Advanced Gas Reactor Fuels Program Review

AGR-2 Irradiation Summary and Uncertainty Results

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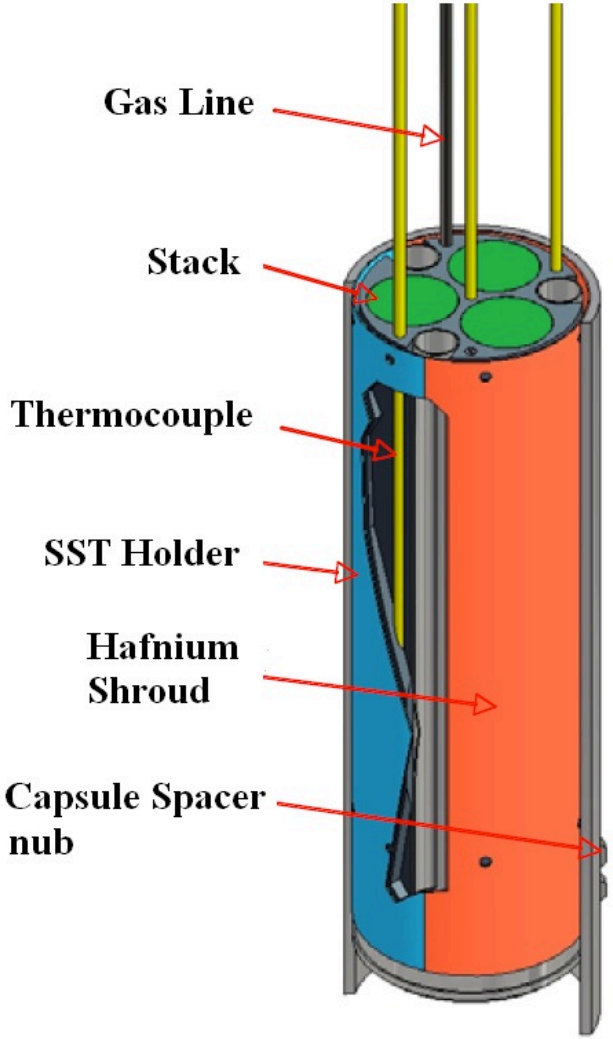
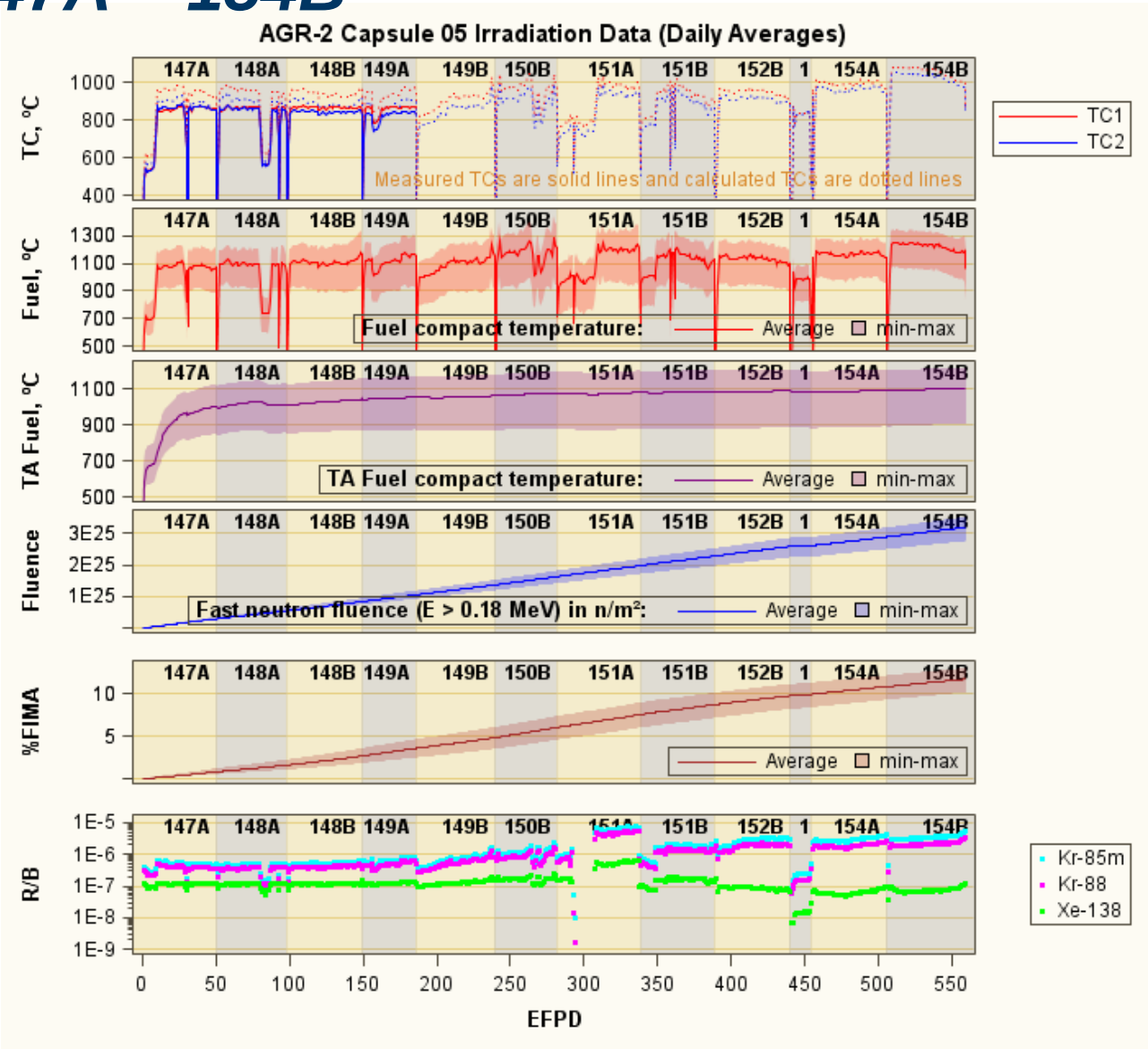
AGR-2 Irradiation

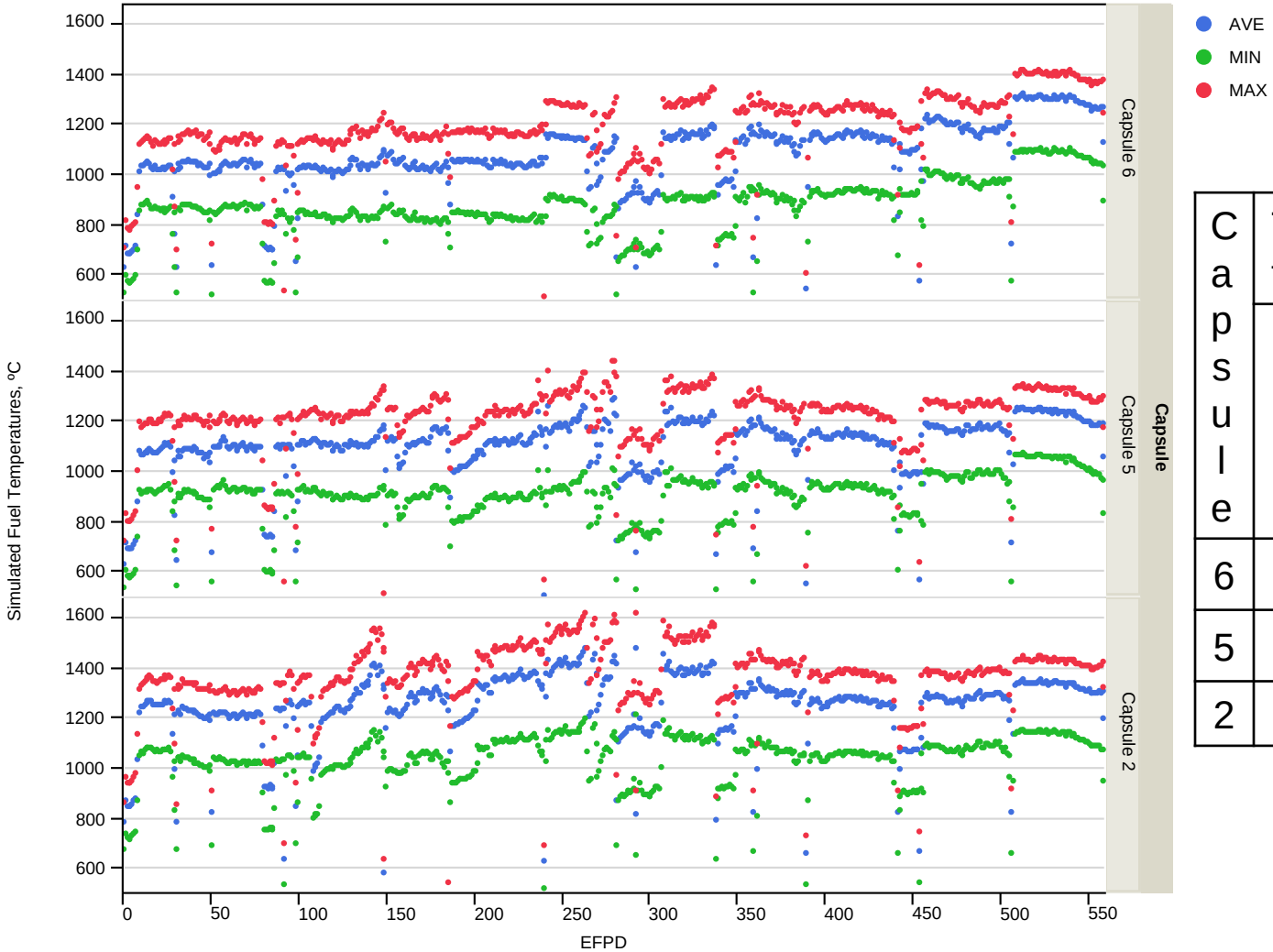
- Each of three AGR-2 U.S. UCO capsules (2, 5, and 6) and one UO_2 capsule (3) contains 38,000 fuel particles and 18,500 fuel particles, respectively
  - No DTF particles
  - No in-pile failure detected
- Fuel particles were irradiated for a total of 559.2 EFPDs
- Capsule-average fast fluence at EOE ranged from 2.39E+25 n/m^2(Capsule 6) to 3.35E+25 n/m^2 (Capsule 3)
- Capsule-average burn up at EOE ranged from 9.32 %FIMA (Capsule 6) – 12.19 %FIMA (Capsule 2)



