INDUSTRIAL MICROWAVE TECHNOLOGY

4th Edition

This document is based on the joint paper presented by Cober Electronics, Inc. and Crompton Corporation, Uniroyal Chemical Division at an Annual Meeting of the Rubber Division of the American Chemical Society and at the June 2002 Symposium of The Connecticut Rubber Group. It presents updated information that is the result of the cooperative effort between Cober Electronics, Inc. and Compton Corporation, Uniroyal Chemical Division in the area of systems, techniques, materials and chemistry for rubber processing.

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UNDERSTANDING INDUSTRIAL MICROWAVE TECHNOLOGY AND ITS APPLICATION

With 85% of the homes in the U.S. containing microwave ovens, most people have experienced the speed and the penetrating effect of the microwave heating and also some of the disadvantages. The intent of this booklet is to explain the principles of microwave heating in a practical and non-mathematical way and illustrate how these principles are used to increase productivity and quality in industrial processing applications. The rubber industry is used as an example since microwave continuous vulcanization of automotive weather stripping used worldwide, wherever automobiles are manufactured.

Conventional and traditional technology for applying heat to rubber during the vulcanization process has relied on labor intensive steam autoclaves (a batch system), long and inefficient hot air tunnel ovens, and environmentally unfriendly high temperature liquid salt systems. These are now being replaced by highly efficient, high speed microwave curing ovens automated with electronic controls and sensors, producing rubber weather stripping of the highest quality to seal passenger car doors from noise and rain thereby providing user comfort. Steam, hot air and molten salt are yielding to the benefit of microwave electronics in factories on a worldwide basis. The authors estimate that there are approximately 1,000 rubber curing systems worldwide that rely on microwave technology.

WHAT ARE MICROWAVES AND HOW DO THEY HEAT?

Microwaves are invisible radio frequency or electromagnetic waves which have properties that enable them to be generated and sent through space and received or absorbed at a distance. Electromagnetic waves are basically identical to the familiar radio and TV transmissions which we receive daily and to aircraft radar (Figure 1). All electromagnetic waves are similar. They differ only in the number of alternatives or oscillations of their field per second. These oscillations are measured in megahertz or millions of oscillations per second (abbreviated MHz). Each electromagnetic wave has a characteristic spatial dimension called wavelength. The higher the frequency of a radio wave, the shorter the length of the wave.

NEED DIAGRAM – THE ELECTROMAGNETIC SPECTRUM – WILL PROVIDE

CHARACTERISTICS OF ELECTROMAGNETIC WAVES

ELECTROMAGNETIC WAVE	WAVELENGTH (meters)	FREQUENCY	SIZE ANALOGY
AC Current	$5x10^6$	60 Hz	Earth
AM Broadcasting	~ 100	560-1600 KHz	Football Field
FM/TV	~*2*	30-300 MHz	Man
Microwaves (2450 MHz)	0.001-1.0 (4.8″)	300 MHz-300 GHz	Flea to Cat
Visible Light	~ $5x10^{-7}$	10^6 GHz	Smallest object seen with optical microscope

Table I

The FCC (Federal Communications Commission) has assigned a number of bands for industrial microwave ovens which will not conflict with communications frequencies. For all practical purposes only *915* MHz and *2450* MHz are used for industrial ovens since components and power sources are readily available at these frequencies. All present day home microwave ovens in use are at 2450 MHz. At this frequency the length of a wave is 4.8 inches in air, a very compatible dimension to mate with the size of most industrial materials (Table I).

PROPERTIES OF FIELDS

CHARACTERISTICS	WIND	MICROWAVE FIELD
Optical:	Invisible	Invisible
Direction:	N,S,E,W	Up, Down, Right, Left

Strength:	Miles per Hour	Volts per Inch
Power:	Horsepower	Kilowatts
Effects Objects:	Transports dust, debris, etc.	Transports ions, electrons
Rotates and Lines Up Objects:	Weather vanes, grass, etc.	Molecular dipoles
Flow:	Steady, gusty Gusts/Minute	Gusty, Gigahertz
Frequency Spectrum:	Bass, baritone, tenor, soprano	Radar, TV, Ovens, etc.

Table II

Microwaves are a combination of electric and magnetic fields perpendicular to each other. It is difficult to visualize a field, however, a good analogy would be to the wind which is invisible, has direction, can vary in strength, be gusty, etc. (see Table II).

Another aspect of microwaves is power, which is usually measured in kilowatts. Power is the expression of how much work microwaves can perform. A kilowatt is approximately 1 BTU per second or 3400 BTUs per hour or about 3.4 pounds of steam per hour or about ¼ calorie per second. One kilowatt of microwave power is able to boil away about three pounds of water at one atmosphere pressure and at room temperature in 1 hour. Microwave ovens used in rubber processing range from approximately 1 kilowatt in power for small preheaters to about 50 kilowatts for large continuous systems and rubber bale preheaters.

Microwave fields have certain properties (Figure 2). They are reflected off metals which they do not heat. Therefore, metals are used as conduits for microwaves. These conduits are called waveguides. Metals are also used for the walls of the microwave oven where they confine the microwaves to a usable region.

NEED DIAGRAM – MICROWAVE PROPERTIES – WILL PROVIDE

Some materials have the property of transmission in a microwave field. That is, they are transparent to the microwave fields and the fields will pass through as light will pass through glass. Microwave transparent materials neither reflect microwave fields nor do they heat.

Such materials are used in microwave ovens as support structures where absorption is not desired.

The most important property of materials in a microwave field is the property of absorption. Materials which absorb microwaves are heated.

HOW DO MICROWAVES HEAT MATERIALS WHICH ABSORB MICROWAVE FIELDS?

