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NDMAS

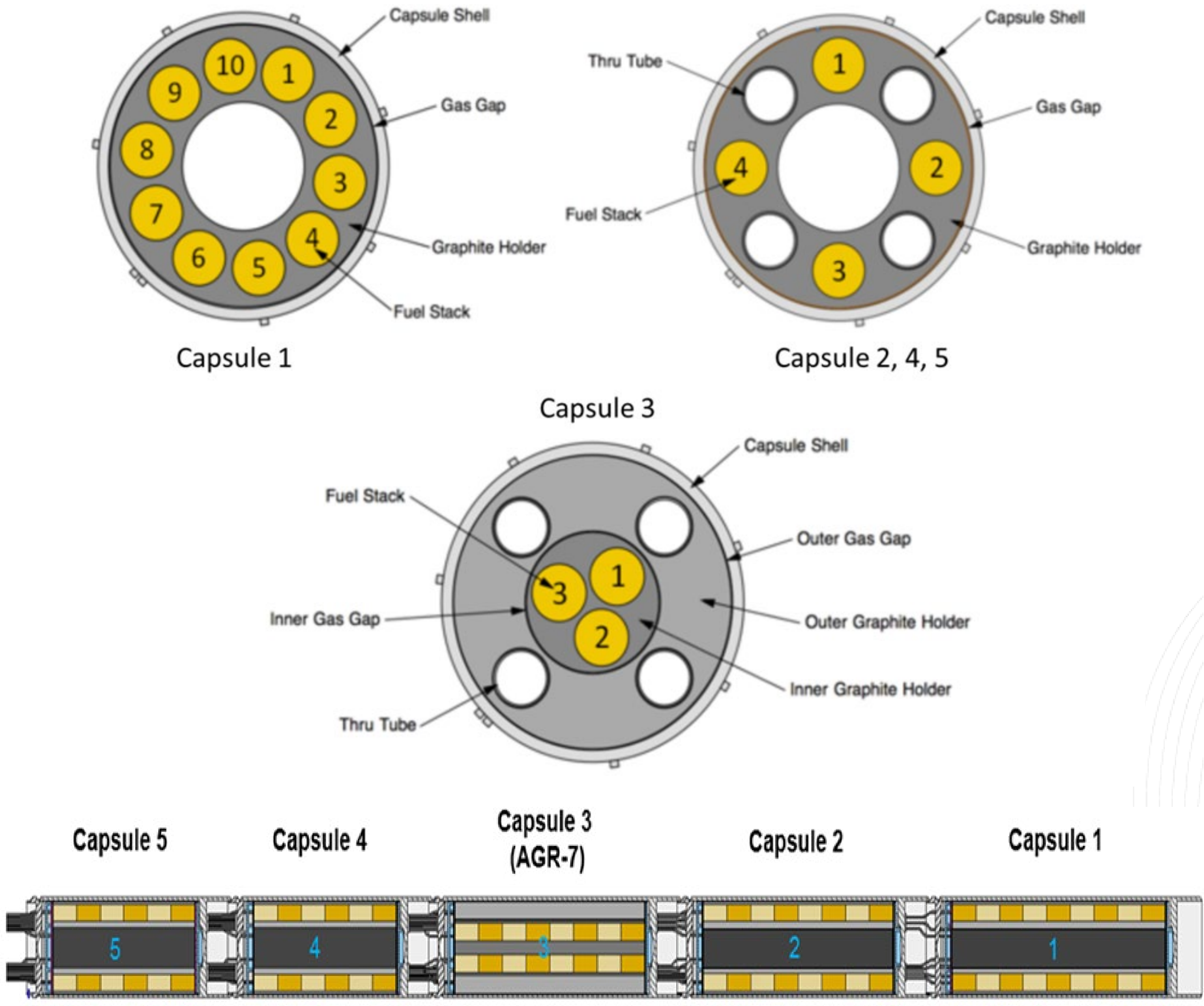
Uncertainty Quantification of Calculated Fuel Temperature for the AGR-5/6/7 Irradiation Experiment

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

AGR-5/6/7 Fuel Irradiation Experiment

- AGR-5/6/7 test train:
  - Five capsules; three different designs
  - 54 thermocouples installed (6 operational at EOI)
  - Irradiated in the ATR Northeast flux trap for 360.9 EFPDs (9 cycles)

	N# of Compacts (levels/stacks)	Number of TCs (installed/failed)	Target Temperature Range (°C)
Capsule 5	24 (6/4)	6/3	<900
Capsule 4	24 (6/4)	6/3	900 – 1050
Capsule 3	24 (8/3)	17/17	1350 – 1500
Capsule 2	32 (8/4)	8/8	900 – 1050
Capsule 1	90 (9/10)	17/17	900 - 1350

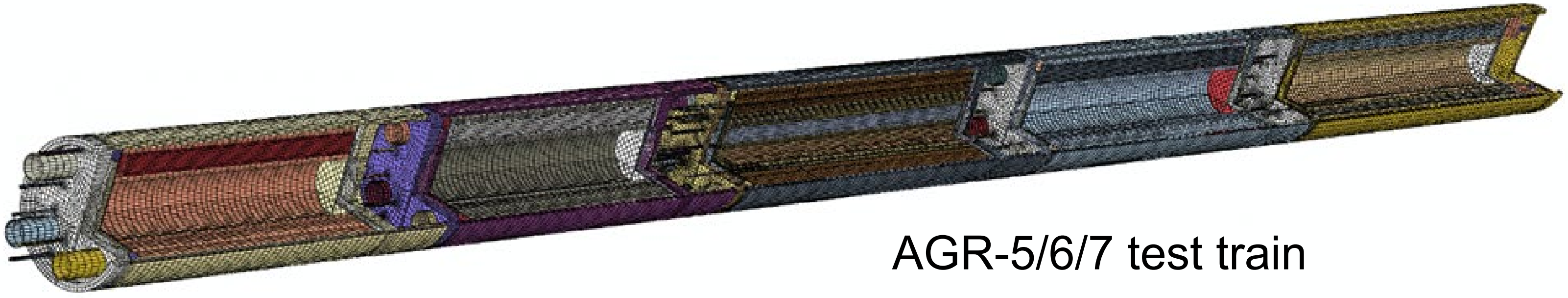


ABAQUS Thermal Model

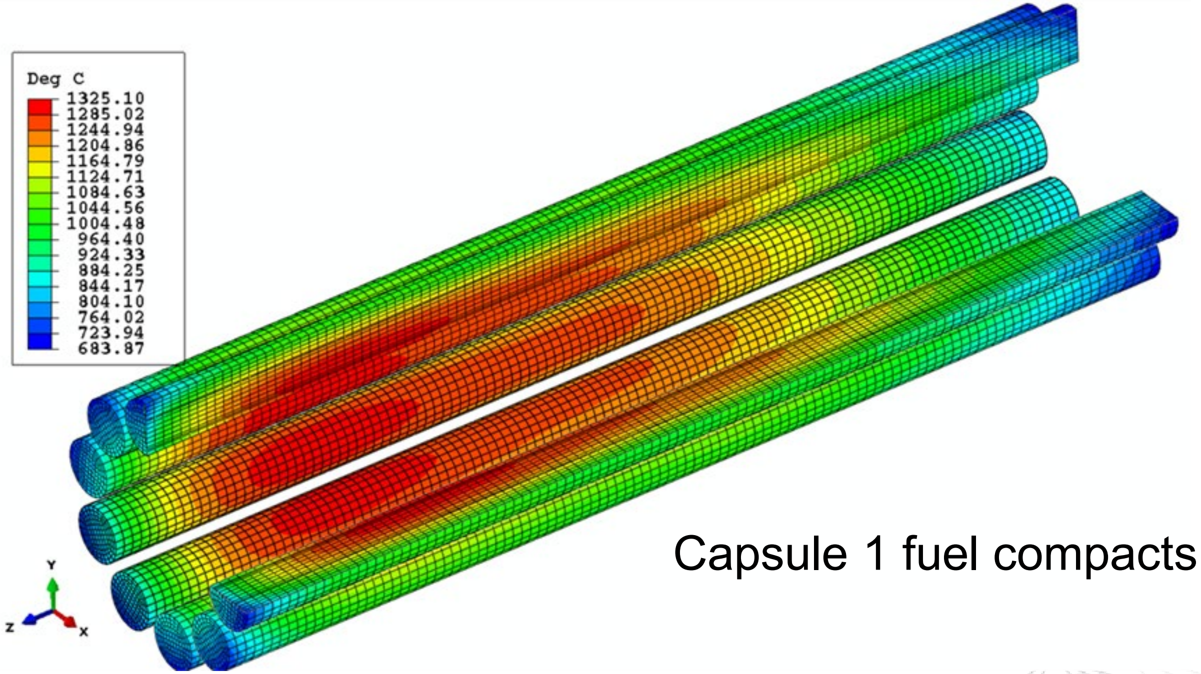
ABAQUS-based 3-D finite-element (1.2E6 elements) thermal model using equations for steady-state heat transfer by conduction and radiation.

