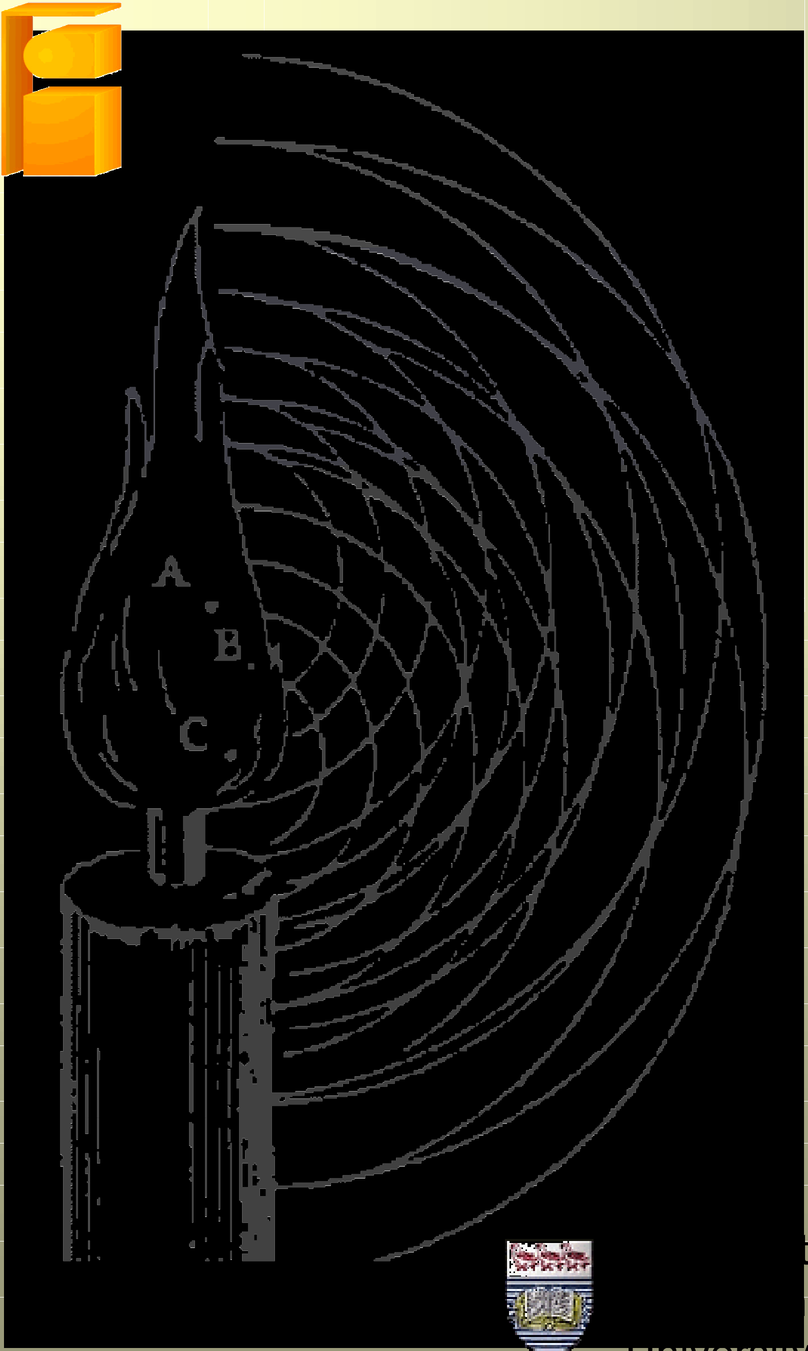


Electromagnetic, Thermal and Mass Transfer Modeling in Food and Wood

Wolfgang J.R. Hoefer
and Poman P.M. So

tional Electromagnetics
Laboratory
University of Victoria, Canada

Faustus
Scientific Corporation

Contact Information

Faustus Scientific Corporation
2187 Oak Bay Avenue,
Suite 213
Victoria, BC, V8R 1G1
Canada

Tel: (877) FAUSTUS {328-7887}
(Toll-free from Canada & US)
(250) 592-6554
Fax: (250) 592-6557
E-mail: marketing@faustcorp.com
Website: www.faustcorp.com

Computational Electromagnetics
Research Laboratory
ECE Department,
University of Victoria , POB 3055
Victoria, BC, V8W 3P6
Canada

Tel: (250) 721-6025 or –6030
Fax: (250) 721-6230

E-mail: whoefer@ece.uvic.ca
Website: www.wjrh.ece.uvic.ca

Summary and Highlights

- **Motivation and Introduction**
- **Research Background** : Activities in the Computational Electromagnetics Research Laboratory (CERL) at the University of Victoria
- **Implementation** : Advanced time domain modeling features in the Multipurpose Electromagnetic Field Simulation Tool (MEFiSTo^{TM}) developed by Faustus Scientific Corporation

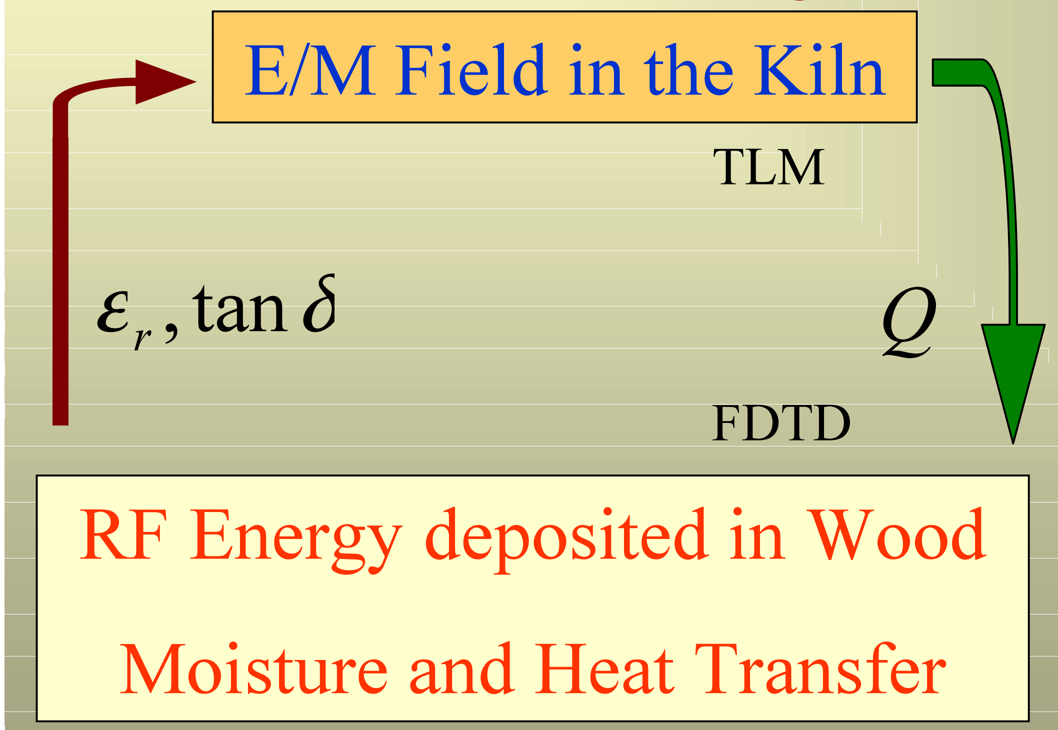
Motivation and Introduction

- Develop algorithms for modeling
  - RF Drying of Softwood Lumber
  - RF Pasteurization of Food
  - Power Handling of Microwave Components
- Modeling Methods used:
  - Electromagnetics: General symmetrical condensed node (GSCN) TLM algorithm;
  - Mass Transfer: Finite Difference Time Domain;
  - Thermal Behavior: Finite Difference Time Domain and Ray Optical techniques.

Modeling of Wood Drying

- Electromagnetic Fields: TLM
  - 3D Spatial Transmission Line Network, Cartesian
  - Diagonal tensor permittivity
  - Time-dependent ε' and $tan\delta$ (functions of moisture content and temperature.
- Heat Diffusion: FDTD
  - FDTD mesh overlaps TLM mesh
  - Forward Time Central Space (FTCS) Scheme)
  - Temperature and moisture dependent diffusivity tensor (diagonal)
- Mass Transfer: FDTD
  - Same as Heat Diffusion

The Coupled Model



Reach steady state
after material changes

E/M Field in the Kiln

TLM

$\varepsilon_r, \tan\delta$

Q

FDTD

RF Energy deposited in Wood

Moisture and Heat Transfer

Compute until properties change by 1 %

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu_r H)$$

$$\nabla \times H = J + \frac{\partial}{\partial t}(\varepsilon_r E)$$

$$\frac{\partial M}{\partial t} = \nabla(D_M \nabla M)$$

moisture diff. coeff.

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + Q$$

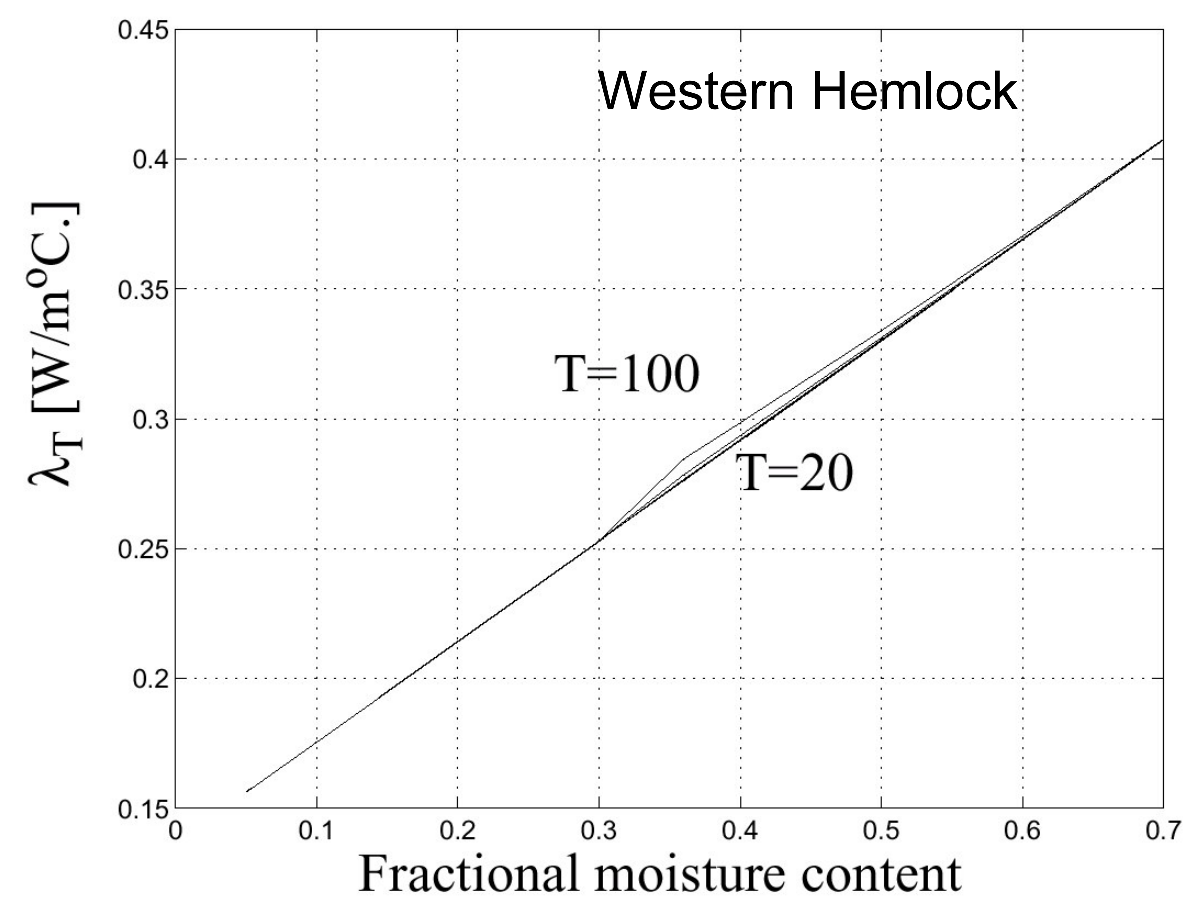
wood density

energy

heat diffusion coeff.

