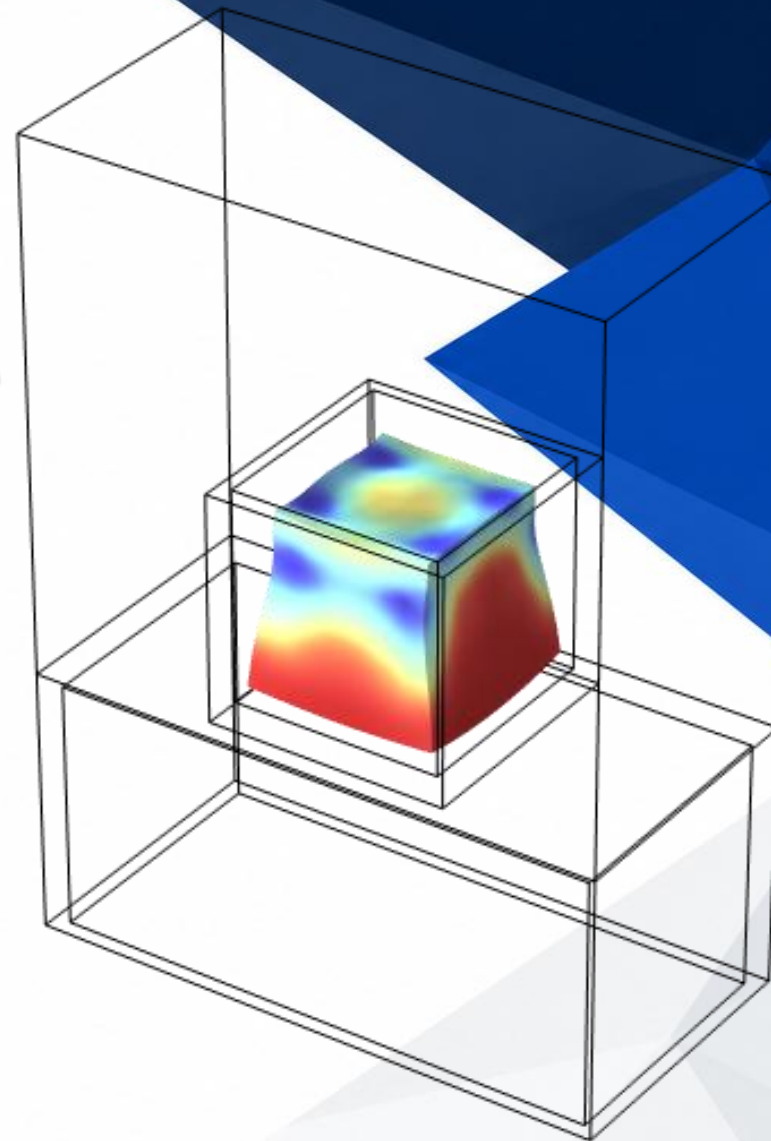


Multiphysics Modeling of Microwave-Induced Tissue Shrinkage Using a Rectangular Waveguide

V. Mongkol¹, K. Junsook¹, W. Preechaphonkul²,
S. Vongpradubchai¹, and P. Rattanadecho¹

¹ Thammasat University, Pathum Thani, Thailand

² King Mongkut's University of Technology Thonburi, Bangkok, Thailand

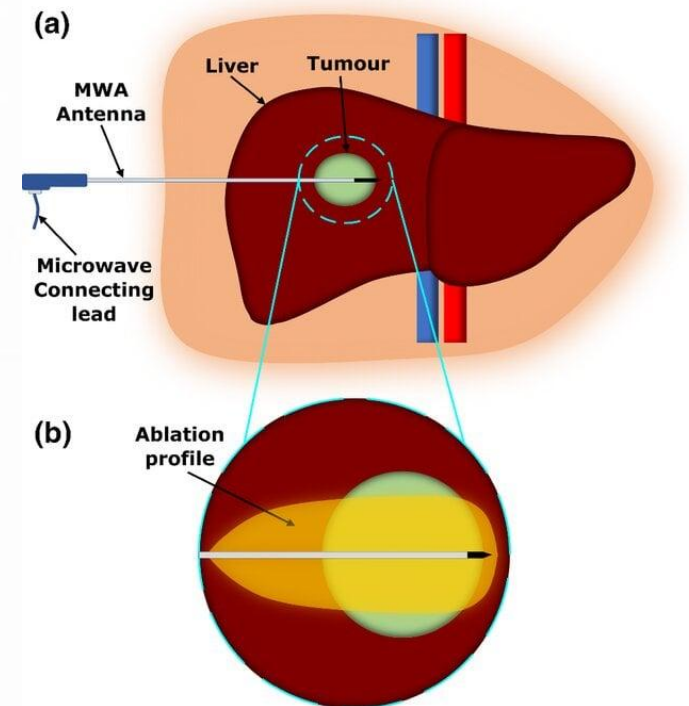


MICROWAVE HEATING FOR TUMOR ABLATION

- MWA destroys tumors through localized heating.
- Tissue exhibits both thermal and mechanical responses.
- Accurate prediction is important for post-ablation assessment.