Main Inputs:

- Heat rate
- Neon/Helium fraction
- Gas gap size
- Thermal conductivity
- Emissivity



AGR-5/6/7 test train

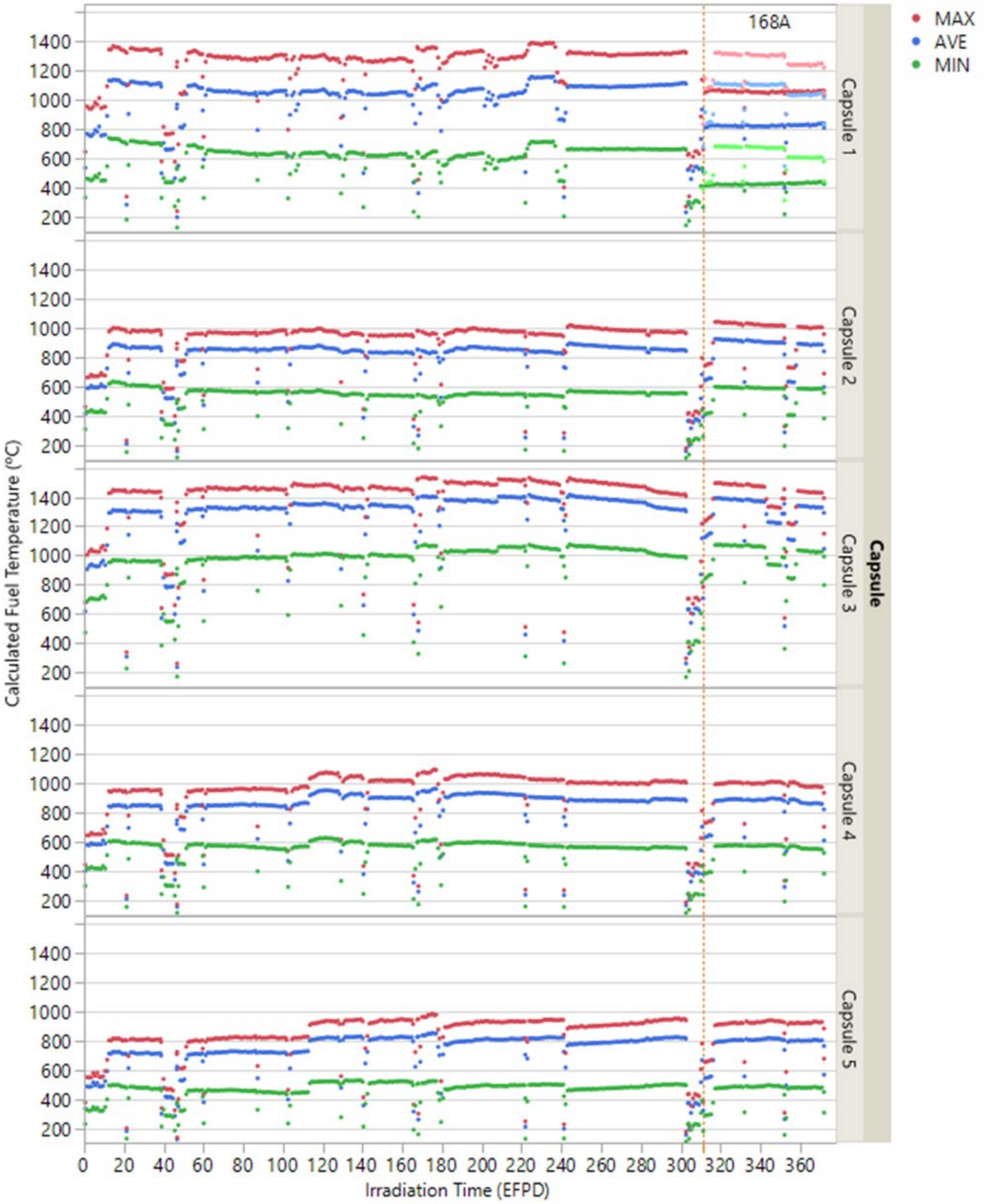


Capsule 1 fuel compacts

Outputs: Daily fuel and TC temperatures

Daily Calculated Temperatures

- For each capsule and each time step (day):
  - Instantaneous volume-average, min, and max (peak) fuel temperatures are calculated from temperatures of the fuel compact elements
  - Temperatures at TC locations
- Time-average, volume-average, min, and max temperatures are weighted averages of instantaneous temperatures by the length of at-power days
- Uncertainty is calculated for both instantaneous and time-average volume-average and peak fuel temperatures, and TC temperatures



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Calculated Temperature Uncertainty

$$\sigma_T^2 = \cancel{\sigma_M^2} + \sigma_P^2$$

σ_M^2 - Model form uncertainty

σ_P^2 - Uncertainty due to input parameter uncertainties

- **Model form uncertainty** --- not estimated in this analysis
  - Effects of choices made in the modeling process
    - definition of the geometry, equations, computational methods, …
  - Magnitude difficult to assess without developing additional models
- **Parameter uncertainty** - incomplete knowledge of the correct values of model inputs

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

σ_i - uncertainty of input parameter *i*

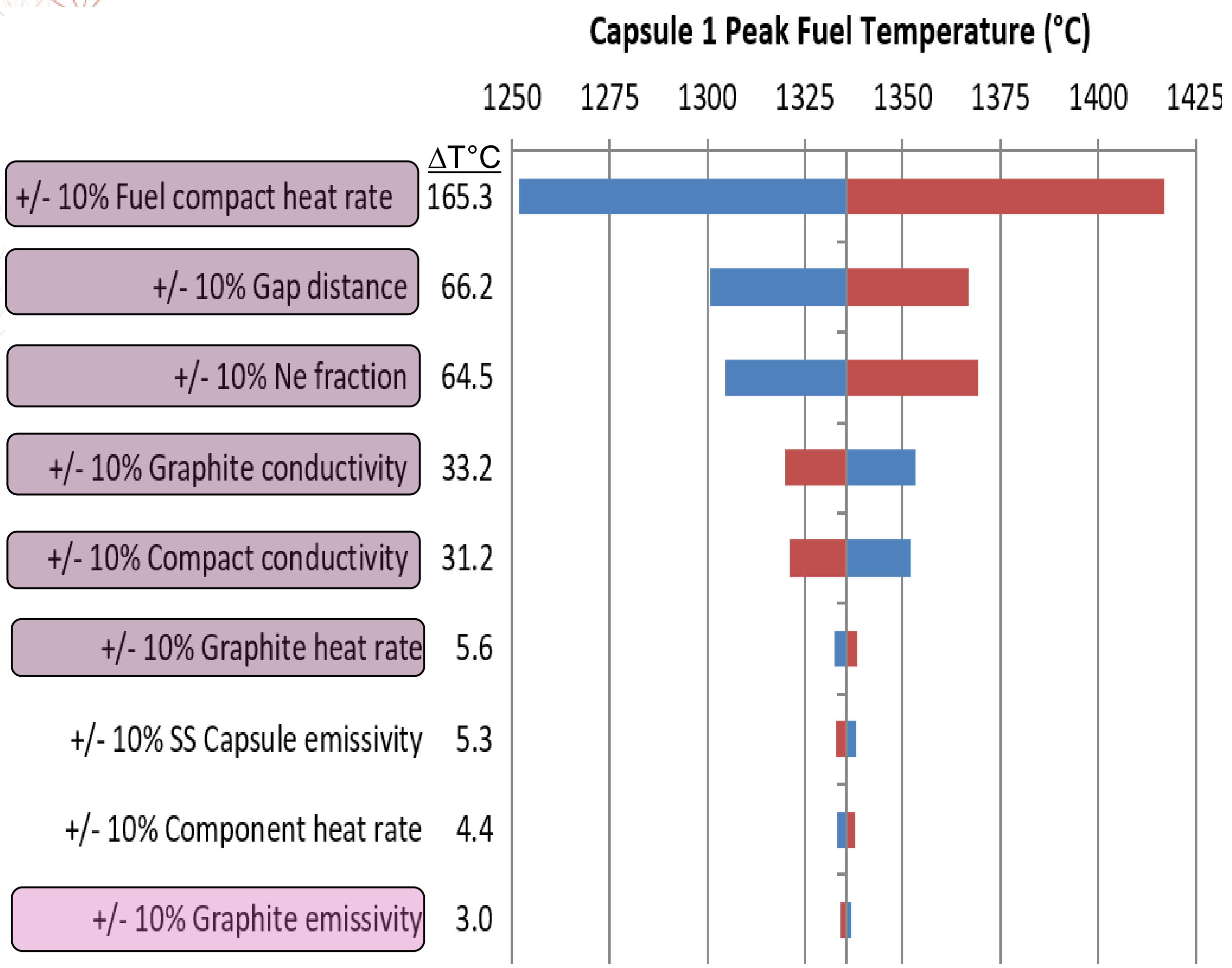
a_i - sensitivity coefficient for parameter *i*

