Considerations for Commercial Success in new RF and Microwave Industrial Heating Applications

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ABSTRACT

Often, novel and extremely clever new ideas have been developed for Industrial RF and Microwave Heating applications, but these have either failed entirely or met with limited commercial success because the opportunities have been poorly exploited by researchers, process developers and equipment manufacturers. The reasons for eventual success or failure are many and varied, but can be grouped into various categories including:

> *A lack of proper understanding of the High Frequency heating process and what is required for success, limitations caused by the laws of physics which are not considered by the researcher, initial choice of equipment supplier and the design and long term reliability of the proposed system and its implications*
>
> *The commercial viability of the proposed process is often ignored. (A strategy which will allow the researcher or process developer to make a quick assessment of the commercial viability of a potential new RF or Microwave process is introduced).*

There are also a number of other additional factors which can affect purchasing decisions by potential customers. These include: achieving a proper understanding of the client's requirements, being able to discuss the issues which arise using terminology that the client is familiar with, and the ability of the system supplier to support the client and the equipment and resolve problems quickly and expediently.

This paper discusses in detail, the reasons behind some of these failures. It is based upon the extensive knowledge of the author who has over 35 years of practical experience at the cutting edge of this technology. It will identify the causes of failure and how to avoid them, and will attempt to suggest some better strategies for research workers and system builders in order to improve the chances of a project eventually achieving commercial success.

Keywords: Radio Frequency, Heating, Drying, Reliability, Equipment suitability, Commercial viability

INTRODUCTION

Radio Frequency Heating has been around since the 1940s when it was first introduced by John Pound of Pye Ltd. (later to become Pye Thermal Bonders Ltd.), for curing the adhesive used for the construction of the wooden framework of Mosquito Bombers (Frankland M. [1]). A number of very successful commercial applications exist. These include the drying of Biscuits (Koral T. [2]), Textiles, Fibreglass and Water-based Adhesive Coatings on paper, Panelboard pre-heating and Plastic Welding. Although a huge amount has been invested over the last 30 years in R&D in an attempt to develop new RF processes, this existing range of applications remains largely unchanged.

The majority of these commercially successful applications have generally been developed and introduced by RF and Microwave equipment manufacturers rather than by researchers. Although it may be a very controversial view, it is the opinion of the author, based upon his experience of over 35 years in the industry, that despite the investment of huge amounts in RF and Microwave R&D by governments and industry, there is very little evidence of any new applications or indeed of any significant commercial benefits to be seen. The author believes that there may be good reasons for this and this paper will attempt to identify and develop a better strategy for capitalising upon the untapped benefits of this technology.

HOW TO PROCEED

1. Estimate the Commercial Costs of the Proposed new Process

The temptation, when a researcher is asked “Can we do this with RF or Microwave heating?” is to immediately take a sample of the material and try to heat it, or to commence an extensive computer modelling exercise. A lot of RF processes have been developed at great cost, without proper consideration as to whether or not they will be commercially viable. Frequently it is found that conventional processes exist which can produce exactly the same results but at 50% of the capital outlay and running costs of an RF or Microwave installation. A good example of this can be found in high volume products such as agricultural commodities (e.g. grain drying, sawdust drying etc.). Of course, due to ever-increasing energy prices, environmental concerns, legislation and other reasons, the evaluation of commercial viability may change, so it is always necessary to take current circumstances into account. Often experience shows that unless significant tangible benefits can be demonstrated, which are unobtainable using conventional technologies, then RF or Microwave will not be the solution of choice.

To estimate the capital cost and dimensions of a plant is very easy. At this stage it is not necessary to know if the RF or Microwave process will work!

For a heating process, it is merely necessary to know the starting temperature of the product, the finishing temperature, the specific heat and the throughput in kilograms per hour. A simple sensible heat calculation based upon this data will then tell you how many kilowatts of RF or Microwave energy is required for the process. If the process is to be a drying process, then it is necessary also to add energy to allow for evaporation of the moisture. To this figure, one would add additional energy for any heat losses, and then multiply by a factor to allow for the efficiency of the conversion process from Mains to High Frequency.