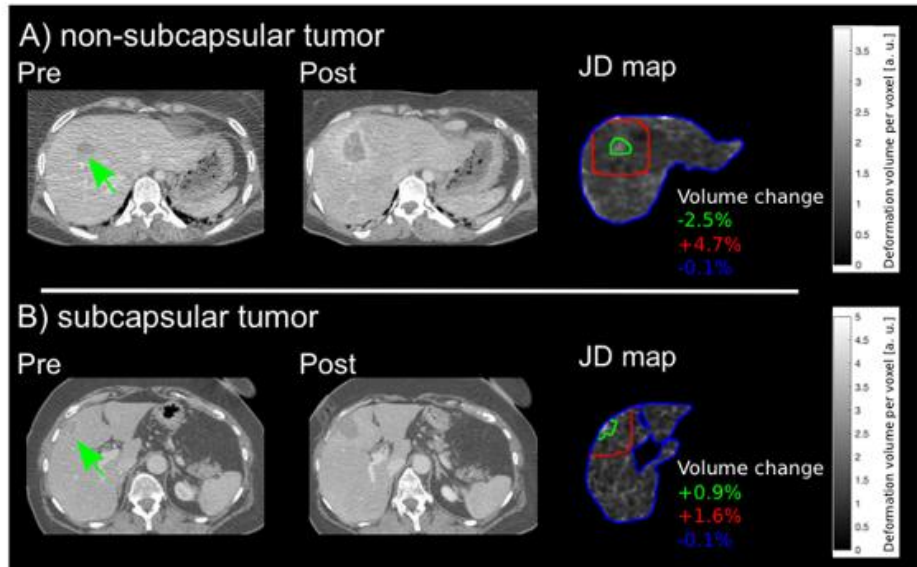
Schaible et al., 2020; *Scientific Reports*; University Medical Center Regensburg



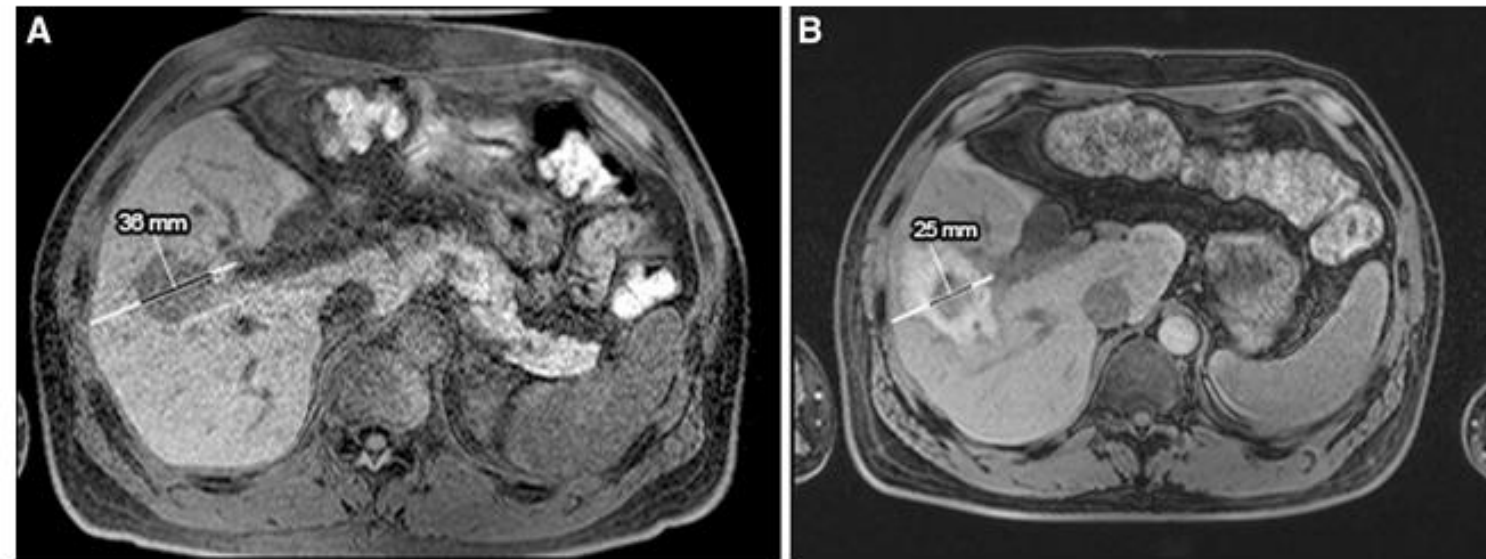
Kernot et al., 2023, *Biomech. Model. Mechanobiol.*, 22(1), 271–280.

TISSUE CONTRACTION DURING MWA

- Post-ablation imaging demonstrates significant tissue contraction.
- Contraction can alter the apparent ablation geometry.
- Mechanical deformation should therefore be included in MWA models.



Pöhler et al., 2022, *Int. J. Hyperthermia*, 39(1), 1371–1378.



Lee et al., 2016; “Microwave Ablation of Liver Tumors”; *Abdominal Radiology*

TWO MECHANISMS ARE EXPECTED TO DRIVE TISSUE SHRINKAGE

- Damage-induced shrinkage strain, ε_{td}
- Water-loss-induced hygroscopic swelling strain, ε_{hs}

$$\varepsilon_{td} = -\xi\theta_d, \varepsilon_{hs} = \beta(W - W_0)$$

Challenge ?

