University of Zagreb
Faculty of Chemical Engineering and Technology
Study programme Chemical and Environmental Technology

MICROWAVE ASSISTED CHEMISTRY
MICROWAVE THEORY

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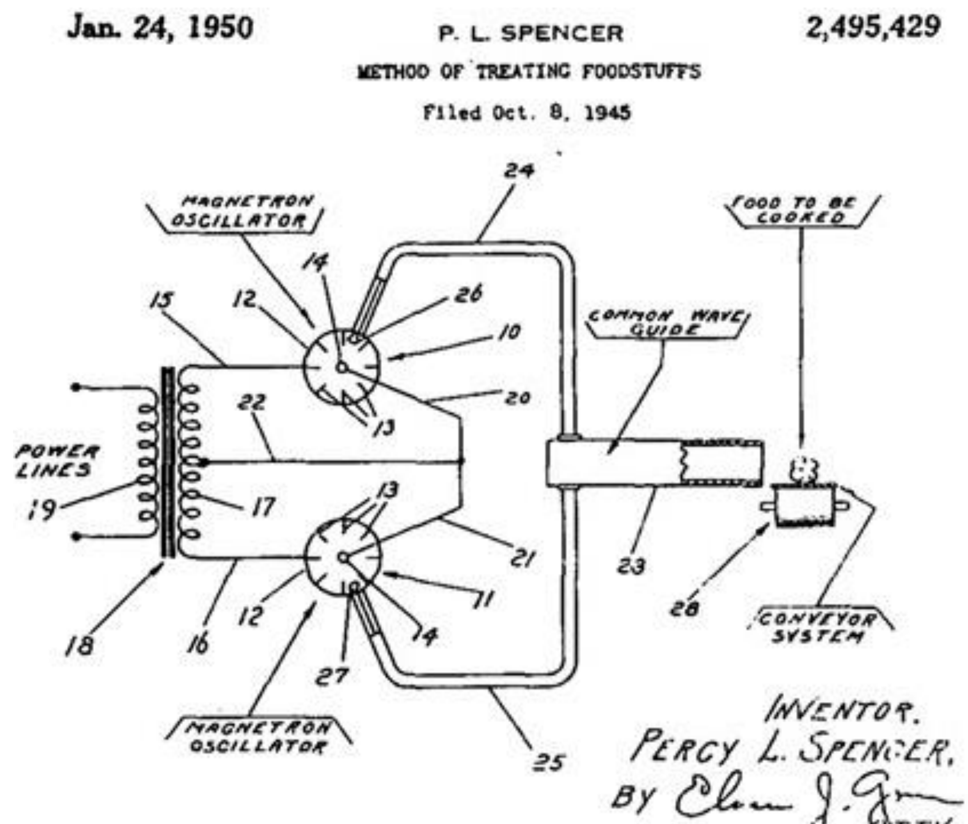
Academic year 2024/2025

INTRODUCTION – historical overview

- 1946. original patent by P. L. Spencer 1947
- the first commercial microwave oven 1955
- home microwave
- In 1976, more than 60% of households in the United States owned a home microwave oven



From Spencer Family Archives

- microwave techniques are developing rapidly during II. World War, especially for military purposes (navigation, radar, communication)
- In the 1980s, the global increase in the use of microwave ovens

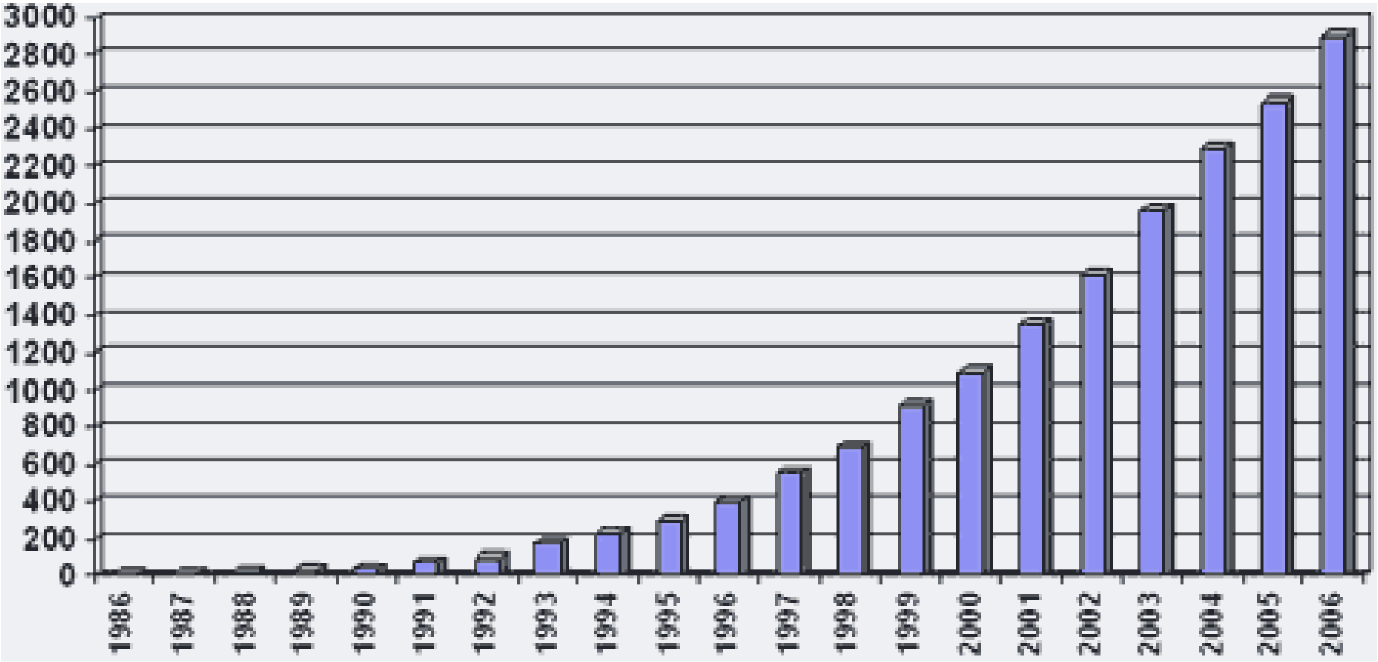
INTRODUCTION – historical overview

P. L. Spencer

first commercial microwave

INTRODUCTION

❖in the last two decades it has been used intensively in organic site; over 3500 published scientific publications

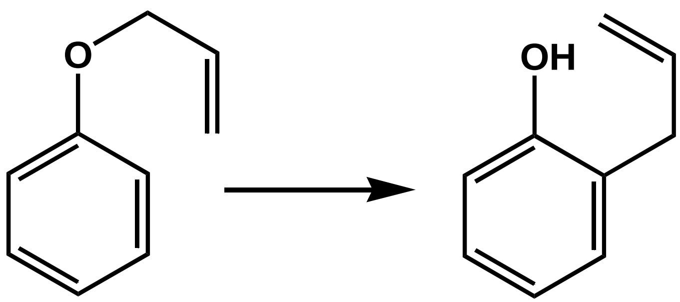


❖In 1986, the first publication describing the use of microwaves in organic synthesis was published

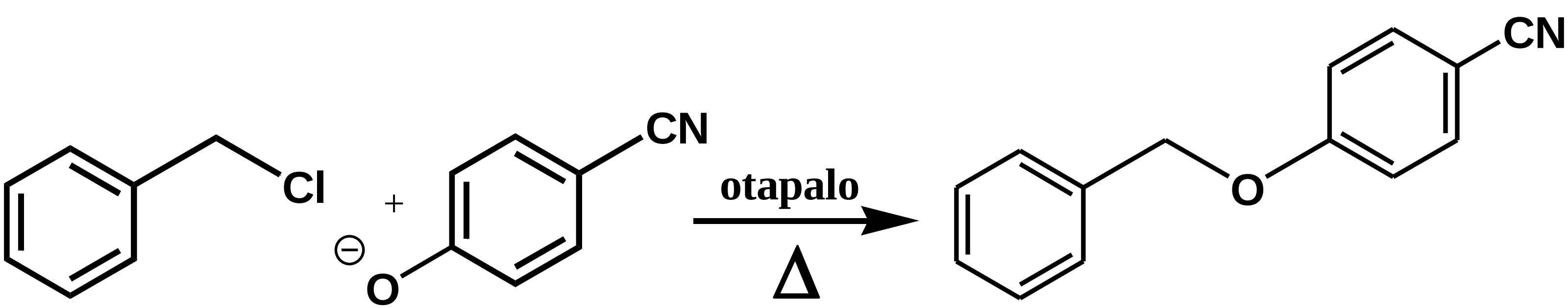
❖ flammability of organic compounds and lack of temperature and pressure control - main problems the first experiments in home microwave ovens

INTRODUCTION

- ❖“Application of commercial microwave ovens to organic synthesis” Giguere, R. J., Majetich, G. *Tetrahedrom Letters* 1986, 27, 4945.
- ❖“The use of microwave ovens for rapid organic synthesis” Gedye, R. N. *Tetrahedron Letters* 1986, 27, 279.



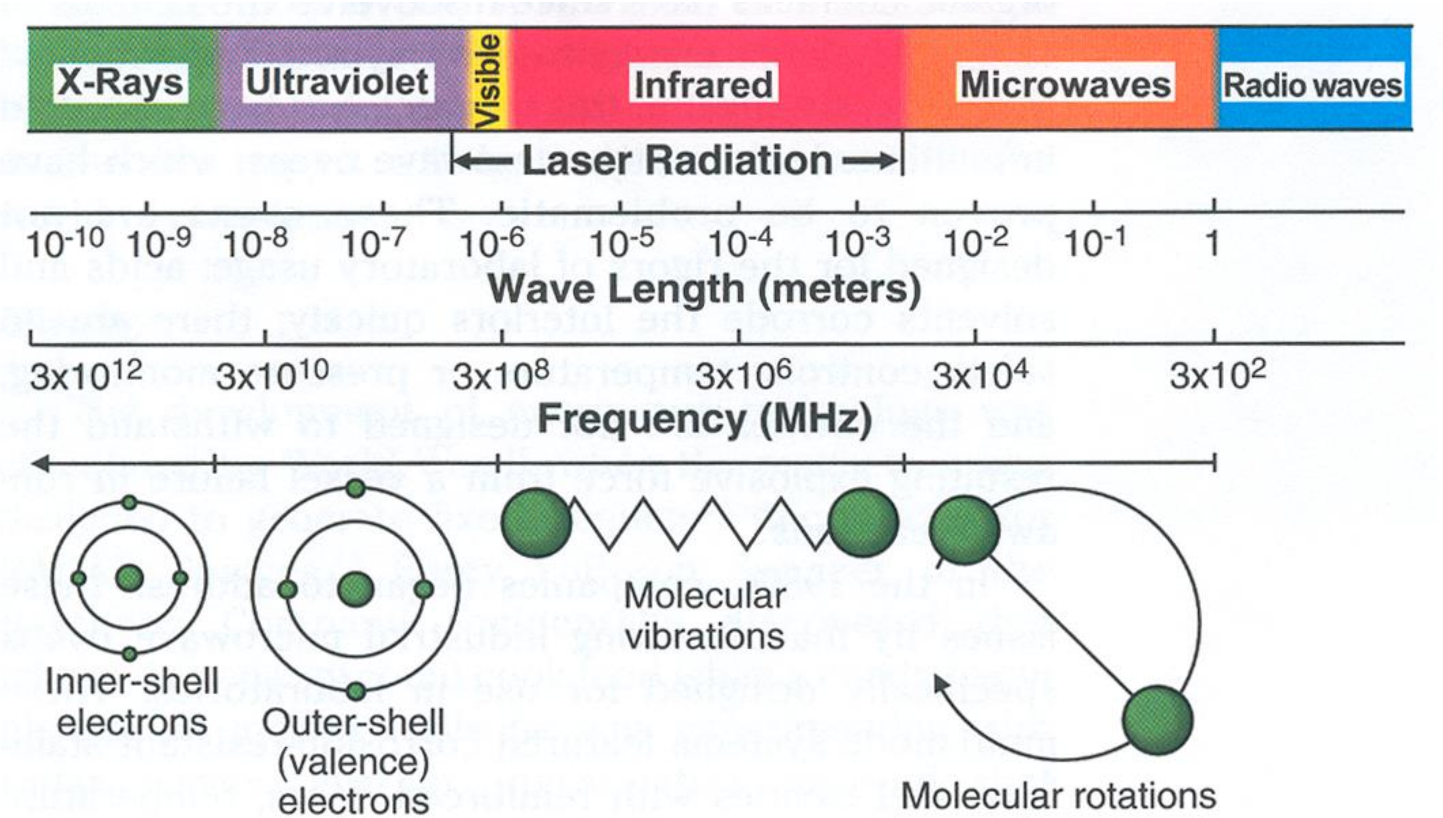
classical synthesis: 6 h (85%)
MW synthesis: 6 min (92%)



classical synthesis: 16 h (90%)
MW synthesis: 4 min (93%)

THEORY OF MICROWAVE IRRADIATION

❖ electromagnetic radiation of frequency 0.3 - 300 GHz



- between the infrared region and the radio wave region
- 2.45 GHz microwave radiation is most commonly used in household and chemical use

THEORY OF MICROWAVE IRRADIATION

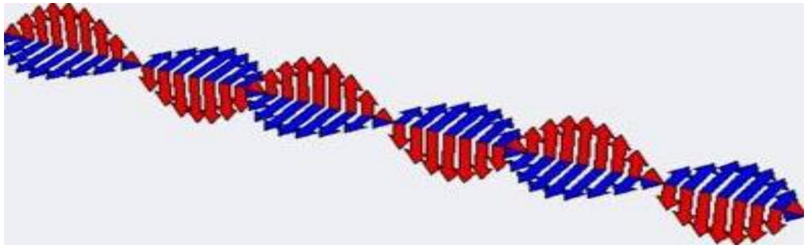
- microwave radiation is generated by dipole polarization or conduction mechanisms
- photons of MW radiation have low energy insufficient to break chemical bonds

