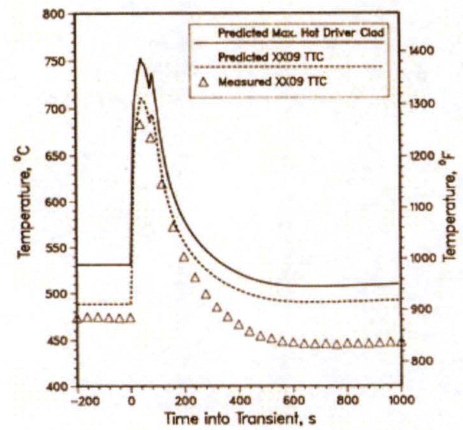
Transient Behavior

Metallic Fuel Characteristics

- Excellent transient capabilities
  - Does not impose restrictions on transient operations capabilities
  - Sample history of a typical driver fuel irradiated during the EBR-II inherent passive safety tests conducted in 1986;

    - *40 start-ups and shutdowns*
    - *5 15% overpower transients*
    - *3 60% overpower transients*
    - *45 loss-of-flow (LOF) and loss-of-heat-sink tests including a LOF test from 100% without scram*

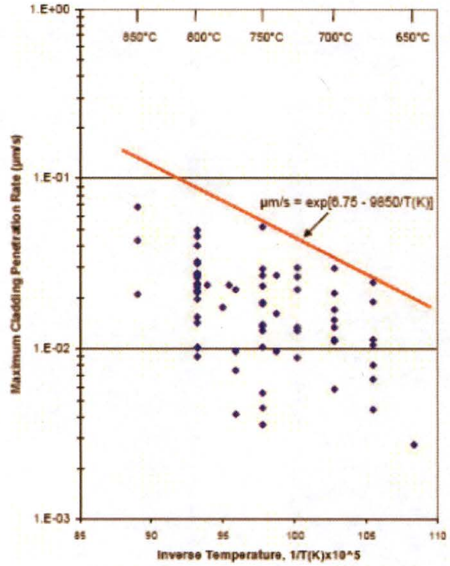
  – **No fuel failures**



Unprotected loss-of-flow test in EBR-II demonstrated the benign behavior predicted (Mohr, et al., 1987)

Transient Tests

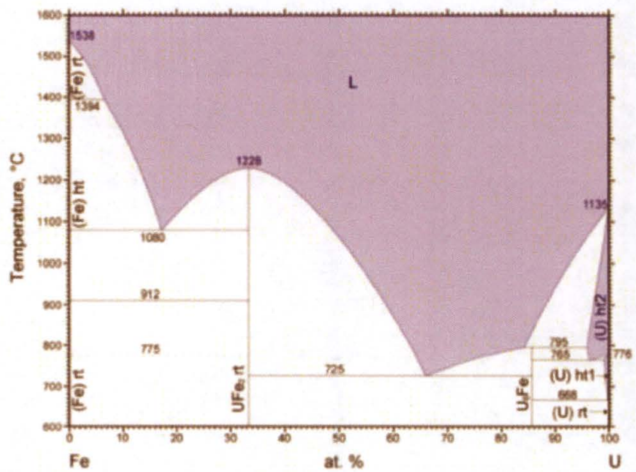
- In –pile TREAT (Transient Reactor Test Facility) tests evaluated transient overpower margin to failure, pre-failure axial fuel expansion, and post-failure fuel and coolant behavior
- Hot cell furnace testing of pin segments (Fuel Pin Test Apparatus), and full length pins (Whole Pin Furnace) showed **significant safety margin for particular transient conditions.**
  - Penetration depth data were measured and provided the basis for penetration depth correlations



Effective cladding penetration rates from FBTA tests for speciments tested for 1.0 hour (Tsai, et al., 2007)

Eutectic Formation Temperature between Fuel and Clad

- Critical parameter for metal fuel design
- Onset of eutectic formation occurs between 650 – 725 ^{o}C
- Rapid eutectic penetration at a much higher temperatures
- Places limits on the coolant outlet temperature to provide adequate margin to onset of eutectic formation



The Iron-Uranium Phase Diagram (Okamoto, 1990)

GAIN Program Collaboration

GAIN (Gateway for Accelerated Innovation in Nuclear) Voucher Program

- **Project:** Legacy Metal Fuel Data Exploration for Commercial Scale-Up
- **Objective:** Support Oklo Inc. activities related to design and licensing of small portable fast reactor system for remote location deployment.
- **ANL Scope:**
  - Assess Oklo current fuel design and data needs, and identify subset of metallic fuel data relevant to design & licensing activities
  - Establish a platform for Oklo access to the information
  - Identify key design and licensing related information needed by a commercial entity to approach regulatory agencies.
- **Oklo Fuel Design:**
  - U-10Zr fuel alloy with steel cladding, low burnup, and fuel/cladding temperature within envelope of existing database

Summary

Summary

- Over 30 years of in-reactor experience with metallic fuel irradiation.
- Extended database of metallic fuel behavior is available, with both excellent steady state and transient fuel behavior.
- Qualified U-10Zr fuel with steel cladding in both EBR-II and FFTF
- GAIN program initiated collaboration between national labs and Oklo Inc to support licensing of their design
- Oklo's operational fuel design parameters lie within the existing envelope of operation of the qualified Mark-III and Mark-IIIA fuel (U-10Zr with 20% CW-316 steel and SS cladding).

Conclusion of Meeting

And Time For Questions