Summary Data for AGR-2 Capsule 5 during ATR Cycles 147A – 154B

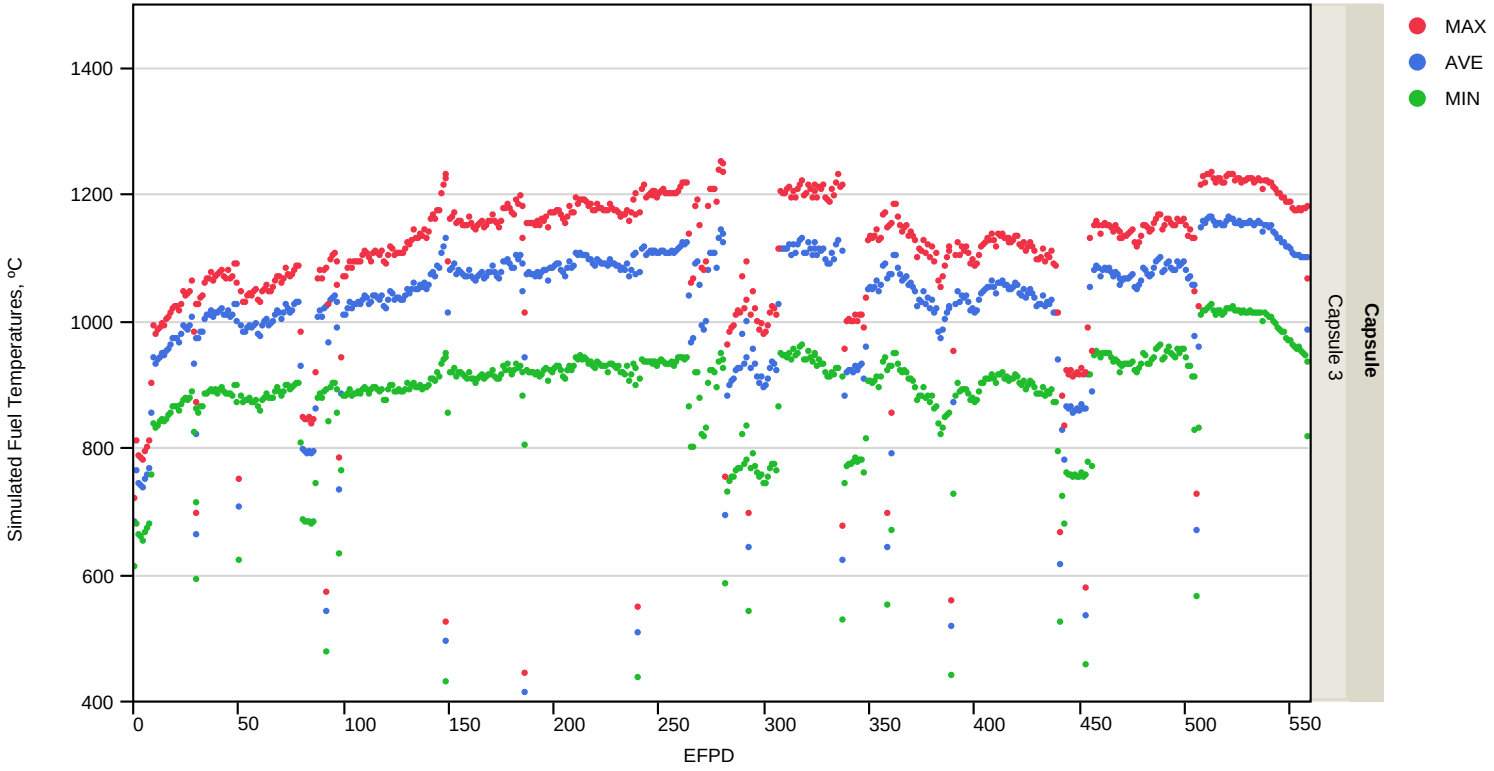


Fuel Temperatures for Three UCO Capsules



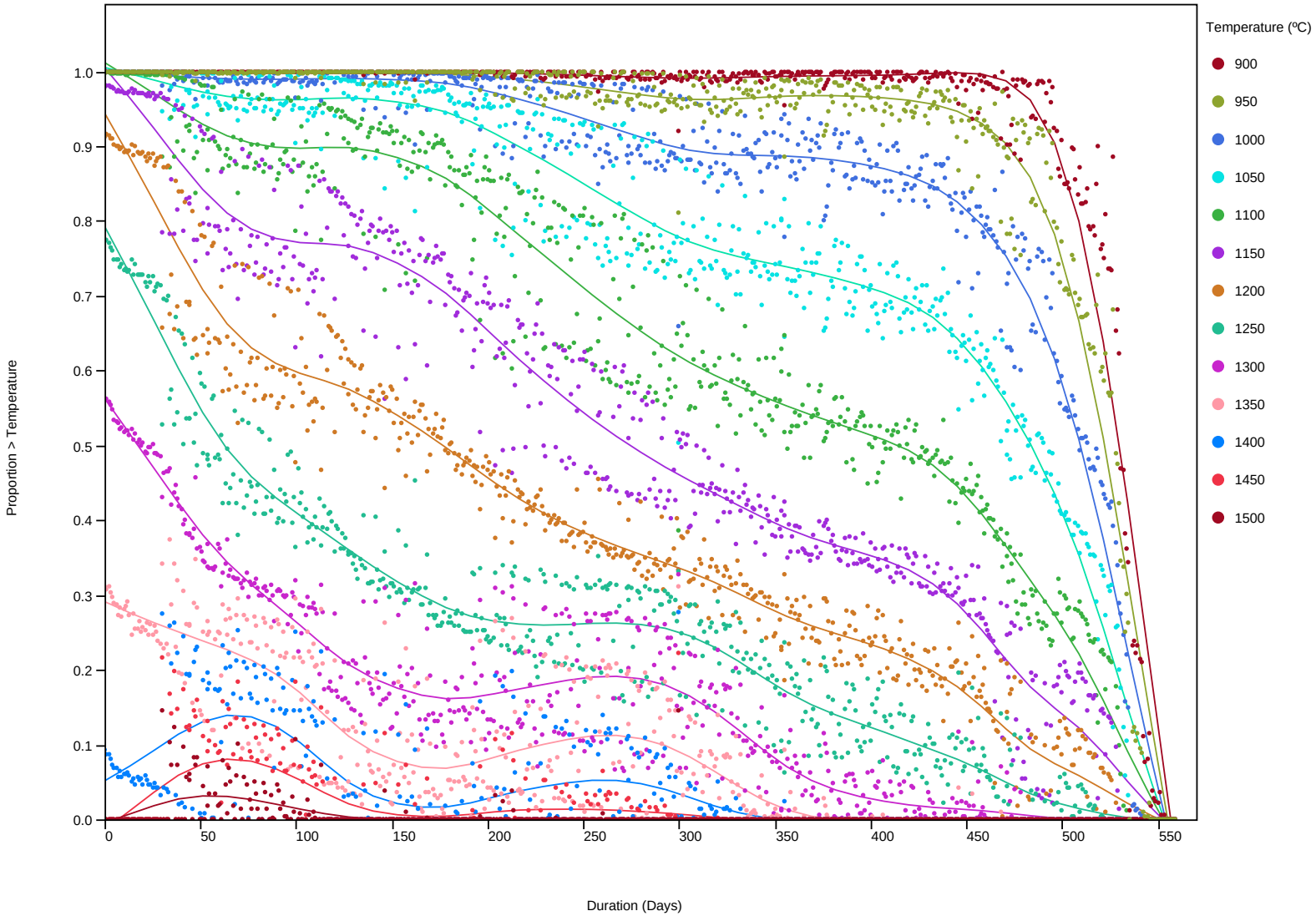
Capsule	TA fuel temperature at the end of Irradiation, °C		
	TA VA	TA Min	TA Max
6	1074	868	1183
5	1101	901	1210
2	1252	1034	1360

Fuel Temperatures for One UO_2 Capsule

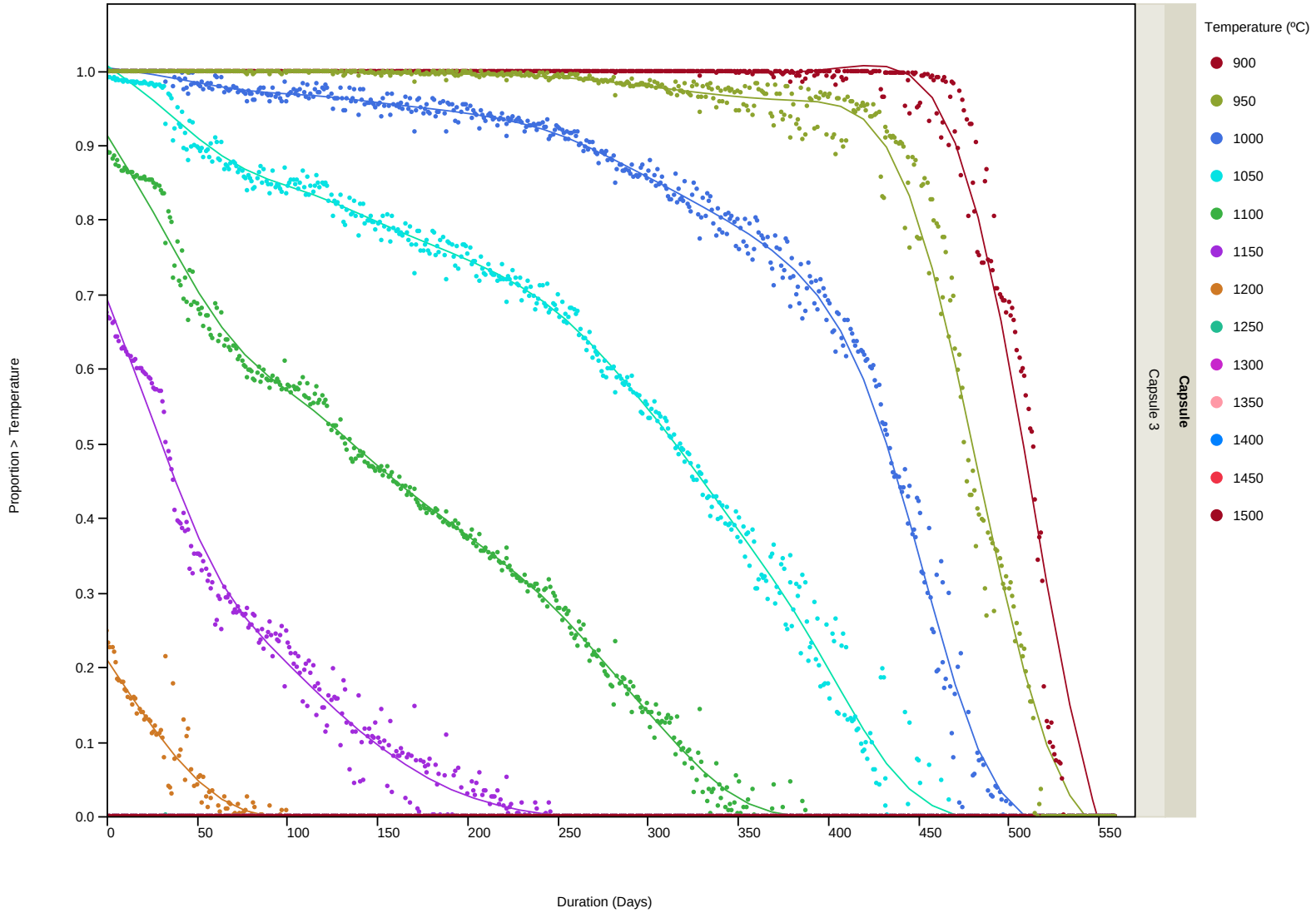


Capsule 3 TA fuel temperature at the end of Irradiation, °C		
TA VA	TA Min	TA Max
1032	889	1105

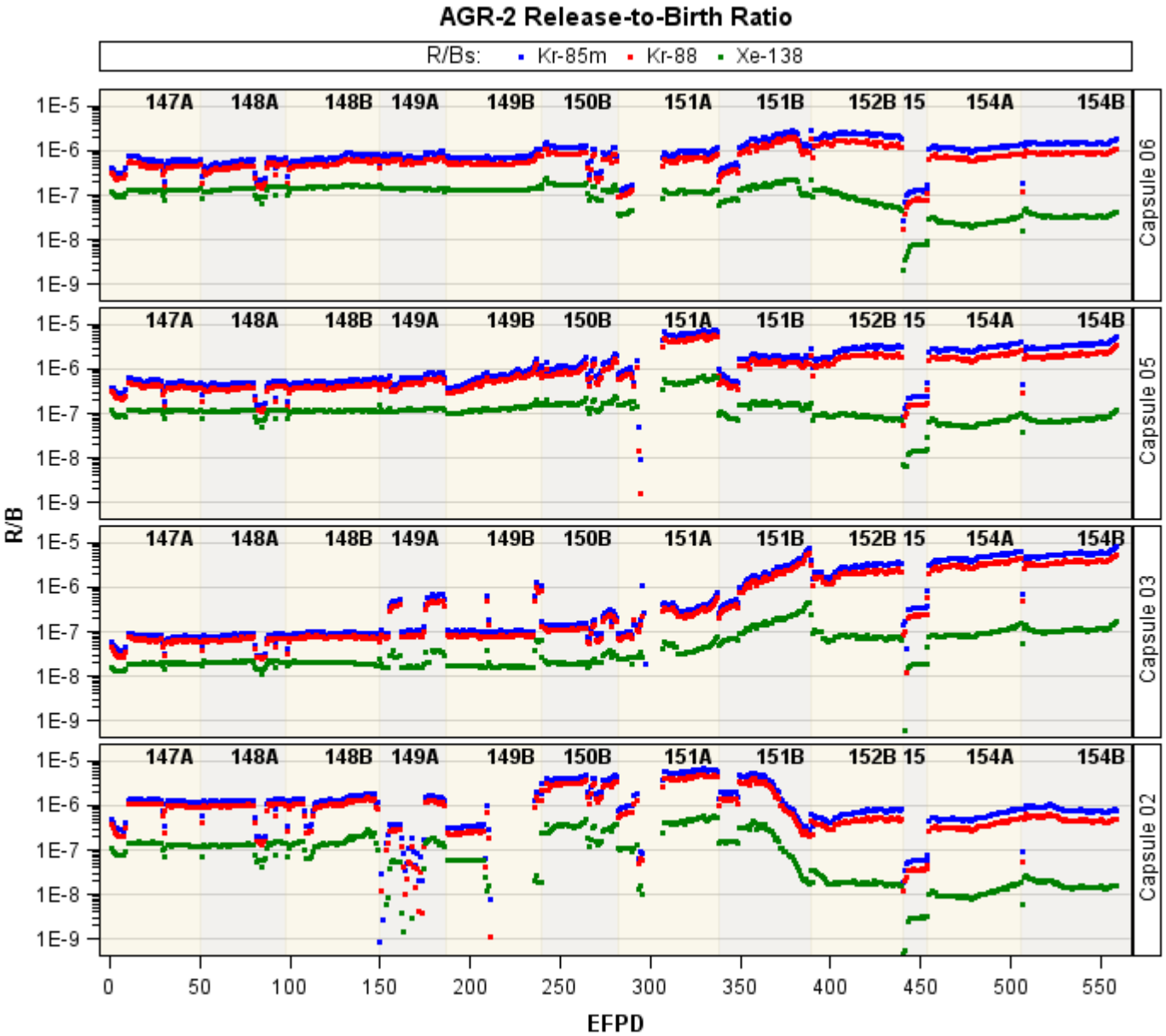
UCO Fuel Temperature in Capsules 2, 5, and 6



