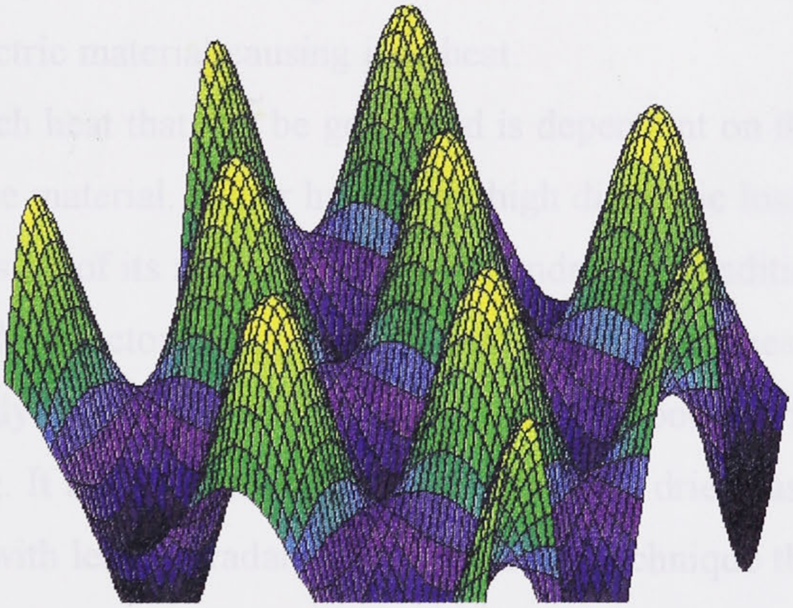
Radio Frequency Vacuum Drying Technology

Applications in Wood Processing
&
Design of a Parallel Plate Applicator



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Executive Summary

Wood drying is a necessary, and to date, arduous task. With existing conventional techniques, such as kiln drying, much caution must be taken to prevent degradation such as checking or warping. This is done through precise and closely controlled scheduling.

Lately, resurfacing to popularity is the Radio Frequency Vacuum (RFV) drying method. Radio frequency (RF) is propagated in waves which alternate with time in a sinusoidal pattern. These waves are formed from two components; electric and magnetic waves. These waves can be passed through a dielectric material causing it to heat.

How much heat that can be generated is dependent on the dielectric properties of the material. Water has a very high dielectric loss factor, which is a measure of its ability to be heated under RF conditions.

Wood's loss factor changes as it dries, since the tissues themselves have exceedingly low factors. This property makes wood a prime candidate for RFV drying. It has been shown that wood can be dried faster, more uniformly and with less degradation with the RFV technique than with other conventional methods.

After reviewing the concepts of RF circuits, generation and wave theory, we proposed an applicator design, that will use the existing RF Callanan generator which produces 8 kW of power at 27.12 MHz and belongs to the Agricultural & Biosystems Engineering department. The flexible design of our applicator, allows for modifications to the allowable volume through the adjustable lower plate. This makes our design useful for future experiments involving this type of drying technique on wood and/or other organic, homogeneous materials.

Acknowledgments

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Introduction and Objectives

Ever since humanity has wanted to preserve or process almost any material, be it food, medicine or building materials they have recognized the need to remove as much of the excess water as possible. These products need to be dried. This need primarily arose in the agricultural products industry. Foods could both be kept for a much longer period and were potentially more useful in their dried state.

Initially, the one way to dry any given material, was to leave it out in the air for long periods of time and wait. As society advanced, however, so did the need for these materials become more prominent. This called for faster ways to make the product available, without ruining the quality; because the consumer wants it now but wants it right.

So, to accommodate the consumer's demands, new methods of drying began to surface. There are far to many to be able to discuss or even list all of these. However, since our main focus is lumber, we will discuss a few of those which are pertinent to that industry.

Interestingly enough, air drying is still used to some extent in the drying of timber. This air drying has been modified to include forced air from extremely large fans, and the forced air may or may not be heated. Also, there have been investigations into how the stacks of lumber should be arranged relative to the flow. All of this to expediate the delivery to the consumer.

There has also been the development of kilns, for wood, which use various techniques to dry the product. Some use heat pumps or dehumidifiers, while others still use the forced air technique, just under much more restricted conditions and regimented schedules. Since nothing is ever perfect, there have been modifications and advances with the kilns as well. Specifically, the addition of the Vacuum system, which works on the principle that water boils at a lower temperature under lower pressures.

There have been other types of dryers, however, they are generally not widely used; either because they are inefficient and/or ineffective or possibly because the industry was not ready for radical changes. The latter is probably the case with Radio Frequency Vacuum (RFV) drying

RFV drying utilizes radio waves from the High Frequency band (3 to 30 MHz) to pass through the wood. Wood is a dielectric material (an insulator), which means that it is affected when an energy field is passed through it. This is essentially the same way that one's microwave oven works. It causes the water molecules to flip back and forth, because they are dipolar and in turn causes them to heat up.

Radio waves are electro-magnetic waves. These waves can travel through space and unlike sound, do not require any mass transfer. The waves travel in the form of a sinusoidal curves and the electric and magnetic ones are perpendicular to each other.

RF generators, generally, use vacuum tubes. They tend to work in closed loop configurations which makes it difficult to identify specific component problems. However, certain RF amplifiers consist of a chain of components, which allows for individual component testing and for easier control of the RF power.

The range of frequencies which are encompassed in the radio region are 10 kHz to 300 GHz. This frequency is directly related to the wavelength by the constant speed at which they travel, the speed of light. Basically, the higher the frequency the lower the wavelength.

The radio frequency region also encompasses the microwave band, which is much higher than the frequencies generally used in most drying techniques. This is because of the need for a slower process to prevent the degradation of the material.

The RFV dryers work on the principle of heating from the inside out. The wood, placed between two electrodes, is subjected to an alternating field, as described earlier. This field then polarizes the water. The water in the wood has a much higher dielectric loss factor, (a measure of the heat related receptiveness to an RF field), than the wood, whose loss factor is essentially negligible. So as the water heats up it is moved to the surface of the wood and then is taken away by the vacuum pumps.

There have been several benefits to this type of drying shown in the past. This is probably why there has been a resurgence of interest in this old but revisited technique. New companies and other universities have been doing some work with RFV drying, with varying success.

Our objectives are two fold. Firstly, we wish to familiarize ourselves with the technology behind Radio Frequency Vacuum (RFV) drying; that is, to understand what radio frequency waves are, how they are generated, and how they can be used to dry wood or other homogenous organic matter.

Secondly, is to design a parallel plate applicator using the 8 kW, 27.12 MHz Callanan RF generator belonging to the Agricultural & Biosystems Engineering department. The dryer is to be a test scaled unit that can be used to study drying curves of not only wood, but other organic products.

Why Dry Wood?

Wood is one of the most important building materials we use in construction today. Unfortunately, wood is not dimensionally stable. Wood tissue is formed in a saturated environment and the water content is the biggest problem in the use of this natural resource. This problem is rarely avoidable. There are several reasons why we want and need to remove this water.

1. When wood dries, it shrinks. It is important to have this shrinkage occur prior to the use of the wood. So we try to lower the moisture content to an appropriate level for the proposed use of the timber. (This shrinkage also reduces transport costs.)
2. When the wood has been dried, a better surface finish can be obtained.
3. If the lumber is dried prior to use it helps to prevent decay. This is also aided by the fact that it becomes easier to inject the wood with preservatives.
4. Sometimes the wood is left to dry simply because it facilitates burning.

To further complicate the situation, the moisture content is not the same in all types of wood (see Table 1) and it will also vary within one piece of wood. The center of the wood is called the heartwood and the outer region is called the sapwood (see Fig. 1).

Fig. 1 (Cross Section of an imaginary wood sample)