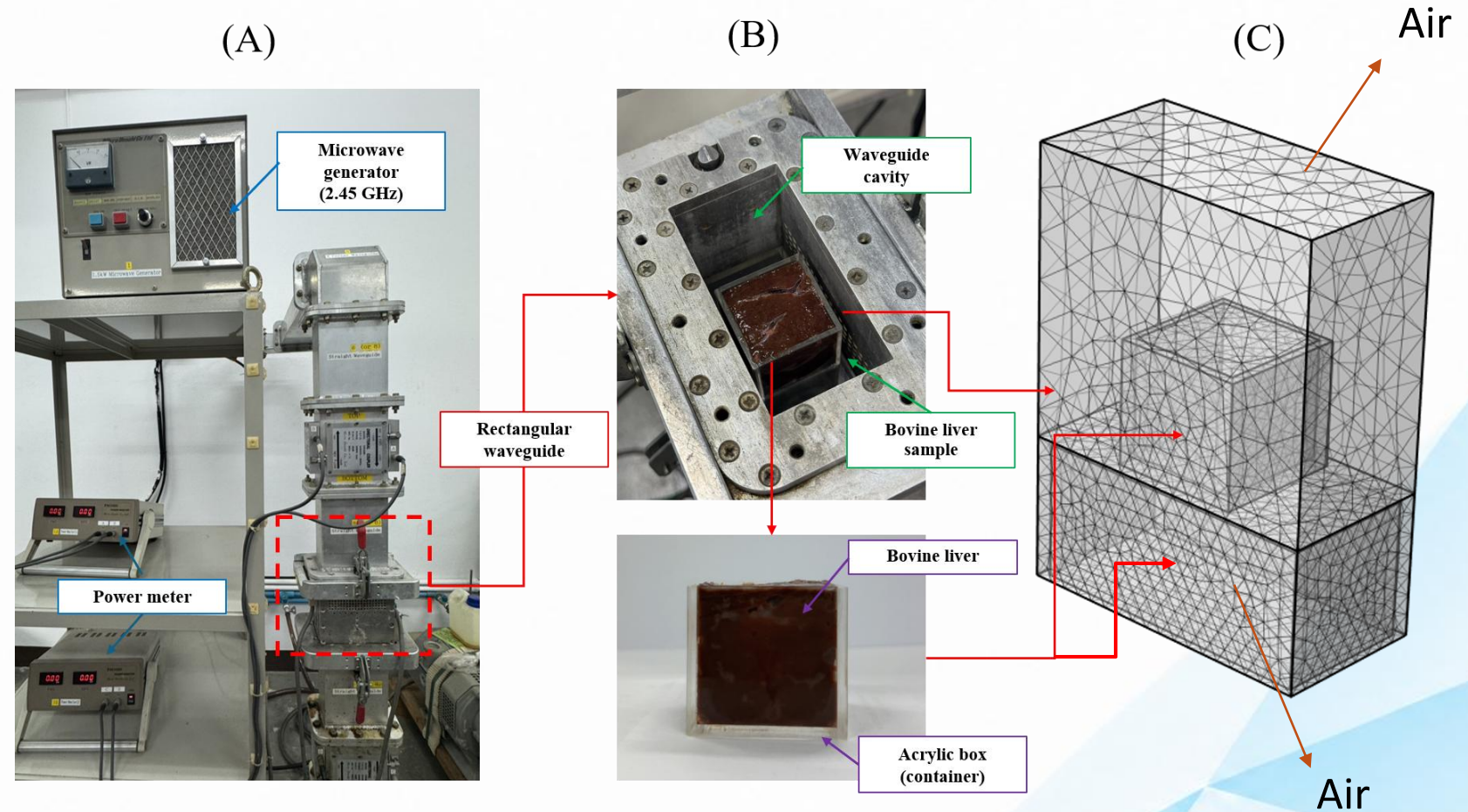
Models capable of predicting tissue shrinkage remain limited due to insufficient experimental data for the shrinkage coefficients, ξ and β .

Goal

- Experimentally estimate the water-loss coefficient, β .
- Calibrate ξ and β for 3D model.
- Validate the 3D Multiphysics model against temperature and deformation measurements.

EXPERIMENT SETUP AND NUMERICAL MODEL

- 2.45 GHz microwave generator
- Power meter
- waveguide cavity
- Acrylic sample container
- Bovine liver $\approx 4 \times 4 \times 4 \text{ cm}^3$
- Heating duration: 10 min
- Add input power for Case 1 and Case 2



Experimental setup and 3D computational model:
(A) microwave system, (B) waveguide cavity with liver sample, and (C) computational domain.

MULTIPHYSICS MODELING FRAMEWORK

- **Electromagnetic Wave Propagation**
 - Specific absorption rate (SAR) distribution
- **Heat Transfer**
 - Temperature evolution, T
 - Water content, $W(T)$
- **Arrhenius Model**
 - Thermal damage fraction, θ_d
- **Solid Mechanics**
 - Damage-induced shrinkage strain, ε_{td}
 - Hygroscopic swelling strain, ε_{hs}
 - Tissue displacement and deformation

MULTIPHYSICS MODELING

Electromagnetic Wave Propagation

$$\nabla \times [\mu_r^{-1} (\nabla \times \mathbf{E})] - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) \mathbf{E} = 0$$

- Calculates microwave propagation and the electric-field distribution.
- Tissue dielectric properties used as function of temperature.
- The absorbed microwave energy is converted into a volumetric heat source:

$$Q_{\text{EM}} = \frac{1}{2} \sigma |\mathbf{E}|^2 = \rho \text{ SAR}$$

MULTIPHYSICS MODELING

Heat Transfer

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{EM} + L_v \frac{\partial W(T)}{\partial t}$$

Assumption:

- Microwave energy is absorbed by the tissue and converted into heat, Q_{EM} .
- Tissue water content, $W(T)$, decreases with increasing temperature and is described by an empirical function fitted to experimental data.