UO_2 Fuel Temperature in Capsule 3



R/B in U.S. Capsules



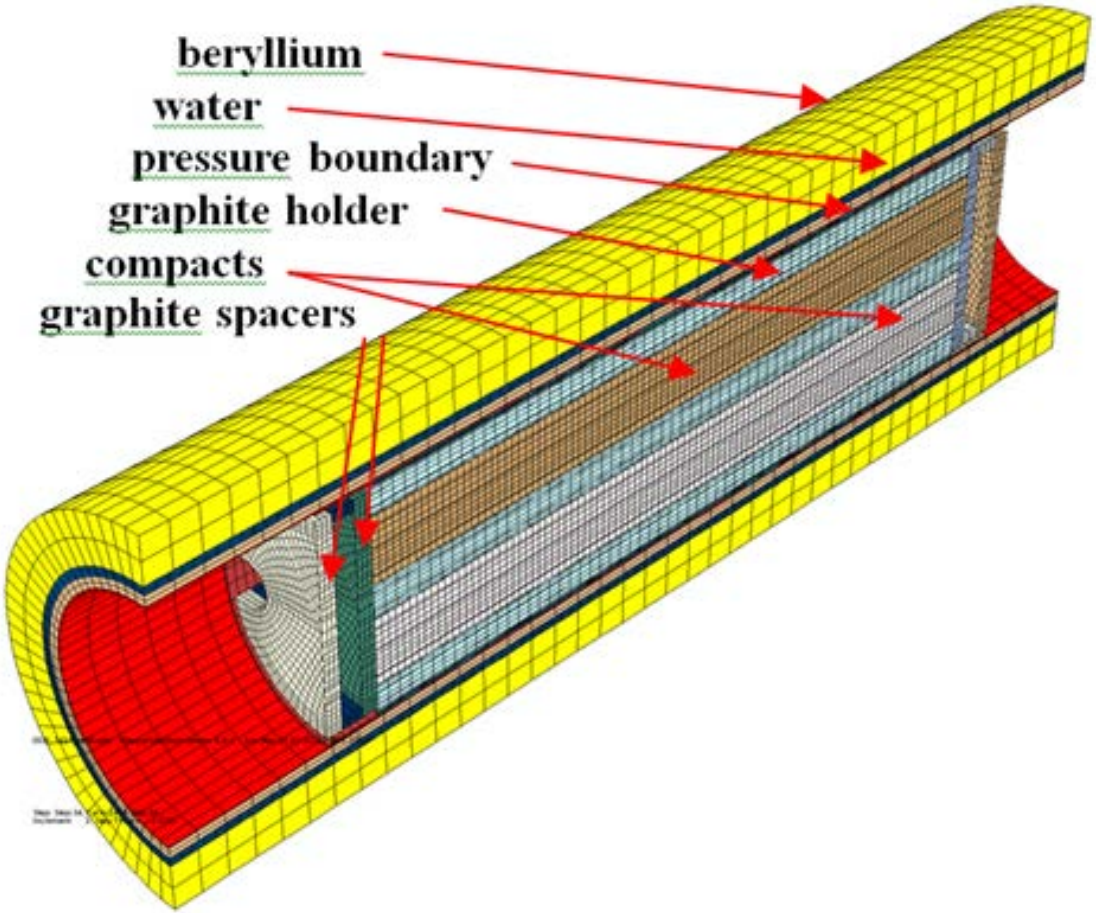
- Only R/B up to ATR Cycle 148B are qualified because
  - Relief valve failure occurred during ATR Cycles 149A and 149B
  - Cross-talk occurred from ATR Cycle 150B to the end of the experiment

Thermal Model for AGR-2 Capsule

ABAQUS-based (Version 6.8-2), three-dimensional finite-element thermal model

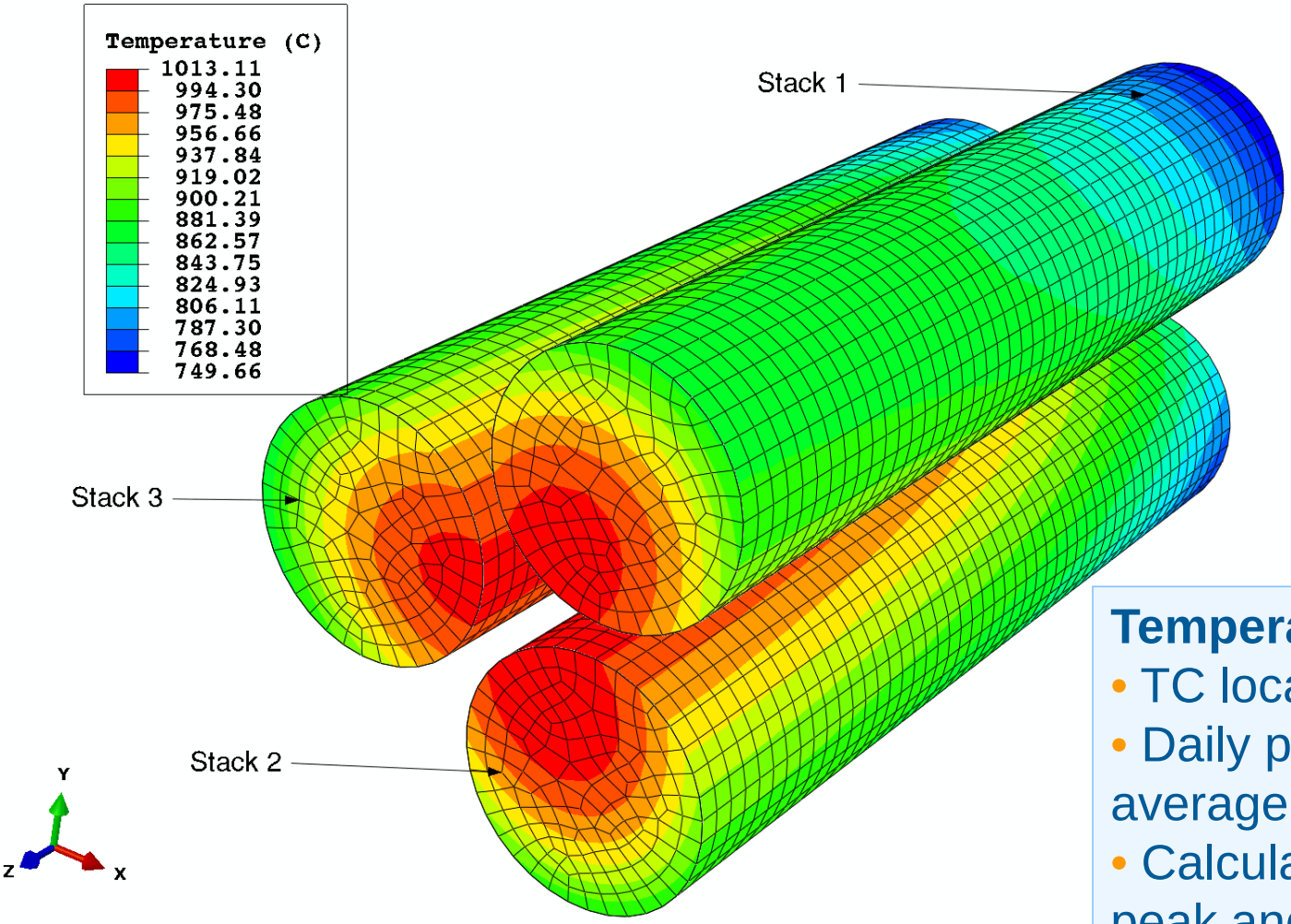
<u>Model Main Inputs</u>:

- Components' heat rates
- Neon/Helium gas composition
- Gas gap distance
- Fuel and graphite thermal conductivities



ABAQUS Mesh for Each AGR-2 Capsule

AGR-2 Thermal Model Temperature Predictions



Temperature outputs of:

- TC locations
- Daily peak and volume-average fuel
- Calculated time-average peak and volume-average from daily results

Uncertainty Quantification Process

Step 1 - Select the set of most influential inputs based on quantification of input parameter uncertainties by subject matter experts and results of sensitivity analysis.

Step 2 - Estimate daily input uncertainties and sensitivities for entire AGR-2 irradiation period.

Step 3 - Quantify calculated temperature uncertainties

- Propagate input uncertainties and sensitivities
- Add any model bias estimated from measured and simulated TC differences

Propagation of Model Temperature Uncertainty

$$\sigma_T^2 = \sum_{i=1}^{n} a_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{j \# i}^{n} \rho_{ij} a_i \sigma_i a_j \sigma_j$$

σ_i^2 - the uncertainty of input parameter *i* in terms of variance

a_i^2 - the square of the sensitivity coefficient for parameter *i*

ρ_{ij} - the correlation coefficient for input parameters *i* and *j*

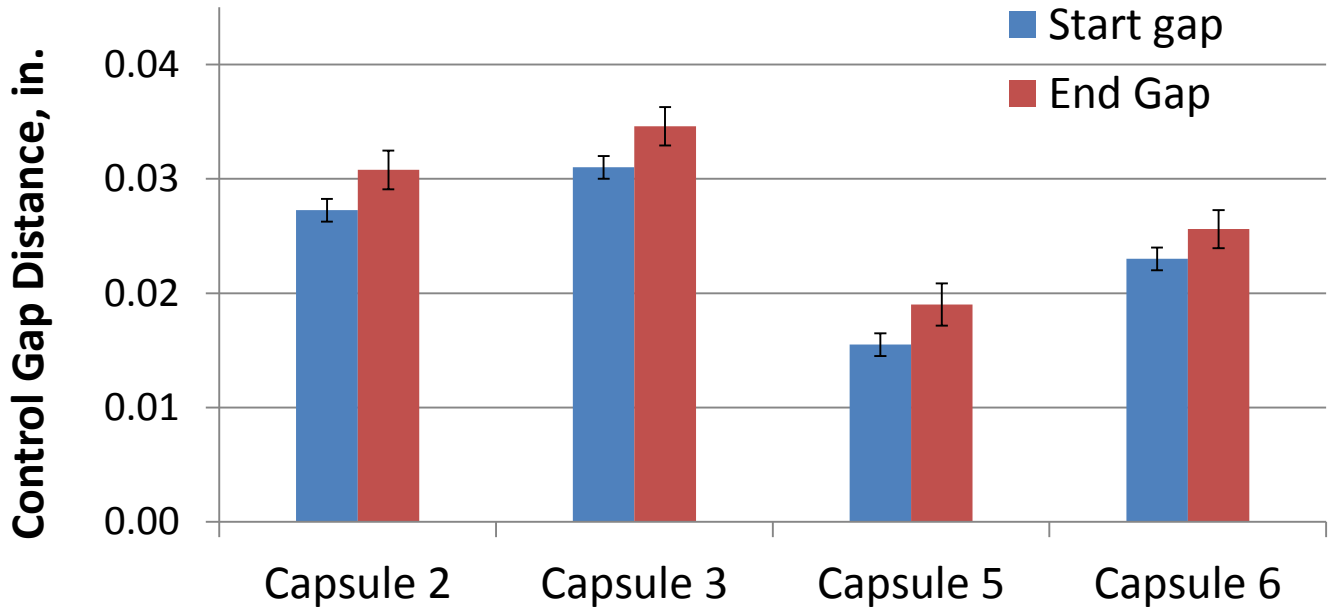
Assumptions:

1. Predicted temperature can be expressed by the weighted summation of input parameters
2. Model bias is negligible (assumption is verified by TC residuals)

Input Uncertainties

Parameter	Estimate of Uncertainty (%)	Comments
Control Gap Width	Cap 6: 4.3 – 6.5 Cap 5: 6.5 – 9.7 Cap 3: 3.2 – 4.8 Cap 2: 3.7 – 5.5	• Initial: 1 mil fabrication tolerance for all capsules. • Uncertainty is increasing over time due to assumption that gap variation can be modeled as a linear function of fast neutron fluence
Neon Fraction	Vary with neon fraction mainly in the range [0 – 30]	• 1.0 sccm flow rate uncertainty of neon, helium, and leadout flows as design specification • Uncertainties doubled between cross talk start and uniform gas mixture start
Fuel Heat Rate	5	• Basis is AGR-1 comparison between predicted and PIE fuel burnup done by J. Harp with additional input from J. Sterbentz.
Graphite Conductivity	15	• Additional conductivity data for the test graphite allows a lower uncertainty estimate for graphite than for fuel.
Fuel Conductivity	20	• Uncertainty is based on work done on surrogate compacts by C. Folsom at Utah State Univ.