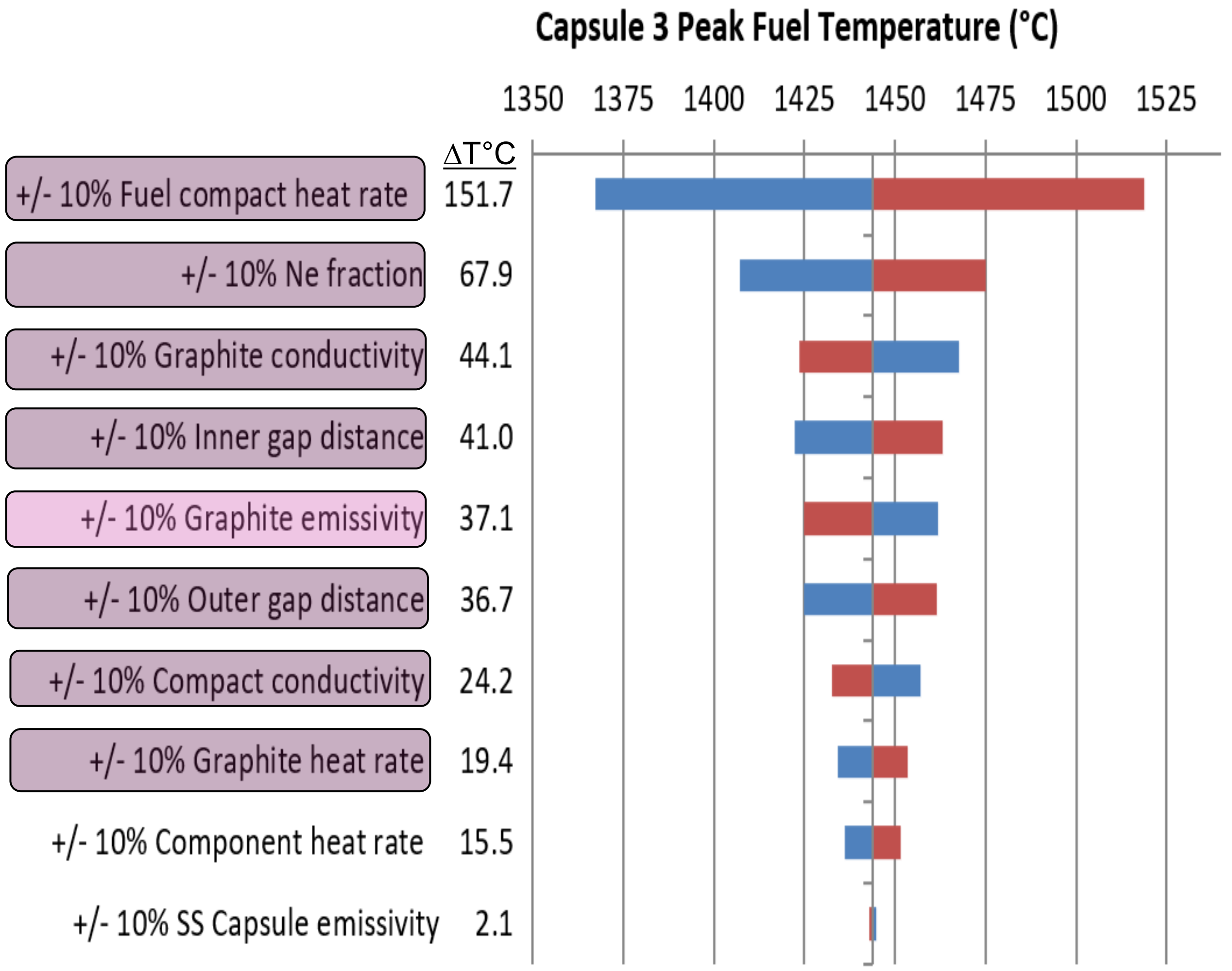
ρ_{ij} - correlation coefficient for input parameters *i* and *j*

Uncertainty Analysis

- Identify model inputs and quantify their uncertainties
- Calculate sensitivity to each input
- Select inputs to vary based on both uncertainty and sensitivity
- Calculate covariance between inputs
- Calculate overall uncertainty for temperatures of interest

Input Sensitivities – Capsule 1 & 3

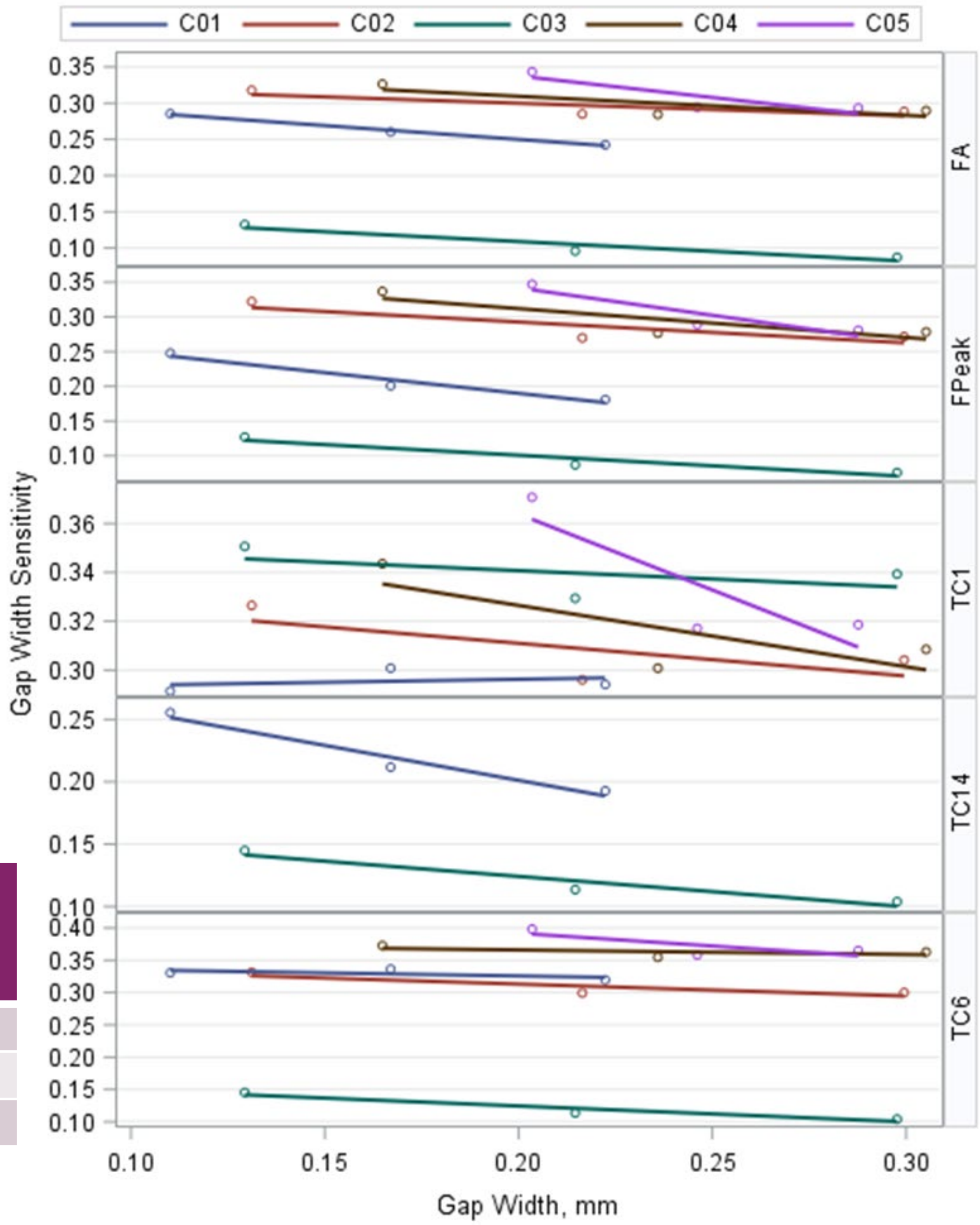




Sensitivity Functions

- For each capsule, run thermal model with ±10% variation of each of selected inputs, with all possible pairs, for three selected time-steps
- For each capsule and each time-step, calculate sensitivity coefficient for each temperature of interest
- Establish linear sensitivity functions from the three sensitivities
- For each time-step, sensitivity coefficient is calculated from the sensitivity function for that parameter