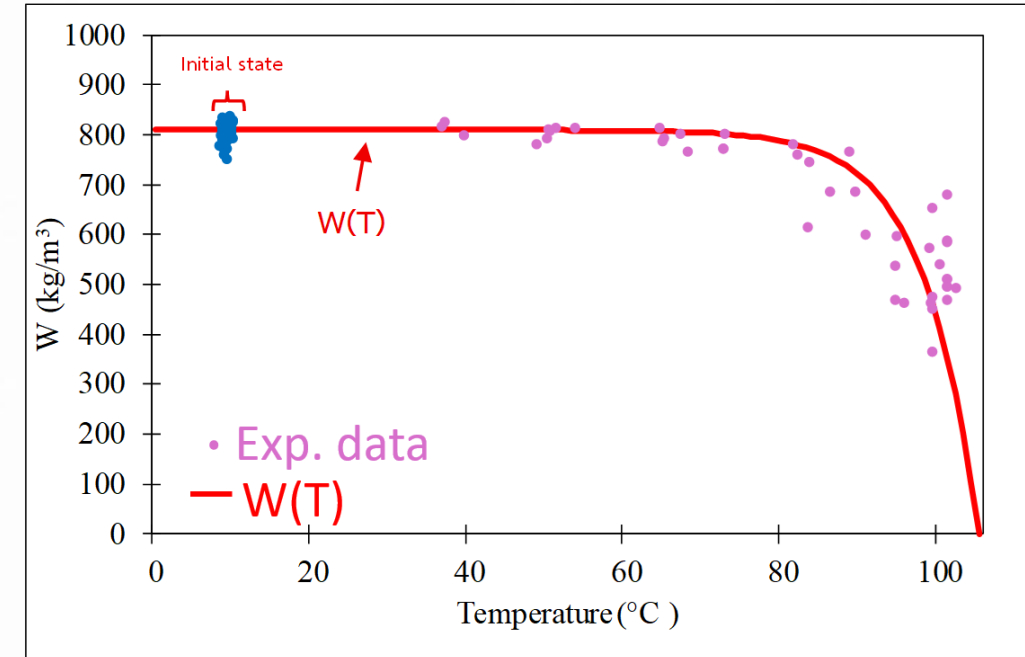
Thermal damage analysis

Arrhenius Model

$$\Omega(t) = \int_0^t A \exp\left(-\frac{E_a}{RT}\right) dt, \quad \theta_d = 1 - \exp(-\Omega) :$$

Ω : accumulated thermal damage
 θ_d : thermal damage fraction, ranging from 0 to 1

Temperature-Dependent Water Content, $W(T)$



MULTIPHYSICS MODELING

Solid Mechanics

Assumption

- Inertial effects were neglected.

Inelastic strain components

- Damage-induced shrinkage strain, ε_{td}
- Water-loss-induced hygroscopic strain, ε_{hs}

$$\nabla \cdot \boldsymbol{\sigma} = 0$$

The total inelastic strain was defined as:

$$\varepsilon_{inel} = \varepsilon_{td} + \varepsilon_{hs}$$

$$\varepsilon_{td} = -\xi\theta_d, \varepsilon_{hs} = \beta(W - W_0)$$

GEOMETRY AND BOUNDARY CONDITIONS

Electromagnetic Waves

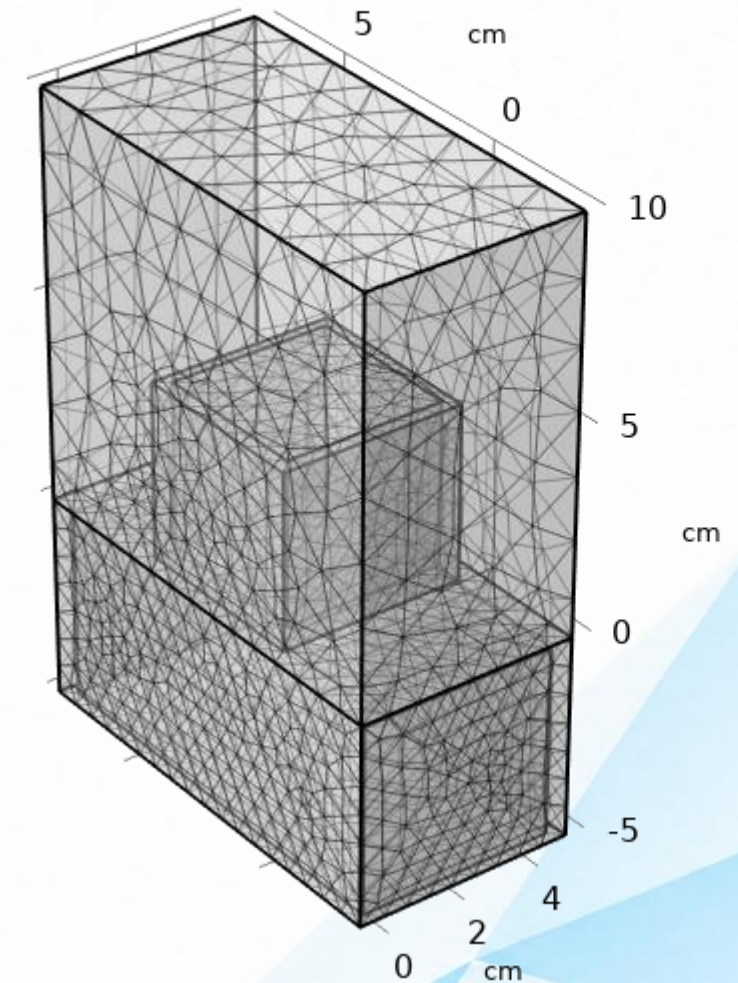
- Domain: Air, Bovine liver, Acrylic
- Top boundary — Port 1: Microwave input, TE_{10}
- Bottom boundary — Port 2: Output port
- Waveguide walls: Perfect electric conductor

Heat Transfer

- Domain: Bovine liver only
- Heat source: Microwave energy absorption, Q_{EM}
- All liver surfaces: Thermal insulation

