

Stochastic reconstruction of thermal protection material properties from arc-jet experiments

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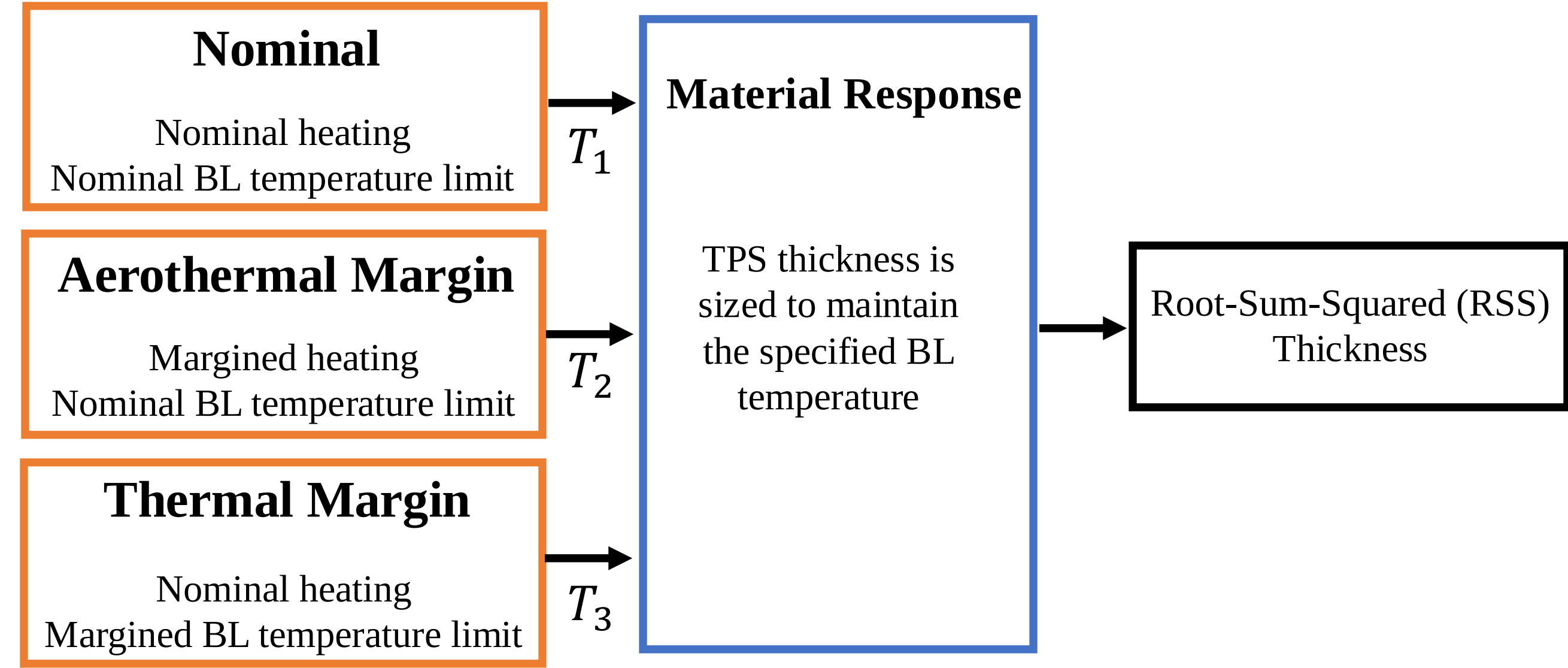
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Introduction

Material response models are required to assess reliability and determine TPS thickness. A common approach is to account for three branches of uncertainty. See [1] for more information.

Objective: Determine required thickness to maintain a “bondline temperature” (BL) at or below a specified design limit. Use the results from each branch to compute the Root-Sum-Squared thickness, $d_{RSS} = d_1 + \sqrt{(d_2 - d_1)^2 + (d_3 - d_1)^2}$



Thermal Margin:

Margin the bondline temperature using a 3σ dispersion based on a series of Monte-Carlo simulations where uncertainty in the material properties is propagated forward.

Problem:

Specific margin policy varies with mission with risk playing a strong role in guiding additional factors of safety. However, for all missions, there is a need to better quantify how uncertainties in material models are systematically identified and linked to ground-based testing and material model development.