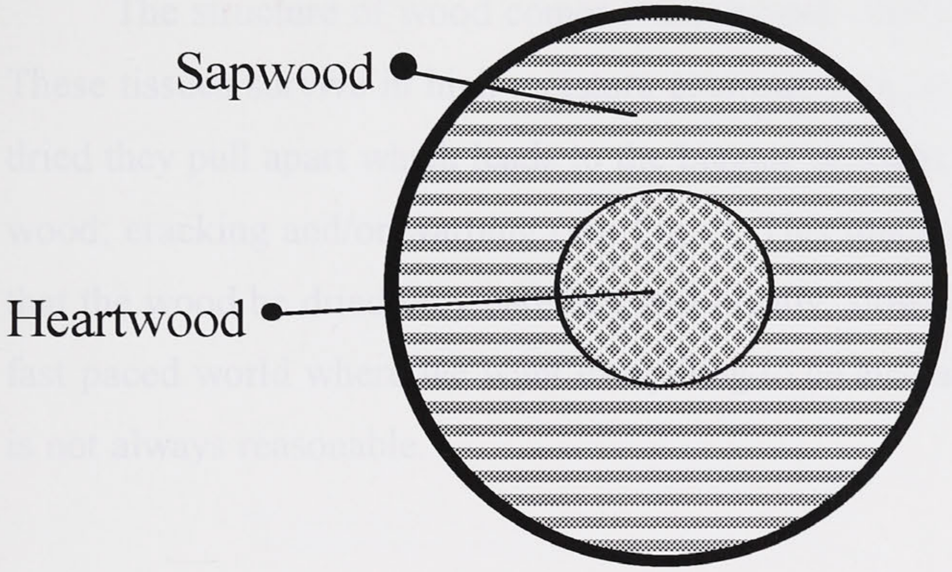


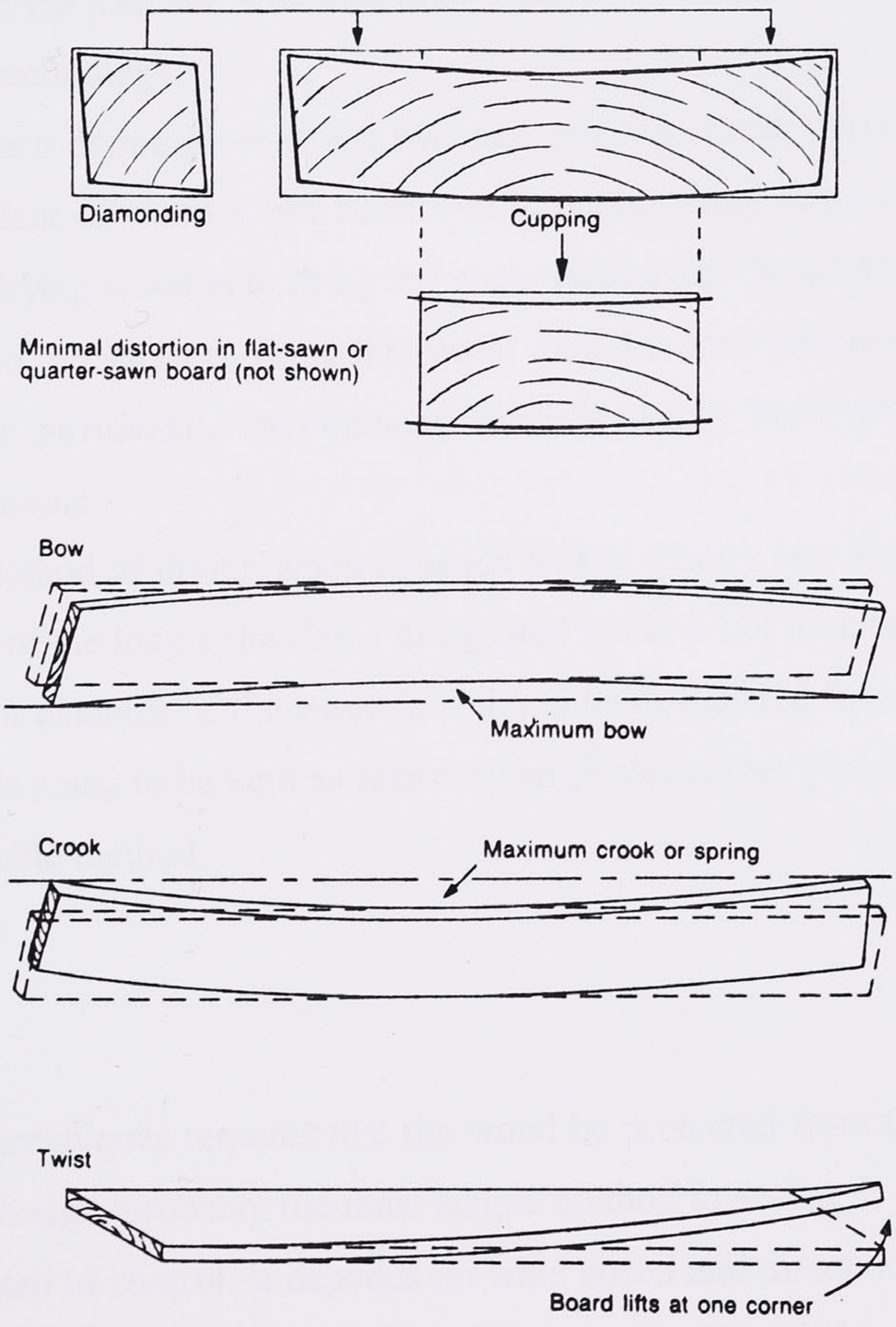
Table 1 (Green Moisture Content {wet basis} values for several species)

Common Name	Heartwood (%)	Sapwood (%)
Hardwoods		
Yellow Birch	75	70
American Beech	55	70
American Elm	95	90
Shining Gum	115	125
Softwoods		
Sitka Spruce	40	140
Slash Pine	40-45	180
Ponderosa Pine	40-45	160
Radiata Pine	40-45	150
Loblolly Pine	35	110
Douglas Fir	40	115
California Redwood	85	210
Western Hemlock	85	170

(Walker, p.70)

The structure of wood comes from the cell wall tissue and the lignin. These tissues survive in high moisture environments, so when wood is dried they pull apart which leads to the biggest problem faced when drying wood; cracking and/or warping (see Fig 2). This limiting factor requires that the wood be dried very carefully and ideally, slowly. However, in our fast paced world where we want everything to be available immediately this is not always reasonable.

Fig. 2 (Various Problems Related to Warping)



(Walker, p.278)

Conventional Drying Methods:

There are a few methods of wood drying some of which were popularized in the past and still used today and some which have come from modern day technology.

The basic drying process is a two step one. As shown previously, the moisture content of wood is not consistent throughout any sample, so the first step in drying wood is to bring the water residing in the center and throughout, to the surface. Then, this water must be removed from the surface to the surrounding environment, which is usually done with a moving air stream.

The method of drying wood depends on the species and also on what the final use of the lumber has been designated to be, if not precisely at least generally. For example, if the wood is going to be designated for outside use lumber and is going to be kept as relatively large pieces then just air drying is an acceptable method.

Air Drying:

This techniques requires that the wood be protected from the elements. Though, probably the most simple method to set-up, it is extremely hard to control. It depends on wind speed and direction, air temperature, hours and intensity of sunshine per day, humidity, season, wood type and size of cut. The effects of some of these factors is obvious. For example, if the weather is very humid, then the water will leave the wood much slower and the drying process will be severely retarded. Rain is also a very significant problem with this method, as water will be absorbed through the capillaries faster than evaporation occurs.

All these factors can significantly effect the drying time; a 25 mm board can take from 30 to 200 days to dry (Walker, p.262). The board thickness is another very important factor to take into account, because doubling the thickness can more than double the drying time.

To optimize the effectiveness of air drying, the site must be well drained and preferably sealed, as the air can absorb moisture from both the ground and the wood. Also, along with dampness, excess waste wood can promote fungi and insect growth. Proper air flow is also a must. Having the site surrounded by buildings or some other form of impedance would severely reduce the flow and therefore drastically increase the drying time.

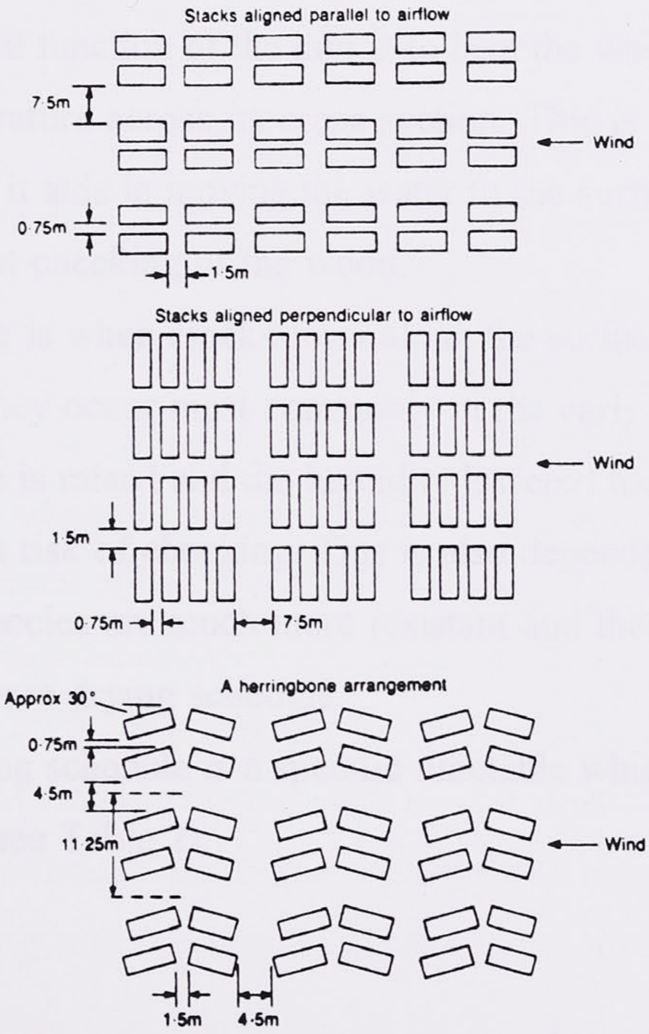
Finigan and Liversidge have investigated trying to control drying times by changing the stacking patterns (Fig. 3). Also, drying will vary throughout a given stack, so the common practice is to put the lower grades of wood at the top and bottom, as they will dry faster and put the better quality woods in the middle.

Pre-Dryers:

These devices are very simple and are designed just to remove the readily available water in the wood. All they require is a roof over the stacks and fans of about 1 to 2 meters in diameter. The air which they force through the stacks is often just at normal ambient conditions. However, if the humidity rises above 85 to 90 % then the fans should be shut off as they will no longer have any benefit.

In some cases the air can be pre-heated to 10 or 20 °C above the ambient temperature which increases the moisture capacity of the air. This is usually done and has its greatest effect in the winter season. When this is done, these pre-dryers can actually be used as low temperature kilns.

Fig. 3 (Stack Placement Pattern Relative to Prevailing Wind)



(Walker, p.264)

Kiln-Drying:

This method of moisture removal is probably the most common and most widely accepted. This method passes air through the wood from one end of the stack to the other. The wood is stacked very tightly in the kilns and is only spaced in between the layers by the stickers. If there is excessive clearance within the kiln, then there will be large losses as the air moves around the stack as opposed to through it.

The initial function of the kiln is to heat the wood so as to have a uniform temperature across its cross section. This is important for two reasons; firstly it aids in moving the water to the surface and secondly it helps to prevent checking of the wood.

Checking is when cracks form along the surface of the wood, parallel to the grain. They occur most commonly in the early stages of drying. If the temperature is raised and the humidity lowered too quickly, then there becomes a high risk of checking. This is also dependent on the type of wood. Some species are much more resistant and therefore can have a much more severe drying schedule.

The drying schedule is a specific timetable which is applied for each load of wood (see Table 2).

Table 2 (Schedule for the accelerated drying and equalizing of 50 mm Radiata Pine framing timber)

Moisture content of the wettest timber in stack	Dry Bulb (°C)	Wet Bulb (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Green	71	60	58	9
50	75	60	49	6.3
20	80	60	39	4.9
Equalizing	80	73	73	9.9
Conditioning	85	84	96	18.5

(Walker, p.269)

This schedule will vary from species to species and can be controlled by a technician. It involves raising and lowering the temperature and humidity for given amounts of time. This needs to be done very carefully, especially in the early stages of the process, as cracking and deformation can occur very easily at these points in the process. Today, the schedule is commonly controlled by a computer which controls the fan speeds and most of the other environmental controls.

Just as much precaution must be taken at the end of the drying cycle. Saturated air at 20 °C has a relative humidity of only 12 % and if the wood, at 60 °C were to come in contact with this air it would heat that which was in its immediate vicinity and further drying could occur.

Kiln drying is far superior to air drying for several reasons. Though there is a seemingly low initial cost for air drying, it does require a large amount of land and this land remains occupied for very long periods of time, especially with hardwoods. With kilns, the start-up costs will be greater, however, the turn over in stock will far exceed air drying. Finally, probably the most important reason that kiln dryers are better is that they are essential to attain the much lower moisture contents needed for many of today's applications.

Heat Pumps and Dehumidifiers:

Heat pumps and dehumidifiers are essentially the same, except that the former has the evaporator outside, where as the latter has both the evaporator and the condenser inside the kiln.

Dehumidifiers are very efficient except near the end of the cycle. They operate at low temperatures (below 50 °C). Near the end, they may require some outside air input, as the machine may not have the capacity to condense all of the water.

