Radio Frequency Dielectric Heating re-emerges as an Effective Process in the Food Industry

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ABSTRACT

Radio Frequency Heating and Drying has been utilized in the Food Industry since the early 1960's.

Until recently, with the exception of a number of enthusiastic companies who were quick to recognize and exploit the benefits to their production quality and costs, the value of this technology has been largely overlooked by most food processing companies and is largely unknown amongst younger food technologists.

The author believes that a combination of a poor understanding of the technology, its benefits, and how to apply it, combined with poor engineering implementation and unsubstantiated claims made by some manufacturers of the equipment has conspired to limit the wider adoption of this technique in Food processing.

Increasing energy costs, together with a drive for 'greener' and more energy efficient technology have heralded a recent resurgence in the use of RF for Drying and other RF thermal treatment processes in the Food Industry.

The paper aims to shed some light on the reasons for the previous lack of enthusiasm for RF heating and drying, and to demonstrate some of the applications and benefits which are now being obtained.

1. A BRIEF HISTORY

Probably well over a million Industrial RF heating installations for various applications have been sold worldwide in the last sixty years.

Radio Frequency Dielectric Heating was originally introduced into the Food Industry in the UK around the beginning of the 1960's.(ref. 1 and 2). Early machines were relatively small, air cooled and had simple electrode applicators. They generally suffered from fairly poor reliability, and poor performance.

Strayfield Limited was founded by John Holland in 1969 to supply equipment for Post Baking of Biscuits and has been the market leader in RF dryers in the food industry for many years now, having a total of around 500 dryers installed in this industry alone. We have also installed several thousand other RF machines in the Textile, Fiberglass, Paper Converting, Plastic Welding, Pre-heating and Woodworking markets.

Over the years, several other companies have attempted to enter the RF food processing market. Virtually all of these have disappeared again after a relatively short time. Industrial RF heating at high power is a very specialized field and relies to a large extent on knowledge gained through field experience.

Very little really useful information on this application has been published, apart from the most basic theory. Often, much of the information available, including that contained in patents has been found to be very simplistic. In many cases, it does not work in practice or is just plain wrong.

2. HOW RF WORKS

Basic Theory

RF heaters and microwave ovens offer direct or volumetric heating. The simplest form of RF applicator consists of two metal plates which form an electrical capacitor (see Fig. 1 below). The material becomes a 'lossy' dielectric (hence the alternative name of 'Dielectric Heating') and absorbs energy from the RF Generator which is connected across the two metal plates (generally referred to as 'electrodes').

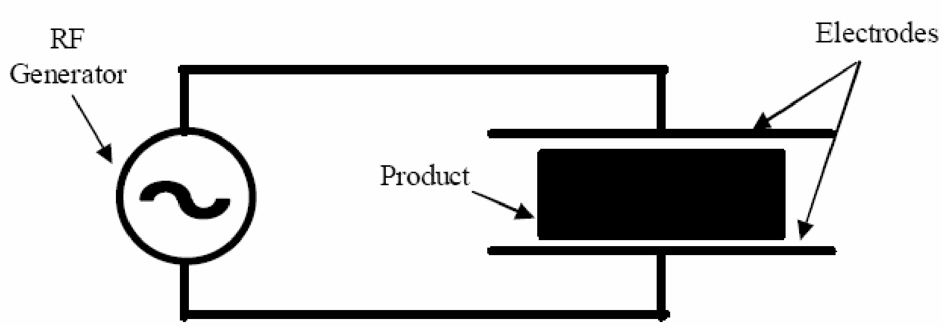


Fig. 1 Simple RF Heating Set-up

For most products, we are dealing with water molecules, which are ionic in nature, although the technique applies to other ionic substances too. The RF heating process depends upon the ionic conductivity of the material being heated. The effect is analogous to that of two bar magnets. If two like poles are placed together, they repel each other. If two unlike poles are placed together they attract. Similarly, polar molecules have positively and negatively charged ions. If the two electrode plates, between which the material is placed, are charged positive and negative respectively, the molecules will tend to line up all in one direction. If the charge on the plates is then reversed, they will tend to flip around and line up in the opposite direction. Fig. 2 shows the way in which this happens.