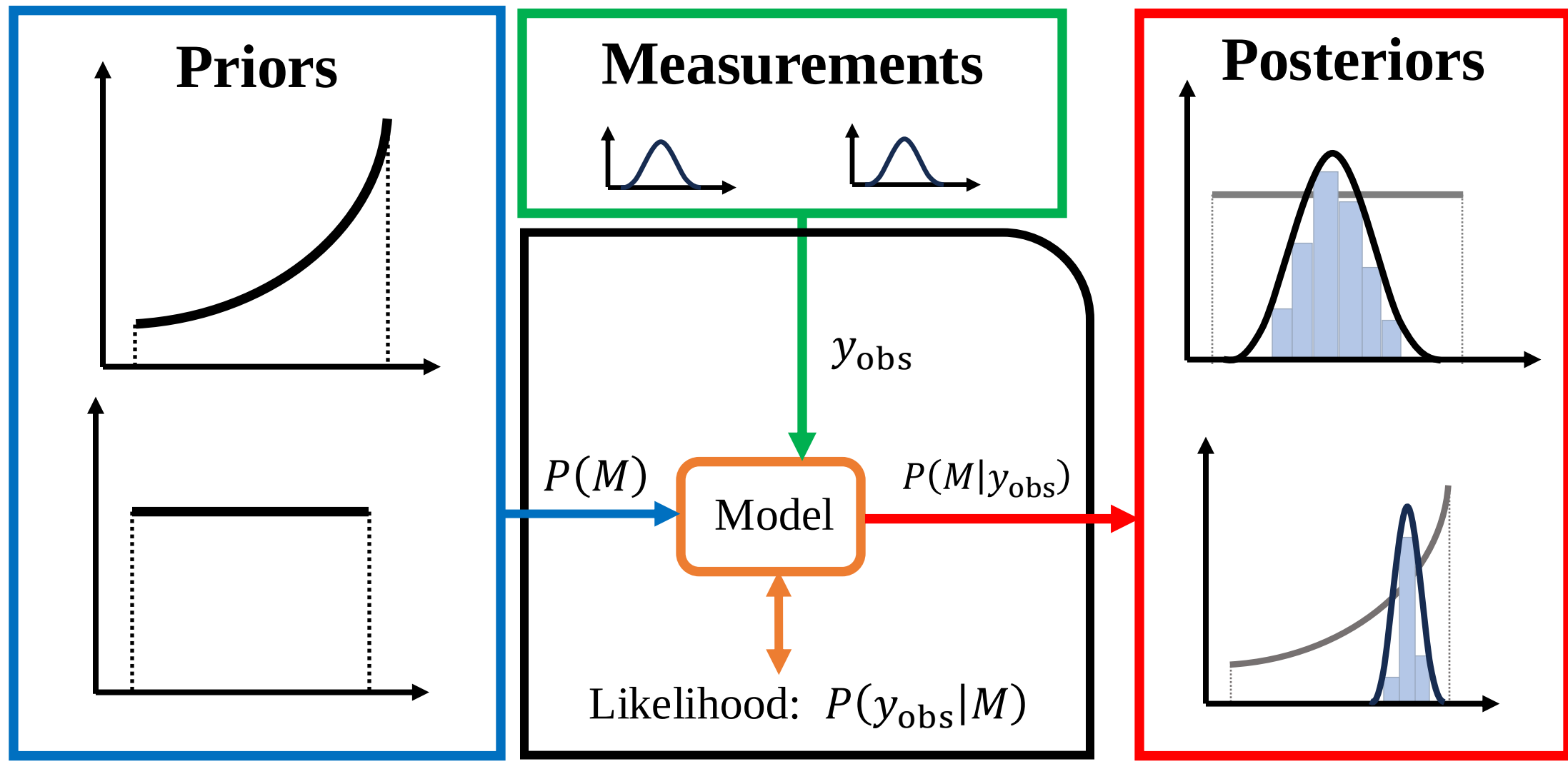
Bayesian Formalism for a safer future

A Bayesian formulation of the inference problem connects all available measurements and their uncertainties jointly to infer the model parameters.

$$P(M|y_{\text{obs}}) = \frac{P(y_{\text{obs}}|M)P(M)}{P(y_{\text{obs}})}$$

Likelihood Function

$P(y_{\text{obs}}|M)$ defines the connection between model predictions and observation by quantifying how likely a set of model parameters results in *good* predictions.