Heat pumps release more heat into the kiln than is required to operate the machine electrically. They are most efficient when the temperature of the ambient air is high.

Vacuum Drying:

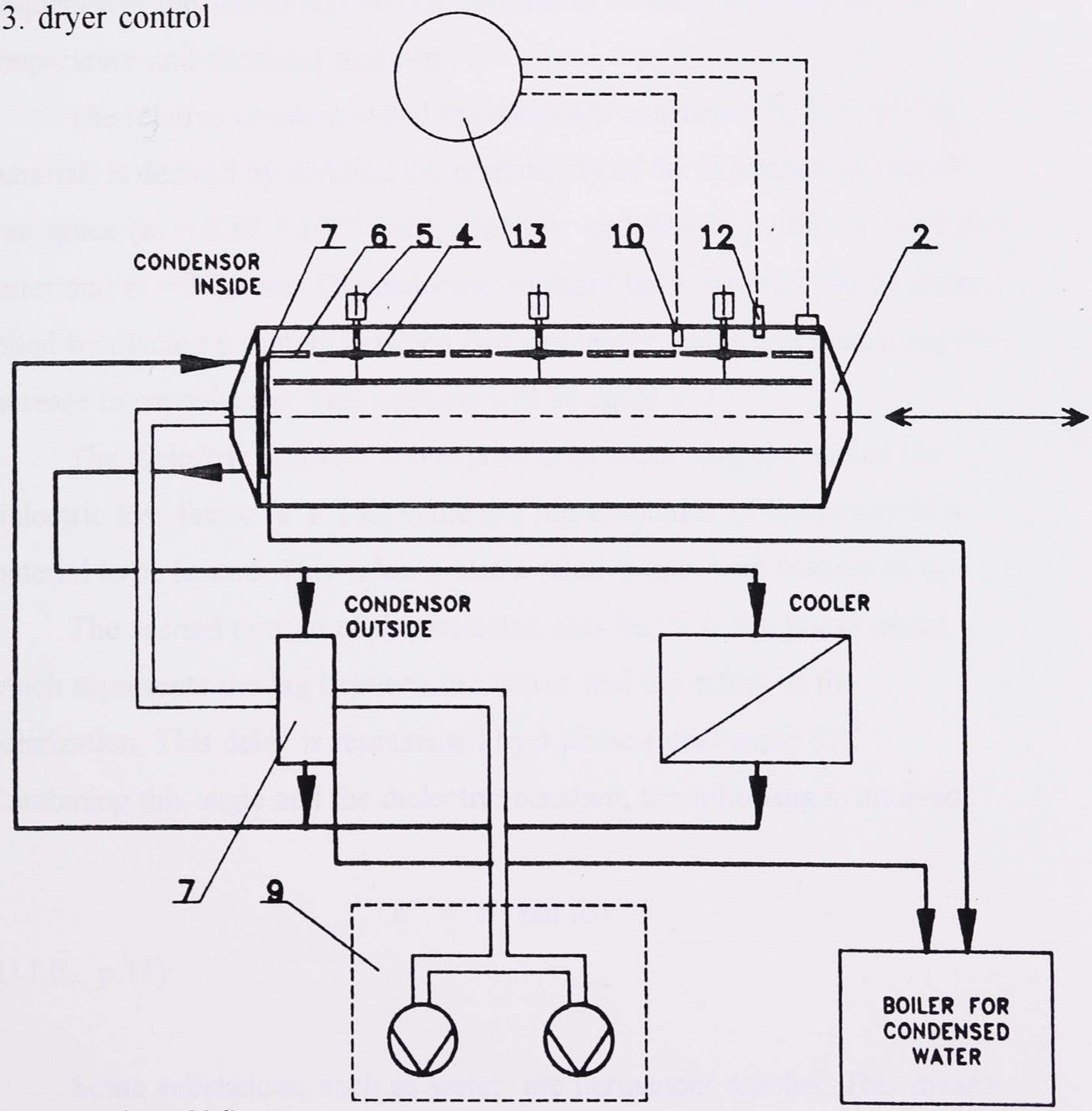
This extra addition on either a heat pump or a dehumidifier, works on the principle that water boils at a lower temperature when under a partial vacuum. "Vacuum drying has all the benefits of high temperature drying without the danger of defects that would develop in some species at 100 °C." (Simpson, 1987). When using the vacuum technique, there usually is a relatively small load of wood placed in the dryer because the size of the pump must be taken into consideration. This size is directly dependent on the volume of the kiln. Also, the vacuum pump motors are generally placed on the outside of the kilns as this promotes longer life and better performance (see Fig. 4).

Radio Frequency Vacuum (RFV) Drying:

This is a technique which involves the use of a radio frequency generator to heat the wood, combined with a vacuum pump to help accomplish the drying. RFV drying uses the dielectric properties of wood to heat it and to remove the water. This drying method will be discussed in much greater detail later.

Fig. 4 (Vacuum Kiln Diagram)

2. gate
4. fans
5. electric motors
6. heating registers
7. condensers
9. vacuum pump
10. recording of ambient climate
12. pressure sensing
13. dryer control



(Vanek ed., p.416)

Dielectrics and Heating

Although nothing is entirely electrically insulated, a dielectric is essentially non-conductive. Each material has a certain ability to be polarized which is a measure of the materials permittivity (ε) . This constant is independent of the electric field strength but does depend upon the frequency of the waves and certain conditions of the material, such as temperature and chemical make-up.

The relative constant called the dielectric constant (ε'), for any one material, is derived by dividing the permittivity of the substance by that of free space ($\varepsilon_0 = 8.85 * 10^{-12}$ F/m), (Solymar and Walsh, p.466). $\varepsilon' = 80$ for water and $\varepsilon' = 1$ for air. The dielectric constant for a material can be simply found by placing a sample between two condenser plates and measuring the increase in capacitance. This increase will be equal to ε'.

The dielectric constant is one portion of something else called the dielectric loss factor (ε''). This value is a representation of the ability of a material to be heated. This value is also a relative one; with respect to ε_0.

The second portion of the dielectric loss factor is the phase angle, which represents the lag between the waves and the effect of the polarization. This delay is represented by a phase (loss) angle (δ). Combining this angle and the dielectric constant, the following is attained:

$$\varepsilon'' = \varepsilon' \tan(\delta)$$

(U.I.E., p.11)

Some substances, such as water, are permanent dipoles. This means that they are non-linear in structure. Water is a triangular molecule, which is what gives it its imbalance. If these substances are exposed to alternating or time dependent fields, they become polarized. This means that they are constantly trying to align themselves relative to the alternating wave.

In the specific case of wood, the loss factor is going to be different for each species. It will probably even vary within a single species. This variation is highly dependent on the water content of the wood. So, to use radio waves, the constant should be tested for, to be able to calculate the required exposure time. Luckily, water, which has a very high loss factor, is very susceptible to radio wave heating where as the woody tissue itself is not. This bodes well for the idea of RFV drying. (All of this will be further explained in further detail in later sections.)

As stated before, ε'' varies with frequency and temperature, as they rise the relative permittivity drops. Also, as the moisture content in certain substances, such as alfalfa, decreases so does the constant.

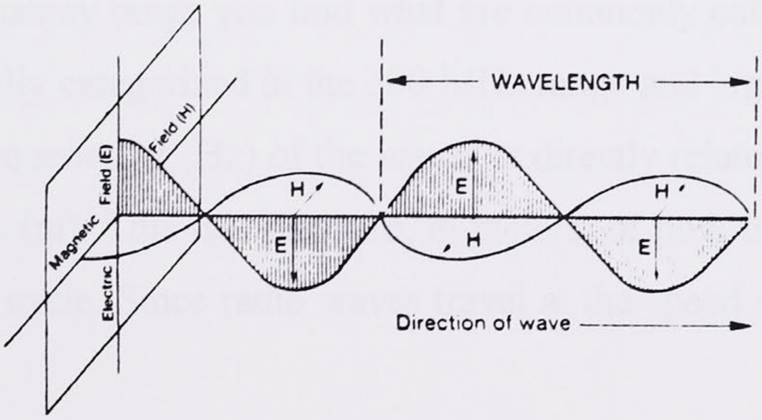
What is RF?

Before understanding Radio Frequency Drying, we must first understand the concept of Radio Frequency (RF) itself. RF is propagated in waves. Where sound waves require some form of mass to be conveyed, such as air, radio frequency waves can travel through evacuated space.

Radio waves are electromagnetic in nature. They are caused by the displacement of electric and magnetic forces. The two fields (electric and magnetic) are always perpendicular to each other.

These waves follow a sinusoidal form, where each cycle goes through 360° (see Fig 5). The frequency of these waves is measured in Hertz (Hz). This unit describes the number of cycles or times which a wave goes through 360° in one second.

Fig. 5 (Components of an electro-magnetic wave)



(Kitchen, p.7)

The frequency from a standard North American outlet is 60 Hz and depending on which source you look at, RF frequency varies from 3 kHz to 300 GHz. These frequencies are lumped into several categories (see Table 3).

Table 3 (International radio frequency designations)

Band No.	Symbols *	Frequency Range	Metric Subdivision
4	VLF	3 to 30 kHz	Myriametric waves
5	LF	30 to 300 kHz	Kilometric waves
6	MF	300 to 3000 kHz	Hectometric waves
7	HF	3 to 30 MHz	Decametric waves
8	VHF	30 to 300 MHz	Metric waves
9	UHF	300 to 3000 MHz	Decimetric waves
10	SHF	3 to 30 GHz	Centimetric waves
11	EHF	30 to 300 GHz	Millimetric waves

* E = extra; S = super; U = ultra; V = very; L = low; H = high; F = frequency
(Kitchen, p.9)

Many forms of energy travel in waves; light, X-rays and also, within the radio frequency range you find what are commonly called, Microwaves. They are usually categorized in the 300 MHz range and higher.

