THIRD MEETING OF THE EXPERT GROUP ON ACCIDENT TOLERANT FUELS FOR LIGHT WATER REACTORS (EGATFL-03)

3-5 March 2015, Paris, France

Ferritic Steels as Accident Tolerant Fuel Cladding for Commercial Light Water Reactors

EJ Dolley, RB Rebak

GE Global Research, Schenectady, NY

Imagination at work.

GE Accident Tolerant Fuel Cladding Team

Focus on cladding material, no fuel development at this time

GE Global Research

SANDVIK

Michigan Engineering

Los Alamos National Laboratory

GNF Global Nuclear Fuel

A Joint Venture of GE, Toshiba, & Hitachi

Oak Ridge National Laboratory

New to team

INL Idaho National Laboratory

Brookhaven National Laboratory

New to team

GE ATF Project Currently in Phase 1B

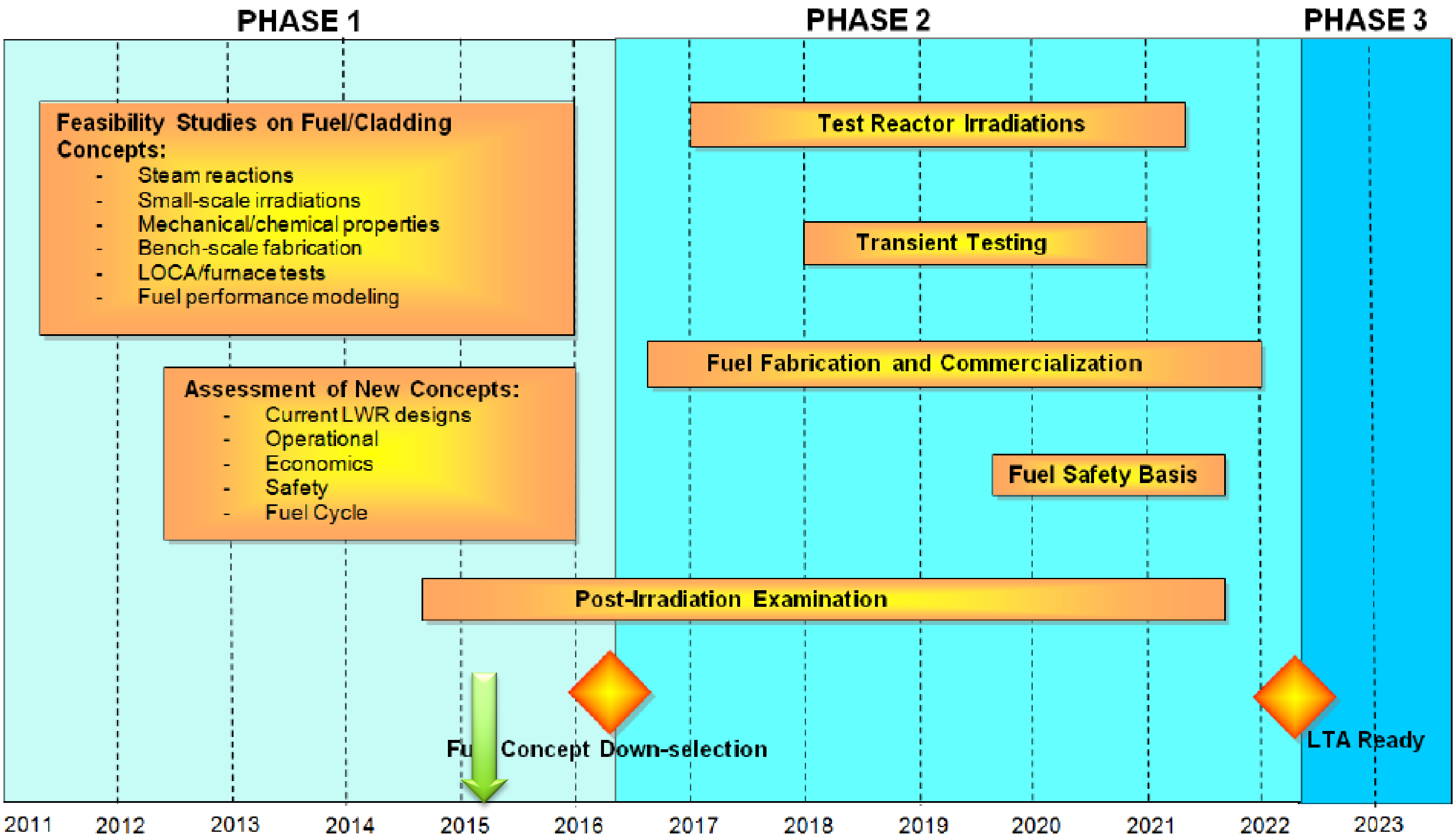


Figure ES-1. Research, development, and demonstration strategy for enhanced accident tolerant fuel development; an estimated timeline for each phase is included.

Approach of GE Research

- Demonstrate that stainless iron based bulk alloys or **Advanced Steels** can be used as fuel cladding materials in commercial nuclear reactors
- The proposed material should be as good as Zr alloys (or better than Zr alloys) under normal operation conditions
    1. Resistant to general corrosion and environmental cracking under normal operation conditions
    2. Resistant to radiation damage
- The proposed Advanced Steels should be able to **outperform** the containment the fuel in the case of an accident scenario (e.g. LOCA) as compared to the current Zr alloys
    1. Better mechanical strength at higher temperature
    2. Enhanced retention of fission products (no cracking)
    3. Improved reaction kinetics with steam
    4. Lower generation of hydrogen gas when reacting with steam

Work to be Done in Phase 1B to Mature Feasibility Concept

Follow Guidelines per INL/EXT-13-29957, FCRD-FUEL-2013-000264, LWR ATF Performance Metrics

1. Environmental confirmatory testing (e.g. tritium/hydrogen diffusion, quench testing, fretting, resistance to debris damage, etc.)
2. Neutron irradiation testing at ATR, proton irradiation testing at University of Michigan
3. Evaluate tube fabrication and manufacturability
4. Economical feasibility for the new fuel concept
5. Preliminary performance and safety assessment
   - Evaluate neutronics
   - Thermal hydraulics
   - Scoping analysis for bounding transients or accidents