specific heat

Heat Diffusion Coefficients



Longitudinal diffusion coefficient:

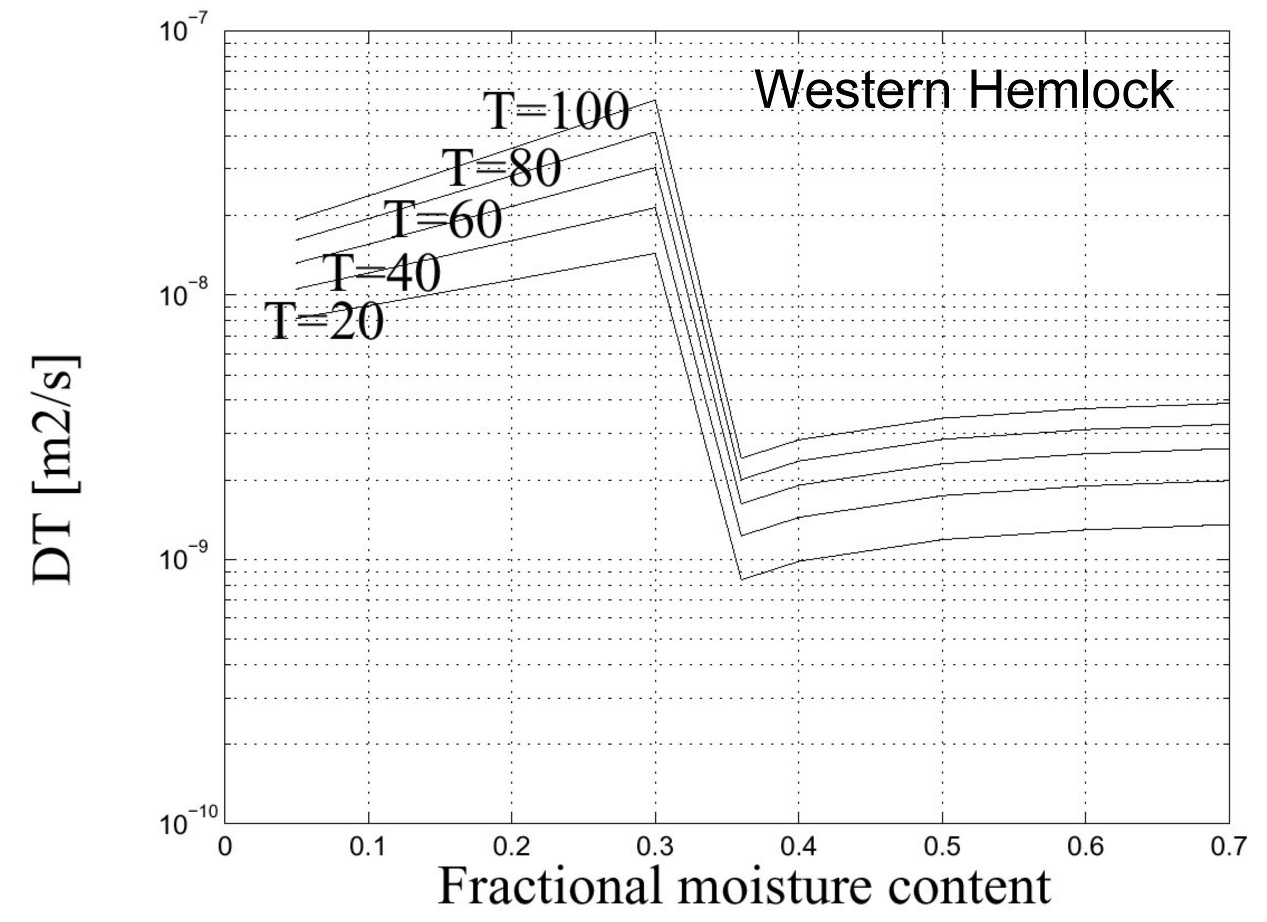
$$\lambda_z = 2\lambda_T$$

Transverse diffusion coefficient for the heat diffusion process as a function of moisture and temperature. Temperatures in degree C.

Moisture Diffusion Coefficients

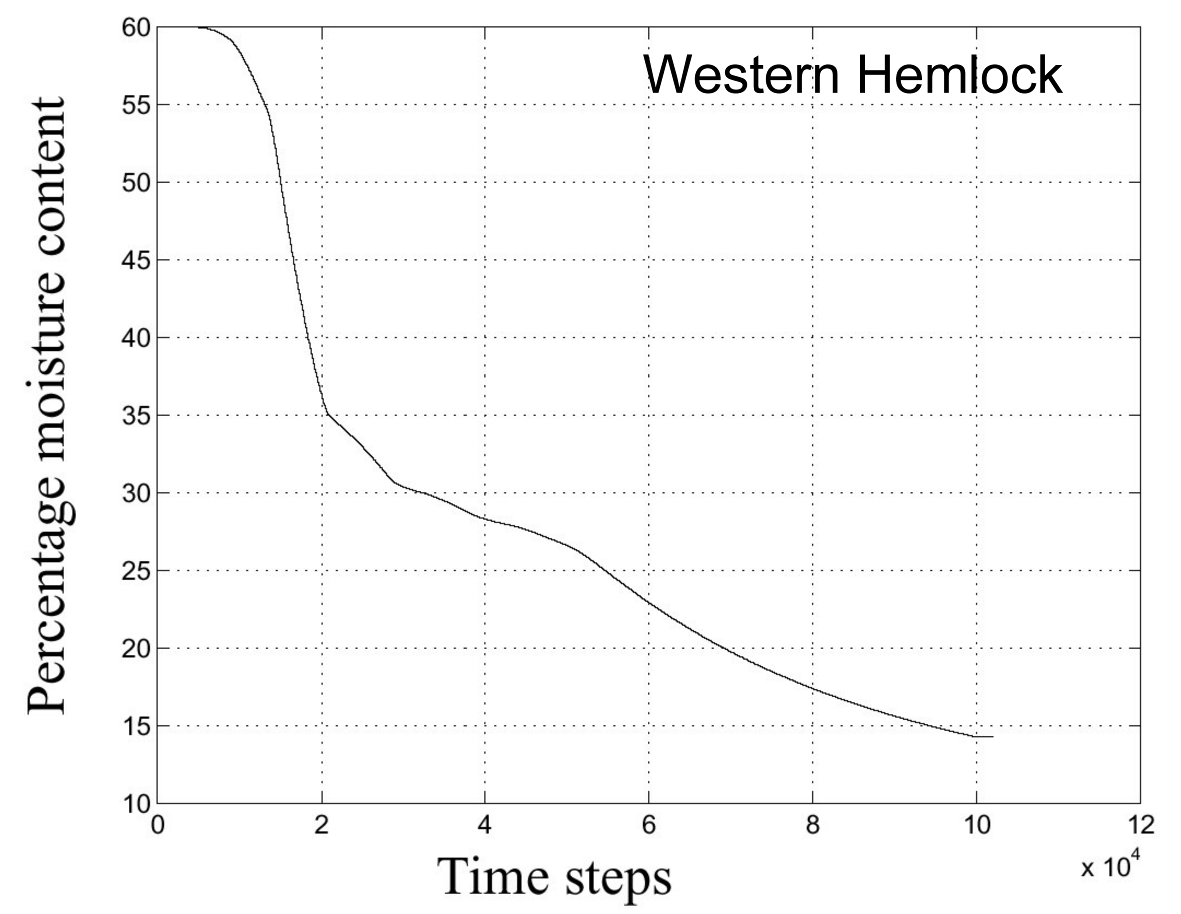
Longitudinal diffusion coefficient:

$$D_z = 2.5 D_T$$



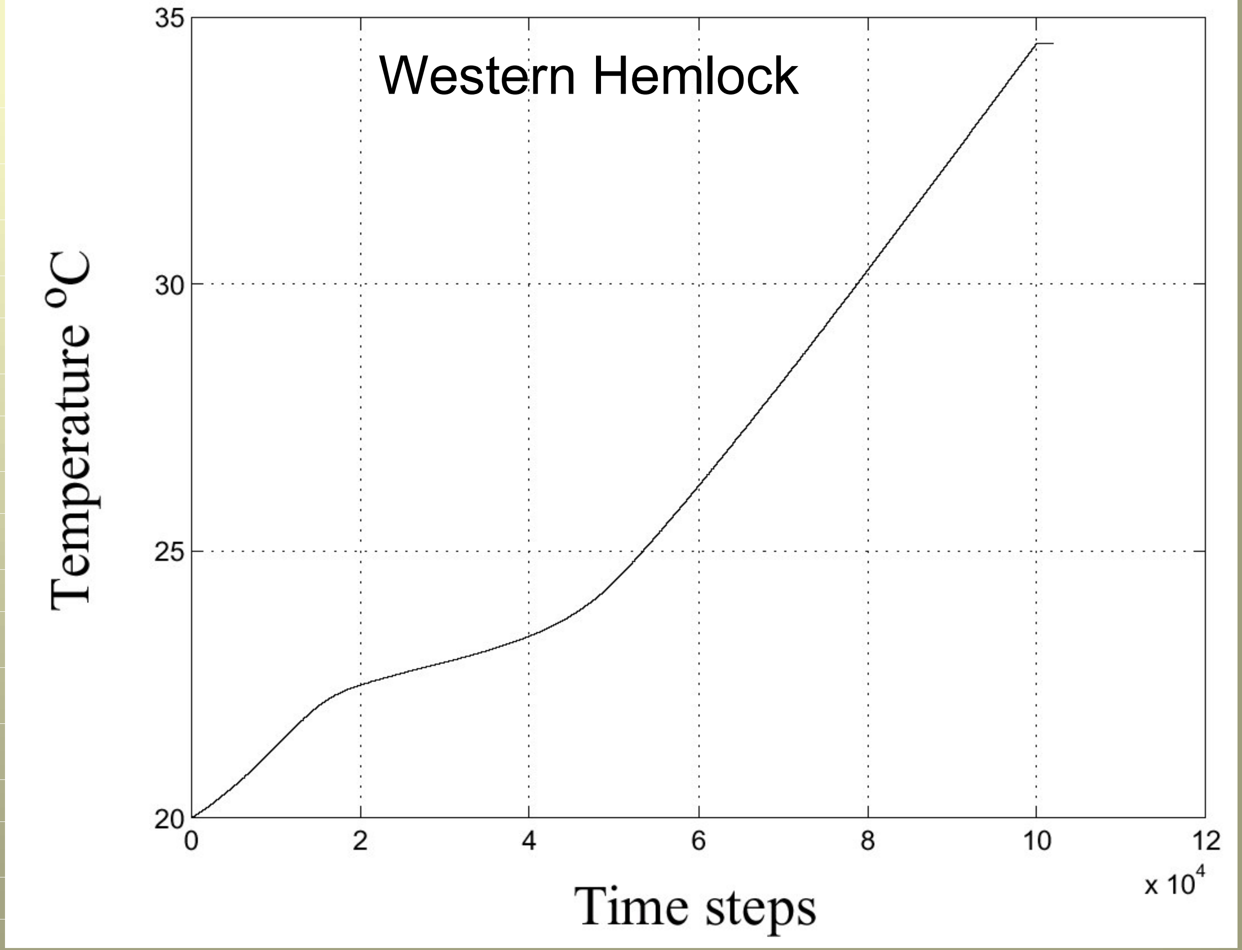
Transverse diffusion coefficient for the moisture diffusion process as a function of moisture and temperature. Temperatures in degree C.

