
***MICROWAVE
FUNDAMENTALS, VFM &
MATERIALS HEATING***

The Electromagnetic Spectrum



- ◆ **Cosmic Rays** > 10^{22} Hz
- ◆ **Gamma Rays** ~ 10^{20} Hz
- ◆ **X-Ray** ~ 10^{17} - 10^{19} Hz
- ◆ **UV** ~ 10^{15} - 10^{17} Hz
- ◆ **Visible** ~ $4 - 7 \times 10^{14}$ Hz
- ◆ **IR** ~ 10^{12} - 10^{14} Hz
- ◆ **Microwaves** ~ 10^9 - 10^{12} Hz
- ◆ **RF** ~ 10^6 - 10^8 Hz
- ◆ **Ultrasonic** ~ 10^4 - 10^5 Hz
- ◆ **Sonic** ~ 10^2 - 10^4 Hz

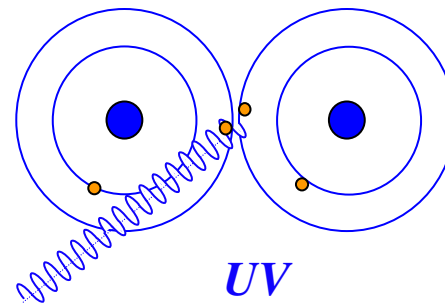
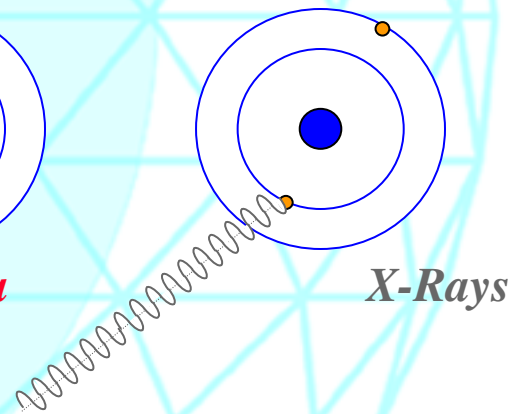
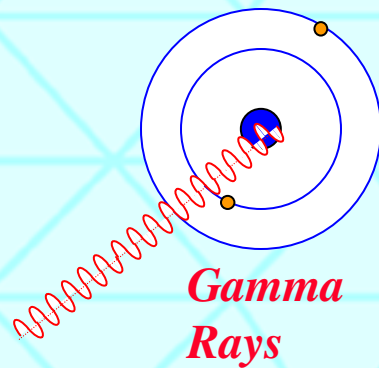
Radiation Fundamentals & Materials Interactions



◆ **Electromagnetic Spectrum**

◆ Gamma Rays	Nuclei	↑ Ionizing Radiation
◆ X-Ray	Inner Electrons	
◆ UV	Covalent Bond Disruption	↓ Non-Ionizing Radiation
◆ Visible	Molecular Vibration (MV)	
◆ IR	MV+Molecular Rotation (MR)	
◆ Microwaves	Charge Flow	
◆ RF		

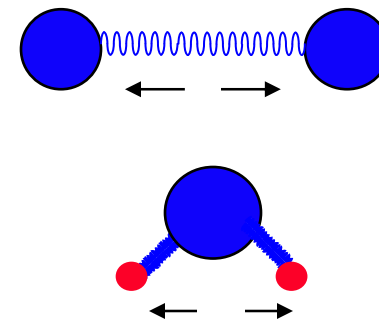
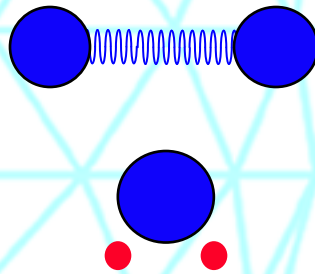
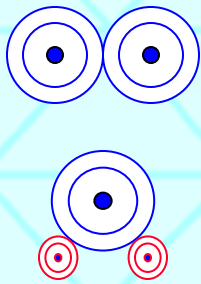
Gamma, X-rays & UV-Energy Coupling



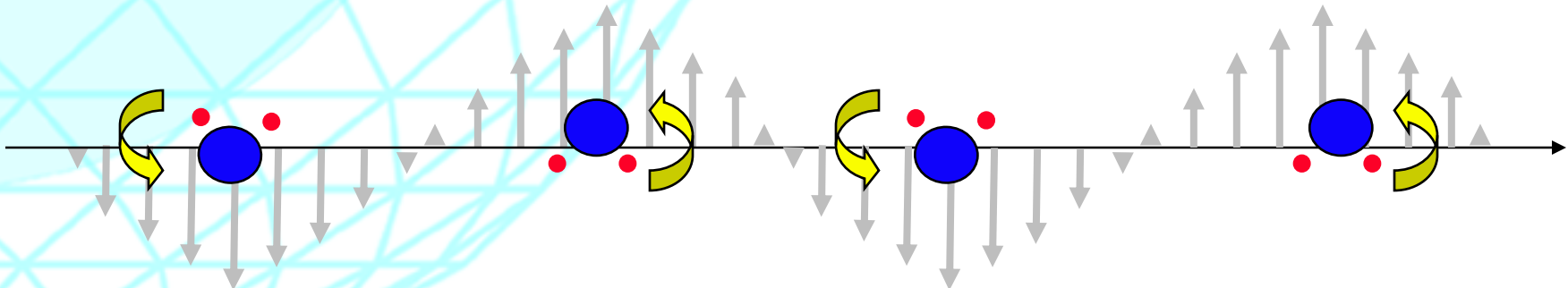
- ◆ Covalent Bonds Disruption
- ◆ Depth of Penetration

IR & Microwave Energy Coupling

◆ IR : Spring Model / Water



◆ Microwaves : Dipolar Rotation of Water



Microwaves



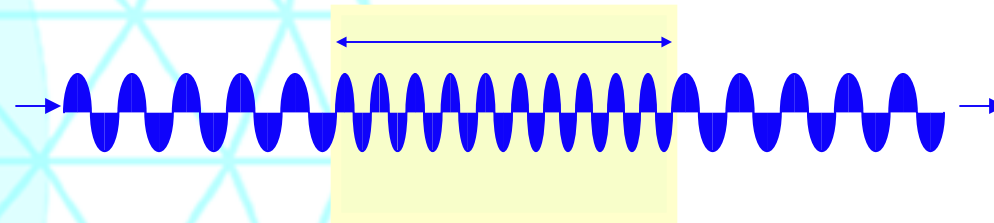
- ◆ **Electromagnetic Spectrum**
- ◆ **Travel at Speed of Light**