Approach to Study and Rate Steels for ATF Application

Environmental Degradation Under Normal Operation Conditions

Environmental Degradation Under Accident Scenarios

Fabrication Capabilities

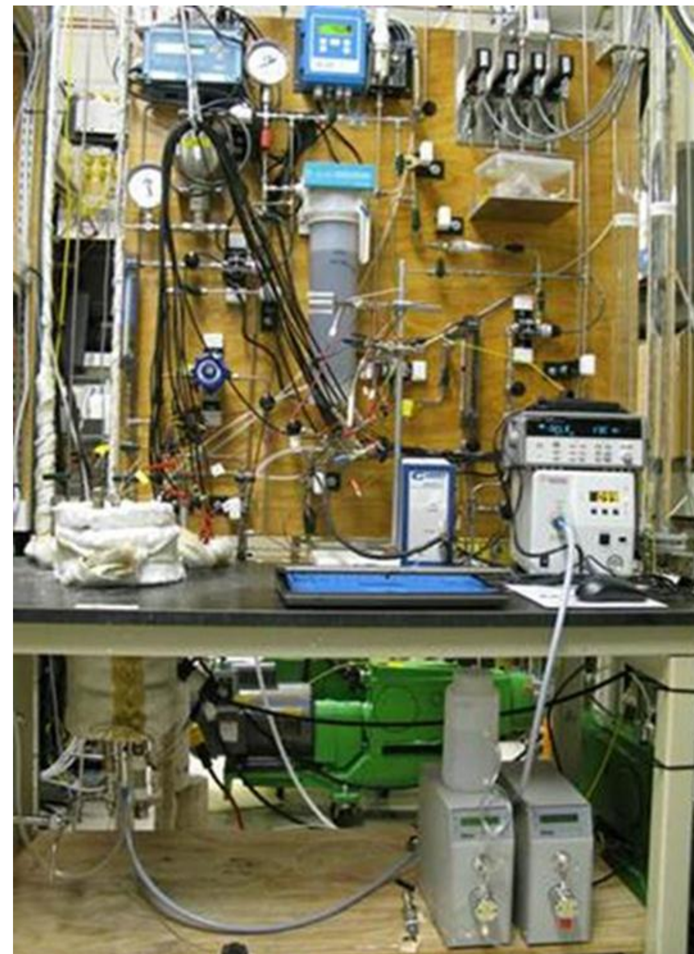
Regulatory Analysis, Fuel Economy

Materials Selected to Study

	Alloy	Nominal Composition
A	Zirc-2 UNS R60802	Zr + 1.2-1.7 Sn + 0.07-0.2 Fe + 0.05-0.15 Cr + 0.03-0.08 Ni
B	Ferritic steel T91 K90901	Fe + 9 Cr + 1 Mo + 0.2 V
C	Ferritic steel HT9 S42100	Fe + 12 Cr + 1 Mo + 0.5 Ni + 0.5 W + 0.3 V
D	Nano ferritic alloys - NFA	e.g. 14YWT; Fe + 14 Cr + 0.4 Ti + 3 W + 0.25 Y_2O_3
E	MA956 or UNS S67956	Fe + 18.5-21.5 Cr + 3.75-5.75 Al + 0.2-0.6 Ti + 0.3-0.7 Y_2O_3
G	APMT	Fe + 22 Cr + 5 Al + 3 Mo
H	Super ferritic, e.g. 4C54, Ebrite S44627	Fe + 25-27.5 Cr + 1 Mo + 0.17 (Ni + Cu)
J	Alloy 33 – UNS R20033	33 Cr + 32 Fe + 31 Ni + 1.6 Mo + 0.6Cu + 0.4 N

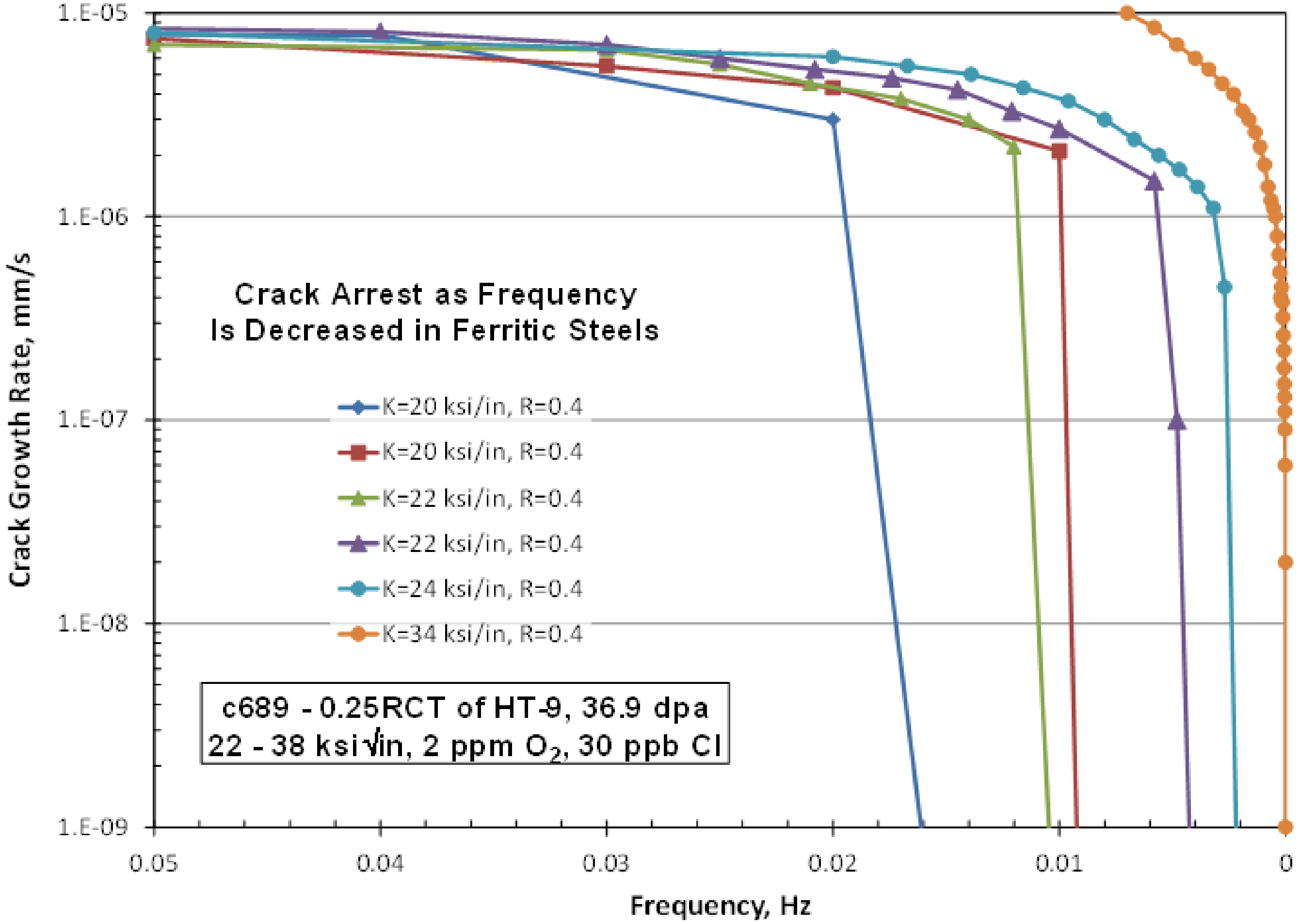
Behavior of Candidate Steels in Simulated Normal Operation Conditions

