Advanced Cladding Irradiation Experiment at the MITR-II

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ATR NSUF Users Week 2012

MIT Nuclear Reactor Laboratory

Support and Collaborators

- *Support*

ATR National Scientific User Facility

U.S. Department of Energy

- *Collaborators*

Ceramic Tubular Products
Gamma Engineering Corporation
Westinghouse Electric Company
Oak Ridge National Laboratory
Electric Power Research Institute

Outline

- Description of the MITR-II
- Intro to SiC for LWR cladding
- The ACI experiment

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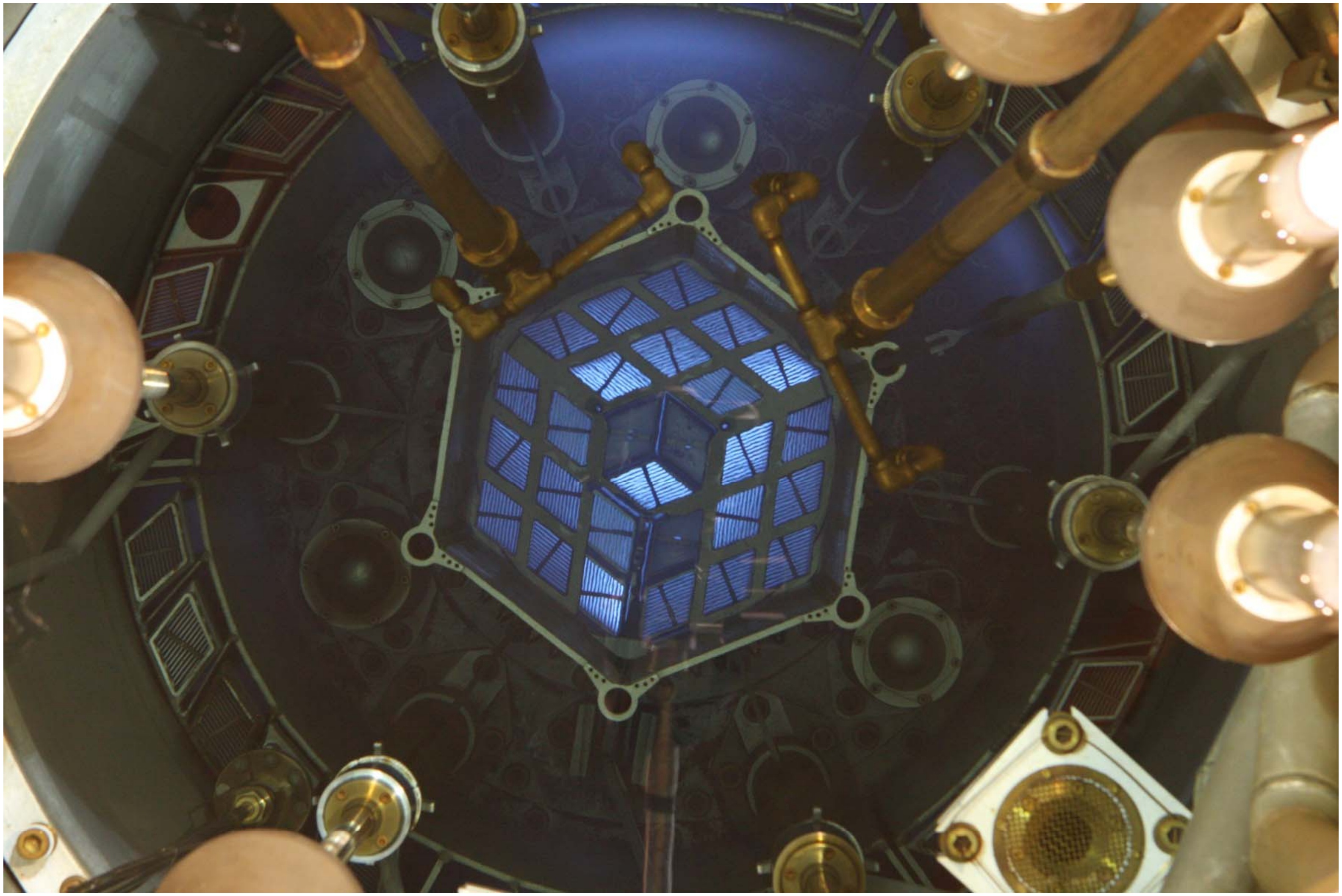
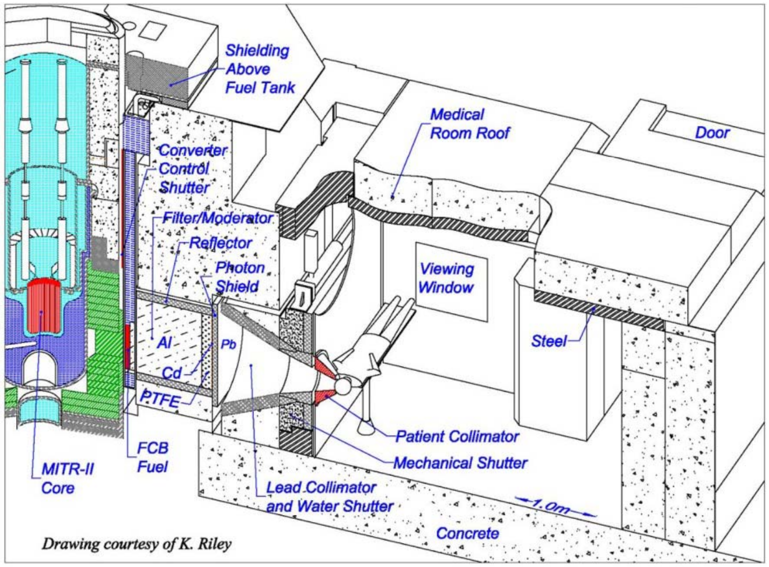
- MITR-II Reactor
  - Operating since 1958
  - Upgraded in 1975
- Operates 24/7 up to 6 MW thermal power
- Light water-cooled, heavy water-reflected
- HEU U-Al plate core
- Provides irradiation for research, education, and industry