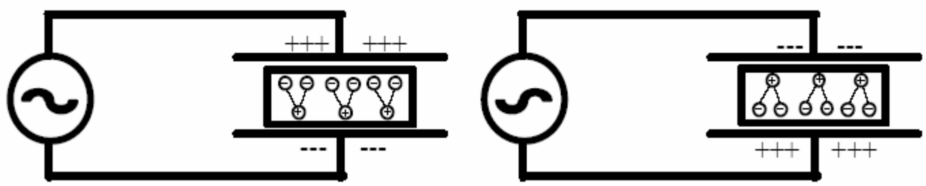


Fig. 2 Reversal of polarity causes the material to heat

Reversing the charge causes the molecules to rub against one another. This causes 'frictional' heating. The heating rate will increase as the frequency of reversal of the charge on the plates is increased. Typically this is caused to occur at high frequencies in the Megahertz range. The RF frequency bands used in dielectric heating are centered on 13.56MHz, 27.12MHz and 40.68MHz. These frequencies are reserved specifically for use by Industrial, Scientific and Medical purposes (I.S.M.) to avoid possible interference with other users of the radio spectrum (i.e. broadcasting, satellites etc.). There are very good technical reasons why most companies in the field use the 27.12MHz band, and these will be dealt with later on in this paper.

3. BARRIERS TO THE INTRODUCTION OF RF

Having spent the last 30 years in this line of business, I believe that I am probably reasonably well qualified to venture an opinion on the relatively slow adoption this technology in the Food Industry. I would suggest that even today, most food industry technologists either have never heard of RF, or, if they have, they consider it as a last resort when all else fails. Why is this?

3.1. *RF drying - a 'Black Box' Technology for Boffins in White Coats?*

Strayfield supplies RF drying equipment to many industries. In the Textile industry for example, dryers are used to dry bobbins of Textile yarn after the coloring (dyeing) process. The RF dryer was introduced into the textile Industry by Strayfield only in the late 1970's. Although this was much later than its original introduction into the food industry (circa 1959), RF textile drying has gained universal acceptance and is now the preferred method for drying over conventional hot air dryers. For over 15 years now, textile people have asked us a very different question from that asked by the food industry. They ask not "how does it work?", but rather, "what capacity RF dryer do I need and how much will it cost?" There are now well over 1000 RF textile dryers in China alone, several of our clients have over 20 dryers on the same site.

This is definitely not the case in the food industry. During my many years spent in the field, I have found that many people who come into contact with RF appear to have a natural antipathy to using it. Quite frequently this is due to either fear, ignorance or in some cases, a previous bad experience with a supplier who did not understand the RF technology properly. Purchasing the wrong machine usually results in problems with reliability, efficiency, poor performance, fires or even worse.

For example, several journal articles, scientific papers and patents have been published which claim to have discovered a so-called "new" technique that enables RF to be used with metal oven bands, or metal pans and the like (ref 3). These are generally based upon simple, small scale, non-representative experiments under lab conditions with brand new, *clean* materials. What the people writing these papers usually fail to understand, are the basics of high frequency, high current, high voltage operation UNDER PRACTICAL, INDUSTRIAL, OPERATING CONDITIONS.

Only experience allows one to appreciate that whilst these ideas may indeed work under laboratory conditions, in practice, it does not work reliably (ref. 4) and often the radiated emissions from the oven exceed the permitted levels (ref. 5). Also the energy losses are high, and the power transfer efficiency is low and this compounds the problem by causing overheating and burning in the RF circuitry. Therefore it is very important to select the right RF supplier in the first place.