- ◆ **Transmitted**
- ◆ **Reflected**
- ◆ **Absorbed**

Microwave Materials Interactions - Specifics

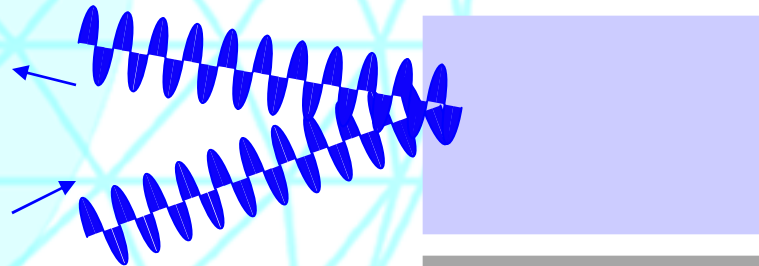


- ◆ Glass & Ceramics



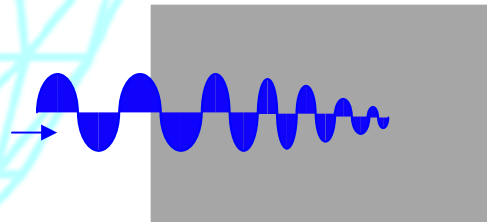
Dp
~2 to 20 m

- ◆ Metals



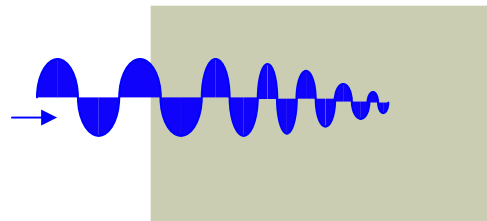
Dp
~2-50 μm

- ◆ Silicon



Dp
~0.01 to 0.2 m

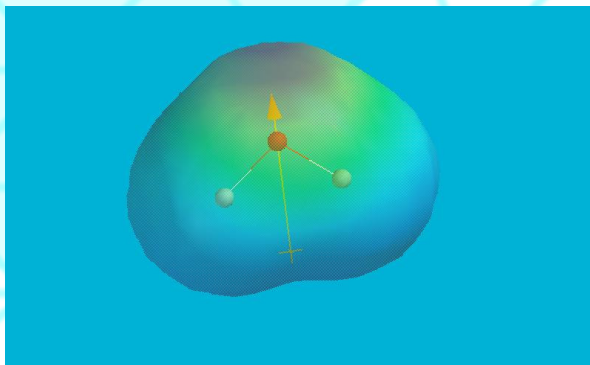
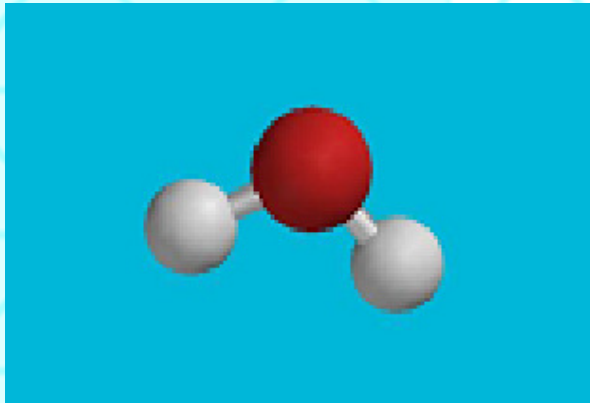
- ◆ Polymers



Dp
~0.1 to 2 m

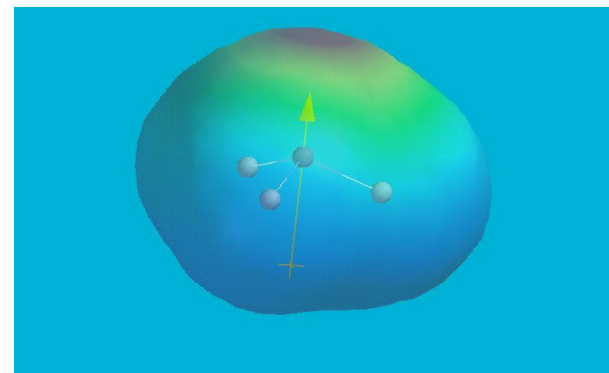
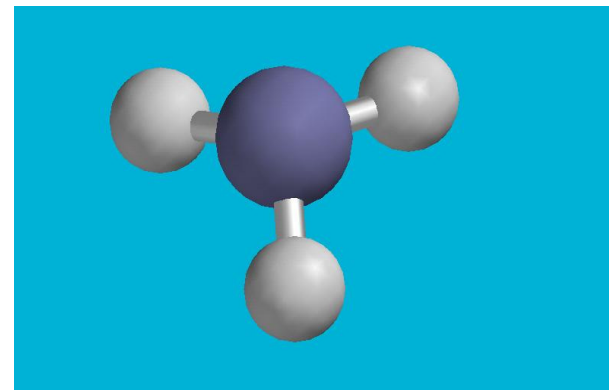
Dipole Orientation

Water (H_2O)



Dipole Moment = 1.861Debye

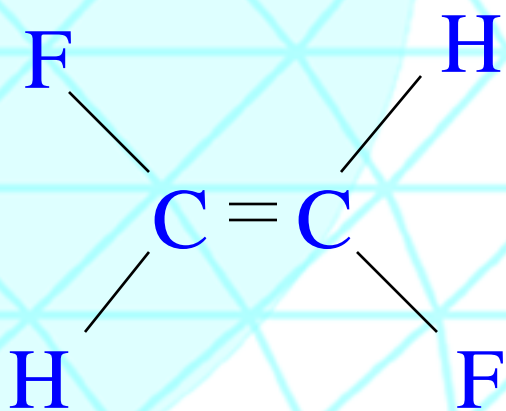
Ammonia (NH_3)