Top-down View of the Core Tank

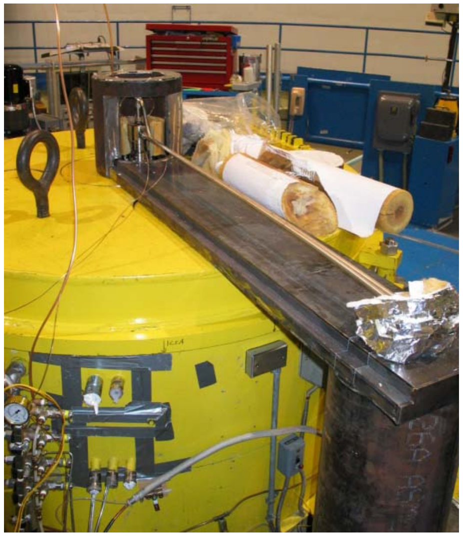


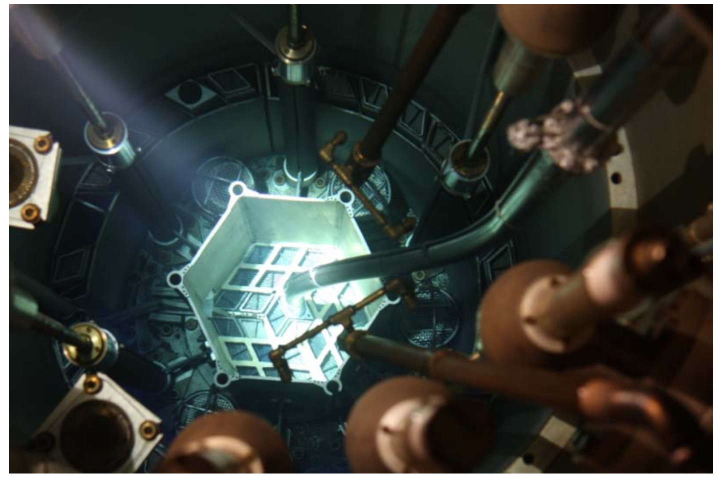
Reactor Facilities

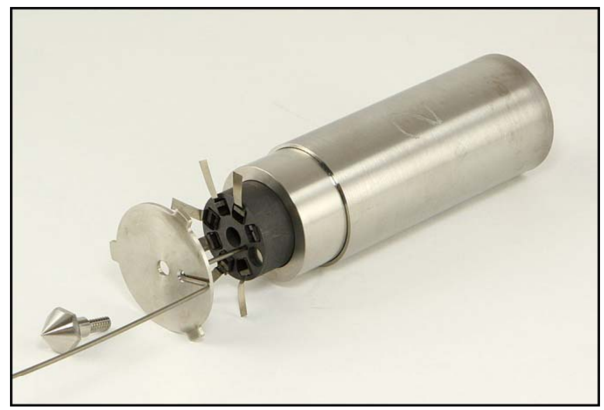


Drawing courtesy of K. Riley

In-Core Experiments





Current and Planned ICEs

- ACI
  - SiC LWR cladding in PWR conditions
- HYFI
  - U-Zr-H LWR fuel rods with liquid metal bonding
- ICSA-Drexel
  - MAX-phase materials at 300-700°C in inert gas
- ICSA-LUNA
  - Fiber optics at 700°C in inert gas
- HTIF-LUNA
  - On-line reading fiber optics at 1200°C in inert gas
- ICSA-FHR
  - Ceramic and metal coupons in FLiBe salt at 700°C
- FHR Natural Circulation
  - Ceramic and metal coupons in flowing FLiBe salt at 700°C

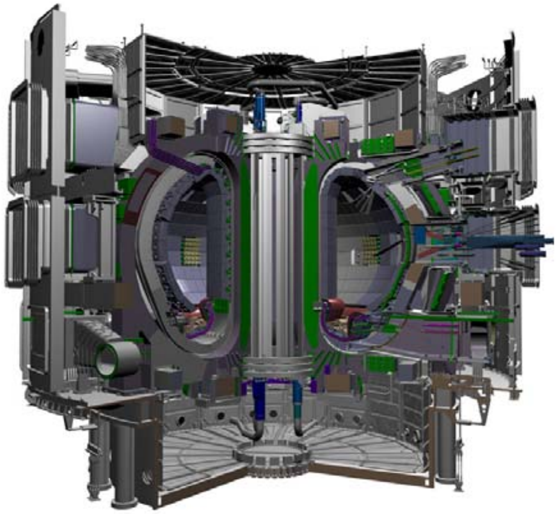
Motivation for New LWR Cladding

- Desire to improve fuel cladding performance in current and future light water reactors.
- Reactor operation is limited by the properties of current zirconium-based claddings and the resulting regulatory environment.
- Fukushima.
- Silicon carbide cladding may allow LWR fuel rods to be run to higher burnup and with better safety margins.

Silicon Carbide Properties

- High strength at high temperature (>1000°C) and neutron fluence (>50 DPA)
- Can withstand temperatures over 2000°C
- Low chemical reactivity with fuel and water
- Smaller neutron absorption cross section than zircaloy
- In LWR core conditions
  - Little creep, high elastic modulus
  - Properties generally stable or quickly saturating with irradiation

