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University-Led Investigations of Thermal-Hydraulic Behavior of Accident Tolerant Fuel Materials

December 2020

Changing the World's Energy Future

Charles P Folsom

Idaho National Laboratory

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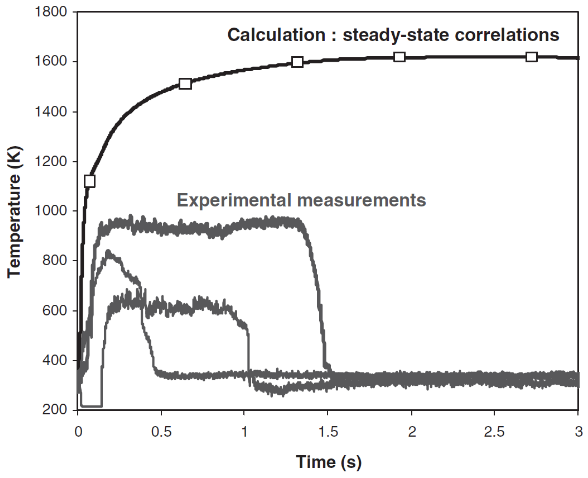
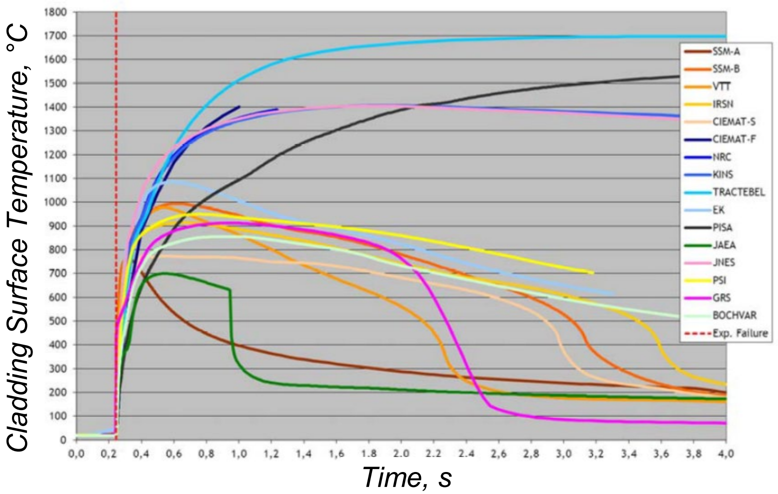
Advanced Fuels Campaign

Thermal Hydraulic Behavior under RIA Conditions

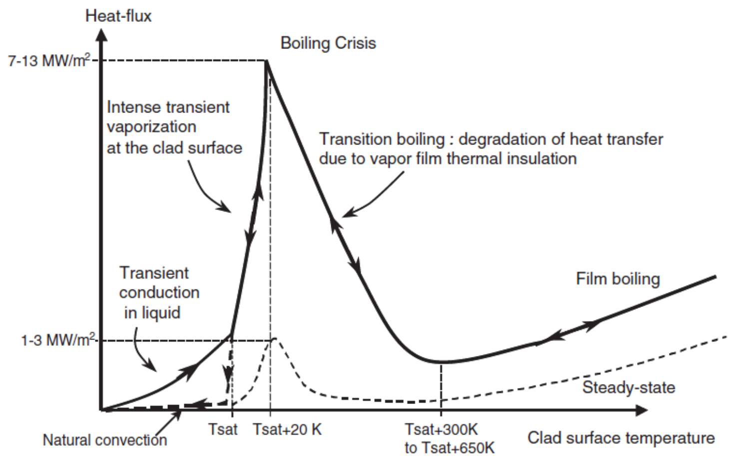
- **Why does the Advanced Fuels Campaign care about thermal-hydraulics R&D?**
- **Cladding-to-coolant heat transfer during transient irradiation conditions remains a critical area of uncertainty in fuel performance predictive capability**
- **Key safety limits for LWRs are intended to avoid critical heat flux (CHF)**
  - Experiments have shown that critical heat flux (CHF) during rapid transient boiling conditions is significantly higher than under steady-state conditions (NEA/CSNI/R(2016)6/VOL1)