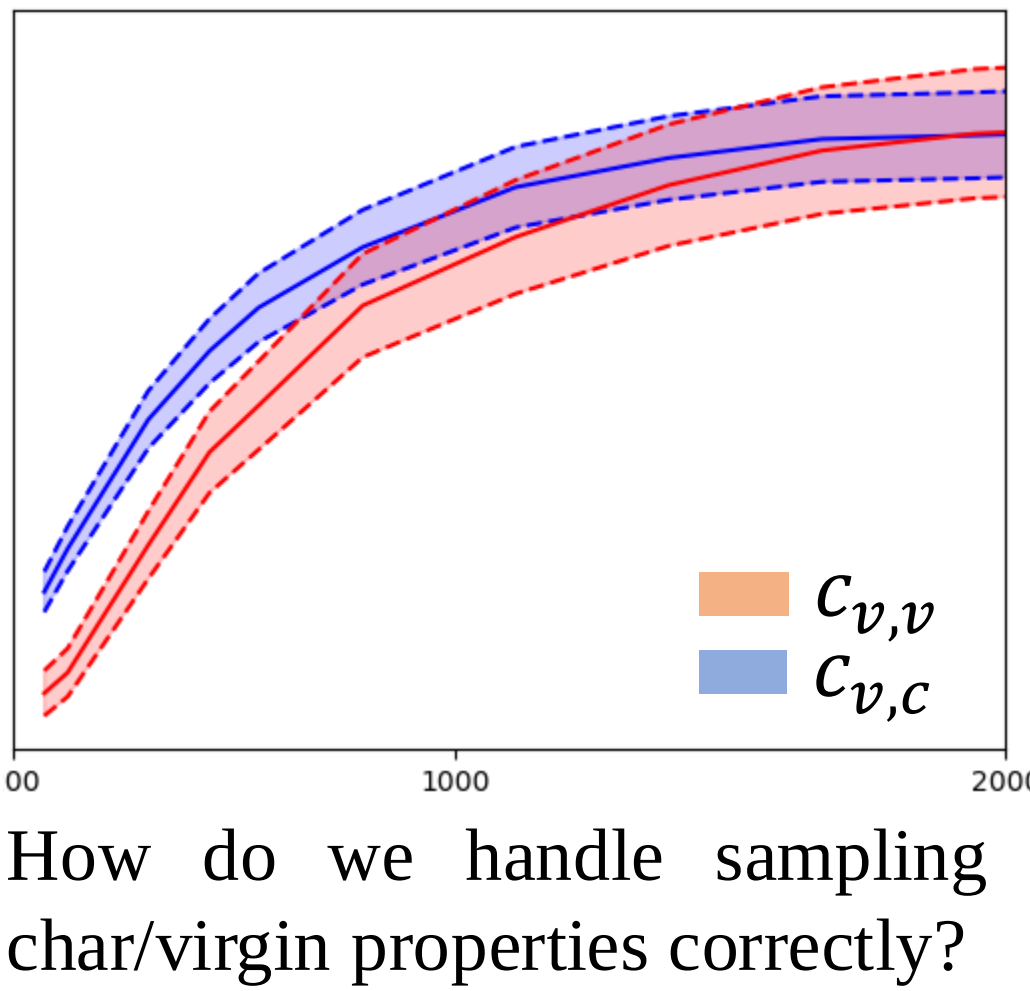


Model Evaluation

The Bayesian process requires evaluating the likelihood function many times. To avoid expensive model evaluations, a Karhunen-Loève expansion (KLE) is used to develop a reduced-order model.