There are essentially two mechanisms for the absorption of microwave power by materials. One is that of dipole rotation which would apply to polar materials such as nitrile and neoprene polymers. The molecules of these polar compounds are electrically neutral, but have a spatially separated positive and a negative electric charge. They appear as molecular electric "compass needles" or dipoles which react to the polarity of field changes and orient and reorient themselves as the amplitude of the field increases from zero in one direction , reaches a maximum, decreases back to zero and then increases to a maximum in the opposite direction. The field has both amplitude and direction. At 2450 MHz, the field is alternating or reversing its direction (polarity) at a rate of 2450 million times per second. The polar rubber molecule in this alternating microwave field will attempt to rotate its negative pole in the direction of the field. It will then return to its normal state of disorder as the amplitude moves to zero, and then will attempt to rotate its positive pole to the opposite direction of the field and do all this activity at a frequency of 2450 MHz (Figure 3).

NEED DIAGRAM – DIPOLE ROTATION OF POLAR MOLECULES IN A MICROWAVE FIELD – WILL PROVIDE

The force exerted on the polar molecule is by definition the field strength which is related to the amount of microwave power available. This action of molecular rotation to orderly align with the microwave field and then return to the normal state of disorder of the molecule forms part of the mechanism of microwave heating. It is instantaneous, uniform and penetrating in the material. The microwave field has transferred energy to the rubber molecule and the rubber molecule has transformed the energy into heat within itself. This instantaneous and deep penetrating effect is the great advantage to microwave processing of rubber since rubber is a thermal insulator. To conduct heat into the rubber in a conventional manner such as hot air is considerably slower than the microwave effect of molecular rotation.

Different materials have different abilities to absorb microwave energy. This ability is expressed in terms of dielectric loss factor. Table III shows the dielectric loss factors for various common materials. The interesting thing to note in Table III is the characteristic of water where it can be seen that the dielectric loss factor decreases as the temperature of the water increases. To put it another way, water becomes less receptive to microwaves as it is being heated. Polar rubber polymers, on the other hand, generally have the opposite characteristic, that is, in most cases they tend to become more receptive to microwave energy as they are heated.

DIELECTRIC PROPERTIES AND PENETRATION DEPTH (CM) OF VARIOUS MATERIALS AT 2450 MHz

Material	**Temperature Degrees C**	**Dielectric Constant**	**Dielectric Loss Factor**	**Penetration Depth D ½ (CM)**
Water (Distilled)	25	78.0	12.0	1.0
Water (Distilled)	45	70.7	7.5	
Water (Distilled)	95	52.0	2.4	
Water + 0.1M Na Cl Solution	25	75.5	18.1	
Water + 0.5M Na Cl Solution	25	67.0	41.8	0.1
Ice	-12	3.2	0.003	800.
Natural Rubber	25	2.2	0.01	200.
Neoprene	26	2.8	0.14	16.1
Polyethylene		2.3	0.001	2045.
Thermoset Polyester	20	4.0	0.02	135.
Teflon	20	2.1	0.001	3256.
Nylon	20	2.4	0.02	104.
Soda Lime Glass	20	6.0	1.02	2.8
Borosilicate Glass	20	4.3	0.02	140.
Glass Ceramic	20	6.0	0.03	110.
Alumina	20	9.0	0.005	809.
Fused Quartz	20	4.0	0.001	5393.

Table III

Water, a liquid, and monomers have small molecules, whereas polymers (polar rubbers) have quite large molecules. The efficiency, or amount of energy converted into heat by each cycle of dipole rotation is optimum when the time intervals of application and removal of the electric field (the microwave frequency) coincides with the time required for the build-up and decay of the induced order. The higher the temperature, the faster the build-up and decay of order imposed by the microwave field. The temperature dependent and the molecular-size dependent time for build-up and decay is called the relaxation frequency. In small water molecules the relaxation frequency is already higher than the microwave frequency and it moves further from the microwave frequency as the temperature increases, causing a slow down of energy conversion. On the other hand, large molecules, (e.g. polar rubber), have a relaxation frequency that is lower than the microwave frequency, but which gets closer to it as the temperature climbs, resulting in faster energy conversion at higher temperatures.

The second mechanism of microwave heating is that of ionic conduction. It is commonly known that non-polar rubbers such as natural rubber, EPDM, SBR, etc., are not receptive to microwave energy but are made receptive by the addition of carbon black. The heating effect of non-polar rubber with carbon black is due to ionic conduction or ohmic heating. Free ions exist at the interface of semi-conductor materials, the interface between the carbon particle and the polymer. These ions are not electrically neutral, but rather are either positively or negatively charged. As such, they are attracted by electric fields and their movements in such fields constitute a flow of current. Their velocity represents kinetic energy given to them by the microwave field. The free ions do not travel very long in the microwave field before they collide with un-ionized molecules giving up their kinetic energy in a randomized billiard ball fashion almost as fast as they obtain it. You will note in Table III the dramatic effect on microwave receptivity when salt is added to the polar water to induce ionic conduction.

It should be noted, as distinguished from dipole rotation, the ionic conduction heating process is not dependent to any great degree on either temperature or microwave frequency. Non-polar rubbers, therefore, which have only the addition of carbon black will tend to remain constant in their ability receive microwave energy as they are heated. In actuality, however, rubber compounds contain many ingredients and chemicals. There is, therefore, a complex mixture of materials, some of which are being heated by ionic conduction and others by dipole rotation within a given recipe.

The creation of compounds which can take advantage of the benefits of microwave processing without having a meaningful increase in material cost is a challenge for the rubber chemist. Uniroyal Chemical Company at its

Naugatuck, Connecticut facility has been of the leaders in this technology. The concepts and formulations that they have created over the past 15 years have helped make microwave continuous vulcanization the preferred method used by industry today.