Saint-Gobain Ceramics



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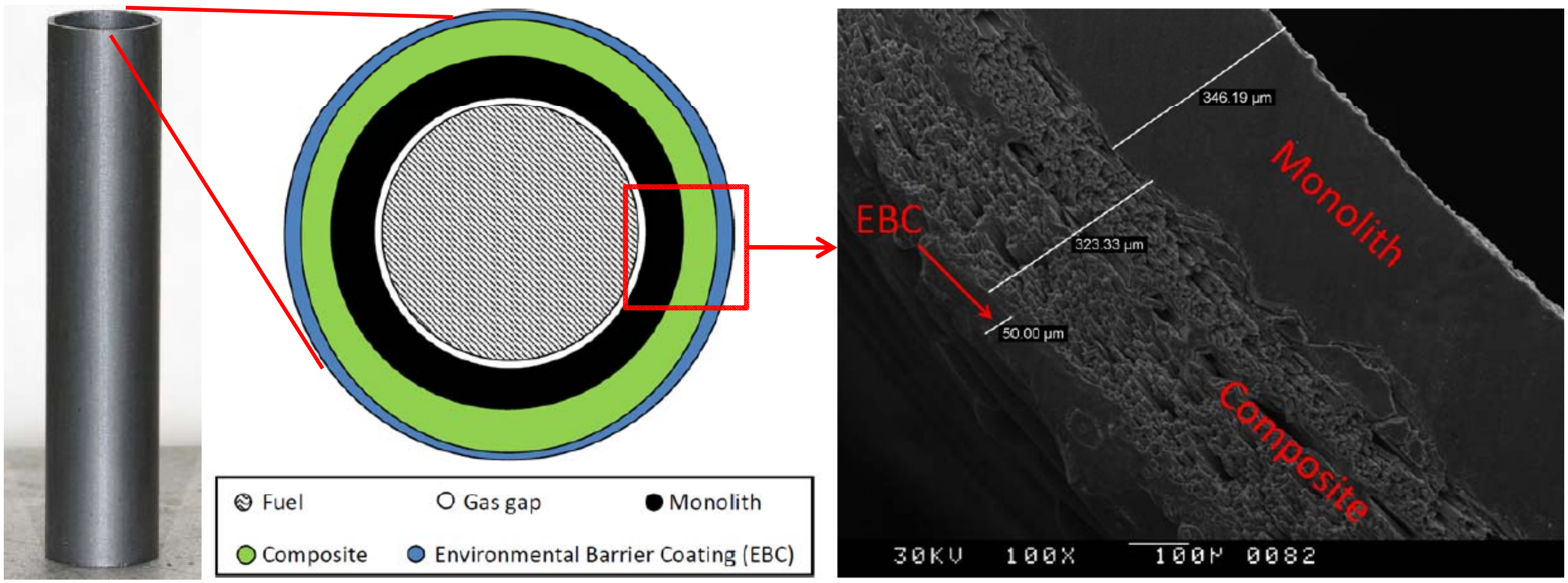
SiC Triplex Cladding Design



- A multi-layered approach to maximize strength and minimize potential for cladding damage
  - Inner monolith for strength and hermetic gas seal (0.3 mm)
  - Woven fiber/matrix composite for strength and protection (0.3 mm)
  - Outer barrier coating to resist corrosion (~100 µm)

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SiC Cladding Specimens

Zircaloy

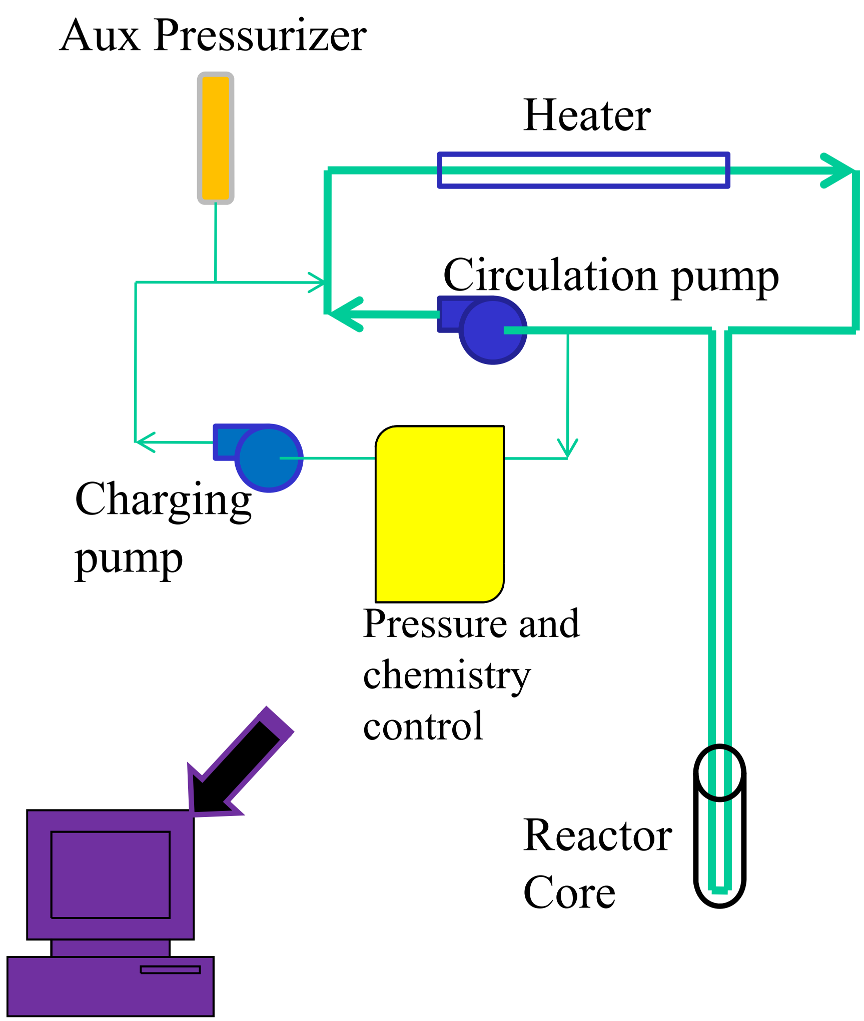
Triplex

Triplex

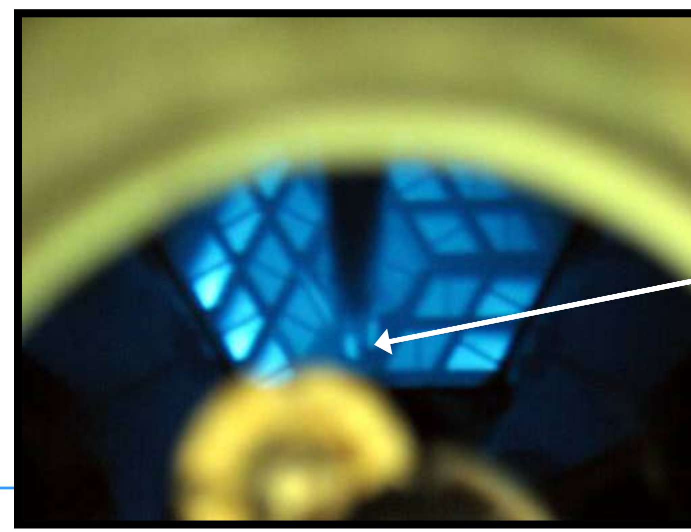
Bond Test

Irradiation
Modules

Irradiation Loop Design



- Exposing prototype SiC cladding tubes to typical pressurized water reactor conditions
- Using a loop to achieve 300°C, 10 MPa, typical LWR flux, H_2 overpressure
- Max exposures >800 EFPD, >3000 MWd