These calculations will give a base figure for the RF or Microwave capacity required in kilowatts. The capital cost of the plant can then be estimated. For plants of 20kW or more, general consensus has based the capital cost on a figure of UK Pounds £1000 to £2000 (US$1500 to US$3000 per kilowatt for “standard” RF equipment and around UK Pounds £2000 to £4000 (US$3000 to US$6000) per kilowatt for “standard” Microwave equipment. In this context “standard” means equipment which a manufacturer has already designed, and where no engineering changes are required. Often these prices can be doubled if alterations to materials handling equipment or specified components (e.g. PLC

Control systems, Switchgear etc.) are required. If a fully bespoke design is specified, and also for smaller laboratory-scale plants, the costs can be in excess of UK Pounds £5000 (US$ 7,500 per kW) or more because there is little saving from size reduction and the additional engineering charges must be recouped as part of the overall build cost for the machine. Knowing the mains supply energy in kilowatt hours required for the process as estimated above, it is then easy to work out the running cost of the plant. A final tip: If the calculation for the required RF or Microwave capacity results in a requirement of over a megawatt or so, the project is fairly unlikely to be viable based on experience.

2. The importance of a proper understanding of the High Frequency Heating Process

Many attempts to exploit the use of RF and microwave Technology have met with little success because the researchers involved have limited previous experience of the technology and virtually no practical knowledge of industrial sized installations. There are of course notable exceptions to this, but this is a very difficult field, with a long learning curve for someone with little or no industrial experience in RF or Microwave systems. Many times, it is reported that a trial was unsuccessful, “due to arcing” or other process issues. Unfortunately, most of the available technical literature on High Frequency Heating tends to be very basic and general, and of limited help, so it is difficult for a researcher to make progress when working alone. However, such problems can often be easily solved by somebody who has extensive practical experience in the field.

Similarly, the equipment manufacturers, whilst being well acquainted with designing and using high power RF systems, do not have sufficient knowledge in related areas such as process requirements, materials handling, process protocols or access to the right industry contacts. Even a lack of knowledge of the accepted industry vocabulary can be a huge handicap to commercial credibility. Terminology is important – each industry has its own terminology and it is important to realise that success is going to be more likely if the client can relate to the technical terms which are employed in discussions. This is particularly true when working with large companies which by nature are very conservative. The above factors make it very difficult for a manufacturer to achieve credibility with the client when trying to promote a new process alone.

The author believes that the best way to achieve positive results quickly, is by forming a syndicate of specialists (e.g. RF/Microwave Specialists, Food Scientists, Process Engineers, Computer Modellers and End Users). Such a group is capable of bringing the necessary range of expertise to the project to achieve the desired result. Direct experience of working as part of several such syndicates confirms that this is definitely the best route to a successful outcome.

3. The relevance of Dielectric Property Measurement and Modelling

In recent years, a lot of effort has been expended in measuring the dielectric properties of all sorts of materials and also in simple computer modelling of processes. Indeed it would appear that some people have spent a significant part of their career carrying out dielectric property measurements alone. The true value of these activities when carried out in isolation and the cost involved of carrying them out is certainly debateable.

Often the process is a heating or drying process, where the dominant dielectric properties are those of the water in the product rather than the product itself. Generally it is unnecessary to know whether the loss factor of a substance is 0.003 or 0.005 as the loss factor of the water is often 100 times greater. Usually, it is only really necessary to have a ball park idea of the loss factor, together with an appreciation of how the product will heat relative to other products and the best way to present the product to the heating system.

Dielectric properties are required for computer modelling, but, provided the values used in the model are not vastly different from reality, an educated guess is often sufficient for practical purposes.

It is essential to be aware of the limitations of computer modelling. Certainly even today's most powerful computer hardware and modelling software just does not have sufficient computational power to be able to generate meaningful models of the dynamics of a high power RF or microwave process working on real products. Even basic computer models take many hours to build and refine, and each run of the solver can take several hours or days, even with powerful processors and sophisticated graphics processors. Simplifying the model to speed up the solver means at best a huge compromise. Often the results obtained from modelling "look good" in presentations and scientific papers and may have good sales and marketing value, but usually bear very little resemblance to a practical industrial system.

The most important points to understand regarding modelling is that firstly, product presentation and practical machine design are crucial to the success of a process and secondly, that the properties of any product will change continually because the product varies, the temperature increases and the fields change as the product moves through the machine. For any production line, the material properties will vary from batch to batch, within a batch, and even from second to second because it is not possible to maintain absolute consistency in that product. It is the ability of the final machine to operate reliably and cope with these inconsistencies which can mean success or failure of the process.