ATR Cycle	EFPD	Neon Fraction	Fluence, $10^{25}n/m^2$	Fuel Heat Rate, w/cm^3	Graphite Heat Rate, w/cm^3	Gas Gap, mm
162B	20	0.87	0.15	115.3	4.1	0.274
164B	162	0.64	1.33	109.8	4.6	0.327
166A	300	0.90	2.55	98.4	4.7	0.383

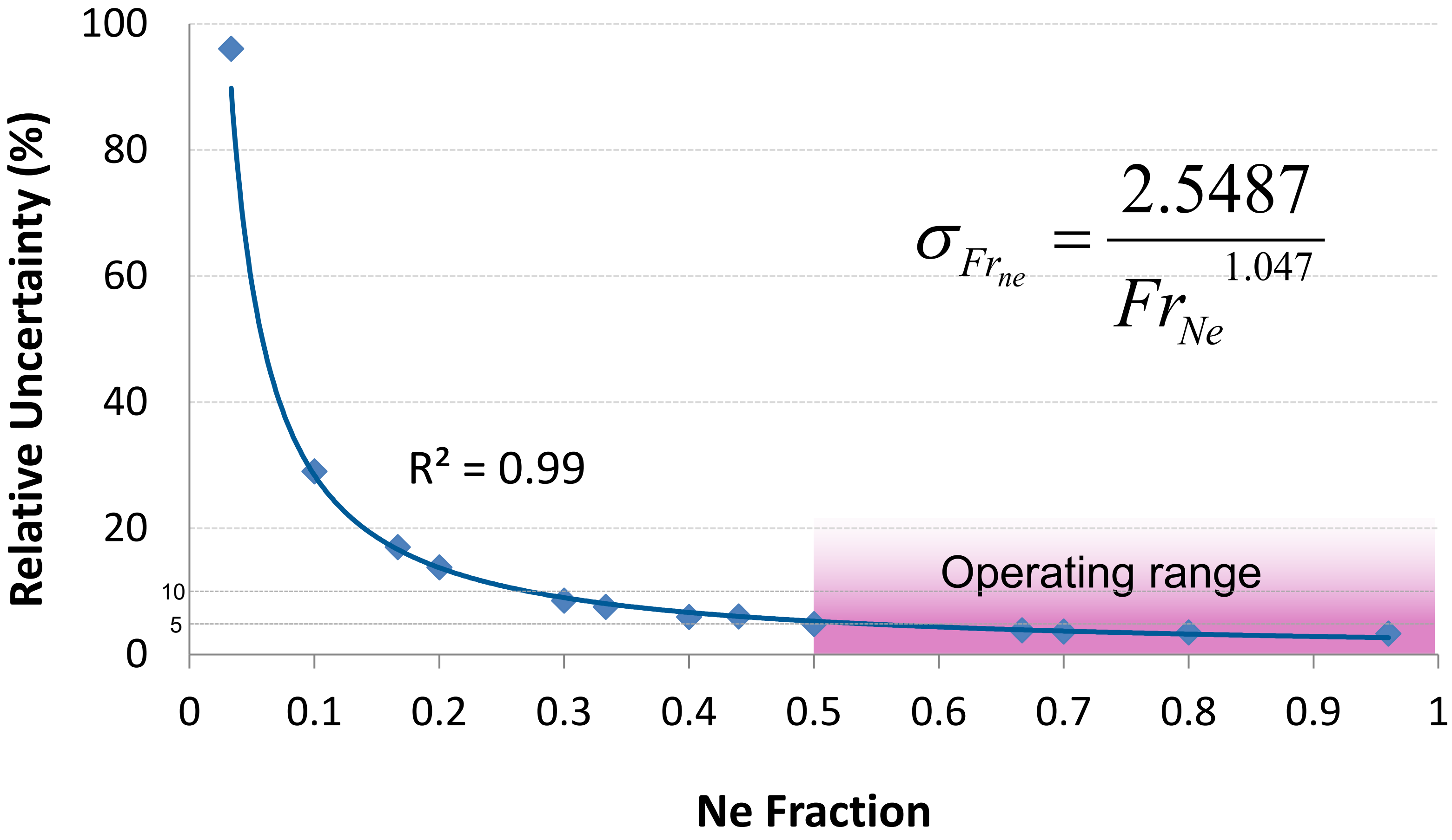


Uncertainties of Selected Parameters

Parameter	Uncertainty	Justifications
Gas gaps	24% – 40%	• Dimensional fabrication tolerance of 0.0254 -mm • 20% uncertainty of thermal expansion coefficient results • 0.127 mm clearance between the holder nubs and capsule shell • Graphite material shrinkage uncertainty.
Ne fraction	3% – 5%	Uncertainty is based on the 1-sccm flow rate uncertainty
Fuel heat rate	5%	Based on the AGR-1 comparison by J. Harp, with additional input from J. Sterbentz.
Graphite heat rate	3%	
Graphite conductivity	15%	Additional conductivity data for the graphite allows for a lower uncertainty for graphite than for fuel.
Fuel conductivity	20%	Uncertainty is based on work done on surrogate compacts by C. Folsom at Utah State University.
Graphite Emissivity	10%	The emissivity, 0.9, used falls within the expected range [0.8 – 1.0].

Uncertainty of Neon Fraction

Due to 1-sccm uncertainty in Ne & He flow rates:



Gap Size Uncertainties

Uncertainty at start of irradiation (SOI):

$$\sigma_{SOI} = \sqrt{\sigma_{fab}^2 + \sigma_{exp}^2 + \sigma_{offset}^2}$$

σ_{fab}= 0.0254 mm σ_{exp}= 0.006 mm

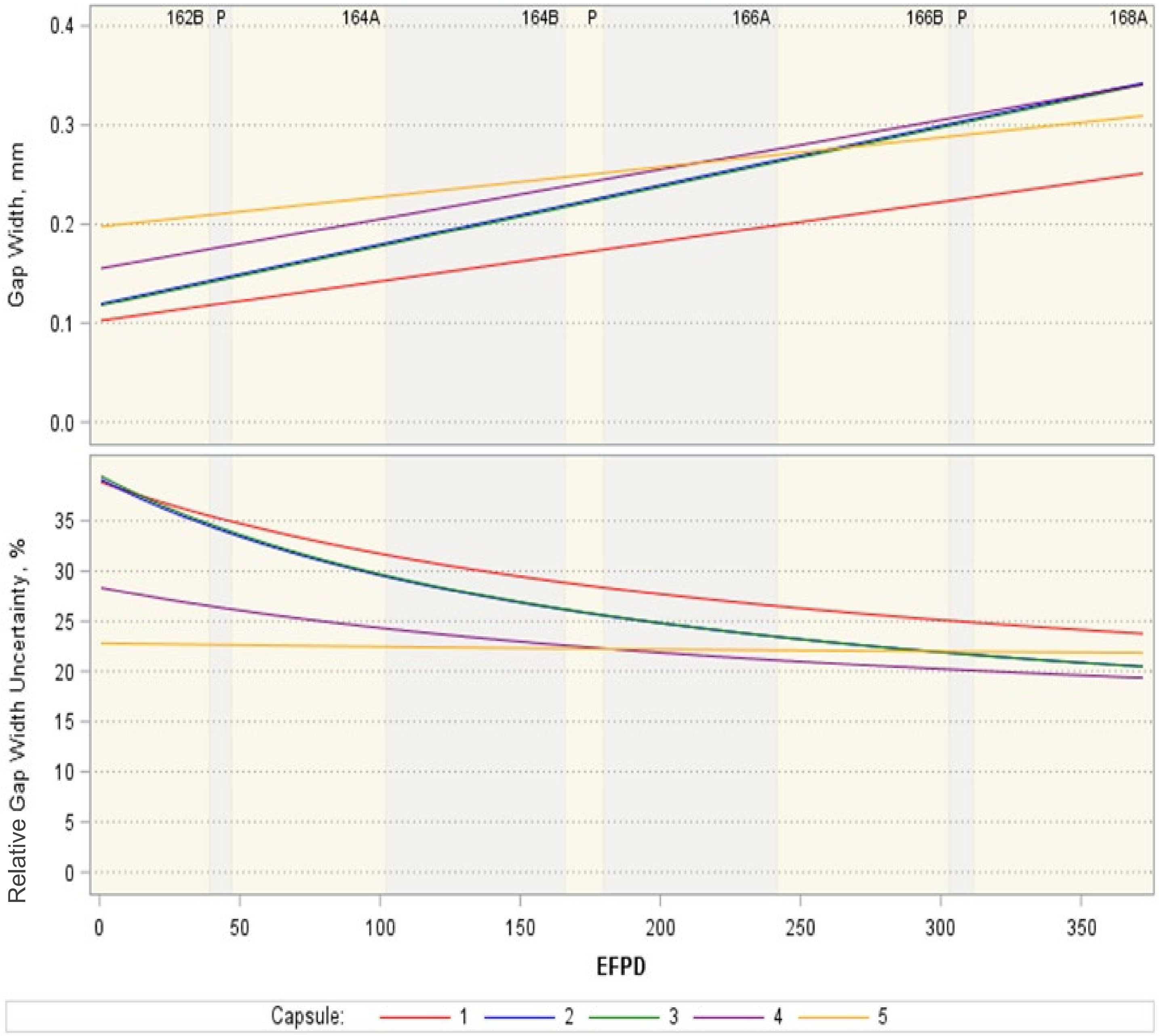
Uncertainty due to nub-to-shell clearance