Table IV shows the dielectric properties of various elastomers at ambient temperature and at a frequency close to that commonly used in microwave ovens. ________ is the dielectric constant and ________ the dielectric loss factor. A loss factor of .1 represents a good receptor of microwave energy. Neoprene is an example. Nitrile, with *.05* is not bad. Both Neoprene and Nitrile have the benefit of being polar elastomers. However, many of the basic elastomers, such as NR, EPDM and SBR are poor in microwave receptivity, yet these are among the major types of elastomers being extruded. This situation had presented the challenge for the rubber chemist. Fortunately, microwave compounding technology has now been well established within the industry. Like a cook using a new home microwave oven in the kitchen, the rubber producer and chemical supplier have to adapt to new microwave technology.

Fortunately, almost all automotive rubber compounds are reinforced with carbon black to improve tensile strength. Carbon black aides the microwave heating of rubber through the principle of ohmic conduction. Figure 4 shows heating rates of basic polymers exposed to microwave energy. The advantage of the polar material is obvious. Figure *5* shows the comparative effect of unfilled non-polar natural rubber with the addition of various types of carbon black. The heating time is almost in direct relationship to the reinforcement performance of the different blacks. The smaller the grain structure, the greater the surface area, the greater the receptivity to microwave energy. Similar techniques are employed for the successful compounding of sponge or dual durometer profiles having sponge components. The blowing agents in sponge are highly receptive to microwave energy and, in fact, can decompose and blow even before there is sufficient cure.

As a rule of thumb, it is not desirable to activate the blowing agent until about 30% of the cure has been completed. In this case, the chemist must decrease the receptivity of the blowing agent to keep it in tube with the cure process. Here again the principle of particle size is employed, but in this case, larger, particle-size blowing agents are utilized.

The processing of multiple durometer extrusions presents similar challenges in that dense compounds tend to be more receptive than sponge compounds. Particular attention must be paid to the areas of extrusion where different densities interface. Uniroyals' technology and the proven demonstrations in their laboratory have helped establish today's accepted standards for microwave processing.

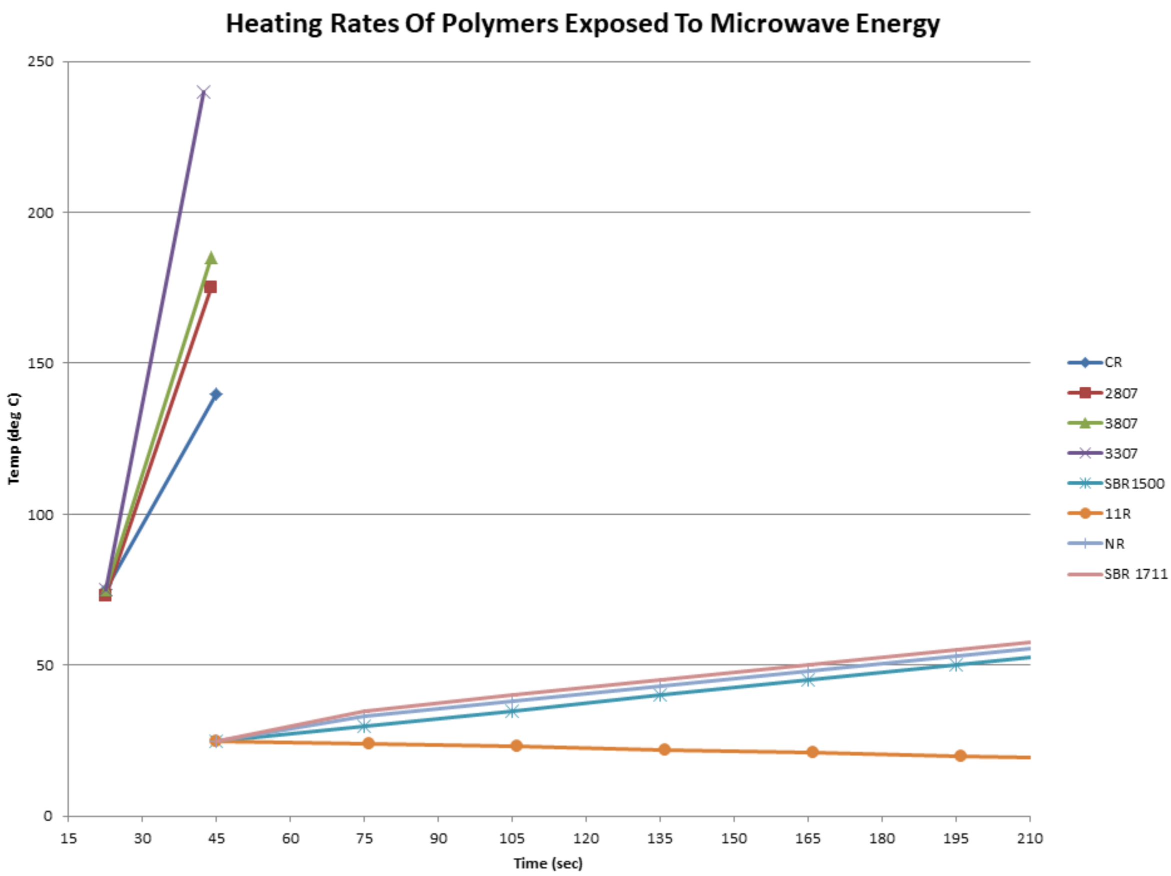
PERMITIVITY OF VARIOUS ELASTOMERS AT AMBIENT TEMPERATURE AND

AT 3 GHZ.