A Typical Drying Curve



Evolution of moisture content in the center of a wood sample when RF energy is applied

A Typical Temperature Curve



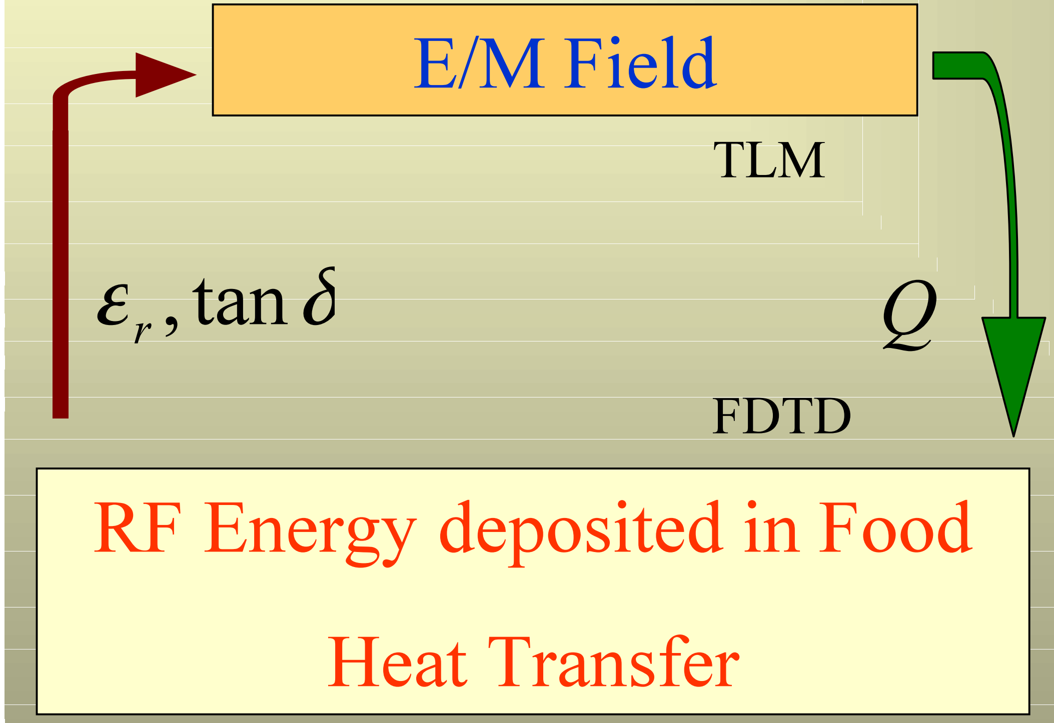
Evolution of temperature in the center of a wood sample when RF energy is applied

Modeling of Food Pasteurization

- Electromagnetic Fields: TLM
  - 3D Spatial Transmission Line Network, Cartesian Diagonal tensor permittivity
  - Time-dependent ε' and $tan\delta$ (functions of temperature.
- Heat Diffusion: FDTD
  - FDTD mesh overlaps TLM mesh
  - Forward Time Central Space (FTCS) Scheme)
- Mass Transfer: not considered (sealed food packages)

The Coupled Model

Reach steady state
after material changes



E/M Field

TLM

$\varepsilon_r, \tan\delta$

Q

FDTD

RF Energy deposited in Food

Heat Transfer

Compute until properties change by 1 %

$$\nabla \times E = -\frac{\partial}{\partial t}(\mu_r H)$$

$$\nabla \times H = J + \frac{\partial}{\partial t}(\varepsilon_r E)$$

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(\lambda_T \nabla T) + Q$$

food density

specific heat

heat diffusion coeff.

energy

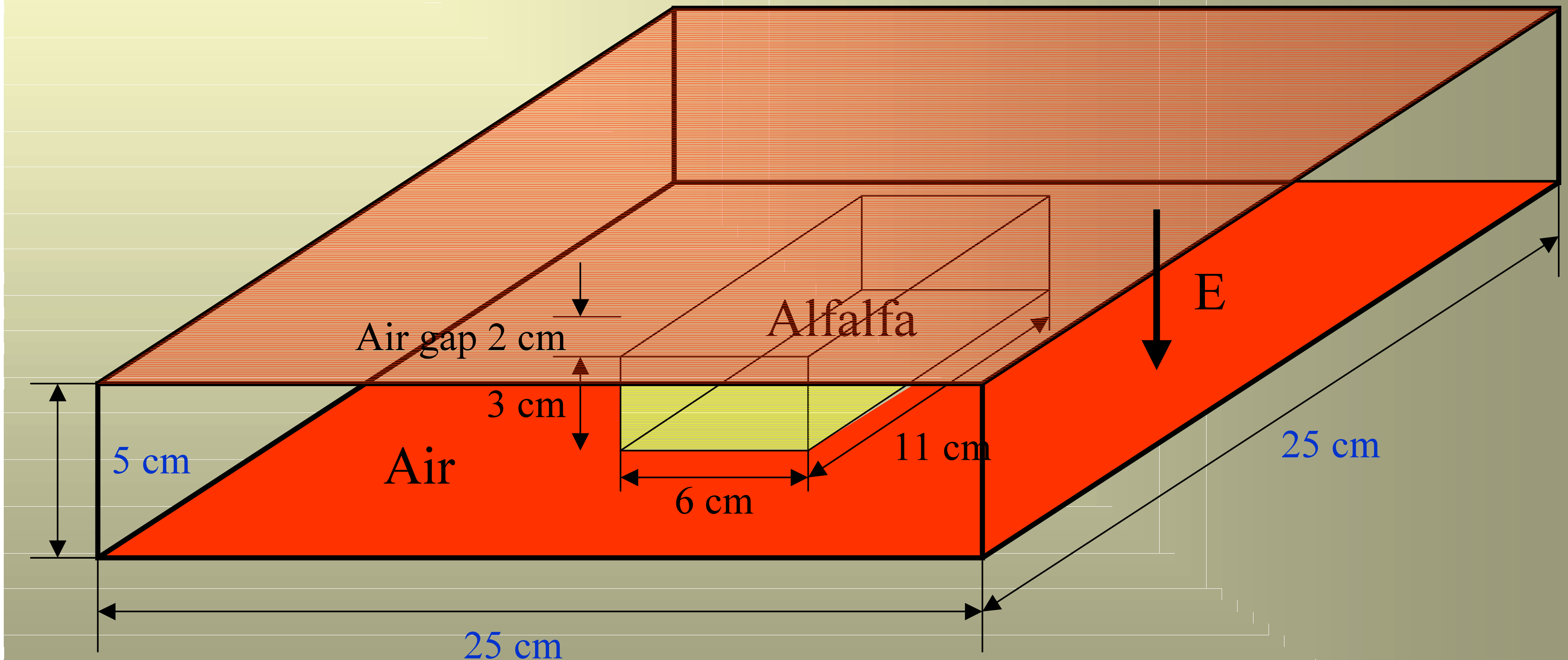
Example: Alfalfa Seeds

- Data from Flugstad Engin. and ORST
- Seeds are packaged >no moisture loss
- Constant power is applied
- EM Phase 1: Compute Steady State
- Thermal Phase 1: Compute rise in T
- EM Phase 2: Recompute Steady State
- Thermal Phase 2: Compute rise in T
- ..etc.