$t_{offset} = 0.127\ mm$

$$\sigma_{offset} = \frac{\left[t_{offset} - \left(gap_{fab} - gap_{hot}\right)\right]}{\sqrt{3}}$$

Uncertainty at time *i* during Irradiation

$$\sigma_{GGi} = \sigma_{SOI} + 0.5 * \sigma_{SOI} * \frac{EFPD_i}{EFPD_{EOI}}$$



ADVANCED REACTOR TECHNOLOGIES

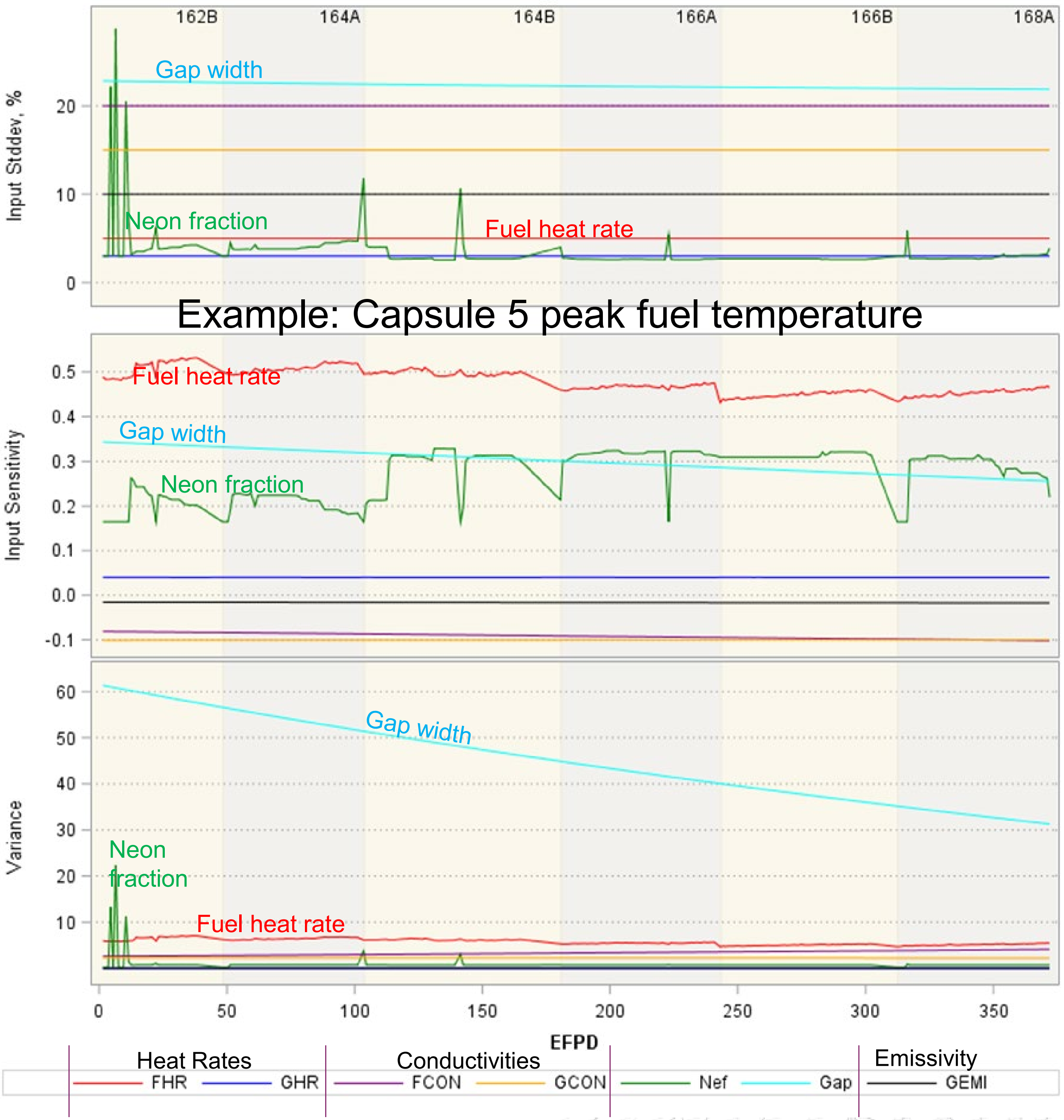
Correlation Coefficients

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

Dominant Factor for Parameter Uncertainty

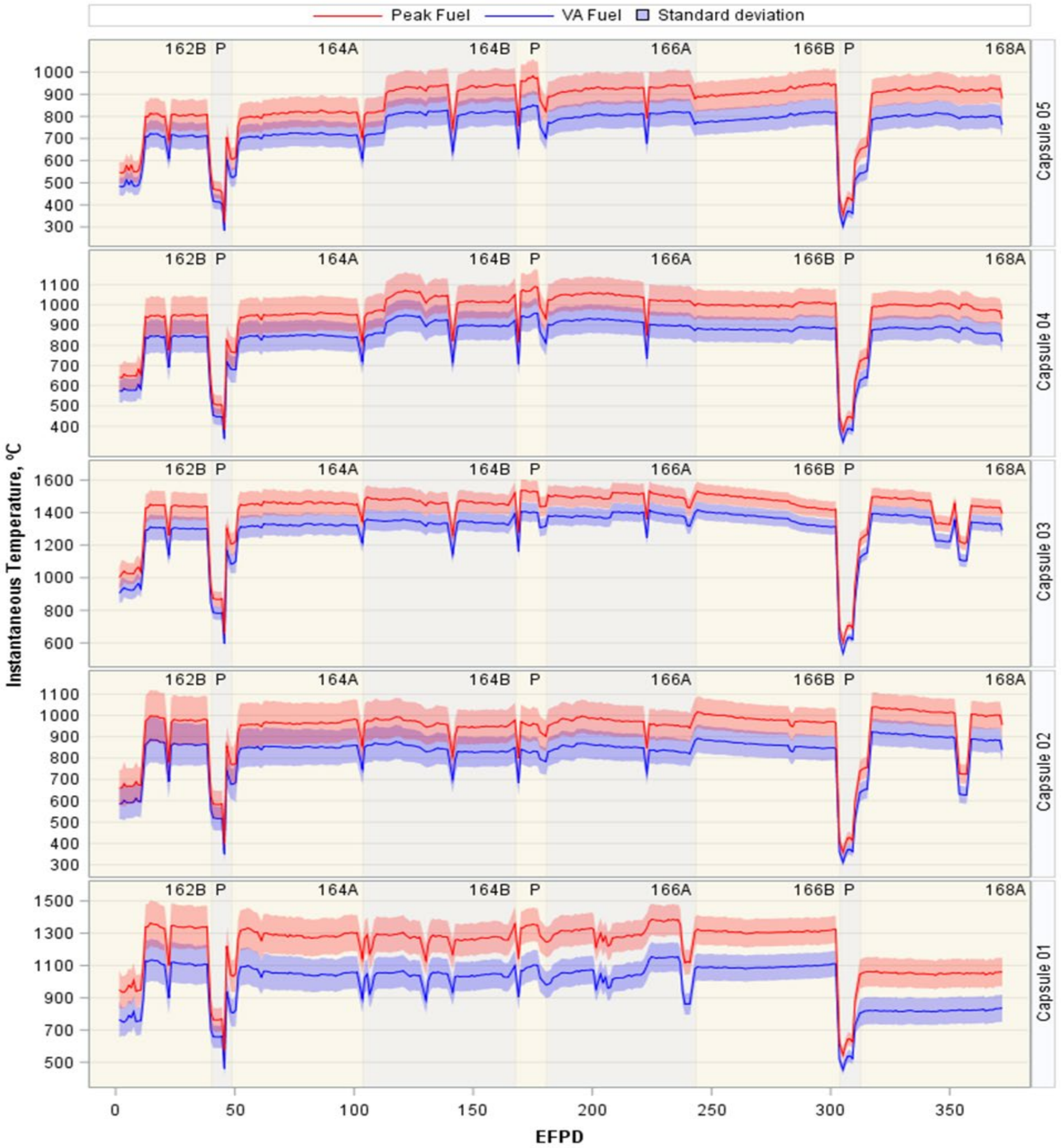
$$\sigma_T^2 = \sum_{i=1}^{n} a_i^2 \sigma_i^2$$