ASTM

Elastomer	Designation	e'	e"
Natural Rubber	NR	2.15	0.00645
Styrene-butadiene	SBR	2.45	0.0107
Polybutadiene	BR	-----	0.00538
Ethylene-propylene	EPDM	2.35	0.0067
Polyisobutylene	IIR	2.35	0.0021
Polychloroprene (Neoprene)	CR	4.00	0.1356
Nitrile	NBR	2.80	0.0504

Table IV


Heating Rates Of Polymers Exposed To Microwave Energy
Temp (deg C)
Time (sec)
CR
2807
3807
3307
SBR1500
11R
NR
SBR 1711

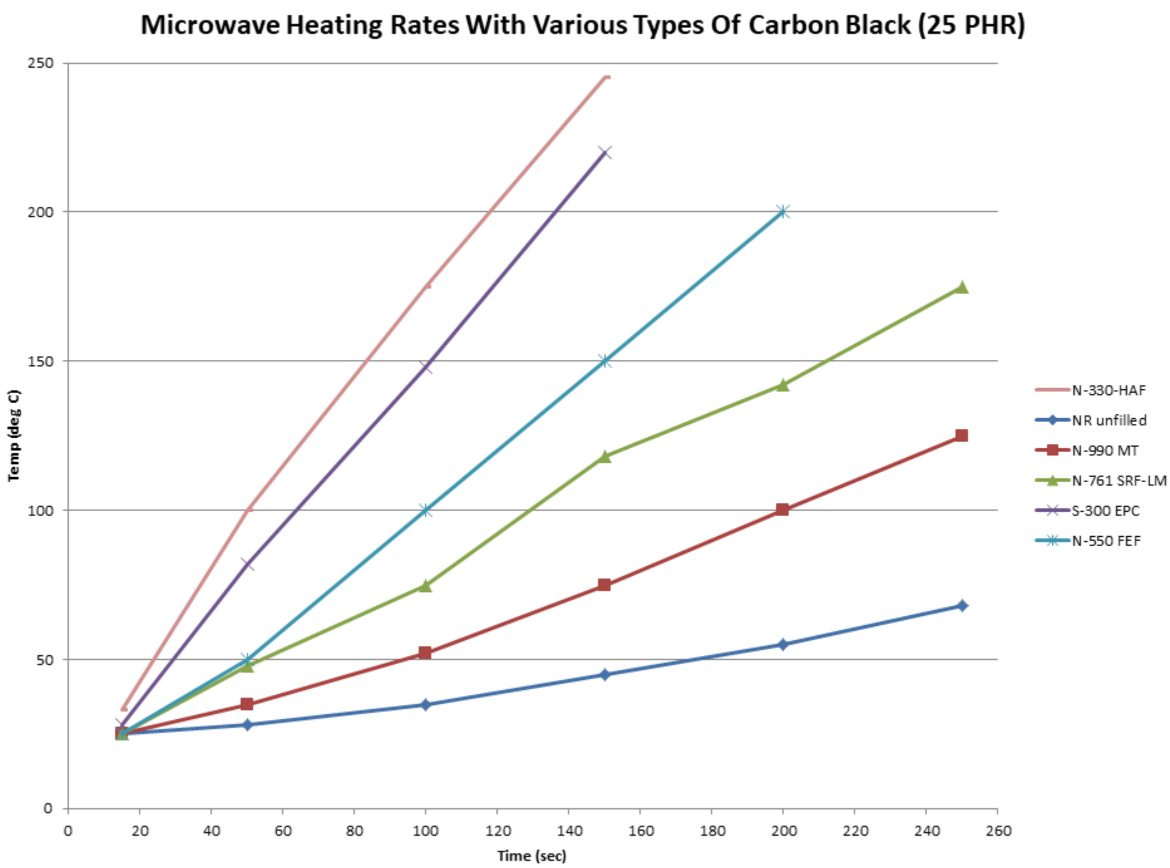

Microwave Heating Rates With Various Types Of Carbon Black (25 PHR)
Temp (deg C)
Time (sec)
N-330-HAF
NR unfilled
N-990 MT
N-761 SRF-LM
S-300 EPC
N-550 FEF

Figure 6 shows why microwaves are so effective. It is noted in the equation that the power that can be dissipated in a polar rubber is proportional to the electrical field strength squared, times the frequency, times the dielectric loss factor which was discussed earlier, times the volume of material that is in the oven. The important thing to note is that one of the multipliers is frequency and microwaves operate at extremely high frequencies. They, therefore, can effectively transfer large amounts of power very rapidly without excessive field strengths. This helps make microwave processing very convenient for industrial usage.