Example: Heating of Alfalfa

Top and Bottom Walls: Electric

Sidewalls: Magnetic

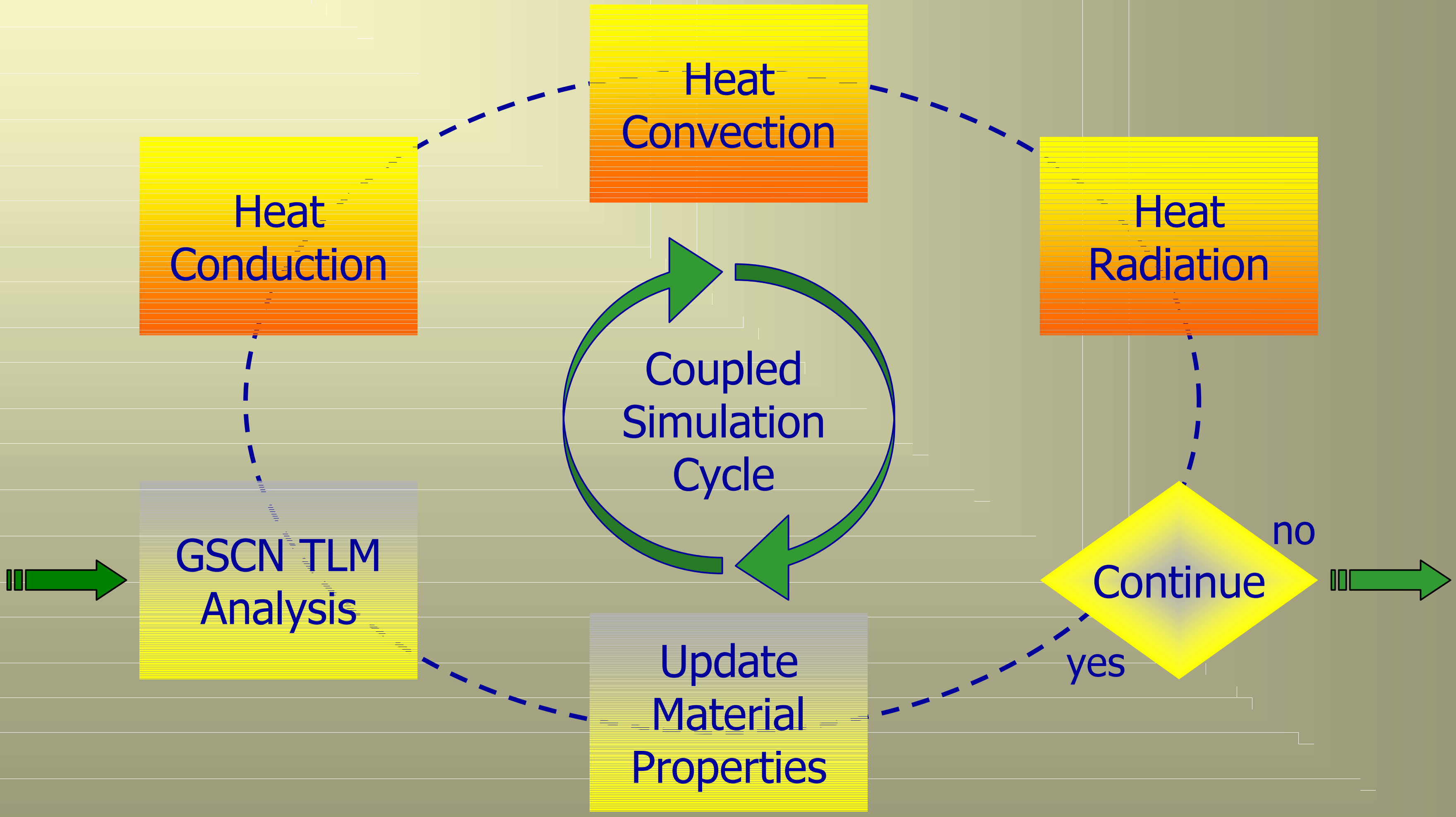


Courtesy of Oregon State University

The MEFiSTo Heat Engine

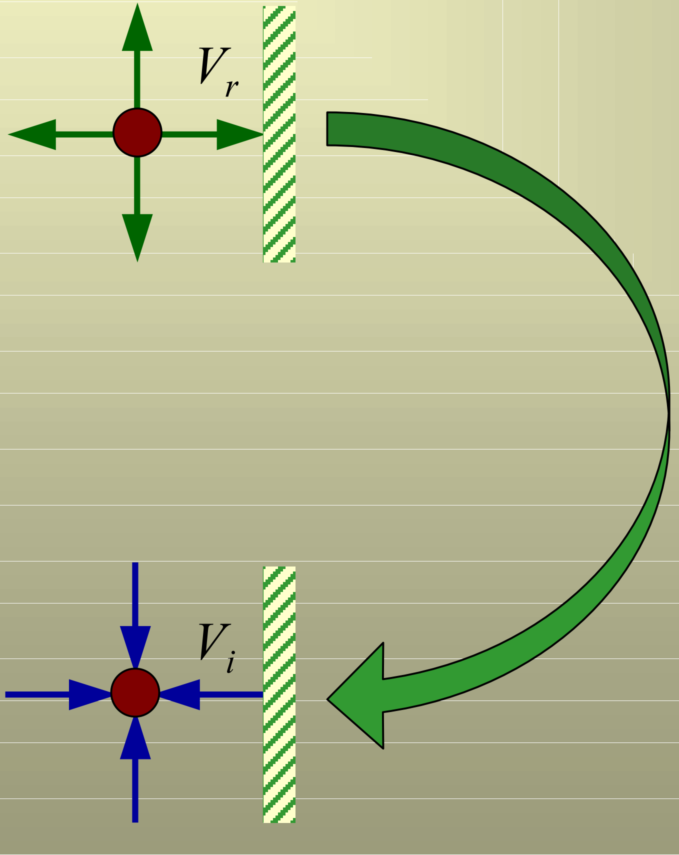
- The transient thermal behavior of objects can be modeled.
- Three heat transfer mechanisms are considered:
  - conduction
  - convection
  - radiation
- SPICE models can be embedded, and their temperature controlled by the MEFiSTo heat engine (presently under development)

Coupled EM-Thermal Engine



The TLM Algorithm

- TLM Boundary Operations



$$V^i = \Gamma_{impulse} \times V^r$$

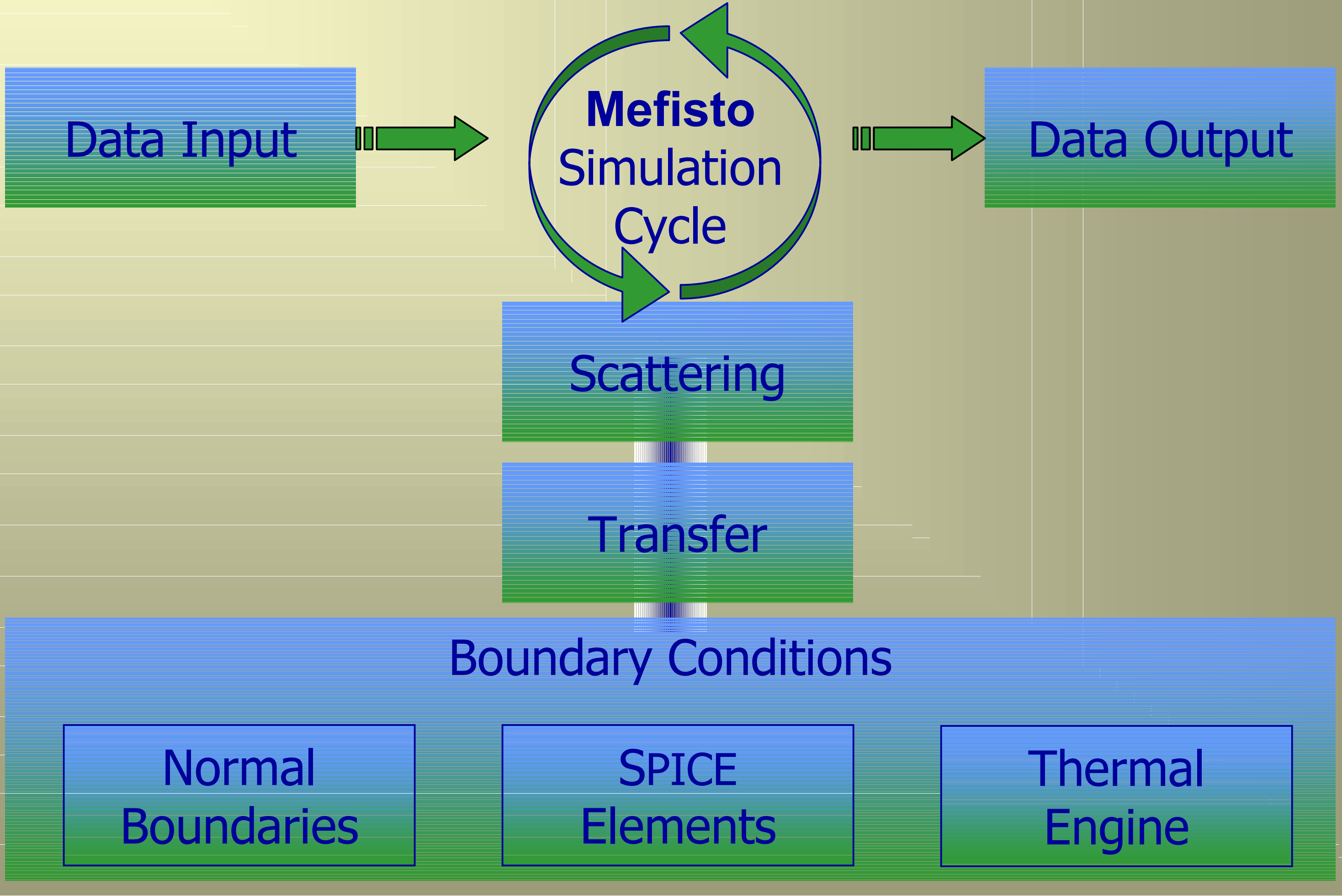
$$V^i = h(k) * V^r(k)$$

•
•
•

$$V^i = SPICE\left(V^r(k)\right)$$

$$V^i = \mathrm{Thermal}\left(V^r(k)\right)$$

Tasks, Threads and Processors



Data Input

Mefisto Simulation Cycle

Data Output

Scattering

Transfer

Boundary Conditions

Normal Boundaries

SPICE Elements

Thermal Engine

Heat Conduction

- Heat conduction is modeled with a finite difference scheme assuming the temperature inside a FDTD cell to be homogeneous.
- A uniform mesh is used for the calculation of conduction heat flux.
- The heat conduction is computed in such a way that for every single cell the power flux in all the six directions is computed individually and then added up to yield the total heat power flux through that cell.

Heat Conduction

- Power flow in the positive x-direction is:

$$PXP_{i,j,k} = \frac{2\Delta l k_{i,j,k} k_{i+1.j,k}}{k_{i,j,k} + k_{i+1.j,k}} (T_{i,j,k} - T_{i+1,j,k})$$

Similarly expressions apply for the other five directions

- The total power flow is:

$$P_{i,j,k}^{COND} = PXN_{i,j,k} - PXP_{i,j,k} + PYN_{i,j,k} - PYP_{i,j,k} + PZN_{i,j,k} - PZP_{i,j,k}$$

Heat Convection

- Calculation of heat convection requires the knowledge of the heat transfer coefficient defined as follows:

$$h = N_u k_{fluid} / l$$

- N_u is the dimensionless heat transfer coefficient.
  k_{fluid} is the thermal conductivity of the fluid.
  l is the characteristic length of the surface that is usually obtained by dividing the surface area by the perimeter in the case of horizontal surfaces, or simply the height of the surface for vertical surfaces.

Heat Convection

- For free convection adjacent to the surfaces of the vertical planes:

$$N_u = 0.68 + 0.670 R_a^{1/4} \left[1 + \left(\frac{0.492}{P_r} \right)^{9/16} \right]^{-4/9}$$

- where $0 < \boldsymbol{R_a} < 10^9$ is the Rayleigh number defined by

$$R_a = G_r P_r = \frac{l^3 g \beta (T_{surface} - T_{fluid}) P_r}{\nu^2}$$

- $\boldsymbol{P_r}$ is the Prandtl number, β is the coefficient of volume expansion, g is gravity and *v* is the kinematic fluid viscosity.

Heat Radiation

- Free heat radiation from the outer boundaries of the structure is computed,
- Heat radiation exchange between inner surfaces of the structure is computed,
- In order to compute the above quantities, the relative positions and orientations among all the cells must be computed first. This is handled via a shape factor matrix.

Heat Radiation

- Shape factor is defined as the part of energy transmitted from one cell surface ***s*** to another cell surface ***s***', divided by the total energy emitted by the surface ***s***.

$$F_{ss'} = \frac{1}{\pi A_s} \int_{A_s} \int_{A_{s'}} \frac{\cos(\theta_s)\cos(\theta_{s'})}{r^2} dA_s dA_{s'}$$

- θ and ***r*** describe the relative positions of the surfaces ***s*** and ***s***'.

