RADIO-FREQUENCY THERMAL TREATMENTS

FOR AGRI-FOOD PRODUCTS

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ABSTRACT

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Radio-Frequency Thermal Treatments for Agri-food Products

Although radio-frequency (RF) methods have been used for decades in many heating and drying processes, there is still a need for more engineering design data related to the design of the applicators and the performance of these systems before costly prototypes are built. Energy, temperature, and the effect produced by the high frequency field parameters on biological materials need to be examined with regard to their effects on the resulting processing requirements.

Wheat-seed infection by a fungus such as *Fusarium graminearum* can considerably lower the seed germination and the quality of the harvest. A study was thus conducted to determine the combined effect of different levels of RF power, temperature, and moisture content on the quality of seed-grade wheat and fungus inactivation. Similar treatment combinations were studied with seed-grade soybean in view on improving germination. For wheat seeds, the results indicated that all variables have a significant effect on the mortality of the fungus and the seed germination vigour. With higher power, higher temperature (90°C) and higher moisture content (14%), the fungus mortality significantly increased, with a fungal vigour of less than 0.1, and the germination quality of the seeds decreased to a germination vigour below 0.3. For soybean seeds, only treatments of low RF intensity (60°C) were successful in improving germination vigour especially at lowest moisture content typically found in stored seeds.

RF treated wheat was studied to identify the relationship between heating conditions and grain quality categorized in terms of kernel viability and structural damage. Definite effects from heating intensity have been found and attributed to the stress cracks developed inside wheat kernels. These cracks were visualized by soft x-ray photography and quantified by a damage index that provides a numerical notation for the cracks. A clear relation among

the parameters consisting of heating intensity, stress cracks and grain quality has been found which justifies the use of damage indices for selecting optimum parameters in highly intense processes such as dielectric heating for grain drying or thermal treatment.

The potential of an RF thermal treatment to improve and extend the storability of vacuum packaged carrot sticks was investigated. The results have shown that it is possible to treat carrot sticks to 60°C in less than 2 min to reduce the initial microbial load. The RF treatments were compared to chlorinated water dipping, and hot water dipping. All storage trials from 0 to 14 days at 6°C, indicated that the reduction of the initial microbial load alone does not maintain the quality of carrot sticks for 14 days. Nonetheless, the quality evaluation of the RF treated samples was greater than for either the control samples or hot-water treated samples. The RF-treatments maintained colour, the vacuum of the packages, and the excellent taste of the carrot sticks.

RF heating was studied for the pasteurization of prepared samples of ham. The ham samples were brought to internal temperatures of 75 and 85°C, by RF heating with a 10 min residence time. The treated samples were vacuum-packed in three different plastic films and stored at 4°C for 1 to 28 days. All samples were examined for moisture loss, colour change, quality attributes such as off odours and sliminess, and total bacterial surface counts. The study indicates that radio-frequency heating can improve the storability of re-packed hams by reducing the bacterial load, reducing moisture loss during storage and maintaining an overall greater product quality.

RÉSUMÉ

Valérie Orsat Ph.D. (Génie Agricole et des Biosystèmes)

Traitements thermiques aux fréquences radio de produits agro-alimentaires

Les technologies de séchage et de chauffage par fréquence-radio (RF) existent depuis plusieurs décennies, cependant leurs principes de conception ne sont toujours pas universels, et chaque nouvelle application nécessite un exercice de conception personnalisé et des tests de faisabilité et de performance avant qu'un coûteux prototype ne soit construit. L'effet d'un champ électrique RF sur la montée en température et la qualité de nombreux matériaux biologiques reste encore largement à étudier.

L'infection de blé de semence par un champignon tel le Fusarium graminearum peut diminuer considérablement son taux de germination et la qualité des récoltes. Le chauffage RF de blé de semence infecté fut entrepris afin d'examiner les effets de diverses combinaisons de puissance, de temps d'exposition et de taux d'humidité sur la qualité des graines de semence et la mortalité du champignon. Ces diverses combinaisons de traitement ont été utilisées pour des semences de fèves de soja afin d'étudier l'efficacité du traitement dans l'amélioration de la germination pour un type de semence ayant une enveloppe imperméable. Les résultats ont démontré que chacune des variables a un effet significatif sur le taux de mortalité du champignon et la vigueur et le pouvoir germinatif des graines de semence de blé. Plus la puissance du champ électromagnétique, le temps d'exposition et le taux d'humidité sont élevés, plus le taux de mortalité du champignon est élevé et moins la semence n'a de pouvoir germinatif. Pour ce qui est des fèves de soja, seuls les traitements à basse intensité RF (60 °C) ont permis d'améliorer le pouvoir germinatif des semences.

