Finding the appropriate complexity to model the charring of timber

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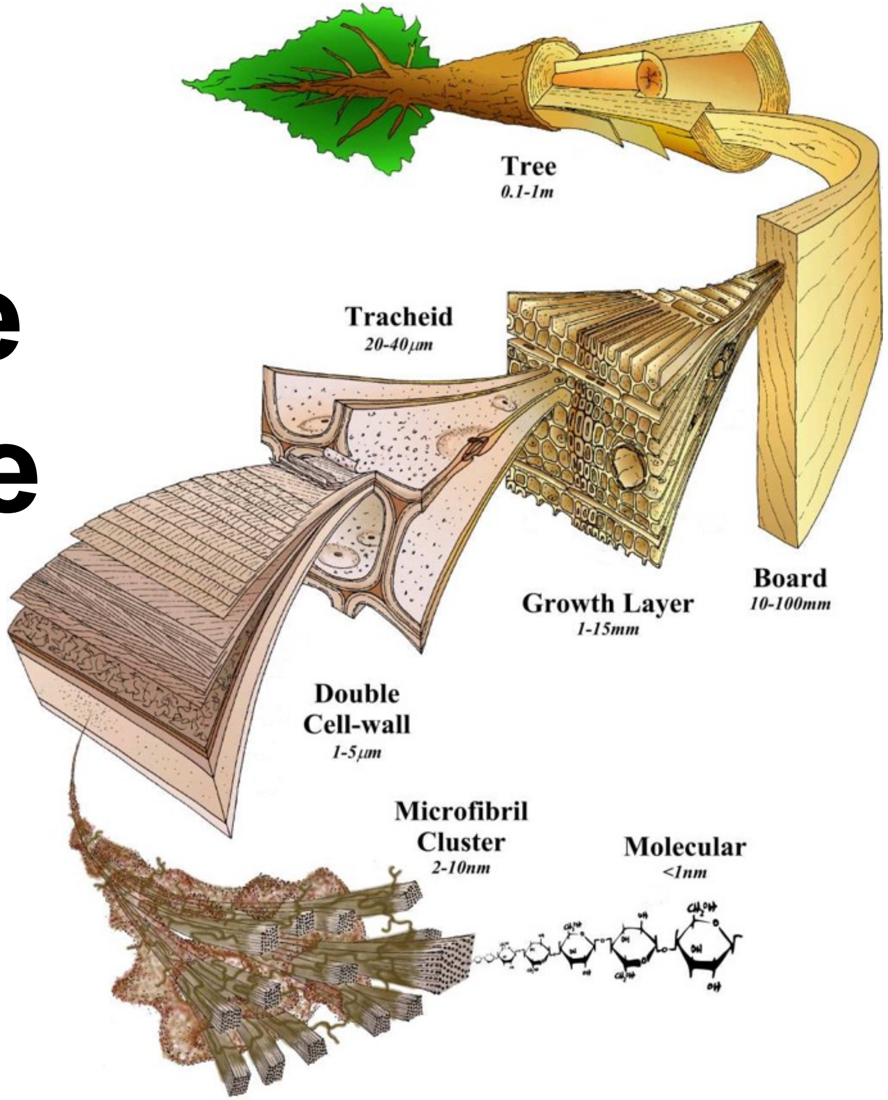
Imperial College London



Artwork by Mark Harrington, Copyright University of Canterbury 1996

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Motivation: Timber

Image from Skidmore, Owings & Merril LLP

Motivation: Timber

Power Pallet, 2015

Image from Skidmore, Owings & Merril LLP

It is about char

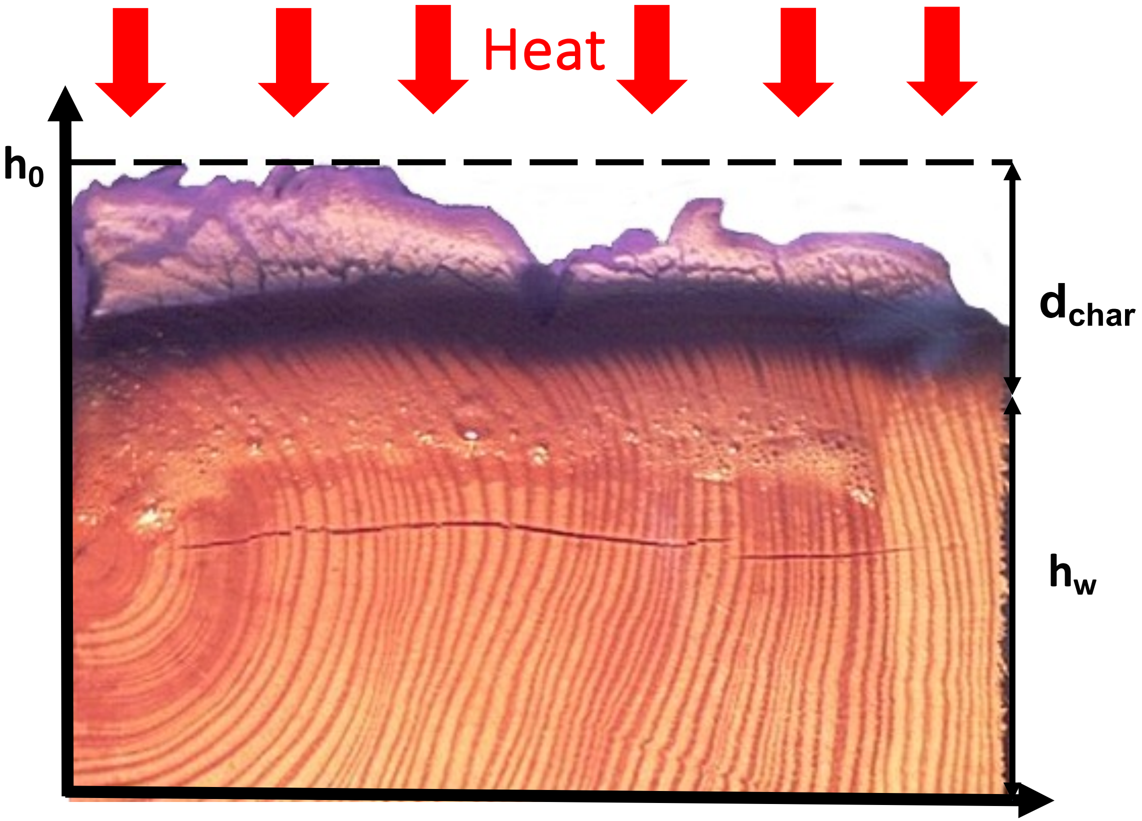
- A structures needs to **maintain its integrity** during a fire
- Char has **negligible mechanical strength** and **increases thermal resistance**
- Charring is assumed **constant** based on the **standard fire**
- Char forms as a result of heat and pyrolysis chemistry. It **depends** on the **fire.**