The frequency, f (Hz) of the waves is directly related to the wavelength, λ (m). This is a measure, in meters, of how far the wave travels in one cycle. Since radio waves travel at the speed of light, a constant of:
$3 * 10^8$ m/s, the relationship between the wavelength and frequency is:

$$\lambda = \frac{3 * 10^8 \text{ m/s}}{f}$$

This is for f in hertz and λ in meters. For example, the wavelength of 27 MHz is:

$$\lambda = \frac{3 * 10^8 \text{ m/s}}{f}$$

$$= \frac{3 * 10^8 \text{ m/s}}{27 * 10^6 \text{ Hz (/s)}}$$

$$\lambda = 11.11 \text{ m}$$

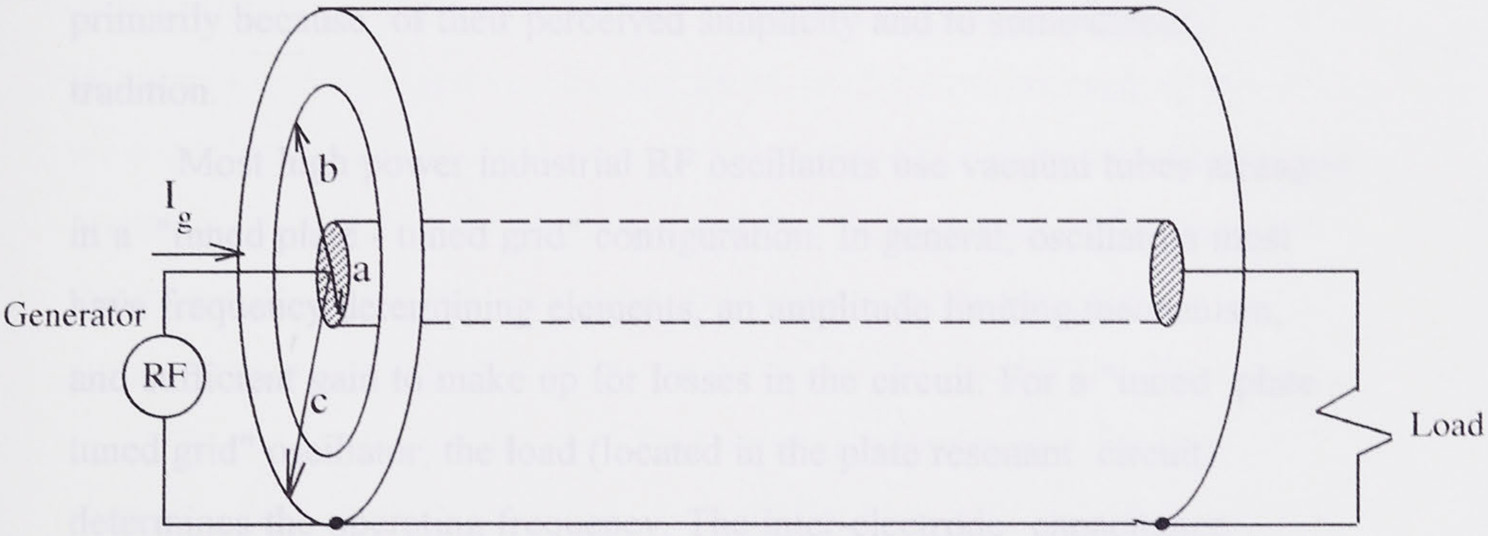
Therefore, the wavelength (λ) at 27 MHz is equal to 11.11 m. Just as a matter of comparison, the wavelength of the electricity from one's outlet (60 Hz) is about 5000 km, a very large difference. Another point of note is that 27 MHz is not a very high frequency in the radio wave band.

It has been shown that higher frequencies of radio waves tend to travel in straight lines. However, when the frequency begins to get lower the waves start to follow the contour of the earth. This is not a real factor in RF heating, as the frequencies are relatively high and the distance between the two plates is quite small relative to the wavelength.

The traditional method of transmission is a coaxial cable (see Fig. 6). Generally the outer cable is grounded so as to be shielded from the environment and so that the environment can be shielded from it (Roussy and Pearce, p.28). One of the most common places to see these cables, is in a home which has "cable" television, the frequency of which is about 30 to 300 MHz.

For over fifty years low frequency RF has been used in induction heating. Generally the frequency used in such processes is around 27 MHz. (The generator we will be using is 8 kW at 27 Mhz.)

Fig . 6 (Coaxial transmission line with load)



(Roussy & Pearce, p.28)

Radio Frequency Generators vs. Oscillators

High power radio-frequency (RF) applications require generators to convert 60 Hz alternating current input power into a time-varying RF output. For RFV drying applications where RF power generation takes place continuously for long periods of time (i.e., many hours or days), energy efficiency is of considerable importance. Over the last 50 years oscillators have generated RF power for dielectric heating applications primarily because of their perceived simplicity and to some extent, tradition.

Most high power industrial RF oscillators use vacuum tubes arranged in a "tuned plate - tuned grid" configuration. In general, oscillators must have frequency determining elements, an amplitude limiting mechanism, and sufficient gain to make up for losses in the circuit. For a "tuned plate - tuned grid" oscillator, the load (located in the plate resonant circuit) determines the operating frequency. The inter-electrode capacitance between the plate and the grid provides the necessary feedback gain. The grid resonant circuit generates a signal 180 degrees out of phase with respect to the plate and also contains the necessary circuitry to limit the overall oscillation amplitude.

Inherent weaknesses with RF oscillators are RF voltage control and relatively poor operating efficiency. Since oscillators operate in a closed loop configuration, it is difficult to test for and identify malfunctions of individual components within the loop. This is critical for maintenance diagnostics. In the case of RFV drying where the load impedance can vary by an order of magnitude over the entire drying cycle and there can be significant changes in the frequency of oscillation with possible drifts outside the allotted frequency bands. Based on past history, the electrical conditions required for oscillation often cannot be maintained throughout the drying cycle without significant modifications to the plate circuit.

Radio Frequency Amplifier:

On the other hand, an RF amplifier consists of a chain of components that begin with a frequency-stabilized oscillator or synthesizer operating at a fixed frequency and providing a low power RF output signal. This is then followed by an amplitude modulator which controls the voltage applied to the load. Next, there is the drive/high power amplifier stage and an active matching network Finally, the load itself that forms a part of the resonant output circuit, is applied. The input and output impedances of all components in the amplifier chain are all designed to be 50 Ω (Ohms).

As the load dries, the matching network compensates for the changing load impedance so that the amplifier always "sees" 50 Ω. Operating in an open loop configuration, each component of the system is designed, measured, and tested individually thereby permitting component failures to be more easily identified. This is a significant improvement to the oscillator-type systems. This directly results in reduced downtimes and much higher productivity. Also, having the capability of directly controlling RF power allows dryers to be easily operated regardless of the wood species or product dimensions.

The design of the electrodes has also progressed since the original first-generation RFV kiln designs of the 1970s'. Modern computational methods such as 3-D modeling of the electric field inside the kiln chamber allows RF engineers to observe stray capacitances and predict the electric field interaction between the electrodes, vacuum chamber, kiln carts, and the drying load of wood. This assures that dryers achieve the optimum electric fields so as to attain the most uniform drying of the product possible.

RF engineers have recently developed proprietary simulation models that have been extended to predict kiln drying performance based on the electrode design. These dynamic simulation models predict the changing dielectric properties of the material in the electric field as it is heated and dried. This allows for the modification of design parameters to optimize certain critical performance criteria such as minimizing the standard deviation of the final moisture content. The electric field model has also been used to design 50 Ω matching networks that operate between the RF amplifier and electrodes.

Safety

Though there have been tests on the effects of RF, it is hard to extrapolate the results. The experiments which are performed, are done on lab animals and, obviously, there can be no testing on humans . These tests which are done on the animals such as rats have results which are very difficult to extrapolate to humans. The size and thermal activity differ between animals and humans and this makes the results inconclusive. There have been questionnaires circulated to people who are considered to be in an area with a certain level of RF. These people are often in the military, as they can be exposed to large amounts of RF from the likes of radar.

The general frequency spectrum which is looked at is the 10 kHz to 300 GHz. From the tests which have been done, there are indications that effects tend to come in "windows". This means that in specific regions of the spectrum, different effects may be encountered. There are other factors, other than the frequency which could be factors as well, such as amplitude, modulation frequency and type. If these are also taken into account, then there become an infinite number combinations which can be studied. There is very little known because of this. At this point the one thing which can be said with confidence is that there is no significant evidence to support a given view point. Unfortunately, counter to this, there is no evidence NOT to support one either.

RF Hazards:

There are three ways in which RF radiation can affect humans:

1. Direct effects on people:

   i. Thermal effects:- heating due to RF Energy absorption. Just like the sample which would be being dried, the human body can absorb the energy and begin to increase in core temperature.

   ii. Shocks and Burns:- If one were to come into contact with an ungrounded conductor in an electromagnetic field, then a serious shock and/or burn could occur (especially with the amount of power these devices tend to be operated at.)

   iii. A possible theory, though it has yet to be proved, is that RF fields may directly affect biological tissue without any signs of heating.

2. Indirect effects:

These effects are those which may be present around electronic devices which people may need for survival, such as pacemakers and insulin pumps.

3. There is the possibility of there being effects on flammable vapors and electro-explosive devices. This problem could become a primary one if and when there are people nearby.

Ranges of Effects:

There are generally three ranges of frequency which are believed to have different effects on the human body. The first range is anything below 100 kHz. In this range, the limiting factors are the current densities in the human body and the electro-stimulation of the tissues.

Here we will go out of sequence for a moment, so as to leave the most relevant range to last. The third range is anything higher than 6 GHz. In this case, the power density limits are generally used to control the exposure.

The second range is from 0.1 MHz to 6 GHz. Here, the Specific Absorption Rate (SAR) is the relevant factor. Generally, machines which use RF generation for some function tend to fall into this category, including ours at 27 MHz.

The SAR is measured in Power per Unit Mass (W/kg) and is used to quantify the absorption of energy in tissues. Unfortunately, the SAR cannot be directly measured, but must be obtained through modeling. Also, the lower the frequency, the lower the absorption rate into the body. Basically the risk increases as the frequency increases.

The absorption does reach a maximum around the human resonance point. This tends to be between 30-80 MHz for the average adult and varies with height. Resonance occurs when the height of a person corresponds to about 0.4 wavelengths.

"Hence using 0.4 for the standard man, $\lambda = 1.75/0.4 = 4.37$ m and the frequency is approximately 300/4.37 MHz = 66 MHz." (Kitchen, p.52). Therefore the taller the individual, the lower the frequency of resonance. Also if the person is "effectively earthy" (Kitchen, p.52) then their resonance frequency will be about half that if they were not. In other words, the previous examples resonance in an earthy state (grounded) would be about 33 MHz.

There have also been tests which seem to indicate that "Hot Spots" can occur in areas such as knees, elbows and other joints. Also, testes and eyes are very sensitive areas as neither have a direct blood supply and therefore cannot easily dissipate heat.

It is estimated that a frequency of 1 to 10 GHz at a power of 1 to 1.5 kW/m^2 might be linked to causing cataracts through thermal related causes. The tests for cataracts have been historically performed on rabbits. Again, there have been studies done in people, primarily those in the military working with radar but the results have been inconclusive, for various reasons. Unfortunately, but for obvious reasons, there has been little testing and therefore little information on the effects of RF on the human testes.