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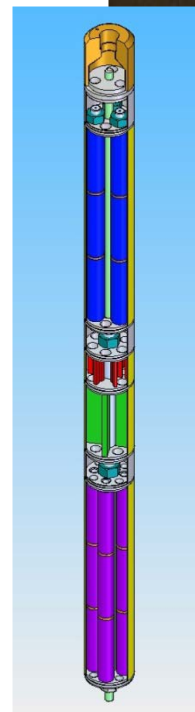
Experiment Assembly



Experiment Installation

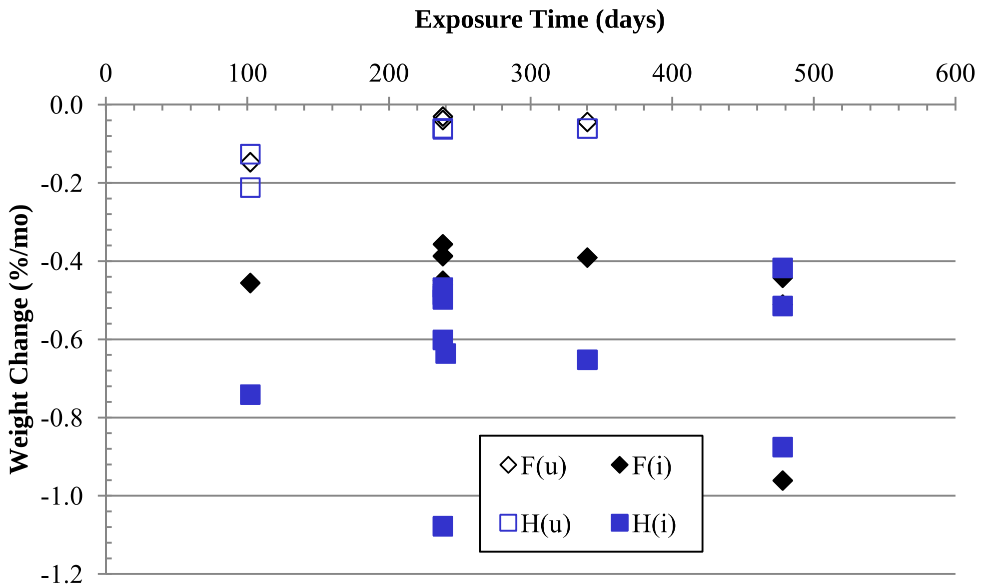
Post-Irradiation Examinations

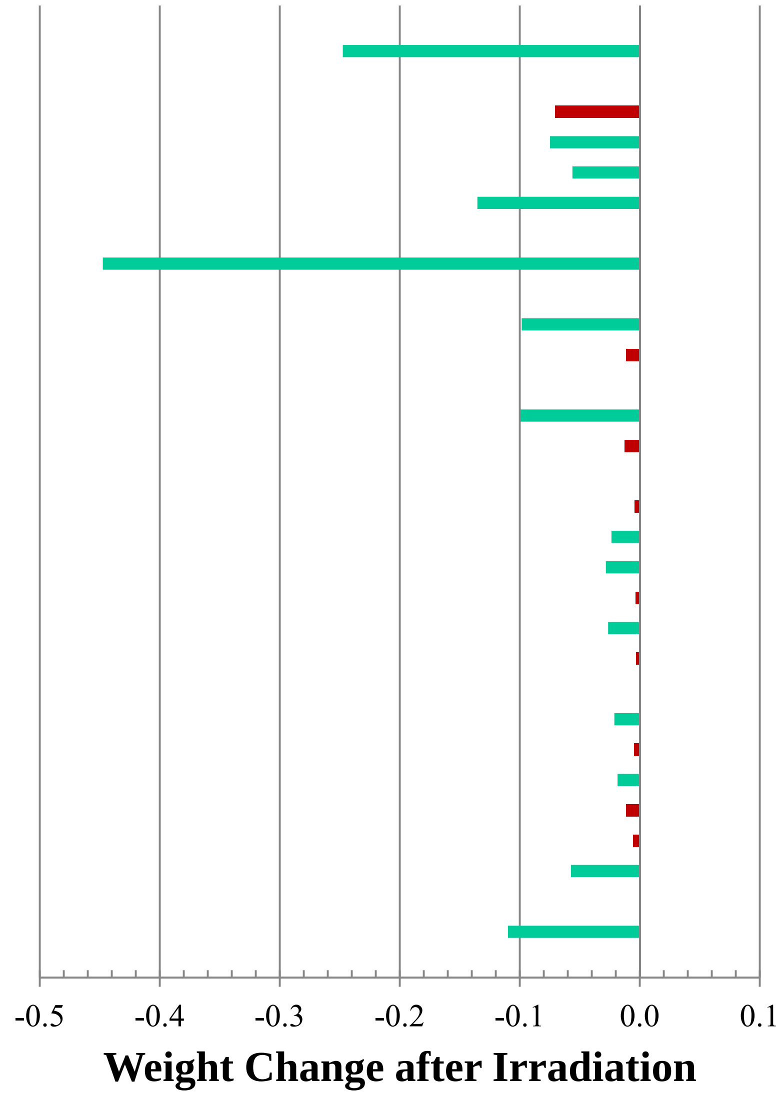
- Samples have been removed/replaced at intervals for weight change and dimensional measurements