MICROWAVES ARE EFFECTIVE BECAUSE OF THEIR VERY HIGH FREQUENCY

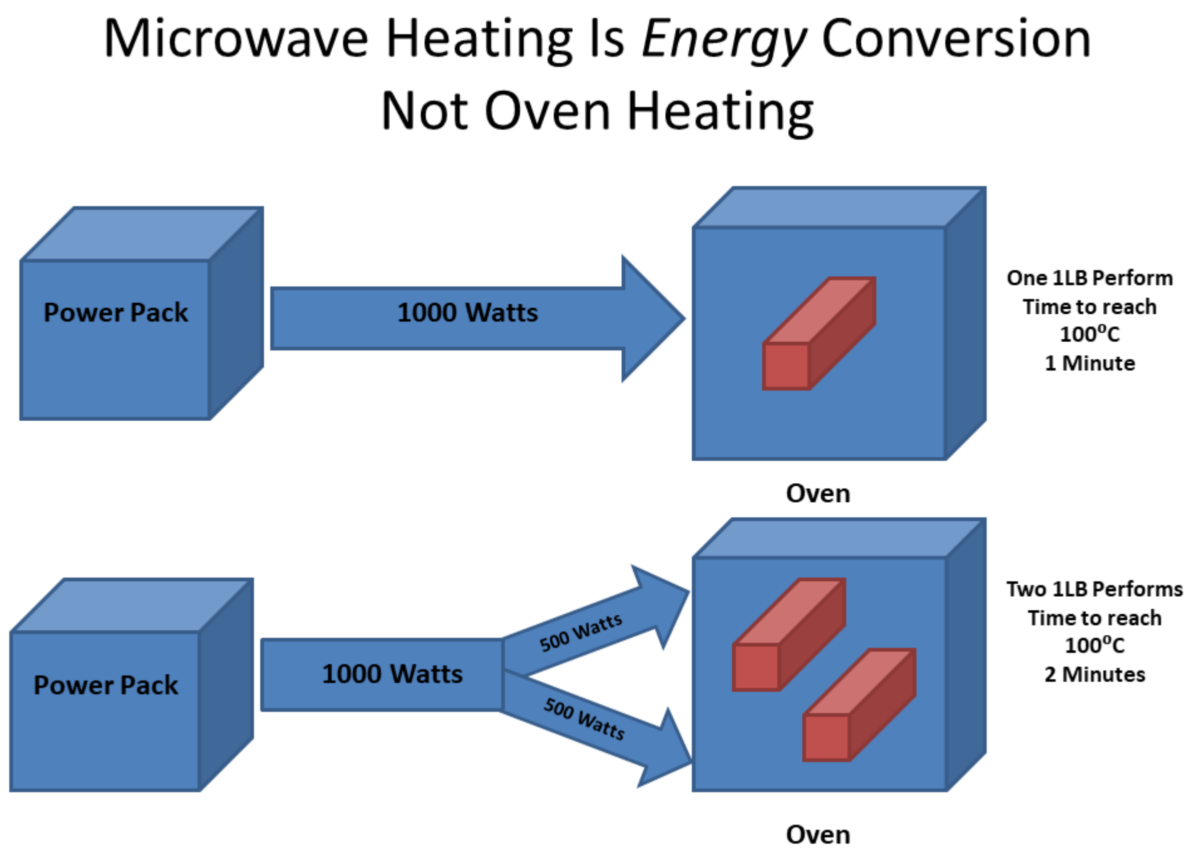
$$P \propto E^2 f \, \varepsilon'' \, V$$

P POWER DISSIPATED IN THE DIELECTRIC
E ELECTRIC FIELD STRENGTH IN THE DIELECTRIC
f FREQUENCY
ε'' DIELECTRIC LOSS FACTOR
V VOLUME OF THE DIELECTRIC

Figure 6

ENERGY CONVERSION OFFERS HIGH SPEEDS

An extremely important concept to appreciate in the microwave process is that microwave heating is energy conversion and not oven heating. This requires a reorientation of conventional processing thinking. People tend to consider ovens as having heat and that material is put into a hot oven. This is not the case in the microwave process. Here, the rubber is put into a microwave field and the rubber converts the energy from this field into heat within itself as stated earlier. This is illustrated in Figure 7 where the oven delivers a constant amount of power. In this example, 1000 watts raises the one pound preform to 100 degree Celsius in one minute. Taking the same oven, remove the heated preform and insert two identical room temperature preforms of the same configuration and weight as the first example, and turn on the 1000 watt oven. Both preforms must now share the available energy, each receiving half of the thousand watts, namely, 500 watts each, and it will, therefore, take two minutes for them to reach 100 degree Celsius in the same oven. Theoretically, therefore, doubling the load, doubles the time if the power remains fixed. To remain at the original one minute time with double the load would require doubling the microwave power.