Gap width uncertainty is the dominant factor for uncertainty in all capsules



Instantaneous Volume-Average- and Peak- Fuel Temperature

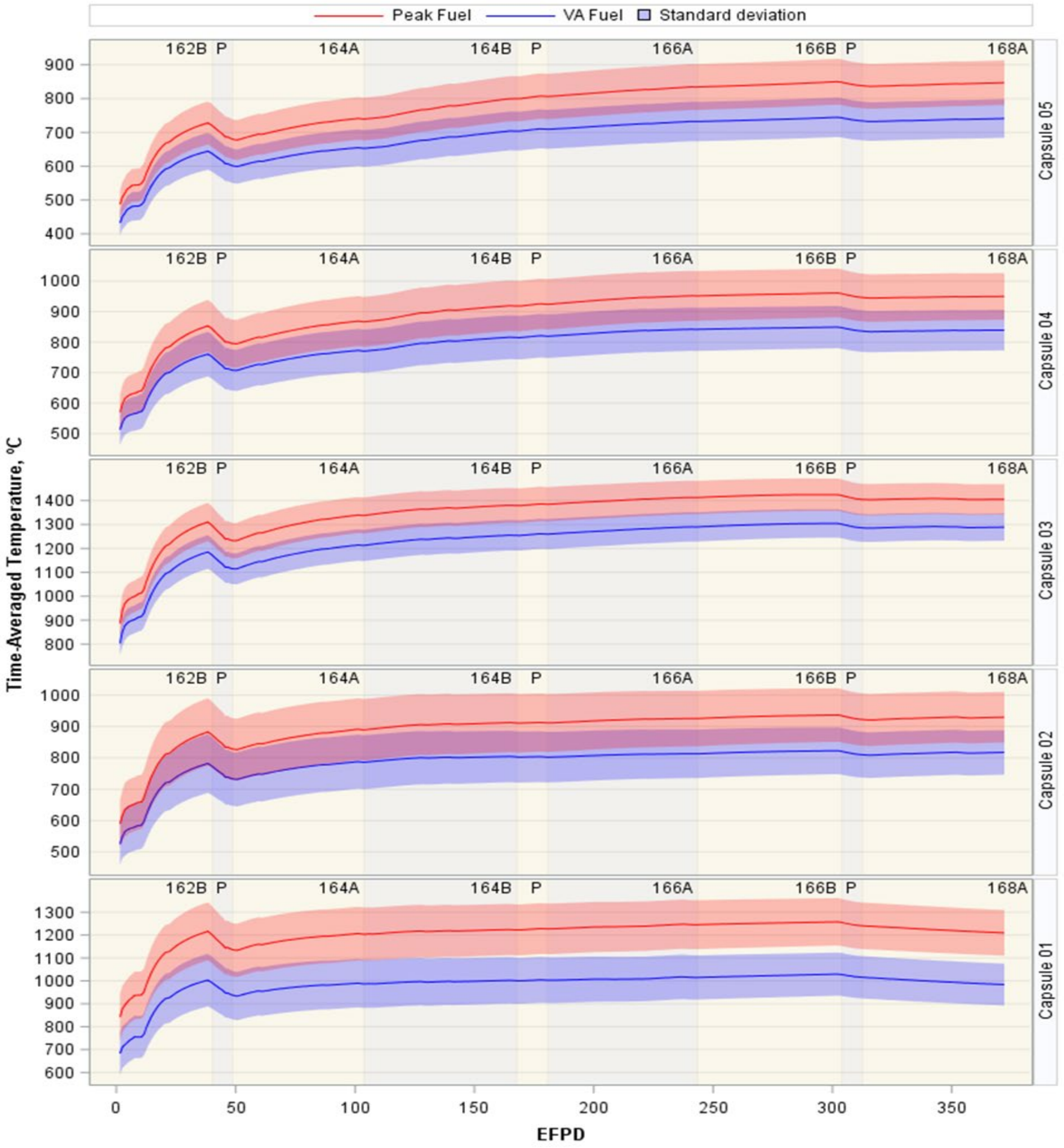
One standard deviation uncertainty bounds



Time-Average Volume-Average- and Peak- Fuel Temperature

One standard deviation uncertainty

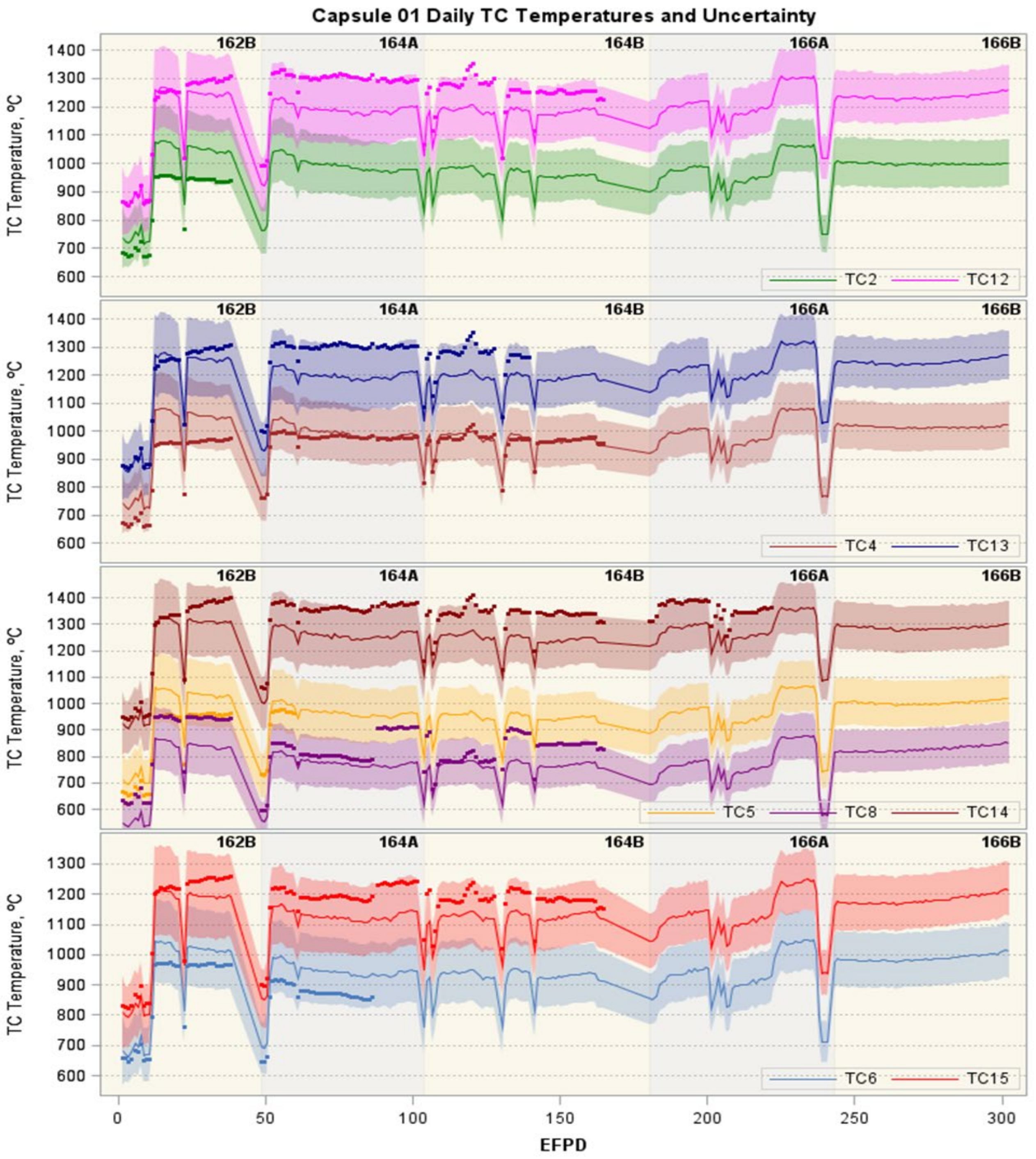
$$\sigma_{T_{TA\,i}} = \sqrt{\frac{\sum_{k=1}^{i} t_k \sigma_{T_k}^2}{\sum_{k=1}^{i} t_k}}$$