Updating Temperature

- Once all the above power fluxes are calculated, the temperature can be updated as follows:

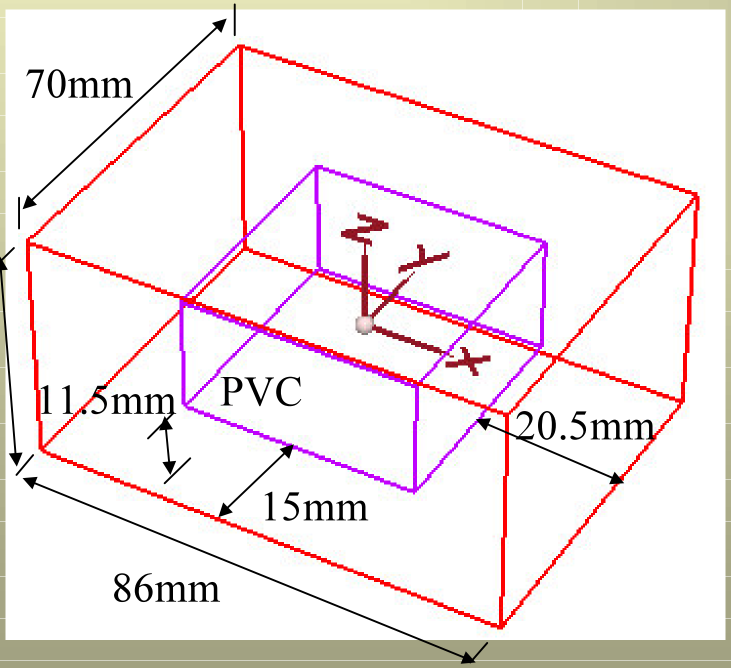
$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \frac{\Delta t}{m_{i,j,k} c_{i,j,k}} P_{i,j,k}^{TOTAL}$$

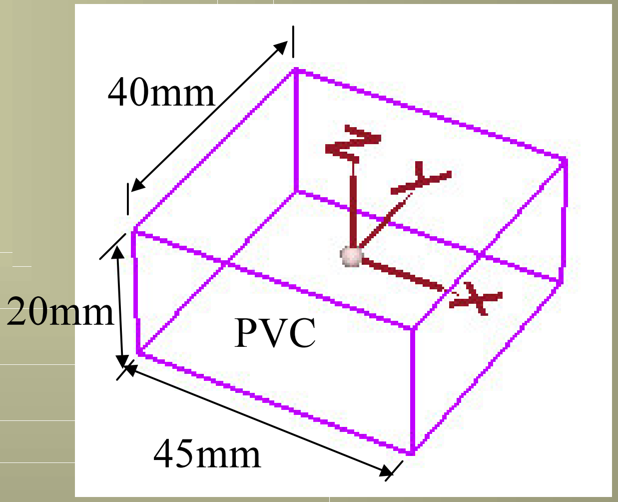
$$= T_{i,j,k}^{n} + \frac{\Delta t}{\Delta l^3 \rho_{i,j,k} c_{i,j,k}} (P_{i,j,k}^{EM} + P_{i,j,k}^{COND} - P_{i,j,k}^{CVEC} - P_{i,j,k}^{FREERAD} - P_{i,j,k}^{EXRAD})$$

- Δt is the thermal calculation time step, ρ is the density and c is the specific heat.
- When the total power flux entering the structure equals to the total power flux emerging from it, the temperature reaches a steady state.