Predict the charring behaviour of timber under all fire scenarios

Seestadt Aspern (Vienna), New Civil Engineer 2016

Reszka 2018

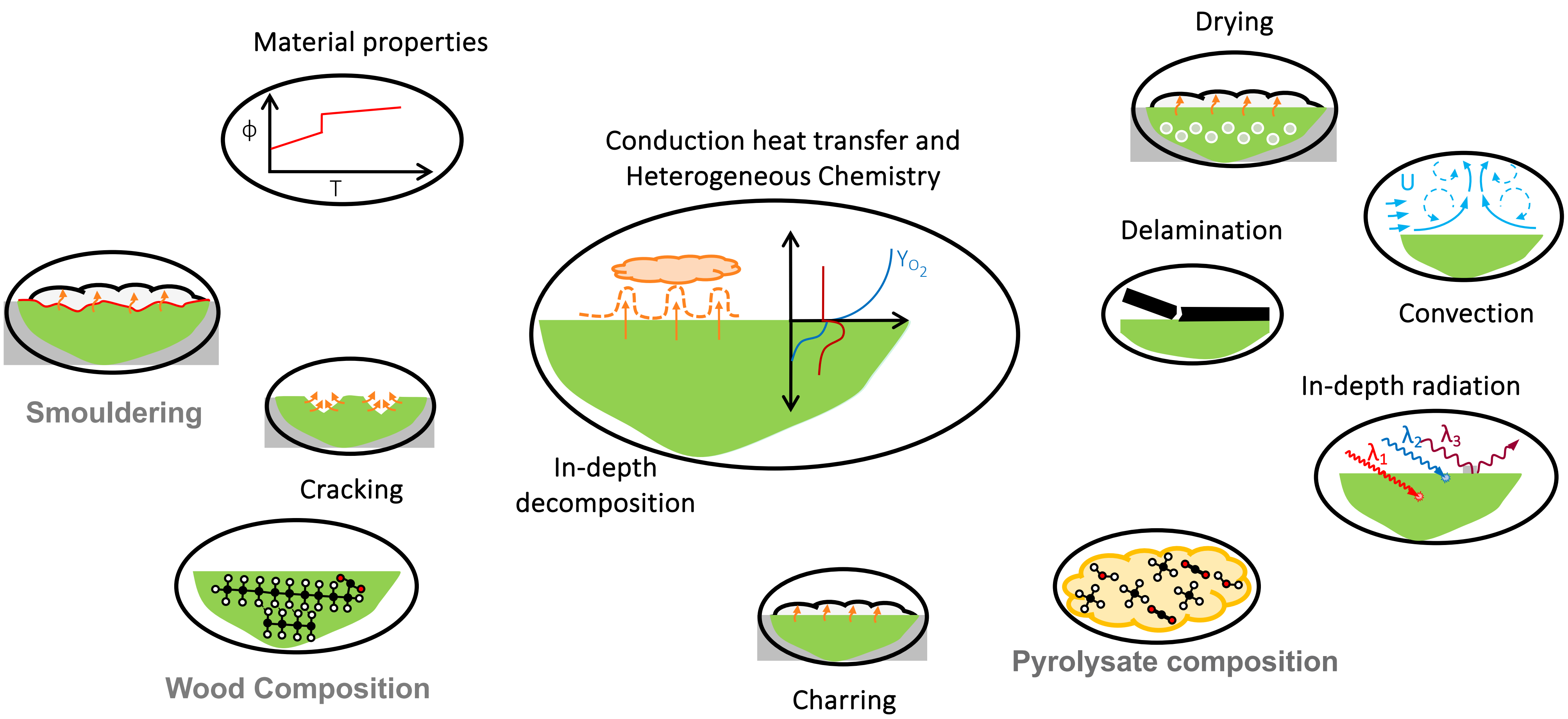
It is about char



Seestadt Aspern (Vienna), New Civil Engineer 2016

Reszka 2018

Charring: a multi-physics problem



Material properties

Conduction heat transfer and
Heterogeneous Chemistry

Drying

Delamination

Convection

In-depth radiation

Smouldering

Cracking

In-depth
decomposition

Wood Composition

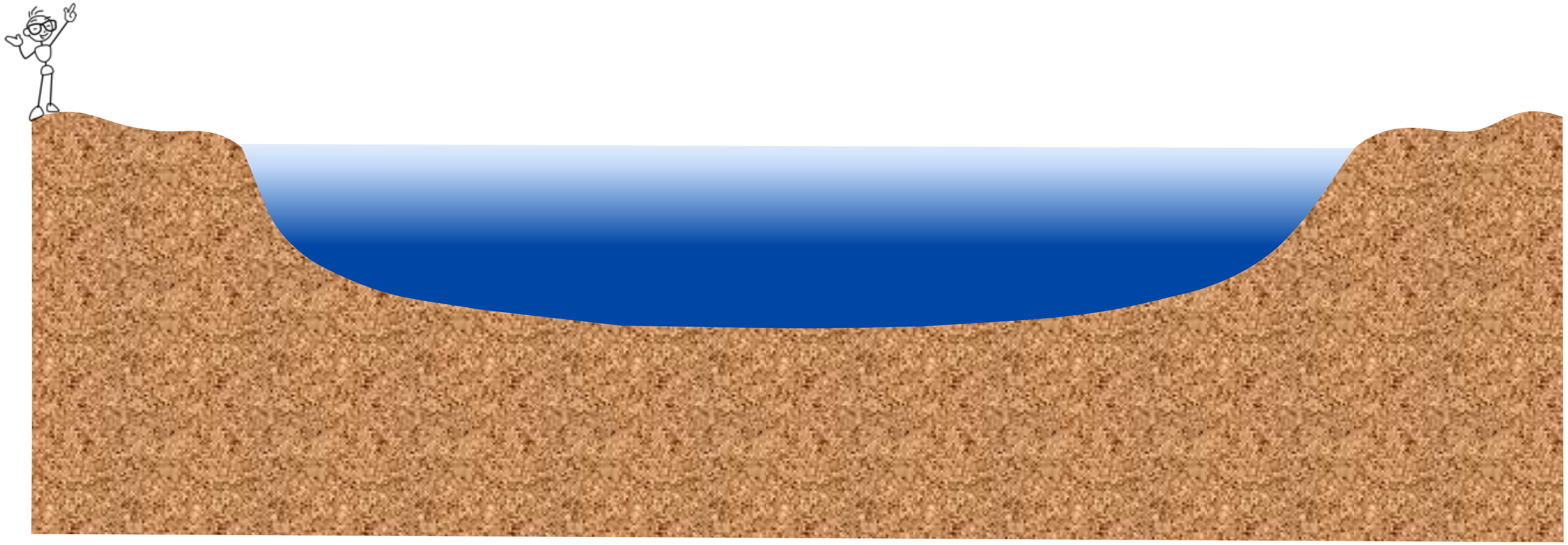
Charring

Pyrolysate composition

Bridge of Complexity

Empirical Model

Computational Model

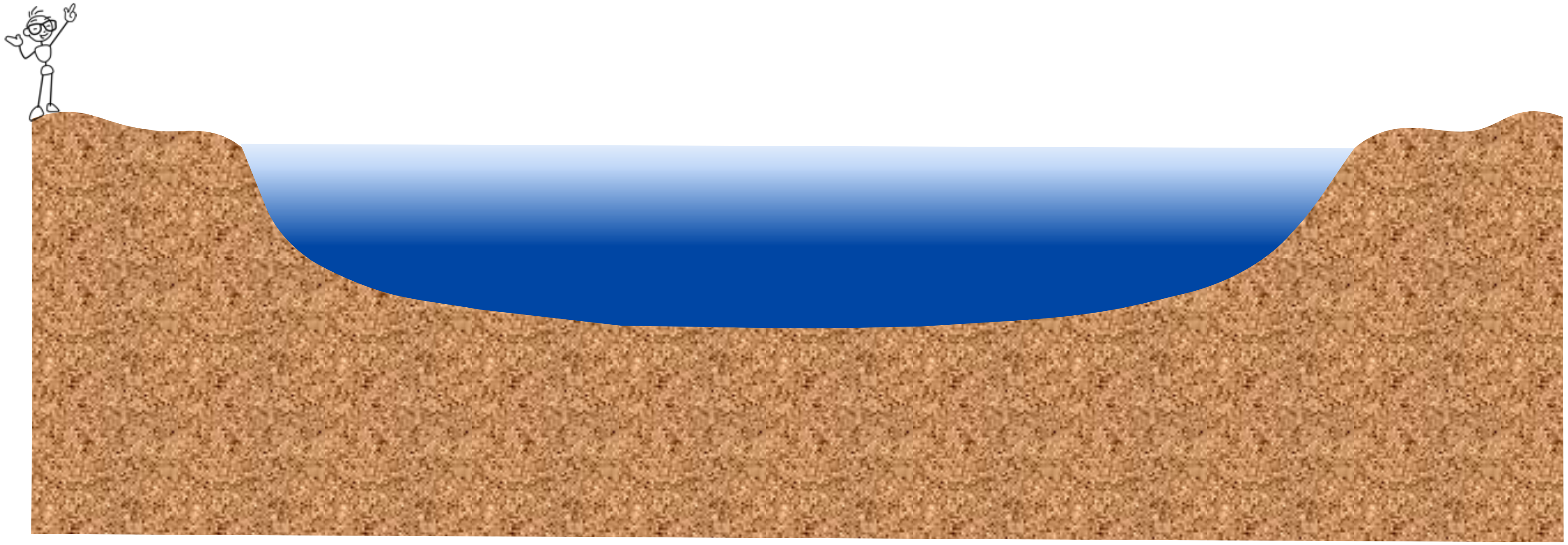


Bridge of Complexity

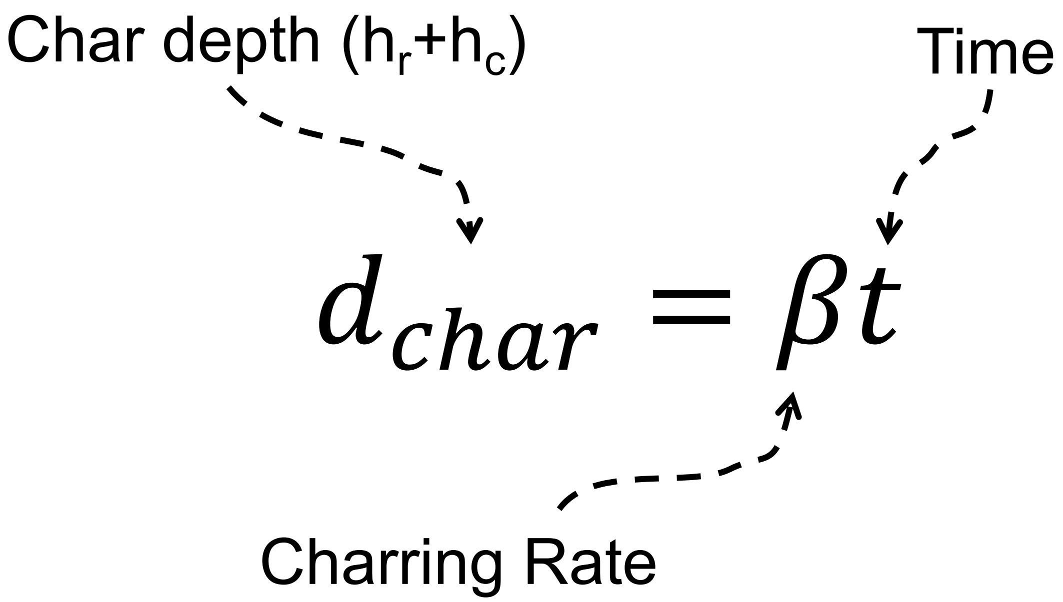
Empirical Model

Computational Model

- Pen and Paper
- Easy to validate and justify
- Only for specific conditions and geometries
- Inaccurate in unknown conditions



Simplest: Universal Charring Rate



Char depth (h_r+h_c)

Time

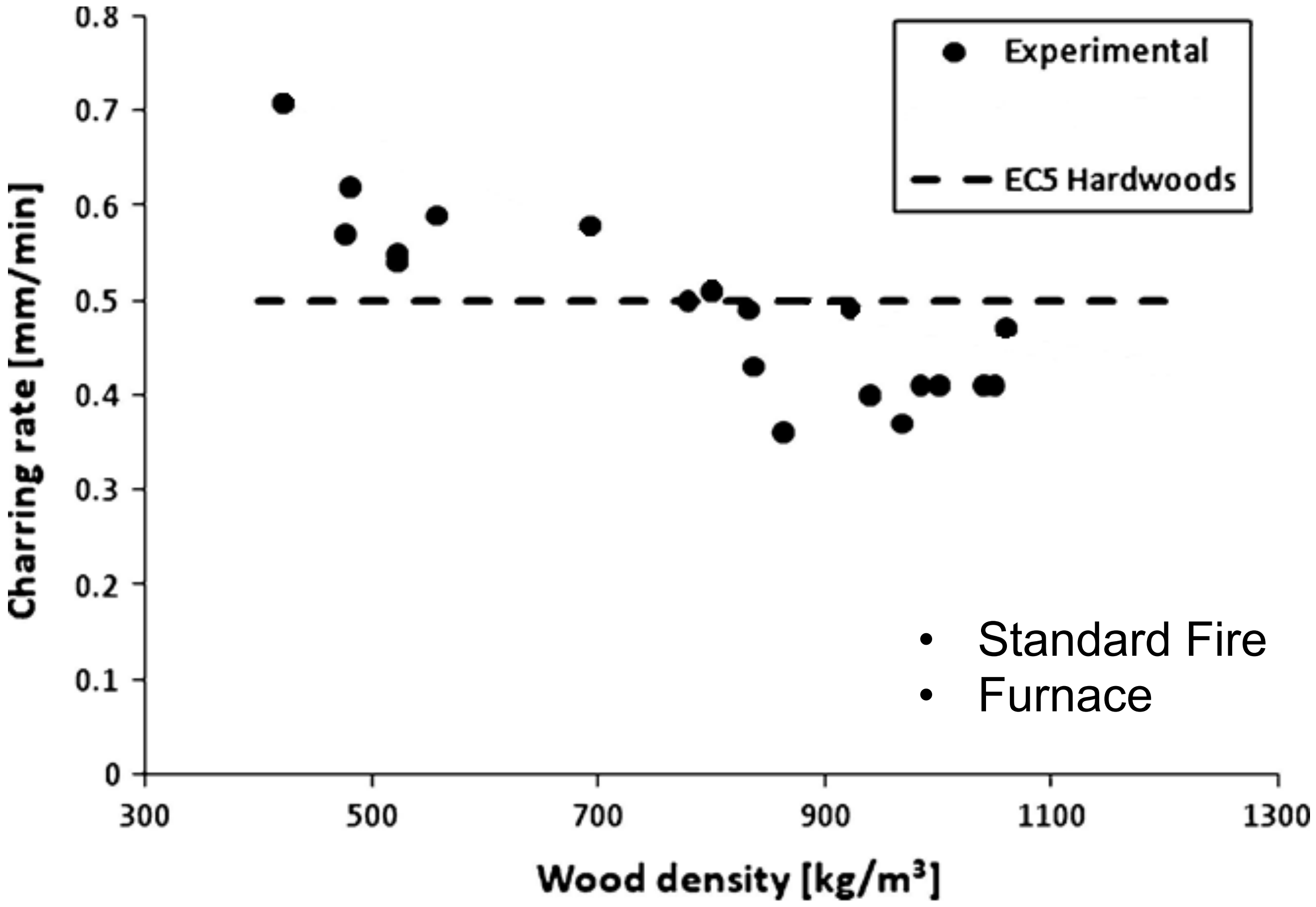
$$d_{char} = \beta t$$

Charring Rate

Limitation:

- Chemical composition
- Permeability
- Moisture Content
- Standard Fire
- Semi-infinite solid

Example: Universal Charring Rate



- Standard Fire
- Furnace

Cachim, P. B., & Franssen, J. M. (2010). Assessment of Eurocode 5 charring rate calculation methods. *Fire Technology*, *46*(1), 169–181.

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Computational Model

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- Hard to validate and justify
- General
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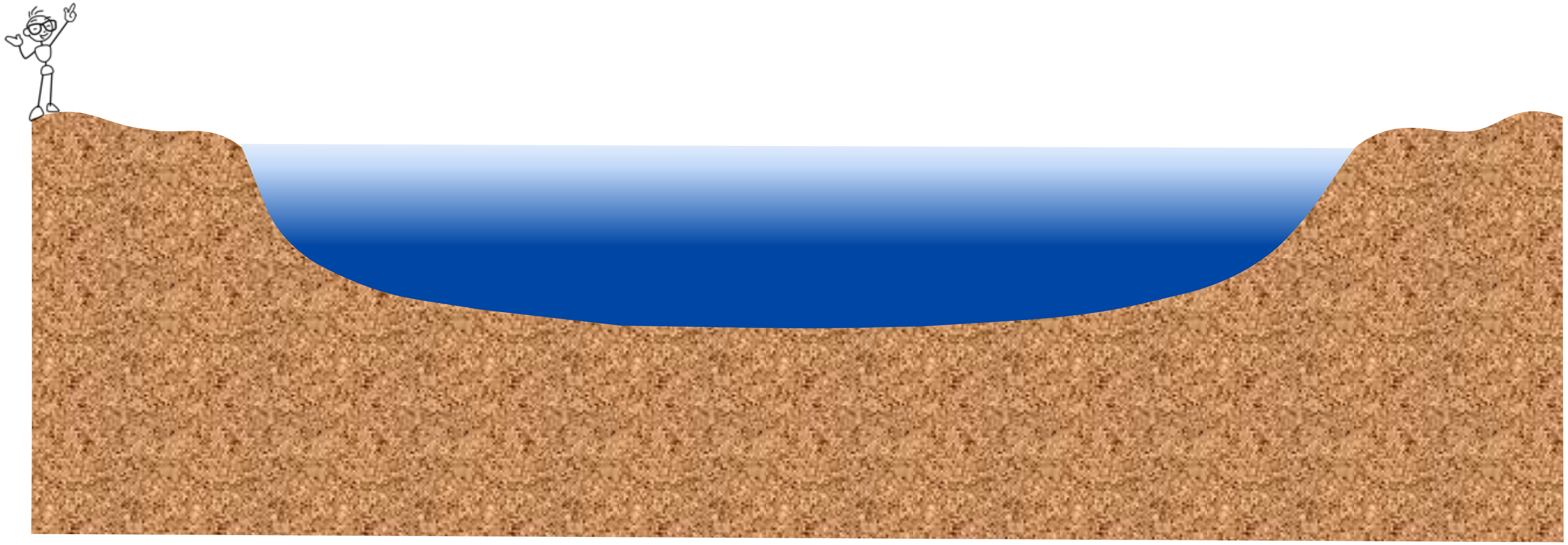
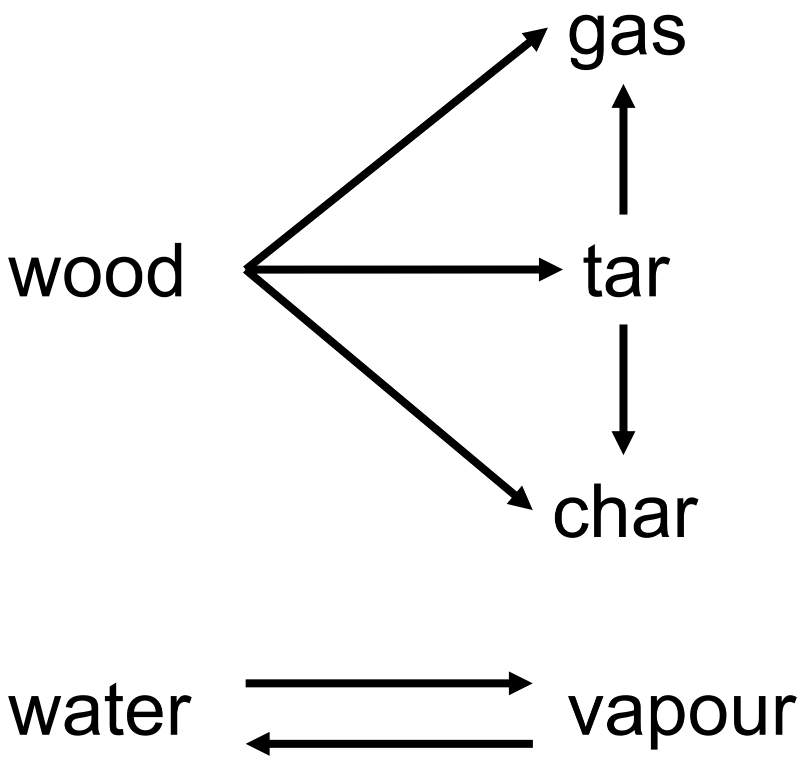


Complex: Bryden’s model



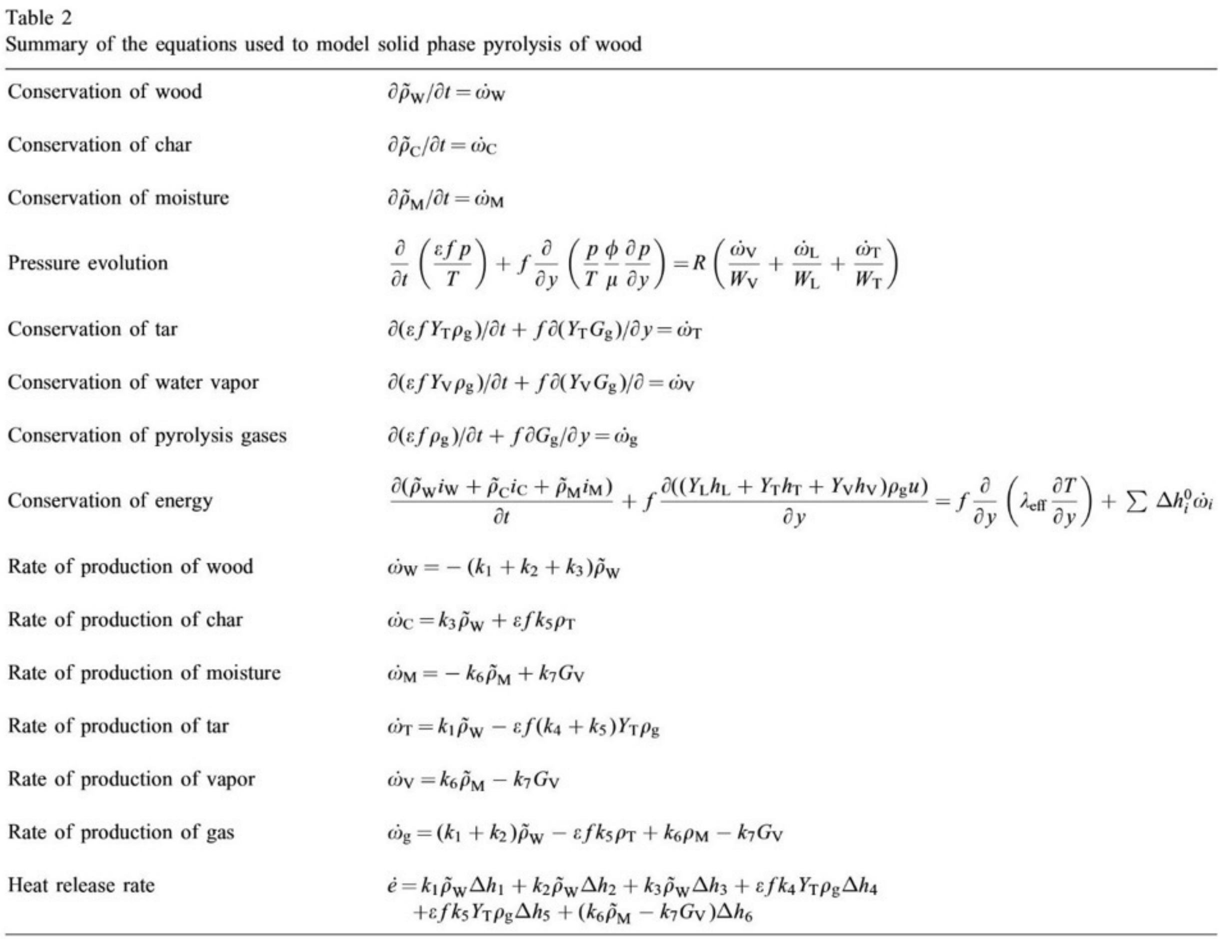
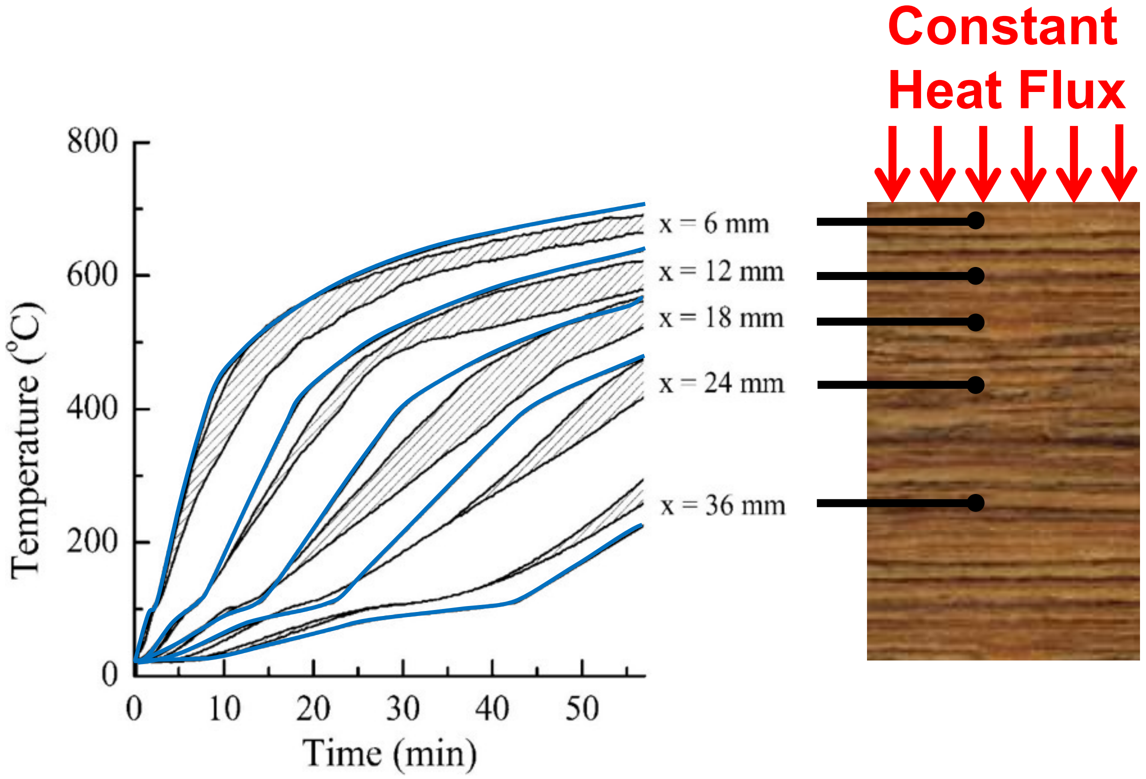