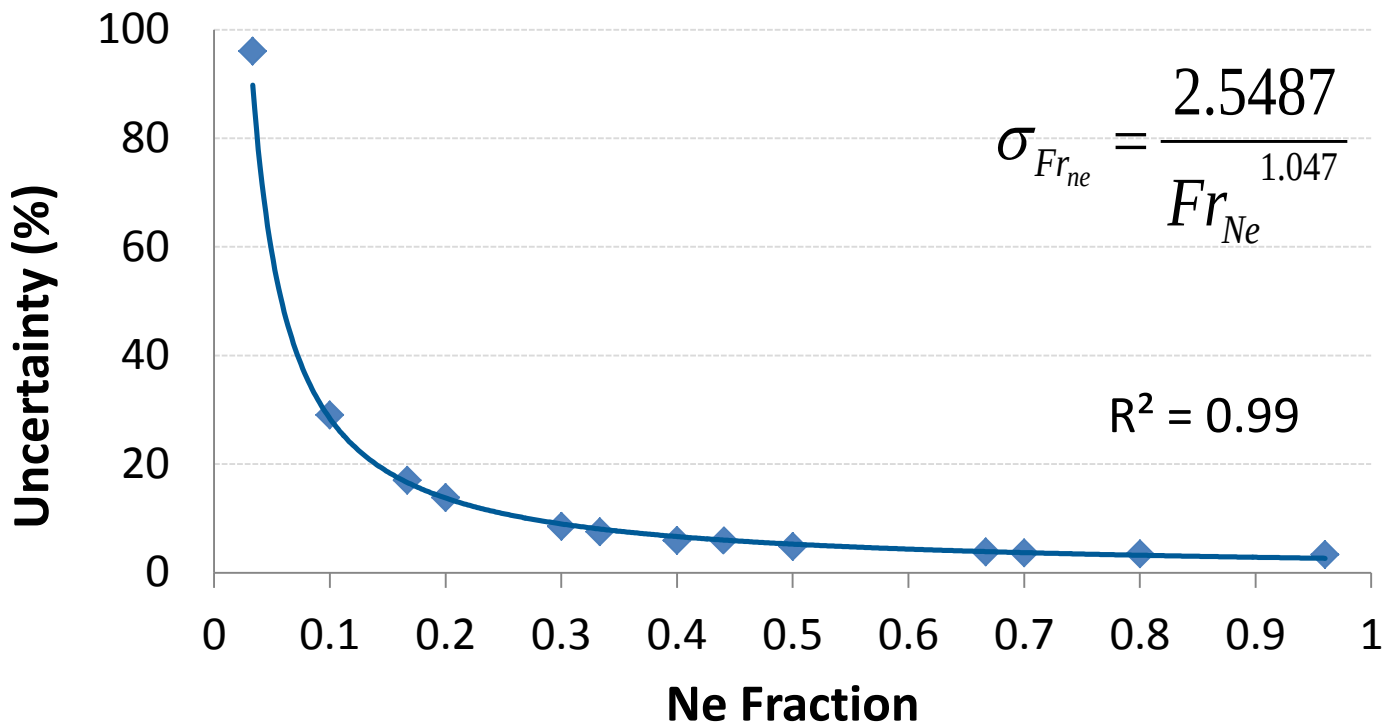
Uncertainty of the Gas Gap as Function of Fluence



Capsule	Initial gap (in.)	End gap (in.)	% Gap change	Fabrication error (σ)	End of irradiation error (σ)
6	0.0230	0.0256	11.3%	4.3%	6.5%
5	0.0155	0.0190	22.6%	6.5%	9.7%
3	0.0310	0.0346	11.6%	3.2%	4.8%
2	0.0273	0.0308	13.0%	3.7%	5.5%

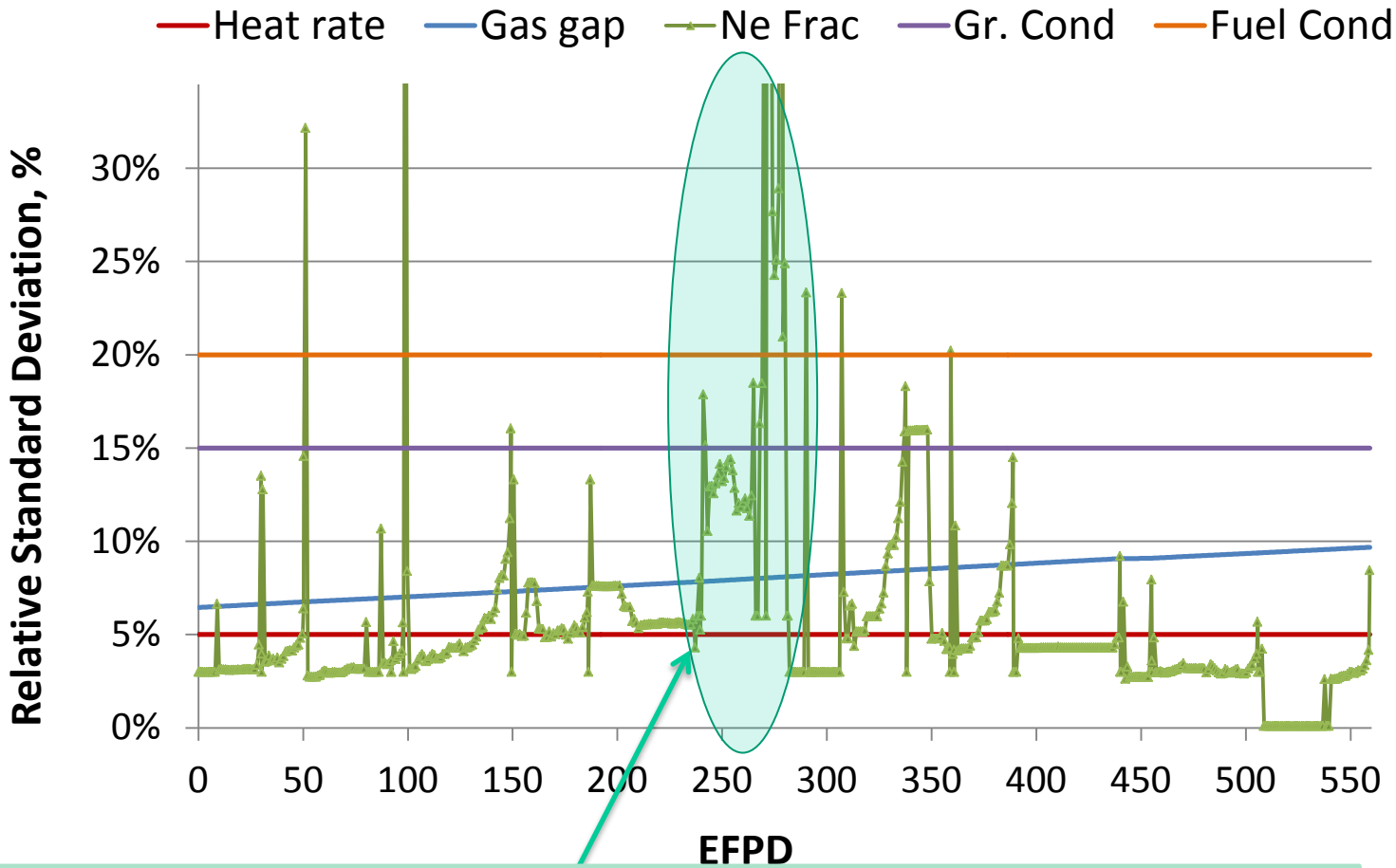
Uncertainty of Neon Fraction is Function of Neon Fraction

- Due to 1 sccm Ne, He flow uncertainties:



** During cross-talk and before application of uniform gas mixture in all capsules and leadout, the neon fraction uncertainty assumed to be double the normal value.*

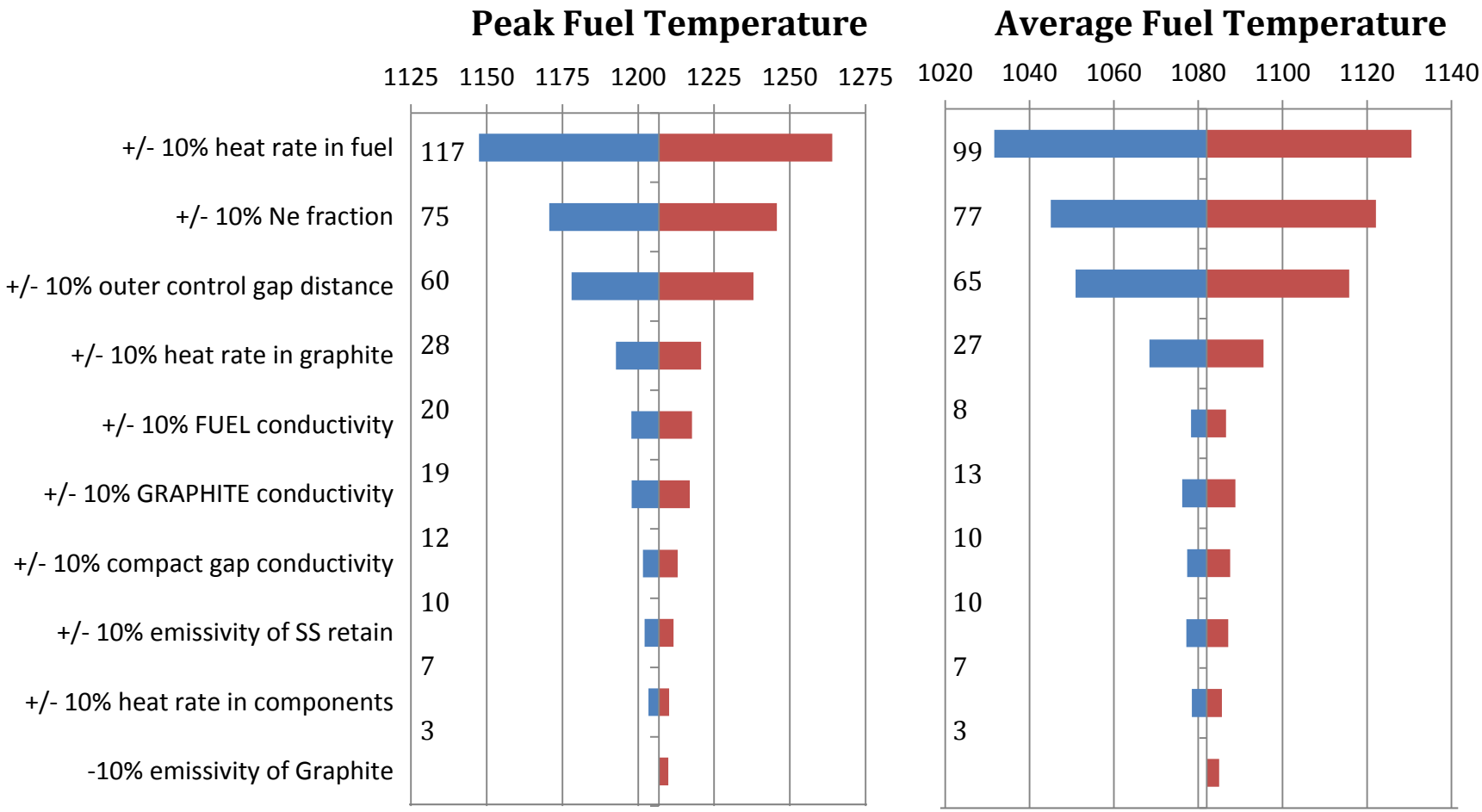
Daily Uncertainties of Significant Parameters as Function of EFPD for Capsule 5



Increased neon fraction uncertainty due to gas line cross-talk before application of uniform gas mixture in all capsules and leadout.