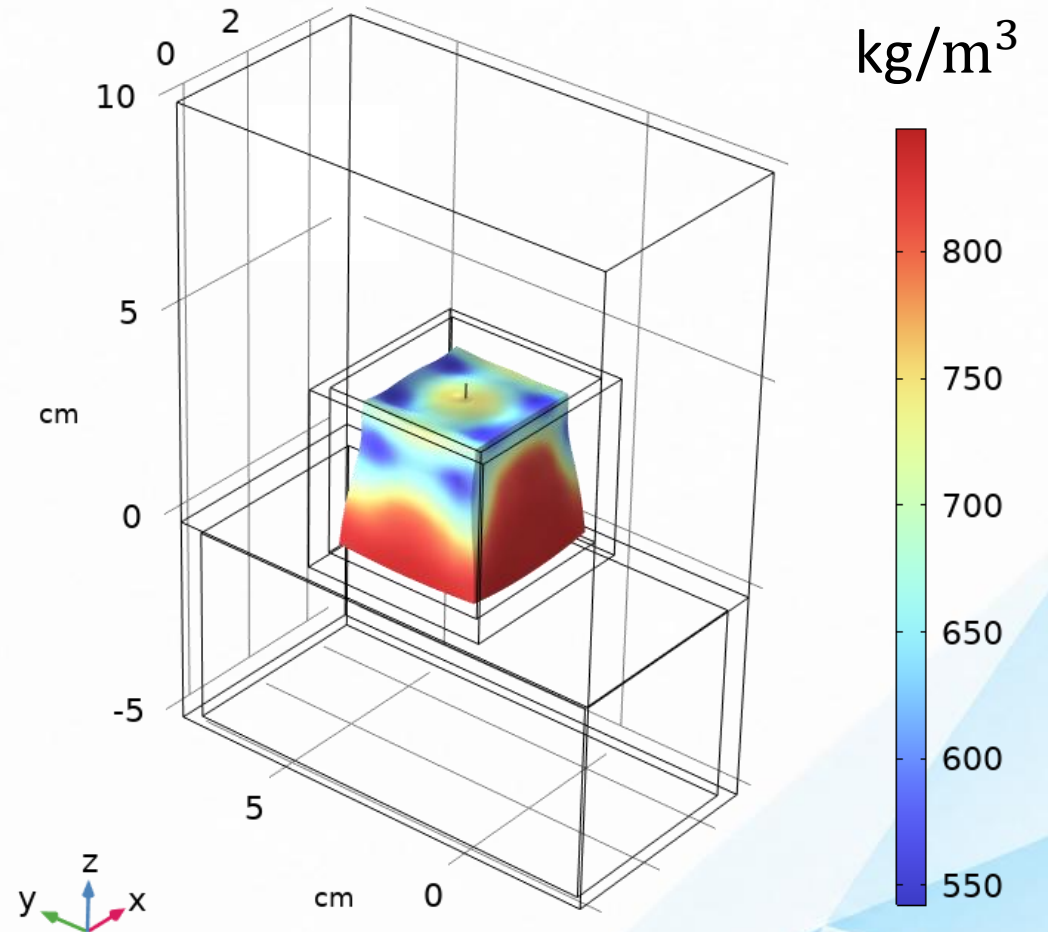
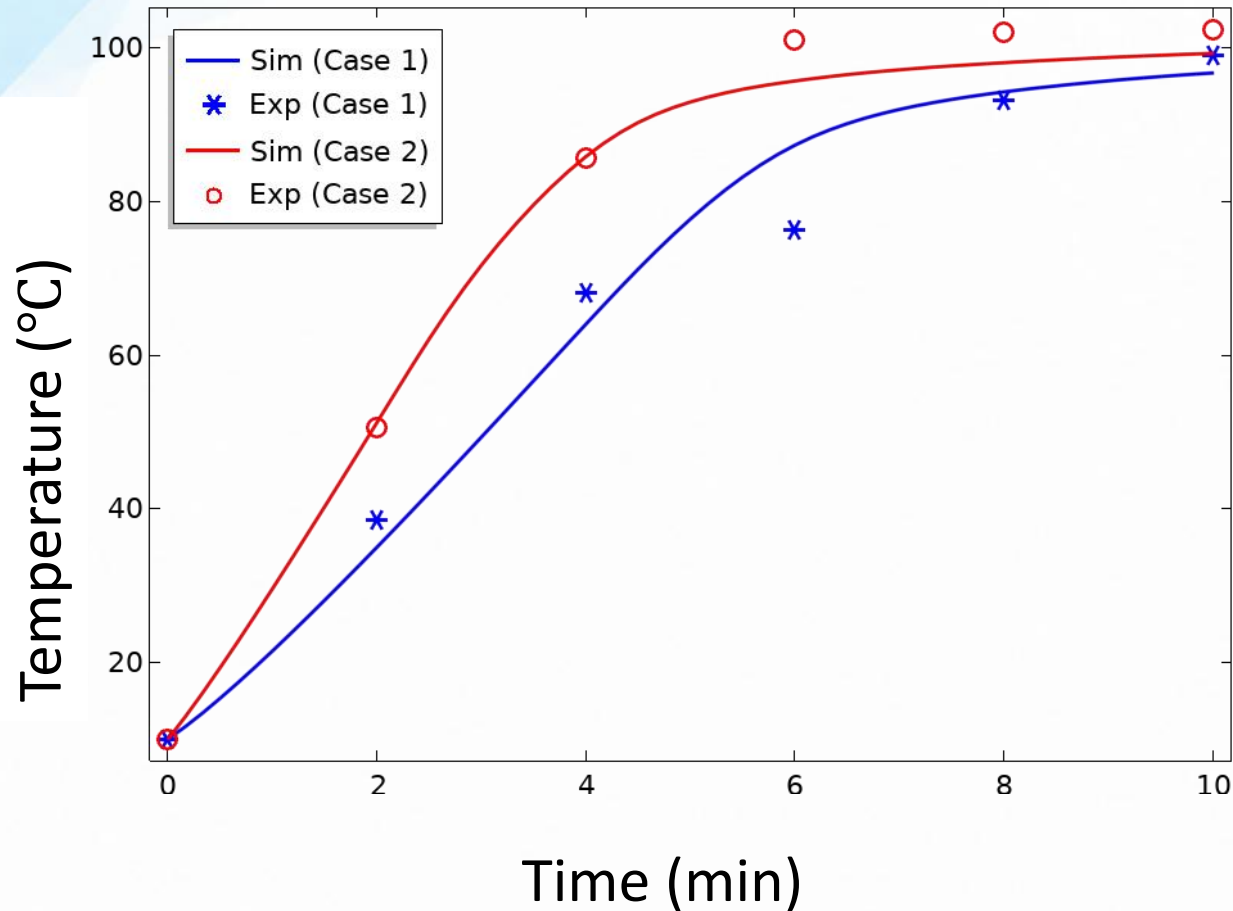
Solid Mechanics

- Domain: Bovine liver only
- Top surface: Free boundary
- Liver–container contact surfaces: Spring foundation