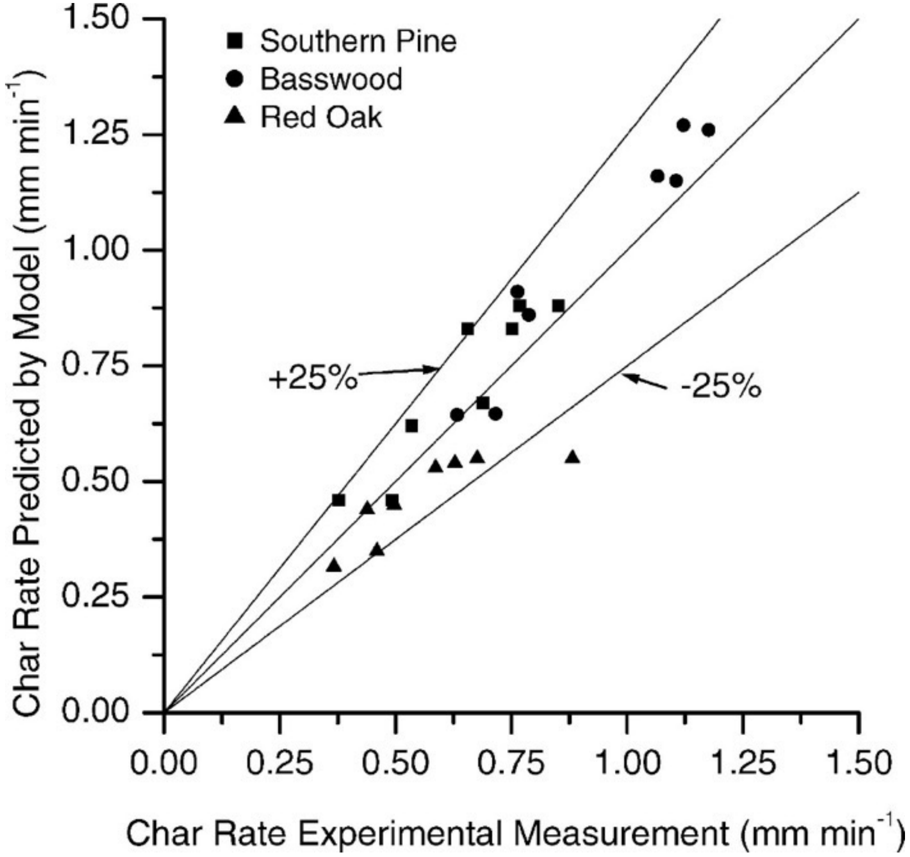
Table 2
Summary of the equations used to model solid phase pyrolysis of wood

Conservation of wood	$\partial\tilde{\rho}_{\mathrm{W}}/\partial t = \dot{\omega}_{\mathrm{W}}$
Conservation of char	$\partial\tilde{\rho}_{\mathrm{C}}/\partial t = \dot{\omega}_{\mathrm{C}}$
Conservation of moisture	$\partial\tilde{\rho}_{\mathrm{M}}/\partial t = \dot{\omega}_{\mathrm{M}}$
Pressure evolution	$\frac{\partial}{\partial t}\left(\frac{\varepsilon f p}{T}\right) + f\frac{\partial}{\partial y}\left(\frac{p}{T}\frac{\phi}{\mu}\frac{\partial p}{\partial y}\right) = R\left(\frac{\dot{\omega}_{\mathrm{V}}}{W_{\mathrm{V}}} + \frac{\dot{\omega}_{\mathrm{L}}}{W_{\mathrm{L}}} + \frac{\dot{\omega}_{\mathrm{T}}}{W_{\mathrm{T}}}\right)$
Conservation of tar	$\partial(\varepsilon f Y_{\mathrm{T}}\rho_{\mathrm{g}})/\partial t + f\partial(Y_{\mathrm{T}}G_{\mathrm{g}})/\partial y = \dot{\omega}_{\mathrm{T}}$
Conservation of water vapor	$\partial(\varepsilon f Y_{\mathrm{V}}\rho_{\mathrm{g}})/\partial t + f\partial(Y_{\mathrm{V}}G_{\mathrm{g}})/\partial = \dot{\omega}_{\mathrm{V}}$
Conservation of pyrolysis gases	$\partial(\varepsilon f \rho_{\mathrm{g}})/\partial t + f\partial G_{\mathrm{g}}/\partial y = \dot{\omega}_{\mathrm{g}}$
Conservation of energy	$\frac{\partial(\tilde{\rho}_{\mathrm{W}} i_{\mathrm{W}} + \tilde{\rho}_{\mathrm{C}} i_{\mathrm{C}} + \tilde{\rho}_{\mathrm{M}} i_{\mathrm{M}})}{\partial t} + f\frac{\partial((Y_{\mathrm{L}}h_{\mathrm{L}} + Y_{\mathrm{T}}h_{\mathrm{T}} + Y_{\mathrm{V}}h_{\mathrm{V}})\rho_{\mathrm{g}}u)}{\partial y} = f\frac{\partial}{\partial y}\left(\lambda_{\mathrm{eff}}\frac{\partial T}{\partial y}\right) + \sum \Delta h_i^0 \dot{\omega}_i$
Rate of production of wood	$\dot{\omega}_{\mathrm{W}} = -(k_1 + k_2 + k_3)\tilde{\rho}_{\mathrm{W}}$
Rate of production of char	$\dot{\omega}_{\mathrm{C}} = k_3\tilde{\rho}_{\mathrm{W}} + \varepsilon f k_5 \rho_{\mathrm{T}}$
Rate of production of moisture	$\dot{\omega}_{\mathrm{M}} = -k_6\tilde{\rho}_{\mathrm{M}} + k_7 G_{\mathrm{V}}$
Rate of production of tar	$\dot{\omega}_{\mathrm{T}} = k_1\tilde{\rho}_{\mathrm{W}} - \varepsilon f(k_4 + k_5)Y_{\mathrm{T}}\rho_{\mathrm{g}}$
Rate of production of vapor	$\dot{\omega}_{\mathrm{V}} = k_6\tilde{\rho}_{\mathrm{M}} - k_7 G_{\mathrm{V}}$
Rate of production of gas	$\dot{\omega}_{\mathrm{g}} = (k_1 + k_2)\tilde{\rho}_{\mathrm{W}} - \varepsilon f k_5 \rho_{\mathrm{T}} + k_6 \rho_{\mathrm{M}} - k_7 G_{\mathrm{V}}$
Heat release rate	$\dot{e} = k_1\tilde{\rho}_{\mathrm{W}}\Delta h_1 + k_2\tilde{\rho}_{\mathrm{W}}\Delta h_2 + k_3\tilde{\rho}_{\mathrm{W}}\Delta h_3 + \varepsilon f k_4 Y_{\mathrm{T}}\rho_{\mathrm{g}}\Delta h_4$ $+\varepsilon f k_5 Y_{\mathrm{T}}\rho_{\mathrm{g}}\Delta h_5 + (k_6\tilde{\rho}_{\mathrm{M}} - k_7 G_{\mathrm{V}})\Delta h_6$

Bryden, K. M., & Hagge, M. J. (2003). Modeling the combined impact of moisture and char shrinkage on the pyrolysis of a biomass particle. *Fuel*, *82*(13), 1633–1644.

Example: Bryden’s model





Bryden, K. M., Ragland, K. W., & Rutland, C. J. (2002). Modeling thermally thick pyrolysis of wood. *Biomass and Bioenergy*, *22*(1), 41–53.

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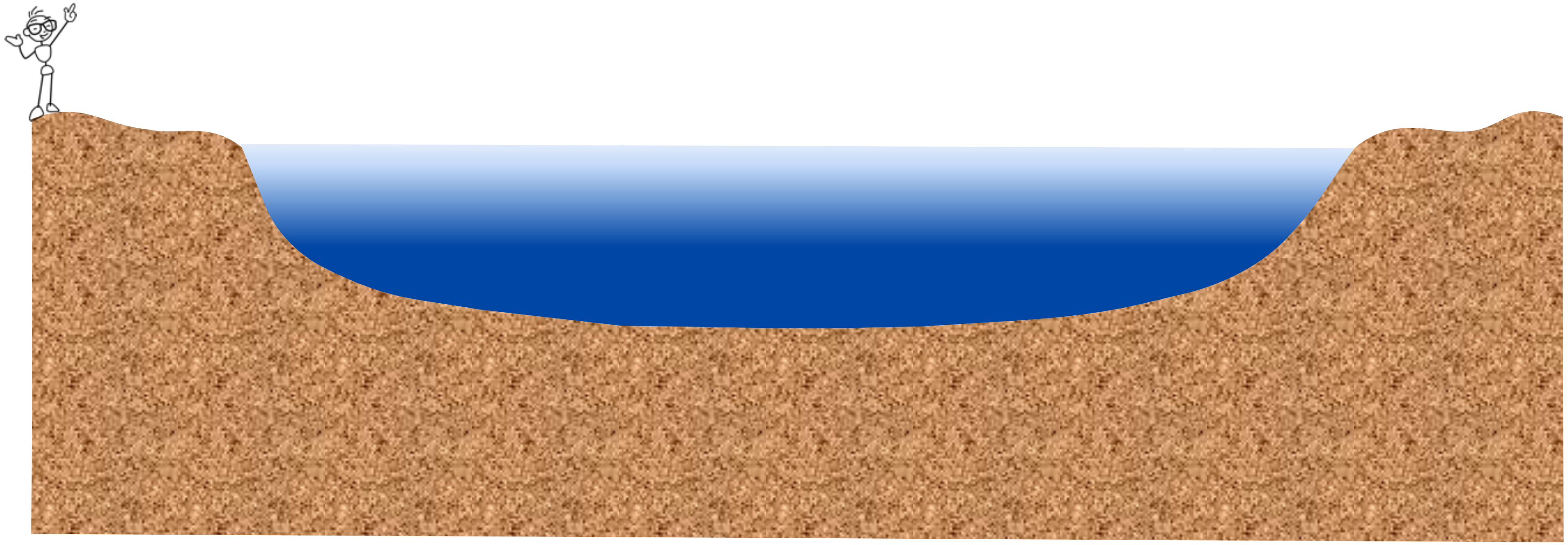

Bridge of Complexity

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Model

Computational
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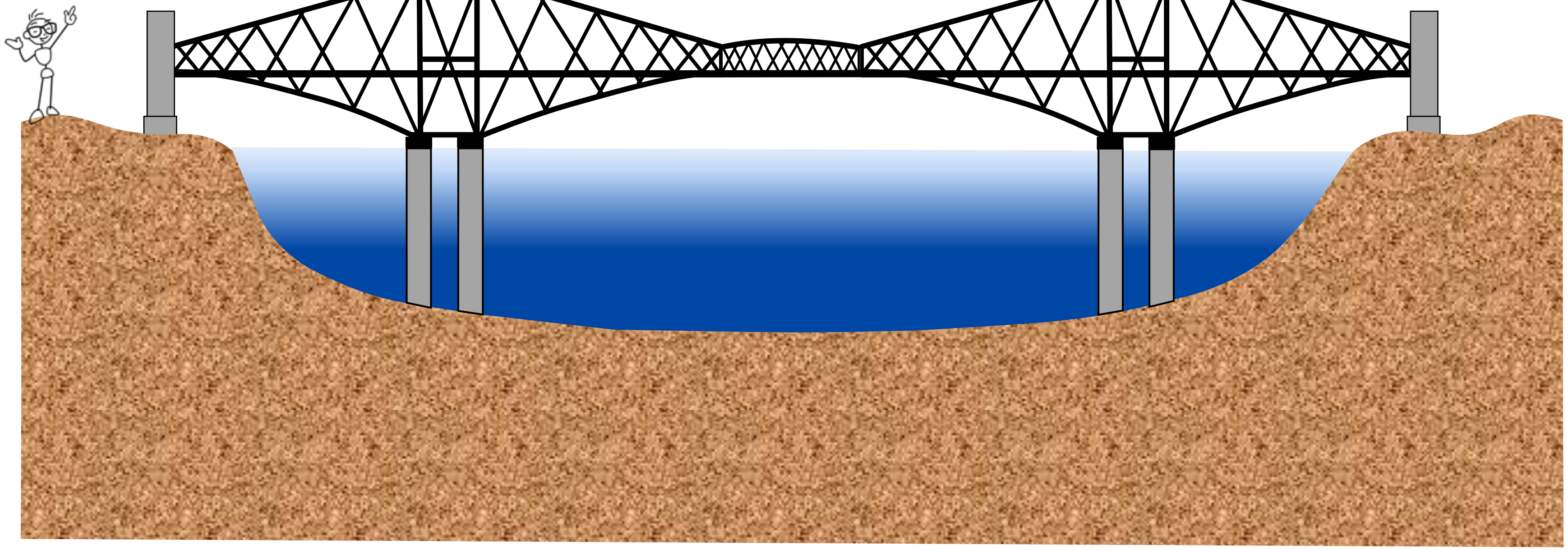