Importance of priors

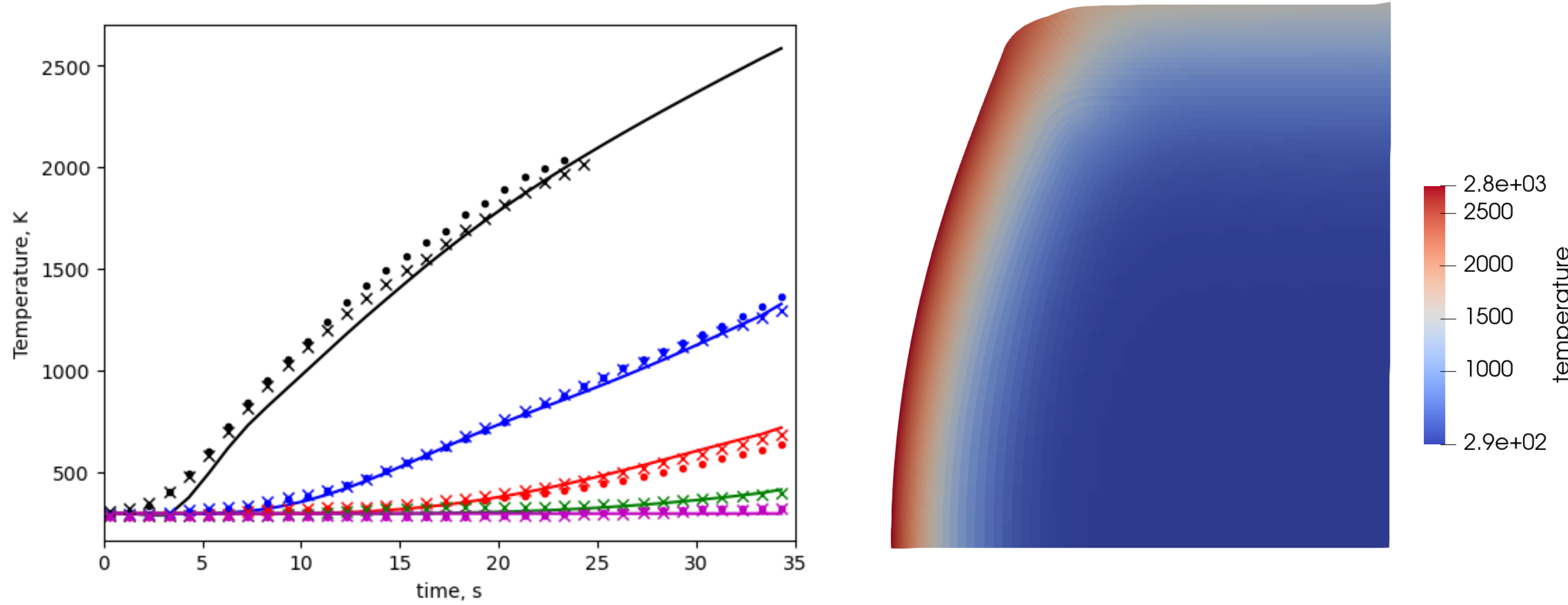
Input	Description	Variability
ρ_s^{virgin}	Virgin material density	$\pm 5\%$
ρ_s^{char}	Charred material density	$\pm 7.5\%$
K_s^{virgin}	Virgin material specific heat	$\pm 7.5\%$
K_s^{char}	Charred material specific heat	$\pm 10\%$
$\lambda_s^{\text{virgin}}$	Virgin material conductivity	$\pm 7.5\%$
λ_s^{char}	Charred material conductivity	$\pm 10\%$
$\epsilon_s^{\text{virgin}}$	Virgin material emissivity	$\pm 7.5\%$
ϵ_s^{char}	Charred material emissivity	$\pm 7.5\%$