1) Crack Propagation Studies
2) One Year Exposure to High Temperature Water
3) Electrochemical Tests



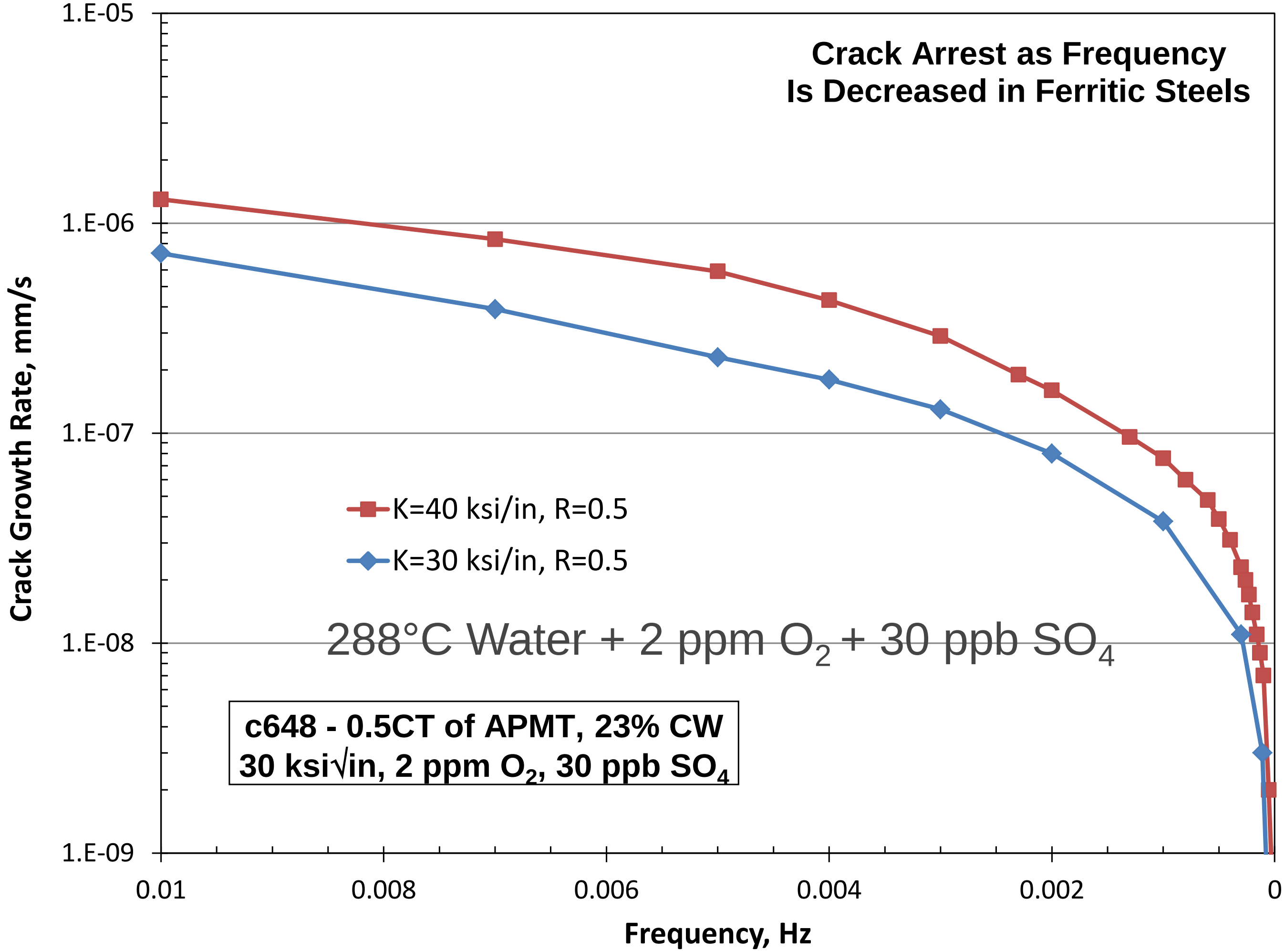
Stress Corrosion Cracking Resistance of HT9 Neutron Irradiated to 36.9 dpa