3.2. *Microwave Heating*

Microwave technology probably does not seem to fare quite as badly as RF in this respect. I believe that there are several important reasons for this.

3.2.1. *Why do people opt for Microwaves in the first instance, instead of Radio Frequency?*

Today, virtually every house, factory cafeteria, and convenience store has at least one microwave oven. For many years, small Microwave ovens have been relatively inexpensive. Typically today, a domestic microwave imported from China can easily obtained off- the-shelf for very little more than a hundred dollars. Most manufacturers have at least one microwave oven in their R&D facilities. Therefore, when food technologists are developing products it is natural to take some of the product, slap it in the microwave, switch on and "see what happens"!

If this very crude test shows signs of success, then the thought pattern goes - "OK – now I just need a bigger Microwave for the final process". It is clearly a natural progression to consider a scale up, rather than to review the alternative, lower frequency option of RF. This is not necessarily a sound proposition for the reasons which I will outline below:

3.2.2. *Uniformity of Microwaves*

Most people will be aware that domestic microwave ovens are fitted with either turntables or mode stirrers. These devices are used to try to overcome the non-uniform field in the microwave oven. A very simple experiment to prove this consists of heating a sponge cake mix under static conditions in a microwave. In nearly every instance, the heating pattern obtained is absolutely awful. This is largely due to the very short wavelength of the microwave energy. The problem is generally worse in larger microwave installations.

Due to the nature of the electrode applicator with RF dryers, and the longer wavelength (approximately 11 metres at 27MHz), it is normally possible, with careful design to achieve a far better heating uniformity than with Microwaves.

I have seen several larger microwave installations which have given precisely this problem of heating uniformity, and have successfully replaced them with Radio Frequency ovens. I would certainly not be naïve enough to claim that RF should always be used in place of Microwaves. RF is clearly not the solution to every problem, but there are certainly many cases where it can, do a far better job.

3.2.3. *Reliability and Running Cost Comparisons*

The major consumable cost with any RF or Microwave generator is the cost of the Triode tube or Magnetron. Kilowatt for kilowatt, the cost of an industrial triode is significantly lower than for an industrial Magnetron. Also, the average life of the Triode in a properly designed and well maintained RF dryer is around 20,000 hours (three years or more), compared with a typical Magnetron life of 3000 to 6000 hours.

3.3. *"Semi-Scientific" claims for the technology*

3.3.1. Several people have claimed over the years that RF can be successfully introduced into the conventional oven. Take it from me, this does not work reliably in practice and the costs of doing so are very high. I have seen several installations supposedly running with metal bands where the RF is on, but it is performing no useful function apart from causing the band to spark if the power is turned up too high. The lack of performance of poorly designed units has only served to turn people off from the true benefits of RF.

3.3.2. It is well known that the heating effect depends upon the frequency used, the RF voltage field and the loss factor of the material being heated. The equation below is well known and determines the heating effect:

$$\text{Power/unit volume} = 2\pi f\, \varepsilon_o \varepsilon_r \tan \delta E^2 \text{ watts}$$

Where f = frequency (Hertz)
E = effective applied RF voltage field in volts/metre
ε_o = permittivity of free space = 8.854×10^{-12} Farads/metre
ε_r = Relative Permittivity of the material to be heated
d = Loss angle
(tanδ = Loss tangent, $\varepsilon_r.\tan\delta$ = Loss Factor)

It is therefore clear (in theory at least) from the above equation, that if you increase the frequency, the voltage field required to heat the product will decrease. However, this is not the full story in practice.

The vast majority of machines installed for Post Baking applications over the years have operated in the 27.12 MHz internationally accepted (Industrial, Scientific and Medical) frequency band. A number of machines have more recently been installed operating at 40.68MHz, (a frequency which not all countries have adopted as an ISM band). Manufacturers of these machines claim (correctly) that they operate at a lower RF voltage and they justify this claim by reference to the above equation. Therefore we are invited to accept that because the voltage is 21% lower at 40MHz "the machine must be less prone to arcing" (flashing to the product).