Simulation Example

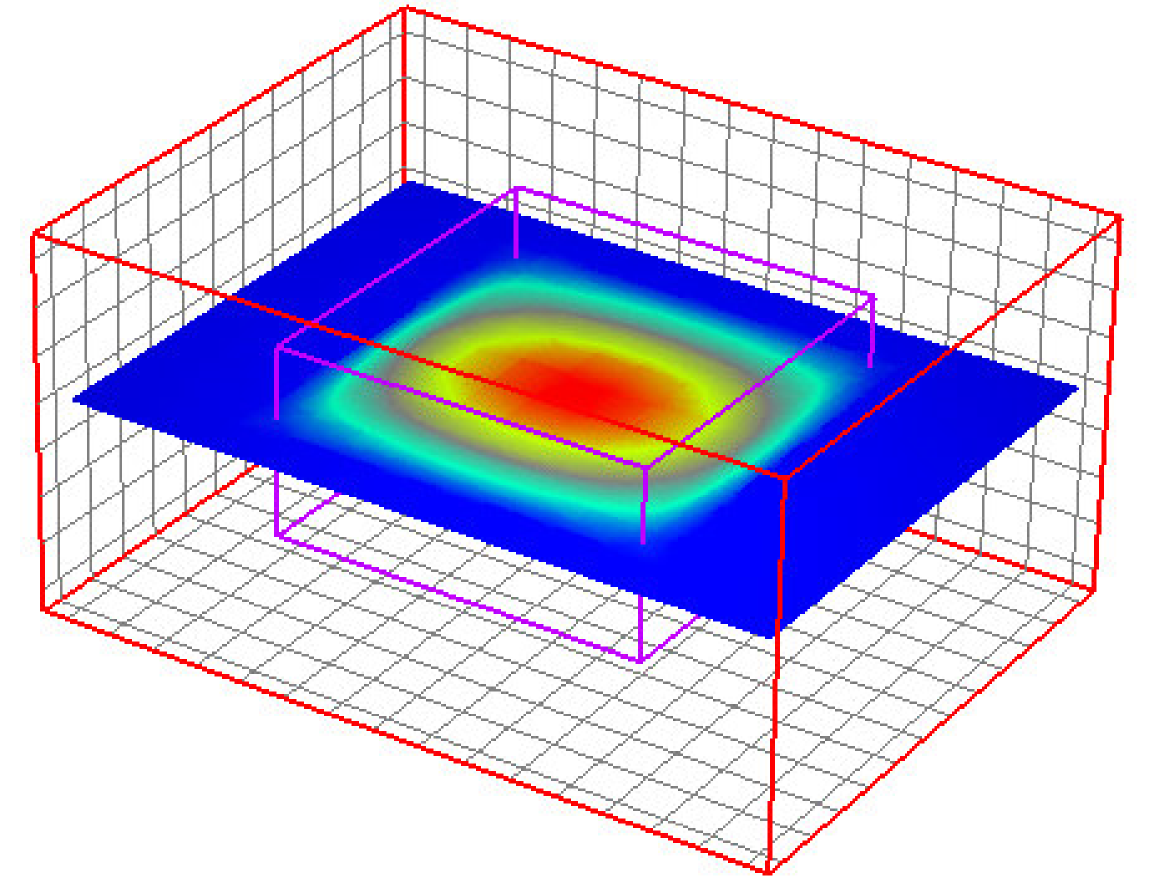
PVC Block in a Rectangular Cavity





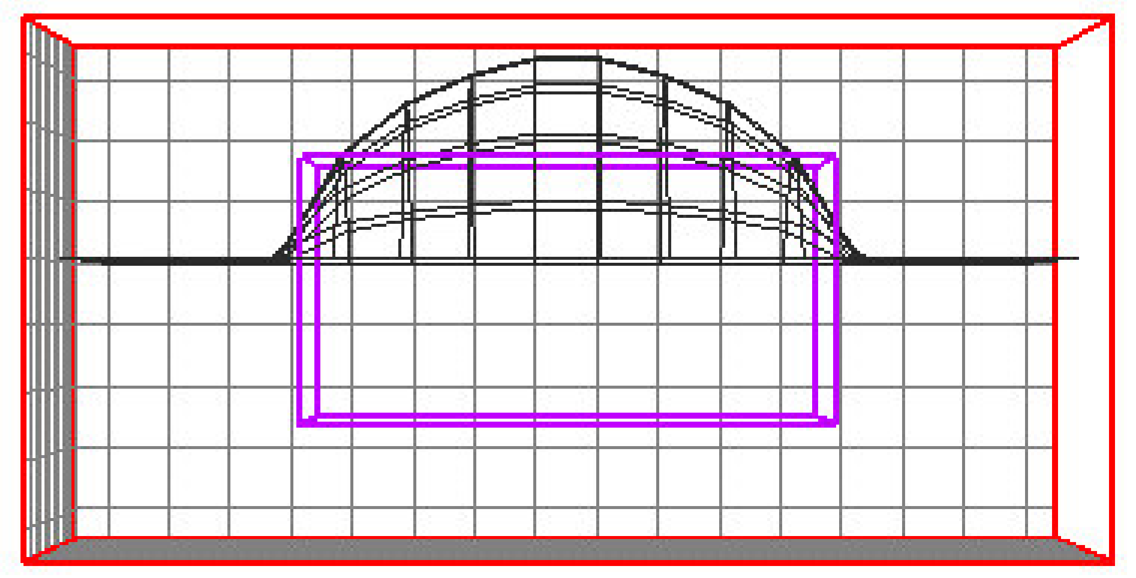
Simulation Example

Power Density Distribution



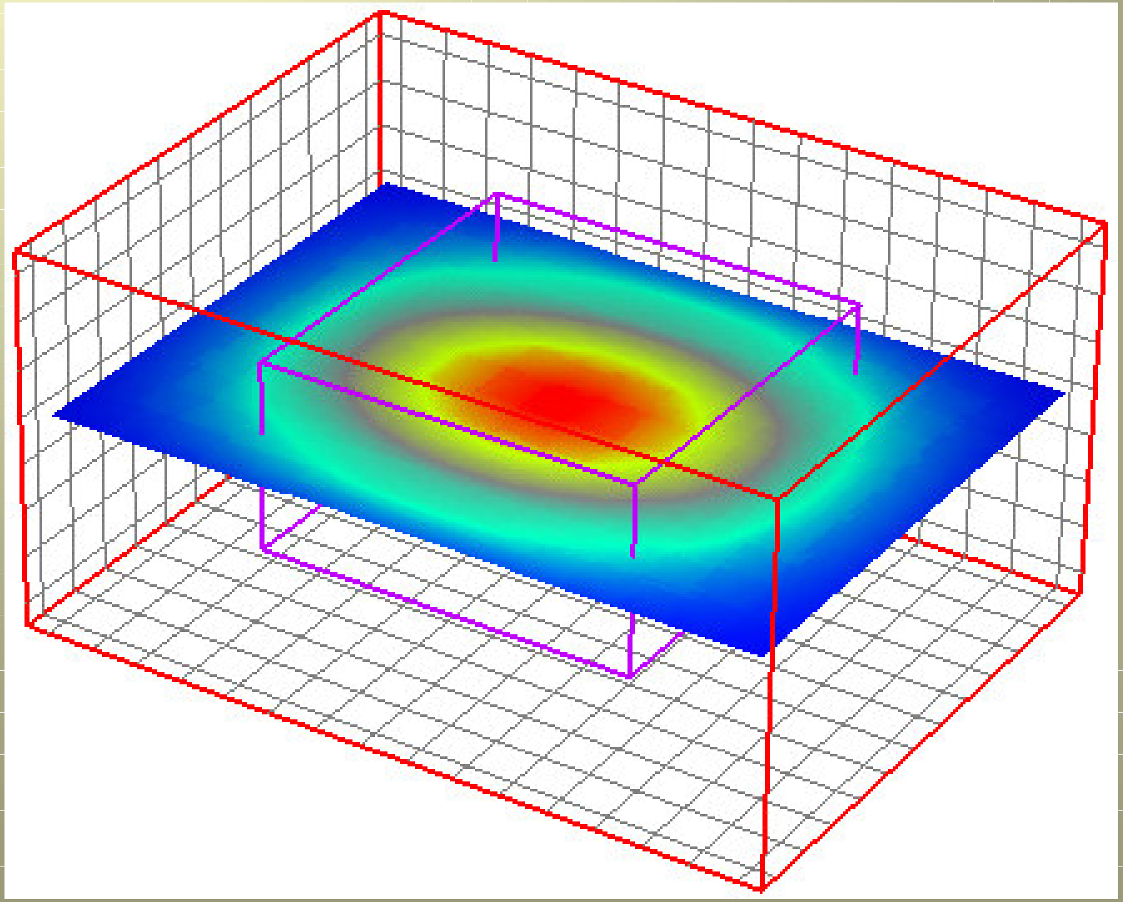
Simulation Example

Power Density Distribution



Simulation Example

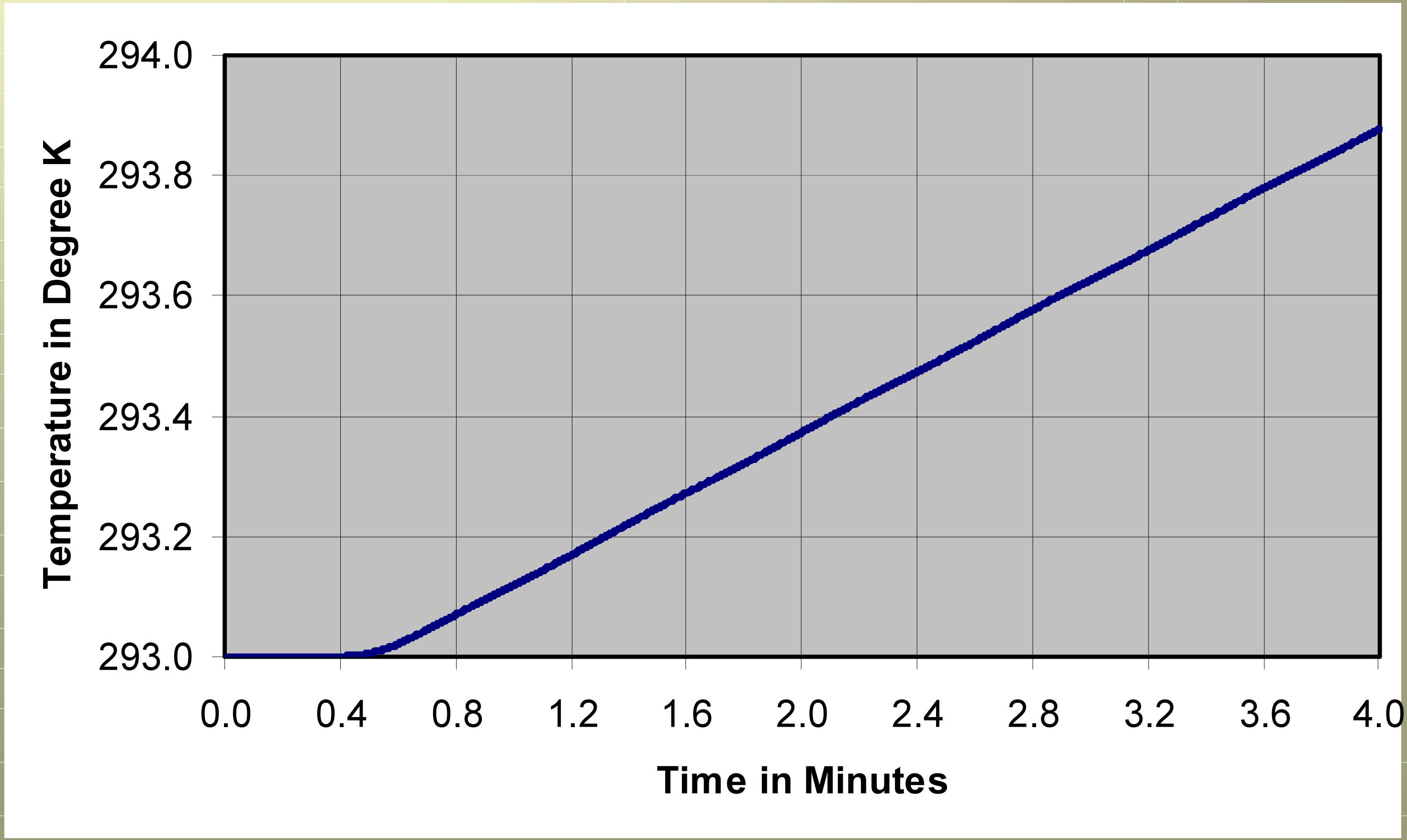
Temperature Distribution



Simulation Example

Temperature Increase in the Air Region

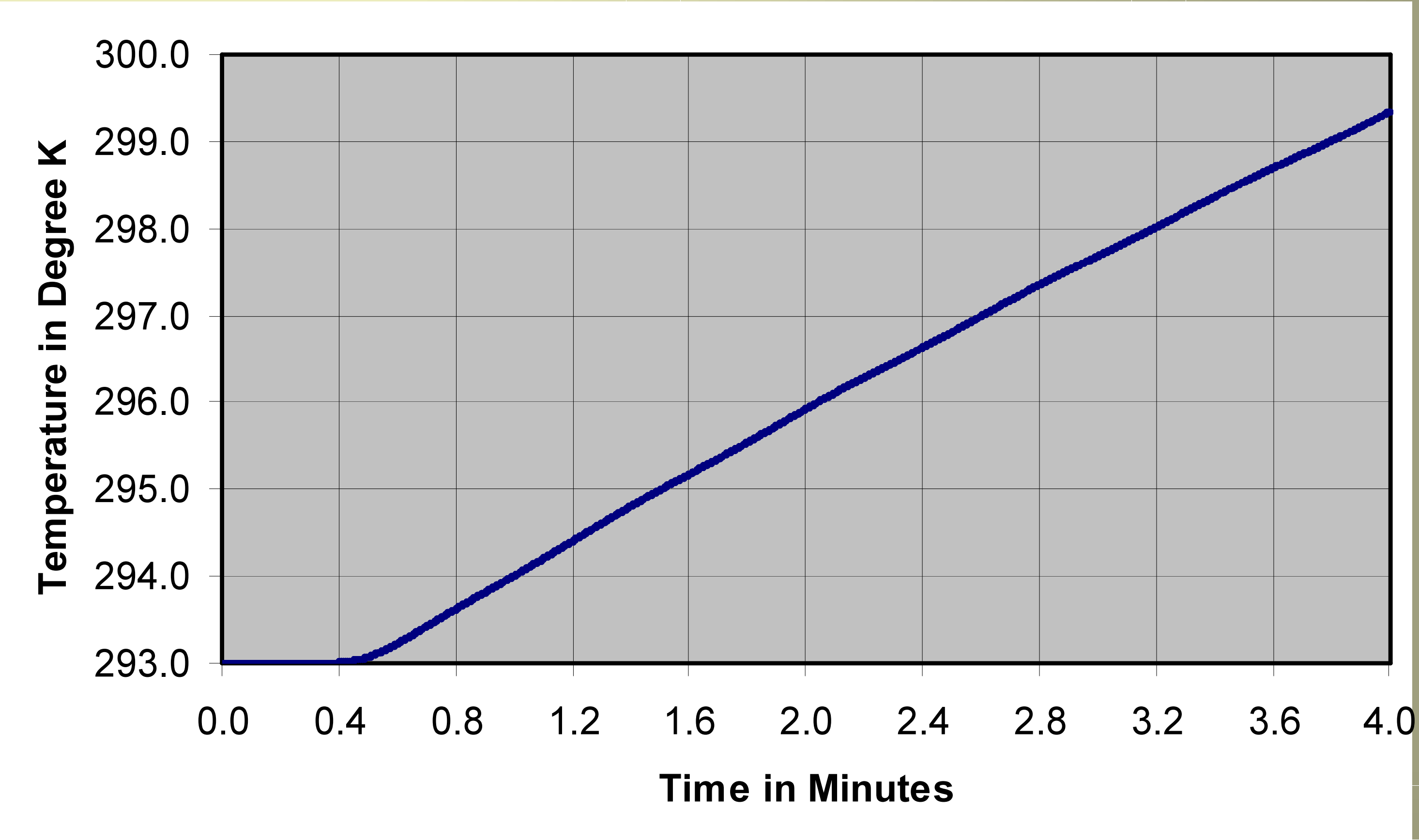
(0.0042 °K/s)



Simulation Result

Temperature Increase in the PVC Block

(Average Dissipated Power: 2 Watts, 0.0305 °K/s)



Conclusions

- Several types of coupled em/thermal/mass transfer simulations of wood, food, and PVC have been performed and presented;
- The coupled TLM/FDTD algorithms of MEFiSTo predict the em field distribution and temperature rise inside general materials and topologies;
- Thermal conduction, convection, and internal and external radiation are considered;
- Both metallic and dielectric material losses are included as heat generation sources.

Conclusions

- The various features discussed in this presentation are being integrated into the MEFiSTo simulation tool.
- Applications range from microwave heating and processing of materials to the evaluation of transient thermal stress and power handling capability of electromagnetic structures.

Appendix

Note: You may download a more detailed set of results from the Faustus Website at
http://www.faustcorp.com/downloads/Benchmark/BMP-1_Results.zip