Capsule 1

Calculated TC Temperatures & 1-σ Uncertainty

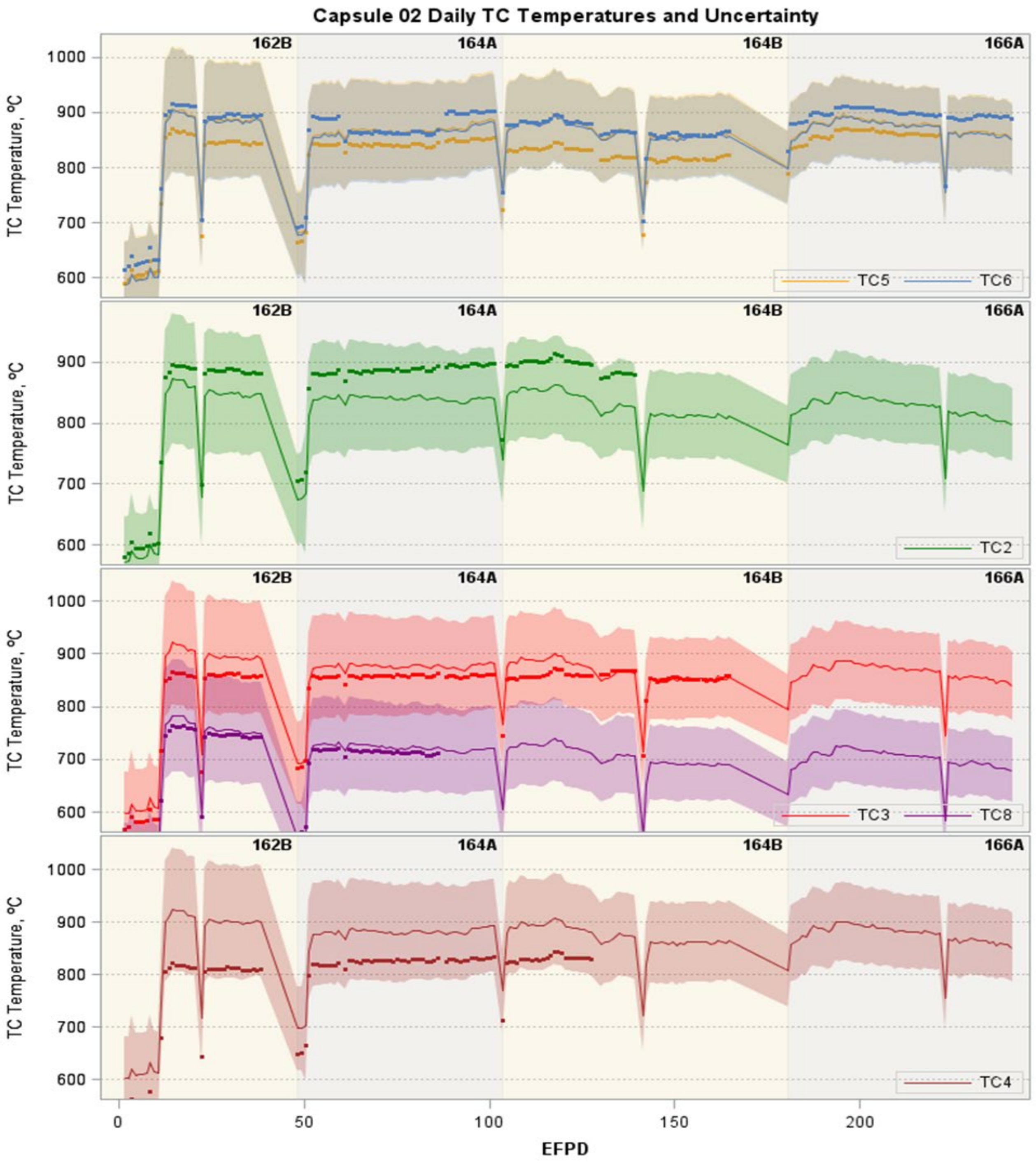
- Parameter uncertainty illustrates how uncertainties in inputs produce uncertainty in the simulated temperature
  - In the absence of model/parameter error and TC error, the TC residuals should equal zero.
  - Distribution of the TC residuals is a quasi - independent measure of the uncertainty of the thermal model, to the extent that TC locations adequately sample the temperature distribution of the volume of interest, over the period of interest.
- <u>For Capsule 1</u>, TCs are within the one-standard-deviation uncertainty band, suggesting that the uncertainty calculation may capture the dominant uncertainty factors for this capsule.