Experimental measured cladding surface temperature during RIA experiments in NSRR V. Bessiron, (2007) J. Nucl. Sci. Technol. 44 (5) 723-732



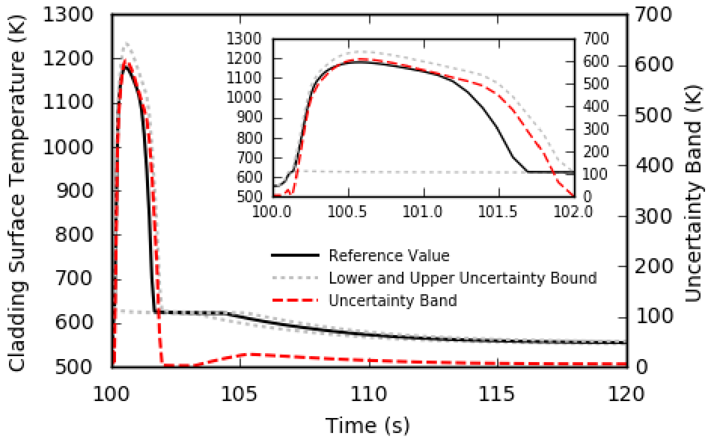
Fuel performance predictions for cladding surface temperature during RIA (NEA/CSNI/R(2013)7)



Transient boiling curve developed by the IRSN V. Bessiron, (2007) J. Nucl. Sci. Technol. 44 (5) 723-732

Thermal Hydraulic Behavior under RIA Conditions

- **Thermal-hydraulic uncertainties lead to uncertainties in fuel performance**
- **BISON uncertainty quantification and sensitivity analysis performed on a TREAT-like RIA experiment**
  - Similar to what would be performed in a MARCH-SERTTA capsule
- **UQ/SA study used 21 inputs on fuel rod geometry, thermal-hydraulic boundary conditions, core power conditions, and physical properties/models (1000 simulations)**
  - ±25% factor on HTC
  - One sided factor on CHF varied from 1-2 (SD of 50%)



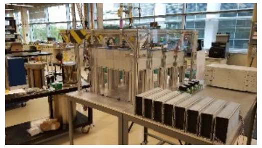
Uncertainty Quantification of cladding temperature from 1000 BISON simulations