Development of Standards/History of Regulations:

It became apparent 40 years ago that some form of restrictions were needed. So in 1957 Bell Standard set a basic limit of 1 mW/cm^2. This limit applied to unlimited exposure times. However, it was also recognized that the acceptable limit could increase as the time in the presence of the radiation decreased. Shortly after this, the concept of time-averaging exposure levels was introduced. This idea was that one could exceed the limit, which had been relaxed to 10 W/cm^2, as long as the time-average did not exceed six minutes.

The standards were and are constantly being re-evaluated. In 1982 the American National Standards Institute (ANSI) recognized the SAR to be the limiting factor, and they also noted the whole body resonance was a region where the absorption rate was much higher. So, with a factor of safety, they decided to make the threshold 0.4 W/kg.

To date, many different institutions have been investigating these levels and publishing their own ideas but they are all very similar, with some small changes between each. Basically, today, the standards are the same as from 1982. The limit is still 0.4 W/kg and the time-average remains at $1/10^{th}$ of an hour. The whole body resonance is set at 1 mW/cm^2 and the time average is based on 10 mW/cm^2.

Radio Frequency Drying History

The use of radio-frequency (RF) as a heating method in the forest industry is not new. It has been extensively used over the last 50 years for applications such as wood veneer heating/drying and adhesive curing. Research has also been carried out to investigate the possibility of combining RF heating with a heated air flow: a semi-conventional drying system. The results have shown mixed success and this technology has found limited application. In the early 1970s', RF heating was combined with a vacuum system for the first time, with the promise of revolutionizing wood drying. There were unsuccessful commercialization attempts made by North American manufacturers such as Power Dry Inc., Drywood Corporation, and General Wood Processors. This is primarily due to a lack of a fundamental technical understanding of RFV drying. Also, the markets general fear of anything new is another possible reason for its failure.

However, the forest industry has shown a renewed interest in the RFV drying of wood products since the successful demonstration project which was conducted by the Council of Forest Industries (COFI) from 1991 to 1994. The COFI project concluded that RFV drying, results in the shortest drying times and minimal product degradation. This results in an exceptionally high quality, uniformly-dried, bright and even-colored lumber. Most importantly, it was demonstrated in a full-scale production environment that commercial drying technology could be built and cost-effectively dry larger dimension softwood and hardwood products such as timbers.

Currently, in Canada, the University of British Columbia's (UBC) wood science department is involved in RFV testing. Also there are new companies emerging with RF heaters and dryers such as Norax Heating Systems, based in Quebec City and Heatwave Drying Systems from Vancouver, British Columbia.

Principles of Radio Frequency Operation

In a radio frequency drying system the RF generator creates an alternating electric field between two electrodes. The material to be dried is conveyed between the electrodes where the alternating energy causes polar molecules of water to continuously re-orient themselves to face opposite poles much like the way magnets would move in an alternating magnetic field. The friction of this movement causes the water in the material to rapidly heat throughout its entire mass. Below is a depiction of a radio frequency drying system with a product between the electrodes. Polar molecules within the product are represented by the spheres with "+" and "-" signs connected by bars (see Picture 1.1).

The amount of heat generated in the product is determined by the frequency, the square of the applied voltage, dimensions of the product and the dielectric "loss factor" of the material which is essentially a measure of the ease with which the material can be heated by this method. Since water is far more receptive to RF than other molecules usually found in wood, glass or ceramics, the water is preferentially heated and then diffused to the surface. The reduction in loss factor as the material dries out provides a valuable safeguard against overheating. This method of drying, therefore, is ideal for applications where uniformity of product dryness is an important requirement.

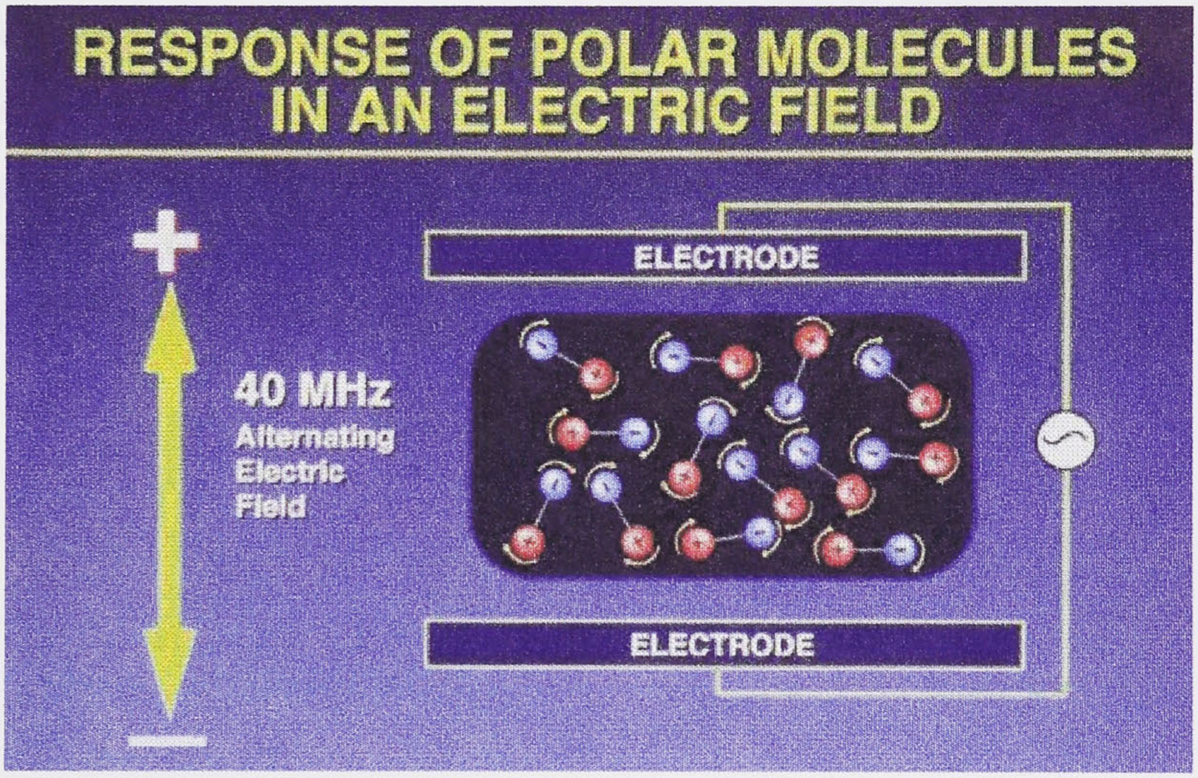


Fig.1.1. Operating principle of a radio frequency dryer (Radio Frequency Co.)

Candidates for RF drying

The more difficult an item is to dry with convection heating, the more likely it is to be a good candidate for RF drying. Materials with poor heat transfer characteristics, such as ceramics and glass fibers, have traditionally been problem materials when it comes to heating and drying. Radio frequency heats all parts of the product mass simultaneously and evaporates the water in situ at relatively low temperatures usually not exceeding 180 °F. Since water moves through the product in the form of a gas rather than by capillary action, the migration of solids is avoided. Warping, surface discoloration, and checking associated with conventional drying methods are also avoided.

Benefits of Radio Frequency Vacuum Drying

In an RFV dryer, wood products are subjected to an RF field that heats the wood from the inside (similar to the process involved in microwave ovens) while a continuous vacuum effectively reduces the boiling temperature and extracts the water. This process has led to many exciting competitive advantages:

High quality:

Wood is dried at lower temperatures and in a controlled environment. This leads to higher yields and less checking degrade and a significant reduction in warping of the timber. Also, a lower amount of resin exudation onto the surface of the wood occurs.

Quick market reaction:

With fast drying times, a minimum of green inventory is required. Producers can set up Just-in-Time production allowing them to react quickly to ever-changing market conditions.

More lumber:

There is always shrinkage involved when drying wood. However, with the RFV drying technique, this is greatly reduced in comparison to conventional methods. Since wood is sold by volume and not by mass, this leads to economical advantages.

Elimination of staining problems:

With RFV drying, water in the form of low-temperature steam leaves the ends of the lumber, not the sides, eliminating staining problems often seen with some species.

Bright and even-colored lumber:

Next to no chemical oxidation occurs during drying, allowing the wood to retain its natural color and beauty and leaving it with the appearance and texture of freshly cut wood.

No heat-related discoloration:

Lumber in conventional kilns is vulnerable to severe degradation and/or over-drying due to the uneven application of heat. This problem is almost completely eliminated due to the uniformity of heating in RFV systems.

Flexible design:

Flexible design allows there to be custom drying systems, useful for almost any size load. This is then perfectly suited for any wood producer's unique drying requirements.

Preserved wood products:

Dryers are ideally suited to help preserve wood products by introducing wood preservatives into the chamber during the drying cycle and accelerating the chemical fixation of waterborne preservatives.

More uniform drying than conventional kilns:

Differences in the initial moisture contents throughout the stack of the wood equalize during the RFV process, leaving a very uniformly dried lumber. This is true through out one piece of wood as well as through out the entire stack.

Unparalleled drying flexibility:

With RFV drying mixed dimensions, species and grades being dried in a single kiln charge is quite viable; therefore allowing for very small orders to be dried with larger more standard loads.

Energy efficiency:

RFV kilns are two to five times more energy efficient than conventional kilns.

<u>Easy material handling - solid packages</u>:

There is minimized lumber handling by eliminating the need to "sticker" the wood (a labor intensive process). Wood is loaded in solid packages and once dried, manufacturers can ship it directly from the RFV kiln without having to do any repackaging. With a refined vertical electrode configuration, material handling becomes a breeze!

<u>Conditioning not required</u>:

As there is little residual stress left in the wood after RFV drying, no stress relief or conditioning is required.

<u>Self monitoring/automatic</u>:

With a self-monitoring system and automatic process control mechanisms, constant supervision is not required. As the product dries, the RF output and vacuum pressure are automatically adjusted according to preset drying schedules ensuring optimum drying conditions. There are many programmable logic controls (PLC) which are personal computer based, that are now available for the monitoring/control systems for RFV drying processes. Spectrum Digital Systems, Siemens and General Electric are some of the companies that are currently supplying industry quality "soft" PLCs.

Proven technology:

RFV kilns utilize proven 50 Ω RF amplifier technology used by radio broadcasters worldwide. Costs for parts and service are quite low relative to kiln drying.

Environmental:

With conventional technology, byproduct steam from the drying process is allowed to escape untreated into the atmosphere. In contrast, RFV dryers work in a closed cycle, condensing the steam and converting it into water. If necessary, it can then be treated to allow its disposal into the municipal sewage treatment system. RFV kilns fully implemented across Canada could reduce environmental CO_2 pollution by 50,000 tons per year (Heatwave Drying Systems, 1996).