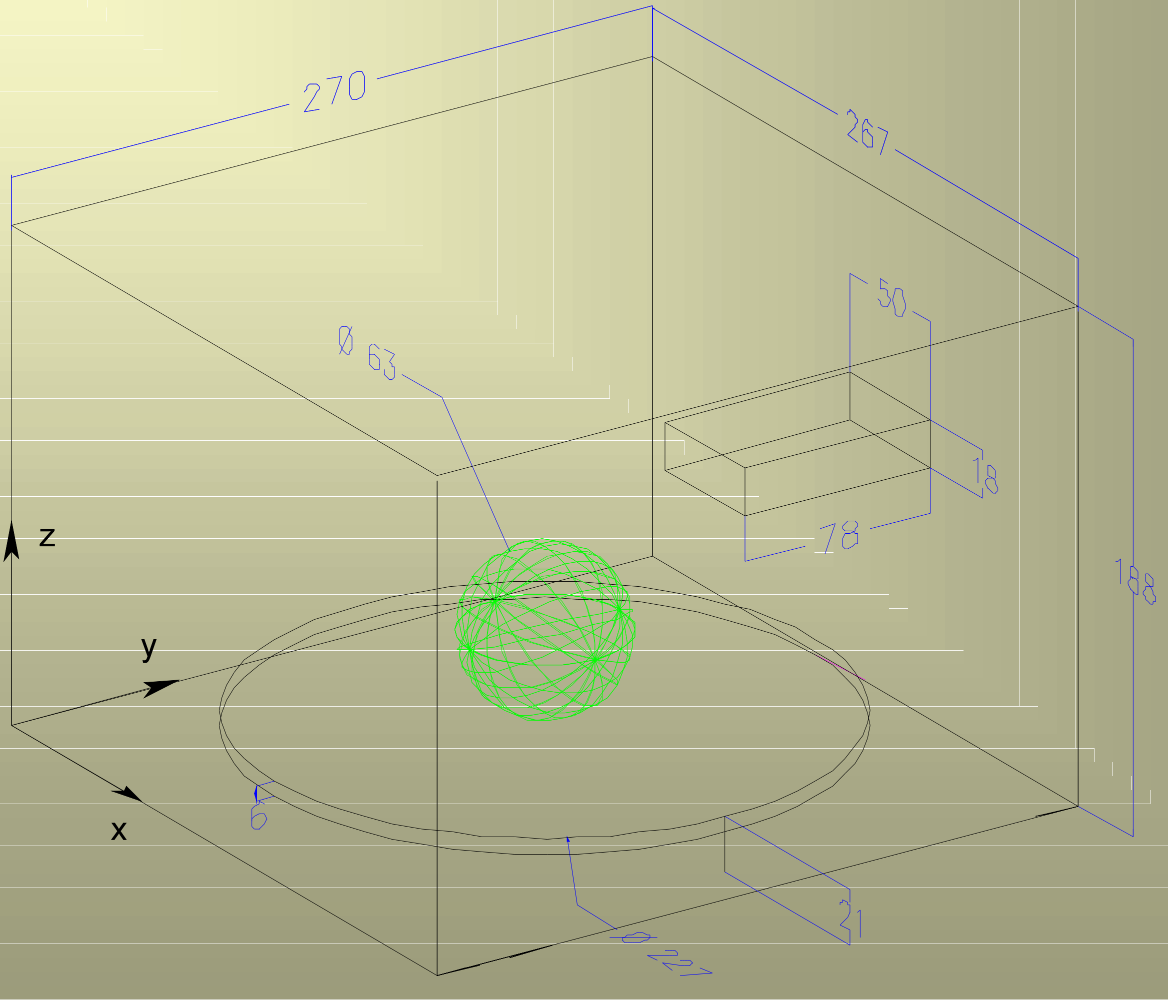
Benchmark Problem 1

ELECTROMAGNETIC PROCESSES IN A MICROWAVE OVEN (2.45 GHz)

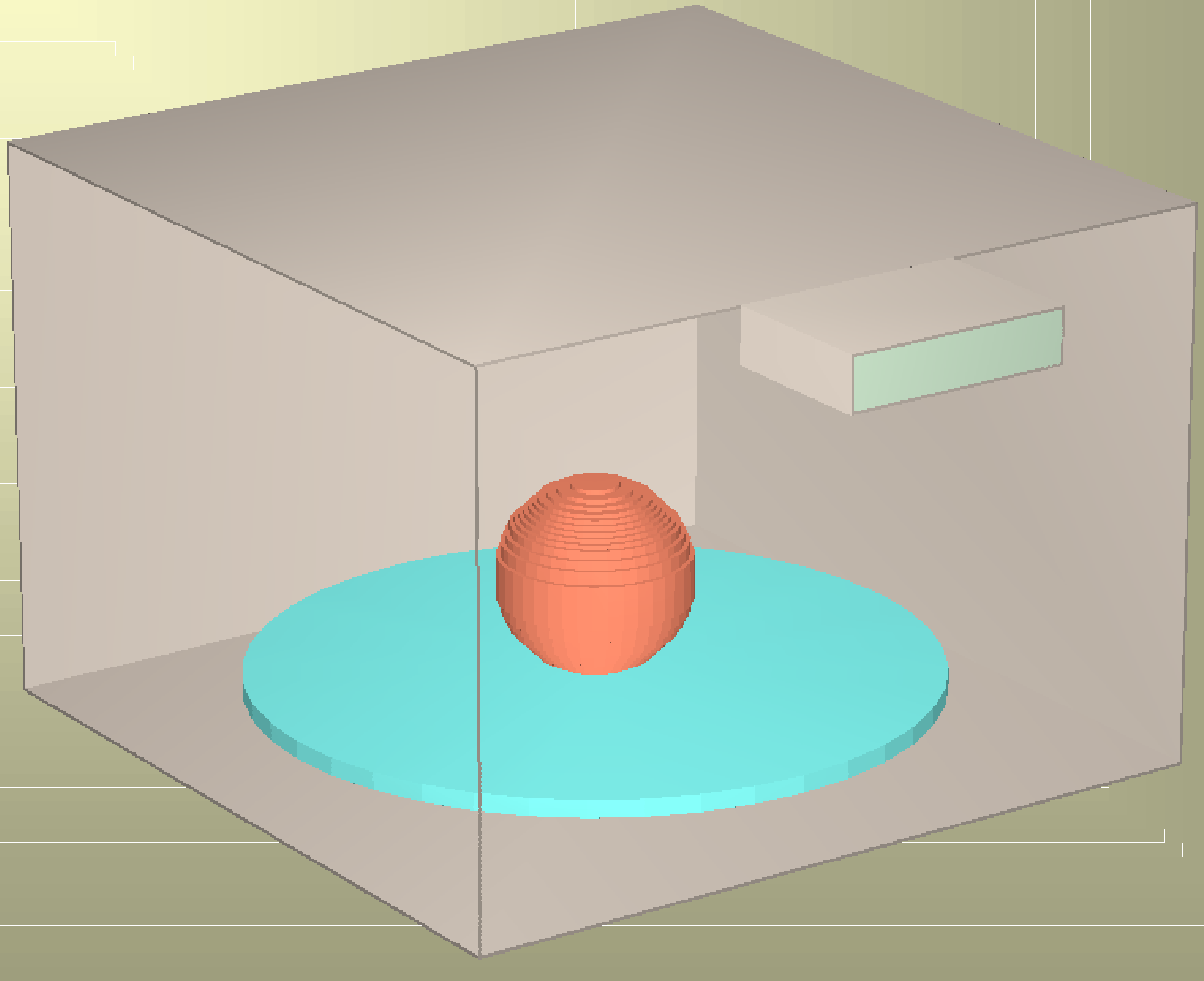
Solutions generated with
MEFiSTo-3D Pro
Wolfgang J.R. Hoefer
16 January 2002

Faustus Scientific Corporation, 2187 Oak Bay Avenue, Suite 213, Victoria, BC, Canada V8R 1G1
http://www.faustcorp.com