Le traitement thermique RF de semences de blé a fait l'objet d'une étude dans le but de déterminer les causes à effets entre les paramètres du traitement et la qualité des semences en termes de pouvoirs germinatifs et de dommages structuraux. Des effets certains existent quant à l'intensité du traitement et le développement et l'étendue de craquelures sur une

graine de semence. Ces craquelures ont été identifiées grâce à l'analyse informatisée de photographies obtenues par rayons X et quantifiées grâce à un barème numérique. Il existe des corrélations entre les paramètres du traitement thermique et le développement de dommages structuraux menant à une perte du pouvoir germinatif qui peuvent être très utiles pour la sélection des paramètres opérationnels d'un traitement thermique phytosanitaire.

Une étude a été effectuée afin de déterminer si le traitement thermique RF pouvait permettre d'accroître la vie utile, jusqu'à 14 jours, de bâtonnets de carotte emballés sous vide et prêts-à-manger. Les essais en laboratoire ont démontré qu'il était possible de chauffer des bâtonnets de carotte dans un applicateur RF en moins de 2 min tout en réduisant considérablement la charge microbienne. Les traitements RF ont été comparés à des traitements à l'eau chlorée et des traitements à l'eau bouillante. Tous les essais subséquents en entreposage ont démontré que le fait de réduire la charge microbienne ne permettait pas de conserver la qualité des bâtonnets de carotte pendant 14 jours à 6°C. Néanmoins, le traitement RF a permis d'améliorer la qualité des carottes en comparaison avec les échantillons traités à l'eau chlorée et à l'eau bouillante.

La pasteurisation RF a été étudiée pour la préparation d'échantillon de jambon emballés sous vide. Les échantillons de jambon ont été traités par RF à des températures de 75 et 85°C pendant 10 min, emballés sous vide dans trois types de pellicules de plastiques et réfrigérés à 4°C pour une période variant de 1 à 28 jours. Tous les échantillons ont été évalués selon les critères suivants: perte d'humidité, changement de couleur, développement d'odeur, présence d'une substance visqueuse, et dénombrement microbien total. Les résultats ont démontré qu'un traitement RF peut améliorer la vie utile de jambon préparé emballé sous vide en réduisant le dénombrement microbien, en réduisant la perte d'humidité et en maintenant une meilleure qualité du produit.

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NOMENCLATURE

List of terms, notations and units

Symbol:		Units:	Term:
A		m^2	Area
B	Tesla	$V \cdot s/m^2$	Magnetic flux density (or Wb/m^2)
C	Farads	F	Capacitance
C_a, C_t		F	Applicator and tank Capacitance
c_0	=299 792 458	m/s	Speed of propagation of electromagnetic waves in free space
c		J/kg·K	Specific heat
D	$=\epsilon E$	Coulomb/m^2	Electric flux density
D-value		min	Time to reduce a constituent's level
d		m	thickness
d_p		m	Field penetration depth
dT/dt		°C/s	Time rate of temperature rise
E		V/m	Electric field strength
E_A		kJ/mole	Activation energy
f	= 1/T	cycles/s, Hz	Frequency
H	Weber	V·s	Magnetic field strength
I or J	Amps	C/s	Current intensity or density
k_i		min^{-1}	Thermal inactivation rate
k	$\gamma=jk$; $k_0 = \omega/c_0 = 2\ \pi/\lambda_o$		Angular wave number

Symbol:		Units:	Term:
k_{at}			Coupling factor between the applicator and the tank circuit
L_e			Equivalent inductance
L_a, L_t			Inductance of the applicator and tank respectively
M'			Mutual inductance
n			Number of petri plates
P		W/g or W/m^3	Power
PDI, or IP			Positional Damage Index
Q_a, Q_t			Q-factor of the applicator and tank circuit respectively
Q_e			Equivalent Q-factor
R		kJ/mole K	Universal gas constant
R		Ω	Electrical resistance
R_s	$1/\sigma d_s = \text{sqrt}(\omega\mu_0/2\sigma)$		Surface resistance
R_a, R_t		Ω	Resistance of the applicator and tank respectively
R_e		Ω	Equivalent resistance
T		s	Period
T		°C or K	Temperature
T_o		°C or K	Reference temperature
v	$=c_0/\text{sqrt}(\epsilon'\mu')$	m/s	Velocity
V		m^3	Volume
V	Volts	V	Electric potential
x			Factor, function of ω and all circuit elements
Z_e		Ω	Equivalent impedance