Previous Work

Alfalfa Drying

Alfalfa has been force air dried for almost a century. This has been done with very high temperatures with good success, with the exception of the uniformity of the drying. This leads to either the stems not being as dry as the leaves or to heat damage to leaves, occurring towards the end of the process. Murphy A., et. al., noted that dielectric heating at various radio wave frequencies had been done for many agricultural products, with the exception of forage crops.

They first had to decide upon the economic feasibility of such a project. So, taking into account the amount of energy required to remove the necessary water from the alfalfa and the efficiency of typical RF ovens, they concluded that it would not be economically feasible to use RF power as the primary drying source. This led them to the idea of having RF as a supplementary power to the standard forced air technique.

Using an RF generator which was capable of 1.5 kW at 27 MHz, they built a chamber which used PVC pipe to transport the heated air and mesh electrodes. This allowed for the air to pass through the sample while being influenced by the radio waves. Using this set-up, they performed three tests; two were just forced air at different temperatures, and the third was a combination of both forced air (at the same temperature as that of the lower of the first two tests) and radio frequency power.

The results showed a less than stellar improvement by the RF power. "There is no indication that the eveness of drying improved by the supplementation of forced-air drying with RF power throughout the drying cycle." (Murphy, A., et. al. p226). There were indications that the orientation of the alfalfa to the field was important. Also, the ends of the stems tended to be much drier than the middle sections. Generally, however, they concluded that it is not economically feasible to use RF power as a supplementary source in the process of drying alfalfa.

RF Drying Uniformity in terms of: Moisture Content, Temperature and Resin Distribution

Though the kiln drying method is still probably the most used and widely accepted one, there has been some serious interest in radio frequency vacuum drying (RVD). Yasushi Kanagawa, et. al. Decided to investigate the difference in uniformity of temperature, moisture content and surface resin deposition between these two techniques.

So using a 2 kW at 13.56 MHz radio frequency generator they tested large sections of Douglas-fir. These wood sections were dried to different moisture contents and measurements were taken at each of these different levels.

They found that the time to dry the wood samples was much lower in the RVD than in the standard kiln drying method. Also, they found that the temperature in the centre was higher than that on the surface which aided in the moving of the water to the surface. This made for a much more evenly distributed final moisture content. The resins seemed to be distributed more throughout the wood as well, instead of being deposited on the surface. It was not entirely understood as to why this occurred. However, it is a favourable result to have the resins not become exuded onto the woods surface.

Generally they concluded that the use of RVD drying for this species of wood was a beneficial and worthwhile endeavour.

RFV Drying of Eucalyptus Timbers

Eucalyptic timbers are one of the harder woods to dry. They need to be put through a very slow process so as to prevent checking and other forms of degradation. Rozsa and Avramidis from the University of British Columbia (UBC) decided to try and use Radio Frequency Vacuum drying to try to see if the drying process could be accelerated with little effect to the quality of the wood.

Using a 10 kW RF generator, running at a fixed frequency of 13.56 MHz they built a cylindrical kiln attached to a water sealed vacuum pump. Performing three tests on two sizes of planks, they assessed the quality of the dried samples.

They found that the orientation of the boards (how they were cut) greatly affected the time of drying. However, the final moisture content of all samples was similar. Also, there was limited surface and internal checking which showed an improvement over conventional methods.

This project was done on a very small scale but the results are quite applicable to more industrial settings. They showed that there was possible improvements made by changing different variables such as: the orientation; the vacuum power; and the drying schedule.

Dielectric Heat Generation Theory

As previously seen, the application of an electrical field across a dielectric material causes a movement of distortion of the alignment of the electrons in the molecules of the materials. The process is reversed as the applied field alternates. The work involved during this process is the useful heat developed in the material. If the electrical characteristics of the material are consistent, then the heat generated will be uniform through out the material.

The depth of penetration of RF waves can be given by (Erickson 1995) :

$$d = \frac{c_v}{2 * \pi * f * \tan\delta * \sqrt{\varepsilon'}} \qquad (1.1)$$

d = Effective depth of penetration (mm)

c_v = Speed of propagation of a wave in vacuum ($4.6 * 10^{11}$ mm/s)

f = Frequency in Hz

ε' = Relative dielectric constant

$\tan\delta$ = Material power factor

Table 4 shows the effective depth of penetration for some materials that can be heated through RF waves.

Table 4 (Effective depth of heating for typical materials in inches)

	Radio Frequency		Microwave	
Material	13.5 MHz	40.5 MHz	2.45 GHz	22.125 GHz
Bakelite	1546	515	10.2	1.1
Nylon	1391	464		
Paper	696	232	3.8	0.4
Glass	4464	1488		
Polyethylene	686979	228993	1549	171
PVC	6956	2319	15.3	1.7
Pyrex	18543	6181	59	6.5
Rayon	3974	1325	17	1.9
Water	772	257	013	0.014
Wood, wet	3617	1206	22	2

(Erickson, p.103)

<u>Power Development</u>:

The power generated within a material subject to RF waves can be calculated with (Erickson 1995):

$$W = \frac{5.55 * V^2 * f * \varepsilon' * \tan\delta * A}{t * 10^{14}} \qquad (1.2)$$

Where:

W = Power generated in work (W)

V= Voltage applied across electrodes (V)

A= Area of material between electrodes (mm^2)

t = Thickness of material (mm)

From this equation, the best way to increase power is by increasing the voltage applied to the system, because it is related by its square. RF installations usually do use a 2 or 3 phase high voltage input. However, there is a practical limit to the availability of the power. For example, if the voltage is sufficiently high, it may break down air.

Table 5 (Effect of loss factor and frequency on power in Watts per cubic inch)

	Loss Factor (ε″)	Power Generated for different frequencies of RF waves		
		13.5 MHz	27 MHz	40.5 MHz
Amber	0.0058	0.69	1.4	2.1
Bakelite	0.18	21	43	64
Cotton	0.03	3.6	7.1	11
Glue	0.25	30	59	89
Paper	0.4	48	95	143
Polyethylene	0.0004	0.05	0.10	0.14
PVC	0.04	4.8	9.5	14.3
Water	0.36	43	86	128
Wood(dry)	0.04	4.8	9.5	14.3
Wood(wet)	0.1	11.9	24	36

(Erickson, p.105)

The multiple (ε'* tan δ) is called the "“loss factor” (ε''). As one can see from the above equation, the higher the loss factor, the more heat is generated within the material. However, a very high loss factor indicates a poor insulator and then there may be a danger of current leakage. The recommended limits for RF heating loss factor in RF heating are $0.01 < \varepsilon'' < 1.0$.

Consideration of Air between Electrodes:

Usually the material to be dried is not in contact with both electrodes. There is often an air space between the electrodes and the dielectric. When this is the case, the capacitance of air must be considered.

The Capacitance of air, is given by:

$$C_a = \varepsilon_o * \varepsilon_{ra} * (A/d_a) \qquad (1.3)$$

Where:

C_a = Capacitance of air (F)

ε_o = Dielectric constant of vacuum ($8.84 * 10^{-12}$ F/m)

ε_{ra} = Relative dielectric constant of air

A = Area of plates (m^2)

d_a = Thickness of air layer (m)

The Capacitance of the work, is given by:

$$C_w = \varepsilon_o * \varepsilon_{rw} * (A/d_w) \qquad (1.4)$$

Where:

C_w = Capacitance of work (F)

ε_{rw} = Relative dielectric constant of work

d_w = Thickness of work (m)

The work and the air capacitance are in essence in series to the applied voltage across the plates.

Therefore:

$$E_a * 2 * \pi * f * C_a = E_w * 2 * \pi * f * C_w \qquad (1.5)$$

Where:

E_a and E_w are the voltage drops in both air and the work

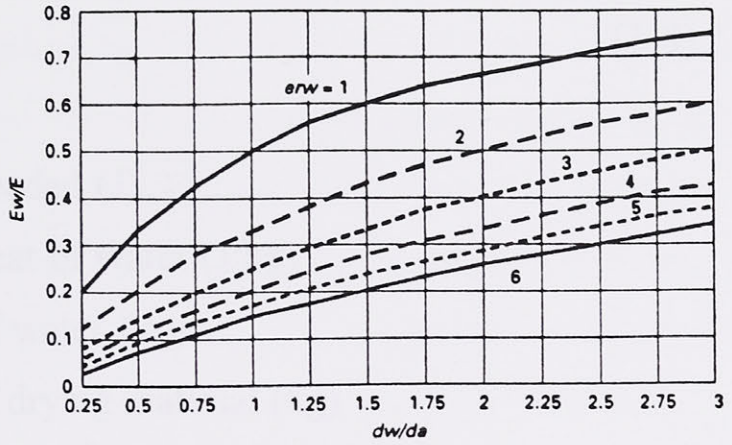
Also, the total voltage applied, $E = E_a + E_w$ (1.6)

Substituting equations 1.5 and 1.4 in for E_a and E_w, and solving for E_w gives (Erickson 1995):

$$E_w = \frac{E}{\left[\varepsilon_{rw} * d_a / (\varepsilon_{ra} * d_w)\right] + 1} \qquad (1.7)$$

Figure 6 shows the effect of an air layer on the voltage across the work, for various materials which have relative dielectric constants of 1, 2, 3, 4, 5, and 6. A quick approximation can be interpolated for materials with different dielectric constants from the graph (see Fig. 7).

Fig. 7 (Effect of Air layer on voltage across load)



(Erickson, 1995)

Power Requirements and Drying:

Most drying processes are slow and wasteful due to the difficulty in supplying the heat of vaporization of the water. This is especially true when the material to be dried is bulky and a poor conductor of heat. Since RF drying heats materials uniformly, the result is a faster, more reliable and more efficient method.

The use of a reduced atmosphere or vacuum, allows for a lower temperature, therefore materials that are sensitive to thermal effects, can be handled easily and safely. When designing, it must be noted that the properties of air are different under vacuum conditions and the proper constants must be used for calculations.

The power required, is simply an addition of all the energy losses in the system and the work done to evaporate of some liquid (in most cases water).

$$Q = H_v * M_w + (C_{pw} * M_w + C_{pm} * M_m)\,\Delta T + \text{Losses in the Chamber} \tag{1.8}$$

Where:

Q = Energy needed (J)

H_v = Latent Heat of water (J/kg)

M_w = Mass of water (kg)

M_m = Mass of drying material (kg)

C_{pw} = Specific heat of water (J/g·°C)

C_{pm} = Specific heat of material (J/g·°C)

ΔT = Change in temperature (°C)

It has been experimentally found (Davis, Simpson 1979) that the power in watts required for general RF drying is given by:

$$P = \frac{H_v W_1 + (K_1 W_1 + K_2 W_2)(\Delta T)}{0.6442\tau} \tag{1.9}$$

Where:

P = Power (W)

H_v = Heat of vaporization (J/kg)

K_1 = Specific heat of water (J/g·°C)

K_2 = Specific heat of material (J/g·°C)

τ = Time (hours)

W_1 = Mass of the water (kg)

W_2 = Mass of the load (kg)

Design of Parallel Plate Applicator

Parallel plate applicators are the simplest and most commonly used in the RF industry. At the edges of the plates, there will be 'fringing fields', which make the surface charge distribution non-uniform. Also in practice, for large loads with large plates (in the order of meters), the plate voltage will not be constant. Decreases in magnitude away from the feed point will occur.