288°C Water + 2 ppm O_2 + 30 ppb Cl



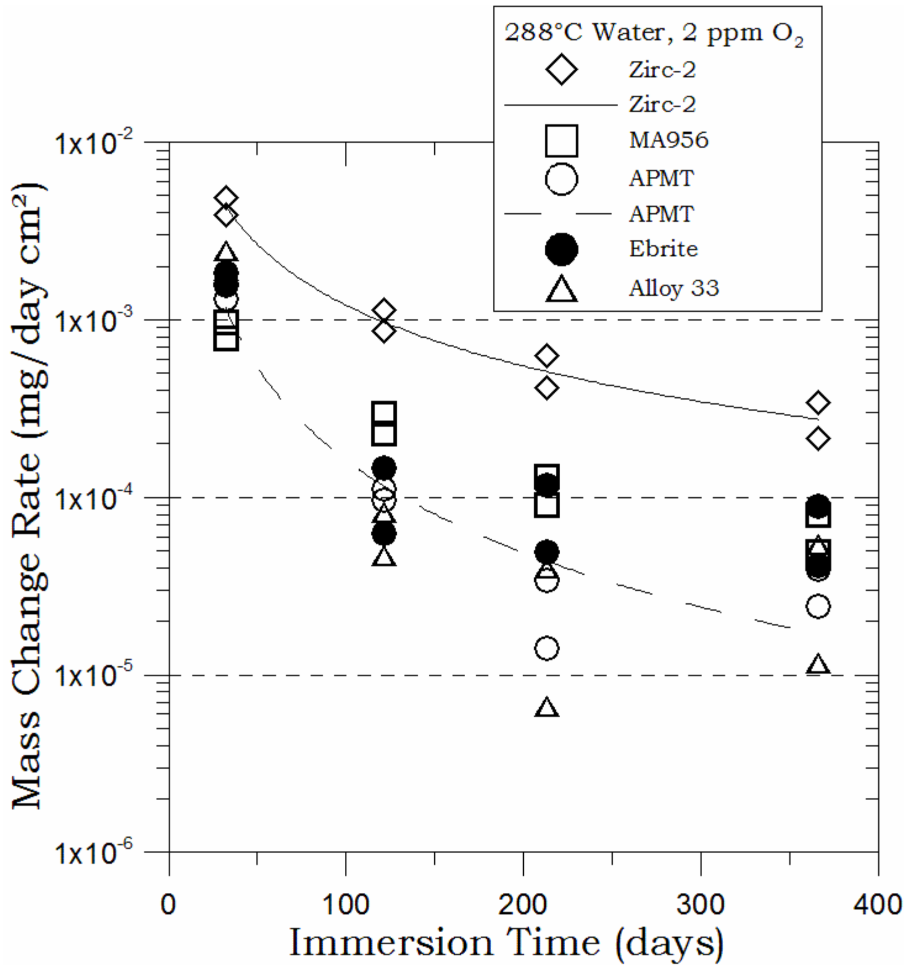
No SCC crack growth under constant K conditions

SCC Resistance in 23% Cold Worked APMT Steel



No SCC crack growth under constant K conditions

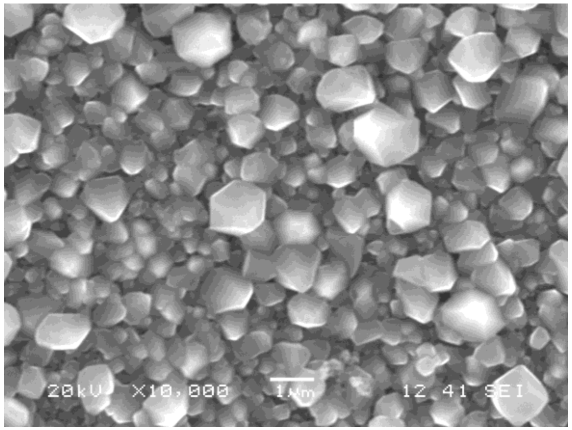
1-Year Exposure at 288°C Water + 2 ppm O_2



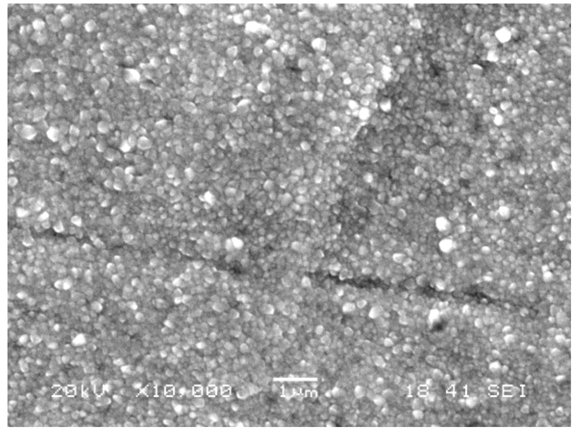
- The rate of mass gain decreased as the exposure time increased
- Zirc-2 coupons - highest mass gain
- APMT offers some of the lowest mass gains as a function of time