- Destructive examinations
  - End-effect corrosion
  - Hoop strength
  - Thermal diffusivity
  - SEM

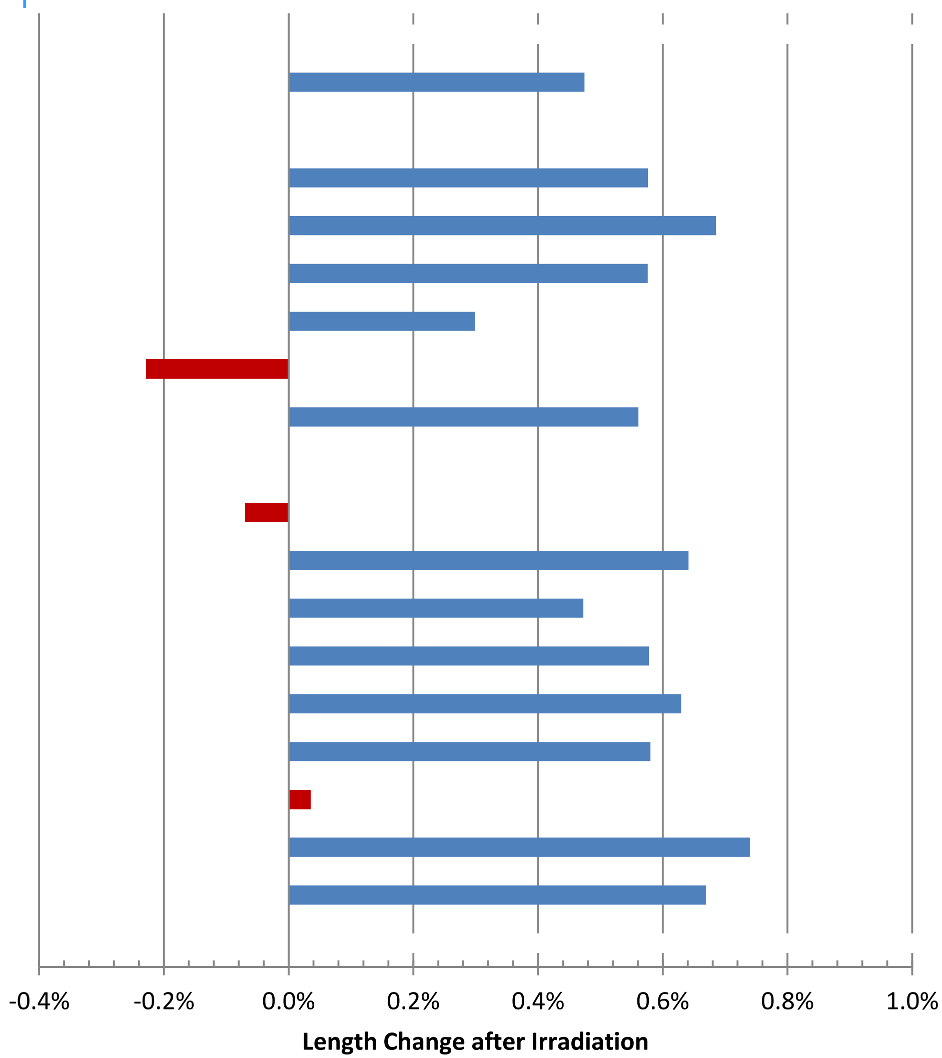
Corrosion

- Monolithic (α and β) SiC corrosion was negligible
- Composite is most vulnerable to corrosion, and CVI barrier coating provides best protection
- Weight change rates are constant over time
- Calculated surface rescision based on weight loss
  - As low as 0.5 µm/mo against 100 µm thick EBC





Swelling



- Linear irradiation-induced swelling of CVD β-SiC will saturate ~0.6%
  - β-SiC swelling is isotropic
  - Composite swelling is anisotropic
  - Swelling saturates within months

Plug Testing

- A hydraulic ram compresses a urethane plug, and the plug expands inside of tube simulating internal pressurization