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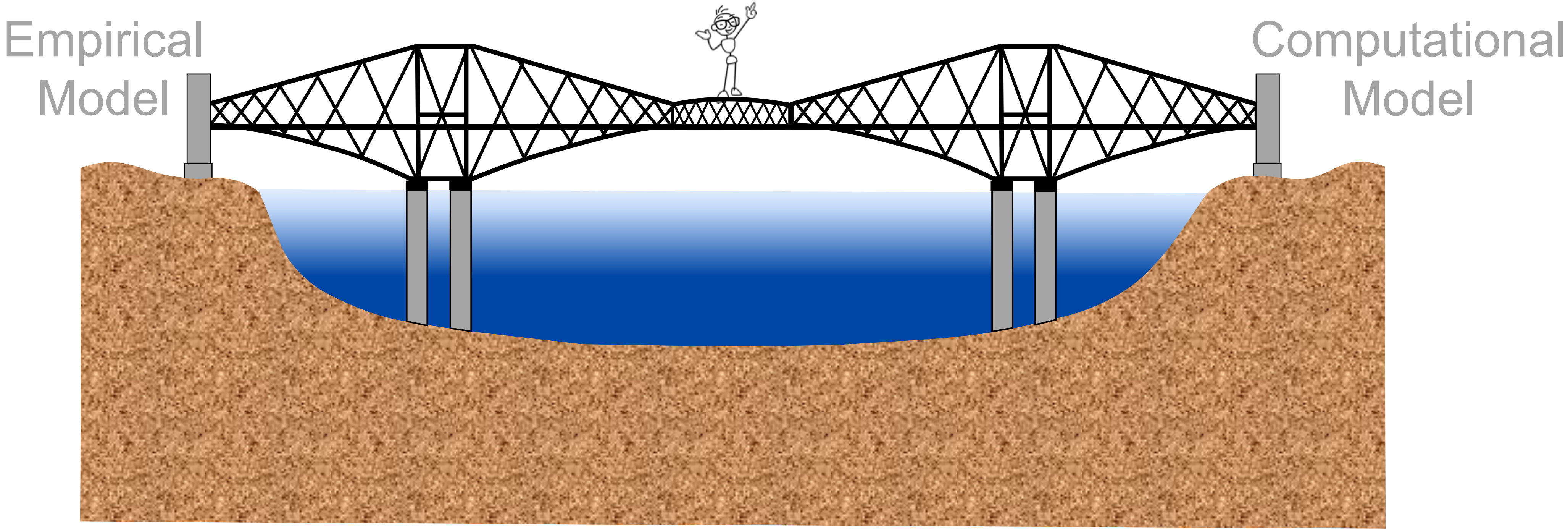

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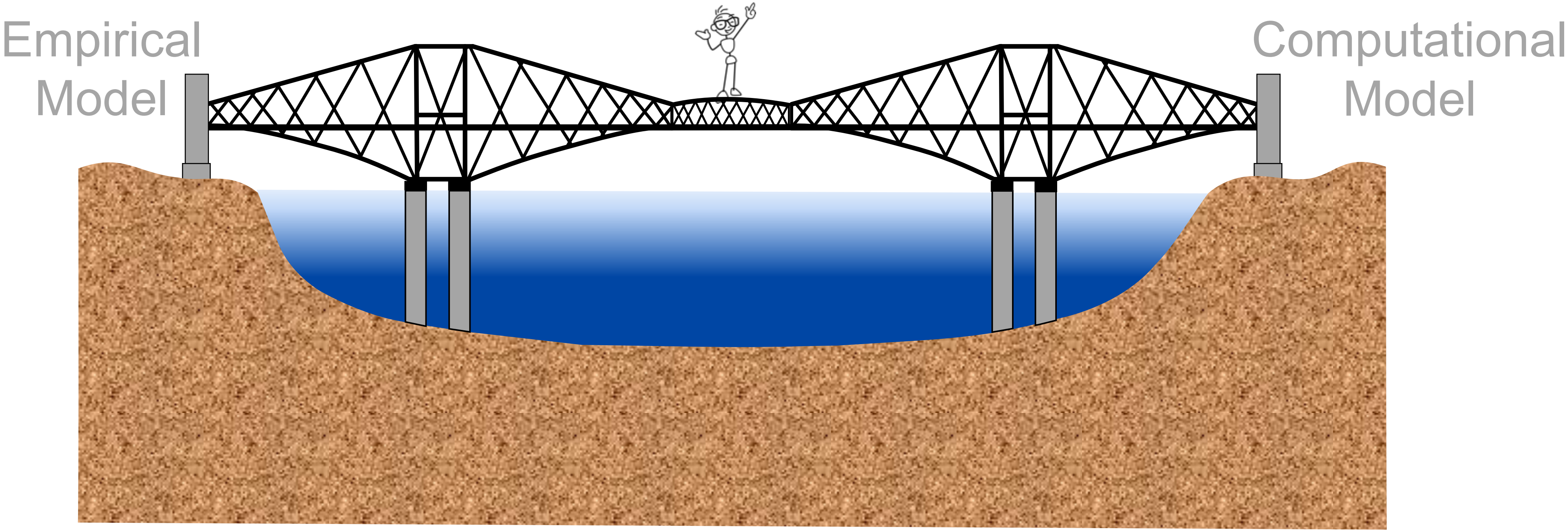
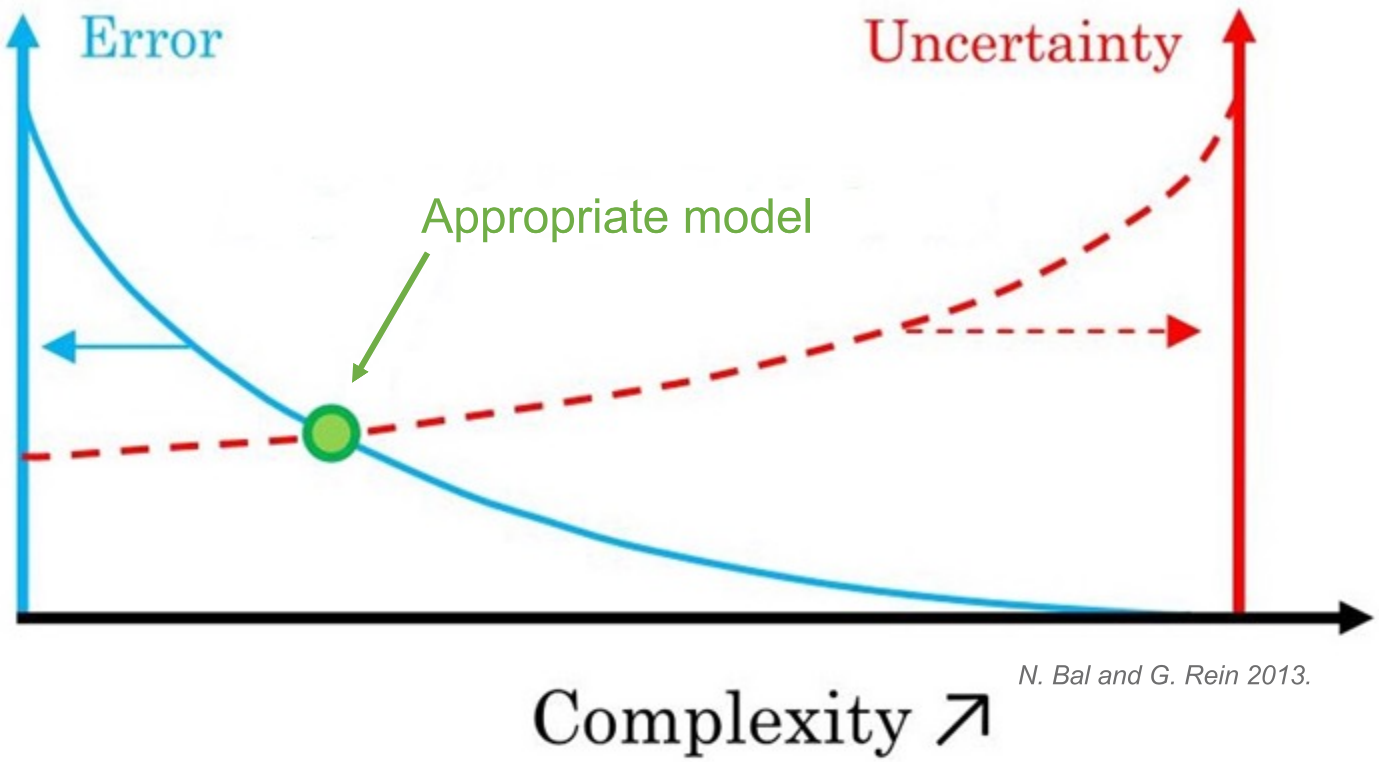


Appropriate Model for Design?

- Simple
- General

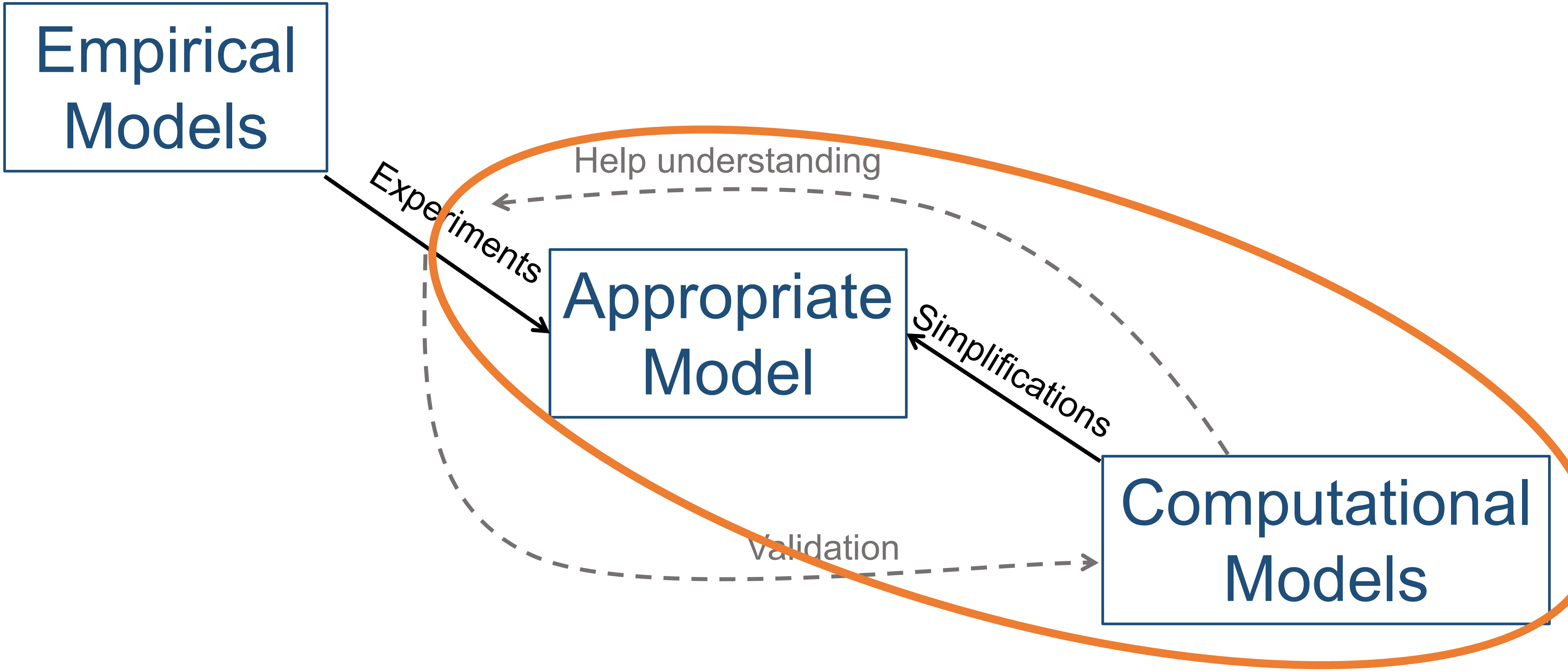
It is about uncertainty



N. Bal and G. Rein 2013.

Appropriate level of complexity is determined by experiments

How do we get there?



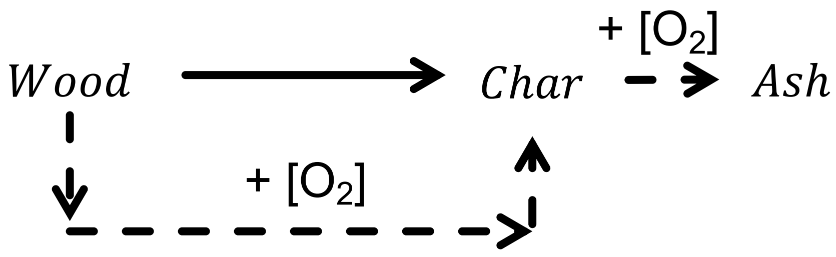
Empirical Models

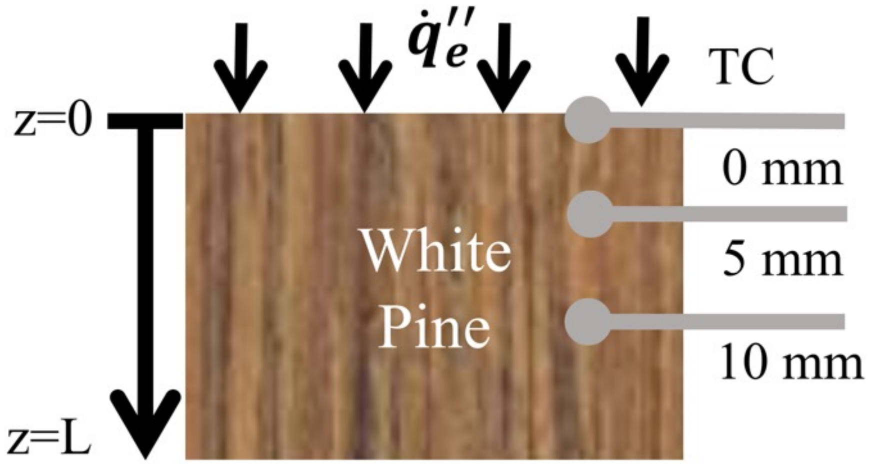
Appropriate Model

Computational Models

The current model

Chemistry


Wood
Char
+ [O_2]
Ash
+ [O_2]



Heat Transfer

Experiments: Kashiwagi, Ohlemiller, and Werner (1987)