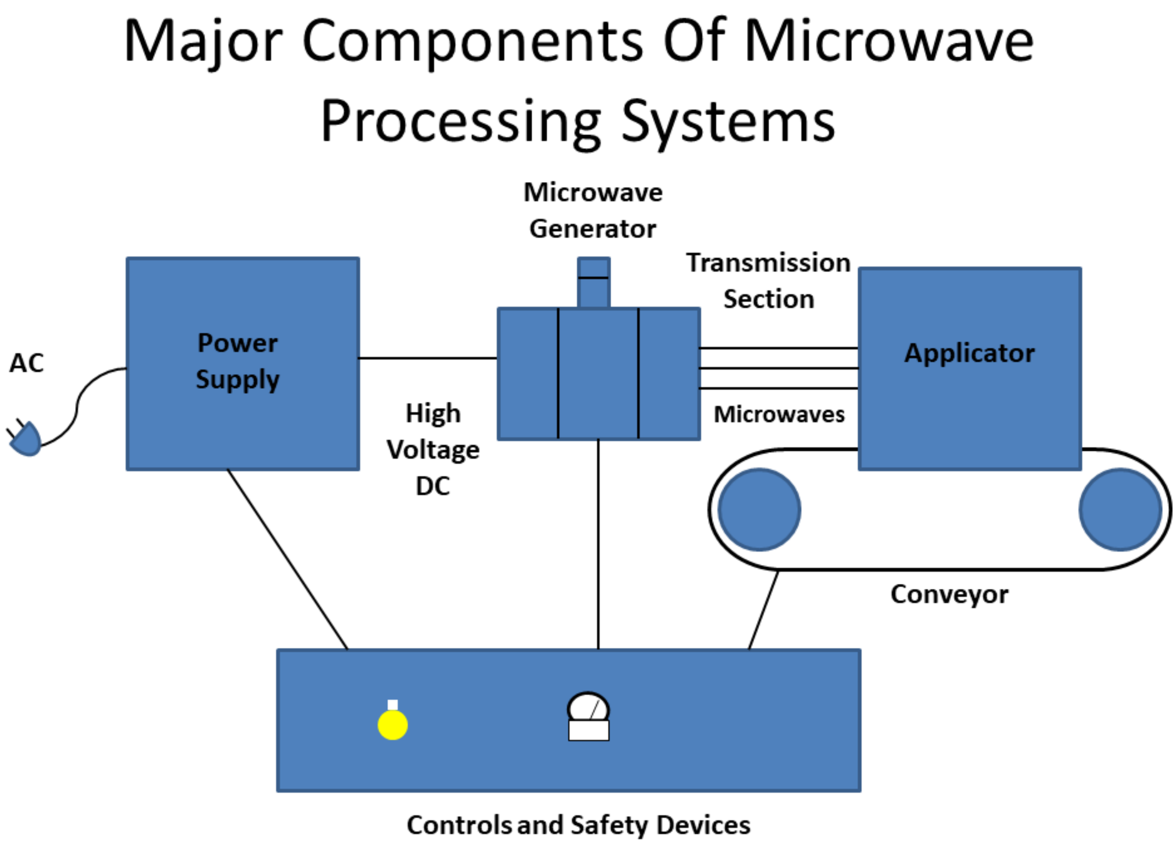


PENETRATION DEPTH

Perhaps the greatest advantage of microwave processing comes from the penetrating effect of microwave energy due to the internal mechanisms of molecular friction which were explained earlier. It is this ability to penetrate which results in very high quality extrusions evenly heated throughout their mass, a very important factor for automotive weather stripping. Conventional methods of processing such as salt bath, hot air and steam put high temperature on the outside of the extrusion and depend upon the thermal conductivity of the rubber to absorb the internal heat. Microwaves penetrate as soon as they are turned on, but indeed, they do heat from the outside in. Their instantaneous effect, however can cause the misconception that they heat from the inside out. We should understand the nature of microwave penetration.

The microwave energy transmitted into the rubber is progressively absorbed or attenuated until it decreases in magnitude as it penetrates. The rate at which the energy is absorbed or decreased is called the penetration depth and, in general, it is defined as the depth at which the power level of the microwave energy is decreased by 50%. This means that half of the power is absorbed between the surface of the rubber and the penetration depth or, that at distances greater than twice the penetration depth, the power of the wave is negligible. Table III illustrates the penetration depth in centimeters of various materials at the microwave frequency of *2450*MHz and at a starting temperature of about 25 degree Celsius. You will note that as microwave receptivity decreases, penetration depth increases. The more receptive the material, the more rapidly it will absorb the energy thereby attenuating the penetration.

As microwave energy enters the material, an amount is reflected in an optical fashion. This relates to the dielectric constant ________ . the energy going into the substance, however, is progressively absorbed and decreases in magnitude relating to the dielectric loss factor ________ as it penetrates into the material.



WHAT MAKES UP A MICROWAVE OVEN?

Figure 8 shows the major components of a microwave processing system. AC power is taken from the plant service line and is converted into DC power at high voltage by the power supply of the microwave oven. This power is placed across the microwave tube (magnetron) which is a vacuum tube surrounded by strong magnets. The microwave tube converts the DC power into microwave energy at the frequency that is determined by the design of the tube. Coming out of the tube, therefore, is microwave power at a frequency of 2450MHz. At this frequency energy is not conducted in wire, but generally is transmitted through waveguide which is a rectangularly shaped conduit whose width is less than one wavelength and greater than one-half wavelength. Its height is approximately one-half its width and its length is long enough to reach from the microwave power pack to the microwave oven. The microwave oven cavity, or applicator, is the chamber that is used to expose the microwave energy to the rubber. This applicator can be either a batch oven or a conveyorized tunnel oven or various other mechanical alternatives. The entire system being electronic has various controls, safety devices and feedback systems to aid in operation.

The microwave cavity, also called the applicator since it is the place where the microwave power is applied to heat the rubber, is usually a metal box of the multi mode type. It is relatively simple mechanically, but yet must be designed to provide extremely good uniformity of microwave heating. It is called multi mode because it supports a large number of resonant modes in a specific frequency range. Generally, the larger the cavity the greater the quantity of modes that are propagated. When the oven is empty, each of these modes shows a sharp resonance response at a given frequency which is close to the operating frequency of the microwave generator. The greater the number of modes, the greater the potential for uniform heating. The number of modes is significantly enhanced as more generators are applied to the same applicator. The permissible bandwidth at 2450 MHz is +/- 25 MHz, ample opportunity for different generators to have very slightly different frequencies creating the mixing of many different modes.

Things change when the oven is partly filled with the load to be heated (the rubber). The modes lose their sharpness and overlap in frequency. The extent to which this happens depends upon the nature of the load and its dielectric properties. Therefore, when answering the question “is the heating uniform?” you have to look at the oven not by itself, but rather with its normal load. The dynamics are complicated, but the end objective is to design the oven not simply for uniformity when it is empty, but rather to uniformly heat rubber.

SUMMARY OF THE BENEFITS OF MICROWAVE PROCESSING

Heating by Energy Transfer

The reader can see now that the microwave heating mechanism is transfer of energy from the microwave generator directly into the rubber itself. Microwaves do not heat the metal oven walls nor the air in the microwave oven. The speed of energy transfer is determined by the amount of kilowatts of microwave power that are installed in the oven, therefore, speeds and heating efficiency can be extremely high. From the viewpoint of the rubber manufacturer, this means minimum floor space, reduced scrap and lower power consumption. Scrap is reduced because with shorter line lengths, manufacturing defects can be seen and corrected early in the process. The high speed of heat transfer also cures the rubber very rapidly and thereby minimizes shape related defects.

Deeply Penetrating Heat

Since microwaves heat through molecular excitation, the effect is not only rapid but also very penetrating. This results in a uniform cure throughout the cross section, which translates into high-quality production. There is no need to place very high temperatures on the surface of the extrusion with salt, hot air or ballotini so that the heat can soak into the rubber. Microwave heating is instantaneous and deep.