TEMPERATURE AND WATER CONTENT

Water content, $W(T)$

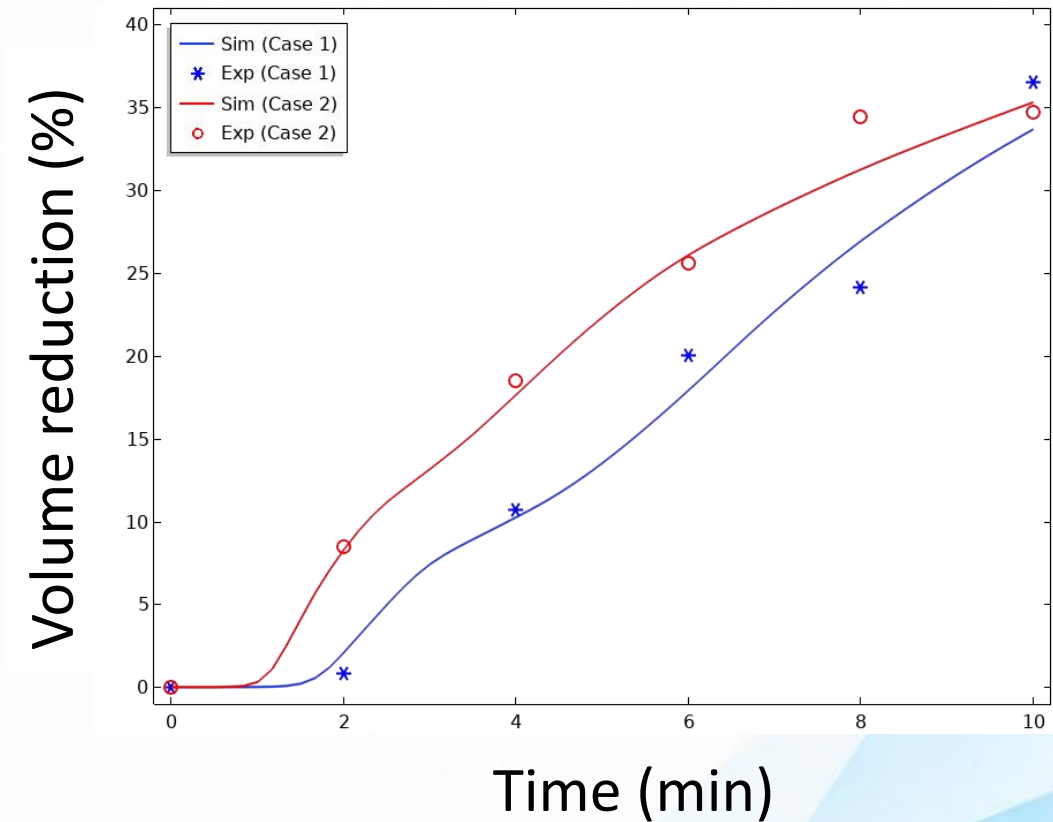
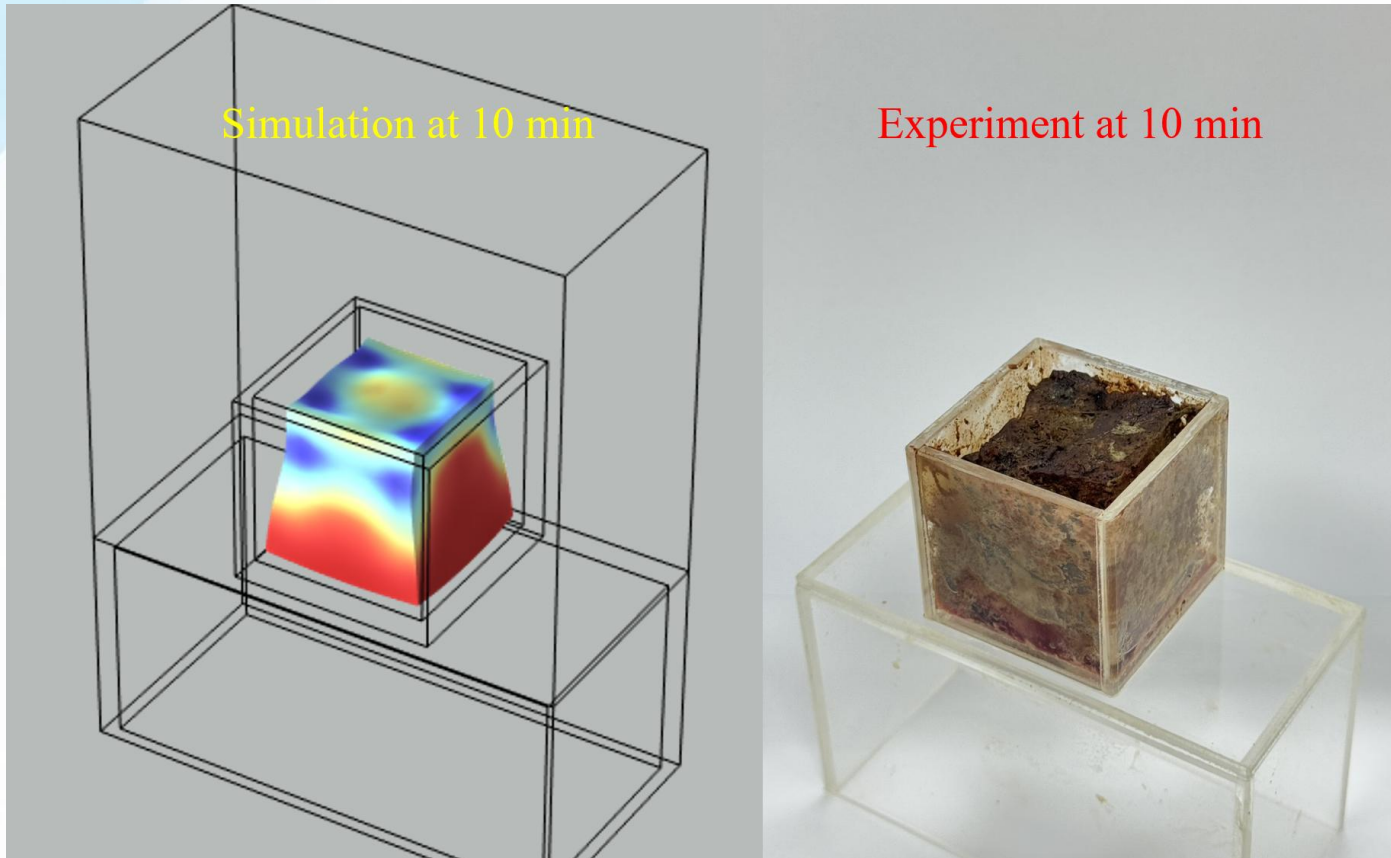


Key observations

- Simulated temperatures agreed well with the experimental measurements.
- Water content decreased locally in the high-temperature region due to evaporation.