Sensitivity Results for One Time Step

Most influential inputs were identified: (1) Fuel heat rate; (2) Ne fraction; (3 Outer control gap distance; and (4) fuel and graphite conductivities



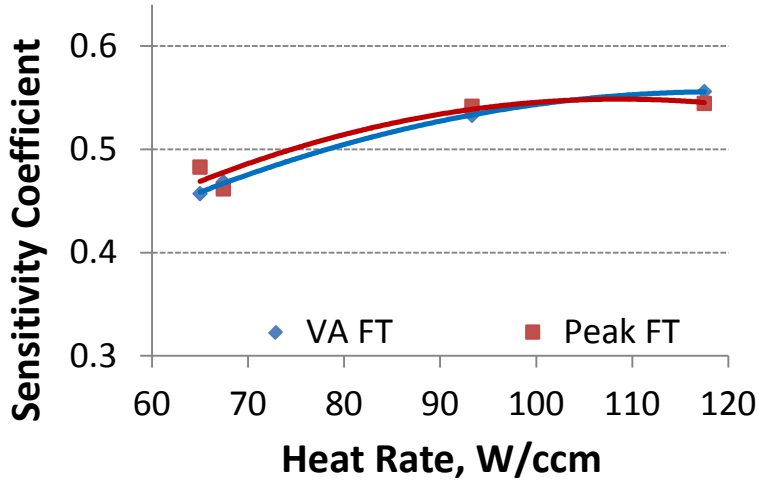
Thermal Conditions for Sensitivity Analysis

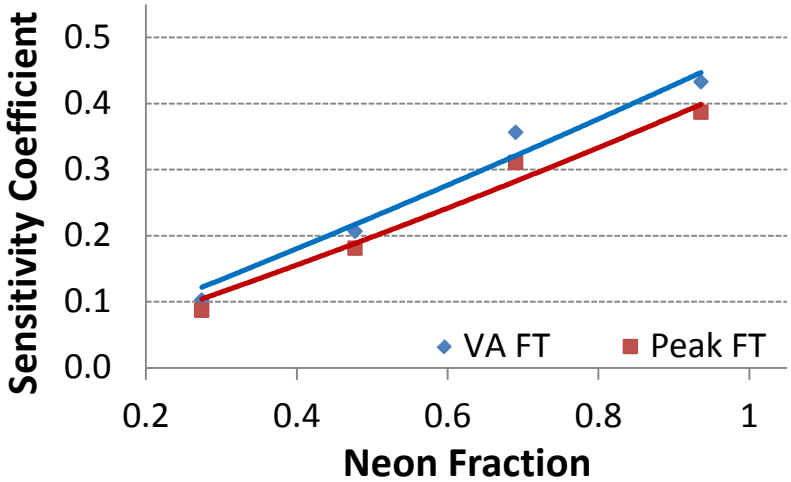
Capsule 5

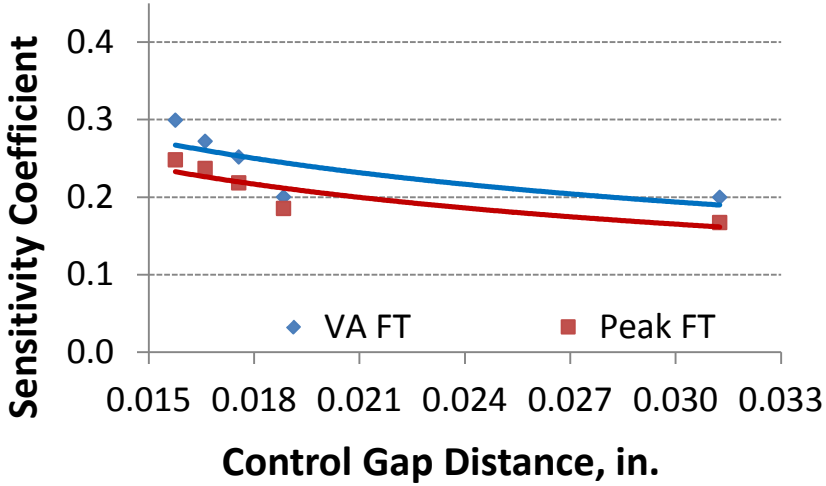
EPFD	Control gap distance (in)	Fuel heat rate (w/cm^3)	Fast fluence (n/m^{2}10^{25})	Neon fraction	Average fuel (°C)	Peak fuel (°C)
40	0.01576	65.01	0.23391	0.690	1,082	1,207
180	0.01661	93.32	1.02364	0.477	1,153	1,281
329	0.01757	117.50	1.91886	0.274	1,207	1,350
545	0.01884	67.46	3.10006	0.936	1,212	1,304

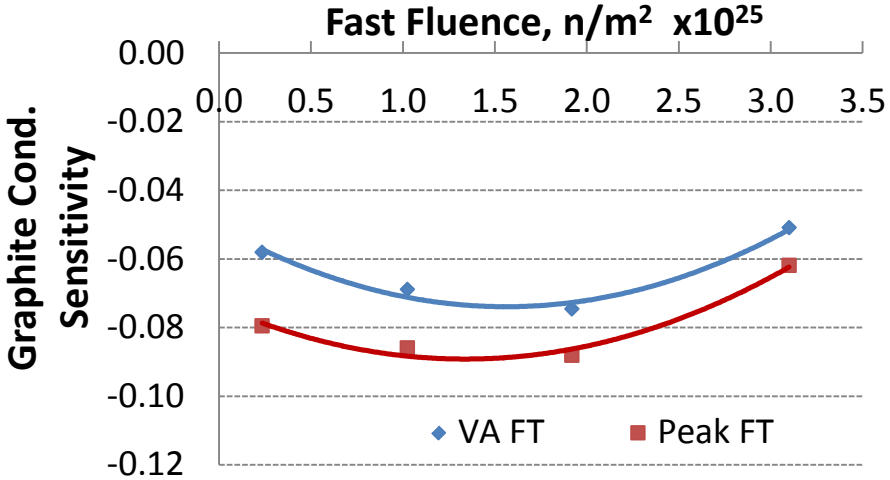
51 runs of the ABAQUS code for one thermal condition: a baseline run for nominal inputs, 10 runs for separate input variation of ±10% to estimate main effects, and 40 runs for variation of input pairs to assess their interactions.

Sensitivity Variation





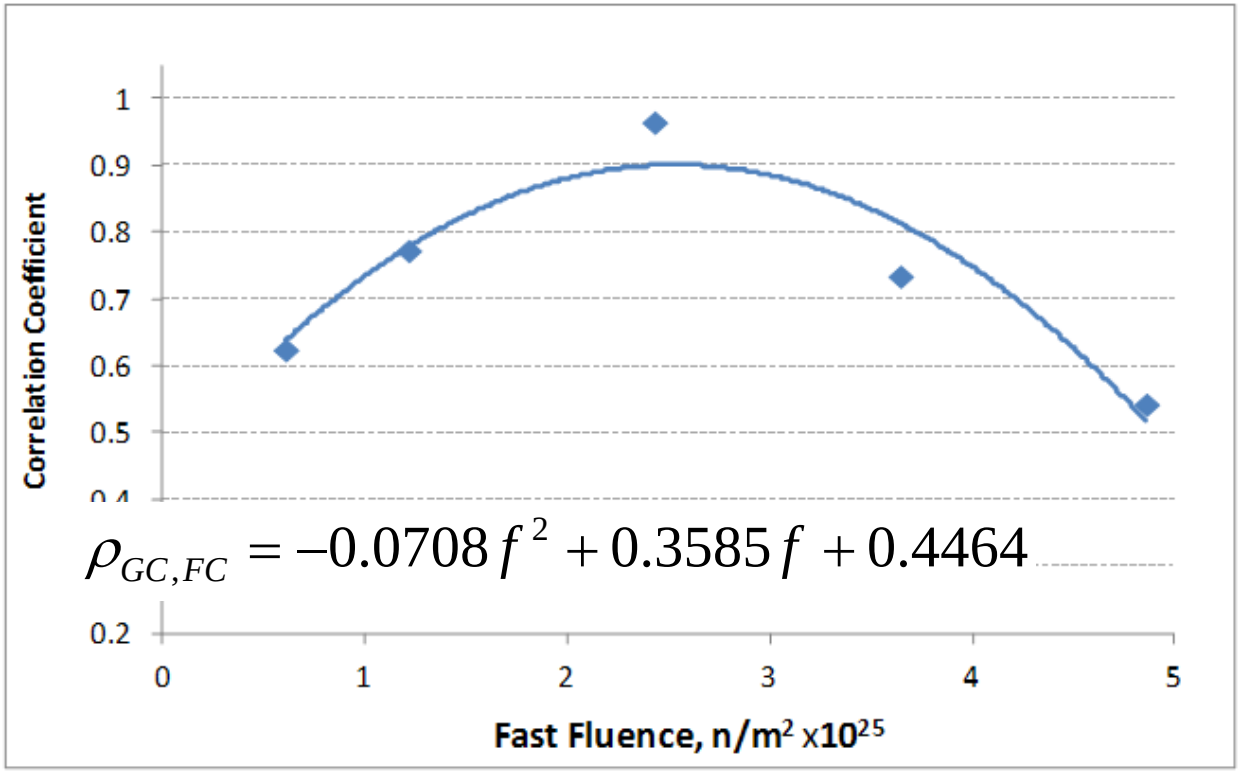




Sensitivities for peak and average (VA) fuel temperatures as function of input.

Correlation Coefficients

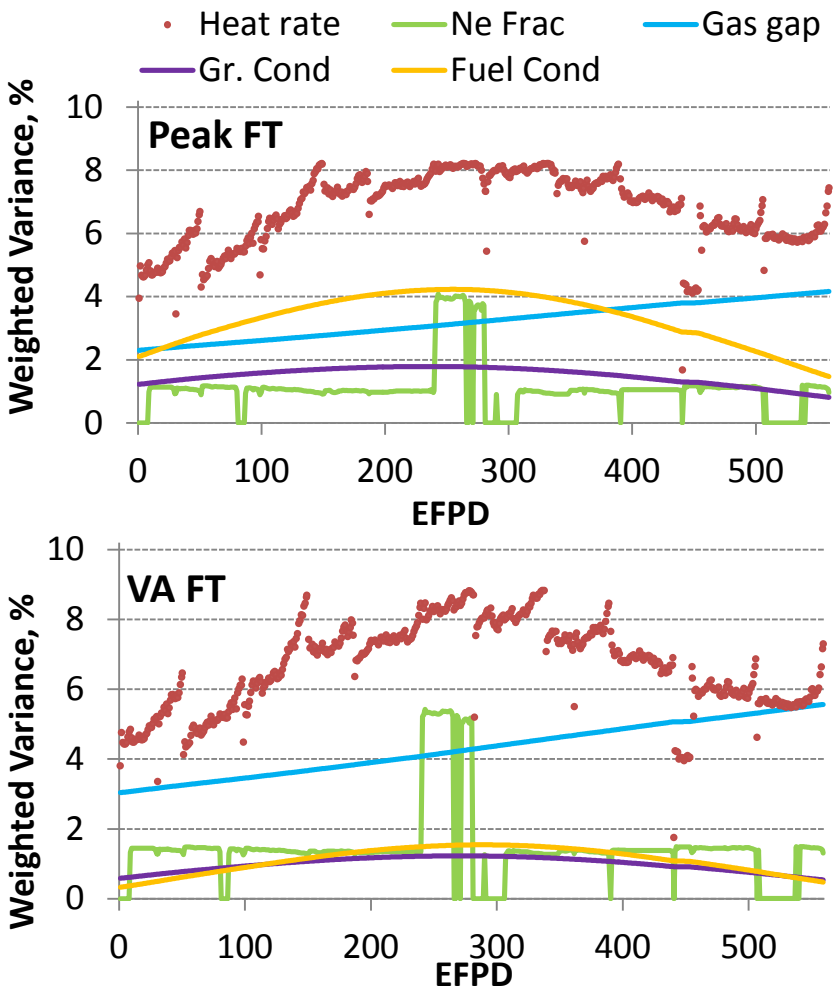
- Between independently measured inputs (e.g., neon fraction and gas gap) is assumed negligible
- Between calculated values such as fuel and graphite conductivities, correlations are estimated using simulation and expressed as function of fluence (f)