When designing a larger scale dryer, there are many tricks used by the industry to increase voltages at the ends of the plates. One is to distribute low capacitance pH to μH inductors (possibly, 3 or 4 turns, 10 to 20 cm in diameter and height, respectively) around the plate's edge (Roussy & Pearce 1995).

However, for the design of the test scale dryer, we will treat the plate applicator as though it is ideal and has a uniform potential. Also, the 'fringing fields' will be ignored, treating them as uniform. For most load configurations, where the load will be inside the perimeter of the plate, these assumptions are quite realistic (Roussy & Pearce 1995).

Under the uniform conditions, a continuous load of thickness c, with an air gap of length d, results in a one dimensional Laplace solution for voltage in the z direction, (see Fig. 2.1).

$$\nabla^2 V = \frac{d^2V}{dz^2} = 0 \qquad (2.1)$$

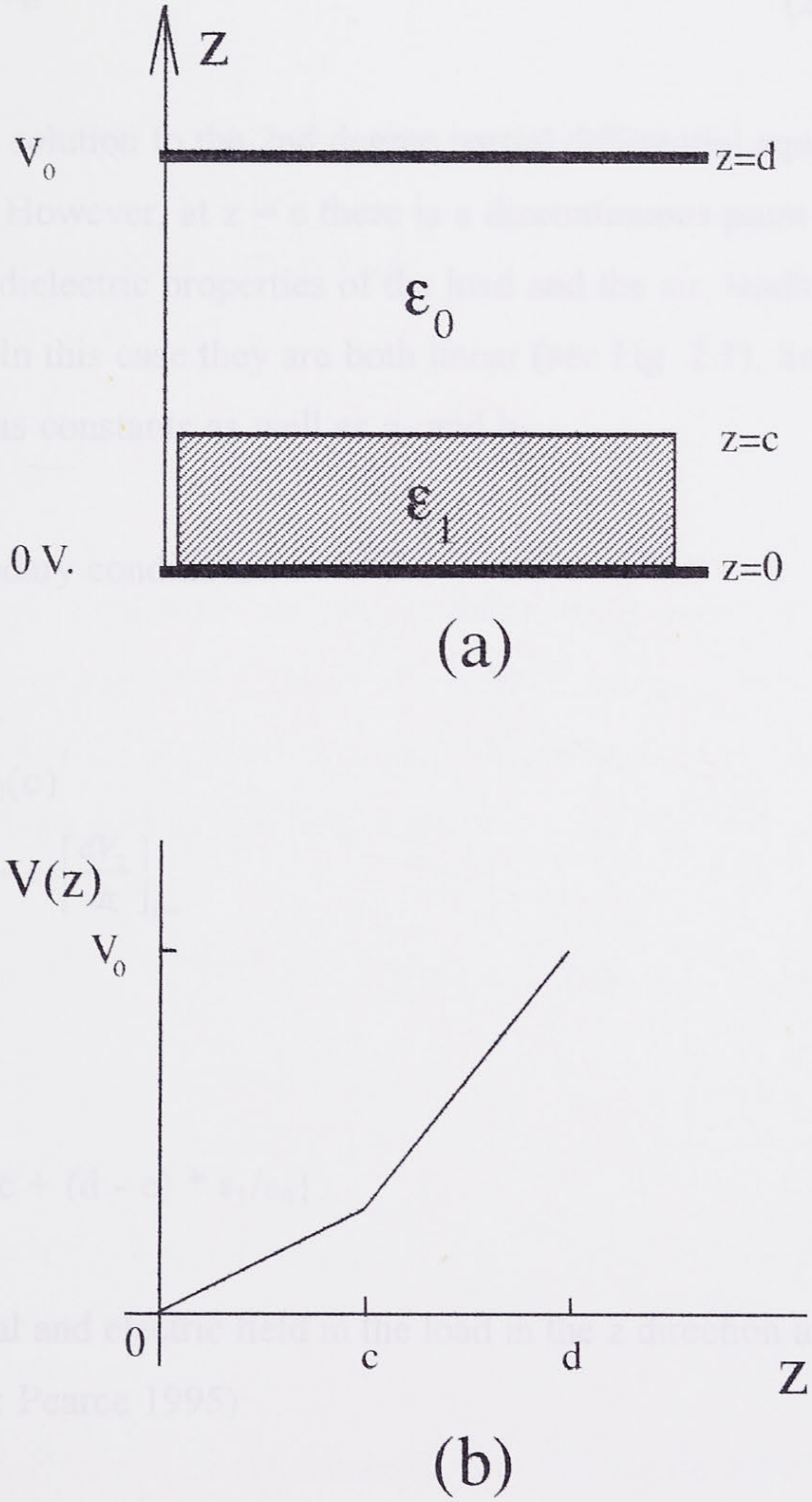


Fig. 2.1. (a) One dimensional Model of applicator.
(b) Laplace equation of planar workpiece solution

This means that:

$V(z) = az + b$ (2.2)

The solution to the 2nd degree partial differential equation has 2 constants. However, at z = c there is a discontinuous point due to the change in dielectric properties of the load and the air, leading to two solutions. In this case they are both linear (see Fig. 2.1). So there will be an a_1 and b_1 as constants as well as a_2 and b_2.

With boundary conditions:

$V_1(0) = 0$

$V_2(d) = V_o$

$V_1(c) = V_2(c)$

$$\varepsilon_1 \left[\frac{dV_1}{dz}\right]_{z=c} = \varepsilon_2 \left[\frac{dV_2}{dz}\right]_{z=c}$$

We get:

$a_1 = V_0 / \{c + (d - c) * \varepsilon_1/\varepsilon_0\}$.

So potential and electric field in the load in the z direction are given by (Roussy & Pearce 1995):

$$V_1(z) = \frac{(\varepsilon_0 / \varepsilon_1) V_0 z}{(d-c) + (\varepsilon_0 / \varepsilon_1) c} \qquad (2.3)$$

$$E_1 = \frac{-(\varepsilon_0 / \varepsilon_1) V_0 z}{(d-c) + (\varepsilon_0 / \varepsilon_1) c} a_z \qquad (2.4)$$

Where:

E_1 = Field in the load

and the capacitance per unit area is:

$$C_{total} = \left[\frac{1}{C_1} + \frac{1}{C_2} \right]^{-1} = \frac{\varepsilon_0}{(d-c) + (\varepsilon_0 / \varepsilon_1) c} (F / m^2) \qquad (2.5)$$

From the solutions we can see that there is quite a bit of voltage drop in the air. For a given V_o, the load's field increases to V_o/c as the air gap decreases ({d - c} approaches zero). However, the impedance given to the generator degreases as this field increases.

$$Z_{system} = V_o / \{E_1 * j * \omega * \varepsilon_1 * \Delta x \Delta y\} \qquad (2.6)$$

Where:

$\Delta x \Delta y$ = Area of the plate

j = Unit vector in the j direction

ω = Frequency of the current

Therefore, it is to our advantage to limit or eliminate the air gap between the load and the plates. In our case we will have no air gap because the applicator's lower plate will be adjustable. Also, for future experiments, the field can be manipulated to suit those experiments' specific needs.

For a Drying space of 0.6 x 0.6 x 1.0 cubic meters (volume between plates = 0.36 m^3), The power generated given by equation (Erickson, 1995):

$$W = \frac{5.55 * V^2 * f * \varepsilon' * \tan\delta * A}{t * 10^{14}} \qquad (1.2)$$

Assuming that The Callanan Generator with a 50 Ω, impedance matched coaxial cable, can supply 2500 Volts RMS between the plates at 27.12 MHz:

$$W = \frac{5.55 * 2500^2 * 27.12 * 10^6 * 0.1 * (600 * 1000)}{(600 * 10^{14})}$$

= 940.73 W

This gives rise to the following power density:

Power density = (Power developed) / (Volume between the plates)
Which is roughly 2.6 kW/m^3. Industrial dryers for wood can have power densities up to 10 kW/m^3.
Note that this can be modified by decreasing the distance between the plates. For example, for a 300 mm distance between the plates, we attain a power density of 10 kW/m^3.

Drying time Calculation:

$$P = \frac{H_v W_1 + (K_1 W_1 + K_2 W_2)(\Delta T)}{0.6442\tau} \qquad (1.9)$$

The energy spent in elevating the temperature of both the water in the load and the load itself can be neglected when calculating the drying time, since it is expected to last several hours (at a 2.6 kW/m^3 power density).

It should be noted at this point that the actual drying time is best determined through an actual experiment. The Latent heat of water will, depending on the thermodynamic conditions in the chamber, be quite a bit lower than the estimated value used in Equation 1.9.

Equation 1.9 reduces to (Davis, Simpson 1979):

$$P = \frac{130 W_1}{\tau} \qquad (2.7)$$

With 940 W of power generated within the drying chamber, and Douglas Fir (density 420 kg/m^3 at initial conditions) as the load, with an initial moisture content of 30 %, by mass, and with a final requirement of 7 %, the time to dry will be approximately:

Total water to be removed = Initial water content - Final water content
= (0.36 m^3 * 420 kg/m^3 * 0.30)
- (0.36 m^3 * 420 kg/m^3 * 0.07)
= 34.7 kg (of water)

$$\tau = [(130)(34.7) / (940.73)] \text{ hrs}$$
$$= 4.8 \text{ hrs}$$

The proposed arrangement of the parallel plates are illustrated in Figures 2.2 through 2.4.