TISSUE DEFORMATION AND VOLUME REDUCTION

Case 2



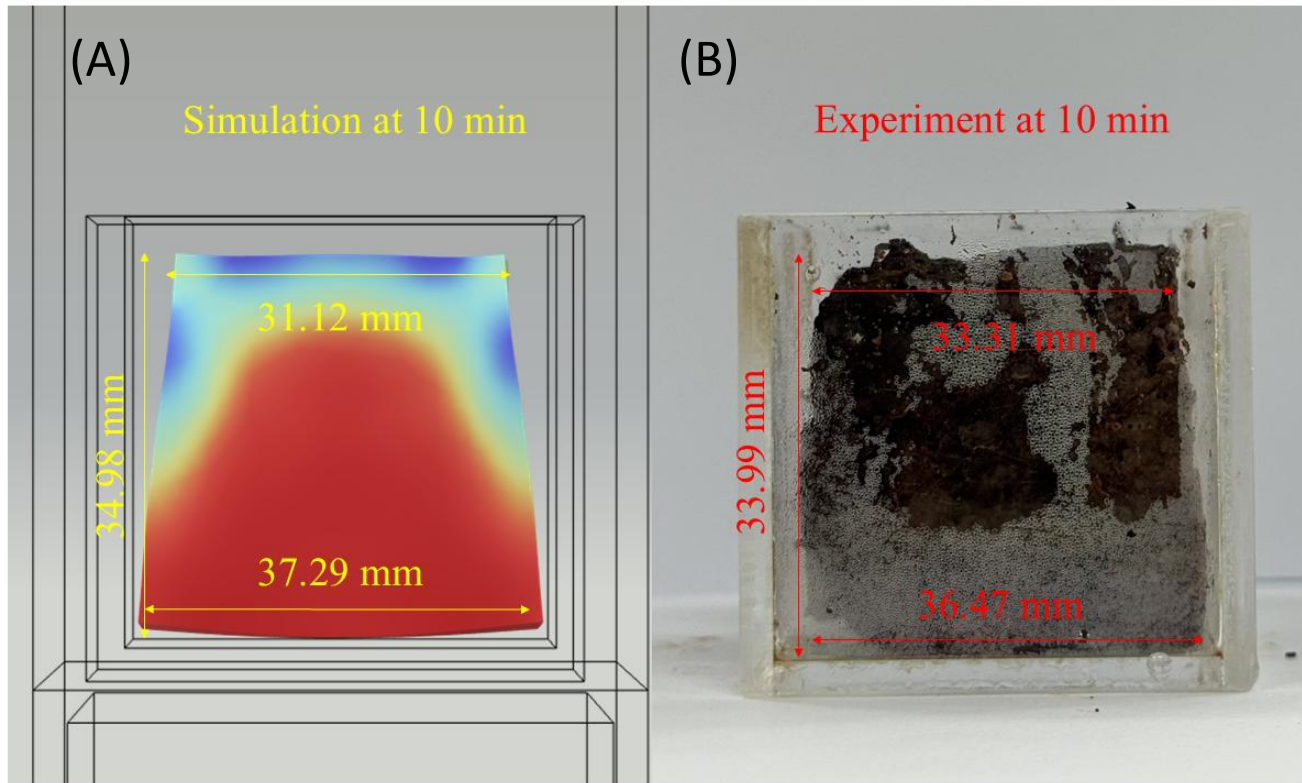
Key observations

- Simulation reproduced the observed inward deformation and size reduction.
- Shrinkage increased with input power.
- Water loss and thermal damage significantly contributed to progressive shrinkage.