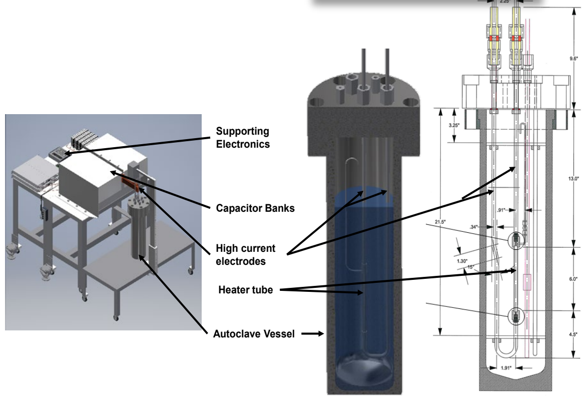
Sobol Indices											
INPUT paramater	RAE	TFC	TFO	TCI	TCO	CTHS	CHS	FOR	PHS	GAP	HFC
Cladding outside diameter	0.009	0.010	0.003	0.003	0.003	0.007	0.004	0.005	0.005	0.003	0.003
Cladding inside diameter	0.004	0.003	0.010	0.003	0.003	0.329	0.198	0.009	0.132	0.110	0.002
Fuel outer diameter	0.008	0.007	0.007	0.002	0.002	0.080	0.042	0.135	0.030	0.034	0.007
Fuel porosity	0.014	0.015	0.004	0.004	0.003	0.003	0.003	0.005	0.004	0.003	0.004
Cladding roughness	0.009	0.007	0.076	0.014	0.010	0.007	0.017	0.007	0.011	0.005	0.421
Fuel roughness	0.005	0.004	0.063	0.016	0.011	0.000	0.021	0.001	0.005	0.000	0.431
Filling gas pressure	0.001	0.001	0.001	0.002	0.001	0.002	0.002	0.002	0.001	0.001	0.001
Coolant pressure	0.004	0.004	0.005	0.007	0.006	0.005	0.005	0.001	0.004	0.003	0.003
Coolant inlet temperature	0.006	0.006	0.008	0.011	0.011	0.004	0.008	0.005	0.005	0.001	0.003
Coolant velocity	0.005	0.005	0.001	0.001	0.001	0.009	0.003	0.010	0.005	0.004	0.006
Injected energy in the rod	0.863	0.868	0.228	0.096	0.060	0.185	0.012	0.273	0.176	0.156	0.008
FWHM pulse width	0.009	0.004	0.015	0.005	0.003	0.004	0.001	0.003	0.004	0.003	0.005
Fuel thermal conductivity model	0.005	0.005	0.036	0.015	0.010	0.003	0.013	0.004	0.004	0.001	0.003
Clad thermal conductivity model	0.006	0.006	0.008	0.007	0.005	0.006	0.002	0.005	0.007	0.004	0.006
Fuel thermal expansion model	0.002	0.002	0.006	0.004	0.004	0.327	0.160	0.507	0.123	0.208	0.002
Clad thermal expansion model	0.003	0.003	0.002	0.002	0.002	0.002	0.003	0.002	0.005	0.008	0.002
Clad Yield stress	0.003	0.003	0.001	0.002	0.002	0.001	0.008	0.002	0.005	0.003	0.001
Fuel enthalpy	0.079	0.091	0.010	0.006	0.005	0.019	0.010	0.031	0.012	0.034	0.003
Clad to coolant heat transfer	0.004	0.003	0.111	0.162	0.169	0.008	0.110	0.003	0.083	0.005	0.009
Coolant CHF factor	0.012	0.009	0.370	0.643	0.702	0.013	0.350	0.013	0.312	0.056	0.007
Gas conductivity factor	0.004	0.003	0.016	0.003	0.003	0.011	0.003	0.008	0.010	0.002	0.060
Summation	1.056	1.058	0.982	1.007	1.014	1.027	0.973	1.029	0.944	0.644	0.986

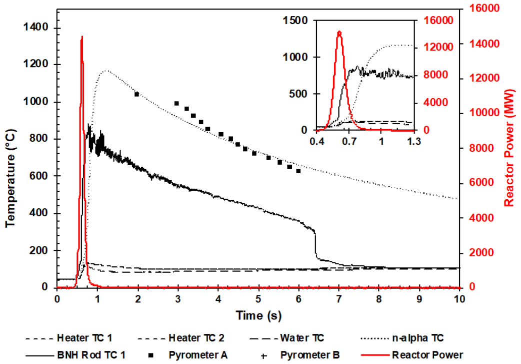
Sensitivity analysis using Sobol indices for the maximum outputs