Capsule 2

Calculated TC Temperatures & 1-σ Uncertainty

Measured TC values within the one-standard-deviation uncertainty bands

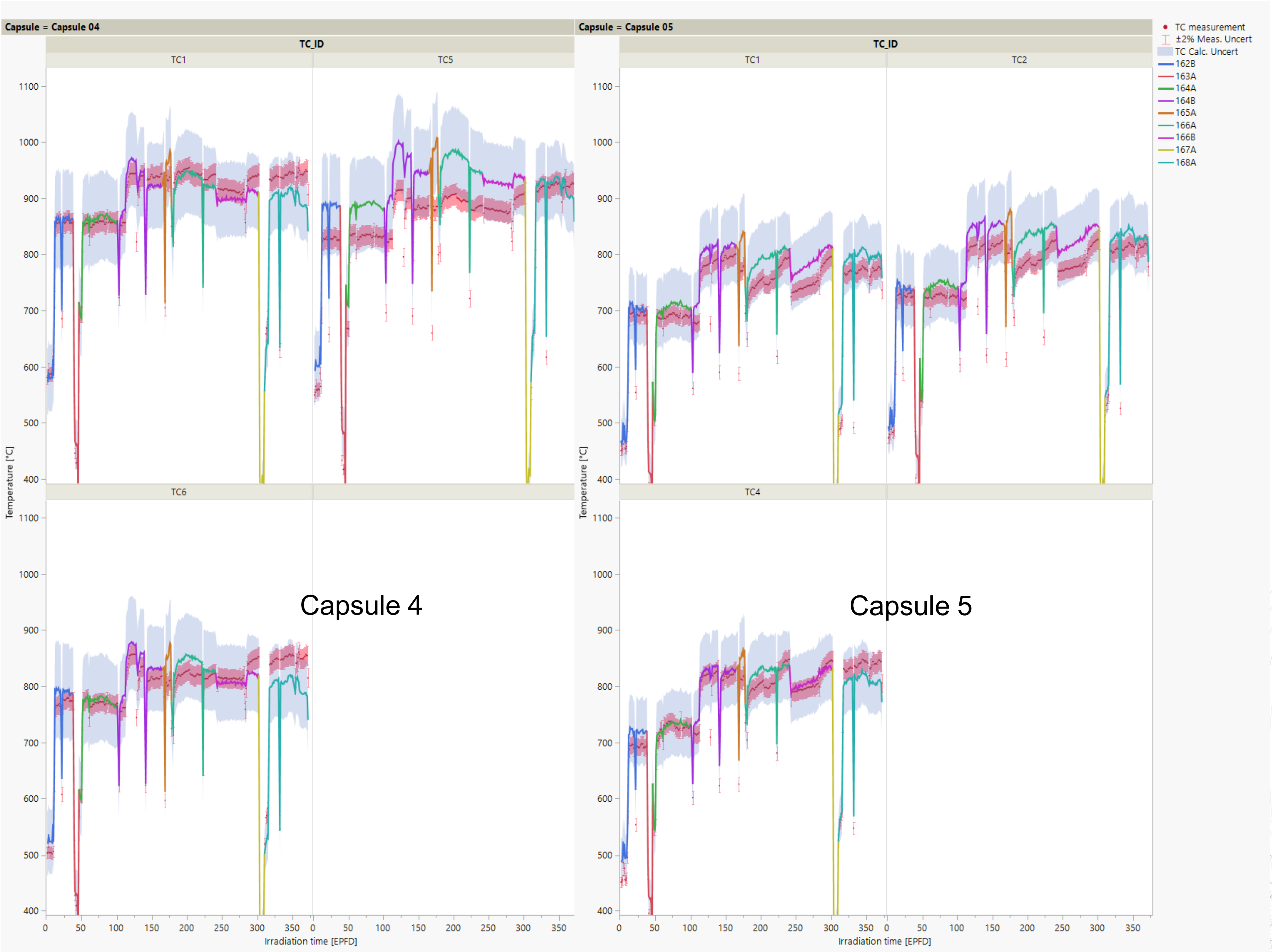


Capsules 4 & 5

Calculated TC Temperatures & 1-σ Uncertainty

TCs within one-standard-deviation uncertainty bands

These TCs were operational throughout the experiment



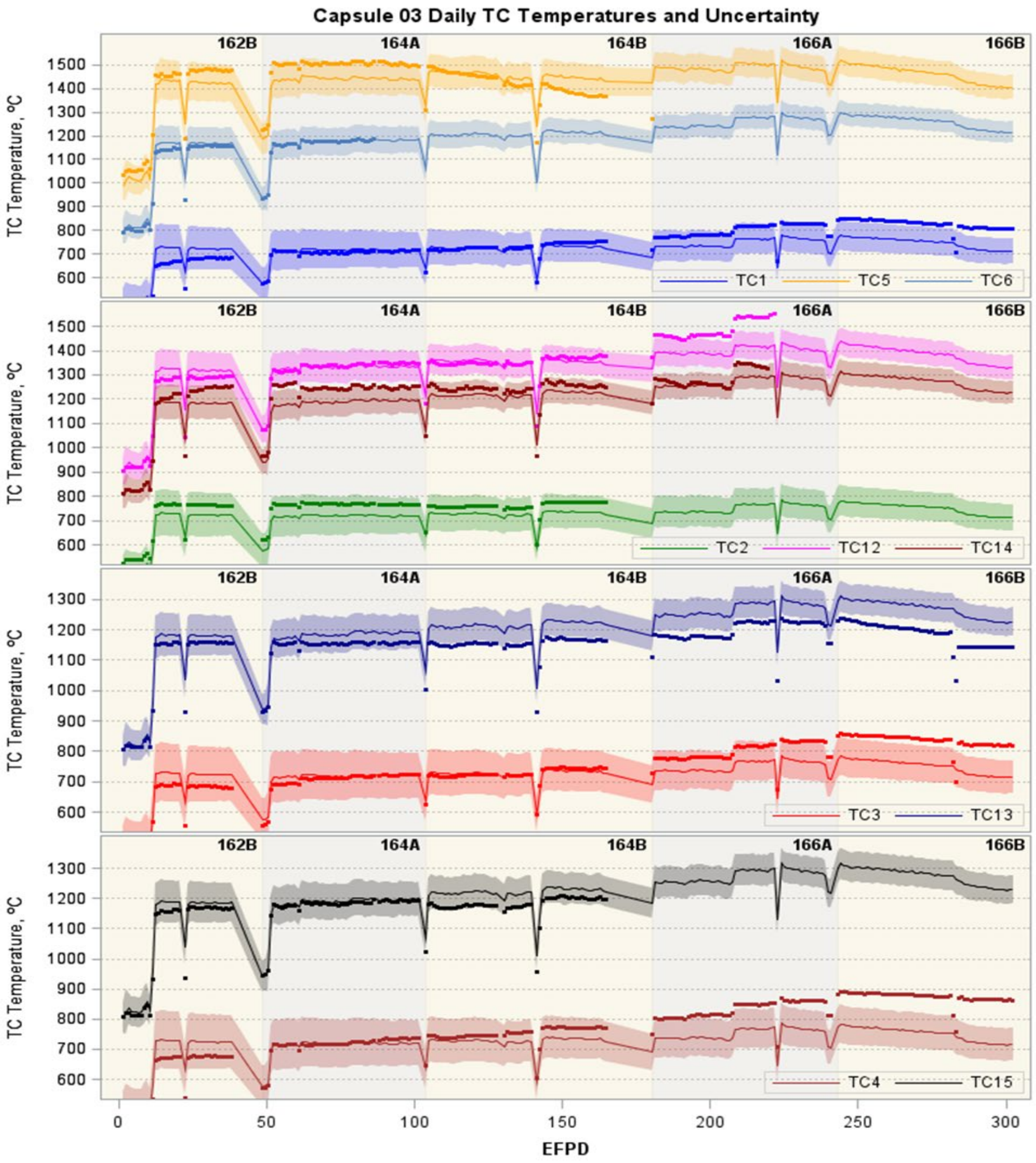
Capsule 3

Calculated TC Temperatures & 1-σ uncertainty

TCs within the one-standard-deviation uncertainty band until the end of Cycle 164B, then readings of the remaining five TCs (1, 3, 4, 12, and 13) exceed those bounds.

Possible explanations:

- Underestimated uncertainty
  - Upward trend of four TCs [1, 3, 4 and 12] suggest underprediction from Cycle 166A on
- TC drift
  - Downward trend in TC5 consistent with expected drift behavior
  - Upward trends in other TCs inconsistent with expected drift behavior



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AGR-5/6/7 Temperature Uncertainty*

Capsule	TCs	Peak Fuel	Volume-Averaged Fuel	TA Peak Fuel	TA Volume-Averaged Fuel
	Relative Standard Deviation % [°C/°C] (min – max for instantaneous)				
5	6.8 – 9.5	6.9 – 9.9	6.9 – 9.8	7.8	7.7
4	6.5 – 11.1	6.5 – 11.1	6.6 – 10.8	8	7.9
3	3.5 – 14.0	3.5 – 8.3	3.6 – 8.3	4.5	4.4
2	6.5 – 15.8	6.3 – 15.7	6.5 – 15.8	8.7	8.7
1	6.4 – 13.5	6.4 – 12.6	7.2 – 14.4	8.2	9.3

** Ranges are over the entire irradiation except for Capsule 1, where Cycle 168A was excluded due to high neon fraction uncertainty.*

AGR-5/6/7 Fuel Temperature Uncertainty Range*

Capsule	Peak Fuel	Volume-Averaged Fuel	Peak Fuel	Volume-Averaged Fuel
	Relative Standard Deviation % [°C/°C]		Standard Deviation °C	
5	6.9 – 9.9	6.9 – 9.8	46 – 76	38 – 65
4	6.5 – 11.1	6.6 – 10.8	49 – 95	43 – 82
3	3.5 – 8.3	3.6 – 8.3	42 – 89	39 – 78
2	6.3 – 15.7	6.5 – 15.8	46 – 122	41 – 107
1	6.4 – 12.6	7.2 – 14.4	77 – 143	67 – 130

* *Ranges are over the entire irradiation, except for Capsule 1, where Cycle 168A was excluded due to high neon fraction uncertainty.*

Summary of Temperature Uncertainty Results

- Dominant factor:
  - Gap width for all fuel and TC temperatures
- Overall temperature uncertainty:
  - Capsules 1 and 2 have high uncertainties for peak-, VA-, and TC- temperatures
    - ~6% to 16%
    - Due to large uncertainty of, and sensitivity to, gap size.
  - Capsules 4 and 5 have lower uncertainty than Capsules 1 and 2.
    - Up to ~10% for fuel temperatures near the start of irradiation and 11% for TC temperatures.
  - Capsule 3 has the lowest fuel temperature uncertainty
    - 3.5% to 8.3%
    - Lower gap width uncertainties due to relatively larger gaps and lower gap width sensitivity, since fuel compacts are in the inner holder, away from the outer gap.
    - TCs suggest model underprediction toward the end of irradiation.
- Uncertainties for AGR-5/6/7 capsules are higher than those seen in the AGR-1, AGR-2, and AGR-3/4 capsules because of higher gap width uncertainty due to the radial nub-to-shell clearance in all capsules.

Questions?