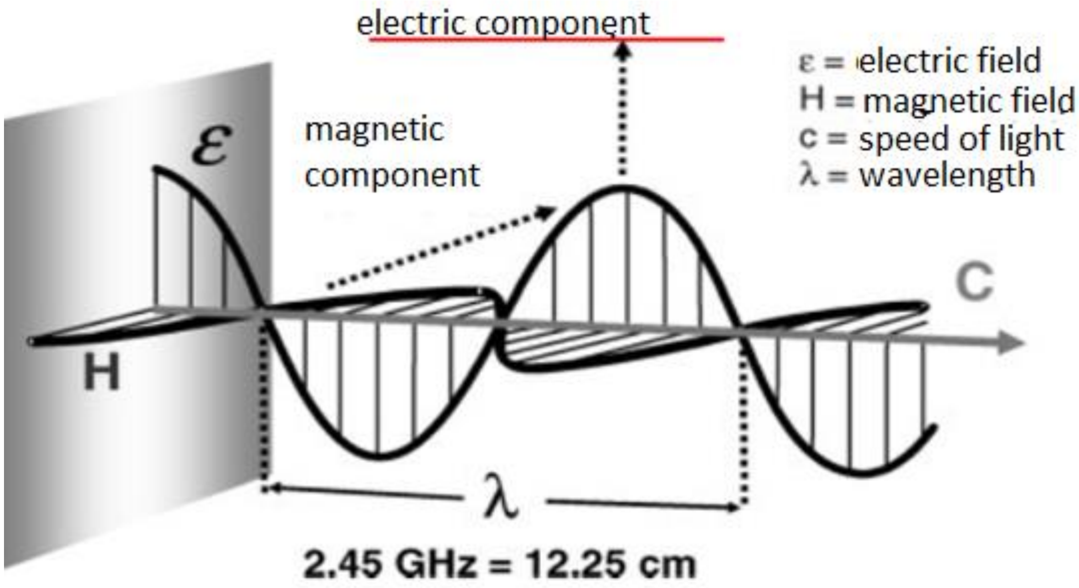
Type of radiation	frequency (MHz)	quantum energy (eV)	Type of bond	Bond energy (eV)
gama rays	3.0×10^{14}	1.24×10^{6}	C–C	3.61
X-rays	3.0×10^{13}	1.24×10^{5}	C=C	6.35
ultraviolet	1.0×10^{9}	4.1	C–O	3.74
visible light	6.0×10^{8}	2.5	C=O	7.71
infrared light	3.0×10^{6}	0.012	C–H	4.28
microwaves	2450	0.0016	O–H	4.80
radio frequency	1	4.0×10^{-9}	hydrogen bond	0.04–0.44

- solvents play a major role in the absorption of MW radiation (polar solvents with dipole moment and high dielectric constant - water, DMF, CH_2Cl_2)
- solvent absorption power - tan δ

THEORY OF MICROWAVE IRRADIATION

- MW radiation - electromagnetic radiation - electrical and magnetic component
- electrical component (E) of MW radiation is responsible for the interaction with matter

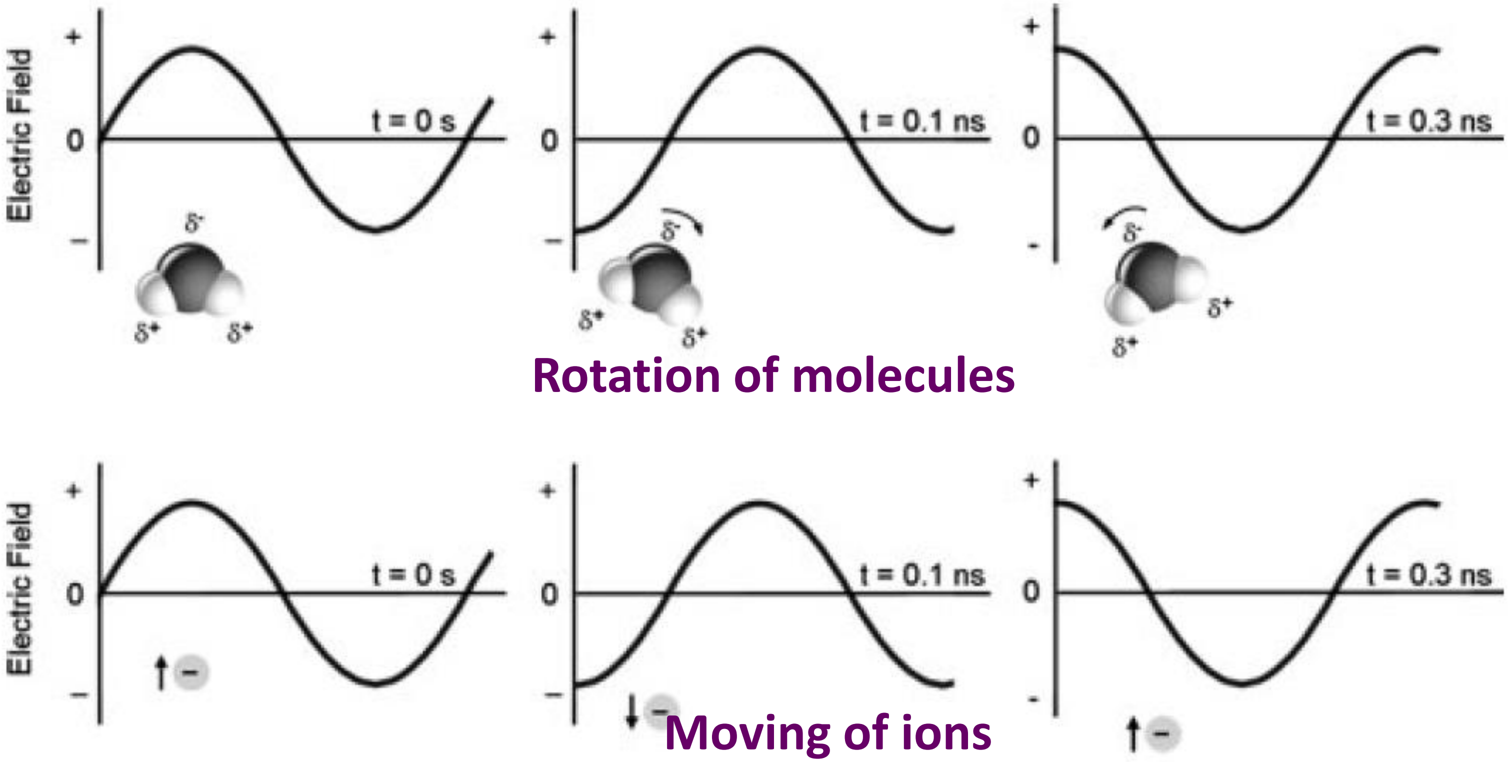




- The E field causes heating by **dipole polarization** (dipole rotation) or **conduction mechanism** (ionic conductivity)
- it induces polarization within matter

THEORY OF MICROWAVE IRRADIATION

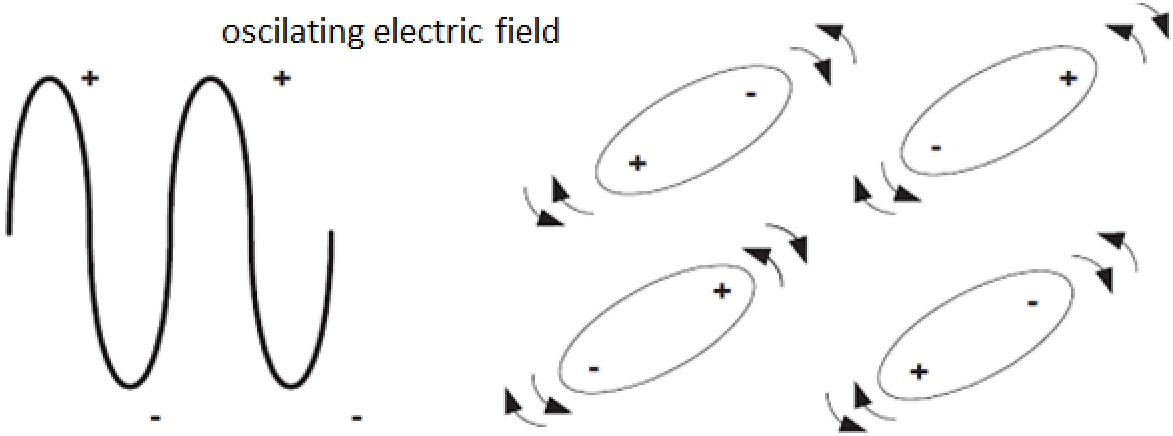
Mechanism of dipole polarization and ionic conductivity:



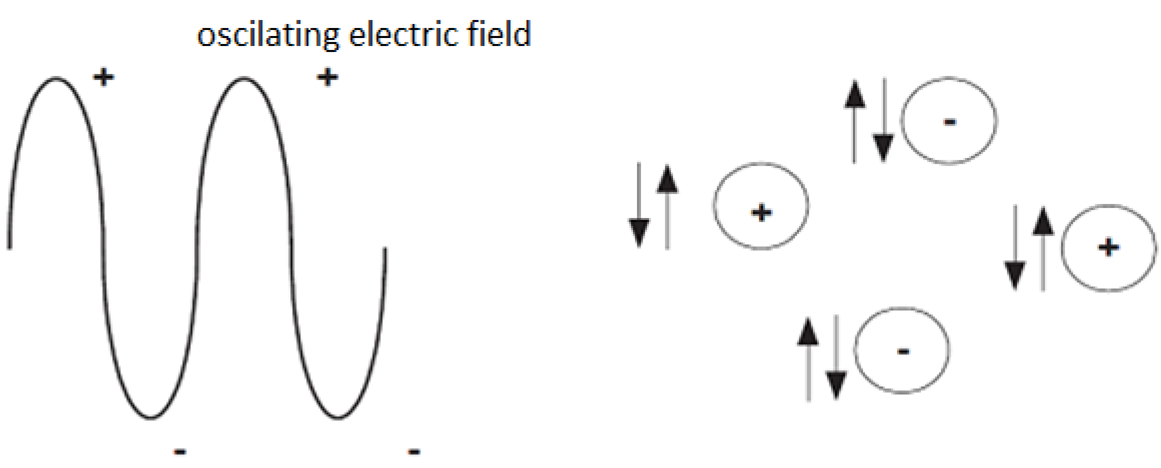
- ❖ in order for matter to be able to absorb energy, it must have a dipole moment - the E field stimulates the rotation of molecules, but their motion is not fast enough and rapid changes in the E field they do not follow - the decay of EM radiation into thermal energy
- ❖ free ions tend to follow the direction of motion of the E field

THEORY OF MICROWAVE IRRADIATION

Mechanism of dipole polarization :

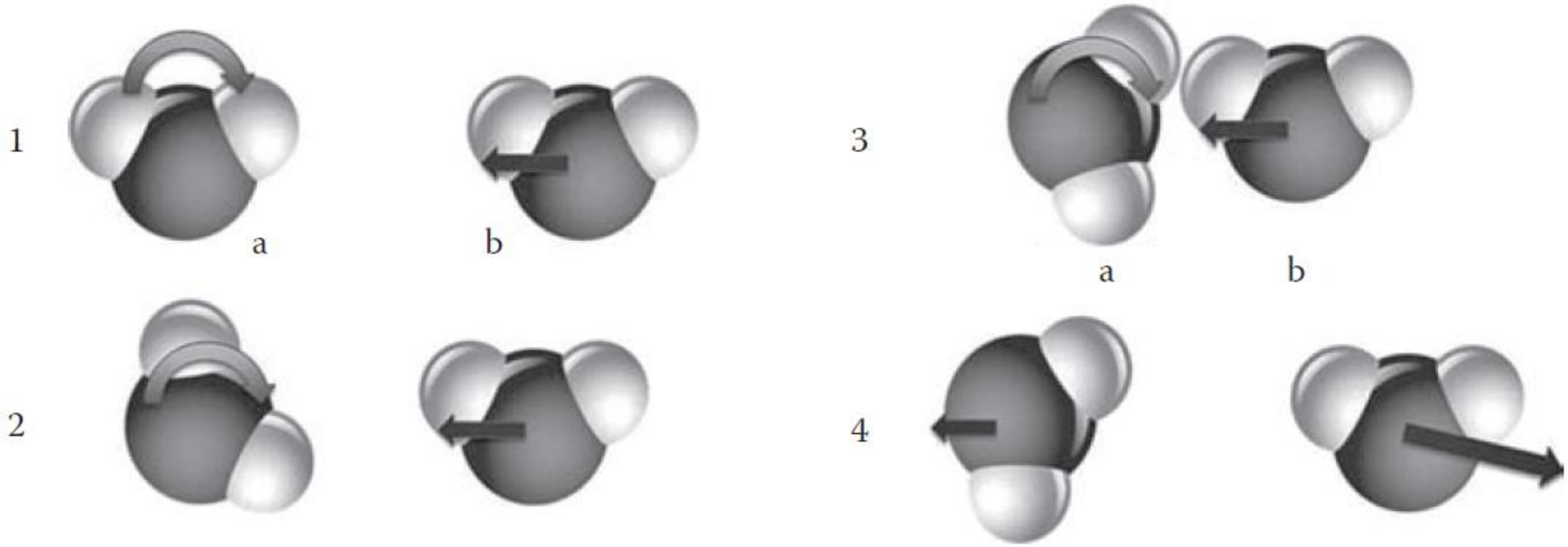


Mechanism of ionic conductivity:



THEORY OF MICROWAVE IRRADIATION

Mechanism of dipole polarization :



- 1-2: molecules rotate under the influence of MW radiation
- 3: due to the mutual influence, the rotational energy of the molecule is converted into translational motion
- 4: increasing the magnitude of the translation vector leads to an increase in kinetic energy

THEORY OF MICROWAVE IRRADIATION

Dipole polarization - an interaction during which polar molecules try to follow the direction of the alternating E field and its strength depends on the polarity of the molecules and their ability to follow the change of the E field

Ionic conductivity - occurs when free ions or ionic species are present in the medium and under the influence of MW radiation their movement occurs by the action of an alternating E field

Dielectric properties of matter

dielectric constant ε' – ability of molecules to be polarized under the influence of E fields - molecules with high dipole moment

dielectric loss ε '' - the amount of MW of energy that is dissipated into thermal energy

tanges of loss tan δ - the ability of matter to convert EM energy into heat energy at a certain frequency and temperature ($\tan \delta = \varepsilon'' / \varepsilon'$)

Dielectric properties of matter

- for a very high ability to absorb MW radiation as well as rapid heating the reaction medium must have a high tan δ
- tan δ is frequency and temperature dependent
- materials with a high dielectric constant do not necessarily have a high tan δ
- low tan δ solvents can also be used in MW-assisted reactions - reactants and catalysts can increase the overall dielectric properties polar additives - alcohols, ionic solutions

Debyeev relacsation theory:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + \varpi^2 \tau^2} \qquad \varepsilon'' = \frac{(\varepsilon_0 - \varepsilon_\infty)\varpi\tau}{1 + \varpi^2 \tau^2} \qquad \tau \approx \frac{3V\eta}{kT}$$

Dielectric properties of matter

Tanges of loss for some solvents:

Solvent	tan δ	Solvent	tan δ
Ethylene glycol	1.350	*N*,*N*-dimethylformamide	0.161
Ethanol	0.941	1,2-dichloroethane	0.127
Dimethylsulfoxide	0.825	Water	0.123
2-propanol	0.799	Chlorobenzene	0.101
Formic acid	0.722	Chloroform	0.091
Methanol	0.659	Acetonitrile	0.062
Nitrobenzene	0.589	Ethyl acetate	0.059
1-butanol	0.571	Acetone	0.054
2-butanol	0.447	Tetrahydrofuran	0.047
1,2-dichlorobenzene	0.280	Dichloromethane	0.042
1-methyl-2-pyrrolidone	0.275	Toluene	0.040
Acetic acid	0.174	Hexane	0.020

- **solvents with high (tan δ> 0.5), medium (tan δ 0.1 - 0.5) and weak (tan δ <0.1) ability to absorb MW radiation**

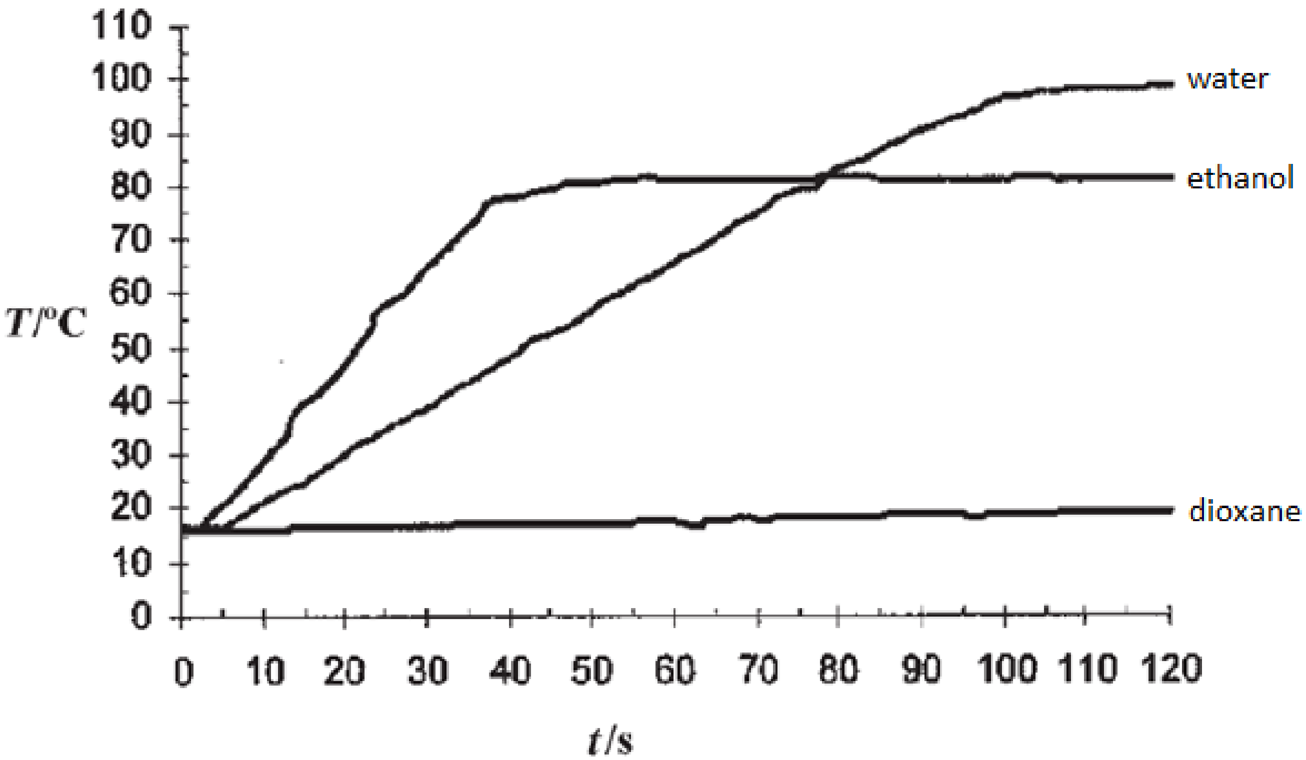
Dielectric properties of matter

- the higher the tan δ, the more efficiently the solvent converts MW energy into thermal energy and heats up faster
- MW permeable solvents that do not absorb MW radiation at all are dioxane, CCl_4 and benzene
- solvent boiling points are no longer so important because the action of MW radiation heats all solvents to boiling point in a few seconds

"High" (> 0.5)		"Medium" (0.1 – 0.5)		"Low" (< 0.1)	
Otapalo	Tan δ	Otapalo	Tan δ	Otapalo	Tan δ
ethylene-glycol	1,350	butan-2-ol	0,447	chloroform	0,091
		dichlorobenzene	0,280	MeCN	0,062
EtOH	0,941	NMP	0,275	EtOAc	0,059
DMSO	0,825	acetic acid	0,174	acetone	0,054
propan-2-ol	0,799	DMF	0,161	THF	0,047
fomic acid	0,722	dichloroethane	0,127	DCB	0,042
MeOH	0,659	water	0,123	toluene	0,040
nitrobenzen	0,589	chlorobenzene	0,101	hexane	0,020
butan-1-ol	0,571				

Interaction of materials with MW radiation

- **water, which is a medium-absorbing solvent, heats up more slowly than ethanol while dioxane does not absorb MW radiation at all**



Dielectric properties of matter

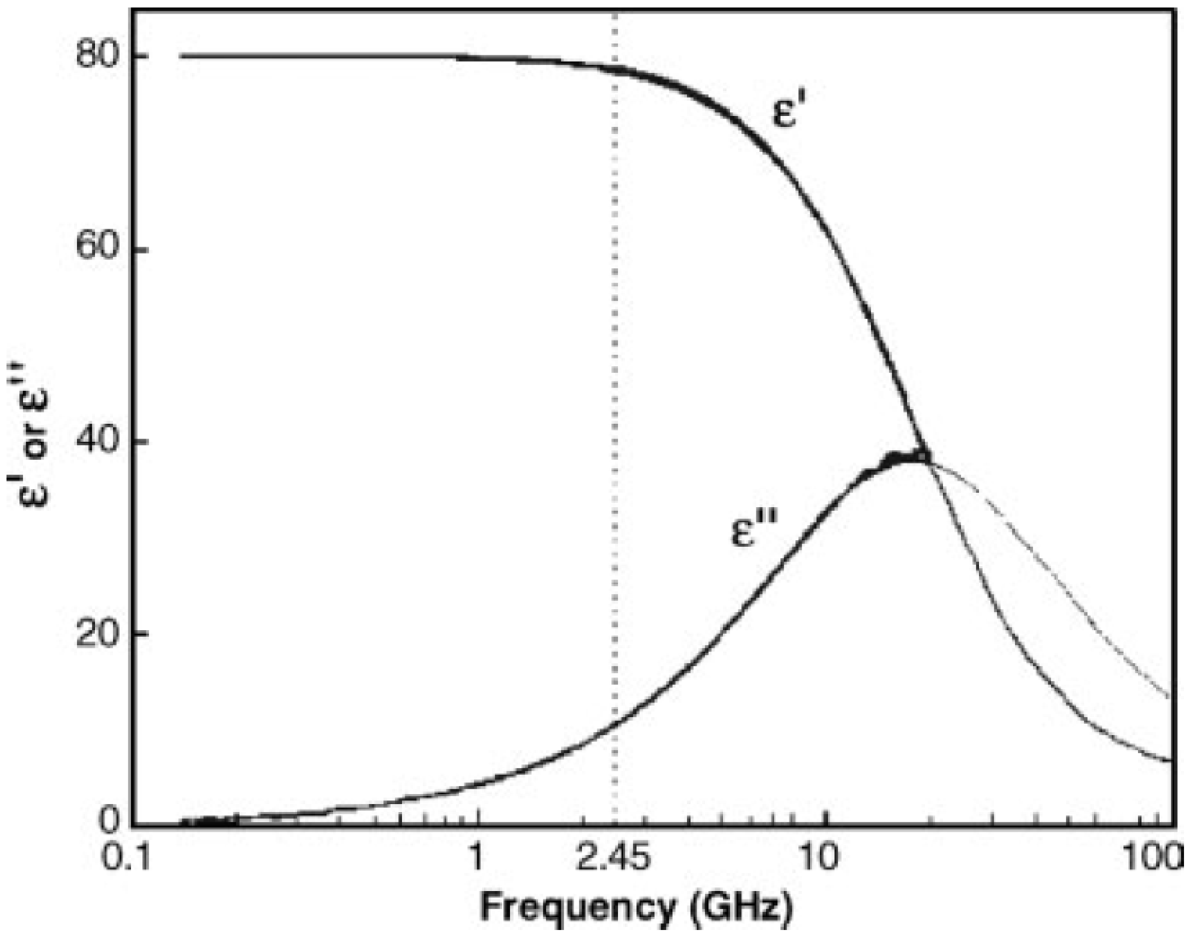
Solvent	Relaxation time τ (ps)	Dipole moment (debye)	Loss tangent at 2.45 GHz
H_2O	9.04	1.54	0.123
MeOH	51.5	1.70	0.659
EtOH	170	1.69	0.941
Propan-1-ol	332	1.68	0.757
Me_2SO	20.5		0.825
$HCONMe_2$	13.05		0.161
$MeNO_2$	4.51		0.064
THF	3.49		0.047
CH_2Cl_2	3.12		0.042
$CHCl_3$	8.94		0.091
MeCOMe	3.54		0.054
$MeCO_2Et$	4.41		0.059
HCO_2H	76.7 (25°C)		0.722
$MeCO_2H$	177.4 (25°C)		0.174
MeCN	4.47		0.062
PhCN	33.5		0.459
CH_2OHCH_2OH	113 (25°C)		1.35

Solvent	Dielectric constant (ε_s)
Water	80.4
MeOH	33.7
Me_2CO	21.4
C_6H_6	2.3

Dielectric properties of matter

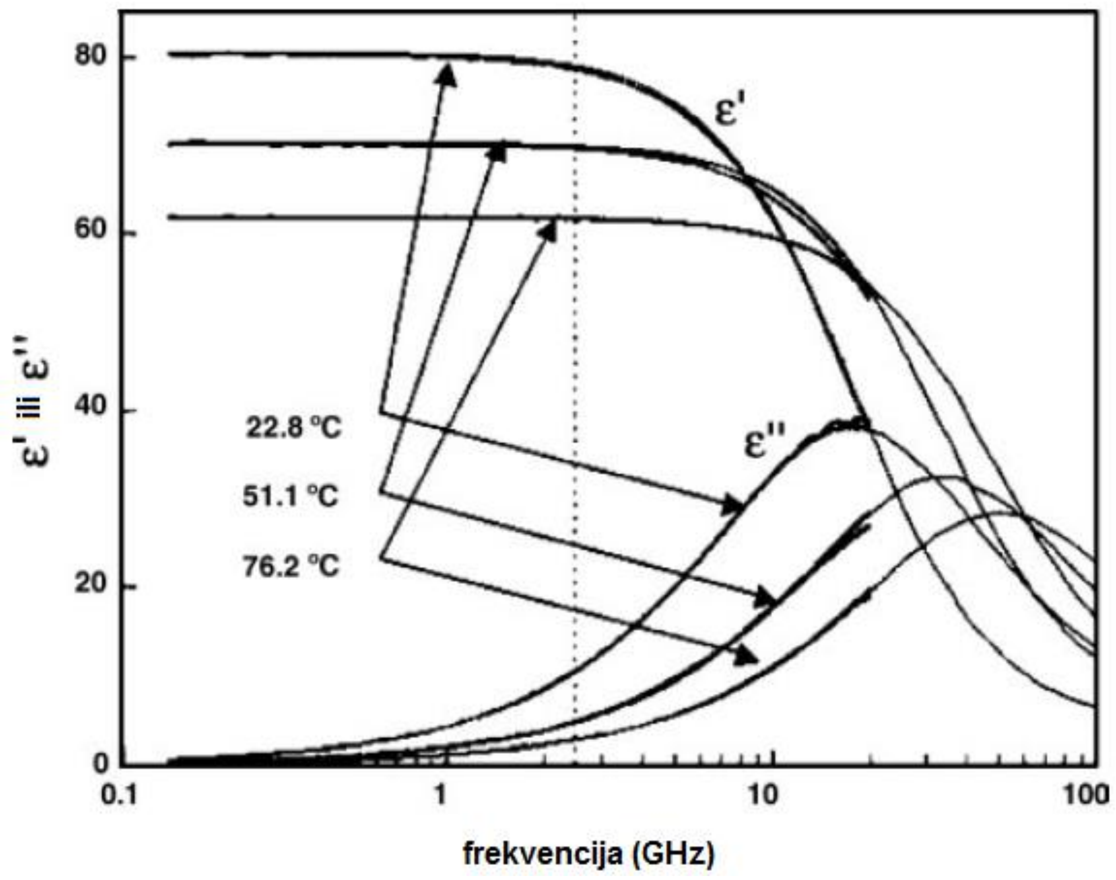
Dielectric characteristics of water as a function of frequency:

- maximum heating about 18 GHz

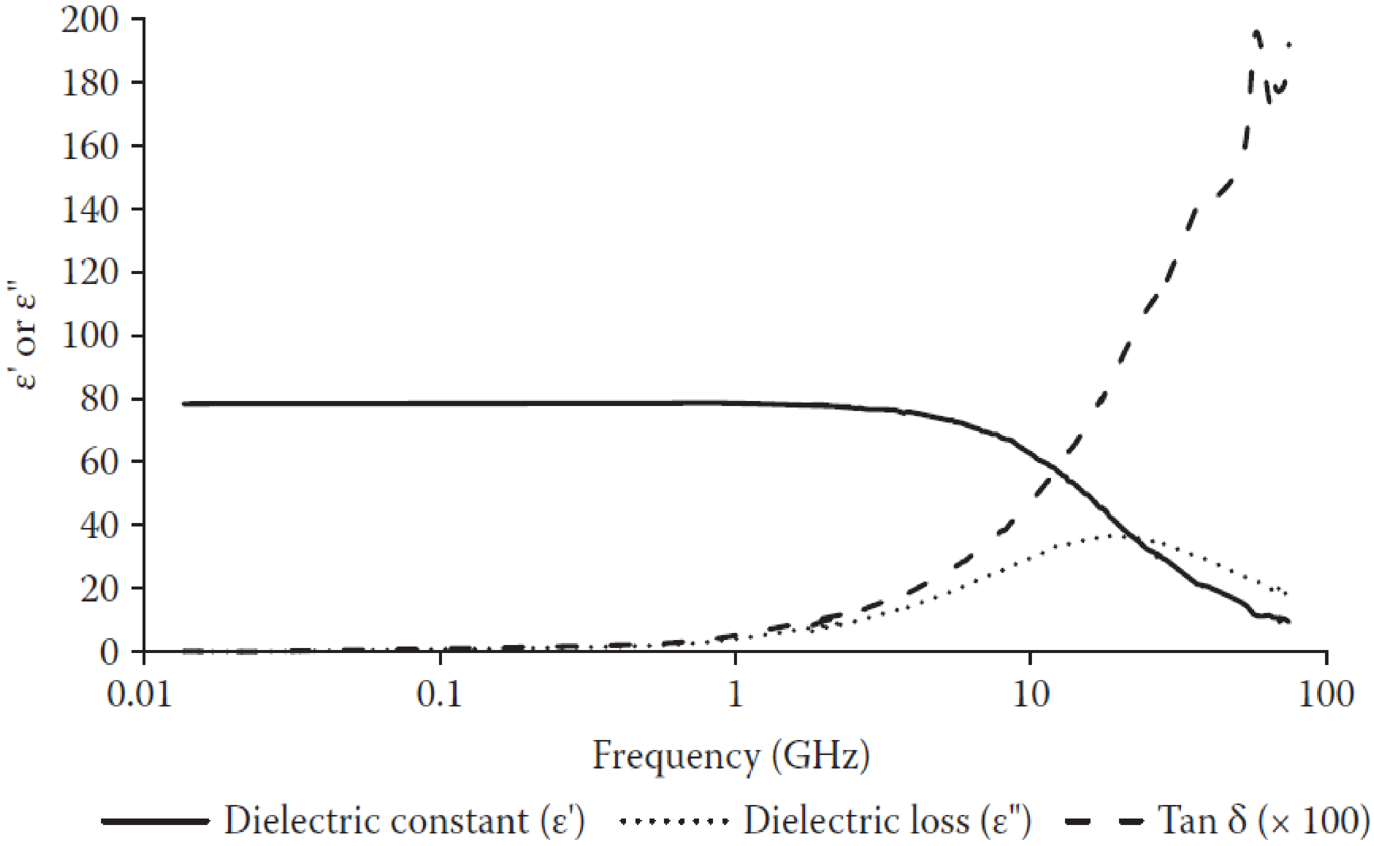


Dielectric properties of matter

Dielectric characteristics of water as a function of frequency and temperature: dielectric loss ε'' and tanges of loss δ of pure water and most organic solvents decrease with increasing temperature



Dielectric properties of matter



Dielectric properties of matter

Dielectric characteristics of some solvents as a function of frequency:

for polar solvents of lower molar mass, a decrease in frequency causes a decrease in the loss tangent δ

frequency	ε′	ε″	tan δ
water			
14 MHz	78.3	0.10	0.001
444 MHz	779	1.70	0.022
900 MHz	78.6	3.51	0.045
2.45 GHz	77.4	9.48	0.122
hexane-1-ol			
14 MHz	8.0	0.70	0.088
444 MHz	5.2	3.6	0.702
900 MHz	4.0	2.3	0.568
2.45 GHz	3.4	1.2	0.341
nitrobenzene			
14 MHz	35.1	0.20	0.006
444 MHz	35.3	4.0	0.113
900 MHz	33.7	7.7	0.229
2.45 GHz	25.2	14.7	0.584
glycerol			
14 MHz	42.5	3.70	0.087
444 MHz	11.4	9.9	0.866
900 MHz	8.41	6.40	0.759
2.45 GHz	6.33	3.42	0.540

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MICROWAVE REACTORS

Prof. Marijana Hranjec, PhD

Academic year 2023/2024

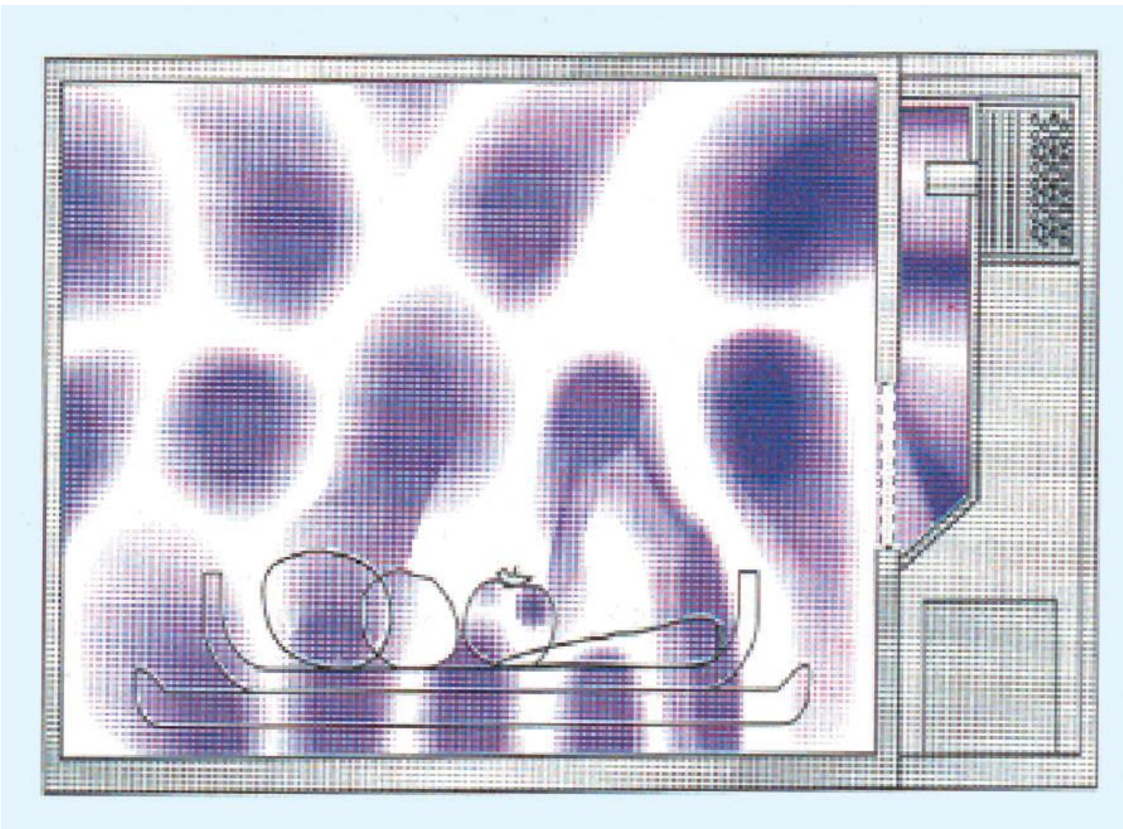
INTRODUCTION

- the first experiments were conducted in home microwave ovens but the reproducibility of such results was very low
- the main disadvantages were the variable radiation power, the inability to measure pressure and temperature and mixing of the reaction mixture, the inhomogeneity of the electromagnetic field, large temperature differences inside the housing, the inability to control safety and the possibility of explosion
- uneven heating of the reaction mixture is a consequence of the occasional shutdown of the radiation source (magnetron)

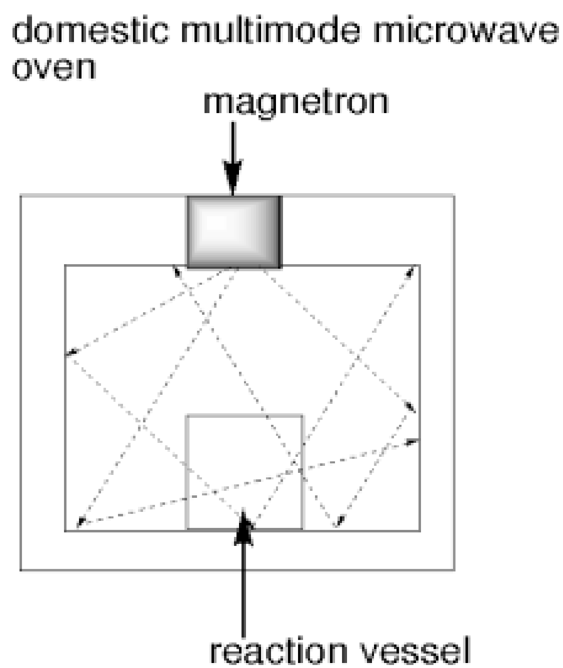
Type of microwave reactors:

1. home microwave ovens
2. 2. single-function reactors
3. 3. multifunctional reactors

INTRODUCTION

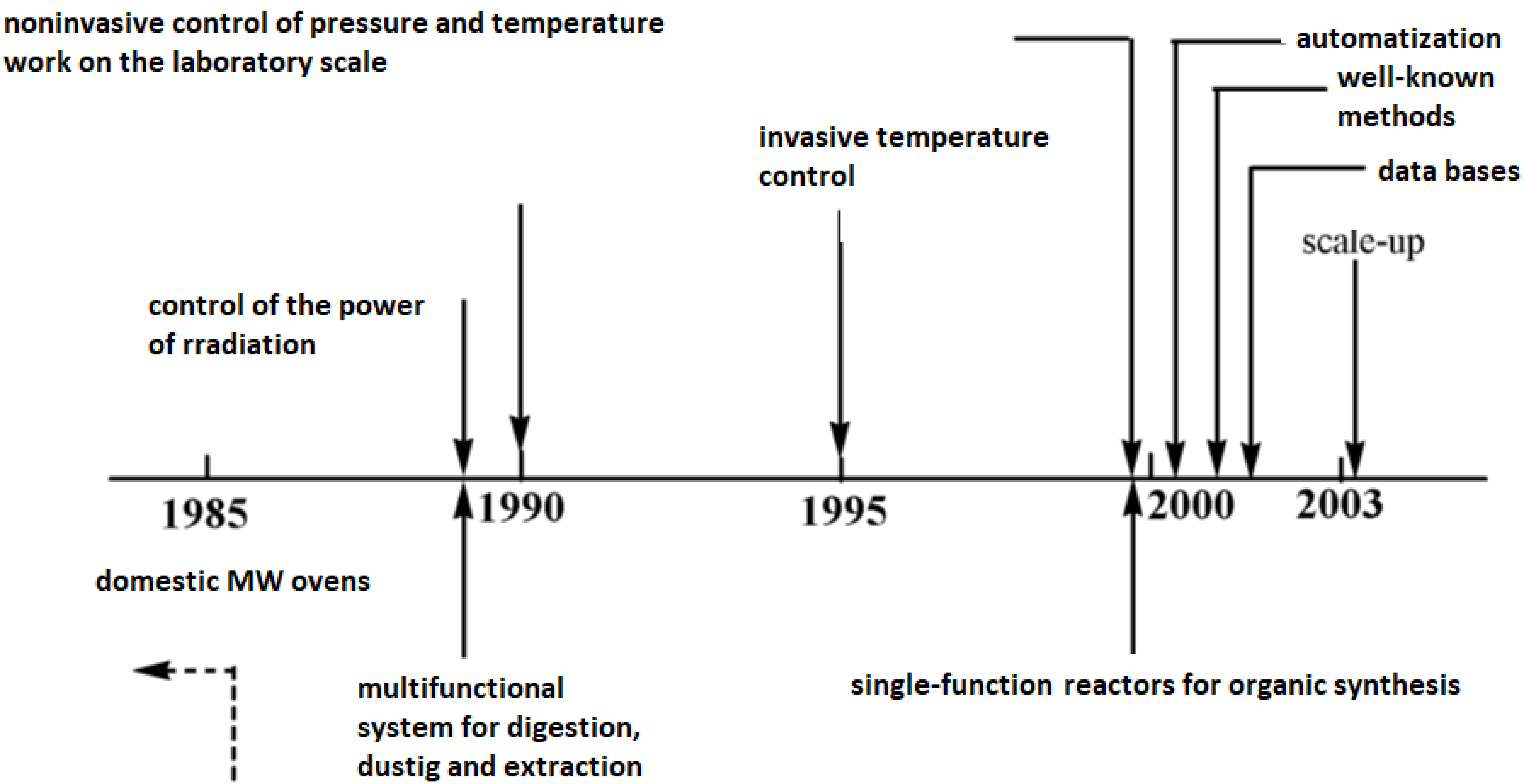


unequal microwave radiation field in a domestic MW oven



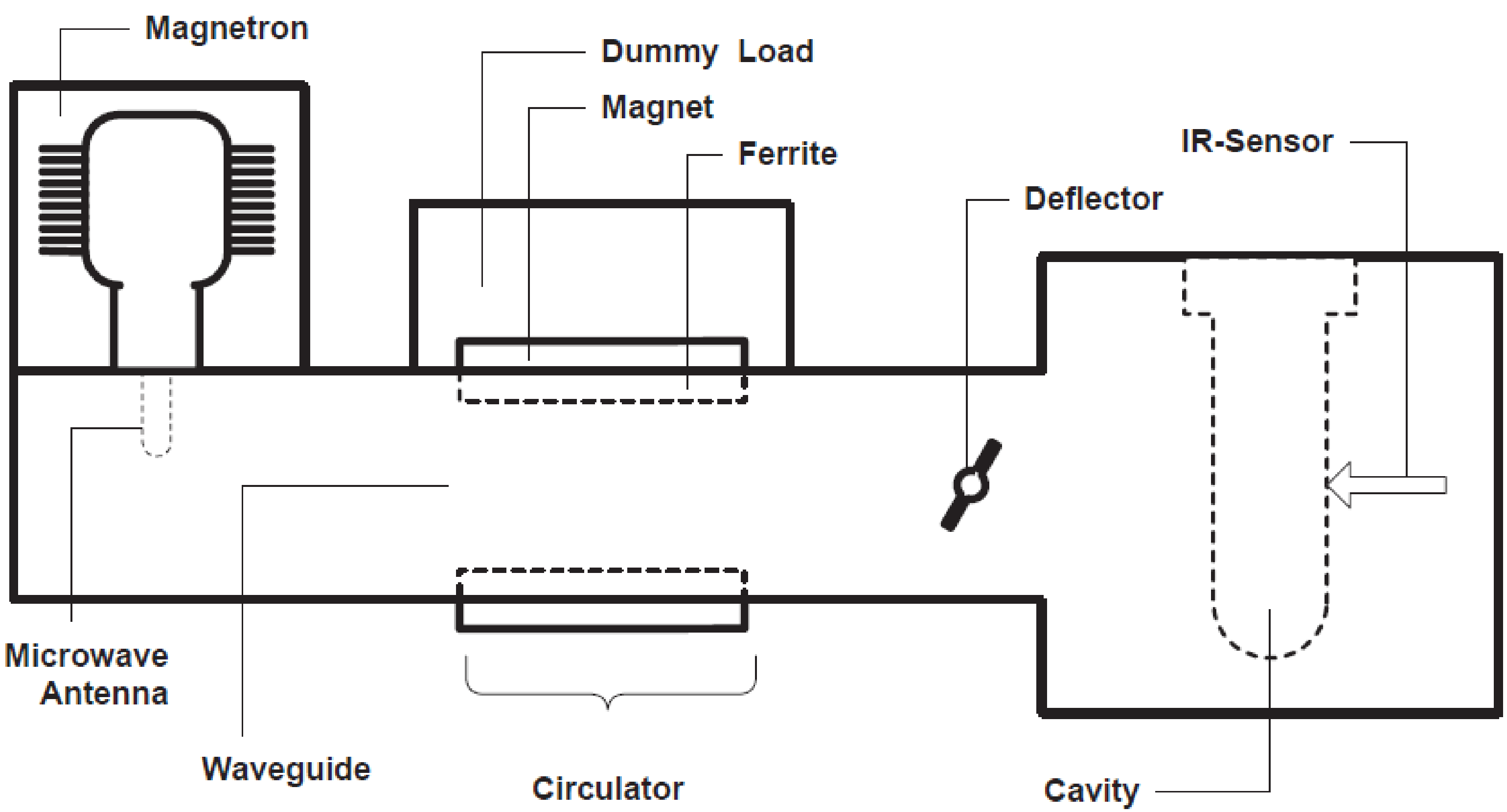
INTRODUCTION

Chronological development of microwave technology:



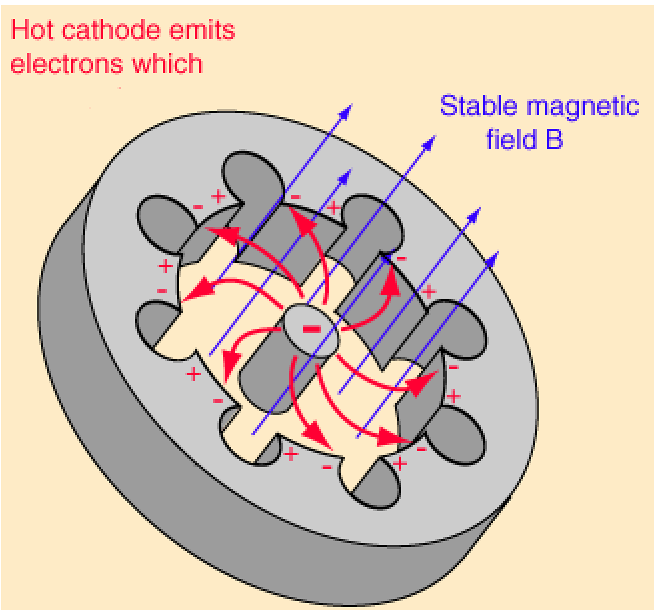
MICROWAVE SYSTEM

❖ microwave system consists of magnetron, waveguide, sample housing, circulator, IR sensor, deflector ...

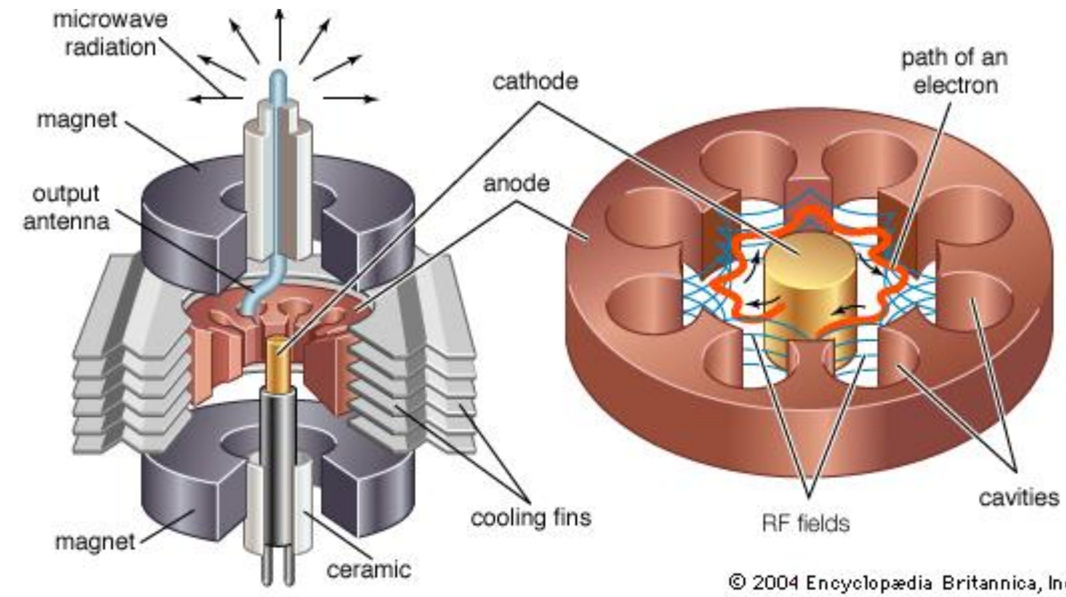


MICROWAVE SYSTEM

- **magnetron** – a source of constant microwave radiation



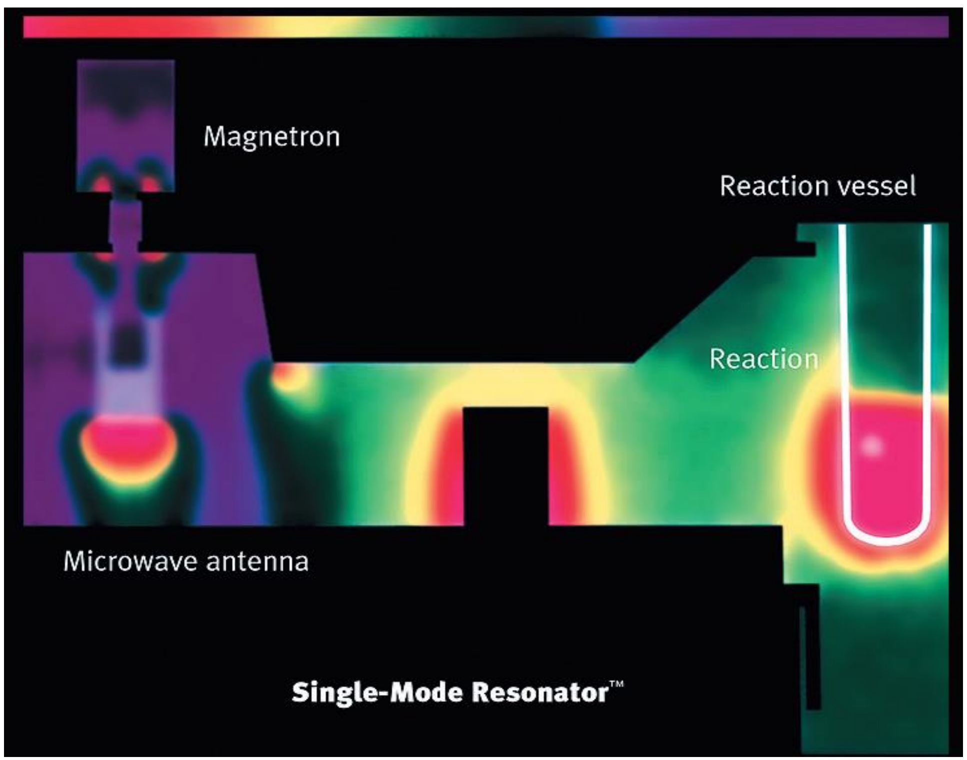
www.hyperphysics.phy-astr.gsu.edu

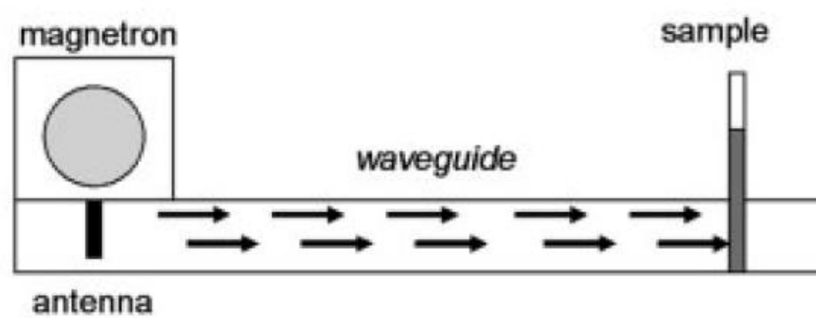


- **waveguide** - leads microwaves to the antenna or microwave applicator (housing)
- **circulator** - protects the magnetron or the entire instrument from reflective microwave radiation
- **deflector** - ensures constant MW radiation - the maximum power of MW radiation is converted into heat

SINGLE-FUNCTION REACTORS

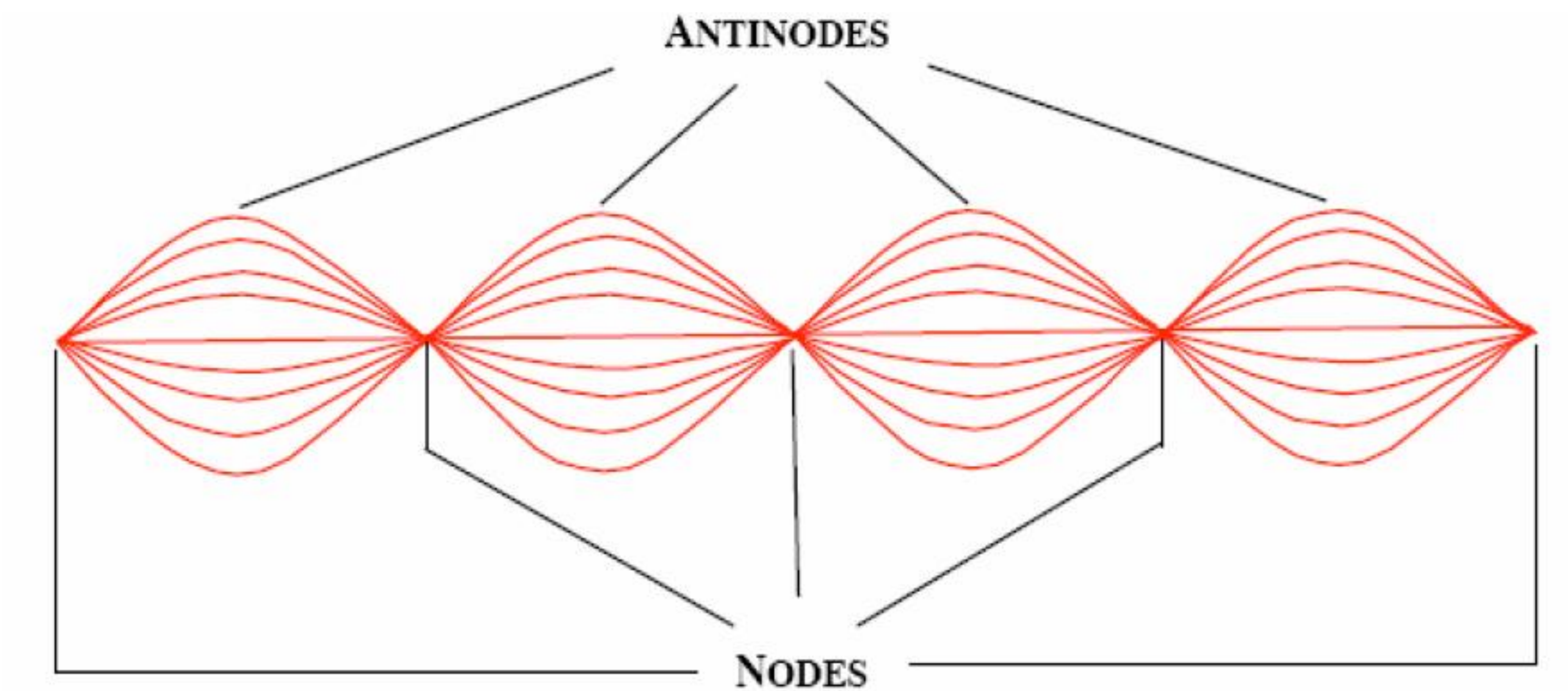
- ❖it has a small housing, it is made with small quantities (0.2 - 50 mL) and one reaction vessel
- ❖the radiation passes through a well-defined waveguide and falls in a directed manner on a reaction vessel
- ❖located at a precisely determined distance from the MW radiation source.





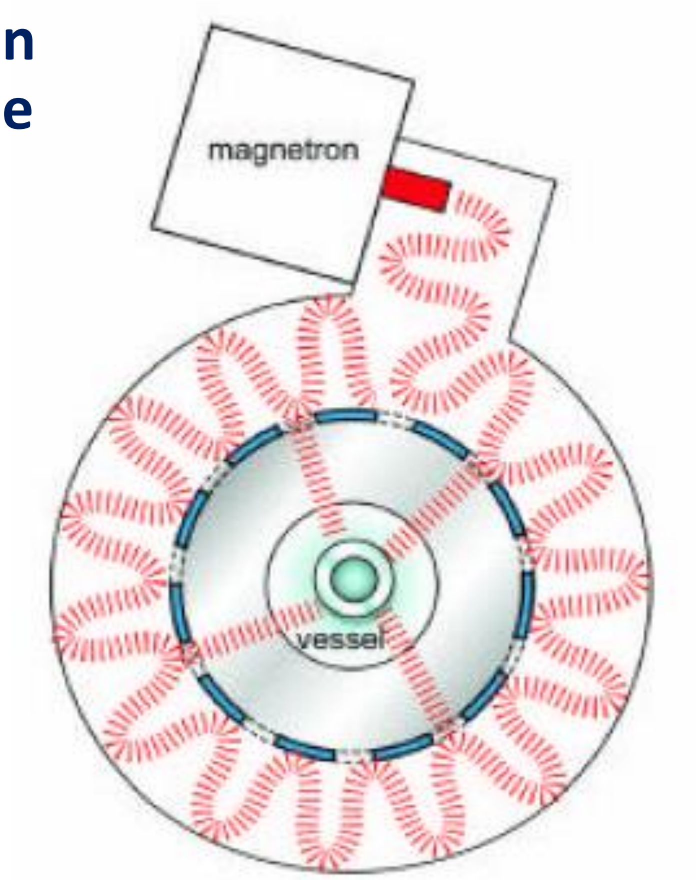
SINGLE-FUNCTION REACTORS

- the main feature of single-function reactors is the ability to create a constant wave profile of MW radiation
- a set of nodes is formed at which the MW energy intensity is zero and a set of nodes where the magnitude of MW radiation is the highest and the MW energy intensity is maximum