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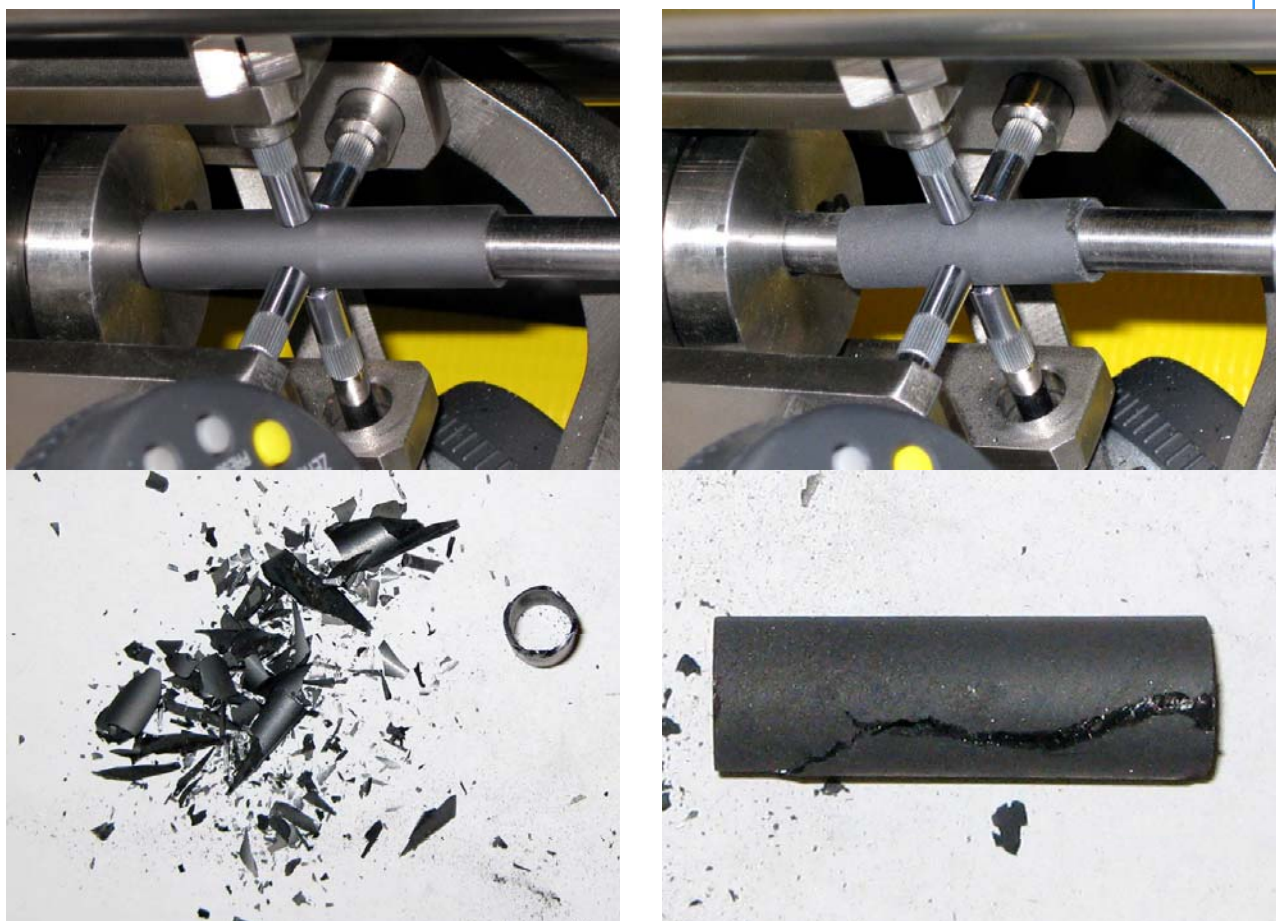
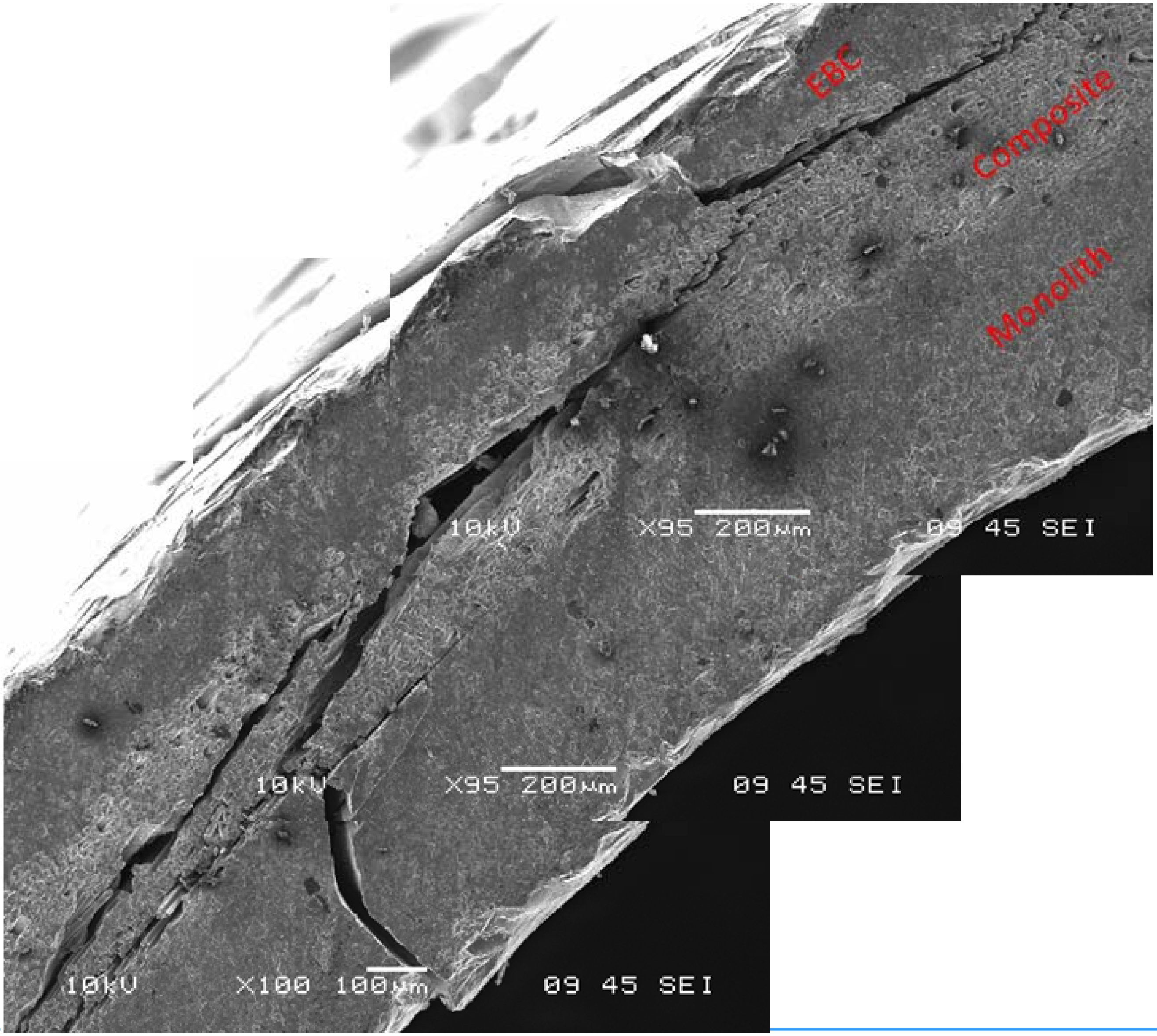
Plug Testing