Code: Gpyro

Solid-Phase: mass, species, and energy

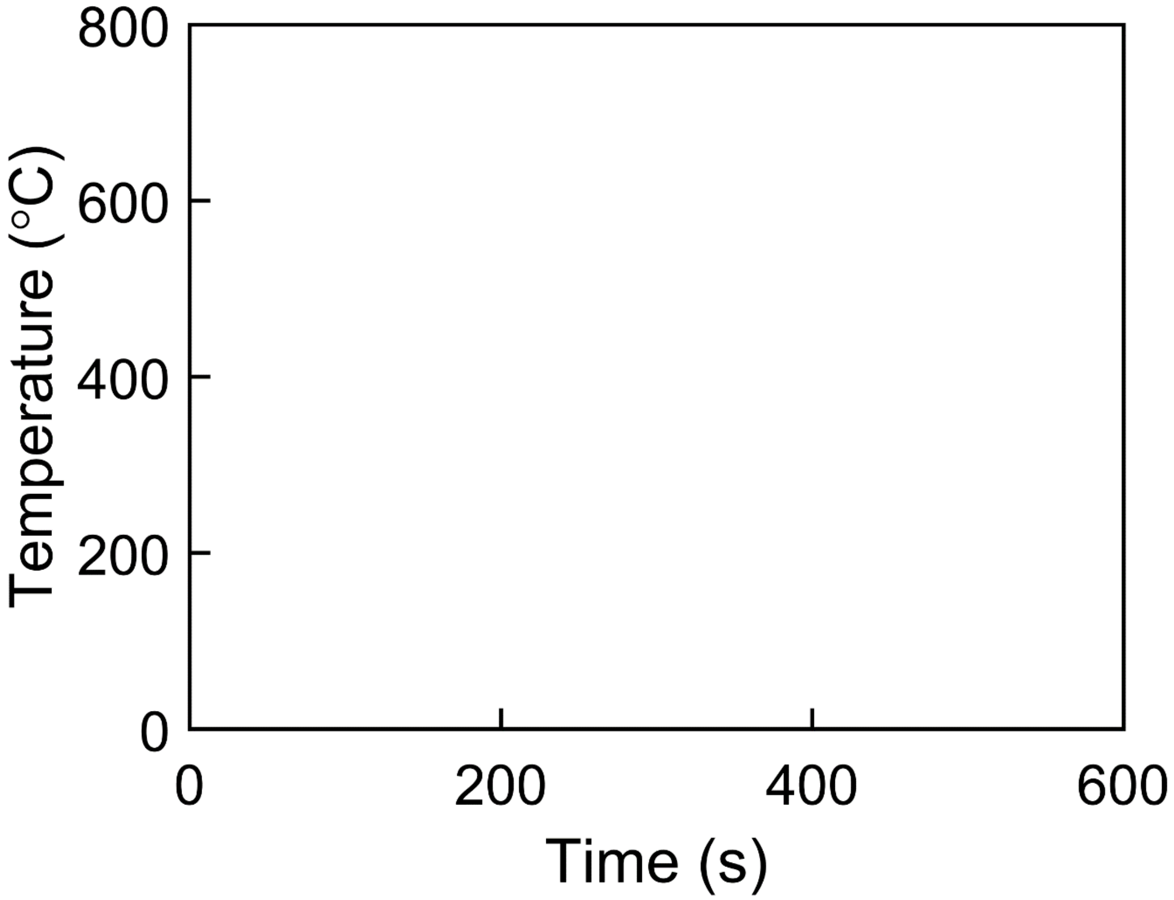
Gas-Phase: mass, species, and momentum

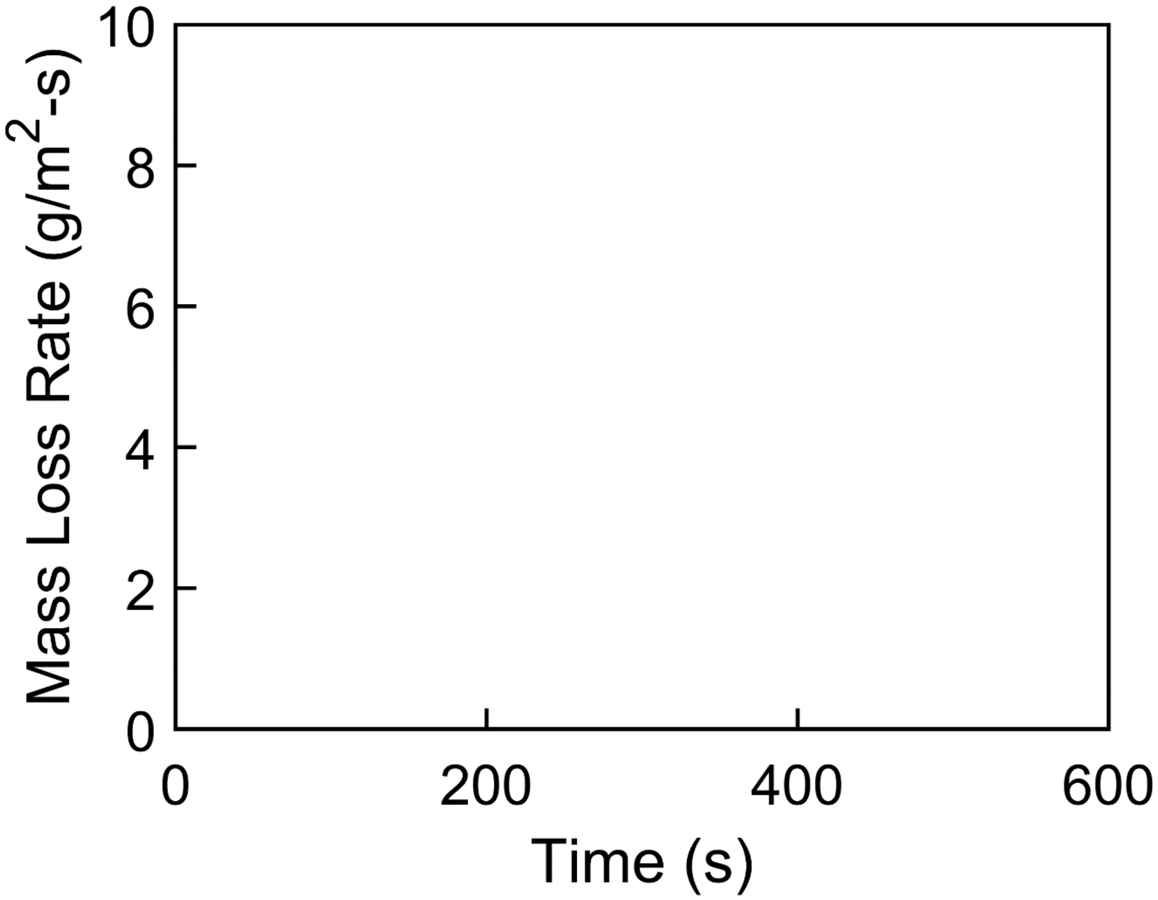
Boundaries: convection & radiation

Properties: Literature

No Calibration

Mesoscale (40 kW/m^2, inert)





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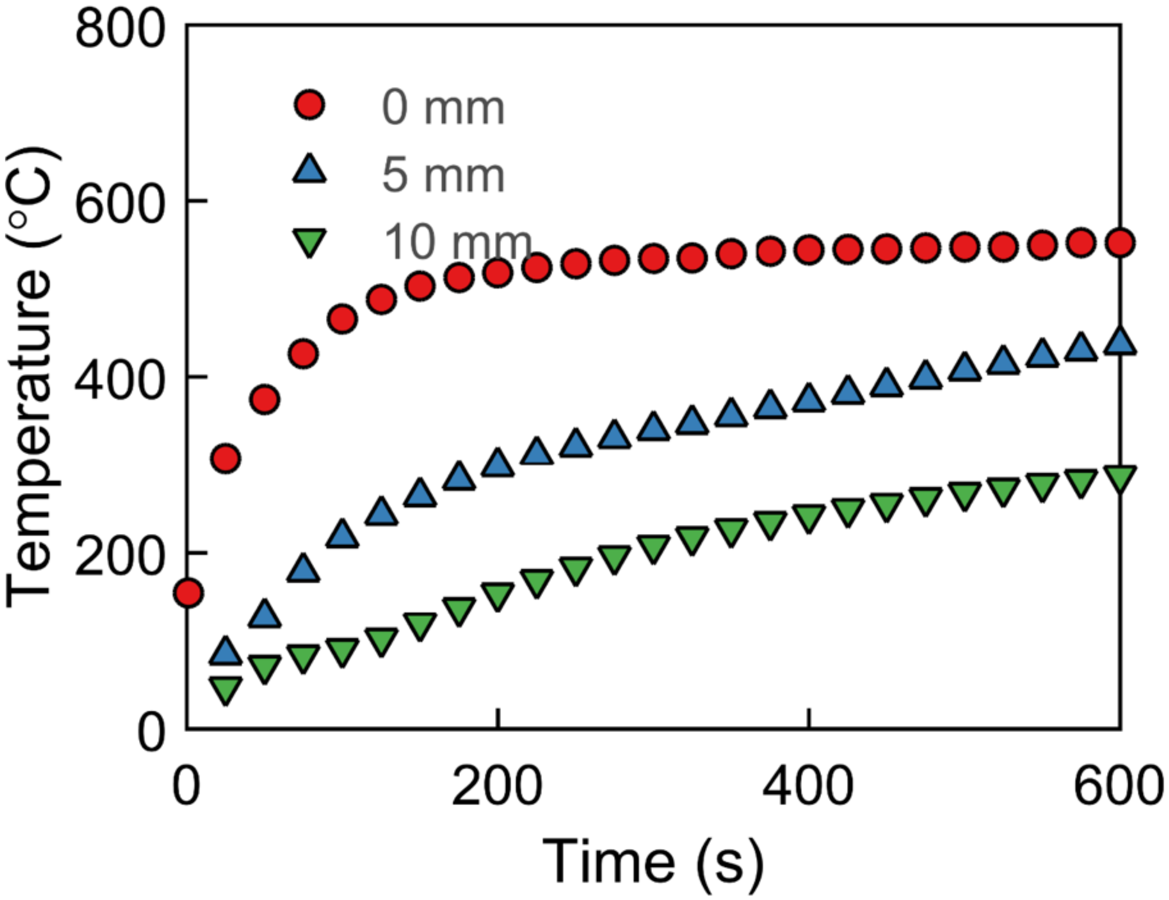

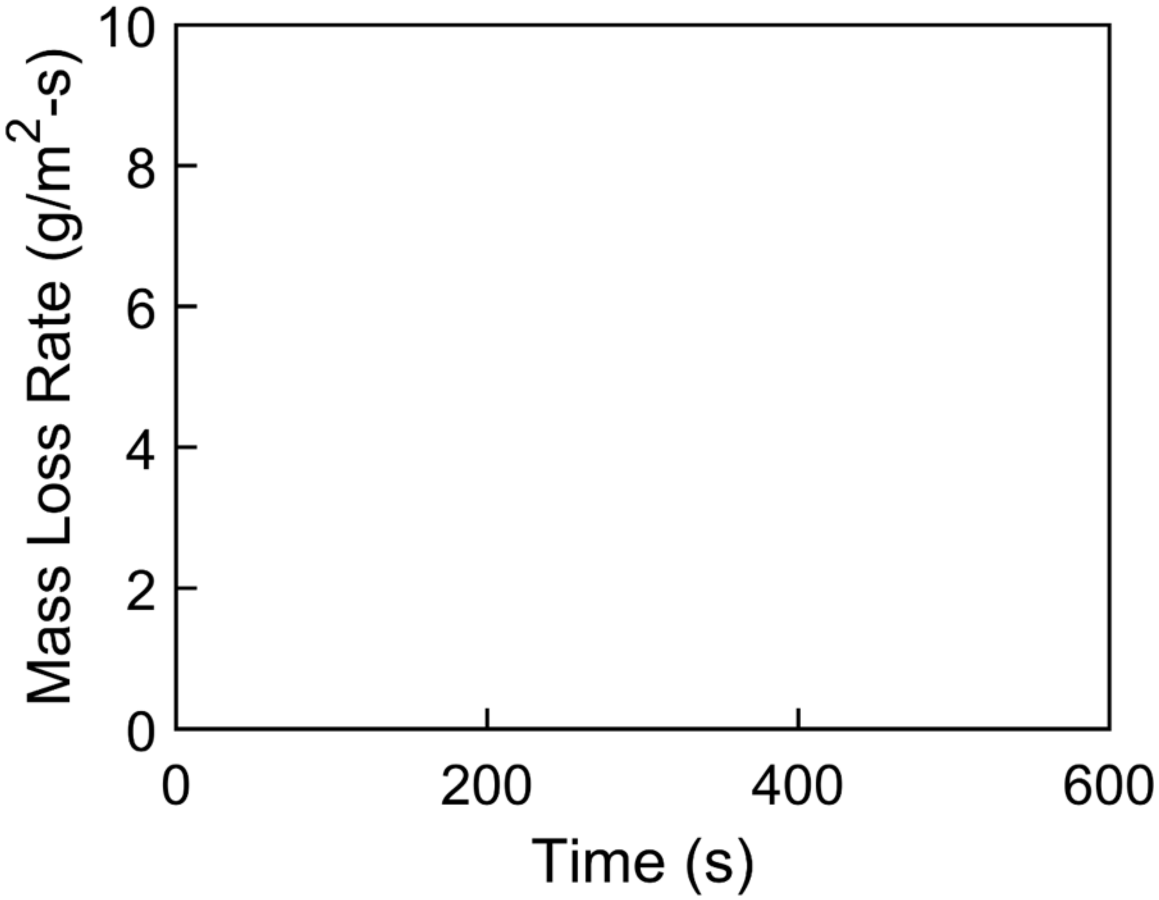

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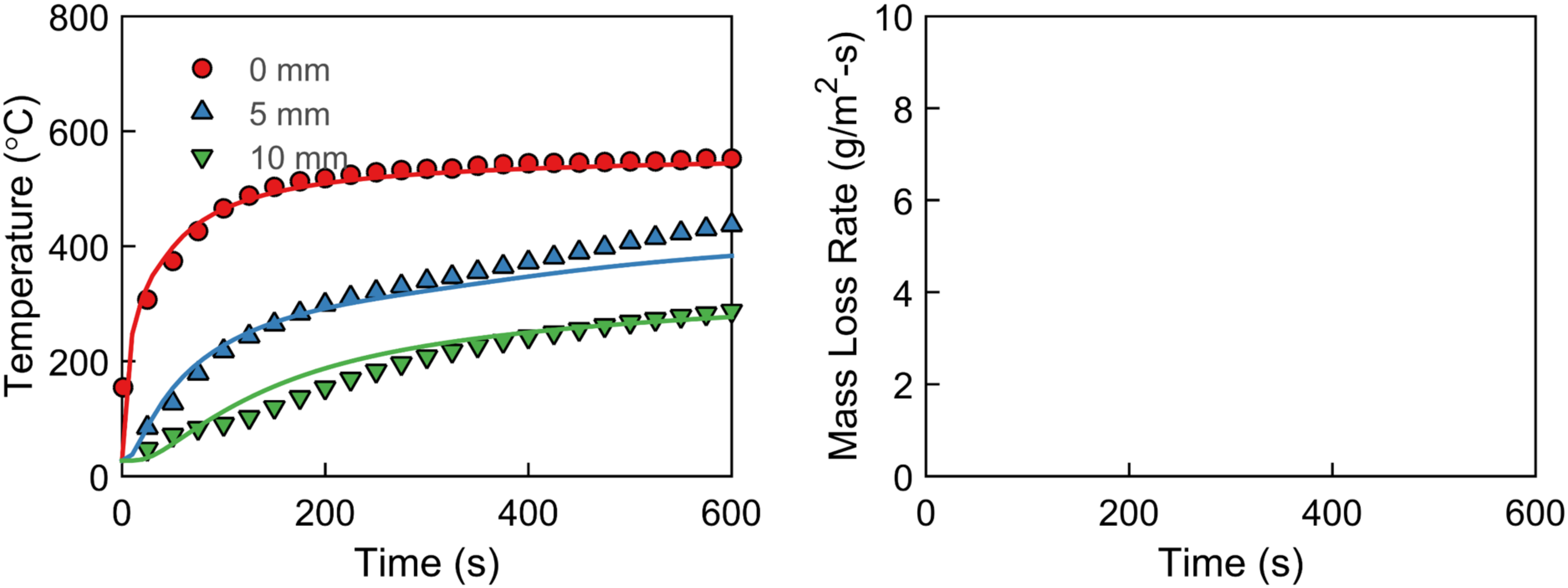