Surface Oxides After 366 Days Exposure to 288°C Water

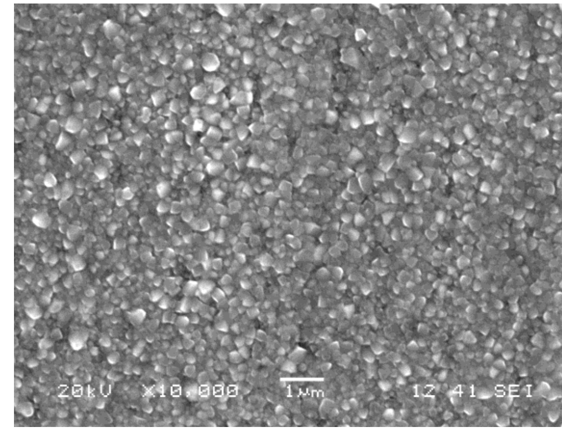
T91, RB2, X10,000



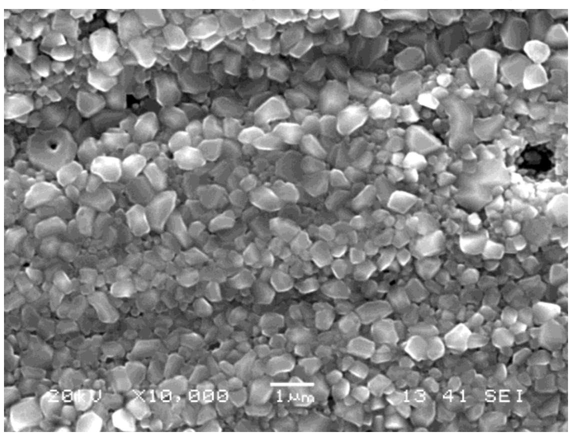
HT9, RC2, X10,000



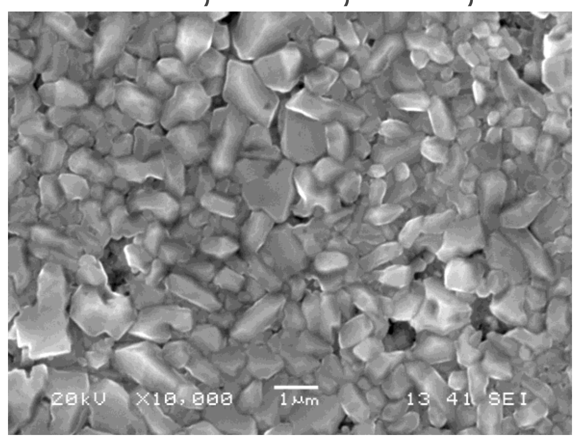
NFA, RD2, X10,000



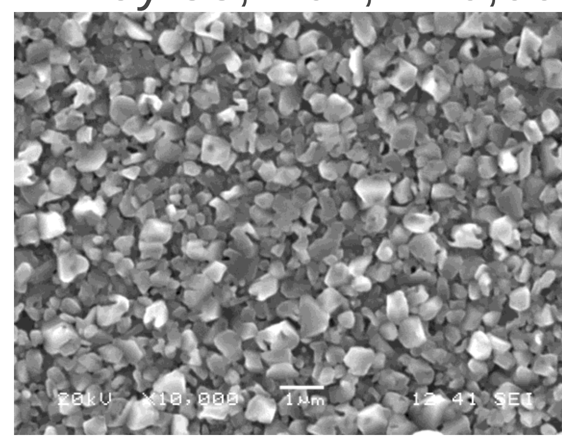
MA956, RE2, X10,000



APMT, RG2, X10,000



Alloy 33, RJ2, X10,000



Tube Fabrication Studies

GE working with Sandvik to develop tube fabrication methodology.

Understand the limitations when cold forming APMT tubing:

- Manufacture a APMT tube with as small dimension as possible.
- If the cold forming trials are successful a tube of 1 m will be delivered with the smallest dimensions achieved.

INL ATR Tests to Demonstrate Chemical Compatibility Between UO_2 Fuel and Cladding

Tests at ATR started on 11-02-2015

Rodlets fabricated by INL using material provided by GE

Fuel Fabricated by GE-GNF

- 300-400°C Cladding temperature
- 300-400 W/cm LHGR
- 20, 80 GWd/mT Burnup
- < 1700°C fuel centerline temperature

Neutronic/Thermohydraulic/Economic Evaluations - Brookhaven National Laboratory

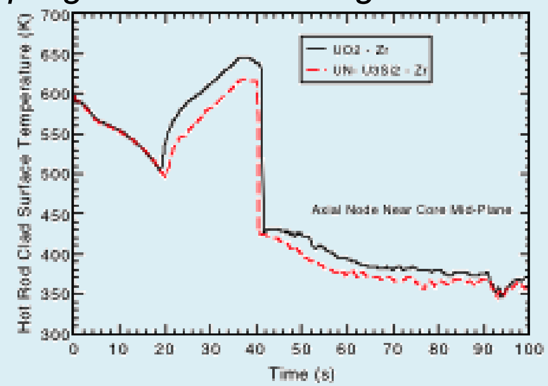
Determine if ATF fuel-clad combinations are a potential "drop-in" replacement for UO_2

Fuel/Clad	Cycle length (Days)
UO_2 - Zr	532.9
UN - U_3Si_5 - AF	533.1
UN - U_3Si_5 - APMT	526.0
UN - U_3Si_5 - UB_2 - APMT	510.5

Transient/safety analyses:

Impact of ATF on accident progression and margins

Time to fuel or clad temperature limits, DNBR



ATF Metrics

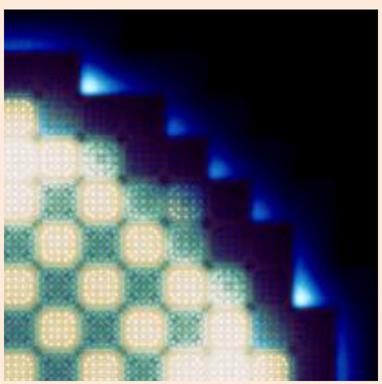
"The assessment must address how implementation of the concept will affect reactor performance and safety characteristics."

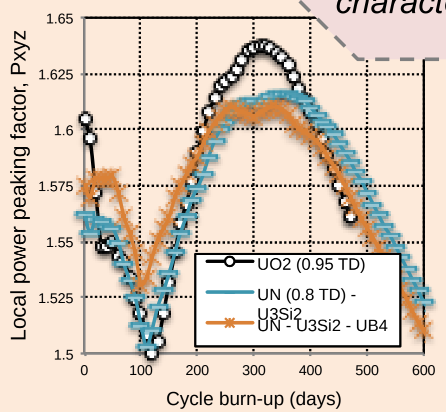
Core analysis of ATF vs. UO_2-Zr:

Power peaking and safety margins (steady-state & transient)

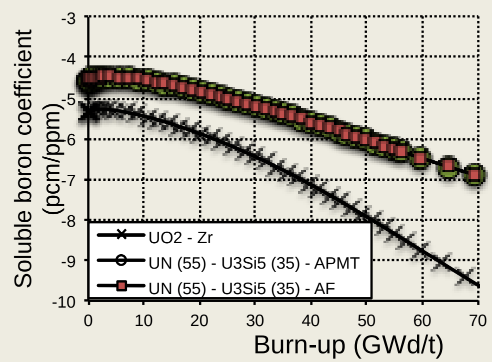
Burn-up history & fuel management

Control and safety parameters





Screening safety parameters for fuel and cladding in LWRs



Reactivity coefficients:

Fuel temperature (Doppler)

Moderator temperature (density and spectral)