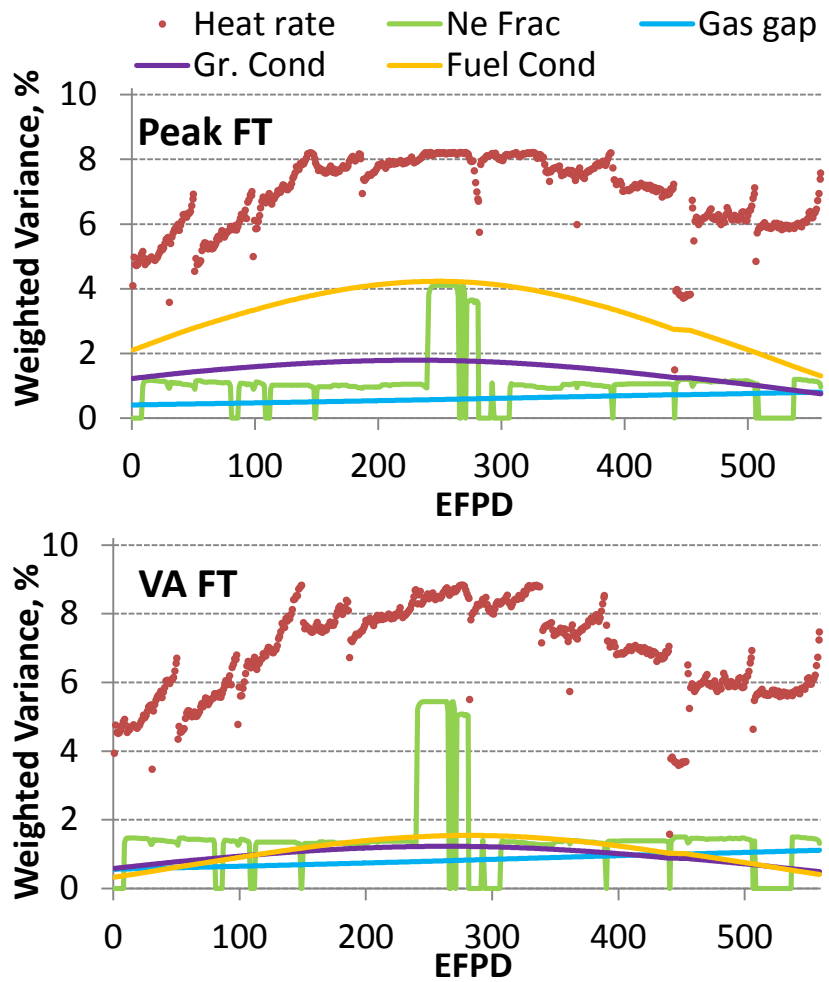
$$\rho_{GC,FC} = -0.0708 f^2 + 0.3585 f + 0.4464$$

Results – Dominant Factors

Capsule 5 – small gap

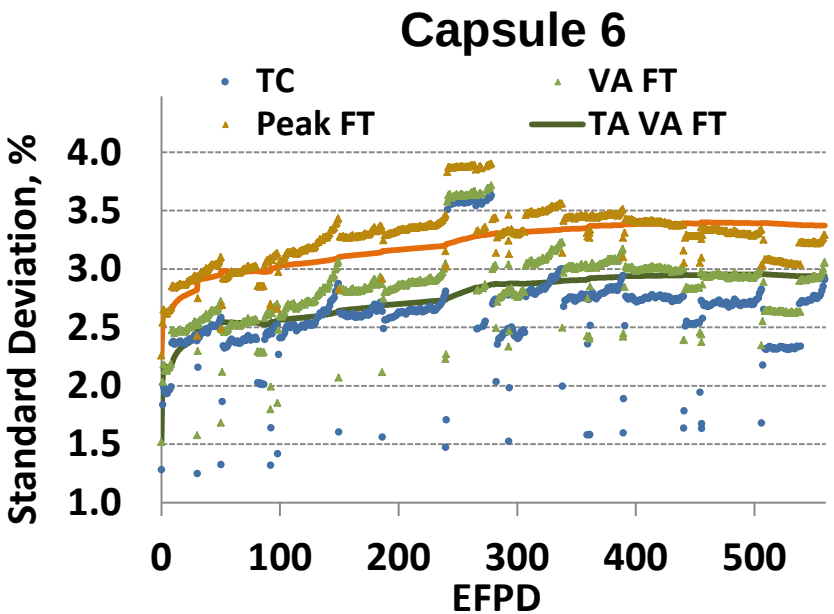


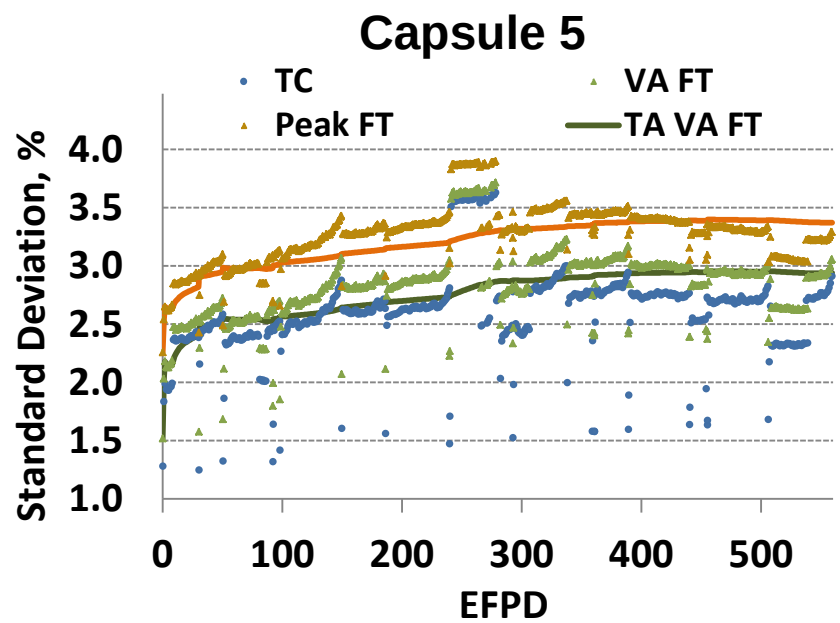
Capsule 2 – big gap

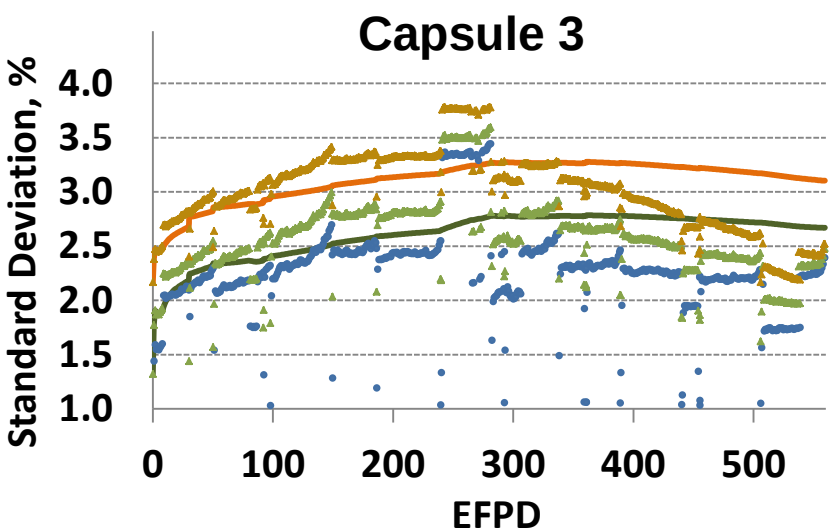


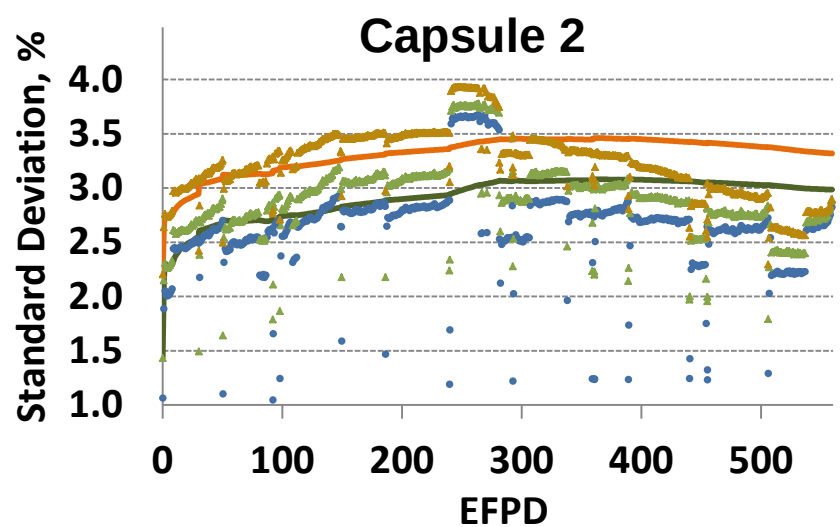
Daily weighted temperature variances due to input uncertainties