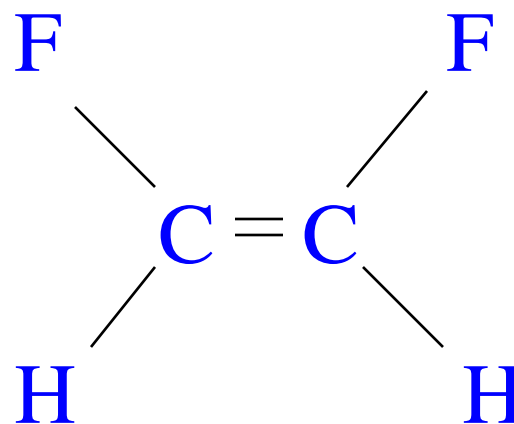
Dipole Moment = 1.847Debye

Dipole Moments - Continued

- ◆ Examples
- ◆ Difluoroethylene – *Trans* & *Cis*



$$\mu_{\text{effective}} = 0$$

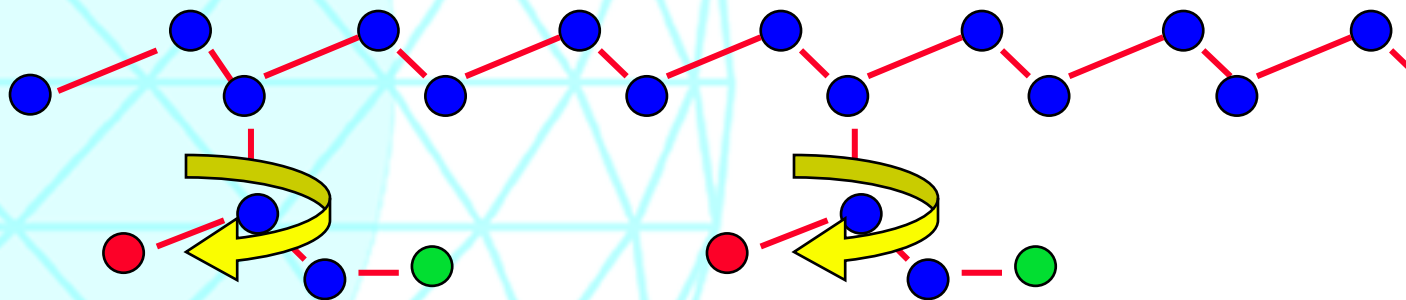


$$\mu_{\text{effective}} = 2.42 \text{ Debye (high)}$$

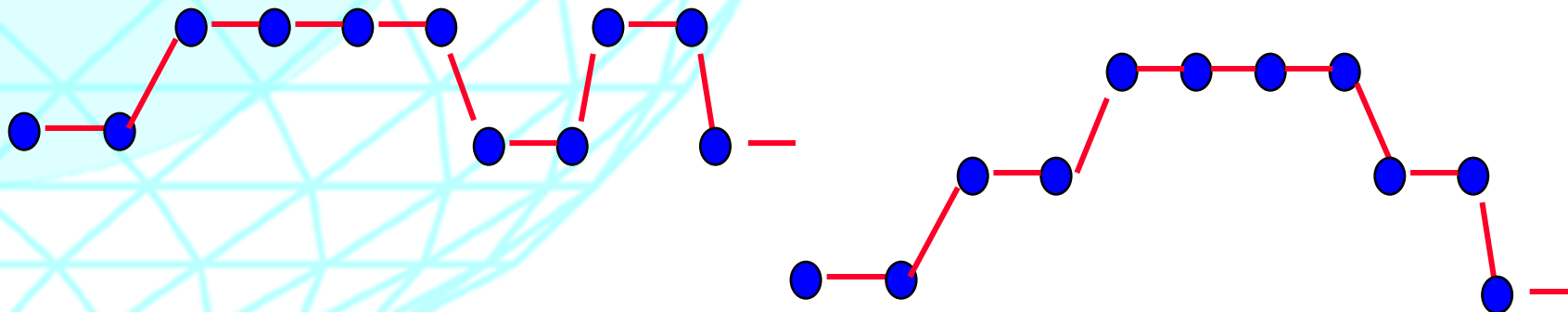
Microwave Energy Coupling in Polymers

Local Motion Of Molecules

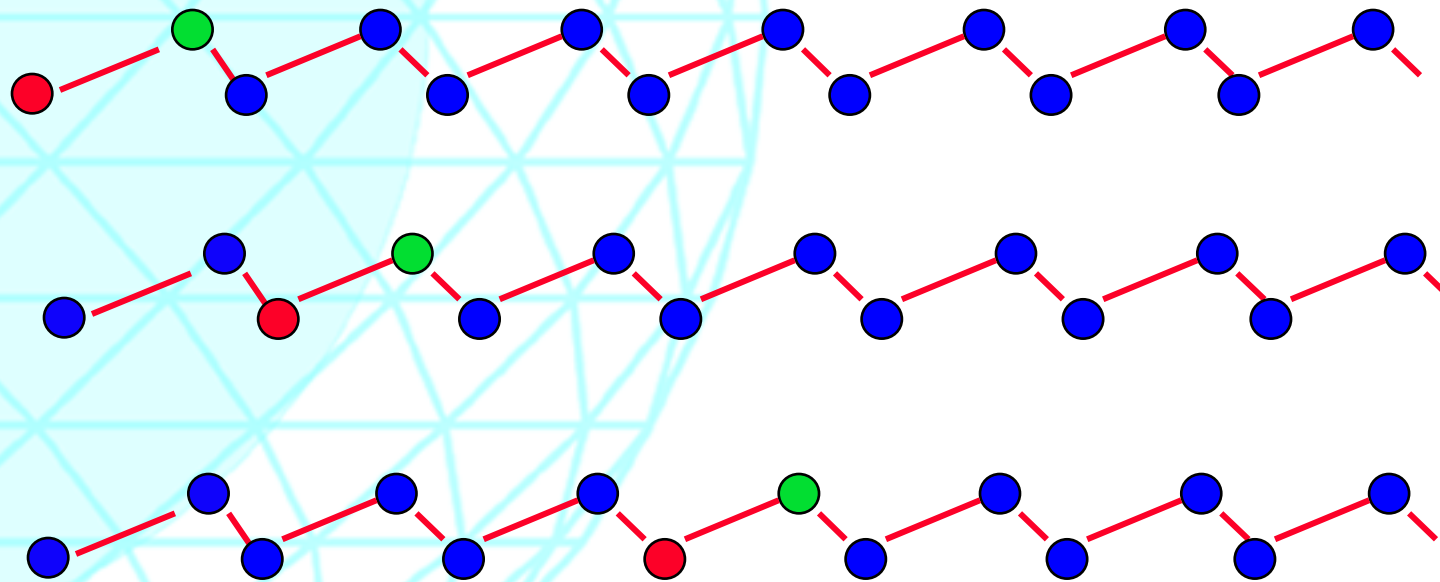
◆ Rotation of a polar side group



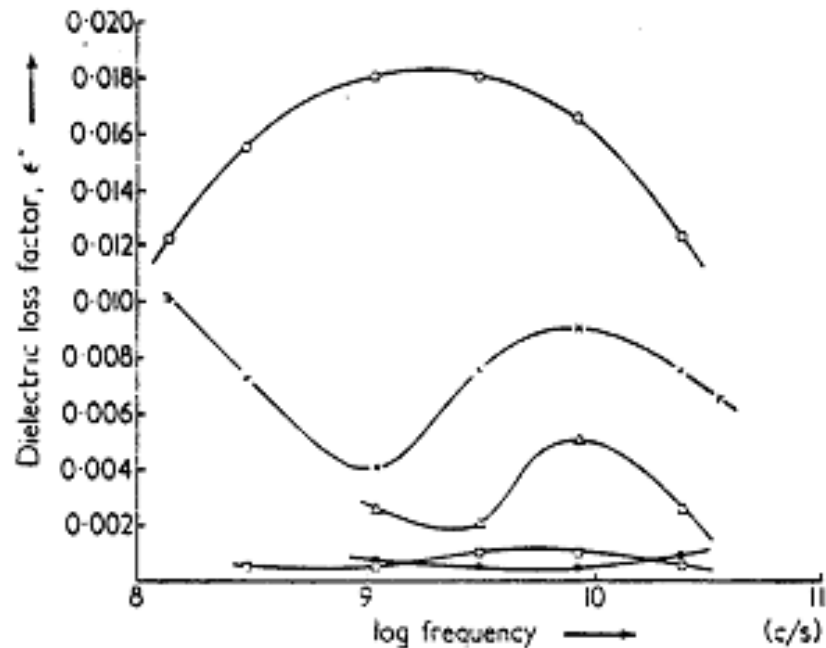
◆ Crankshaft-type rotation



Dipole at Different Positions in Chain



Microwave Absorption in Esters



- o Methyl behenate, $\text{CH}_3\text{O}\cdot\text{CO}\cdot\text{C}_{21}\text{H}_{43}$
- x Ethyl stearate, $\text{C}_2\text{H}_5\text{O}\cdot\text{COC}_{17}\text{H}_{35}$
- Δ n-Butyl stearate, $\text{C}_4\text{H}_9\text{O}\cdot\text{COC}_{17}\text{H}_{35}$
- \square n-Dodecyl laurate, $\text{C}_{12}\text{H}_{25}\text{O}\cdot\text{COC}_{11}\text{H}_{23}$
- Cetyl palmitate, $\text{C}_{12}\text{H}_{33}\text{O}\cdot\text{COC}_{15}\text{H}_{31}$