On the face of it, the scientific facts are irrefutable, however in practice, it has been clearly demonstrated that there is little actual difference in arcing performance between the two frequencies. Virtually all incidences of arcing can be attributed not to the machine frequency, but to poorly presented, misshapen or otherwise unsuitable individual product pieces becoming excessively overheated **because they contain significantly higher moisture than normal**.

It is this high moisture which causes the machine to arc, rather than the other way around. This is due to the fact that the product cannot tolerate the concentration of power which is required to remove this higher moisture. In simple terms, the product behaves rather like a fuse which ruptures under excessive current flow. First of all, the sugars within the product caramelize, then they carbonize, and finally, the carbonized product begins to burn. The flame then ionizes the air between the electrodes, and the flash occurs. If you think logically about this, the frequency used, and the various schemes of arc suppression, or arc anticipation are at best damage limitation devices – once the product begins to burn, it is too late - the damage is already done!

Information obtained from users of both types of equipment over the last 10 years also shows that the higher 40.68 MHz operating frequency also gives rise to a reduction in equipment reliability, cooling problems, and consequently increased operating and maintenance costs, mainly caused by the shorter life of the triode tube and the failure of other components such as ceramic capacitors which tend to become self resonant at just over 27 MHz.

The higher operating frequency also tends to cause voltage distribution variations along and across the electrode in full scale applications, giving rise to heating uniformity problems due to the shorter wavelength at 40MHz. Another disadvantage of operating at 40.68MHz or 13.56 MHz is that the permitted frequency band for operation is +/- 20kHz at 40.68MHz, and +/- 7kHz at 13.56MHz whereas at 27.12MHz it is +/- 163kHz. In practice, very few machines at the higher and lower frequencies operate within the permitted band.

4. ADVANTAGES OF RF HEATING FOR FOOD PRODUCTS

4.1. *A Unique Attribute of RF – the ability to profile Moistures*

The free-running Triode Oscillator circuit can, if correctly designed, be dynamically matched to the load. The power absorbed by the load is automatically controlled by the load itself. **The RF dryer is uniquely suited to moisture control.** It is able to profile the moisture content of the product passing through the dryer. If there is high moisture in the product, then more power is drawn automatically.

This moisture profiling effect is a unique feature specific to free-running triode tube oscillators and to the knowledge of the author has not, or cannot yet be satisfactorily implemented by microwaves or even with the so-called “50 ohm Technology” which was much hyped a few years ago.

Microwave Generators usually are matched to deliver a fixed power into a fixed load and require the dumping of surplus RF power into a water load by means of a circulator to prevent the power being reflected back into the Magnetron. It is not possible to run a Microwave generator in an ‘off-load condition’ which is typically what you need to do on a normal biscuit production line. Running at fixed power does not accommodate variations in moisture which occurs on all lines due to the modulating of the conventional oven burners.

Although heavily promoted at the time, it would appear that 50 Ohm technology has failed to make a commercial impact in the marketplace and has virtually disappeared for drying applications. This is probably due to a number of reasons:

i. The cost of the equipment is unacceptably high. The typical power required for a serious industrial sized application is around 40 to 50 kilowatts or more at 27MHz. This can easily and economically be achieved with a relatively unsophisticated free-running single triode oscillator design.

ii. The equivalent 50 Ohm design is far more complicated than a free running triode oscillator. A typical 50 Ohm setup usually requires at least a solid state driver oscillator, plus a large Class C Tube powered amplifier (this part alone is considerably more expensive than the triode oscillator), and on top of this, a matching and tuning circuit is required.

iii. Nearly always, this latter part of the system utilizes at least two variable vacuum capacitors. These being a similar high vacuum technology, are individually almost comparable in price to the cost of a triode tube. Variable vacuum capacitors of the required size also tend to be self-resonant at close to 27MHz, their reliability tends to be very poor in practice and they are prone to frequent failure.

iv. Like Microwaves, 50 Ohm systems do not appear to be equipped with the option to automatically determine the RF power according to the moisture content of the product so they do not make a good job of moisture profiling.

v. The setting up and maintenance of the 50 Ohm system requires specialist RF knowledge, particularly in matching the generator to the load. This is generally way above the level of technical ability of staff in most food processing plants. Basically 50 Ohms equipment is suitable for Scientists, not for the food Industry.