Symbol:		Units:	Term:
Z_t		Ω	Impedance of the tank
Z_{na}		Ω	Impedance across the coupling loop of the Network Analyzer
Z-value		°C	Temperature needed for a given D-value
tanδ	$= \epsilon''/\epsilon'$		Dielectric loss tangent
ϵ_0	$= 1/(c_0^2\mu_0)$ $\approx 8.854188 \times 10^{-12}$	F/m	Absolute permittivity of vacuum
ϵ	$D/E = \epsilon_{abs} = \epsilon_0\epsilon = \epsilon_0(\epsilon'-j\epsilon'')$		Relative complex permittivity
ϵ_{abs}		F/m	Absolute permittivity
ϵ'	$=\mathrm{Re}\,\epsilon$	F/m	Relative real permittivity (dielectric constant)
ϵ''	$= -\mathrm{Im}\epsilon$	F/m	Relative dielectric loss factor (loss factor)
η_0	$=c_0\mu_0=1/(c_0\epsilon_0)$ ≈ 376.7303	Ω	Wave impedance of free space
λ		m	Wavelength
λ_0	≈0.122366 m at 2.45GHz		Wavelength in free space
λ_c		m	Critical wavelength
μ_{abs}	H/B	H/m	Absolute permeability
ν	$=\lambda/\lambda_0=f_0/f$		Normalized wavelength
ρ		kg/m^3	Density
σ	$\sigma_{\epsilon''}=\omega\epsilon_0\epsilon''$;	S/m=1/Ωm	Conductivity
ω	$2\,\pi\,f$	rad/s	Angular frequency
ω_0		rad/s	Resonant operating angular frequency

PREFACE

For an electrical engineer, the study of Radio-Frequency (RF) systems is a little more complex than your standard capacitive systems. For a biosystems engineer, the study of RF systems and their applications with biological materials is far more complex and still under-developed. In view of this opportunity for development, this body of research was undertaken to clarify the basics behind RF technology. This document wishes to take the reader in a journey through the intricacies of radio-frequency technology and demonstrate the potential for applications' development in various agricultural and food sectors.

The thesis first presents, a short literature review (Chapter II) of the existing applications of RF heating and drying. The literature review is followed by some of the details of how RF heating works and the hardware associated with the design of RF applicators (Chapter III).

In terms of applications development, we first studied the use of RF heating as an anti-fungal treatment for wheat seeds infected by a common fungus (Chapter IV). The results of this study were not as good as we had hoped. In essence, in order to eradicate the fungus by means of RF heating, the treatment intensity required to be such that the germination quality of the seed suffered to a level rendering the treatment inadequate. From that point, it was argued that perhaps the seeds' were absorbing the RF energy preferentially in some areas, perhaps the embryo, leading to stress cracking and reduced germination. A study of the impact of RF energy on stress crack development in wheat seeds was undertaken (Chapter V). The study was conducted by means of x-ray photography and computer analysis of the scanned photographs of the magnified stress cracks. Although the study yielded interesting results, it did not indicate any sort of preferential heating within the seeds themselves which may have lead to lowered germination caused by higher stress crack occurrence in the embryo of the seeds.

In the meantime, a Québec company approached us to carry some investigative research in the potential use of RF for mild thermal treatments of ready-to eat carrot sticks (Chapter VI). The hypothesis here was that a mild heat treatment could be used to control

fungal and microbial diseases in minimally processed carrot sticks as well as reducing the metabolic activity of the produce to reduce bulging of the plastic packaging. Our client was interested in vacuum packaging the carrot sticks in plastic pouches for retail sale as individual servings. We obtained some interesting results with RF heating of carrot sticks with high product quality and reduction in the initial microbial counts. However, the combinations of RF heating with vacuum packaging of fresh (highly respiring) carrots and high refrigeration temperature (6°C) which were studied (boundary conditions from our client) may not have been the best combinations. It is likely that non-vacuum packaging would yield more promising results.

Last but not the least, we studied various combinations of RF heating of ham as a means of improving quality and food safety of vacuum packed prepared ham (Chapter VII). In these trials, we obtained very promising results, with reduced microbial counts and improved product quality.

Of course, this work has only scratched the surface of the potential uses that an electro-technology, like Radio-Frequency heating can have in the agricultural and food sectors of the future.

CHAPTER I - INTRODUCTION

1.1. ABSTRACT

Radio-frequency (RF) dielectric heating and drying have been used for industrial application for many years, especially in textile, paper and some food industry processes. According to the fact that the energy is directly transferred inside the product, applications of RF present obvious advantages over other conventional techniques (reduction in processing time and space, improvement in product quality, etc.). The objectives of this research work were to investigate the potential of RF energy in some agricultural and food applications.