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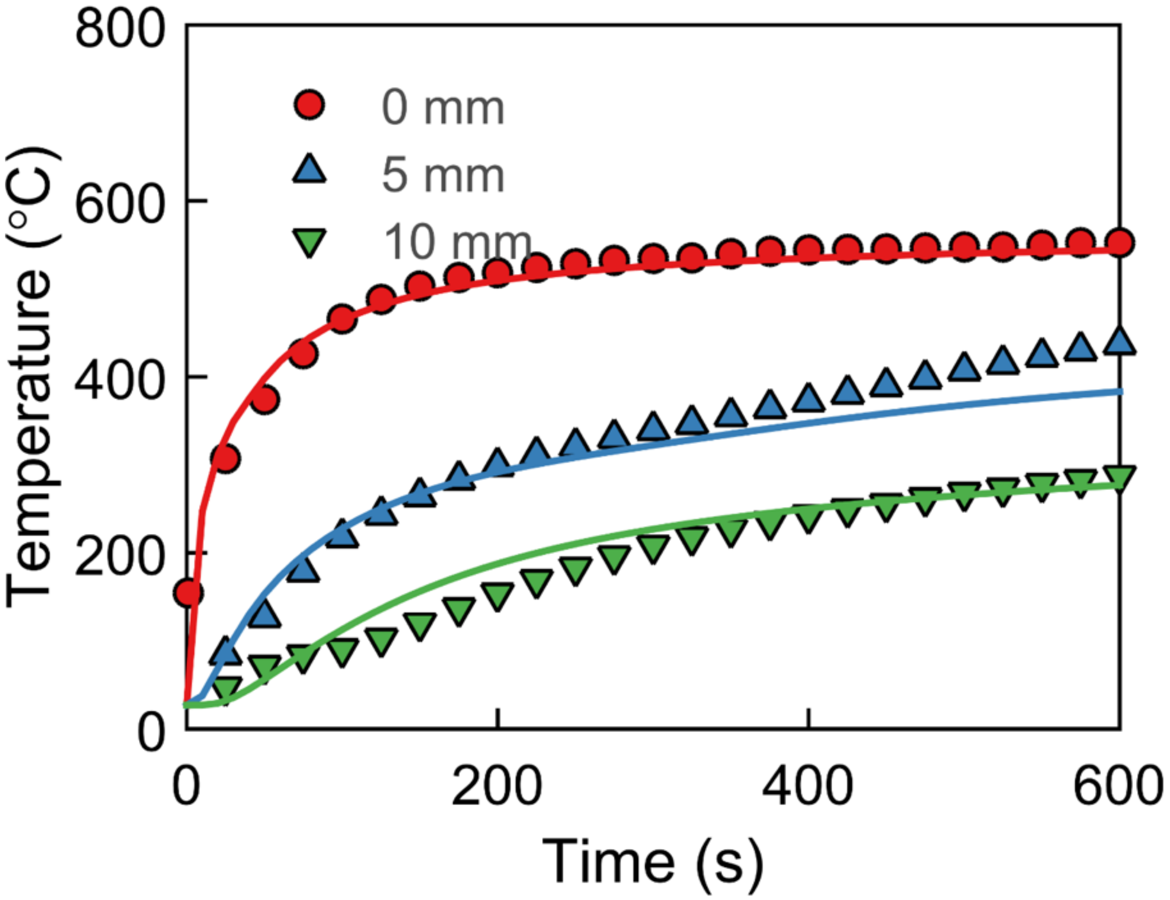

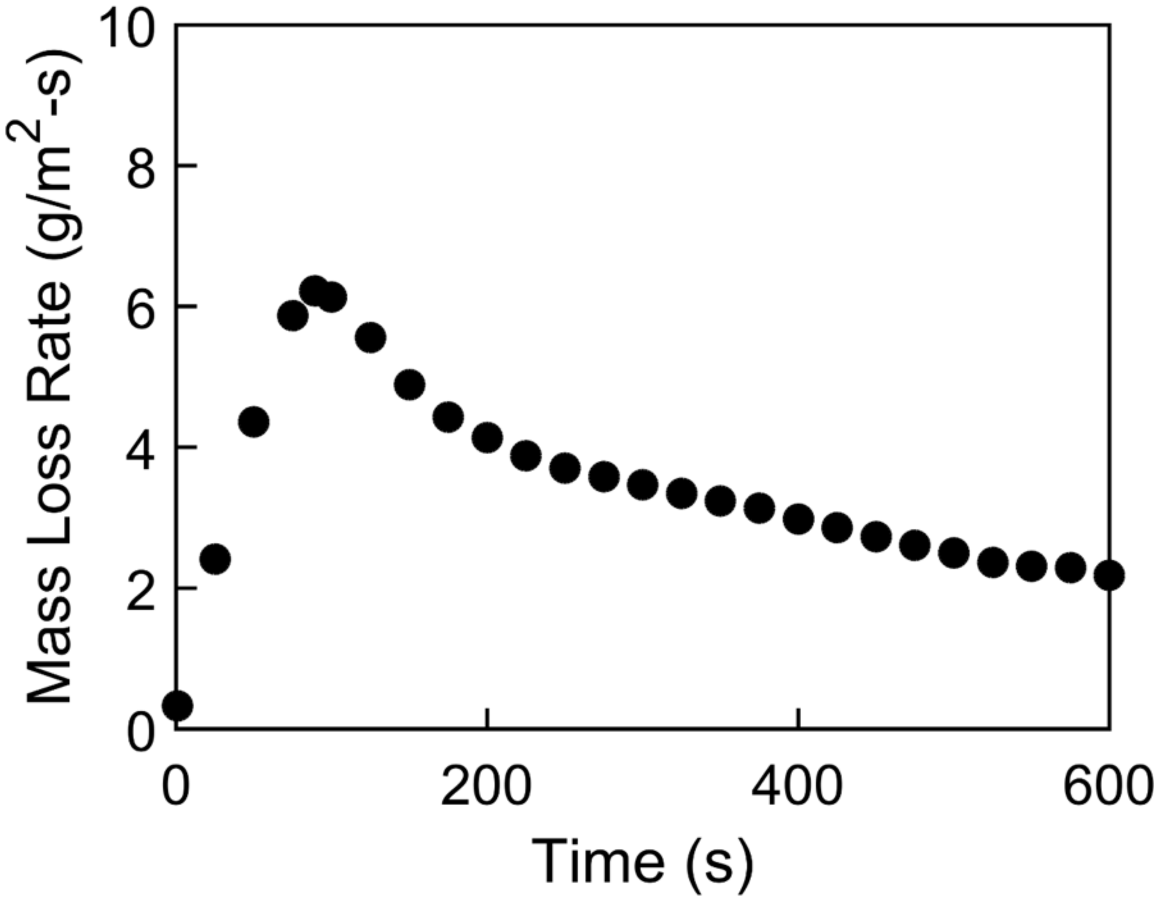

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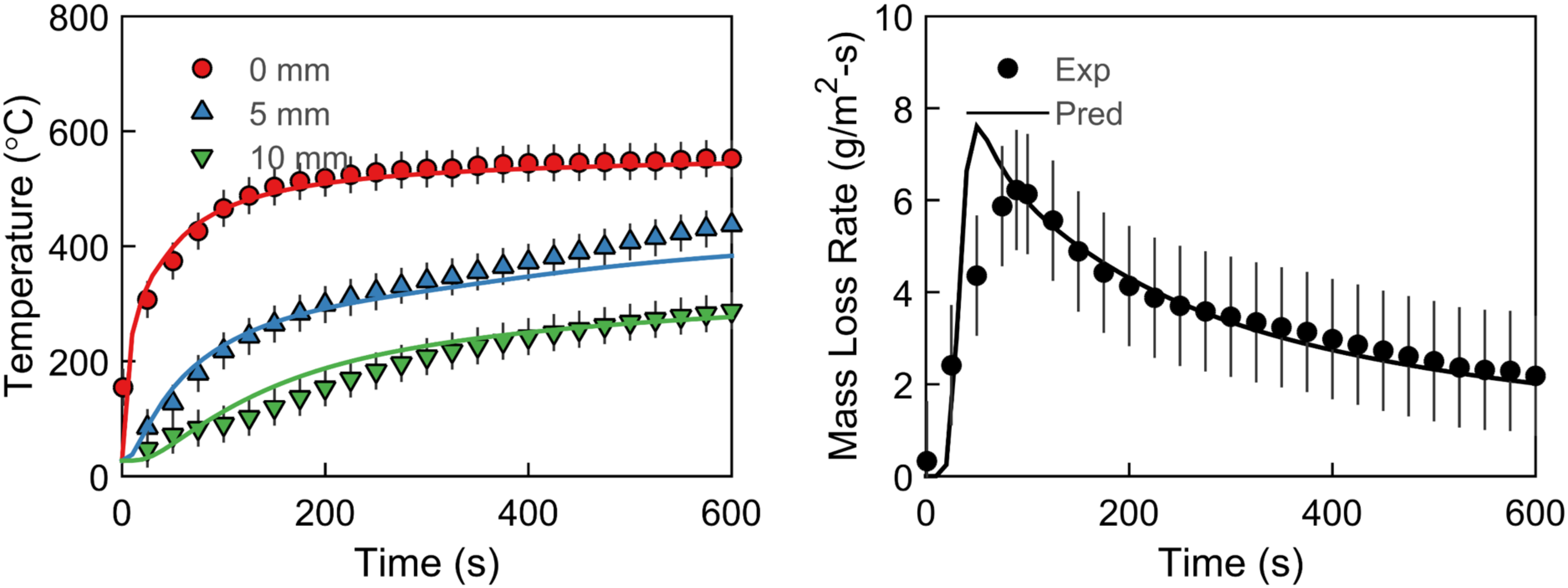


Experiments: Kashiwagi, Ohlemiller & Werner 1987

Is the 300 Isotherm conservative?

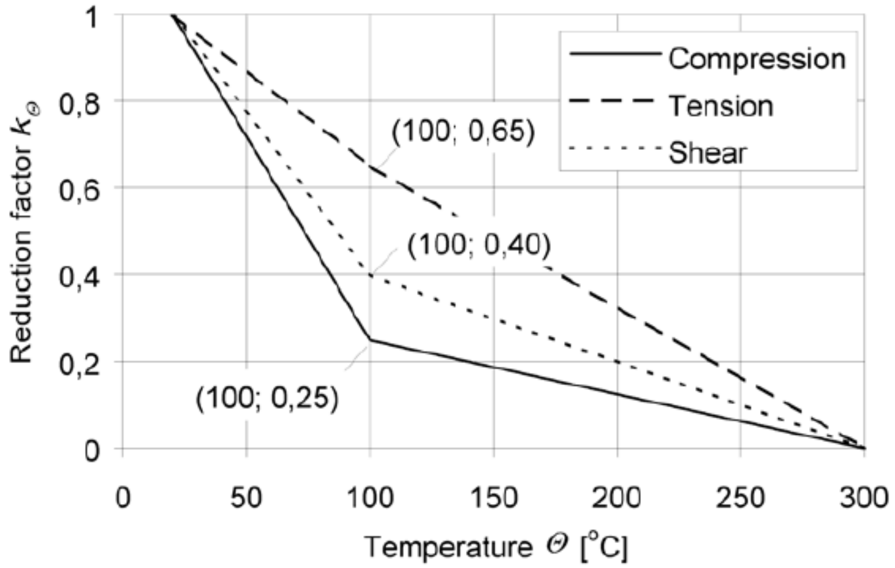
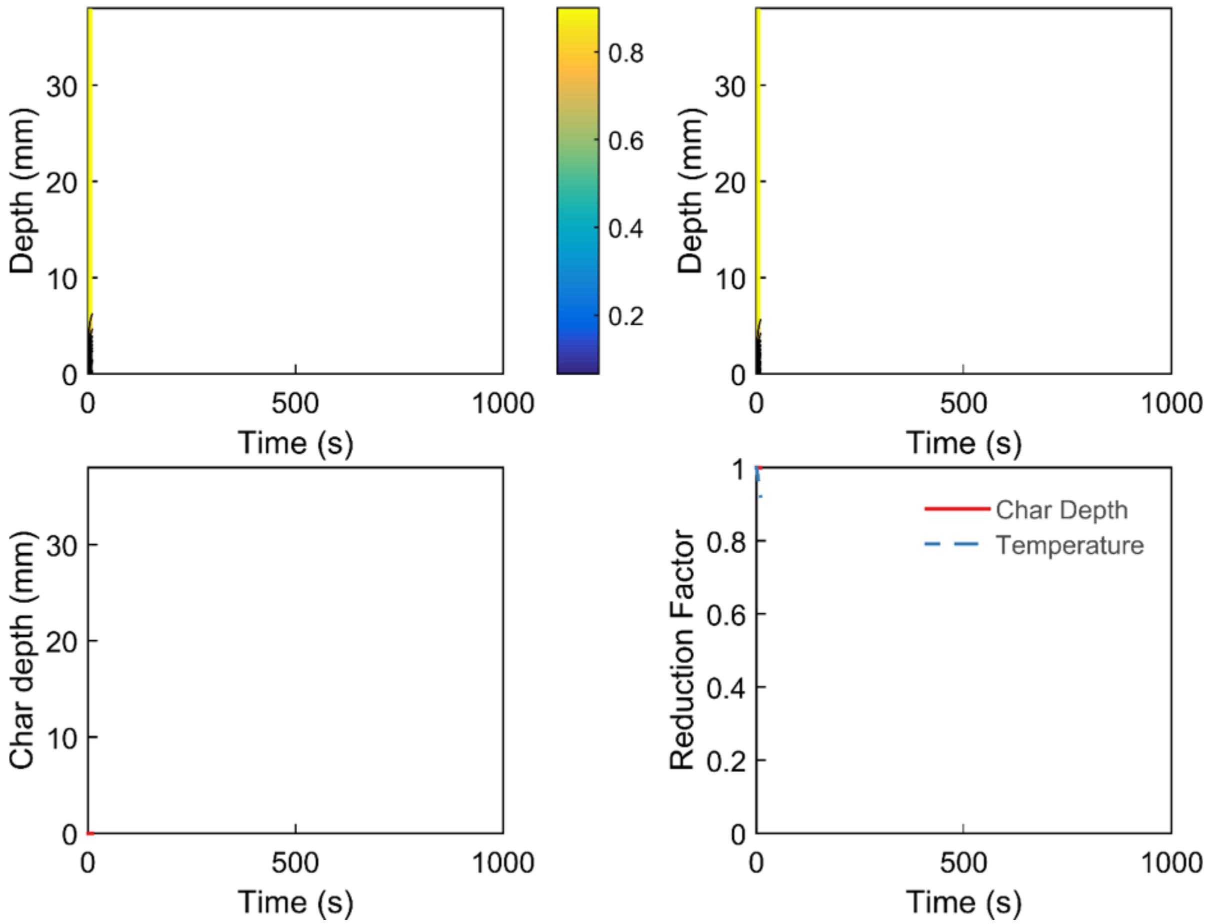


Figure B4 – Reduction factor for strength parallel to grain of softwood

Eurocode, 1995



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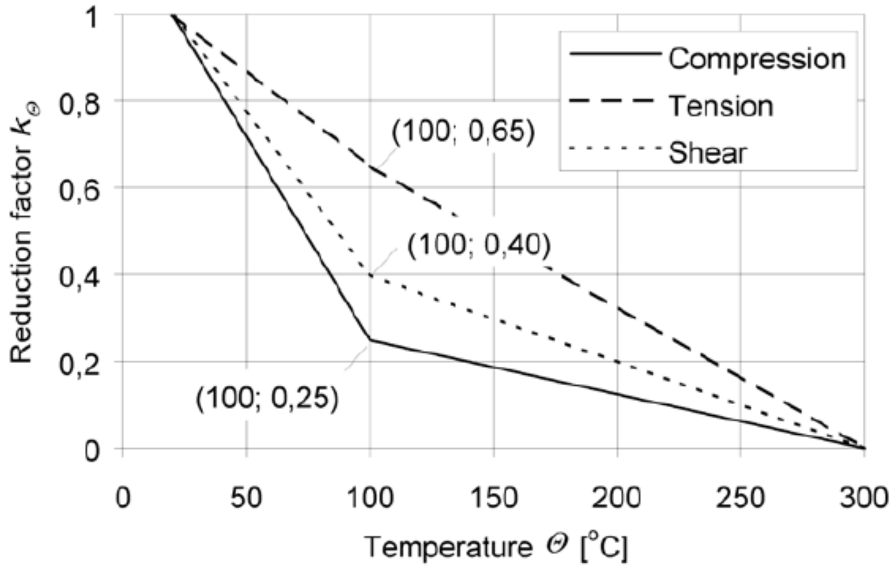