Boron and control rod worth

Brookhaven National Laboratory Evaluations

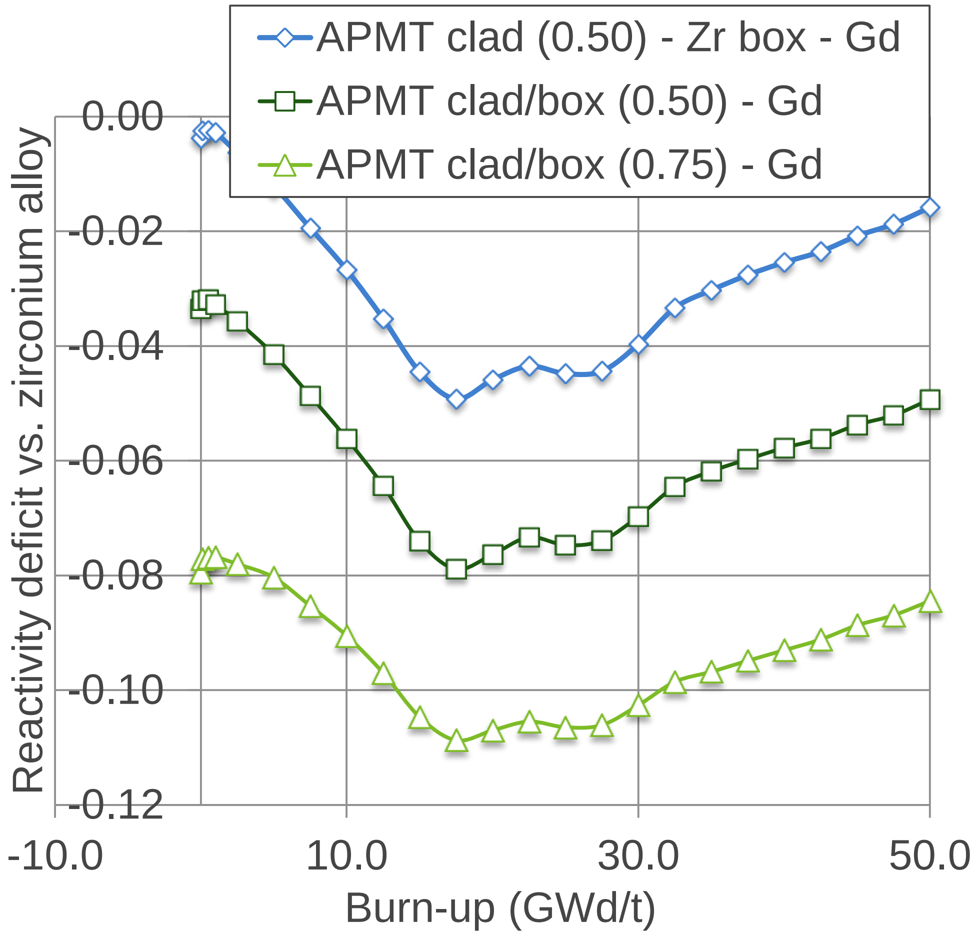
1. Scope of analyses includes PWRs and BWRs.
2. Objective to determine benefits and detriments for ATF concept.

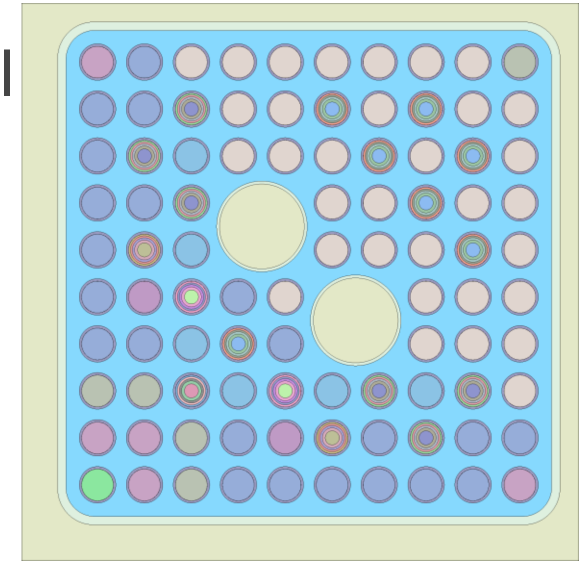
- Fuel management: cycle length, discharge burn-up
- Fuel cycle: Uranium utilization and electricity cost
- Safety: Reactivity, control, kinetics
- Core analysis: Local peaking and transient behavior