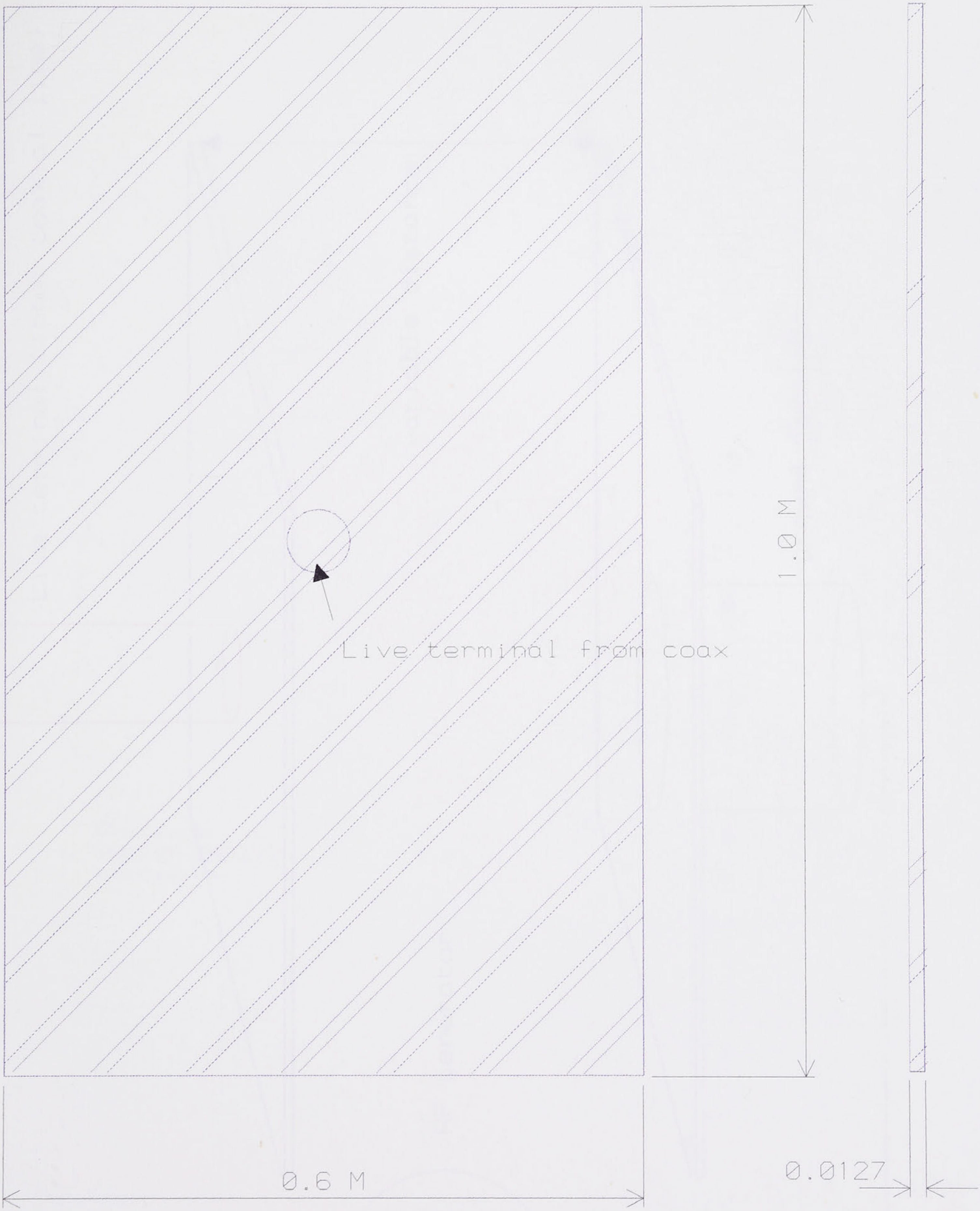


Fig. 2.2. Top Plate
Scale 1:5

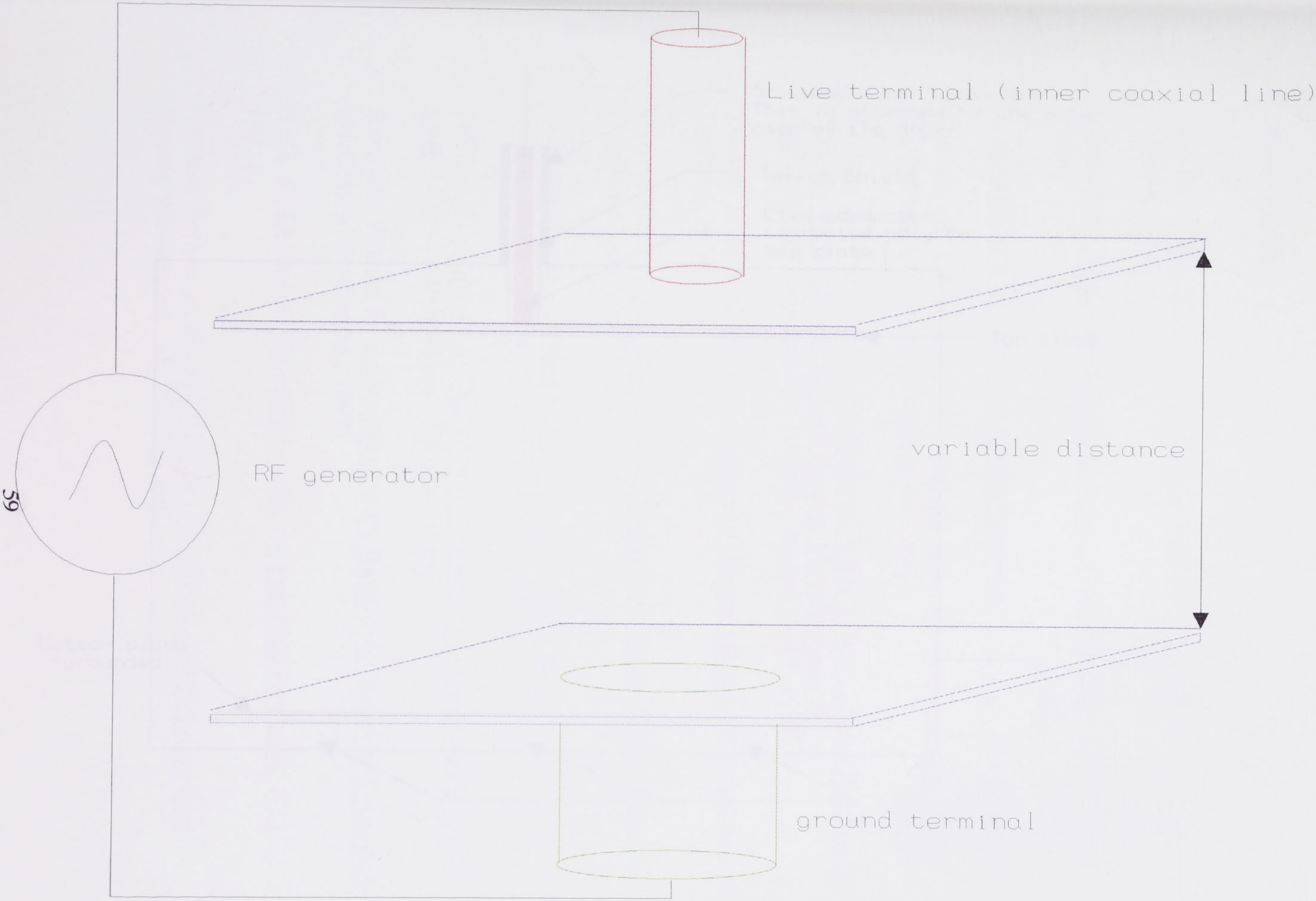


Fig. 2.3. Parallel Plates illustrated with generator.

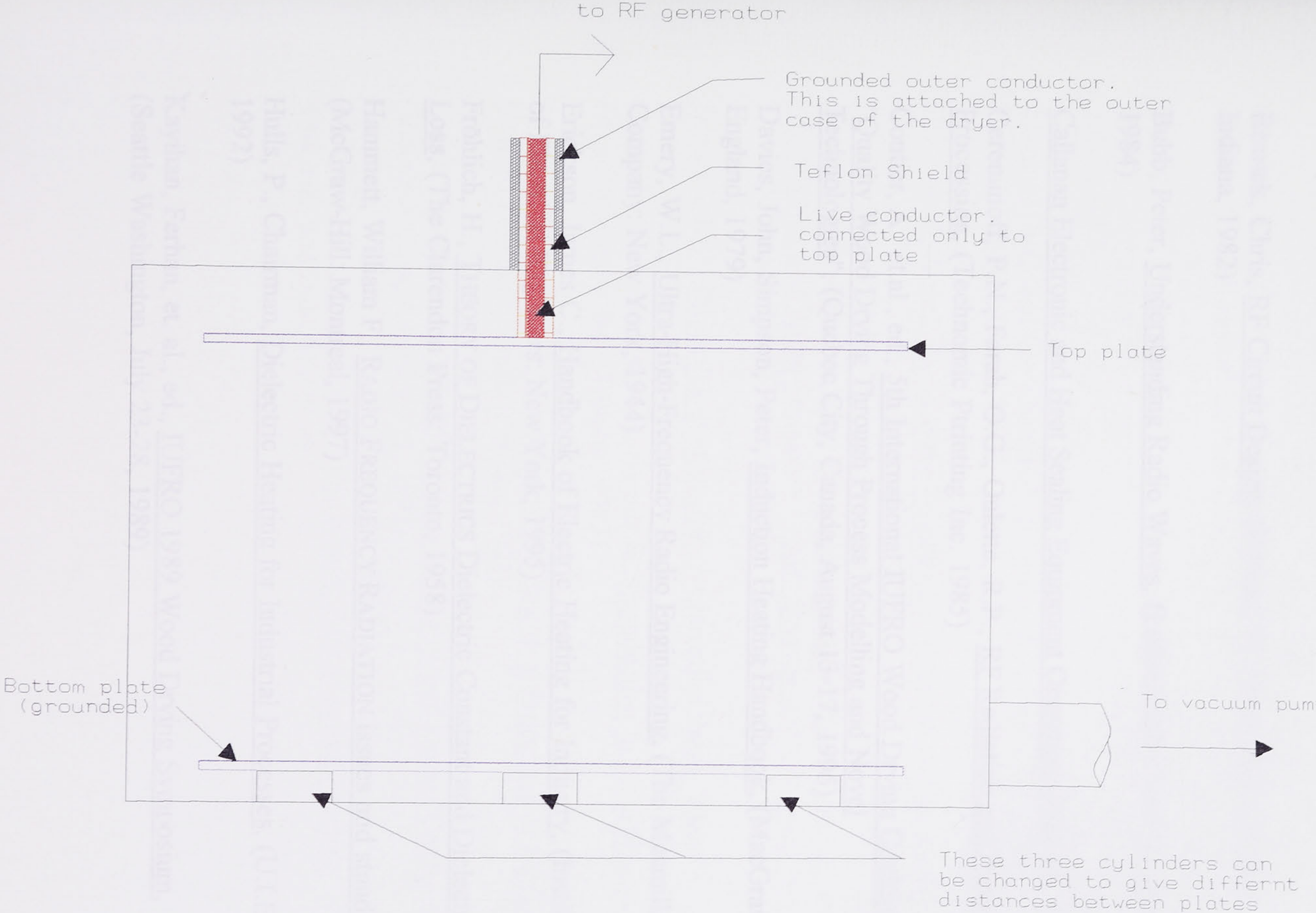


Fig 2.4. Side view of proposed plate arrangement
scale 1:8

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