Dielectric loss for esters with polar group in different positions of the molecular chain

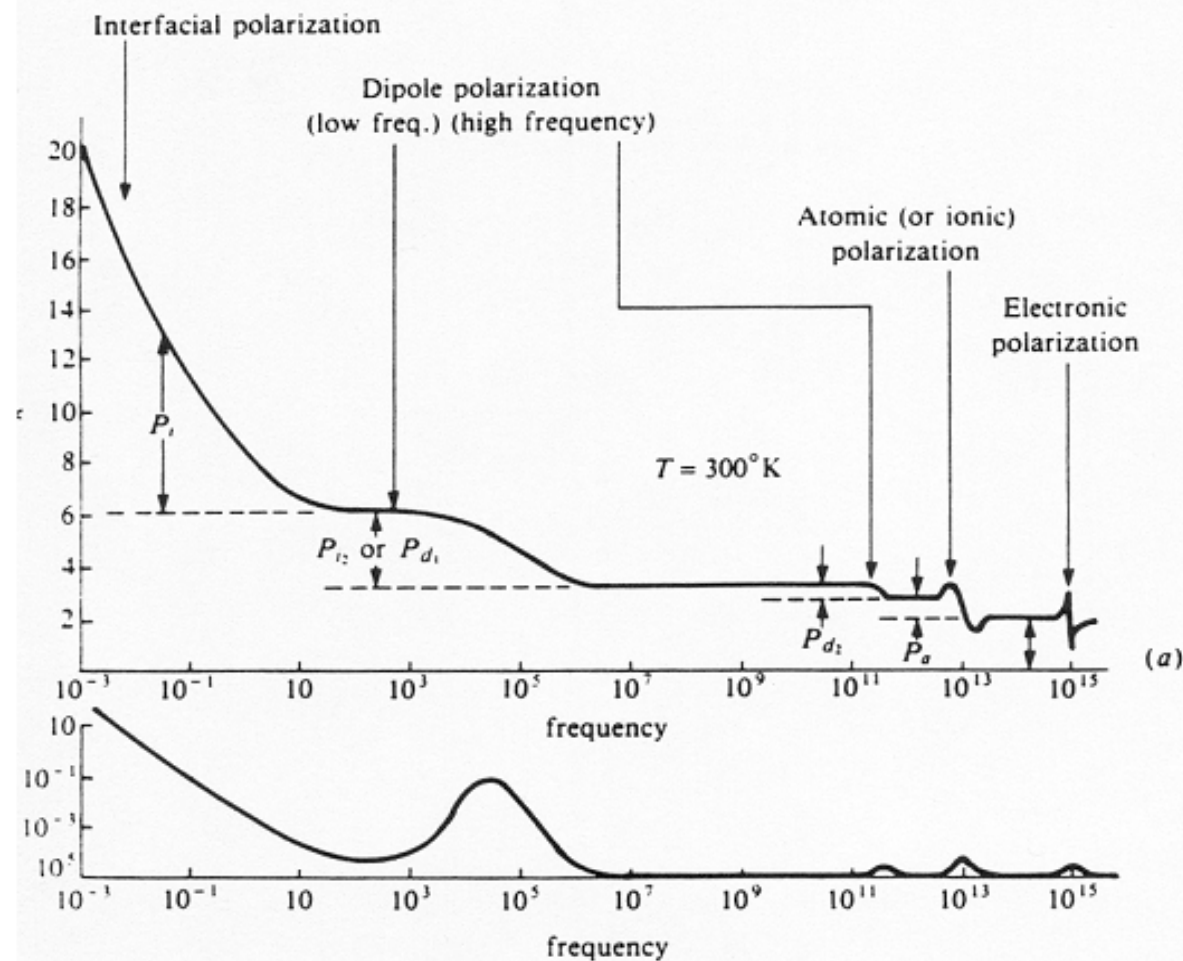
Rapid Curing of Adhesives



Rapid curing -- 10 to 20 times faster

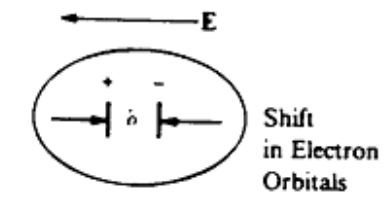
- ◆ **All adhesives cure at high temperatures recommended by manufacturer**
- ◆ **Microwaves cause additional rotational movement of molecules thereby increasing the probability of the monomers to cross-link and form the polymer**
- ◆ **This results in the rapid curing process**

Polarization Mechanism versus Frequency



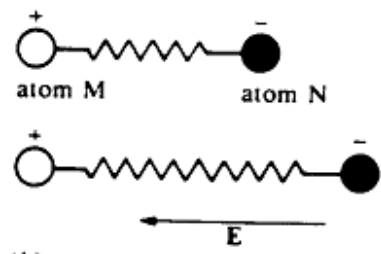
Schematic of Polarization Mechanisms

Electronic



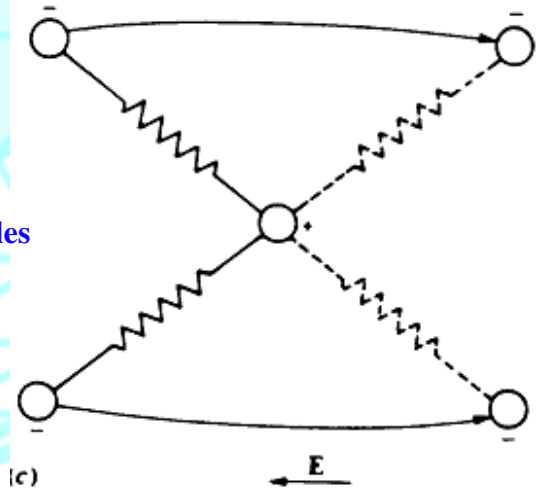
(a)

Atomic or Ionic

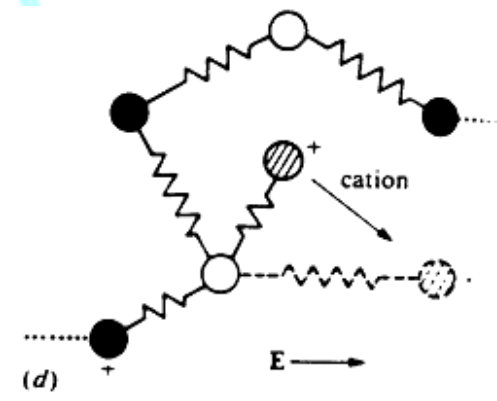


(b)

High Frequency Oscillating Dipoles

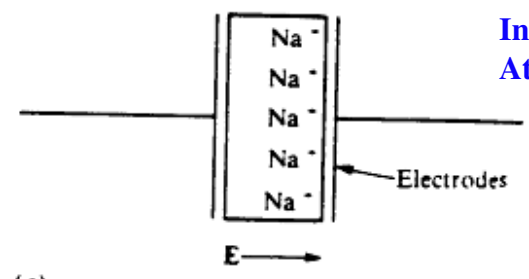


(c)