1.2. INTRODUCTION

In today's food market, consumers want low fat, healthy, biologically grown, preservative-free, high quality produce. Alternatives being used to answer the preservative free issue, are freezing, sterilizing, drying, refrigeration and distributing a fresh product. Pasteurization can solve some shelf-life problems if a producer has the capability of distributing a refrigerated product (Harlfinger, 1992). Sterilization on the other hand can offer greater shelf-stability to foods. In some applications, dielectric sterilization can deliver products that taste good because electromagnetic waves are able to heat the product 3-5 times faster than conventional sterilization systems. The sterilized product is not temperature abused, so the food looks better, has better texture, and tastes better than products processed by any other available technology; however, sterilization requires a high temperature of >113°C (252°F) which does affect the organoleptic quality of the product (Harlfinger, 1992). Pasteurization destroys yeasts, moulds, and vegetative bacteria but does not destroy spore formers. If spore formers are the issue of concern related to a particular product because of

pH, water availability and storage temperature, then sterilization must be employed. Sterilization destroys yeasts, moulds, vegetative bacteria, and spore formers, and allows the food processor to distribute its products at ambient temperature with a longer shelf-life (Harlfinger, 1992).

Microbial and pest reduction by microwave heating, has been studied in a large number of experiments on many types of foods, including; meat and meat products, poultry, eggs and egg products, fish and shellfish, fruit and vegetable products such as canned fruit, fruit juice and jam, soy milk, sugar beet molasses, pea protein concentrates, ready-cooked meals, milk and its products, puddings, cereals, breads, cakes, pasta, starch, and spices (Rosenberg and Bögl, 1987). The frequencies used did not exceed 2.45 GHz. Continuous microwave equipment have been designed for industrial use which provide an effective destruction rate. Microwave treatment to sterilize food products has been successful (Harlfinger, 1992; Rosenberg and Bögl, 1987). However, conventional cooking and heating techniques generally yield lower colony counts than microwave treatment. The difference usually is in the order of 1-2 decimal reductions, when both techniques are compared for similar final conditions and temperatures of the product. For example, the *Escherichia coli* cell content of precooked beefsteak was reduced from 10^4 to 10^2 bacteria/g by microwave treatment, while no colonies were found after water-bath warming (Rosenberg and Bögl, 1987).

Bacterial spores can, of course, be inactivated by dielectric heating, provided that the temperature and treatment time are sufficient. This does not apply to the process of preparing and warming of meals in microwave ovens. Indeed, the usual microwave treatment, particularly the process of warming up precooked meals, causes a stimulation of the spores in many cases, increasing their germination, leading to a higher content after heating.

With regard to the resistance of the various bacterial types, the same applies for dielectric treatment as for any other heating technique. For example, moulds and yeasts are, of course, more rapidly killed than bacteria. The product composition is decisive for the amount of microbial reduction. The question whether a substance or microorganisms subject to a dielectric treatment may be expected to show changes that are not due to heat

development alone, in addition to the purely thermal effects of microwave energy, is still a matter of debate. According to an energy balance, no nonthermal effects are expected. Obviously the temperature level is the most important factor responsible for the lethal effects especially in the radio-frequency and microwave frequency ranges. This may be concluded from the results of some experiments with very dry agents in which no microbial reduction was detected without heating. Experiments conducted to reduce dried bacterial spores, vegetative cells and spores in dry soil, or microorganisms on cardboard discs were as unsuccessful as the attempt to sterilize spices without heat exposure (Rosenberg and Bögl, 1987).

Selective heating of insects in cereals has been shown to be possible and permits killing of the pests without entailing unfavourable effects on the milling and baking properties (Fleurat Lessard, 1989; Nelson et al., 1966). However, some literature suggests that selective heating of pest may only be possible in the high-frequency range from 1 to 100 MHz, and not in the microwave range (Rosenberg and Bögl, 1987; Nelson et al., 1998). For successful selective heating of the pests in the carrier material, the ratio of the dielectric properties is of importance and $\epsilon'_{insect}/\epsilon'_{food}$ must be as small as possible and tan δ_{insect}/tan δ_{food} as high as possible. It may therefore be concluded that a lower water content of the products is more advantageous for selective heating of the pest.

The process of heating through permanent and induced polarization is called dielectric heating. The overall process of heating by microwaves and RF is defined by the dissipation of electrical energy in "lossy media". The polarization effect is a function of the radiation frequency, the dielectric and electric properties of the material, the viscosity of the medium and the size of the polar molecules (Rosenthal, 1992).