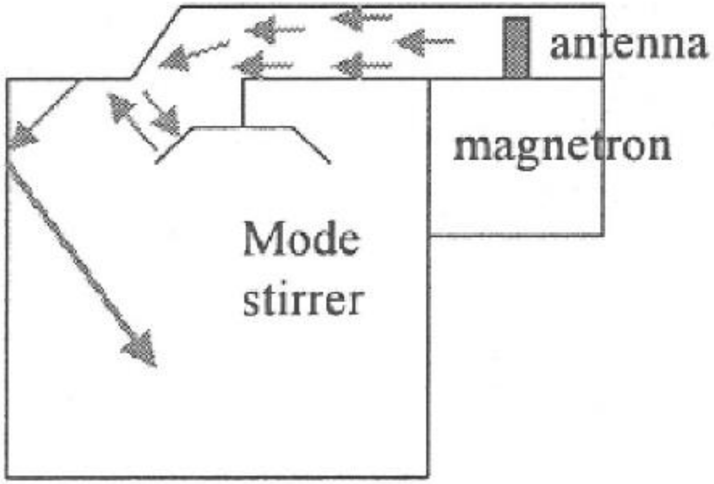
SINGLE-FUNCTION REACTORS

- the reaction vessel must be located at an appropriate distance from the magnetron in order for the sample to be located at the nodes with the maximum energy of MW radiation
- the main disadvantage of single-function reactors is one reaction vessel that can be irradiated at the same time



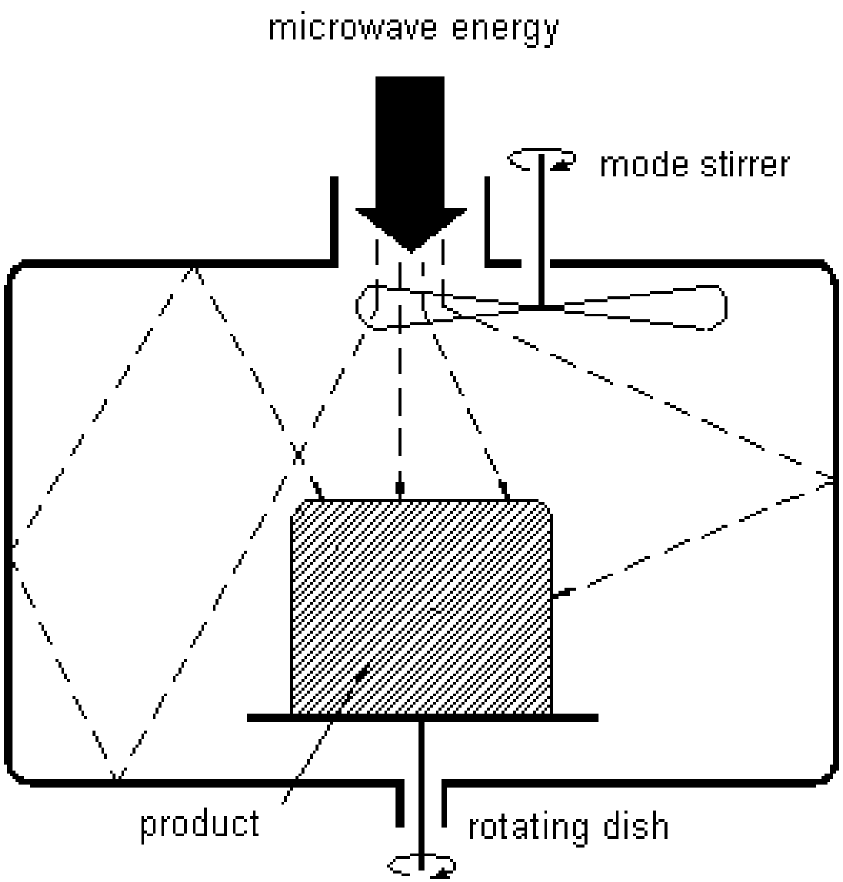
MULTIFUNCTIONAL REACTORS

- have a large housing within which MW radiation is distributed in all directions by reflection on the walls of the housing
- the reaction vessels rotate and thus a homogeneous distribution of the electromagnetic field is achieved



MULTIFUNCTIONAL REACTORS

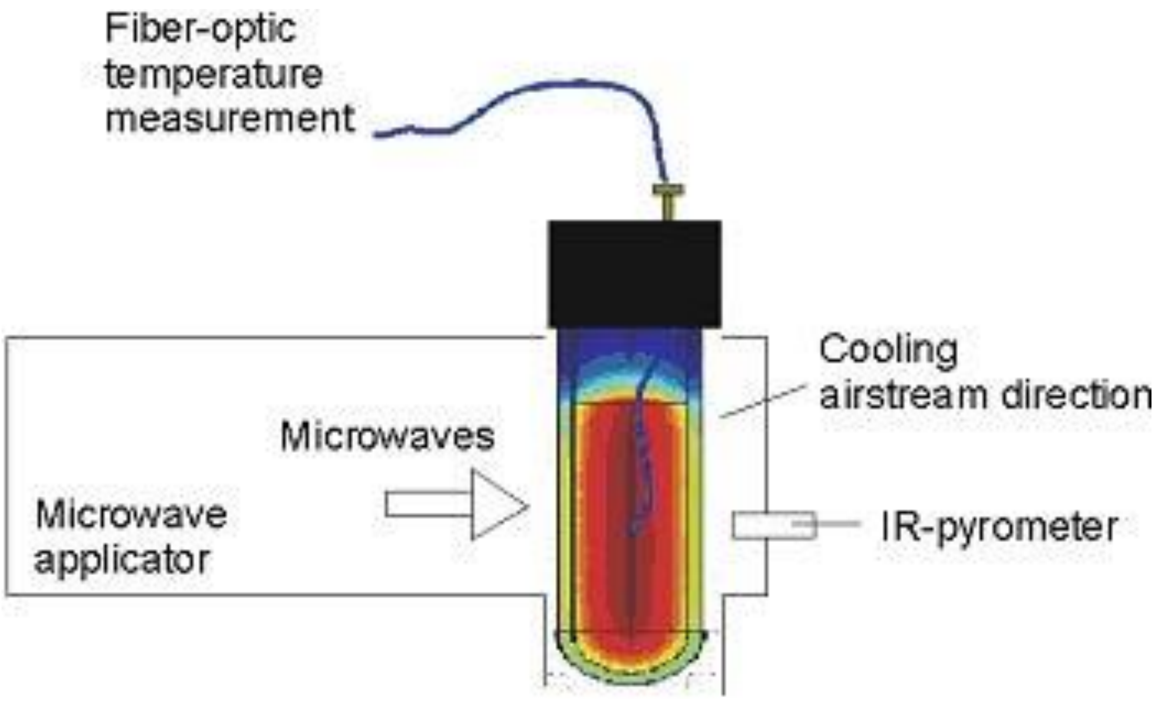
- no constant wave profile of MW radiation is created
- the goal is to obtain the maximum dispersion of MW radiation and thus increase the area that can cause effective heating within the reaction space



- in this way several reaction vessels can be irradiated simultaneously and equally
- works with larger quantities (several liters)
- the disadvantage is the inability to fully control the heating of the samples

Microwave recator with cooling

- cooling the reaction mixture being heated simultaneously
- increased proportion of MW radiation power temperature can be measured simultaneously and independently
- using two temperature sensors



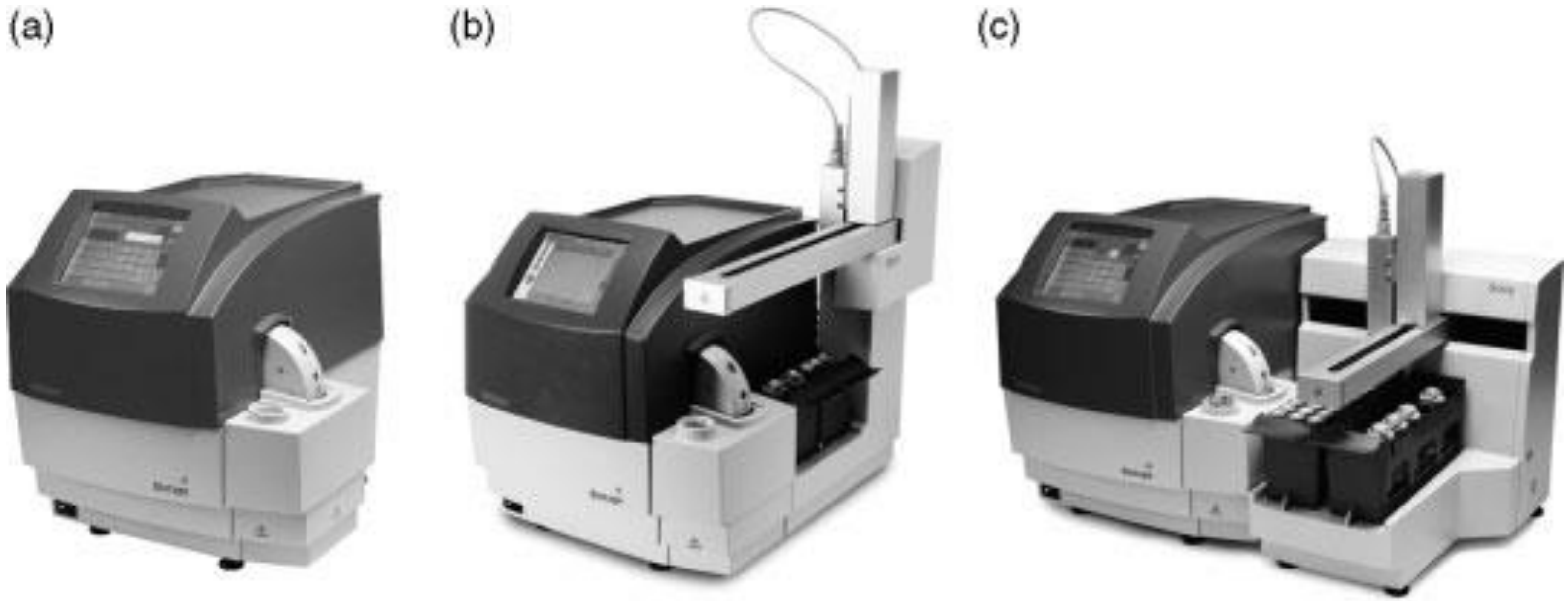
SINGLE-FUNCTION REACTORS

- 1990 - the first single-function reactor
- the French company Prolabo -simple layout with rectangular waveguide and magnetron with a maximum output power of 300 W
- designed for the use of cylindrical glass or quartz vessels of various diameters

SINGLE-FUNCTION REACTORS

Biotage

- ❖ single-function reaction initiator reactor
- ❖ different reaction vessels (from 0.2-0.5 mL to 20 mL)



SINGLE-FUNCTION REACTORS

Biotage

- 2004. “Emrys Liberator”
- reaction vessels from 0,5 – 5 mL

- up to 120 reactions in parallel
- fully automated device
- from 60 - 250 °C max. pressure 20 bar
- temperature control by IR sensor

SINGLE-FUNCTION REACTORS

Biotage

- "Chemspeed SWAVE", max 240 samples
- fully automated work - from sample preparation, reactions, reagent addition to product purification by extraction, filtration, chromatographic analysis

SINGLE-FUNCTION REACTORS

CEM

- ❖ from 2001, “Discover system”
- ❖ a round housing that allows equally energy
- ❖open (up to 125 mL) and closed systems (up to 50 mL) maximum power up to 300 W

SINGLE-FUNCTION REACTORS

CEM

- "Discover CoolMate" – for reactions at low temperatures
- from -80 do 65 °C
- integrated in situ reaction monitoring camera

SINGLE-FUNCTION REACTORS

CEM

- ❖“Voyager Systems”
- ❖ automated system - designed for "scale-up" up to 1 kg



SINGLE-FUNCTION REACTORS

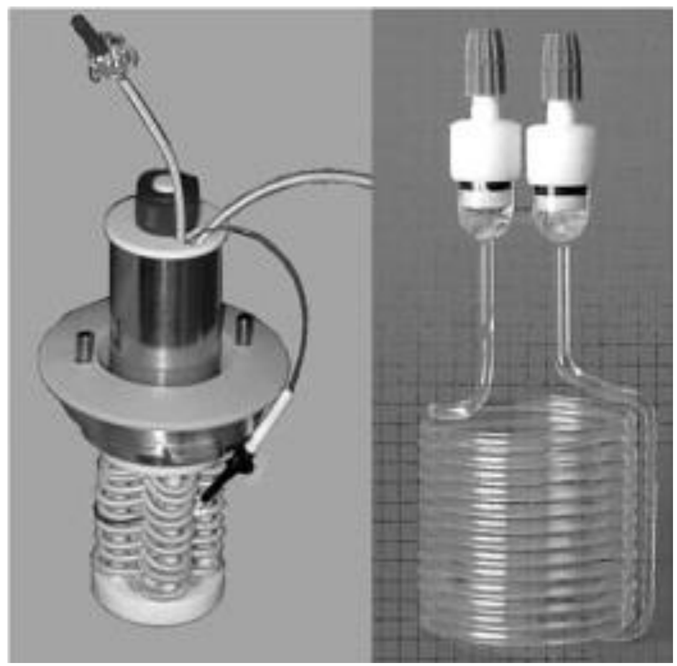
CEM

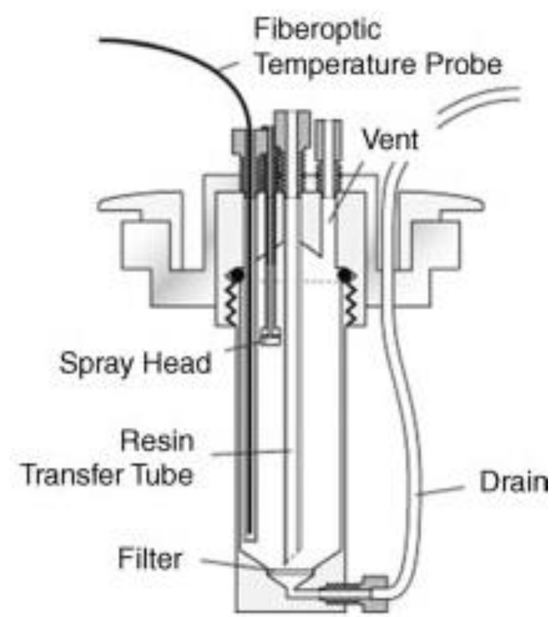
- “Voyager$_{SF}$ System”
- reaction vessel of 80 mL, up to 250 C and 18 bar
- reactor for heterogeneous reaction mixtures, emulsions and solid phase reactions

SINGLE-FUNCTION REACTORS

CEM

- "Peptide Synthesizer" – solid phase peptide synthesis
- fully automated MW reactor synthesizes up to 12 peptides
- suitable for 25 amino acids