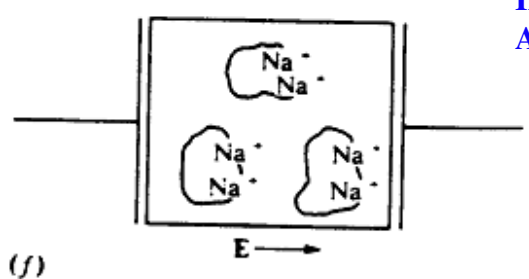
(d)

Low Frequency Cation Dipole



(e)

Interfacial Polarization At Electrodes



(f)

Interfacial Polarization At Heterogeneities

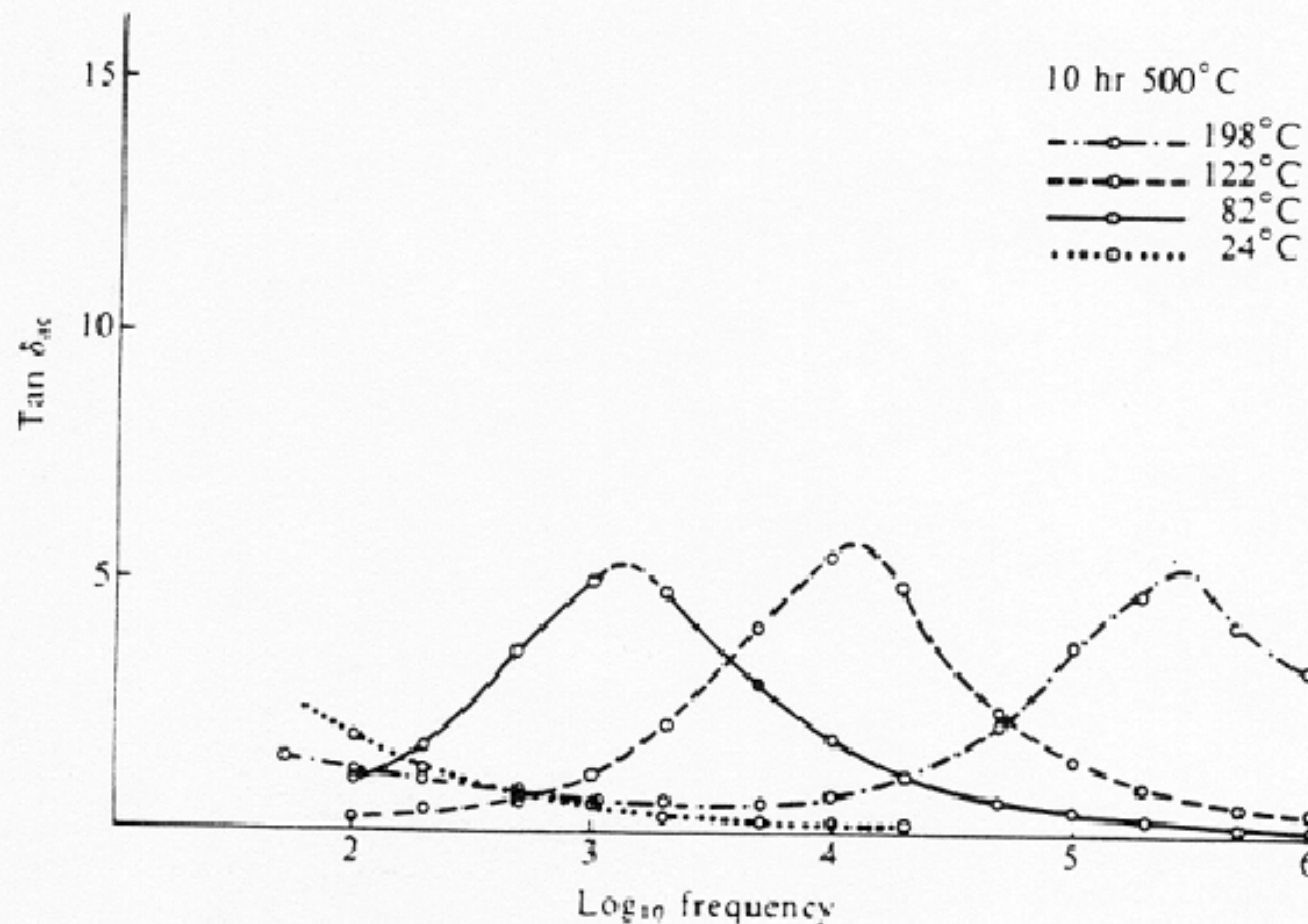
Dominant Polarization



The dominant polarization mechanisms that contribute to microwave heating are

- ◆ **Orientation/Dipole polarization**
- ◆ **Interfacial polarization**

Shift in loss peak with temperature



Shift of the dielectric loss peak in lithium silicate glass with increasing temperature

Additional Losses



- ◆ **Conductivity losses**

 - Dominant at low frequencies

- ◆ **Magnetic losses**

 - ◆ Fe_2O_3 , Fe_3O_4 , NiO and other materials exhibiting a strong magnetic permeability.

Microwave Power Dissipation



$$P_{av} = \omega \epsilon_0 \epsilon''_{eff} E_{rms}^2 V$$

P_{av} = Average power dissipated

ω = Angular frequency

ϵ''_{eff} = Dielectric loss factor

E_{rms} = Electric field intensity (rms)

V = Volume of the load

Microwave Penetration Depth



$$D_p = \lambda_0 (\epsilon')^{1/2} / (2\pi\epsilon''_{\text{eff}})$$

D_p = Penetration depth

λ_0 = Wavelength

ϵ''_{eff} = Dielectric loss factor

Rate of Temperature Rise



$$(T - T_0)/t = \omega \epsilon_0 \epsilon''_{\text{eff}} E_{\text{rms}}^2 V / (M C_p) \text{ } ^\circ\text{C/s}$$

$$(T - T_0)/t = \omega \epsilon_0 \epsilon''_{\text{eff}} E_{\text{rms}}^2 / (\rho_b C_p) \text{ } ^\circ\text{C/s}$$