GEOMETRIC VALIDATION

Case 2

X-Z plane



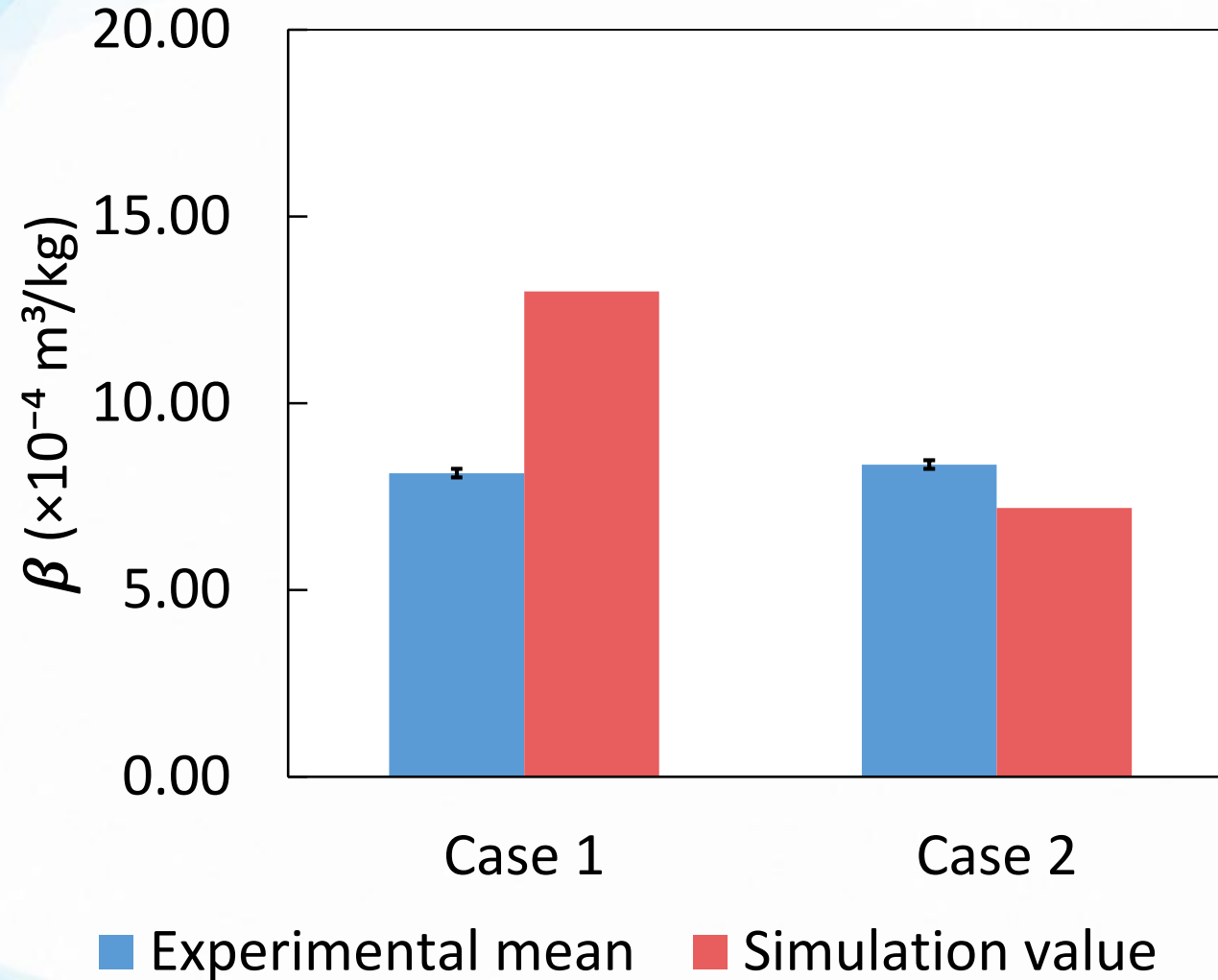
Dimension	Sim. (mm)	Exp. (mm)	Error (%)
Upper width	31.12	33.31	-6.6%
Lower width	37.29	36.47	+2.2%
Height	34.98	33.99	+2.9%

(A) Simulated deformation and dimensions and

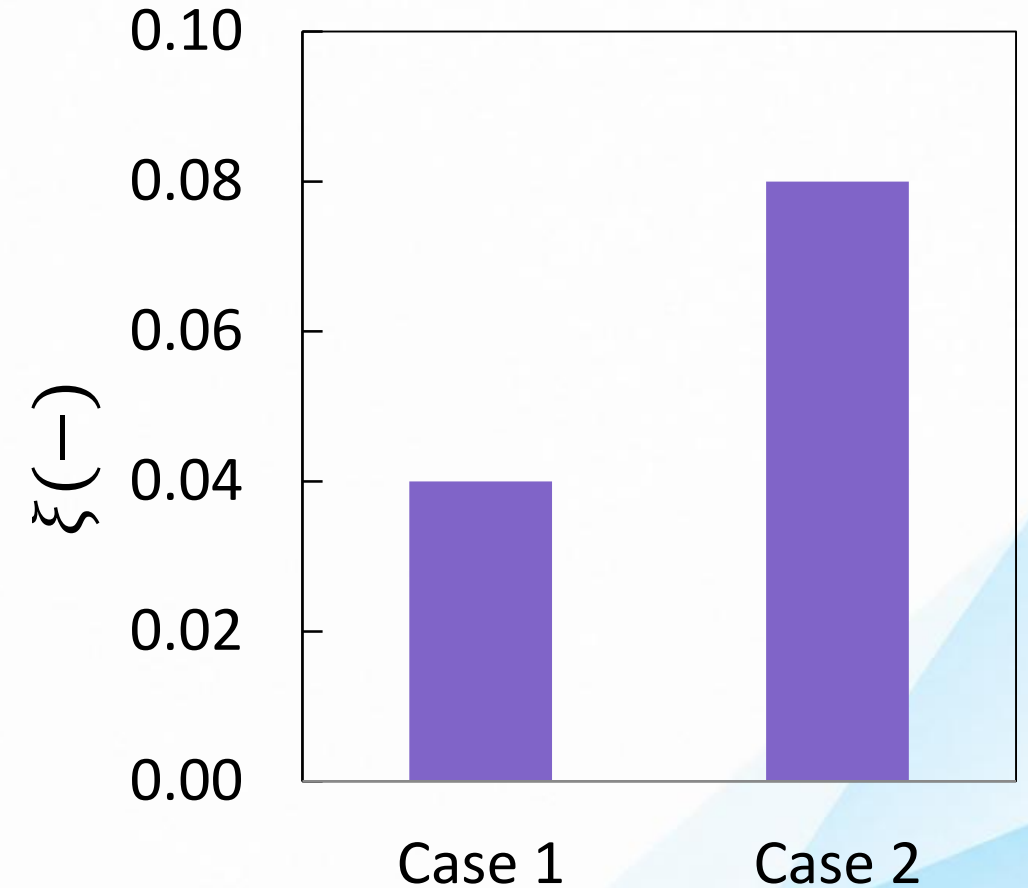
(B) Experimental geometry and dimensions for Case 2 at 10 min.

EXPERIMENTAL AND CALIBRATED PARAMETERS

Hygroscopic swelling coefficient, β



Damage-Induced Shrinkage Coefficient, ξ



WHY IS THIS IMPORTANT?

- **Improves treatment assessment:** Tissue contraction may alter the apparent ablation geometry.
- **Provides mechanical insight:** The model describes deformation associated with thermal damage and water loss.
- **Supports parameter evaluation:** Comparison with experiments helps assess the suitability of ξ and β .
- **Provides a modeling framework:** The approach can guide further development of thermomechanical models for MWA.



THANK YOU FOR LISTENING
QUESTION ?



Hub of Talents
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