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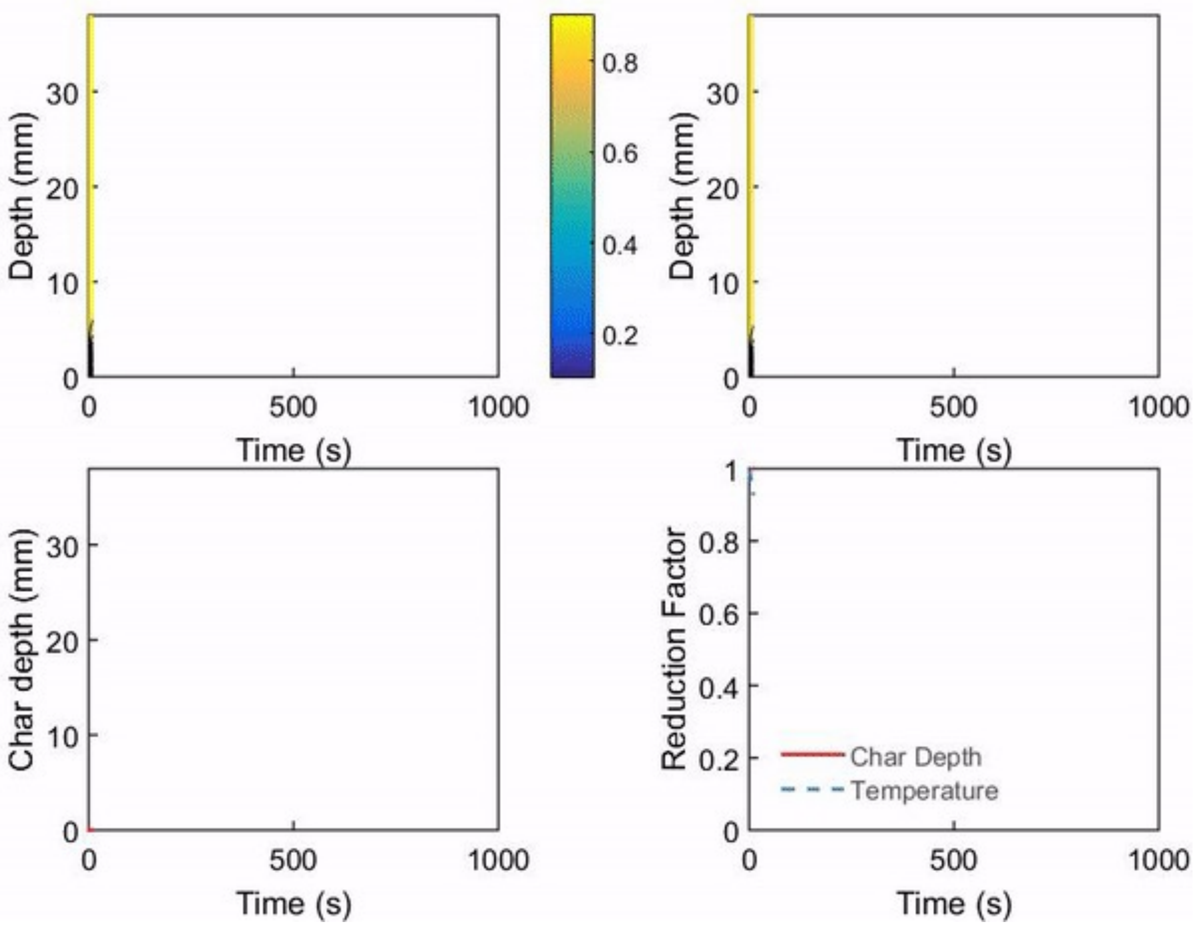

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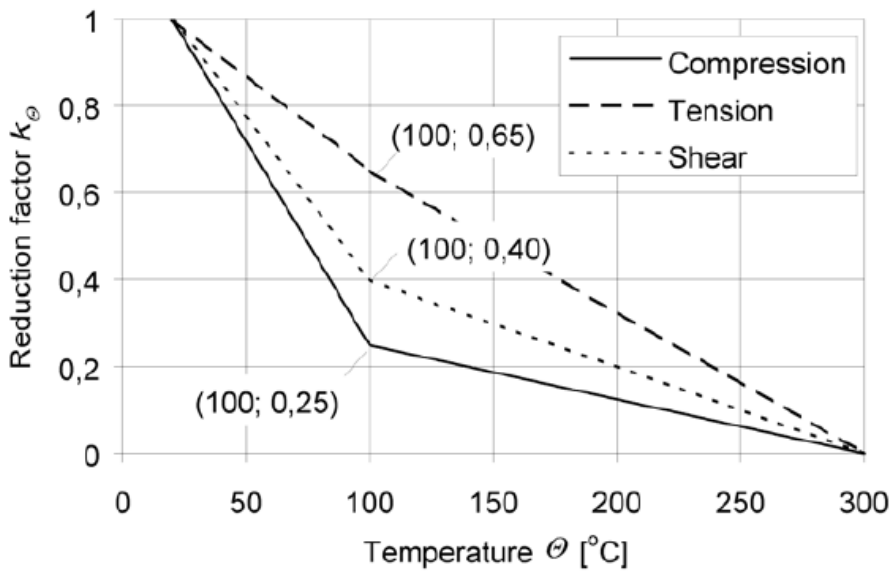

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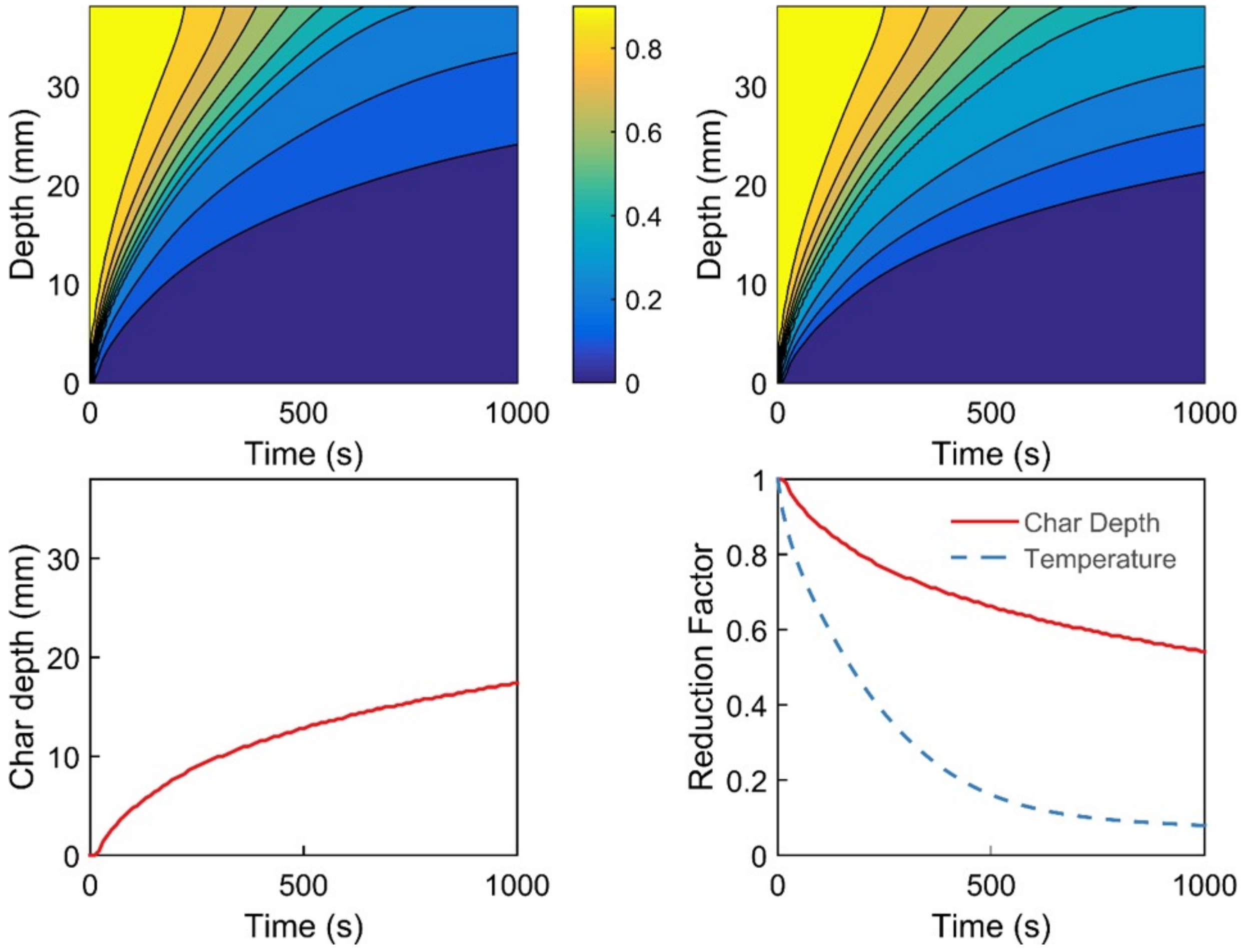


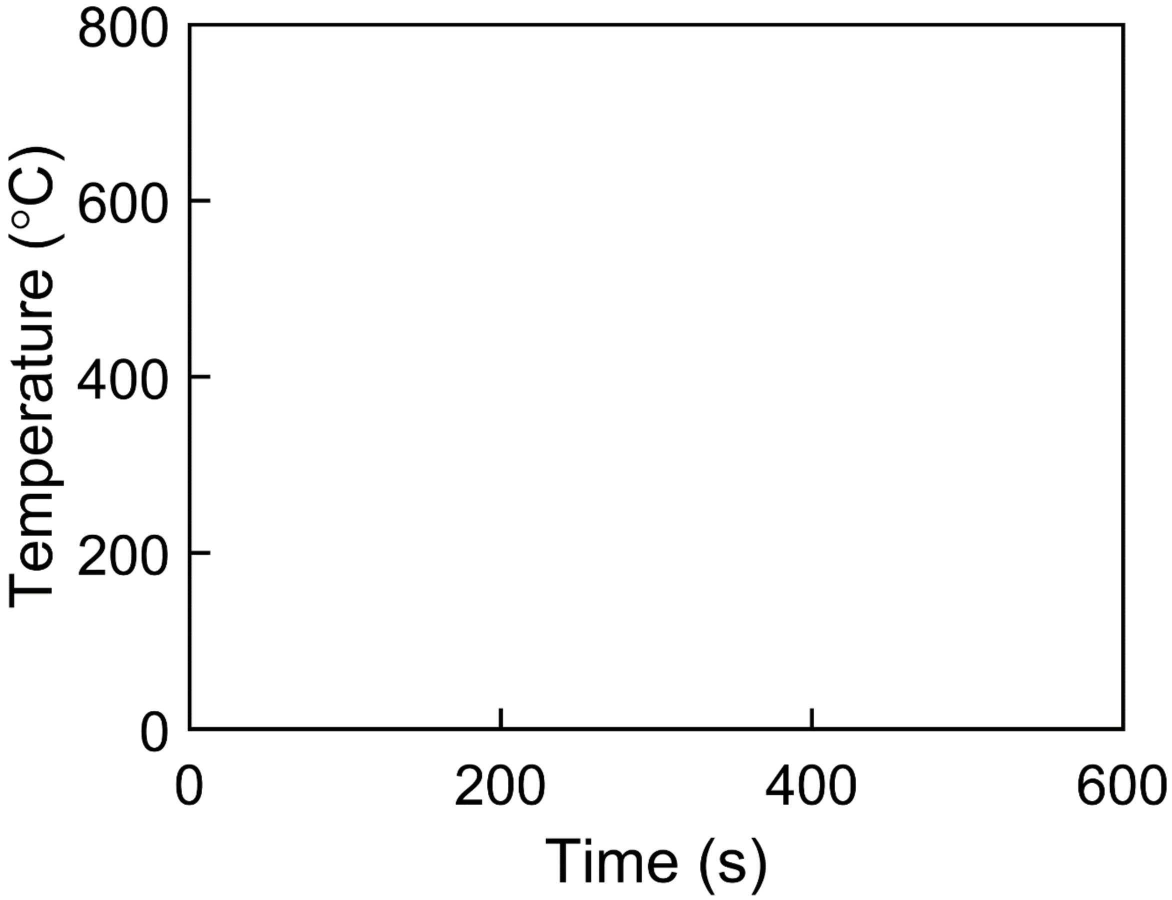
Conclusion

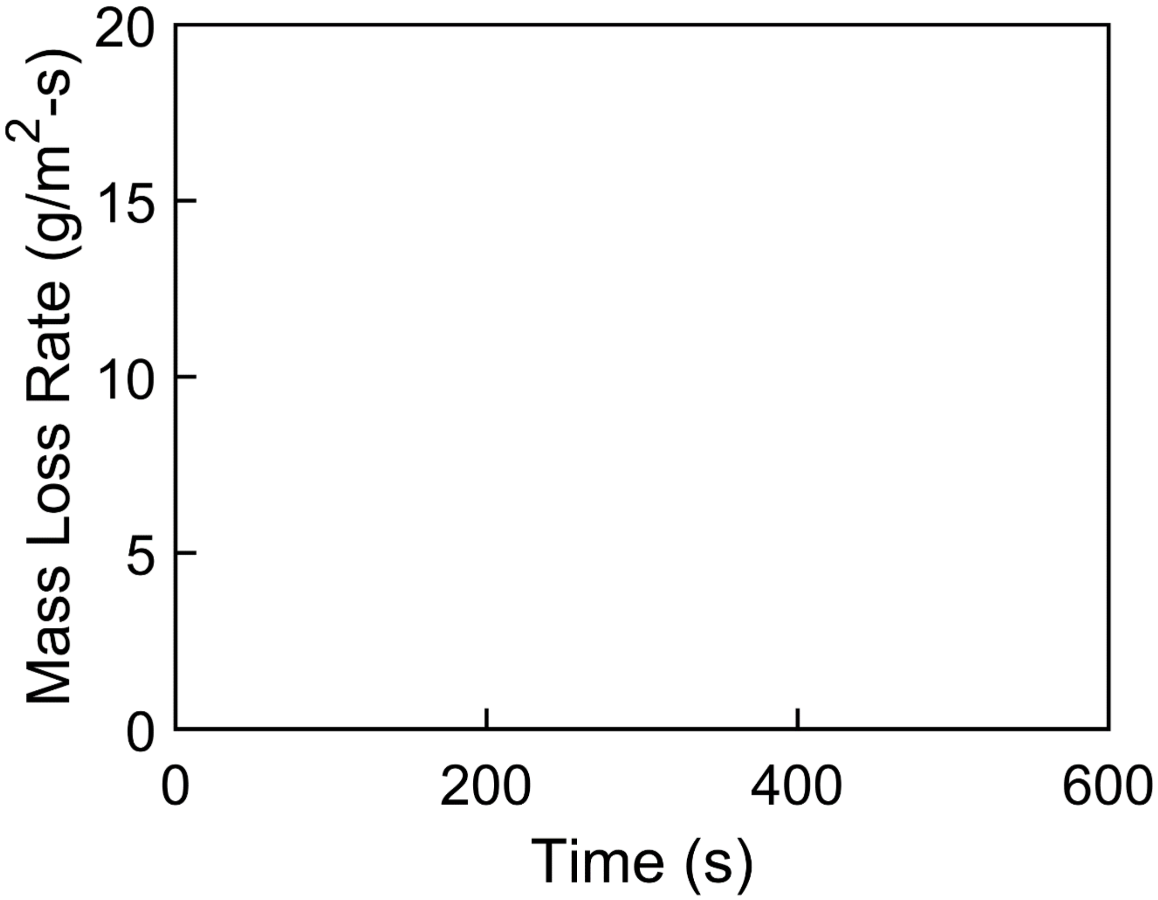
- The appropriate model is neither the most complex or the most simplest.
- We developed a novel model that performs well across scales
- It gives new insight into the strength decay of timber
- Introduced a framework for complexity and uncertainty
- The universal charring rate might be non-conservative under certain heating conditions.