$T - T_0$ = Increase in temperature

M = Mass of work load

ρ_b = Density of work load

C_p = Heat capacity

Thermal Runaway



Localized uncontrolled heating

Can result in severe deterioration of the product

- ◆ **High level of impurities**
- ◆ **Low density area**
- ◆ **Inhomogeneous**

Loss Increases with Temperature

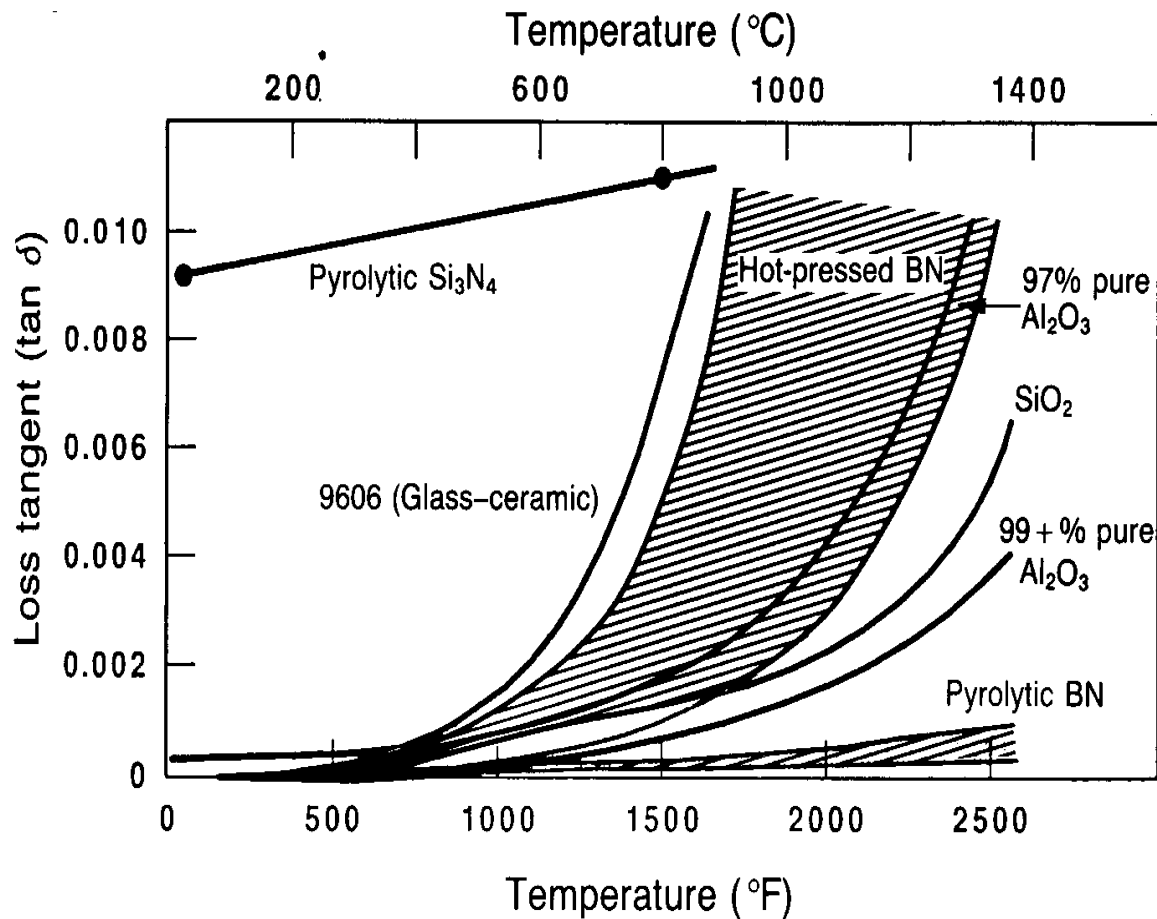


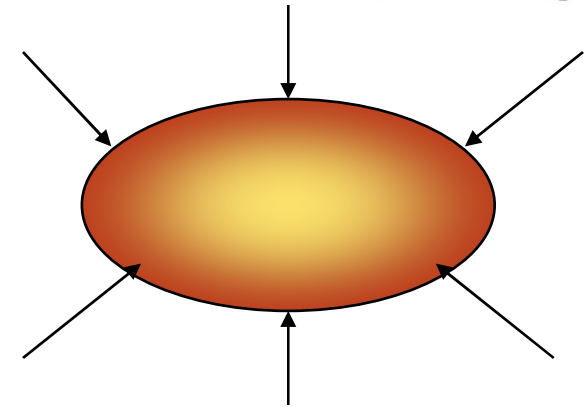
Fig. 5. Loss tangent (8 to 10 GHz) versus temperature (adapted from Walton¹¹).

VFM Technology

Conventional Heating



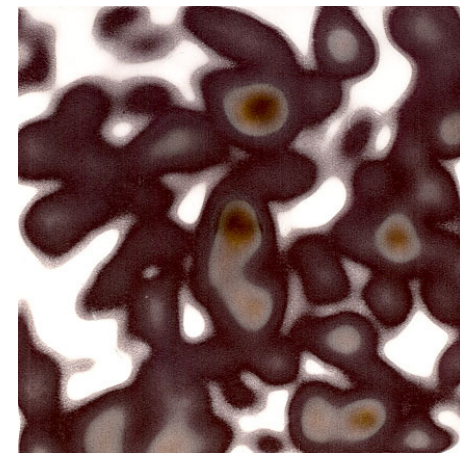
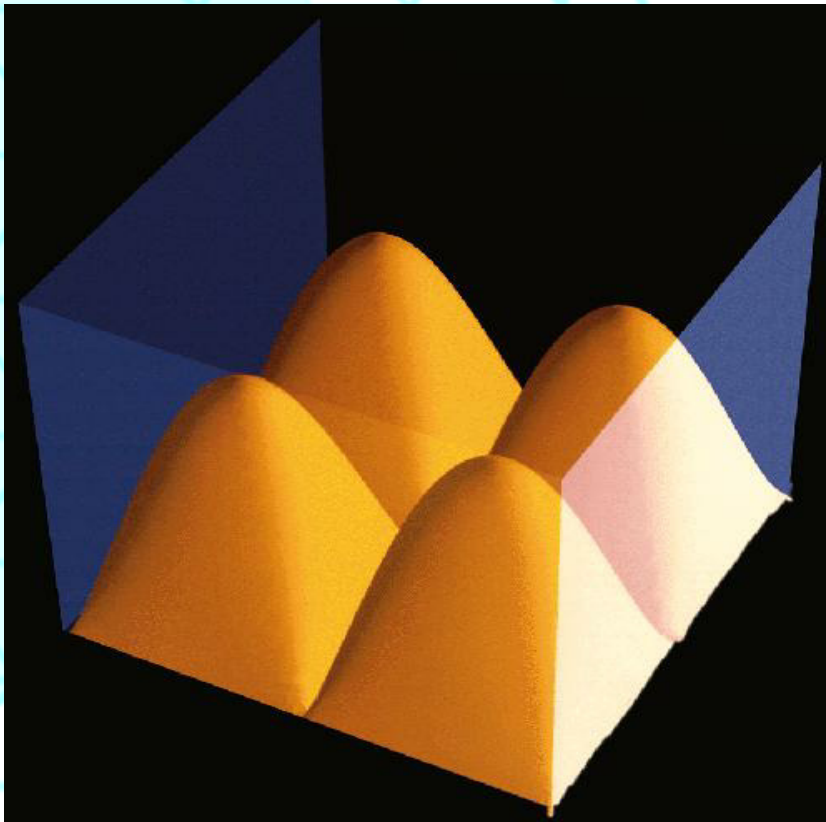
- ◆ External Heat Source
- ◆ Surface Heating
- ◆ Sample (interior) Heating Dependent on Thermal Conductivity
- ◆ The Entire Chamber Heats