4.2. *A solution for increased production where space is at a premium.*

Many bakeries become 'landlocked'. There is just no room to extend the conventional oven to increase production as the space at the end of the oven is already filled to capacity with coating, sandwiching or packaging equipment. RF can solve this problem as we will see below.

5. APPLICATIONS IN THE FOOD INDUSTRY

5.1. *Post Baking of Cookies and Crackers*

Photo: Latest 50kW RF Post Baking Unit - Courtesy of Fox's Biscuits Batley, Yorkshire, UK

The most well know application for RF in the food industry is in Post-Baking of Biscuits (i.e. cookies and Crackers). In many cases where space is at a premium, and an increase in production throughput of 30% to 40% is required, whilst maintaining product quality, the only realistic option for many bakeries is to install an RF unit.

Uniform shapes can easily be processed in Monolayer. It has been determined from experience that more difficult irregular shapes benefit from reduced power density. This is usually achieved by packing more product under the electrode (typically forming a bed), so that although the power used remains the same, the residence time in the RF field is increased, thereby reducing the watts per product piece.

Referring back to the equation given in 3.3.2 above, if the power density is reduced, the voltage field strength required is therefore significantly reduced.

5.2. *Drying Before Slicing*

Photo: 4 x 25kW units used for Drying of Bread Loaves before Slicing

Many processes exist where bread is sliced following de-panning (removal from the metal baking pan). This is usually a discontinuous process whereby the loaves are taken off-line after baking and stored in huge conditioning rooms for 24 to 48 hours before they can be sliced. It has been shown that this labor-intensive activity can be completely eliminated by using RF drying to remove 2-4% of moisture, followed by reduced conditioning on a continuous accumulation conveyor. The point to make here is that the incorporation of RF into the line allows the size of the accumulation storage to become practically feasible and thus makes uninterrupted continuous processing possible. Without RF, the size of the accumulation storage required would be unacceptable. This process has worked very well for several customers in Italy producing packaged, toasted bread, and also for customers processing Bagel Chips.

5.3. *Pre-Heating of Yeast-based Doughs*

Dough Proofing on a continuous basis usually requires a very long proofing oven in order to raise the temperature of the dough slowly to prevent the yeast culture being killed due to over-heating. This is because it is easy enough to heat the surface of the product, but the dough is a good insulator and so it takes a long time for the heat energy to penetrate to the centre of the product. RF rapid pre-heating, followed by a reduced length proofing tunnel to hold the temperature at 37 deg C (98 deg F) can accelerate this process and allows the length of the proofing tunnel to be reduced by up to 60%. This has been successfully implemented for a variety of products including Croissants, cake batters for Italian Pannetoni production, pretzel sticks and bread slabs (for breadcrumbs). In fact for breadcrumbs, good quality Japanese crumb can be manufactured using just RF energy alone.

5.4. *Other Non-Bakery Food Applications*

5.4.1. *De-infestation of Walnuts and similar Products*

Photo Courtesy of WSU and Diamond Walnuts

RF heating has been demonstrated to be a proven alternative to banned chemicals like Methyl Bromide and Phosphine for de-infestation of post-harvest pests in nuts and similar products. (refs. 6&7). The photo above shows the set up for a 3 month industrial scale RF trial on Walnuts undertaken jointly by WSU, University of California Davis, USDA Fresno and Strayfield at Diamond Walnuts in California. The results were excellent and showed a 100% mortality rate for even the most resistant insect pests. Similar work has been carried out at WSU and elsewhere on almonds and other related products.