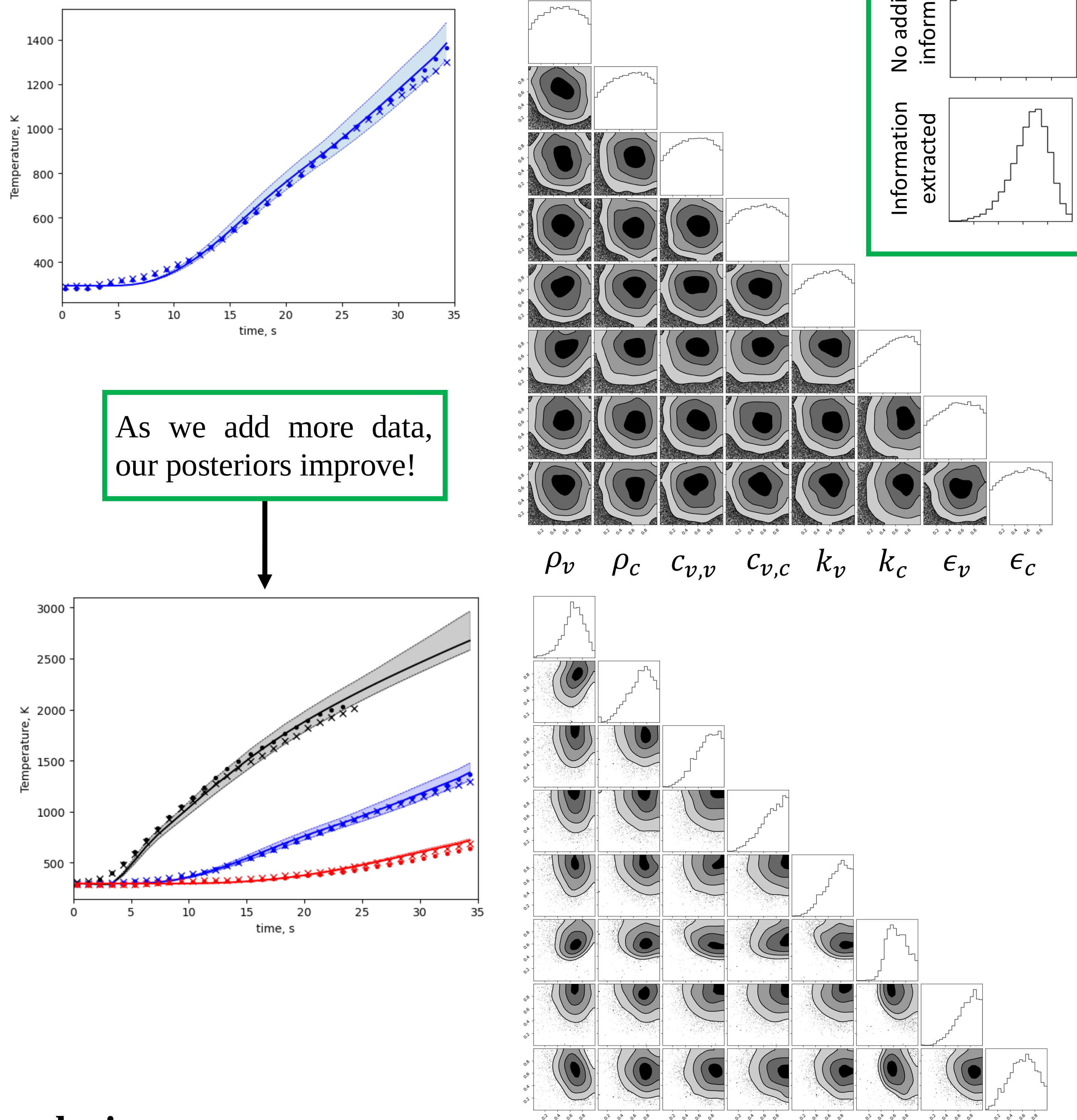
Arc-jet experiments used to validate the PICA material model

Milos *et al.* [2] documents the extensive arc-jet test campaign to characterize the PICA material response model used in FIAT. While a subset of the material properties, such as density and heat capacity at lower temperatures, could be easily determined from dedicated experiments, other material properties had to be estimated, especially at higher temperature. In particular, the thermal conductivity was adjusted after its estimation to be consistent with the thermocouple readings.

Icarus material response solver has been extensively verified against FIAT and validated against thermocouple measurements for all the cases in the aforementioned paper, in our attempt to make it a suitable tool for sizing of future NASA missions. A part of this validation effort is presented below for the conditions Case 4 (495 W/cm²) of the seven studied experiments.



Results of the Bayesian inversion



Conclusions

- Bayesian analysis shows that we can extract information about the variances of our material properties
- Approach shows promise in our ability to better inform margin analysis
- Lots of future work
 - Influence of our priors and exclusion of other uncertainties, i.e., arc-jet environment
 - Inclusion of other test data
 - What are the limitations?
- Extend to inverse estimation of gas-surface interactions for reusable materials

Acknowledgements

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References

[1] Mahzari *et al.* (2022), doi: 10.2514/6.2022-3951 [2] Milos *et al.* (2010), doi: 10.2514/1.42949