Metsaewood, 2016

Back –UP Slides

Mesoscale (40 kW/m^2, air)





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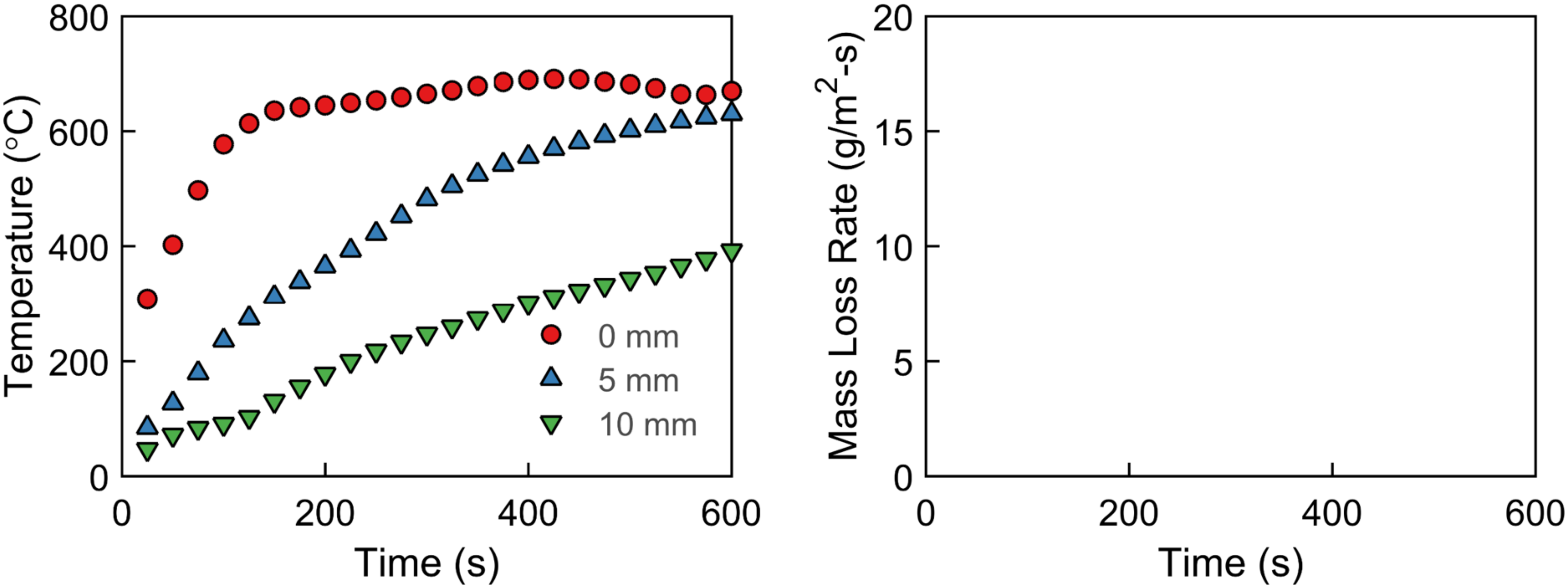

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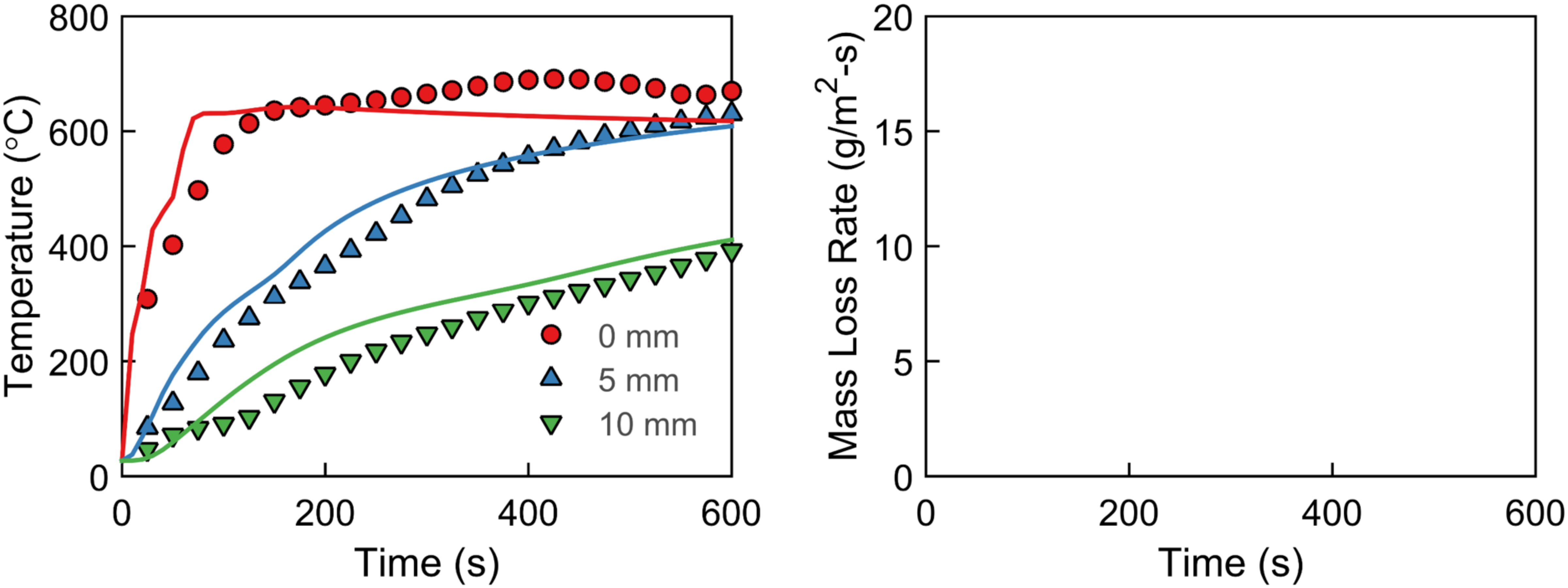

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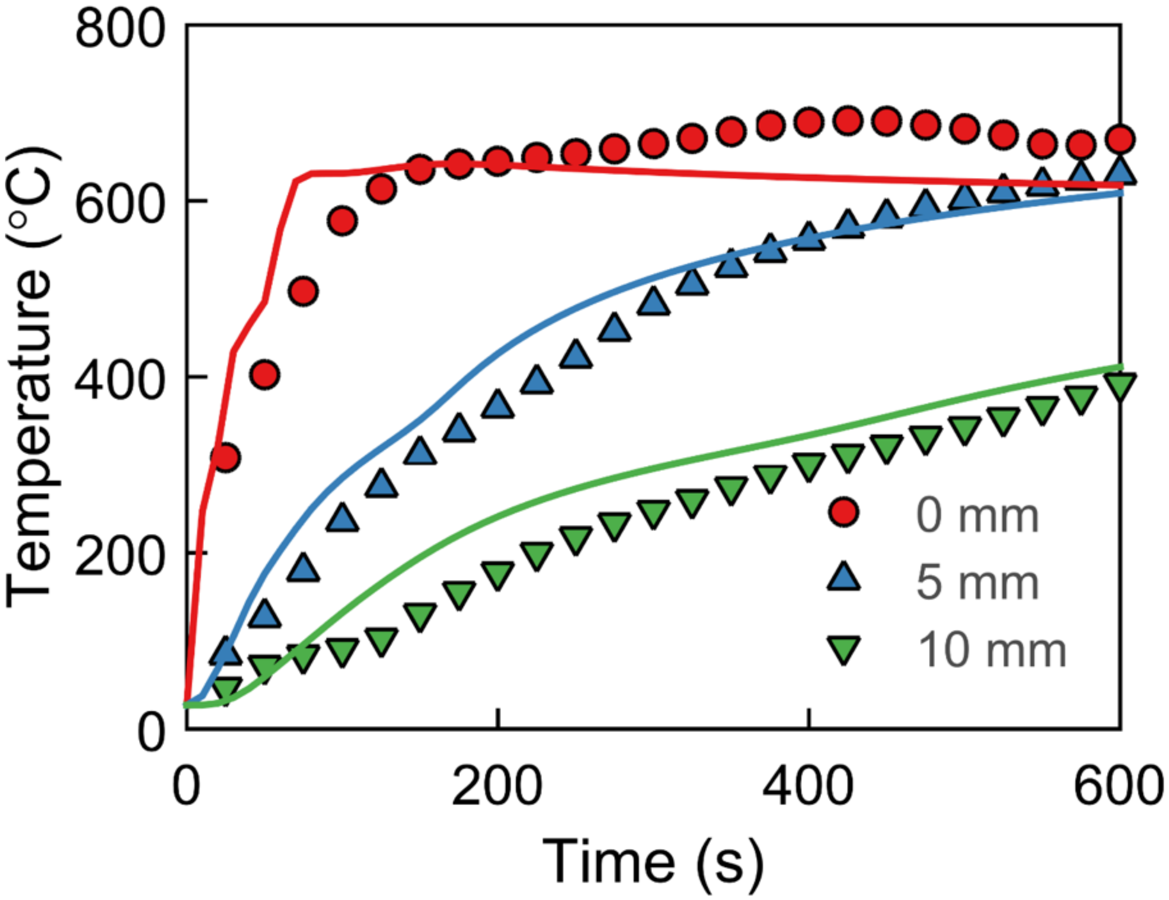

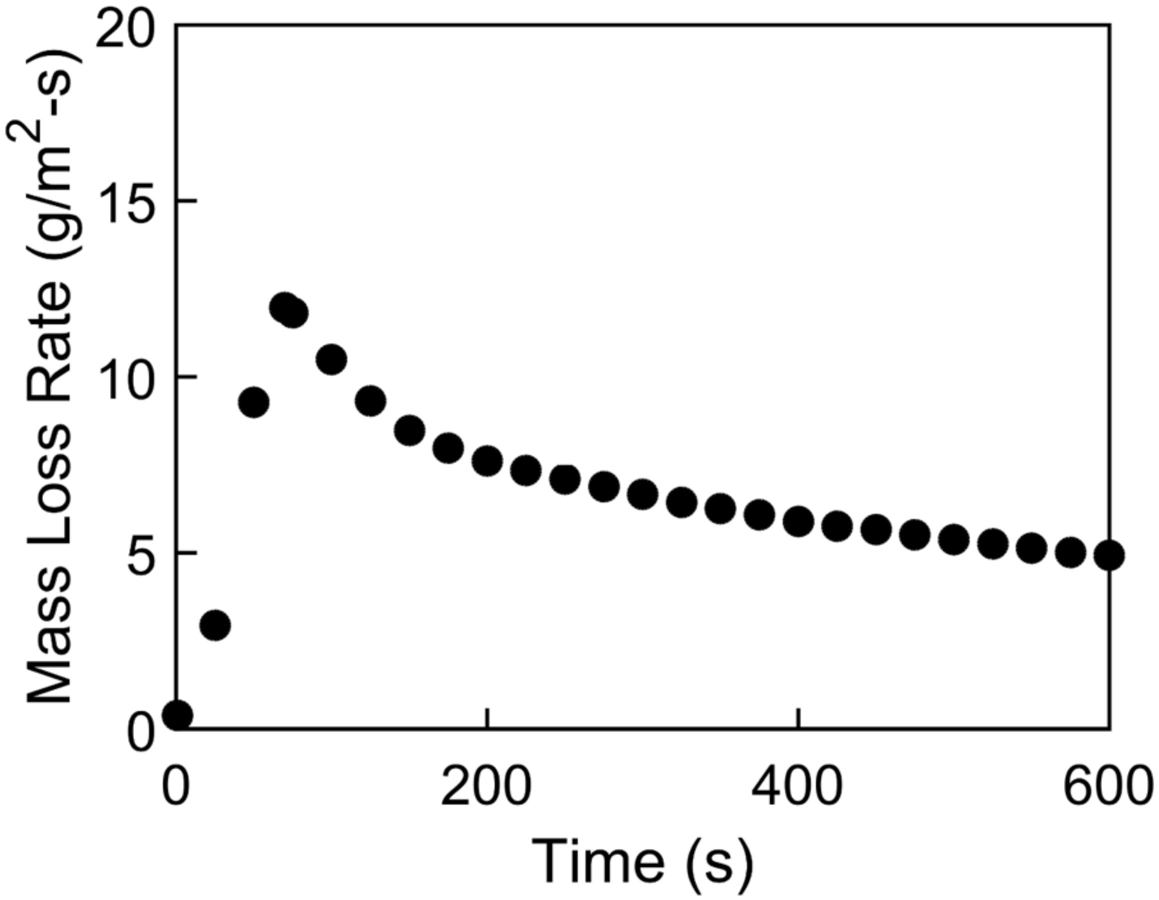

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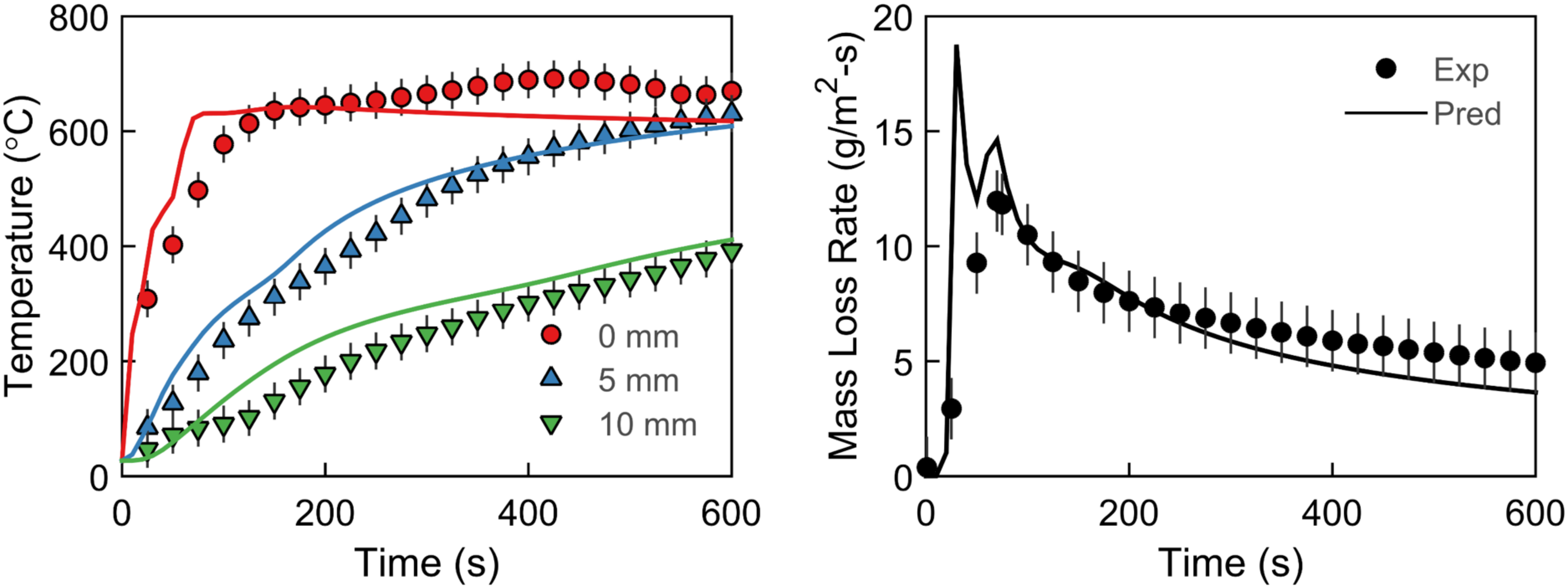

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