Electronic

Microwave heating is an electronic process. As such, it readily ties into labor saving automation and process control. Feedback systems, instrumentation and data logging are all means for achieving high quality repeatable precision extrusions with minimum labor.

This form of electronic heating is quiet, and clean. This can be appreciated when you consider conventional alternative techniques which require salt bath or glass beads. Further, salt and glass beads are consumable requiring cost for replenishment, as well as extra measures for environmental control, cleaning and safety.

WHAT ARE THE APPLICATIONS OF MICROWAVE IN THE RUBBER INDUSTRY?

Continuous Vulcanization

Microwave continuous vulcanization ovens the type shown in Figure 9 have the ability to continuously vulcanize extruded rubber weather stripping and similar mechanical goods at extremely high speeds and with high quality results. The microwave oven provides the temperature rise from the extruder up to cure temperature and a hot air oven or ovens set at the cure temperature downstream of the microwave oven provides the necessary residence time at that temperature to complete the cure.

In the case of sponge or multiple durometer extrusions with a sponge component, the microwave is usually preceded by an infrared or hot air tunnel whose purpose is to put an attractive skin on the sponge prior to its being blown in the microwave oven. Hot air or infrared technologies are used since shallow penetration only to the surface of the extrusion is necessary to achieve this skin. Figure 9 shows an infrared full round pre-heat tunnel followed by the microwave which is then followed by the post-cure hot air.

Bale Pre-Heating

Microwave energy is also used in the mixing room to rapidly pre-heat bales of natural rubber prior to mixing. Conventional heated tempering rooms are not necessary since frozen rubber blocks can be promptly tempered for processing as a result of microwave pre-heating. Figure 10 shows a large batch pre-heater which can accommodate multiple skids of rubber bales.

Figure 11 depicts a Cober automatic conveyorized bale pre-heater which tempers 4,500 pounds of rubber per hour and automatically dumps the bales into the banbury mixer according to the program sequence.

Microwave Boost

An application that is increasing in popularity is the insertion of a short, continuous microwave tunnel in an existing conventional and hot air, salt bath or ballotini line. The microwave boosts the temperature of the rubber when it comes out of the extruder thereby permitting the line to run at speeds 25-40%

higher with complete cure. Figure 12 shows a microwave booster which is only 3 meters long, yet powerful enough to provide a uniform and significant temperature rise.

Continuous Heating of Hose

A significant challenge to the hose industry is to develop technology to build multi-layer hose on a continuous basis from start to finish. Microwave technology is ideal for this application since very many hose structures have a tube made of a material which happens to be microwave receptive and a cover which is microwave transparent. The continuous microwave hose oven shown in Figure 13 is a hybrid oven having both microwaves and hot air capabilities. The microwave energy penetrates through the non-receptive cover to heat the tube while the cover material directly sees the hot air; a very beneficial synergy.

The fact is that hybrid ovens with both high temperature high velocity hot air and microwaves are a feature used in all Cober continuous vulcanization systems including those for weather stripping. Hot air assists not only in curing, but in achieving uniformity of heating and also in helping to keep the internal structures of the oven clean by burning off condensate.

WHAT ARE THE REQUIREMENTS TODAY FOR A MODERN MICROWAVE CV OVEN?

The bottom line requirement for a modern continuous vulcanization system is to produce high quality rubber at minimum cost and be flexible to cover a broad line of rubber products being produced now and being considered for future expansion. This means that the CV system must have the following characteristics:

- Ability to operate 24 hours a day with minimum maintenance;
- Must be able to produce a broad range of rubber products using low cost materials;
- Must have precise controls to minimize scrap and to save labor;
- Must be safe for operating personnel and friendly to the environment.

Ability to Operate 24 hours a day with Minimum Maintenance

The design of the microwave generator and the protection of its most costly component, the microwave tube, is of utmost importance. In high power applications where individual tubes of 6kW or greater are used in multiples to meet the total power requirement, the costly tube requires protection from excessive reflected power, arcs in the waveguide system which can be caused by dirt or other issues, precise tracking of the filament cutback over the full range of power that the tube has to put out and protection from the ___________ mode which can cause the tube to mode and fail if it is initiated at the wrong frequency. It is not important in this dissertation to explain each of these details, rather, the rubber producer should recognize the importance of built in safety features on high power microwave generators and he should look for truly industrial design and construction.

For systems which use smaller power modules in multiples such as the microwave boost oven shown in Figure 12 which has six 2kW microwave generators the maintenance concept is different and somewhat simplified in that the generators are smaller modules and maintenance is a matter of changing modules. The control system, of course, must indicate which module to be replaced.

Ability to Produce a Broad Range of Rubber Products Using Low Cost Materials

It is important to recognize that the focus of the CV system is to produce rubber and not just the details of the application of microwaves. There is a very important benefit from employing high velocity hot air in the microwave oven because significant results can occur from this synergy. The rubber manufacturer needs all the benefits of microwave productivity, plus he must be able to run the entire spectrum of materials that the manufactures regardless of shape, color, or chemistry. To achieve this goal, a brief discussion of the heat transfer physics of hot air is beneficial.

The heat transfer coefficient, h, is defined $h=h_r + h_c$ which consists of two parts: the h_r expresses energy transport between the radiant components of the oven and the mass of the extrudate and h_c expresses the convective energy transfer portion between the hot air system and the extrudate.

The value of h is defined as the number of joules imparted to the surface of an extrudate per unit area, A, per unit time, T, per degree temperature difference, T, between the extrudate and the oven.

In other words, the joules delivered in a conductive or convective heating process to the surface of the rubber is given by joules = h x A x t x T. Typical units for time and area are hours and square meters.