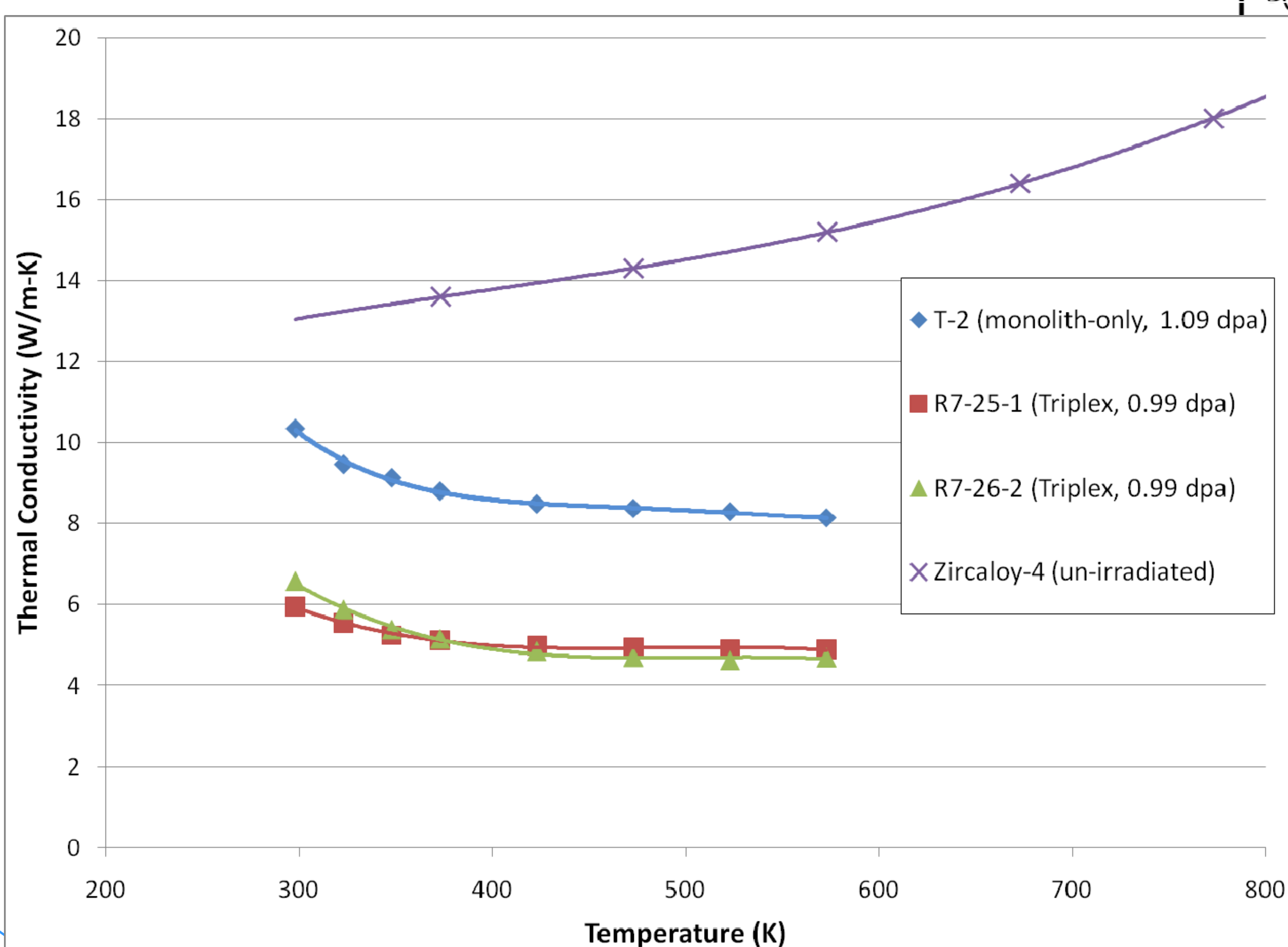
- All monolithic tubes failed with instant fragmentation
- Composite layer maintains integrity and internal fragments
- Triplex tubes are able to withstand additional strain after failure



Crack Propagation - SEM



Thermal Conductivity



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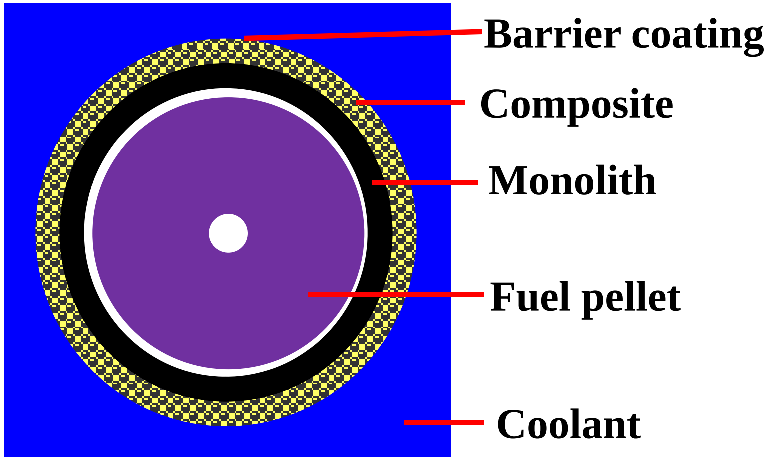
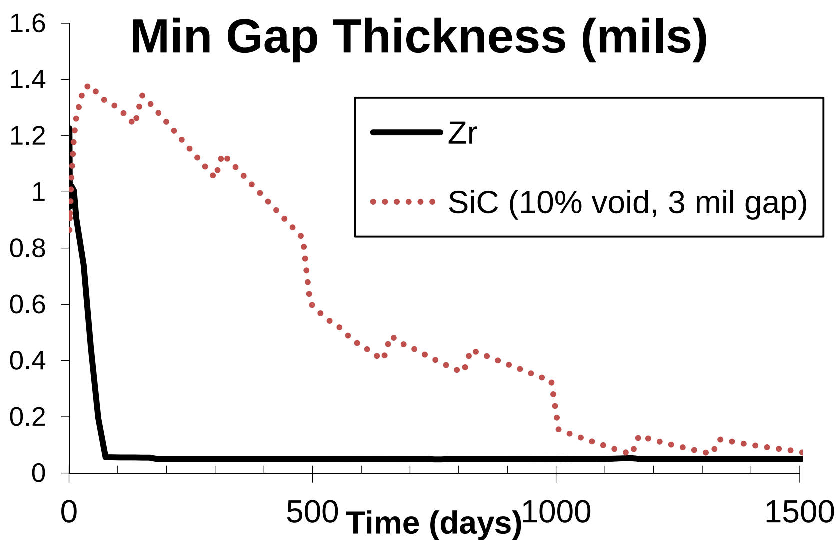
Modeling In FRAPCON