Overall Uncertainty – Relative Standard Deviation

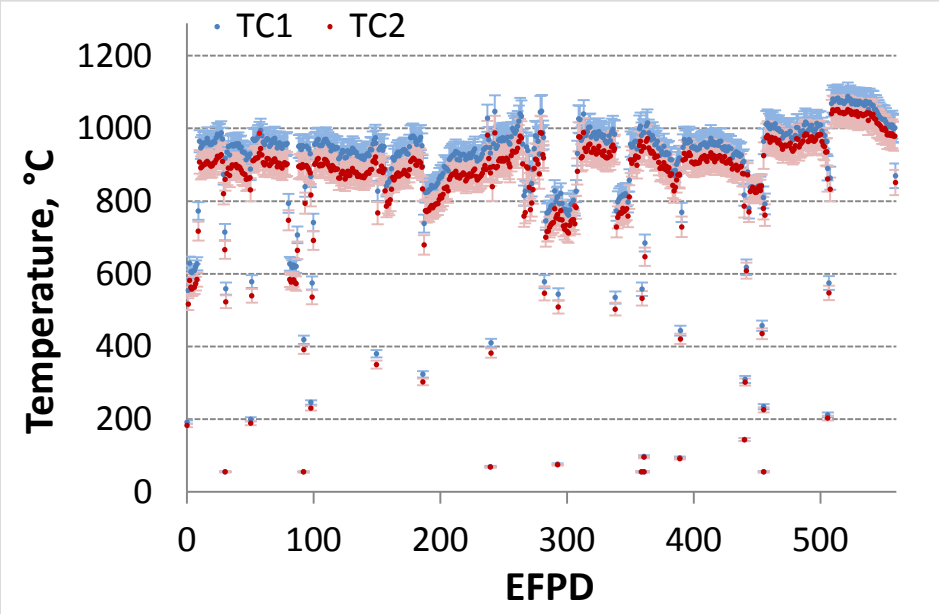


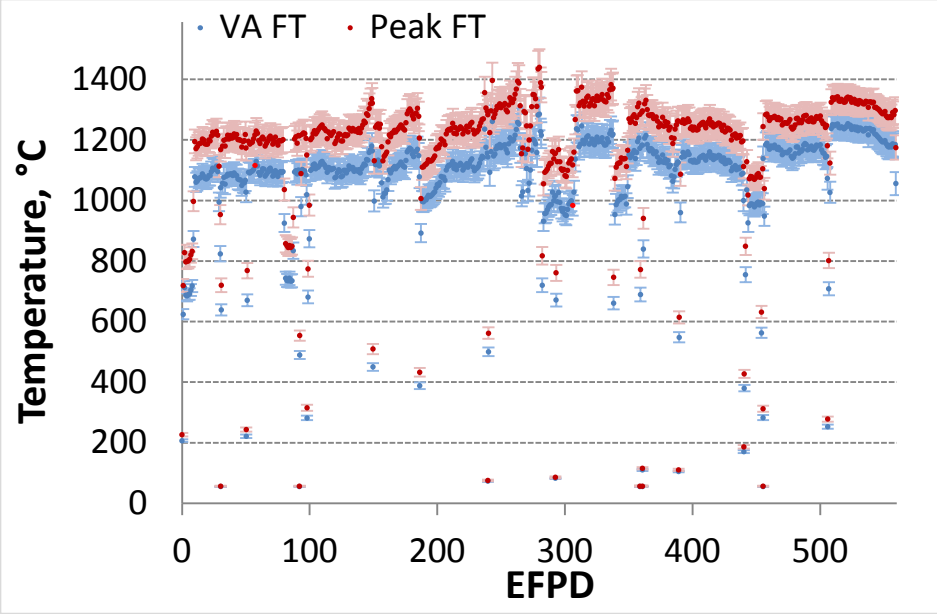




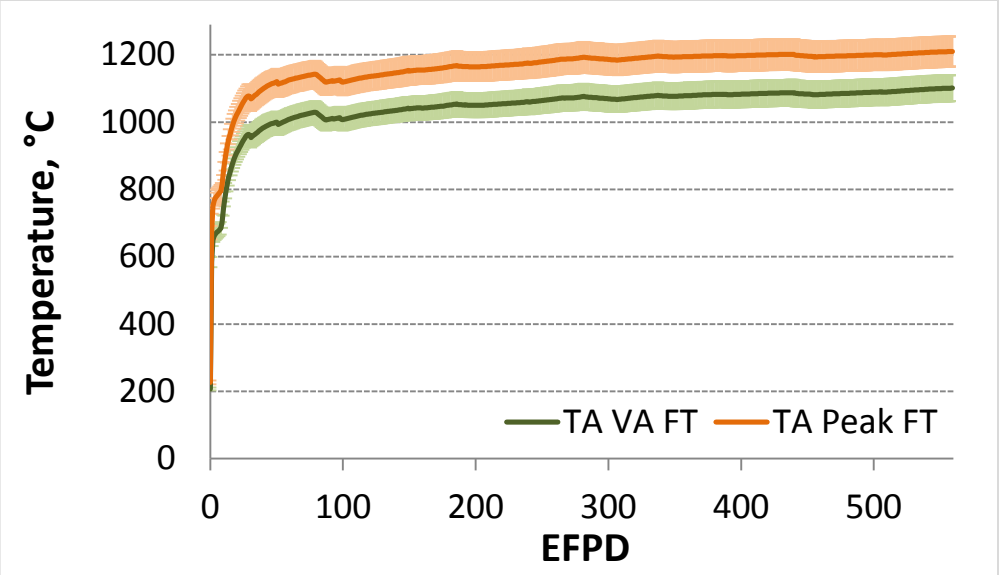


Overall Uncertainty - Absolute Temperature





Capsule 5



Summary of AGR-2 Temperature Uncertainty

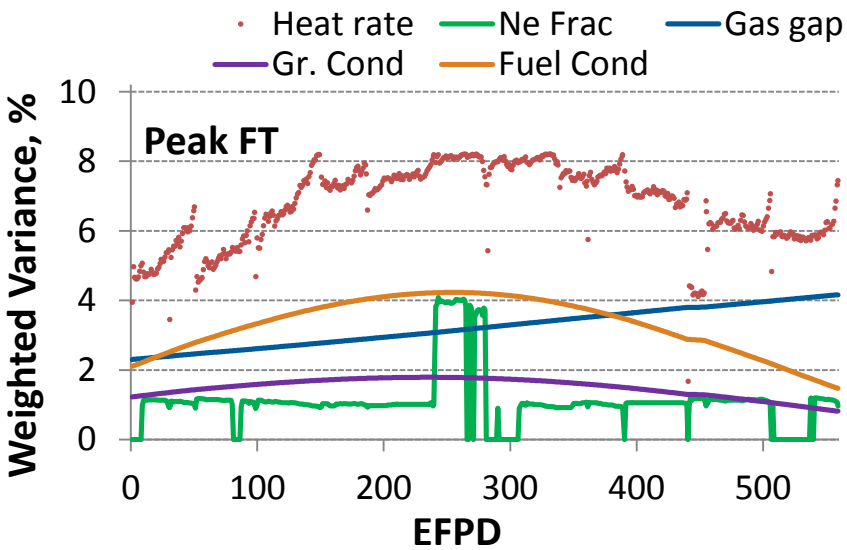
- Quantification considered all potential sources of uncertainty

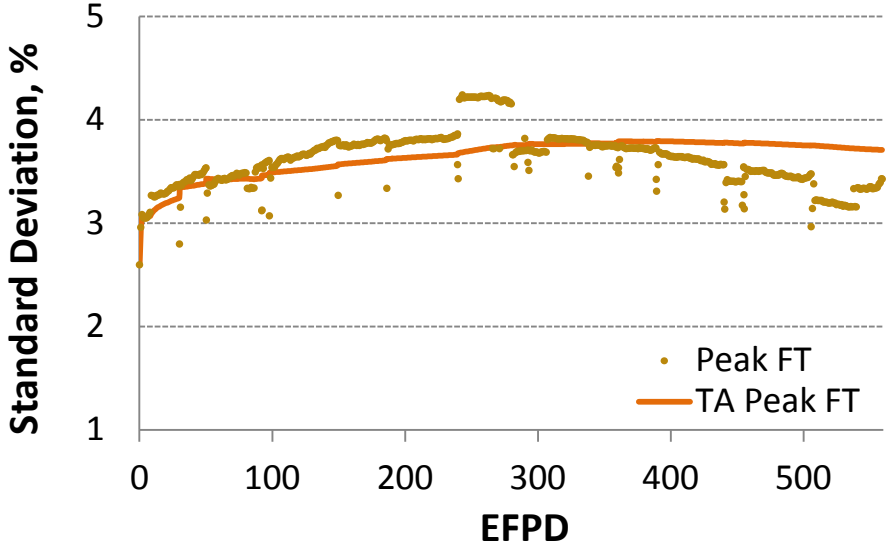
- Dominant factors contributing to overall uncertainty
  - Fuel heat rate uncertainty (5%) for fuel temperatures in all capsules and TC temperatures in Capsules 2, 3, and 6
  - Control gas gap for TCs in Capsule 5

- Overall uncertainty results of the AGR-2 calculated temperatures
  - Daily TC temperatures – 2.1% to 4.5% (17°C to 46°C)
  - Daily fuel VA temperatures – 2.2% to 4.2% (21°C to 54°C)
  - Daily fuel peak temperatures – 2.7% to 4.2% (27°C to 62°C)
  - TA VA temperatures at end – 2.7% to 3.5% (28°C to 39°C)
  - TA peak temperatures at end – 3.1% to 3.7% (34°C to 45°C)