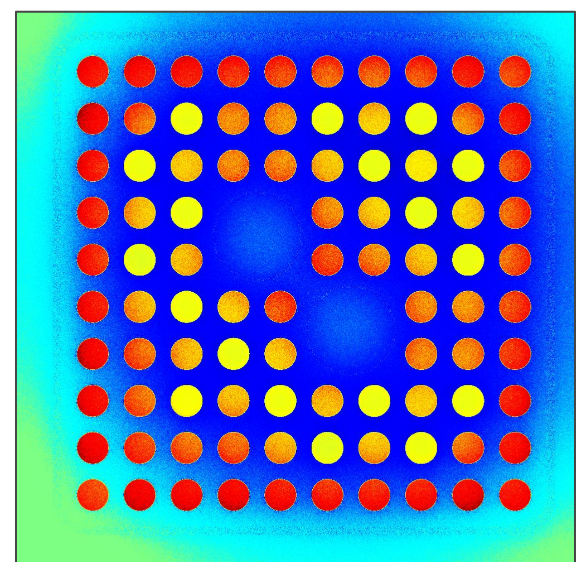
BWR Neutronics: Assembly Level

Poisoned (Gd) BWR assembly

Reactivity deficit with APMT clad and channel box at 50% - 75% thickness

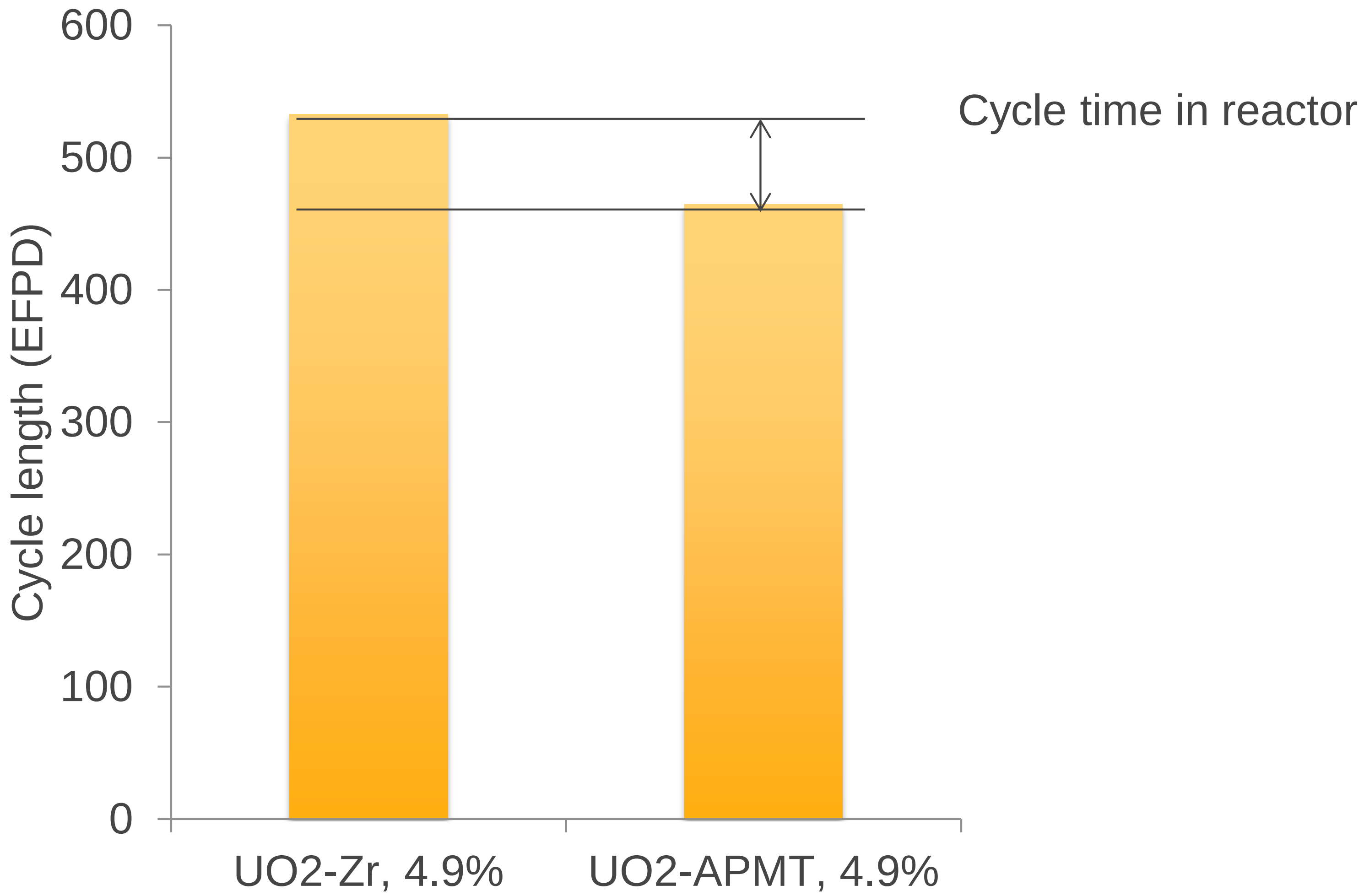






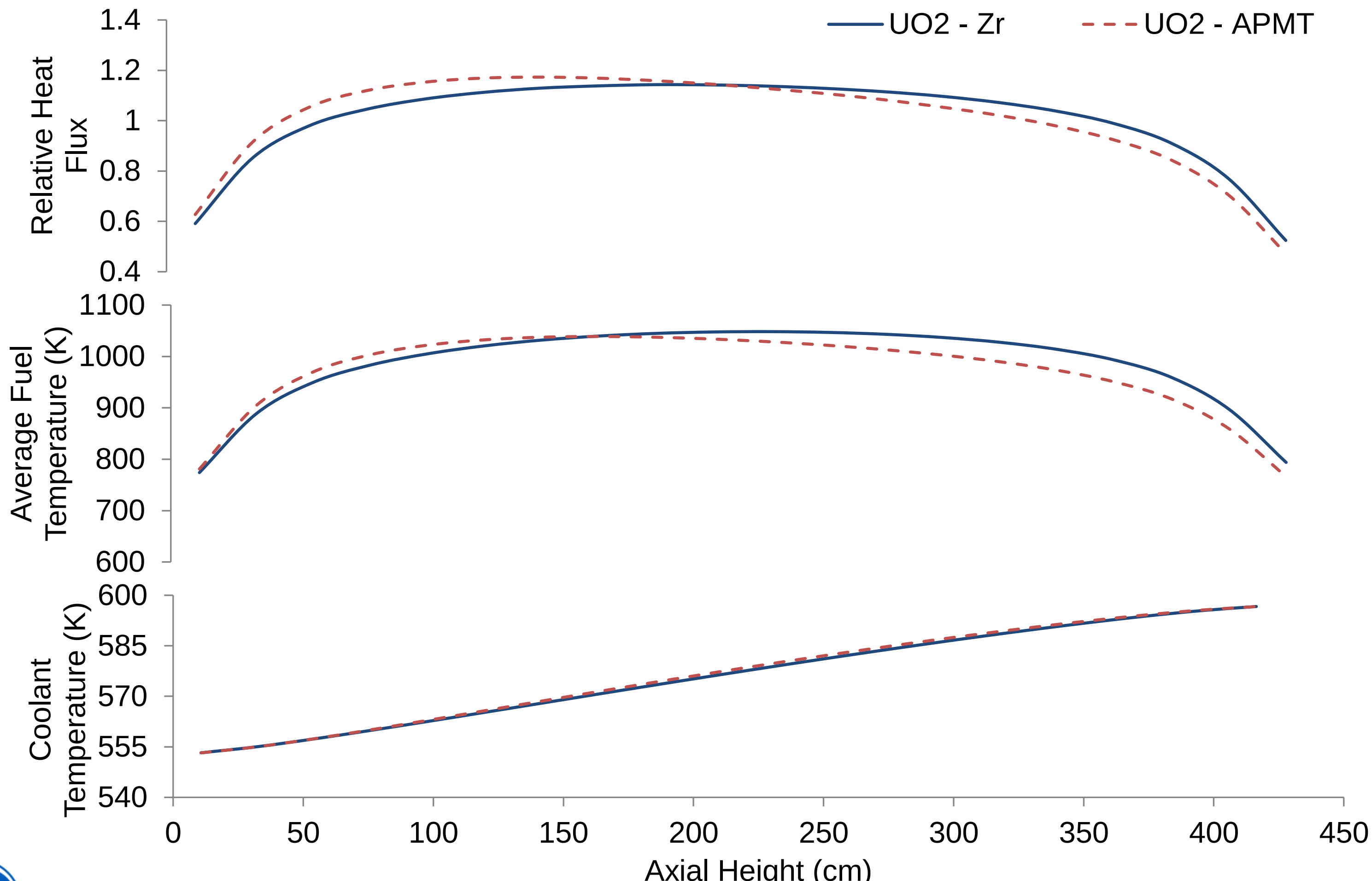
Cycle Length (PWR)