1.3. MATERIAL PROPERTIES

Water is the major absorber of electromagnetic waves in foods and, consequently, the higher the moisture content, the better the heating. The organic constituents of foods are

dielectrically inert ($\epsilon' < 3$ and $\epsilon'' < 0.1$) and, compared to aqueous ionic fluids or water, may be considered transparent to electromagnetic waves. Only at very low moisture levels, when the remaining traces of water are bound and unaffected by the rapidly alternating field, do the components of low specific heat become the major factors in heating. In high carbohydrate foods, such as bakery products, syrups, and alcoholic beverages, the dissolved sugars and alcohol are the main susceptors (Rosenthal, 1992). Foods with phases of diametrically opposed dielectric properties are likely to be heated with drastically different temperature gradients: highly absorbing components suspended in a continuous phase of low absorbance (jelly inside a doughnut); low absorbance components suspended in a continuous phase of high absorbance (meat and vegetable pieces in soups); or layered products with alternating phases of low and high absorbance (cheese and dough layers in pizza).

The overall efficiency of heating is affected by the radiation frequency, the food composition, the size of the material, its salt content, its moisture content, its temperature and few other factors. Foods of a lower density heat faster at a given level of power absorption than do denser foods of similar composition. Air is practically transparent to electromagnetic waves because of its low dielectric constant ($\epsilon'=1$) and therefore its presence in a material reduces the amount of power absorbed and increases the penetration depth. In spite of a low dielectric loss, and a poor absorption, a compound of a low specific heat can be heated up easily by electromagnetic waves because of the lower amount of calories needed per unit weight to raise the temperature. In the context of foods, this property is most relevant for fats and oils. Although the relative dielectric constants ($\epsilon'<3$) and loss factor ($\epsilon''<0.1$) of oils and fats are much smaller than that of water at 20°C ($\epsilon'=80$), they heat considerably faster since the thermal capacity of 2 kJ/kg°C is less than half that of water (4.2 kJ/kg°C). This becomes very important in the treatment of meats and meat products. The thermal conductivity will influence the homogeneity of the heating process. Heating is a direct relationship between the amount of energy for heating and size of material subjected to heating. If the size of an individual piece is very large in comparison to the wavelength, superficial heating is favoured, whereas for sizes closer to the wavelength, temperature may be higher in the centre. The more regular the shape, the more uniform the heating. Thinner parts may be overheated

compared to larger parts. This effect may be controlled by reducing the power input and extending the heating time. Although the speed of heating can be easily increased by boosting the electromagnetic power, in practice, this option is treated with caution as an excessive rate will lead to nonuniform temperature profiles. While in conventional heating the limiting factor of the heating rate is the thermal conductivity of the material, with dielectric heating, the heterogenous dielectric properties are the determinant. Each processing operation, such as cooking, baking, drying, pasteurizing, etc. requires specific optimized heating gradients to enable the desired physico-chemical changes to occur properly. Cooking with electromagnetic waves confers no qualities to food other than those due to efficient heating. Although there are contradicting scientific reports, the general consensus would lead to say that the lethal effects on microorganisms are due to heat. Speed and evenness of heating are influenced by the composition and mass of food as well as by features of the heating unit. Since the heating during dielectric cooking could be uneven, the presence of relatively cool regions might account for the survival of bacteria even when very high temperatures are recorded in other parts of a food.

1.4. DIELECTRIC HEATING

The difference between Radio Frequency (RF) and Microwave (MW) is principally in the technology. In RF, an electric field is developed between electrodes while in MW, it is a wave being propagated and reflected under the laws of optics. RF works well with large quantities having high ionic conductivity. MW works well with small quantities of a dipolar nature. At 27.12 MHz, the wavelength is in the order of 10 m. The skin depth is very small in conducting metals and the transfer of the RF is carried onto the perimeter thus requiring the use of thin strip connectors rather than cables. RF is often perceived as a mysterious technology since each installation requires individual tuning and specific design characteristics (Electra, 1987).

Only certain frequency bands are allowed by law for industrial and scientific use in

order to avoid interference with bands used in communications. The frequency bands currently used are 27.12 MHz (central wavelength 11 m), 915 MHz (central wavelength 32.8 cm), 2450 MHz (central wavelength 12.2 cm) and 5800 MHz (central wavelength 5.2 cm).