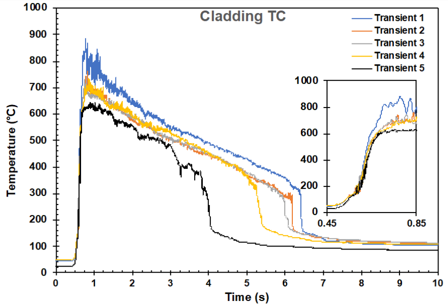
Transient Boiling LDRD

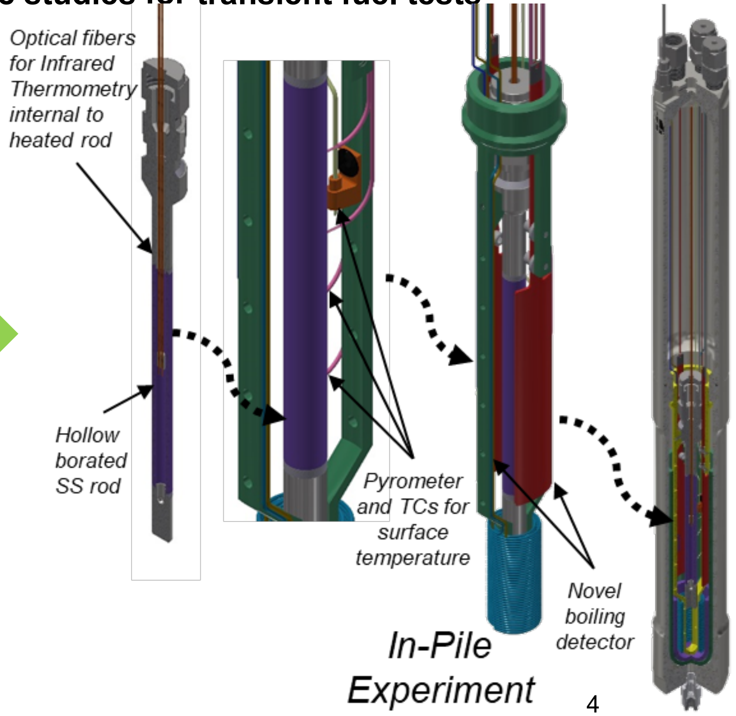
- **At INL a LDRD was funded to study transient-CHF**
- **Capitalize on unique accessibility for instrumentation, power control (high heat rates), and irradiation effects in TREAT**
  - Connect out-of-pile experiment results with in-pile results through M&S
    - *Design out-of-pile transient boiling experiment system*
    - *Design in-pile experiment using a novel, neutron-heated, fuel simulator rod*
    - *Develop theoretical understanding of transient boiling based on state-of-the-art*
- **Recently demonstrated both facilities – performing post test analysis now**
- **The in-pile and out-of-pile transient CHF test program demonstrates the significance of thermal-hydraulic studies for transient fuel tests**
  - Relevant for LOCA and SFR fuel tests (plans for an out-of-pile LOCA testbed)











Advanced Fuels Campaign

NEUP Projects

- **In 2018, the Department of Energy launched, through the Nuclear Energy University Program (NEUP) four projects aimed at investigating the thermal-hydraulics behavior of ATF cladding materials**
  - Mainly focused on three ATF cladding materials: Cr-coated Zircaloy, FeCrAl, and SiC
- **Project 17-12549: “Critical Heat Flux Studies for Innovative Accident Tolerant Fuel Cladding Surfaces,” led by the University of Wisconsin at Madison (UWM)-1 in collaboration with Westinghouse Electric Company, LLC (WEC) and General Atomics (GA).**
- **Project 17-12647: “Determination of Critical Heat Flux and Leidenfrost Temperature on Candidate Accident Tolerant Fuel Materials,” led by the Massachusetts Institute of Technology (MIT) in collaboration with UWM-2, WEC, and GA.**
- **Project 17-12688: “An Experimental and Analytical Investigation into Critical Heat Flux Implications for Accident Tolerant Fuel Concepts,” led by the University of New Mexico (UNM) in collaboration with the University of Tennessee at Knoxville (UTK), Oregon State University (OSU), Framatome, General Electric (GE), and Idaho National Laboratory (INL).**
- **Project 17-13019: “Evaluation of Accident Tolerant Fuels Surface Characteristics in Critical Heat Flux Performance,” led by Virginia Commonwealth University (VCU) in collaboration with UWM-2, BWX, Framatome, and GE.**