The author would contend that computer modelling can be most useful as a tool for the refinement and de-bugging of an existing design (or design concept) by an experienced RF designer, rather than as a tool for designing such a system from scratch. Again, this is where the concept of a syndicate comes into its own, as very often, the computer modelling expert is unlikely to be an expert in industrial RF or Microwave systems. However, if a workable, practical system is modelled, then field anomalies can be identified and specific issues can be identified and solutions tested on the model, thereby shortening the development process considerably.

4. It is important to consider the Laws of Physics!

Frequently, high frequency heating projects are initiated by placing a small quantity of the product in a standard microwave oven. Today most of us have access to inexpensive microwave ovens at home, in the office canteen or in the laboratory, so it is only natural that the nearest microwave is the first thing to try when considering an electroheat process. There is nothing wrong in doing this and indeed it is often the recommended technique for a quick "look see". However, if the small scale tests are successful, generally through lack of experience, the mistake that a lot of researchers then make, is to assume that it is simply a case of scaling up the process to an "industrial sized" microwave. Whilst this can indeed be successful for some products, many projects have failed at this stage due to the fact that simply scaling up the process does not always work as expected.

One of the main factors often overlooked, is the wavelength of the applied energy. By definition, microwaves have a very short wavelength (12.24cm at 2450MHz, 32.79cm at 915MHz). This means that the uniformity of heating is frequently poor at these frequencies. Many people claim to have "solved" these heating uniformity problems over the years, but often these are made by newcomers to the business who are unfortunately just repeating same the learning curve as their predecessors. The microwave wavelength can cause major problems under various circumstances although acceptable solutions can be found, hence the continued need for turntables, "mode stirrers" or other devices in most microwave ovens and restrictions in applicator width etc.

Due to the prevalence of microwave heating in our daily lives, and the fact that Radio Frequency Heating has had relatively less (and often poor) publicity, many researchers totally overlook the possibility that their process might actually work considerably better at the lower (i.e. RF) frequencies.

Equipment manufacturers generally specialise in either microwaves or RF, but not both technologies. Clearly there is no incentive for any company specialising in Microwave systems to recommend to a potential client that RF might be a better choice for their process – and so it is often the case, that the researcher will spend considerable time and money studying what may in the end prove to be a suboptimal solution which is eventually rejected, rather than considering what might well be a better alternative.

5. Initial choice of equipment and supplier

Frequently a poor choice of equipment can mean the difference between failure and success of a process. For RF frequencies there are two distinct system technologies available on the market. These are the "classic" Free-running Oscillator (FRO) and the so-called "50 Ohm technology". A study of most current literature would tend to indicate that the system of choice should be 50 Ohm technology. However, it is the opinion of the author based on his own extensive knowledge of the industry, that this reflects mainly the opinion of academia, and does not reflect true industrial reality. In terms of numbers of industrial installations, there are literally thousands of FRO based systems used for heating or drying in industry today. By comparison, there have been probably less than 150, 50 Ohm systems of 20kW or more installed in the last 30 years. (50 Ohm systems of up to 10kW or thereabouts dominate in the semi-conductor industry, but we are not concerned with these RF plasma applications in the context of this discussion). Indeed today, the worldwide manufacturing output of FRO systems of over 25kW capacity is estimated to be about 200 to 300 units or more per year, with many being in excess of 85kW.

The reasons usually given for choosing 50 Ohm systems are: flexibility, reduction in radiated emissions and ease of tuning (Marchand C. [3]). Whilst this may be partially correct when applied to systems intended for research, there are a number of points which need to be made in order to give the true picture from Industry.

a. Cost – the capital cost of a 50 Ohm system is often at least 50% to 100% more expensive than an equivalent FRO system.

b. Flexibility – using the same RF system for many different applications is a useful consideration for research purposes. However, many production lines are dedicated to specific tasks, and the design must be optimised for that task. For example, in the food industry, the use of food approved materials, stainless steel cabinets, and sturdy construction are paramount. Water cooling is often preferred over air cooling due to improved reliability. By contrast, in the textile industry, lowest possible capital cost is always a primary consideration.

c. Whilst it is probably easier to achieve compliance with emissions legislation (i.e. EN55011) for a 50 Ohm system, compliance is not guaranteed and frequently adjustments to the design have to be made when the system is assessed for compliance. Often the 50 Ohm generators will be checked for compliance, running into a simple "off the shelf" 50 Ohm water load. It is essential to understand that this is not the same as checking the entire system which may be a tunnel oven. Despite statements to the contrary in the literature, a modern, properly designed and constructed FRO system is easily capable of achieving compliance. However there are a lot of non-compliant FRO systems made by unscrupulous manufacturers on the market which are falsely CE marked!