Outside - In

Traditional Microwave

- *Fixed Frequency(2.45 GHz)*
- *Fixed Modes Create Hot Spots*



Actual Results

VFM Technology - Principles

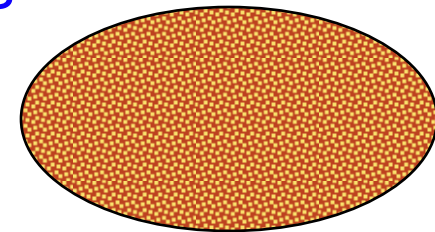


- ◆ **Controlled, multimode oven.**
- ◆ **Within the bandwidth, 4096 frequencies are launched through electronic control which excite a large number of modes resulting in a uniform energy distribution.**
- ◆ **Rapid frequency sweeping eliminates conditions that can cause arcing on metal components.**
- ◆ **Enhanced coupling efficiency via tuning center frequency.**

Variable Frequency Microwave Heating



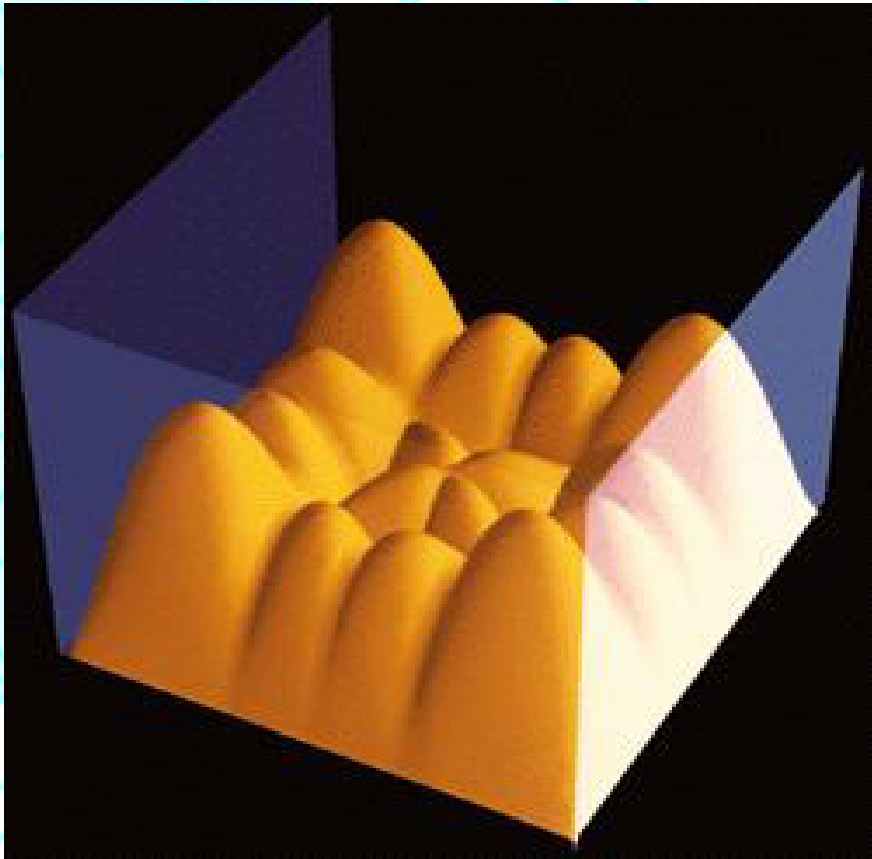
- ◆ Heating is Volumetric, Generated Selectively Only within the Materials Absorbing Microwaves
- ◆ Heat at the Molecular Level by Forced Rotation of Polar Bonds
- ◆ Heating Independent of Thermal Conductivity of Material
- ◆ A Material's Ability to Absorb Microwaves Depends on:
 - The material's Dielectric Properties
 - Frequency of Microwave Energy
 - Temperature of Material