5.4.2. *In-Tube heating using RF Energy*

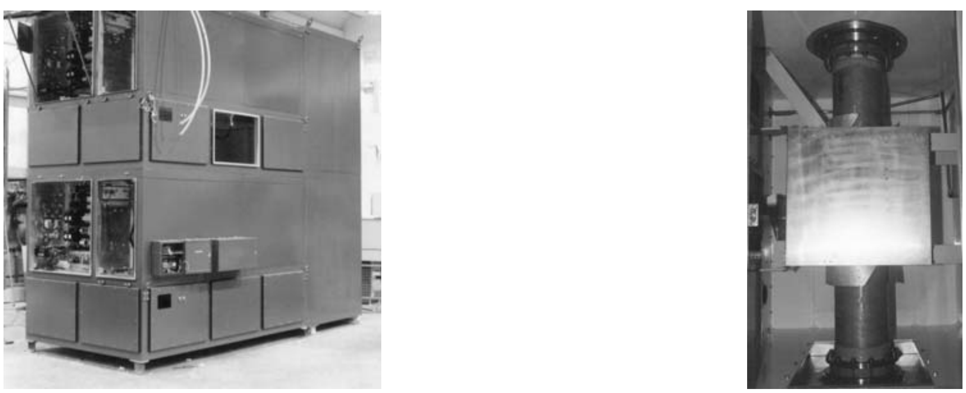


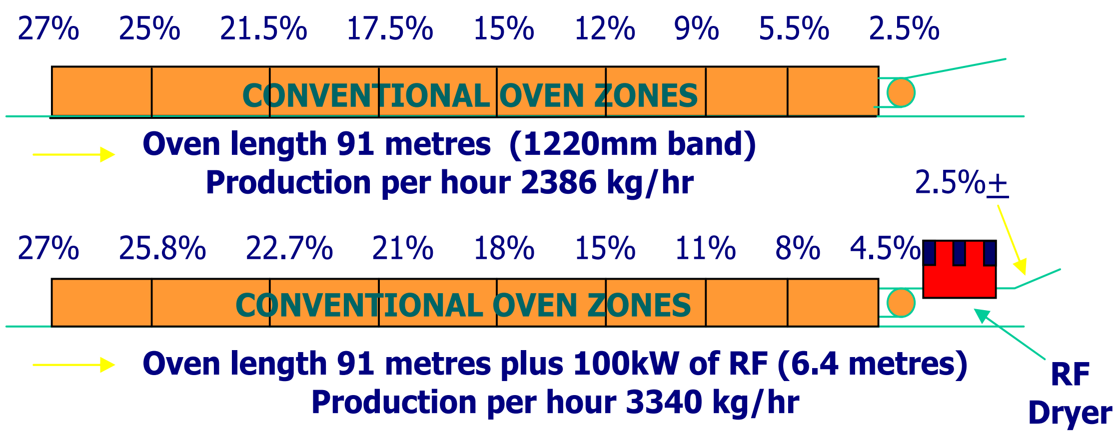
Photo: 100kW Vertical Tube Heater with 300mm dia. tube under construction in the UK

Due to the unique ability of RF and Microwave energy to supply direct heat generated within the product, a field of opportunity opens up to be able to heat flowable or pumpable products within a tube. This concept has been successfully used to heat rice and also to fix dyestuffs onto textile fibers. The photos above show such a system under construction at our plant in the UK. There are limitations to this process, and the main one of these is the conductivity of the product. High conductivity limits the penetration depth of the energy and it has been found that products such as meat for deli products (which would be an ideal candidate) can only be processed either in solid form up to 1 inch diameter or in applications where meat in liquid is moved around within the tube.