From an overlook of the RF technology for dielectric heating, its use in industry is not widely spread although its usefulness has been demonstrated in a few industries (UIE, 1992). The problem of heating organic materials for industrial processing has to be studied. First of all, organic materials are subject to damage from relatively low temperatures, and the degree of damage is a complex function of time, temperature and rate of temperature rise. Bio-materials are usually not sufficiently strong to withstand wide temperature distribution from the standpoint of stresses and structural damage may result from such treatment. Organic materials may also contain volatile matter which is given off during the heating cycle which may significantly alter their quality. Many such substances are colour sensitive to temperature, and rigorous temperature control must be maintained to preserve the appearance of the material. Temperature excesses or extended periods of time at tolerable temperatures may change the appearance, taste, or quality of the food product. Additional research on mutual interactions between food products and dielectric processing equipment is still needed to provide a practical basis for process control and minimizing of process energy costs, microbial safety and product quality. Processes for high-moisture solid foods have been less successful in extensive research conducted at 2450 MHz, unless combined with convection heating methods. This results, to some extent, from low penetration depths that could be increased at frequencies below 2450 MHz, such as 915 and 27.12 MHz.

1.4.1. How does RF heating work?

In a radio-frequency heating system, the RF generator creates an alternating electric field between two electrodes. The material to be heated is placed between the electrodes where the alternating energy causes polarization, where the molecules in the material continuously reorient themselves to face opposite poles. When the electric field is alternating at radio frequencies, for example 27.12 MHz, the electric field alternates 27,120,000 cycles

per second. The friction resulting from the rotational movement of the molecules and the space charge displacement causes the material to rapidly heat throughout its mass. 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 radio waves. Dielectric materials exhibit the property of polarisation because their molecular structure has strongly bound electrons unlike that of conductive materials which have free or loosely bound electrons. Polarisation can take place at both the atomic and molecular levels. In the case of heating at radio-frequencies there exist principally two mechanisms of polarisation namely dipolar polarisation, where polarised molecules are realigned with the alternating field, and; space charge polarisation, where some charge carriers migrate under the influence of the alternating field.

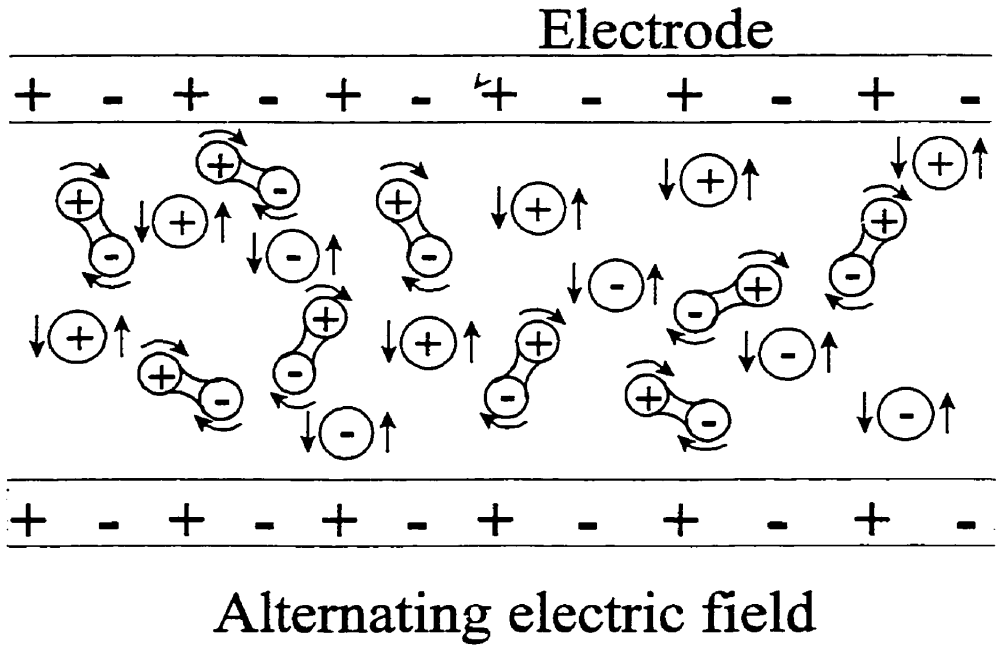

Figure 1.1: Space charge and dipolar polarisation in an alternating electric field at radio-frequencies.

The polarisation in a RF field is illustrated in Figure 1.1. When a material is placed in an alternating field at radio-frequencies, its charged carriers are pulled towards opposite electrodes at the speed of the alternating electric potential. At the same time, its polar molecules are rotated with the alternating field in search of the proper alignment. The realignment of charge carriers and polar molecules with the alternating field results in the generation of heat within the material caused by the polarisation itself and by the friction between the moving parts.

The Applicator

The success of an RF heating set up lies in its design and in the impedance matching between the power generator and the applicator. The quality of the applicator's design is very important for its efficiency. Attention must be given to the choice of materials (quality of the electric contacts, resistance to corrosion, dielectric behaviour of insulators, etc.) and to the set up as a whole (rigidity, durability, electrode set-up and practicality, efficiency of the enclosure and grounding, etc.). Low level measurement of applicator impedance permits a study of the behaviour of the applicator. Values of impedance for the empty and loaded applicator allow to verify the quality of the matching between the electric field and the material. The measurement of the impedance requires the use of a network analyzer. This instrument gives the real and imaginary parts of the impedance of a dipole in a given frequency band.