   To guarantee CE compliance and efficient power transfer, the oven and generator should always be checked <u>as a complete system using a load which is truly representative of the actual product</u>. Buyers of high power systems are strongly advised to insist on an independent site survey as a condition of machine acceptance.

d. The claimed "ease of tuning" for the 50 Ohm system is questionable. To properly tune a 50 Ohm system requires an in-depth knowledge of High Frequency matching techniques, and expensive specialist equipment (typically a network analyzer). From experience, if there is a problem with the tuning system (e.g. component failure, or out of range load impedance), it is most unlikely that an operator, factory electrician or other reasonably competent person will have insufficient skill or experience to correctly understand and resolve the problem without expert support.

e. One major difference between the 50 Ohm system and the FRO which is particularly worth mentioning here is in their suitability for drying purposes. In both 50 Ohm and Microwave drying systems, it is standard practice to calculate the amount of HF power required to remove the moisture, and then the tuning system of the machine, will adjust the matching of the circuit and attempt to deliver that quantity of power into the product constantly. If the impedance of the product changes, then the matching system will always adjust to maintain the impedance match.

The above situation is fine if the product remains absolutely constant, but many researchers and even some manufacturers fail to appreciate that changes in the load happen frequently for many reasons and can be a MAJOR problem for such systems. For example: what happens when you run out of product? The matching system cannot match into an empty oven system (or it would dump all the power into the metallic components of the system!). This means that **Microwave Ovens and 50 Ohm systems cannot usually be run with an empty oven**.

Empty ovens can and do occur regularly on many production lines. Of course, this is an extreme condition, but if the matching is based upon constant power, there are many situations (e.g. product dryer or wetter than usual, or for run-in and run-out conditions) where maintaining constant power is not appropriate. In cases such as partial loading or where product is drier than average, this can actually be very dangerous, because if the product is over-dried by having to absorb too much power, then it can scorch or even catch fire.

By contrast, the FRO system, (*if correctly designed – not all are!)* is the only system capable of delivering precisely the correct amount of power to the product according to the quantity of moisture under the electrode system at that particular time. Therefore it is uniquely ideal for moisture profiling in a drying operation. It also works very efficiently in many conveyorised non-drying operations. **This is not the same as using the feedback from a moisture sensor after the heater to control the applied power.**

Another advantage is that it does not matter if the oven runs out of product. **The FRO system will run without problems with a completely empty oven**! This is explained by the diagram sequence below. **It is included here because most people are completely unaware of this important and unique property of the FRO**.

A simple FRO capable of moisture profiling consists of two tuned circuits, the oscillator circuit (C1/L1) and the applicator/oven circuit (C2/L2) which are closely coupled. A typical basic circuit of such a machine is shown in Fig. 1 below:

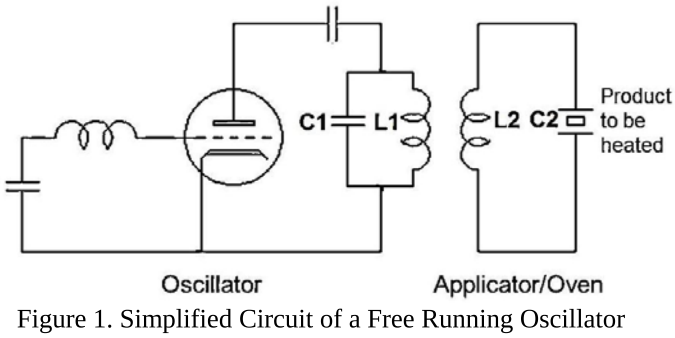

Figure 1. Simplified Circuit of a Free Running Oscillator

For a parallel resonant circuit such as C1/L1 or C2/L2, the frequency of resonance is determined by the formula:

$$F = 1/(2\pi\sqrt{LC})$$

Where F= Frequency in Hz, L= Inductance in Henries, C = Capacitance in Farads

Therefore it can be seen that by adjusting the values of L1 and C1 in the oscillator we can determine the required frequency (e.g. 27.12MHz in this example). A parallel resonant circuit such as this will have a frequency response as shown in the diagram Fig. 2:

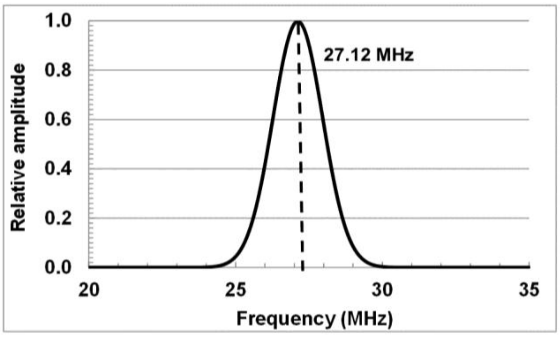

Figure 2. Frequency response of Oscillator (C1/L1)

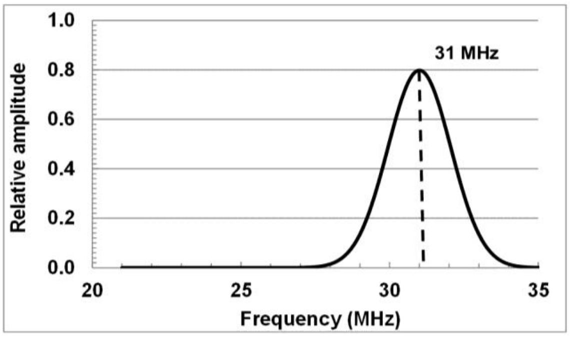

Figure 3. Frequency response of Oven (C2/L2)

Similarly, the applicator/oven circuit can be arranged to have a corresponding resonance as indicated in Fig 3. This is usually slightly higher in frequency (say 31MHz) than the oscillator circuit (say 27MHz). It is the relationship between these two frequencies which is very important and this determines the amount of power transferred to the product.

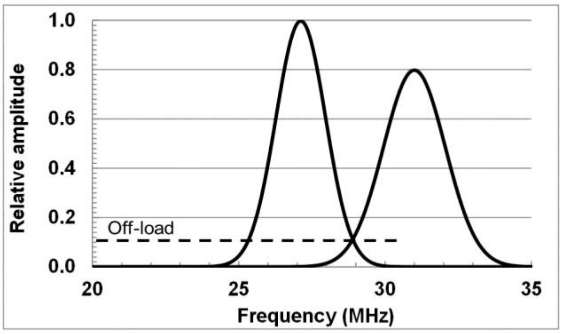

Figure 4. Off Load (empty oven) condition

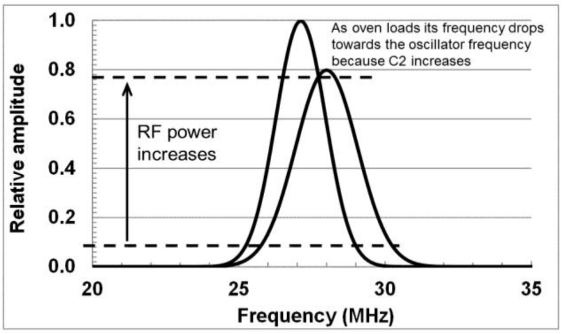

Figure 5. Fully loaded Oven condition

In the diagram Fig 4 above, the frequency curves are someway apart, so that the overlap is minimal. The power transfer to the product load is therefore also minimal and represents an off-load or empty oven condition. However if the frequencies are moved closer together as in Fig 5, then the power transfer is increased. This can be achieved by increasing C2 or L2 (as C,L increase, frequency drops), or it can be due to a change in the properties of the load (increasing C due to higher moisture content, increased volume/density of product, increased dielectric loss factor etc.).

This ability to change the amount of power is an important and unique feature of the FRO, because, with careful design, it enables the dryer to use the moisture in the product to control the amount of RF power delivered to it, thereby allowing the power level to auto-regulate depending upon the moisture content of the product: If the product contains high moisture, then the power delivered to it is increased due to the increase in capacitance of the oven which lowers the oven frequency, but if the moisture level in the product reduces, then the capacitance reduces and the amount of power delivered also reduces. Thus we have an ideal moisture profiling dryer which adjusts itself instantaneously to the moisture level of the product actually in the dryer. This effect cannot be achieved by conventional dryers, 50 Ohm systems or Microwave ovens (or indeed by some inferior designs of FRO!).