- FRAPCON evaluates a single fuel rod in steady-state LWR conditions
  - Code was developed to model UO_2 and MOX fuel with zircaloy cladding to 65 MWd/kg in LWR conditions
  - High burnup fission gas release adjusted by Dr. Yun Long
- Previously implemented conservative SiC property models
  - Thermal conductivity, modulus, swelling, thermal expansion, creep
- Feedback from experimental work to FRAPCON
  - Swelling models are appropriate
  - Corrosion and crud deposition not a significant effect
  - Waiting on additional thermal diffusivity data
  - Tensile strength data used to check credibility of output

FRAPCON Results

- Used SiC with annular pellet (10% central void)
  - Void reduces peak temperature at cost of fuel volume
- Good performance up to 100 MWd/kg (2500 days)
  - No FCMI until late in life
  - Fuel-cladding gap width drives fuel temperature
- Clad conductivity and open fuel-clad gap both contribute to elevated fuel temperatures
  - Improving gap conductance will alleviate other problems





Physics and Economics

- Reactivity and core reloading modeling
- Fuel cycle optimization and economics study
- Results
  - Physics of SiC clad cores similar to Zr clad
  - At comparable discharge burnup and fabrication costs, SiC has lower fuel cost
  - Larger SiC cost advantage at higher burnup – even larger advantage from 24 m cycles & uprate
- Fabrication cost adder for SiC is unlikely to eliminate SiC advantage

Summary

- β-SiC is a promising material for LWR cladding, and the triplex cladding design combines the advantages of monolithic and fiber composite ceramics

- Irradiation experiments at the MIT reactor showed the corrosion, swelling, and strength behavior is acceptable in PWR conditions

- Computer modeling of the behavior of a SiC-clad fuel rod in typical PWR operating environment identified a need to adjust the fuel rod design to reduce fuel temperatures

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Thank You

MIT Collaborators

- Prof. Mujid Kazimi
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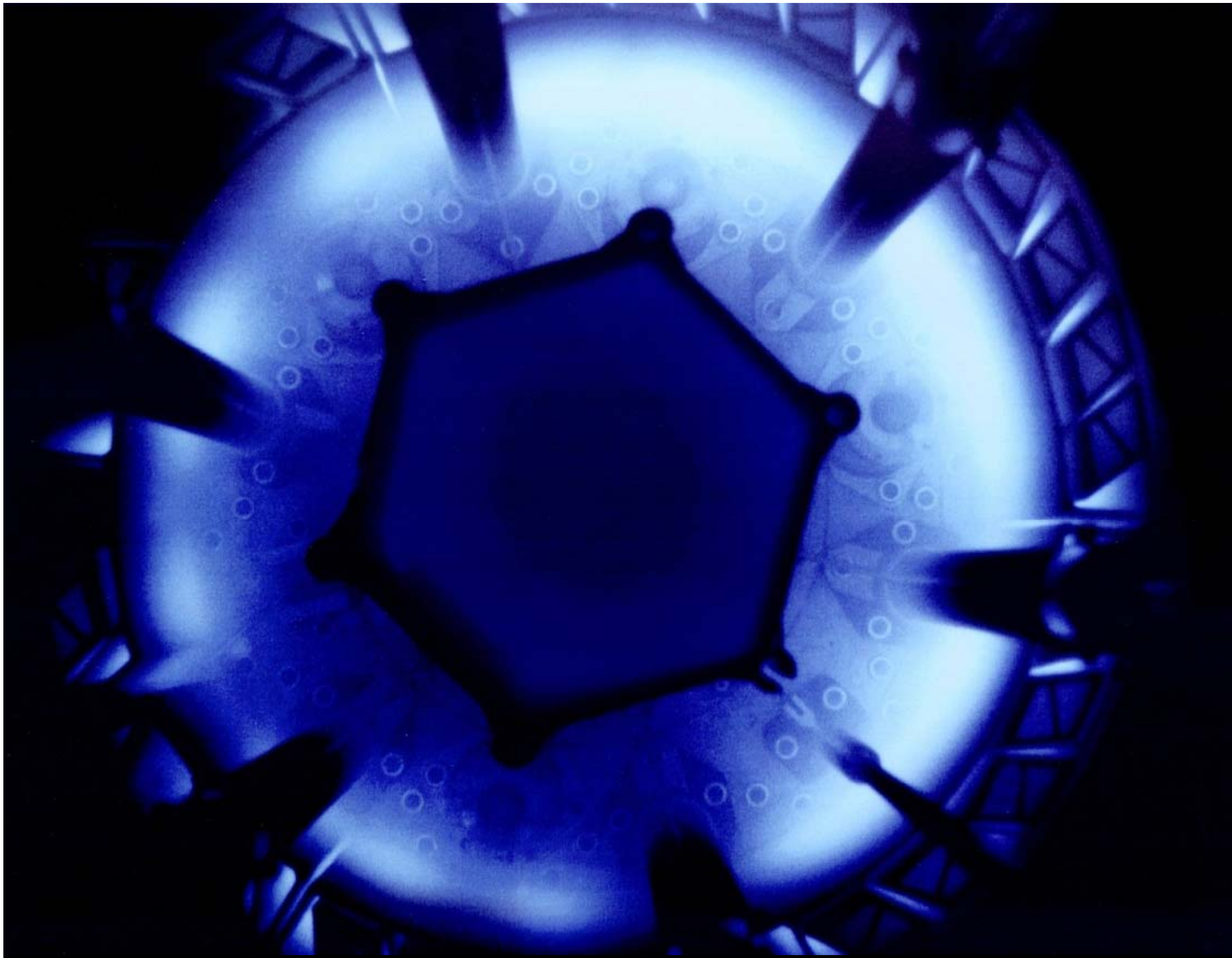
- Dr. Ed Pilat
- Dr. Sung Joong Kim
- Yakov Ostrovsky
- Jacob Dobisesky
- John Stempien
- Uuganbayar Otgonbaatar



Questions?