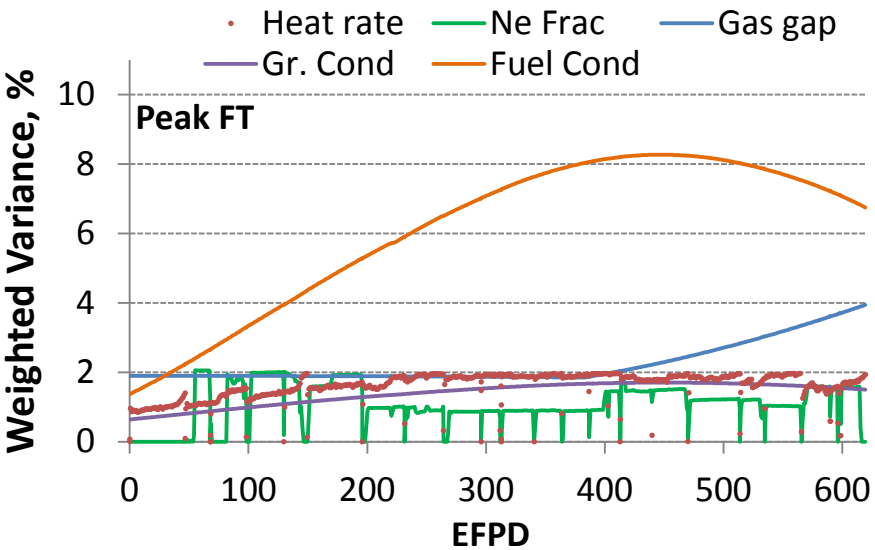
AGR-1 and AGR-2 Peak Fuel Uncertainty

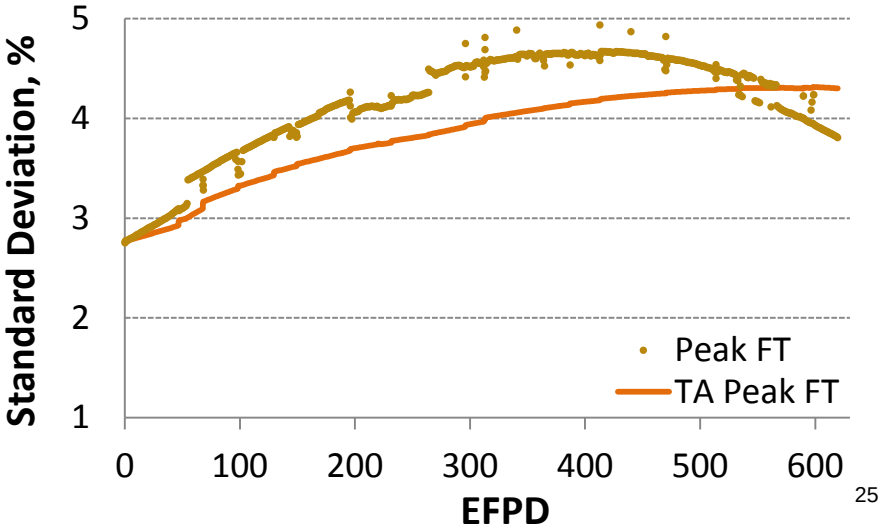
AGR-2 Capsule 5 – 5% heat rate





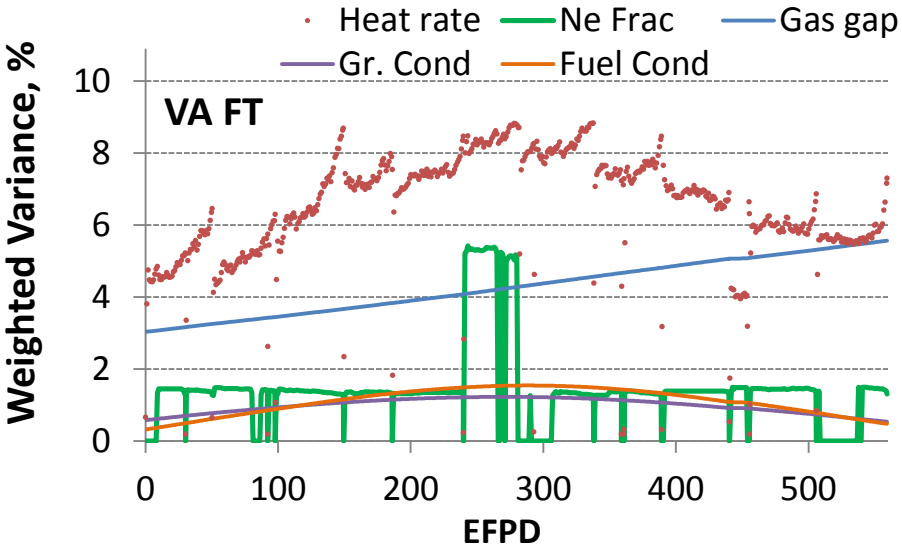
AGR-1 Capsule 5 – 2.5% heat rate



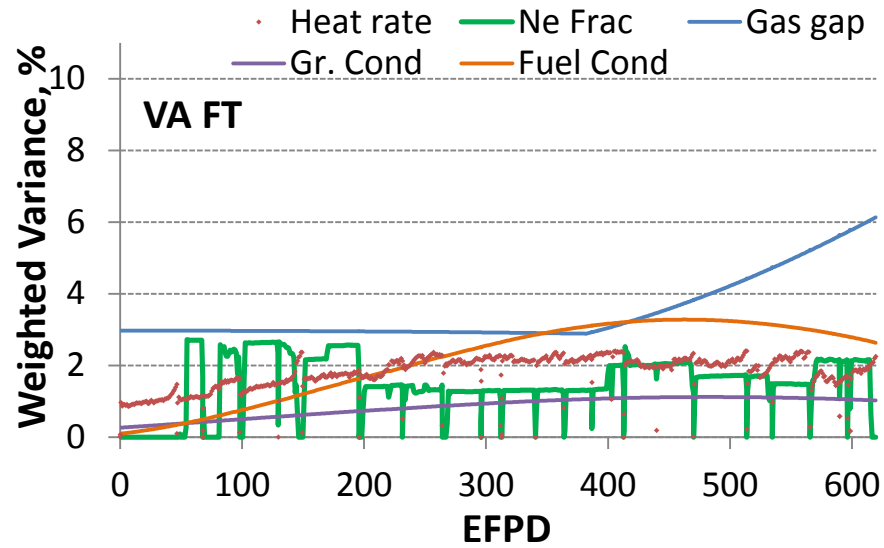


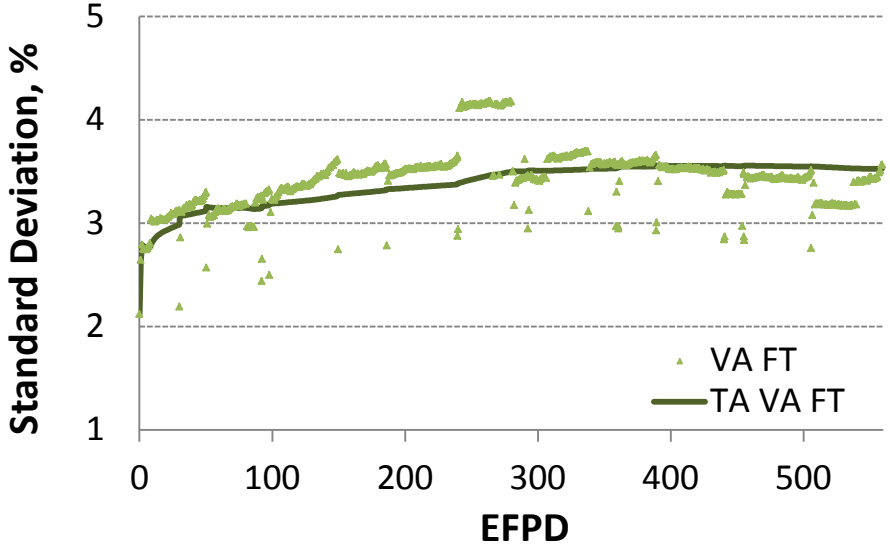
AGR-1 and AGR-2 VA Fuel Uncertainty

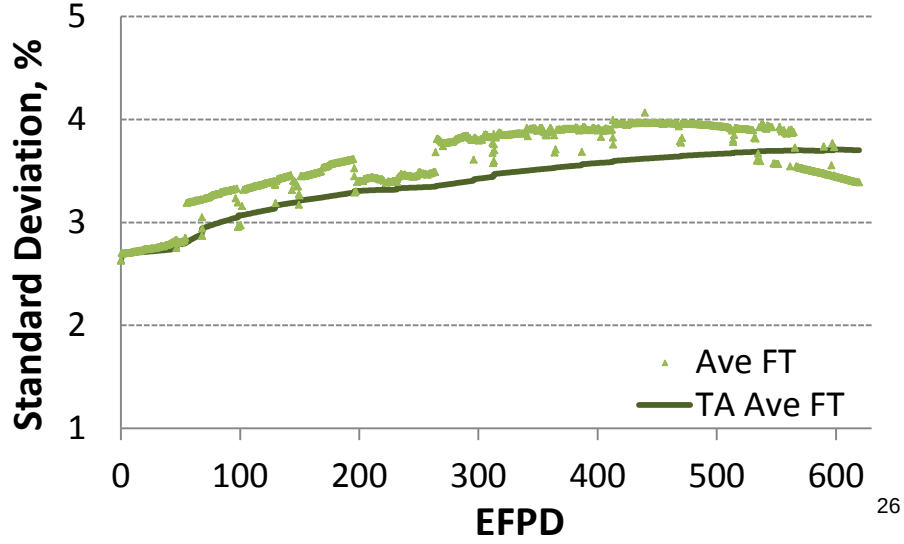
AGR-2 Capsule 5



AGR-1 Capsule 5





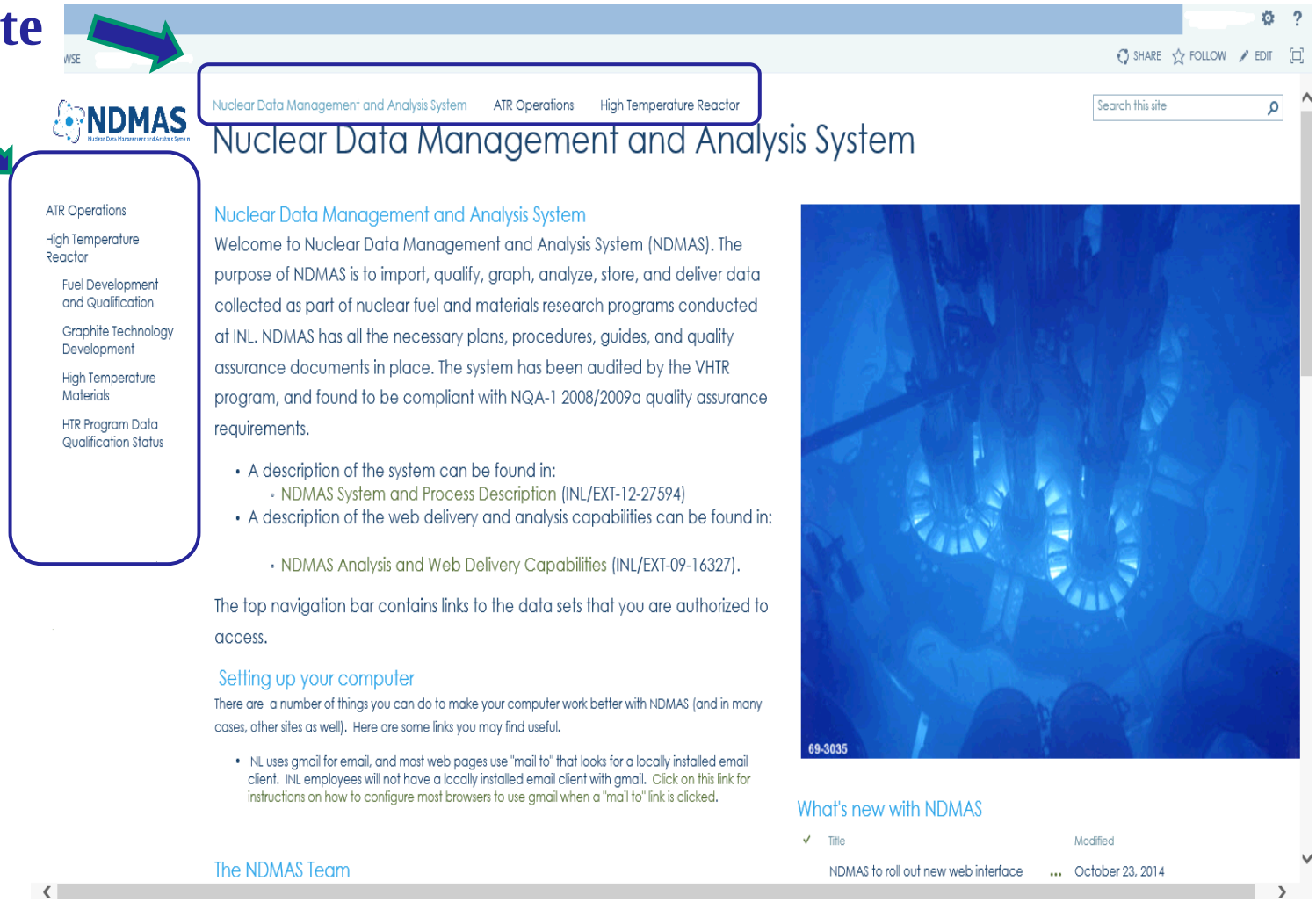


AGR-1 and AGR-2 Comparison

Temperature	AGR-2	AGR-1
Different factors		
– Heat rate – Sensitivity of fuel conductivity	– 5% in all capsules – up to -0.10	– 2.5% in all capsules and 10% bias in Capsule 6 – up to -0.15
Overall uncertainty results		
Daily TC	2.1% to 4.5% (17°C to 46°C)	2.0% to 6.5% (10°C to 78°C)
Daily fuel VA	2.2% to 4.2% (21°C to 54°C)	2.0% to 5.8% (12°C to 74°C)
Daily fuel peak	2.7% to 4.2% (27°C to 62°C)	2.2% to 5.5% (15°C to 79°C)
TA VA at end	2.7% to 3.5% (28°C to 39°C)	3.2% to 5.0% (33°C to 55°C)
TA peak at end	3.1% to 3.7% (34°C to 45°C)	3.8% to 5.0% (45°C to 60°C)

NDMAS SharePoint Site Now Available

Navigate to data



Fuel Development and Qualification

Fuel Development and Qualification
- Fuel Fabrication
- Fuel Irradiation
- Fuel Post-Irradiation Examination
- Technical Coordination Team
- AGR Data Qualification Status

Graphite Technology Development

High Temperature Materials

HTR Program Data Qualification Status

TRISO Fuel Development and Qualification Program

Tristructural isotropic (TRISO) fuel development and qualification R&D consists of seven experiments that will be assembled, irradiated, examined, and tested to provide a baseline fuel form qualification data set to support the licensing and operation of the Advanced Reactor Technologies (ART) high temperature gas-cooled reactor (HTGR).

- The first experiment, (Advanced Gas Reactor [AGR]-1) using laboratory-scale produced uranium oxycarbide (UCO) fuel, was inserted into the instrumented test train and irradiated in the ATR at INL from December 2006 through November 2009. In FY-15, AGR-1 is completing post-irradiation examination (PIE) and safety testing in the MFC Hot Fuel Examination Facility (HFEF) main cell, Analytical Laboratory, and Electron Microscopy Laboratory, as well as at ORNL.
- The second experiment, AGR-2, using large-scale coater produced UCO and uranium dioxide (UO2) fuel from the United States (U.S.) and UO2 fuel from France and South Africa, was inserted into an instrumented test train and irradiated from June 2010 through October 2013. PIE and safety testing began in FY-14 and will continue for several years at INL and ORNL.
- The third and fourth experiments, AGR-3/4, were combined into a single instrumented test train in an effort to save money and reduce the overall program schedule. These two experiments were irradiated in ATR from December 2011 through April 2014, and are being sized in preparation for shipment to MFC for PIE. These experiments contained "designed-to-fail" (DTF) fuel particles in compacts that will be used to measure fission product transport data and perform qualification of source terms.
- The fifth, sixth, and seventh experiments, AGR-5/6/7, will also be combined into a single instrumented test train and are expected to begin irradiation in FY-17. These experiments will contain UCO fuel fabricated by a United States-based commercial vendor using production-scale equipment and will be used

Data Plots and Links to Download Data

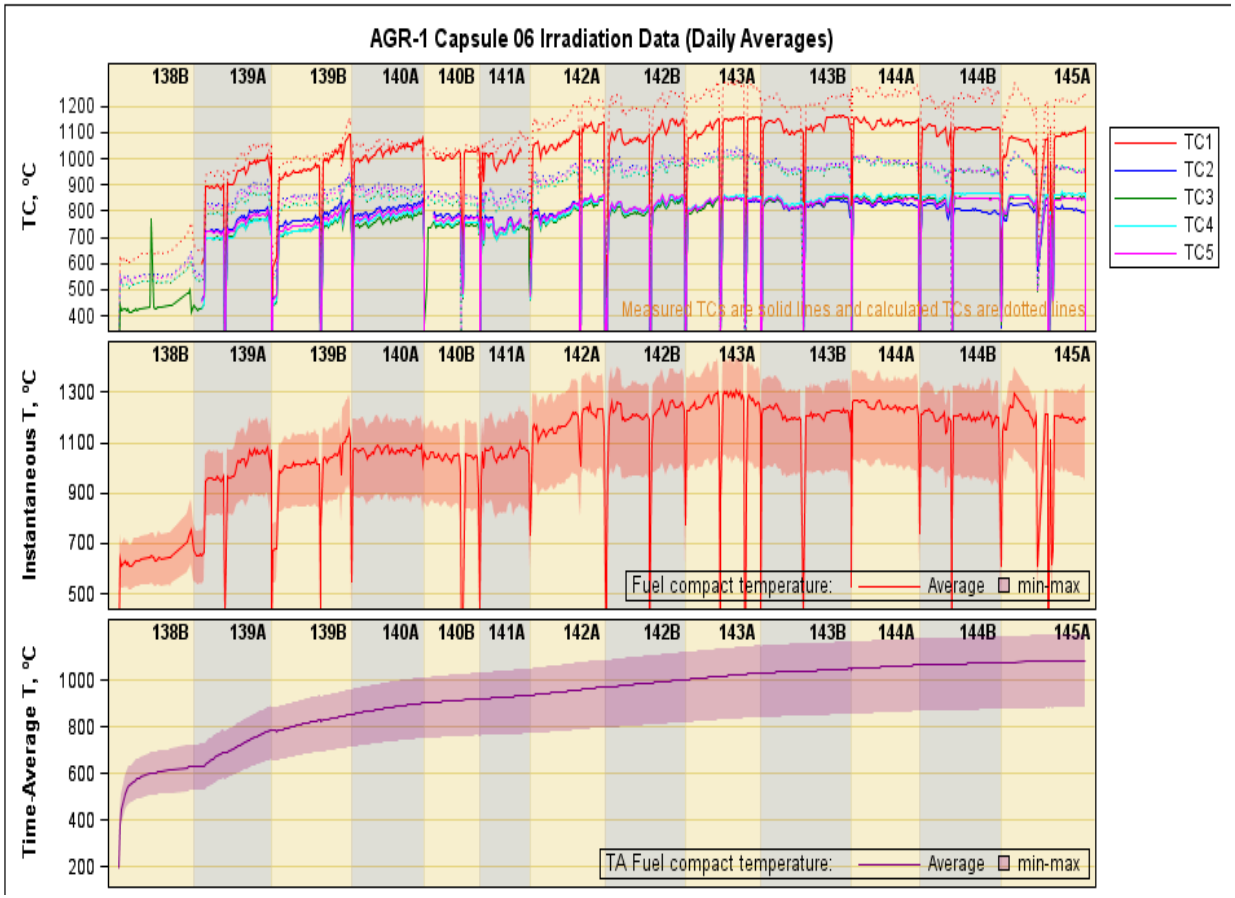
Graphical Summary Plots and Daily Data

Summary Data:

- Capsule 06
- Capsule 05
- Capsule 04
- Capsule 03
- Capsule 02
- Capsule 01

Download Irradiation Data for AGR-1 Capsule 06 (Daily Averages)

Download Physics Data for AGR-1 Capsule 06 (Daily Averages)



Web Page Access

- Address
  - https://htgr.inl.gov/
- NDMAS web page can be accessed from within INL firewall with Windows user name and password (single sign-on)
- For instructions on getting a collaboration portal account contact:
  - Nancy Lybeck, nancy.lybeck@inl.gov, 208-526-1033
  - Larry Hull, laurence.hull@inl.gov, 208-526-1922

Acknowledgements

- Binh Pham, INL – uncertainty analysis
- Grant Hawkes, INL – sensitivity analysis

Questions?

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