For a given part, t and A remain constant. Therefore, we can look at the important relationship as being the fact that watts are proportional to h x T. the heat transfer coefficient for a conventional hot air oven is approximately 20; for a high velocity air oven it is approximately 60. This means that three times the number of watts of energy are provided to the surface of the rubber under conditions of high velocity air.

On parts which are thin i.e. 3 mm and less, the contribution of high velocity hot air is significant. Keep in mind that the watts are transferred to the surface of the rubber.

The overall result depends on how well the rubber conducts the surface heat throughout its mass to achieve uniformity and final cure. The thicker the rubber, the more difficult and the less effective is the application of hot air or salt or fluid bed, since rubber is a poor thermal conductor.

The microwave mechanisms of heating, dipole rotation and ohmic conduction are not surface phenomena. They cause molecular action throughout the mass. The most important thing to note here is that regardless of how marginal the compound may be, the microwave process imparts heat to the center of the rubber and throughout. (the more marginal the compound in terms of microwave receptivity, the more microwave kilowatts needed.)

This mechanism is complementary and synergistic to the radiant and convection means of heat transfer which only induces heat on the surface of the rubber. Both mechanisms in combination represent the fundamental concepts of a new and more universal technology. We have named it the “CoberCure” system.

The end result is a multiple energy curing system using three modes of heat transfer: microwave, infrared radiant heat and high velocity hot air, all in combination; a delight for the electro-technologies. Rubber can be run productively with poor compounds and even with the microwave turned off if need be (although at much slower speeds).

<u>Precise Controls to Minimize Scrap and Save Labor</u>

The ability to automate and precisely control electronic systems such as industrial microwave ovens is significantly enhanced by the use of PLC and micro-controller technology. Cober systems have advanced control capabilities and data bus interfacing. They tie into the plant control system and are easily installed and connected through the data highway. Sensors in the microwave oven can feedback to the control system programming the optimum utilization of the microwave generators and sensing product information in the oven chamber, the status and control of high velocity hot air systems, the safety interlock and fault status, and the material handling system including conveyor speeds, etc.

All of this information is processed not only at the master control panel, but can also be transmitted externally by a telephone line through the built in modern. This feature called DOL or Cober Diagnostics On Line permits real time monitoring of the oven system and immediate consultation by the Cober engineering department when necessary. In fact, through DOL Cober can adjust operating parameters remotely in order to meet required specifications.

Safe for Operating Personnel and Friendly to the Environment

Microwave chokes are important devices to prevent microwave leakage out of the entrance and exit vestibules of the tunnel and through the clean out doors. Standards for industrial microwave ovens are very rigorous and similar to the standard on home microwave ovens. The difference is that on industrial side we are dealing with much larger openings and higher powers. Certain rubber extrusions can be 5-6 inches high. Conveyor belts can be 1 foot in width. Additionally, industrial regulations consider whole body exposure to the worker, not just leakage.

Advanced choke design should not be dependent on moveable gates which are adjusted by the operator because operators tend to leave things wide open, particularly if the rubber is moving across the belt or is snaking as it is growing. The choke design, therefore, must be safe and effective no matter what is being run and it should be in place without adjustment. Devices of this type are designated as quarter-wave reactive chokes. This type of advanced design takes advantage of the wave length of the frequency of the microwave oven in mechanical structures that prevent electrical fields from propagating. In effect, these chokes reflect the microwave energy back into the oven rather than permit it to escape through the orifices. Quarter-wave chokes also must be at the clean out doors since contraction and expansion of the metal in the oven can change structures during heat up and cool down and present gaps for leakage of microwave energy.

The cleanliness of curing with microwaves is apparent when compared to both salt and fluid bed materials which are contaminating to the water system and must even be cleaned from the rubber extrudate.

RELY ON YOUR ELASTOMER AND CHEMICAL SUPPLIER FOR MICROWAVE RECIPES

Suppliers of elastomers and chemicals realize that microwave processing is an important technology in use in many plants today. They can supply users with microwave recipes necessary to meet a broad variety of extruded rubber specifications. Cober Electronics, Inc. and Uniroyal Chemical Company, a Crompton Business, have cooperated over the past 15 years to lead the development of this technology and to help make microwave processing and microwave chemistry the highly productive process that it is today. Uniroyal Chemical Company, a Crompton Business, has a very complete laboratory to formulate, mix and extrude microwave compounds to meet customer specifications. The laboratory has the latest technology for extrusion, preheating, microwave heating and hot air post cure in order to run demonstrations for their customers.

Table V is an example of a Royalene extruded dense compound for microwave curing and Table VI is a Royalene extended sponge compound for microwave curing. These are typical EPDM examples that have proven very successful. Rubber producers are invited to call Uniroyal with their specific questions.

CONCLUSIONS

The demands for productivity and energy efficiency require the application of microwave processing in a modern rubber factory. The mechanisms of microwaves have been explained and the reader should be able to grasp the advantages of this most rapid form of energy transfer.

Microwave equipment is available today to offer the reliability and versatility demanded by rubber manufacturers.

For optimum results the entire CV line should be looked at and planned as a complete system from extruder to packaged product.

Compounding and chemical technology has advanced to where recipe and compounding assistance is readily available from suppliers, thereby taking the heavy burden off the chemist in the rubber factory. Further, this continued assistance plus the concepts of the “Cober Cure” technology assures that the microwave installation will remain as a versatile system for a broad variety of new rubber products that the rubber manufacturer may run in the future.

Specific questions can be answered by calling the service department of Cober Electronics, Inc. 151 Woodward Avenue, S. Norwalk, CT 06854, Telephone number (203) 855-8755. Fax number (203) 855-7511, or call the Technical Service Center of Uniroyal Chemical Company, a Crompton Business at Spencer Street, ISSC Building, Naugatuck, CT 06770. Telephone number 800-243-5098.