COMPARISON OF SINGLE-FUNCTION REACTORS

Features	Biotage Initiator 2.0	CEM Discover
Waveguide	rectangular	circular
Max. output power	400 W	300 W
Operation temperature	40–250 °C	rt–300 °C
Max. pressure	20 bar	20 bar
		15 bar (80 mL vessel)
Vessel sizes	0.2–20 mL	4–80 mL
		max. 125 mL round-bottom flask
Sealing mechanism	permanent with crimped caps	"Snap-on" IntelliVent caps
IR sensor	from the side at a defined height	from the bottom
Fiber optic	×	✓
Simultaneous cooling	✓	✓
Closed vessel	✓	✓
Open vessel	×	✓
Magnetic stirring	300–900 rpm	3 different speeds
Method programming	touch screen	touch pad or PC

MULTIFUNCTION REACTORS

Anton Paar

- "Synthos 3000" – one of the most commonly used reactors
- for volumes up to 1L and chemistry under high pressure and temperature
- two magnetrons and a continuous power of 1400 W enable a series of reactions that finally yield a large amount of product

part for introduction gases

filter part

MULTIFUNCTION REACTORS

Anton Paar

- reactors for 8, 16 and 48 reaction vessels
- depending on the material, different temperatures and pressures can be achieved

	4×24MG5/ 64MG5	48MF50	16MF100	16HF100	8SXF100	8SXQ80
No. of vessels	96/64	48	16	16	8	8
Volume (mL)	5	50	100	100	100	80
Operating volume (mL)	0.3–3	6–25	6–60	6–60	6–60	6–60
Max. temperature (°C)	200	200	200	240	260	300
Max. pressure (bar)	20	20	20	40	60	80
Liner material	glass	PFA	PTFE-TFM	PTFE-TFM	PTFE-TFM	quartz
Pressure jacket	×	PEEK	PEEK	ceramics	ceramics	×
Pre-pressurizing	×	×	×	10 bar	20 bar	20 bar

MULTIFUNCTION REACTORS

Biotage AB

- reactions up to 350 mL - from 10 to 100 g of product
- 1200 W, up to 250°C

MULTIFUNCTION REACTORS

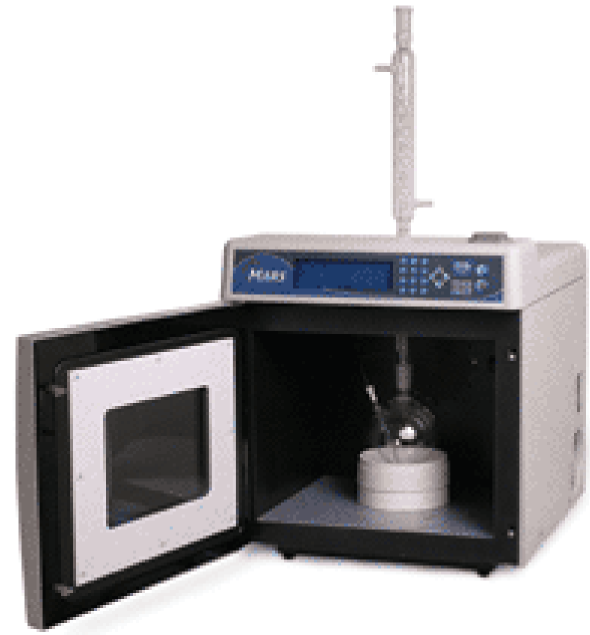
CEM

- “MARS S” system
- temperature up to 300 °C and pressure of 100 bar
- volume up to 48 L, max. power up to 1400 W but experiments are usually performed using 400 to 800 W power (low power level)

MULTIFUNCTION REACTORS

CEM

- “MARS scale-up” system
- reaction vessels 2 to 4 L

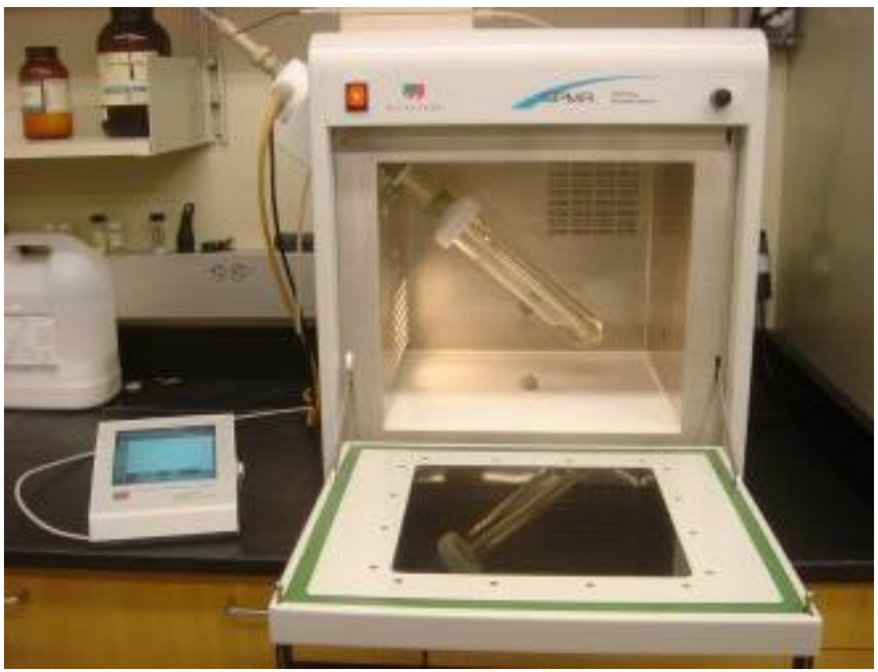


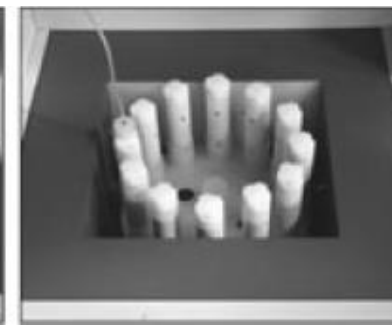
	GlassChem	MARSXpress		XP-1500+	HP-500+
No. of vessels	24	40	40	12	14
Vessel volume (mL)	20	55	10–75	100	100
Operating volume (mL)	3–14	6–35	1–50	10–70	10–70
Max. temperature (°C)	200	300	260	300	260
Max. pressure (bar)	14	35	35	100	34
Vessel material	glass	TFM	PFA	Teflon, Pyrex, quartz	
Temp. control	fiber-optic	IR	IR	fiber-optic + optional IR DuoTemp	

MULTIFUNCTION REACTORS

MILESTONE

- a large number of various multifunctional MW reactors for conducting reactions of volume up to 3.5 L in a closed system
- there is the possibility of a single-function and multi-function system in the same MR reactor

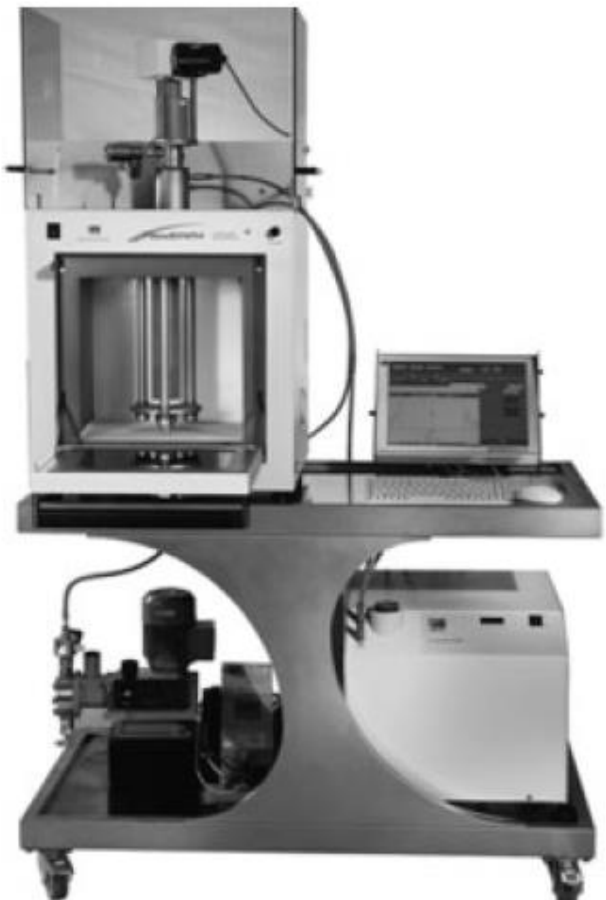




MULTIFUNCTION REACTORS

MILESTONE

- “Pilot 4000 labstation” i “ETHOSpilot 4000” in industry
- to obtain large quantities of products - up to 1 kg



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INTERACTION OF MATERIALS WITH MW RADIATION

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Academic year 2023/2024

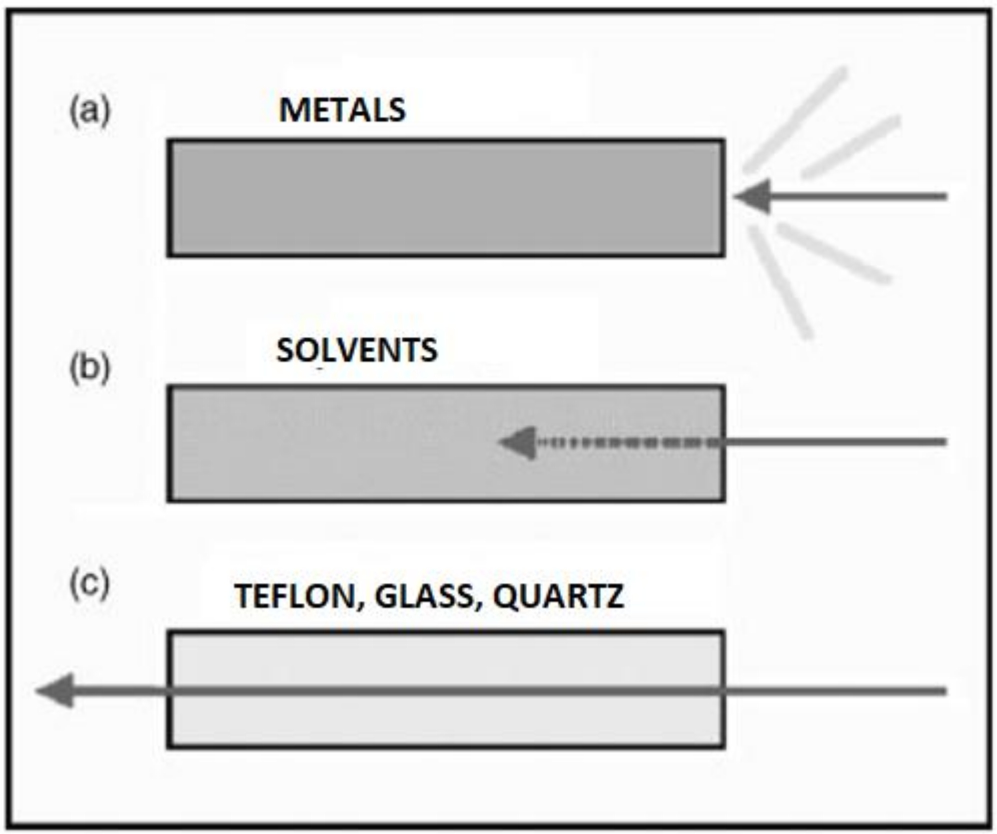
INTERACTION OF MATERIALS WITH MW RADIATION

- the ability of materials to absorb MW radiation is characterized by the **penetration length**: the point at which 37% of the initial power of MW radiation is still present

Material	tan δ ($\times 10^{-4}$)	Material	tan δ ($\times 10^{-4}$)
Quartz	0.6	Plexiglass	57
Ceramic	5.5	Polyester	28
Porcelain	11	Polyethylene	31
Phosphate glass	46	Polystyrene	3.3
Borosilicate glass	10	Teflon	1.5

INTERACTION OF MATERIALS WITH MW RADIATION

- characterized by three basic processes: **reflection, absorption, and transmission**