These values are for 75% of zirconium alloy thickness with steel cladding (4.9%-enriched)



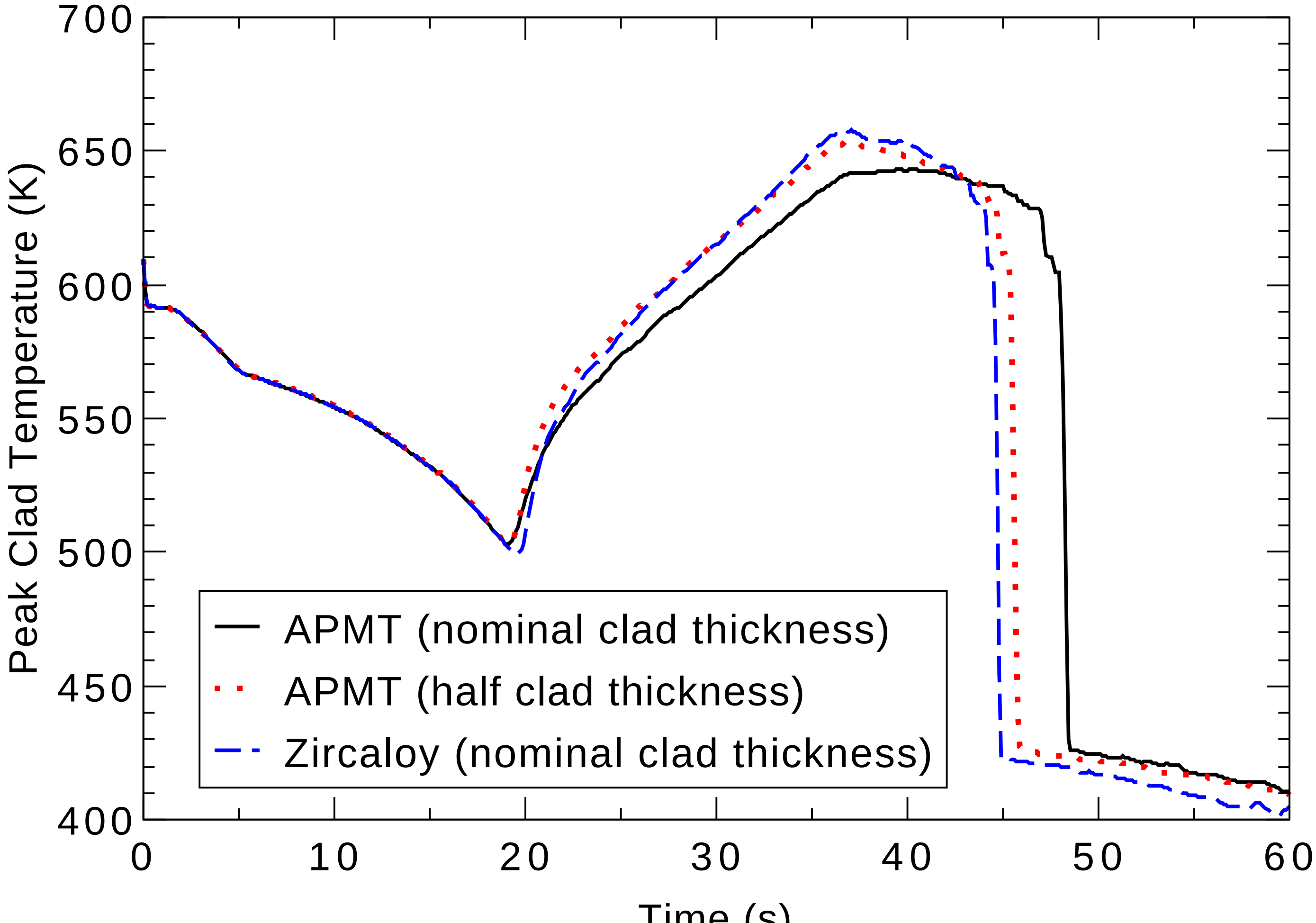
Thermal Hydraulics of Average PWR Channel

- **From a PARCS core calculation: not major impacts**



Transient Analysis: Large Break Loss-of-Coolant with Station Blackout (PWR)

- **From a TRACE (NRC tool) transient calculation**



Summary and Conclusions

1) The proposed advanced steels are better than zirconium alloys under normal operation conditions
   - Resistant to general corrosion and environmental cracking
   - Resistant to shadow corrosion
   - Resistant to radiation damage
2) The advanced steels outperform the zirconium alloys under accident conditions
   - Better mechanical strength at elevated temperature
   - Enhanced retention of fission products
   - Improved reaction kinetics with steam
   - Lower generation of hydrogen gas when reacting with steam
3) Other areas currently being studied
   - Irradiation studies at ATR (dry and water loop)
   - Neutronics, thermal hydraulics
   - Tritium release, hydrogen absorption
   - Long term storage of spent fuel in dry casks
   - Fabrication of tubing
   - Economics

Acknowledgement

This material is based upon work supported by the Dept. of Energy [National Nuclear Security Administration] under Award Number DE-NE0008221.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.