6. Design of the Equipment

Good reliability is often absolutely key to the success of RF and Microwave processes. Today many large industrial plants work on a 24/7 basis, and with downtime for such a line costing usually around UK Pounds £10,000 (US$ 15,000) or more per hour (for idle labour plus loss of production), it is essential that the equipment must be as reliable as possible. Reliability studies have shown that properly designed RF equipment will have a reliability of better than 99% - which is comparable to, or better than, the reliability of most other equipment in a process line. However, significant bad publicity has accumulated generally for RF and Microwave heating equipment because of poor design, poor maintenance and poor reliability when the wrong machine is selected, or when the process is not correctly set up. Often this has been due to people with little experience who have "dabbled" with RF or Microwaves, but the adverse publicity generated as a result has served to undermine confidence in the entire industry - "We tried RF 20 years ago but it didn't work".

A commercial system has to be designed to accept a reasonably wide range of product variation. It is often the way that the product is presented to the heater, and the consistency of that presentation which will determine the success or failure of the process. Frequently, processes have failed because the process designers and operators have failed to understand the significance of bad or incorrect product presentation. This is where extensive experience of industrial HF systems really counts.

When considering RF or Microwave equipment for an Industrial process it is also important to consider various aspects of the environment in which it is to operate and to ensure that the supplied equipment will perform well enough to succeed and operate reliably in that environment. A frequent mistake is to try to use equipment which worked for a few relatively short tests or which is based on a "duty cycle" design (such as an RF plastic welder or RF wood glue dryer) as the design basis for a robust continuous production oven required for 24/7 operation.

Repeating the learning curve is often encountered. Several times it has been claimed that it is acceptable to use metal conveyor bands in RF equipment. Whilst the metal band does indeed work satisfactorily when clean and new (as it would be in a laboratory test setup), after a couple of weeks in a production environment the band quickly picks up contamination which causes it to heat and arc due to high resistance rubbing contacts. In several such installations, metal bands were found to last only four to five weeks before they needed to be replaced. In one case, measurement of the actual energy transferred to the product indicated that approximately 70% of the available 75 kilowatts of RF power was being lost as heat in the conveyor band!

One of the more expensive "consumables" in a high power RF or Microwave heating system is the electronic tube – usually a Triode or Magnetron. There is great variation in tube life between different equipments. Often this is down to the design of the equipment. For example, in poorly designed RF Generators, the triodes will often last only 3000 hours or less, however, with proper attention to the design and good maintenance of the equipment, average tube lives of 14,000 hours for air cooled, or 20,000 plus hours for water cooled generators can easily be obtained.

It is important to know when to use air cooling and when to use water cooling for the Electronic Tube. Whilst air cooling is generally cheaper, it is generally more difficult to maintain cooling efficiency than with water cooling – which often makes water cooled equipment better suited to an industrial environment, especially when the ambient conditions are hot and/or dusty.

There are many other factors, too numerous to list here which have a bearing on performance and reliability, however, the main point to be made is that a bad choice of equipment may cause the failure of a viable process. Obtaining objective expert independent advice in this respect is important as a bad choice of equipment can often kill the project and there are usually no second-chances.

7. Supporting the Customer

The capability to support the customer is probably more important for RF and Microwave Heating applications, than for most other technologies used in Industry. It is self evident that this is a relatively unknown, unexplored area of technology and therefore it is common to find that the client needs significantly more support at the time of installation and throughout the lifetime of the equipment. Also, MW and RF heating systems tend to be treated by the client as "Black Box" technology, and often, technicians and engineers do not feel confident in their ability to maintain the equipment and diagnose problems alone. It is therefore essential to ensure that that adequate training and support is made available to the customer, particularly just after the initial start-up phase when most problems generally arise.

CONCLUSIONS

This paper has attempted to suggest ways by which the possibilities of commercial success for RF and Microwave Heating applications can be improved for the future in order to make better use of funding and resources. These are:

- Determine from the beginning, whether the process is likely to be commercially viable in the context of current and future market circumstances and customer requirement to avoid wasting time and money.

- Working in syndicates comprised of Academic Research specialists, Industrial RF and Microwave experts, the Equipment Manufacturer and the End User improves the chances of developing a successful process and avoids wasting money.

- Consider using expert advice to understand the benefits and limitations of the various systems available and their suitability to the end process and to select the most suitable and reliable equipment for the project.

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