The development of new applications for RF and the design of applicators require sophisticated tools (network analyzer) and considerable amount of expertise for fine tuning. The investment costs are high, from five to ten times higher (per kW) than conventional means of heating. The efficiency of energy conversion to the product is in the vicinity of 60%.

1.4.2. Why dielectric heating?

The market pressure to put out ever-tastier, ever-cheaper low- and no-fat, chemical-free and safe products is one of the most pervasive trends in today's food industry. Low-fat

baked goods, crackers and snacks need to be dried carefully, because the stiffness of their dough makes them especially fragile. To drive out the last 1 to 2% of moisture, it is sometimes necessary to overheat the crust, which can lead to surface checking, breaking and crumbling. Radio-frequency heating offers a way around that dilemma, offering electromagnetic energy of a much longer wavelength than microwave, which allows it to be directed more accurately. The crust avoids damage because radio-frequency heating targets the product, not the air surrounding it. In fact, because the interior of the product gets hot as quickly as the rest, RF treatment tends to drive moisture out through the crust, equalizing moisture throughout the product. A no-fat tortilla chip maker, gets most of the moisture out of the chips with a conventional drying oven, but uses a *Proctor Strayfield* RF dryer to drive out the last 3% of moisture. Many applications of RF heating, as supplemental heat, have been developed successfully in the food drying industry for pasta, crackers, and snacks (UIE, 1992). However, the development of applications in the agricultural and food sectors are still very limited.

Conventional fuel sources are likely to be depleted soon. The development of new sources of energy, the introduction of solar and nuclear energy stimulate the more efficient utilization of electric power. In this respect, dielectric techniques might play an important role in the future. The rationale selection of the conditions of dielectric energy input and its occasional combination with conventional technologies lead to products which meet, and often improve, the quality requirements of existing products and open the field for new products (Demeczky, 1985).

Attempts to portray dielectric heating as the universal solution to all heating and drying problems is distinctly counter-productive and only when the process parameters of material constituents, production rates, quality and value-added are shown to be suitable, can a sustainable case be made for the wide adoption of the technology (Jones, 1987).

The capital cost of RF and MW equipment is high and without doubt many applications, although technically feasible, are not at the present, economic, except when the process can offer an added-value or when the process must cope with new environmental constraints, new production means or health risks.

1.5. OBJECTIVES

In view of extending the applications of RF heating in the agricultural and food sectors, the present study had the following objectives:

1) To present the available literature on existing and developing RF applications;
2) To clarify the means and procedures involved in the design of an RF applicator;
3) To study the potential of RF heating to disinfect wheat seeds and to improve the germination vigour of soybean seeds;
4) To study the impact of RF heating, on the quality of seed grade wheat, through germination testing and x-ray analysis of structural damage;
5) To study the RF thermal treatments of minimally processed carrot sticks as a means of enhancing their packaged shelf-life; and
6) To evaluate the potential of RF pasteurizing of prepared ham to improve shelf-life and safety of vacuum packages destined for retail outlet sale.

Physical control is an important means for integrated pest management in post-harvest handling of agricultural and food commodities. Physical control methods may not offer residual protection, as chemicals do, nonetheless, physical means should be considered as a hurdle, one of many, in the grand scheme of post-harvest handling.

CHAPTER II - LITERATURE REVIEW

2.1. ABSTRACT

The literature review presented here covers briefly the published literature on various researched and developed RF applications for heating and drying. More detailed literature review, pertinent to the subject of the subsequent chapters, can be found in each such chapters.

2.2. INTRODUCTION

Viewed from their domain of application, radio frequencies form an ensemble. The interaction with the product is achieved by phenomena of ionic conduction and polarization in the High or Radio Frequency (HF or RF) domain, and by rotational polarization in the Microwave (MW) domain. We are dealing with relaxation phenomena stretching over a very large domain of frequency. This explains the fact that many types of chemical bonds are affected by these frequencies in each product and that often the criteria for choice between the two techniques are related to the appropriateness between the technology and the character of the product, the industrial environment, and the investment cost. It is at the level of the technology, that microwave and high frequencies differ with regard to industrial applications (Bialod, 1985).

The essential problem in the applications of radio frequencies is the transfer of energy from the generator to the product placed in an industrial environment. The efficiency of the generator being around 60%, and taking into account the high investment cost per usable kilowatt, the major part of the emitted energy must be absorbed by the product with acceptable uniformity. Certain applications are well known and RF generators are readily available, e.g. preheating of rubber, wood drying, textile drying, baking and post-baking.