6. HOW DO THE COSTS STACK UP?

Case Study #1 – North American Cracker Manufacturer

The diagram below shows how a typical cookie or cracker line can benefit from the addition of RF drying. This is a typical North American cracker production line producing Saltine crackers. It can be seen that the introduction of an RF dryer at the end of the line makes it possible to increase the production rate from 2386 to 3340 kg/hour (which is an increase of 40%) without increasing the length of the line or any major modification to it apart from the obvious necessity to ensure adequate packaging capacity is available. The quality of the product is enhanced because the breakage or "checking" of the crackers is significantly reduced. This is impossible to achieve with any other technology. Lines like this have been installed in many of the major bakeries in the USA and around the world and have run well for over 30 years now. Therefore we can state with confidence that RF technology is definitely "proven and reliable".



Case Study #2 – Indian Biscuit Manufacturer

Previously many Asian countries have shown relatively little interest in bakery products like cookies and crackers. However, the last few years has seen the market really start to take off, particularly in places like China and India as a more 'western' way of life has developed. Quality appears to be of lower importance in these markets, and the introduction RF drying must usually be justified on cost alone. The tables below (please refer to Tables 1 &2) contain actual figures indicating the savings obtained by a customer in India for two different high volume, low margin products:

Table 1

Semi- Sweet Biscuit	**Without RF** (at 6 min 5 secs Bake Time)	**With RF** (at 4 min 40 secs Bake Time)
Production	14.36 Tonnes	19.113 Tonnes
Direct Cost/Kg	US$ 0.08	US$ 0.068
Monthly Production	1206 Tonnes	1605 Tonnes
Savings/month		US$ 20650
Savings/year		US$ 247,800

Table 2

Marie-Type Biscuit	**Without RF** (at 4 min 30 secs Bake Time)	**With RF** (at 3 min 15 secs Bake Time)
Production	11.302 Tonnes	15.602 Tonnes
Direct Cost/kg	US$ 0.086	US$ 0.074
Monthly Production	949 Tonnes	1311 Tonnes
Savings/month		US$ 16,704
Savings/year		US$ 200,448

From the data given above it can be stated that the payback for both these examples is about 18 months.

Case Study #3 - SUNSHINE BISCUITS USA

An independently documented study (ref. 8) was carried out at Sunshine Biscuits in the early 1990's. Sunshine Biscuits were manufacturers of crackers and cookies in the Los Angeles area. The problem the bakery faced was one of air quality compliance and the need for product quality improvement.

After a visit to Southern California Edison CTAC and in conjunction with EPRI, they installed a 100 kW radio frequency post-baking oven following the conventional gas oven to complete the drying on their crackers.

By doing so the company was able to increase its production rate by 30%, meet air quality standards, and save 600 barrels of oil per year plus $715,000 in operating and maintenance costs per year. The introduction of RF Drying also improved cracker quality by providing more precise moisture control.

(The plant closed a few years ago and the dryers were transferred to a Kelloggs Inc. plant elsewhere).

7. CONCLUSIONS

Radio Frequency heating has acquired somewhat of a varied reputation over the years due to poor understanding of the process and poor design and implementation. However, with a proper equipment design, properly implemented, RF can be very successful indeed. With suitable products, the correct equipment and an experienced supplier, increased production, reduced costs and improved quality are easily attainable.

A second important point concerns how processes are developed: In the past, many companies and also scientific institutions have purchased small RF units and carried out research projects alone with little or no success. This happens because the R&D people are primarily food scientists and they do not properly understand the RF technology and how solve RF related problems. Frequently such projects have been abandoned after a short while. I would advocate from experience that the only way to properly exploit this technology is for Academics to work in close partnership with Equipment manufacturers and the end Users. Strayfield has several such partnerships which have worked to the advantage of both parties. Of particular note here is our partnership with Juming Tang and his team at WSU. The key ingredient for success here is that the arrangement must be a win-win situation for all parties concerned.

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