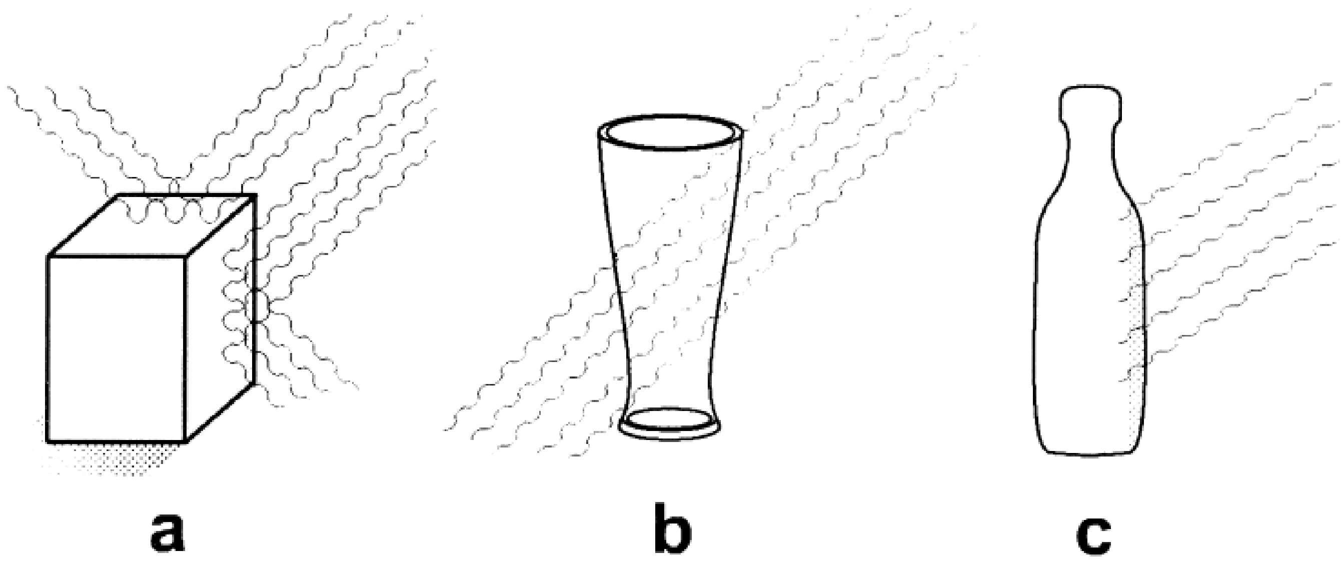


electrical conductors
reflection

absorption materials
absorption

insulators
transmission

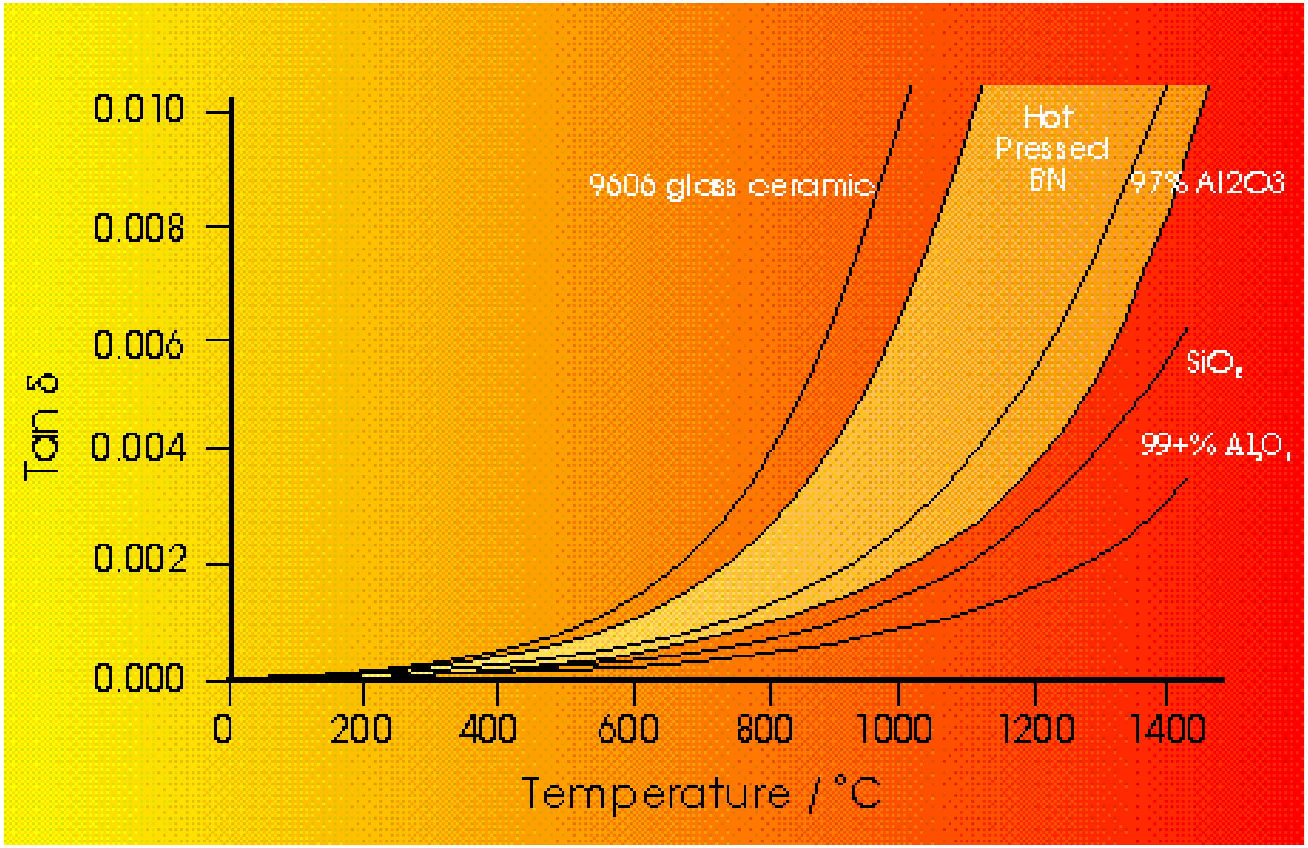
INTERACTION OF MATERIALS WITH MW RADIATION



- **a**: electric conductor - high conductivity
- **b**: insulator - non-polar materials
- **c**: absorption materials - rapid heating of the medium

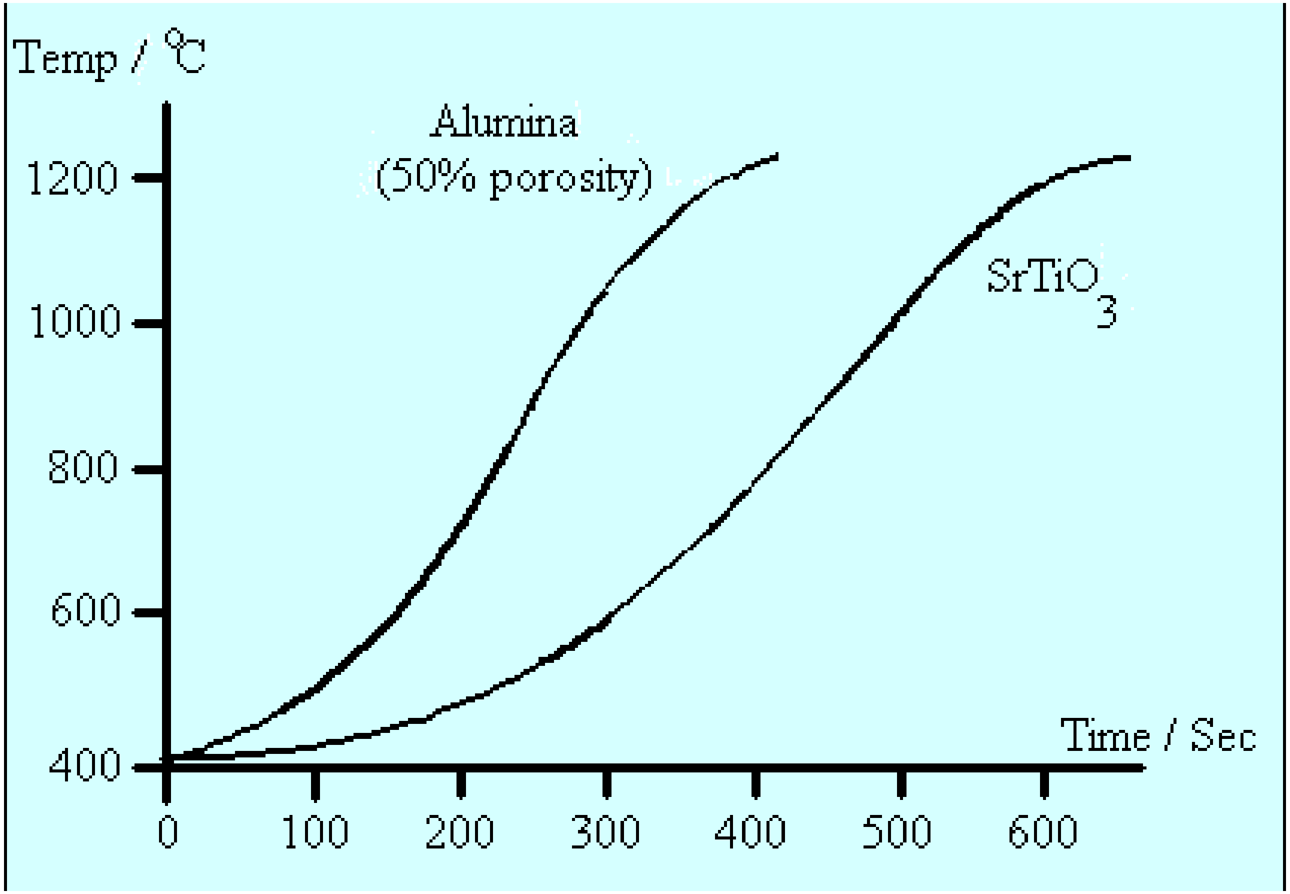
INTERACTION OF MATERIALS WITH MW RADIATION

Dependence of tan δ on the temperature of some ceramic materials: **many metal oxides or sulfides can reach very high temperatures after a short exposure to MW radiation**



INTERACTION OF MATERIALS WITH MW RADIATION

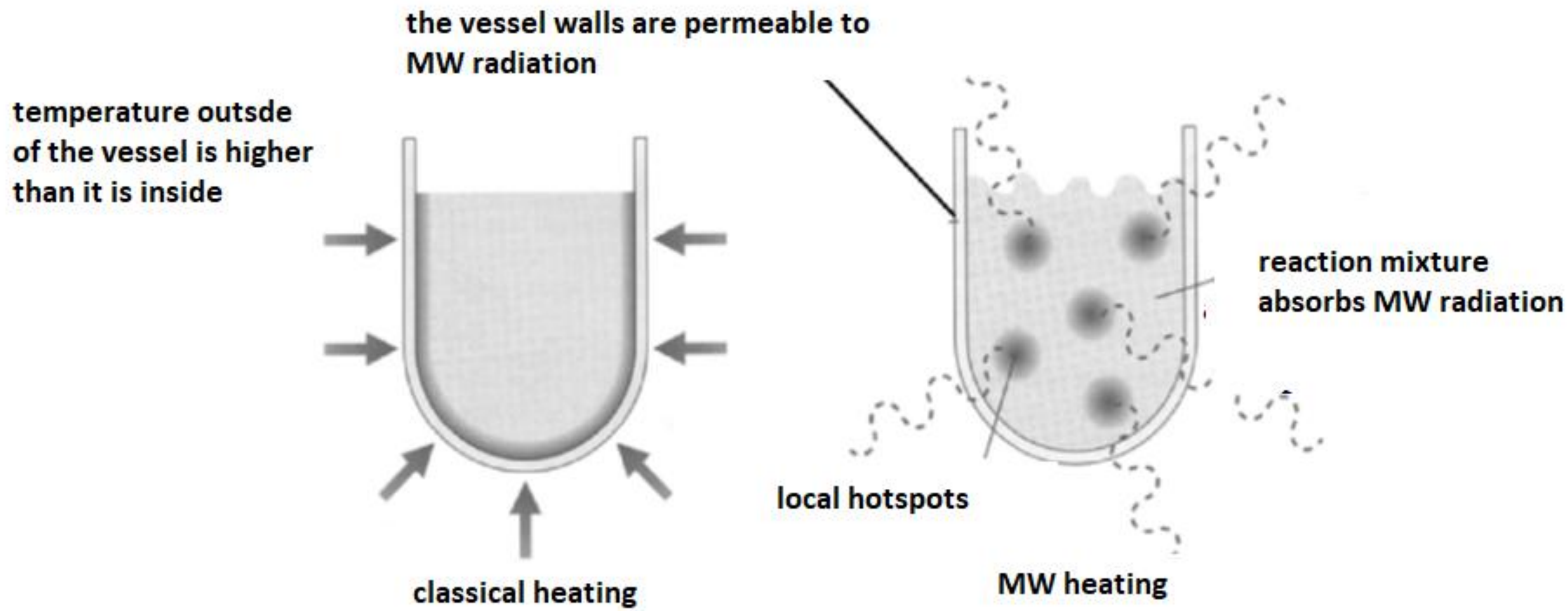
Temperature dependence on heating time:



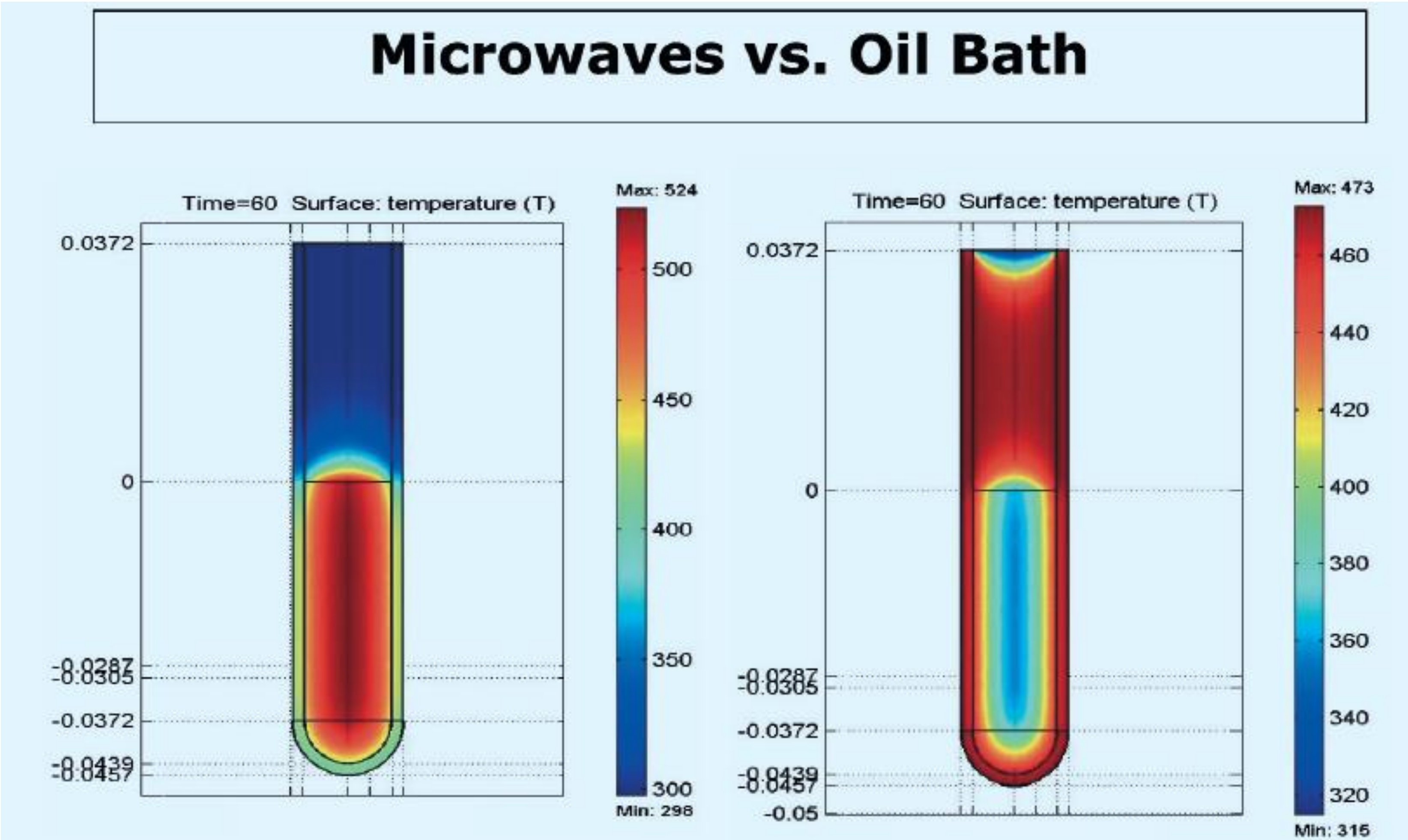
Comparison of classical and MW heating

CLASSICAL SYNTHESIS – heating the reaction vessel with an external heat source where the heat is transferred from the source to the vessel walls and to the solvent and reactants - depending on the thermal conductivity of the vessel material - the vessel is heated more than the reaction mixture - longer equilibrium period

MICROWAVE SYNTHESIS - the reaction mixture directly absorbs energy because the walls of the vessel are permeable - controlled reactions



Comparison of classical and MW heating



temperature profile after 60 seconds of heating with microwave and classical heating

Comparison of classical and MW heating

- **microwave heating achieves an ideal temperature profile, heating is highly controlled**

IDEAL TEMPERATURE PROFIL