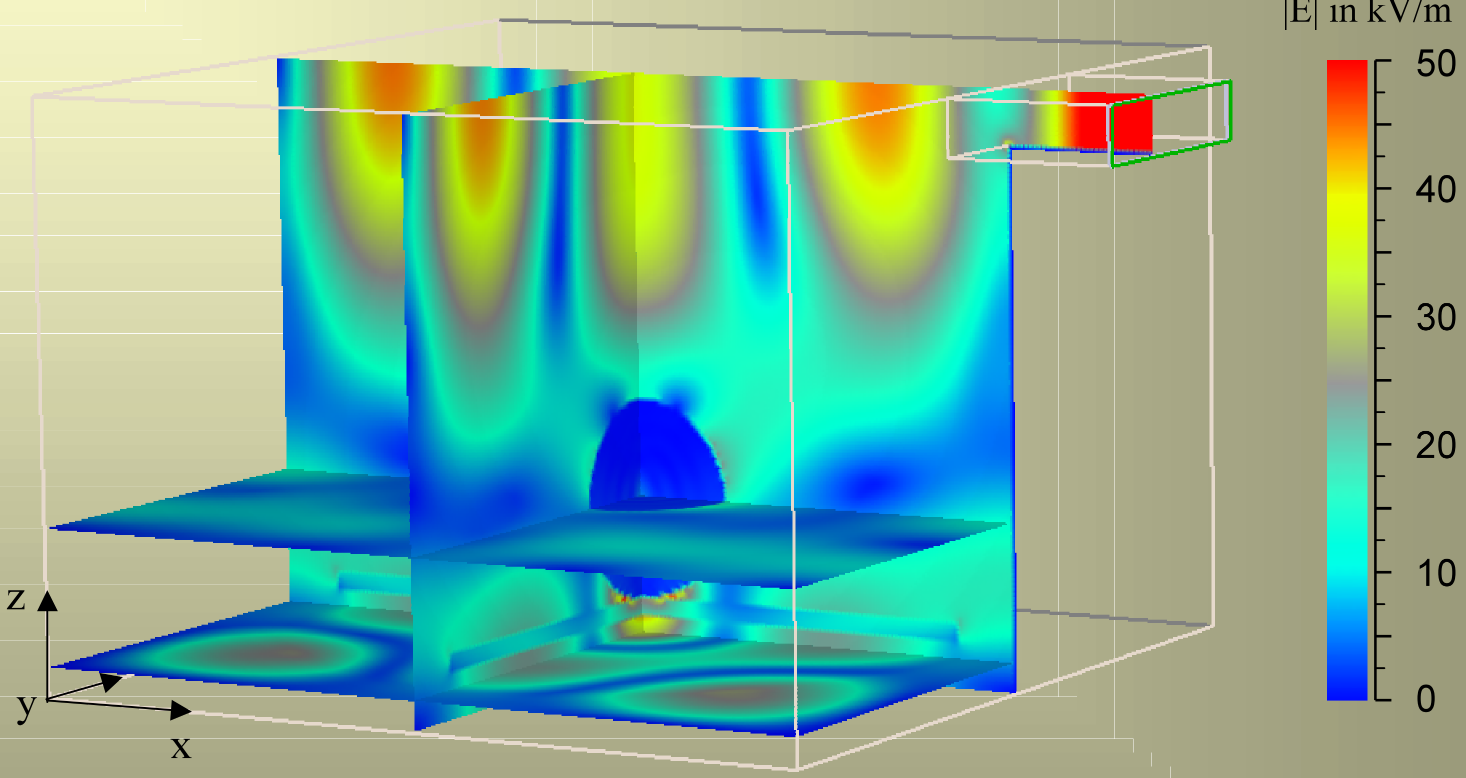
3D View and Dimensions



3D Solid View of the Oven



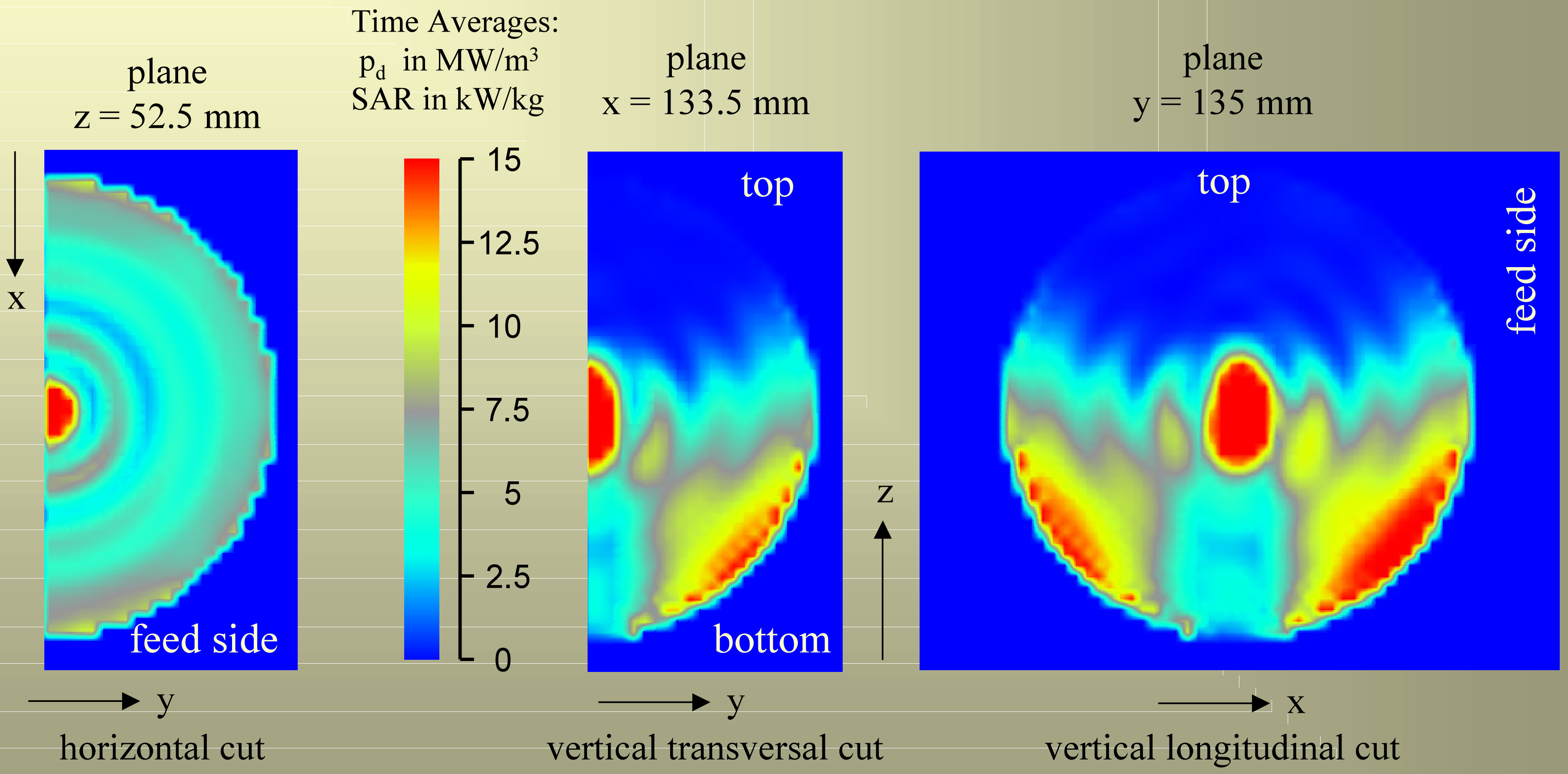
Distribution of the Envelope of |E|



Envelope of the peak value of the electric field $|E|_{max}$

1 kW magnetron matched to the waveguide, f = 2.45 GHz, steady state

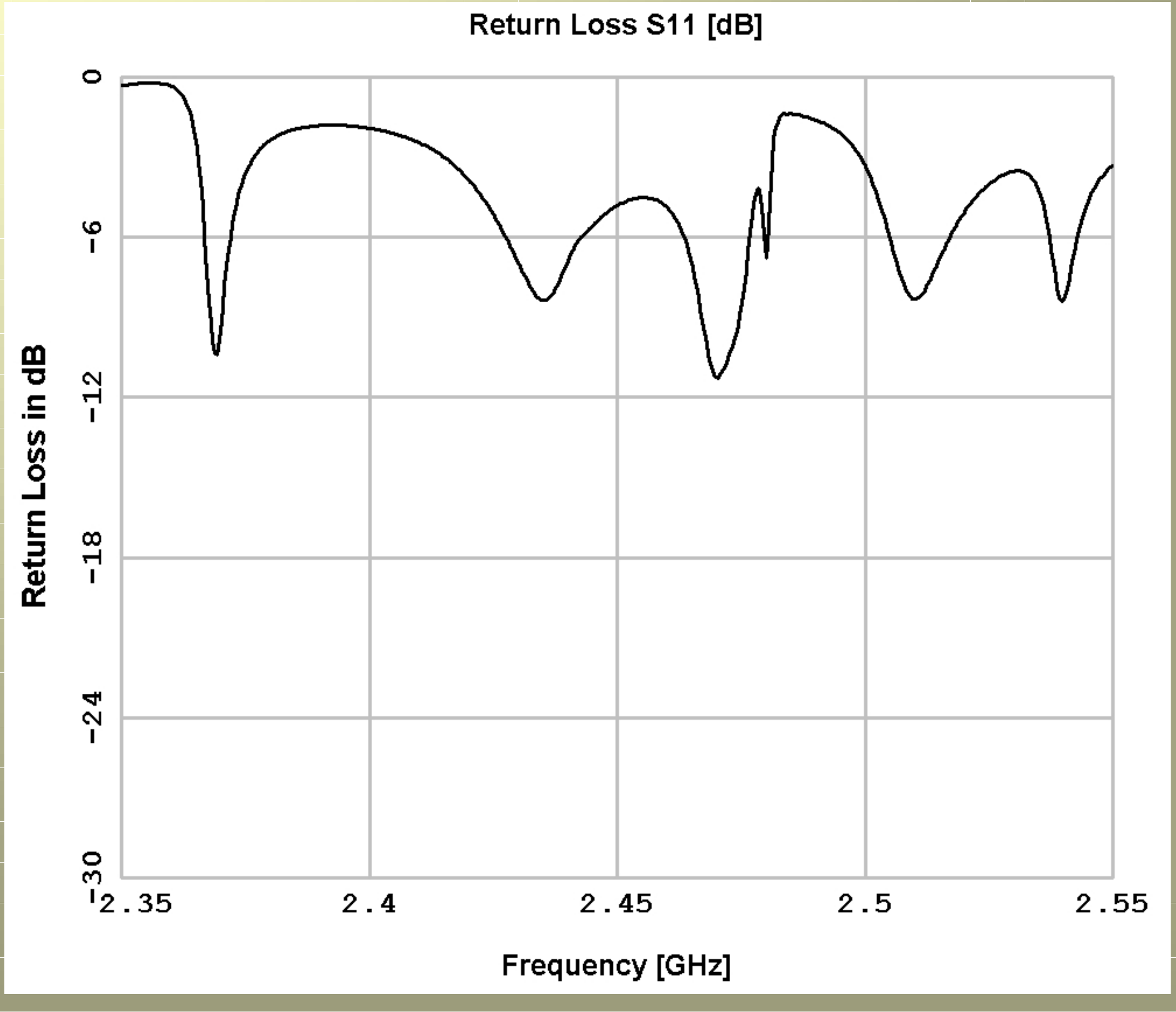
Dissipated Power Density and SAR



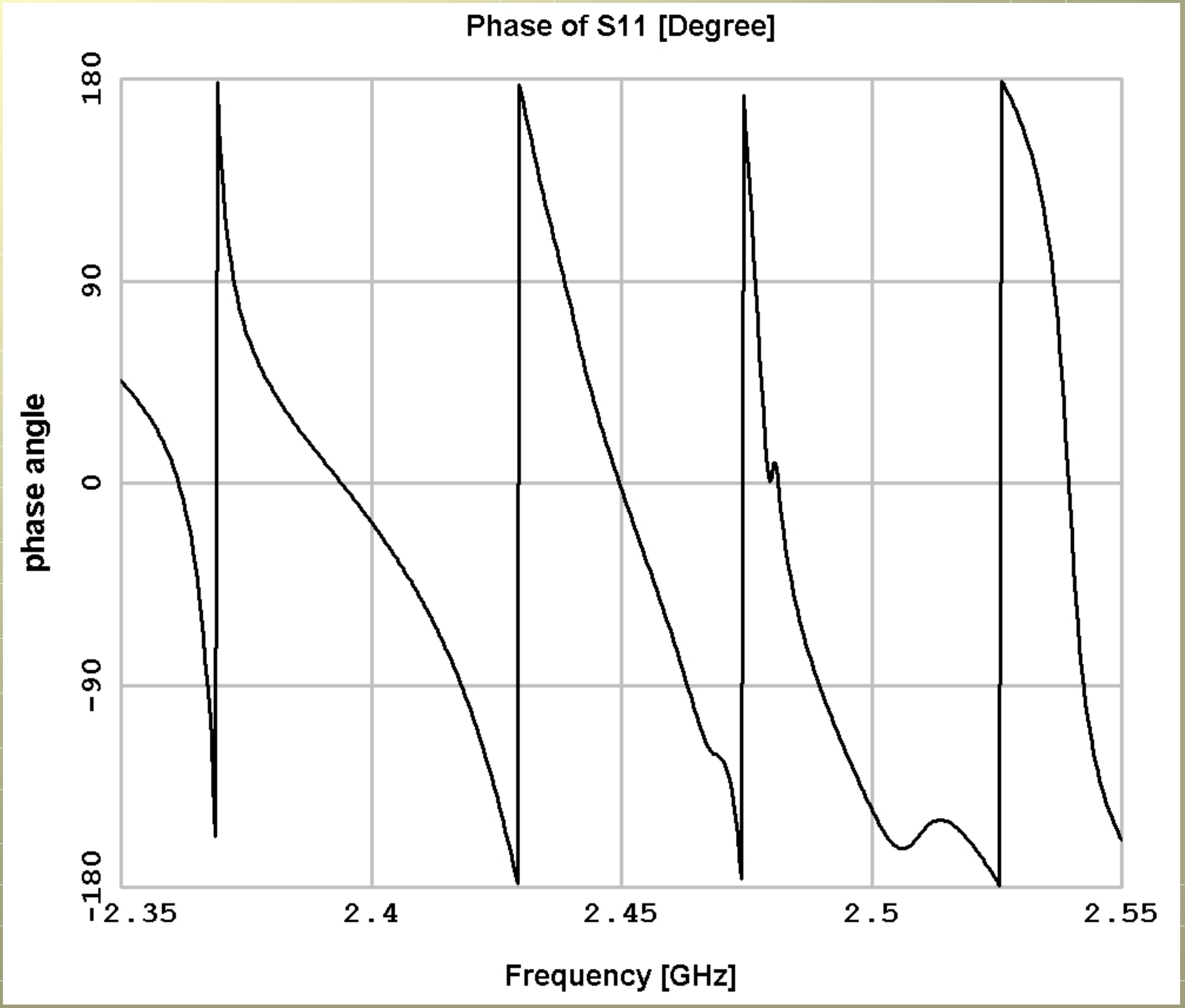
Density of average dissipated power (p_d) and SAR in the potato

1 kW magnetron matched to the waveguide, f = 2.45 GHz, steady state

Return Loss of the Oven in dB



Phase of S_{11} of the Oven



Some Characteristics at 2.45 GHz

Reflection Coefficient at 2.45 GHz at 50 mm from the inner wall of the oven:

$$S_{11} = 0.574\, e^{j0}$$

Return Loss at 2.45 GHz

$$RL = 20 \log |S_{11}| = -4.83\ dB$$

Average power delivered by the magnetron (incident power), reflected, and absorbed by the oven at 2.45 GHz:

$$P_{inc} = 1000 \text{ Watts} \qquad P_{ref} = 329 \text{ Watts} = 32.9\% \qquad P_{abs} = 671 \text{ Watts} = 67.1\%$$

Average SAR for the potato:

$$SAR_{avg} = \frac{P_{abs}}{V_{potato}\,\rho_{potato}} = \frac{671 \text{ W}}{0.131 \text{kg}} = 5.125\ kW / kg$$

End of Presentation

The End