Microwave Heat
Molecular Level

Variable Frequency Microwave

- Frequency is Swept for Uniformity

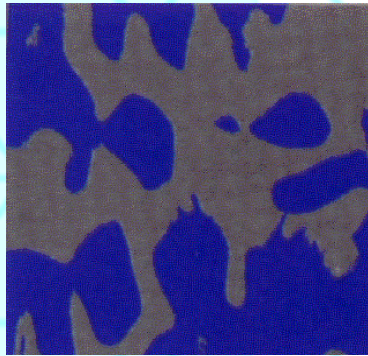


Actual Results

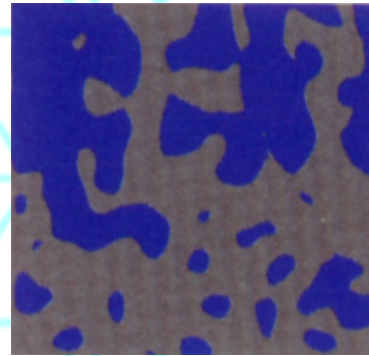
VFM Uniformity is 3-Dimensional



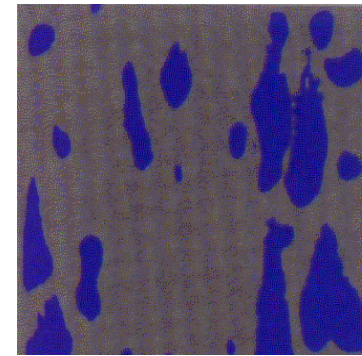
***Fixed
Frequency
Processing***



3 GHz



5 GHz



7 GHz

***Variable
Frequency
Processing***



Top Layer

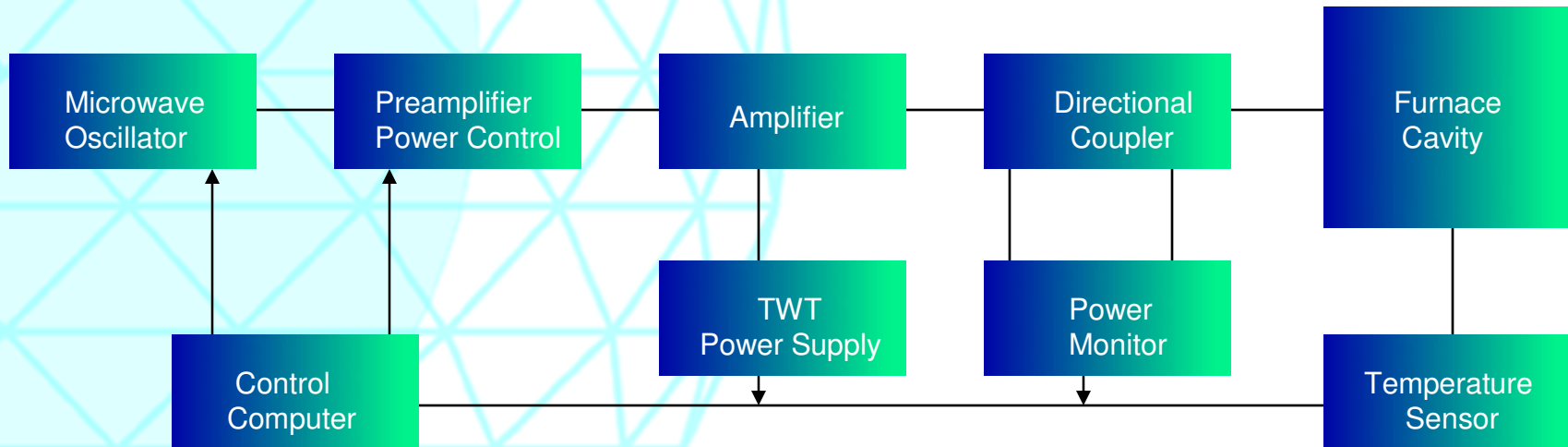


Middle Layer



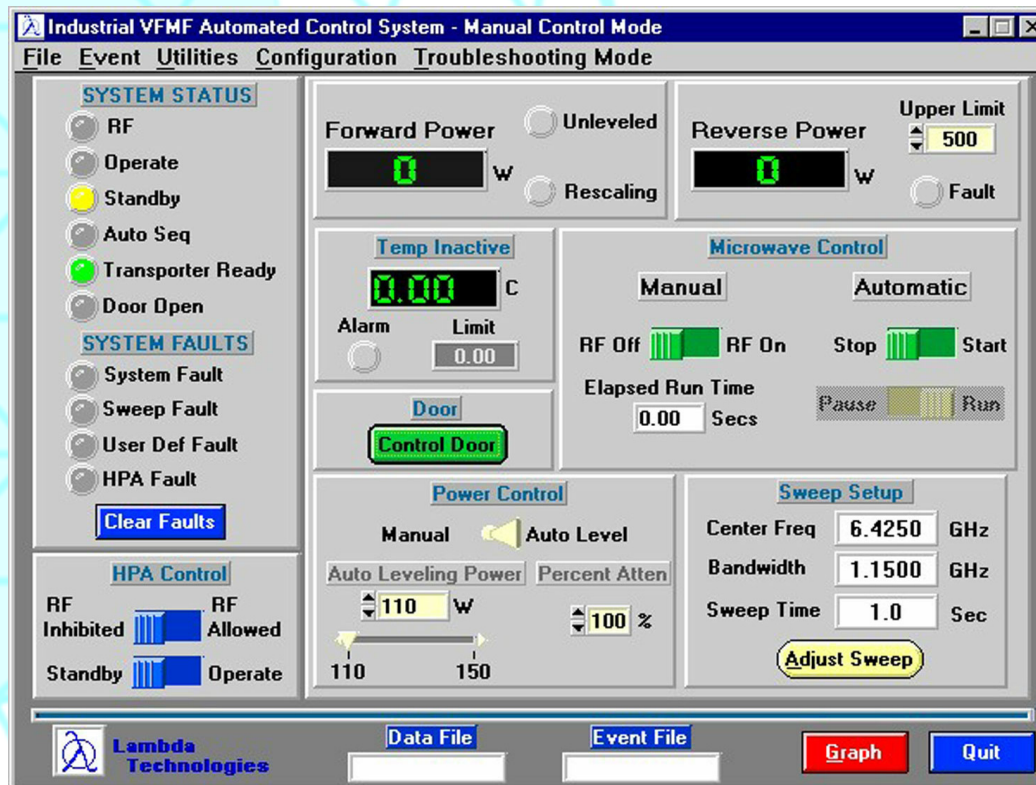
Bottom Layer

Control



Closed loop automated system

Control Interface

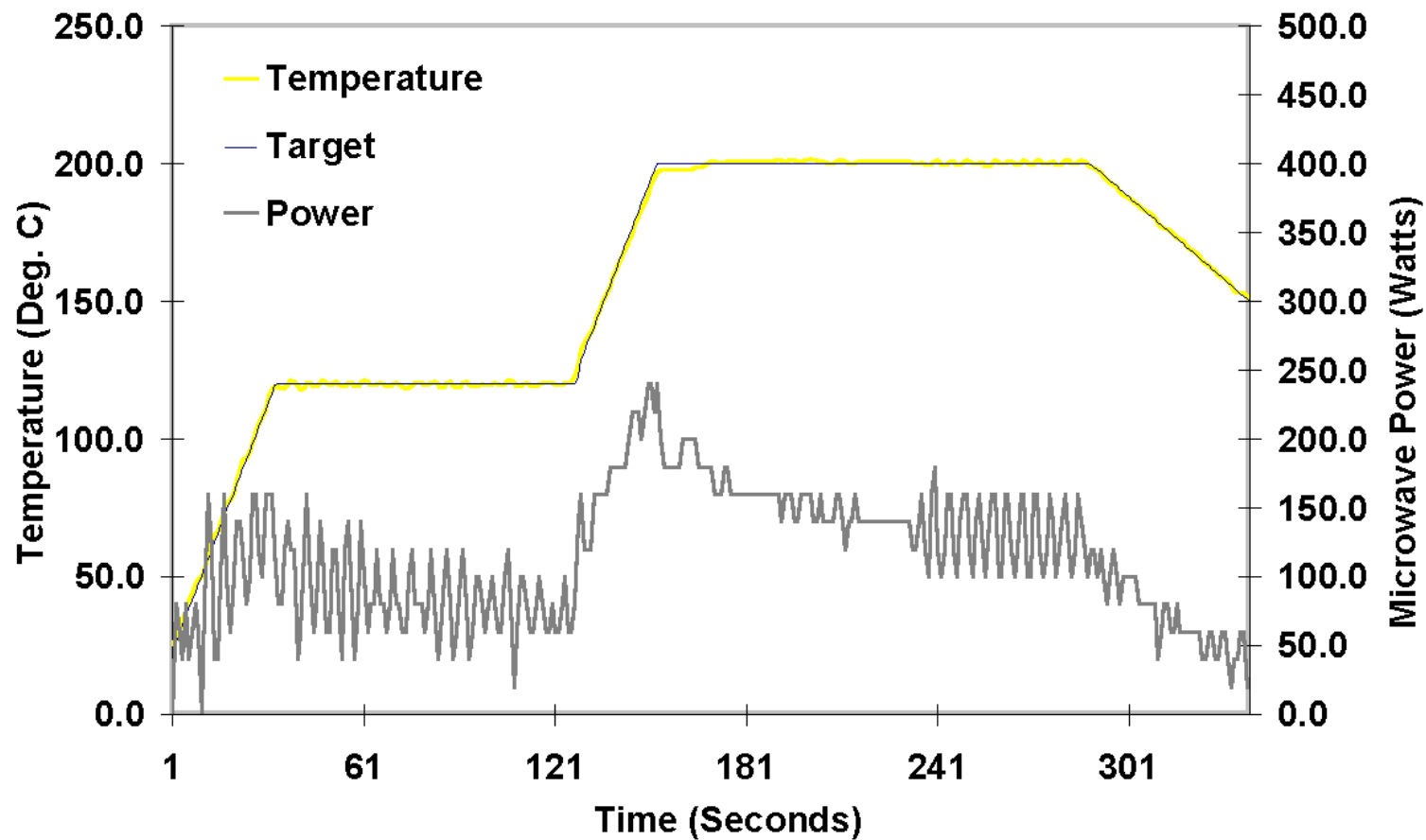


Software control enables the adjustment of all key parameters pertaining to the process and to the equipment interface

VFM - Precise Control of Step Cycle



Controlled Temperature Profile with VFM



Variable Frequency Microwave Processing

The Benefits



- Rapid Heating and Curing Cycles.
- Typical Process Cycles are 1/10 to 1/2 of Convection Cure Times.
- Potential for Lower Stress Curing Due to Selective Heating.
- In-Line and Just-in-Time Curing Process.
- High Efficiency of Energy Utilization.
- Reduced Floor Space and Work-in-Process.

Questions?



1-888-290-CURE

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