For new applications, the design and installation of radio frequency equipment consist in the development of equipment specific to the needs of the product and of the application. Each new equipment is considered as a prototype requiring extensive testing which is translated in prohibitive investment costs and industrial risks.

Perhaps we could first look at defining the technology itself and at what has been done by others in terms of developed applications and their uses.

2.3. ELECTROMAGNETIC HEATING

Electro-heat is defined as the branch of science and technology dealing with the transformation of electric energy into thermal energy for useful purposes. It is divided into resistance heating, infrared heating, arc heating, induction heating, radio-frequency heating, microwave heating, electron beam heating and plasma heating. An electromagnetic wave is seen to be a blend of an electric component (E) and a magnetic component (H). In principle, a classification of the group of electromagnetic heating processes may be based on substance properties as defined by the equations relating current density **J**, electric and magnetic flux densities (**D, B**) to the corresponding field strengths (**E, H**) (Risman, 1991). The basic substance properties are σ (conductivity, 1Ωm), ϵ_{abs} (absolute permittivity, F/m), and μ_{abs} (absolute permeability, H/m) which are expressed as follows:

$$J = \sigma E \tag{2.1}$$

$$D = \varepsilon_{abs} E \tag{2.2}$$

$$B = \mu_{abs} H \tag{2.3}$$

Dielectric heating lies in the electromagnetic spectrum in the range of frequencies from 300 kHz to 300 GHz. Radio-Frequencies (RF) range from 300 kHz to 300 MHz and Microwaves (MW) range from 300 MHz to 300 GHz (Table 2.1).

Table 2.1: Dielectric heating frequency ranges (Assenheim et al., 1979).

300 - 3000 kHz	Medium frequency (MF)
3 - 30 MHz	High frequency (HF)
30 - 300 MHz	Very high frequency (VHF)
300 - 3000 MHz	Ultra high frequency (UHF)
3 - 30 GHz	Super high frequency (SHF)
30 - 300 GHz	Extremely high frequency (EHF)

In one class of application frequencies, namely between 1 MHz and 300 MHz, the electromagnetic characteristics of the non-magnetic workpiece (dielectric material) are dominated by the permittivity. The permittivity is then so small, the frequency so small that there is no appreciable influence on the heating pattern due to the wavelength of the time-varying electric field. This class is defined as the dielectric method of heating where the heating pattern is determined by the action of a quasi-electro-static field of a frequency ranging from 1 MHz to 300 MHz, in the radio-frequency range. At microwave frequencies, both electric and magnetic fields are of importance both in the applicator and the workload. Furthermore, engineering and safety considerations are different to those at lower frequencies. The term microwave heating is simply to define heating of a substance by electromagnetic energy operating in the frequency range 300 MHz to 300 GHz. For lower frequencies, the terms high frequency (HF) and radio frequency (RF) are generally used.

The permittivity is found as follows (Risman, 1991):

$$\frac{D}{E} = \varepsilon_{abs} = \varepsilon_o \varepsilon = \varepsilon_o (\varepsilon' - j\varepsilon'') \tag{2.4}$$

where, ϵ_o is the absolute permittivity of vacuum, also called the electric constant (ϵ_o = 8.854188 $\cdot 10^{-12}$ F/m). It is not possible to separate the various power absorption mechanisms by macroscopic measurements at a given frequency, the imaginary part ϵ'' generally includes the conductivity contribution $\sigma/\omega\epsilon_o$, where ω is the angular frequency ($\omega = 2\pi f$) and $\epsilon''_{abs} = \epsilon'' + \sigma/\omega\epsilon_0$. The dielectric constant ϵ' varies significantly both with temperature and frequency for many typical workload substances and in many microwave and dielectric

heating applications it is actually necessary that it changes during the process. The ratio ϵ''/ϵ' is often called loss tangent in dielectric and microwave heating. The terms recommended are dielectric dissipation factor or loss tangent for $\epsilon''/\epsilon'=\tan\delta$.

Where:

ϵ	relative complex permittivity;	ϵ'	relative real permittivity
ϵ''	relative dielectric loss factor;	$\tan\delta$	dielectric loss tangent

The permittivity is a measure of a material's ability to store electrical energy, and the loss factor is a measure of its ability to dissipate electrical energy. The loss tangent $\tan\delta = \epsilon''/\epsilon'$ is related to the material's ability to be penetrated by an electrical field and to dissipate (attenuate) electrical energy as heat (Mudgett, 1986).

Theoretically, the power penetration depth is defined as the depth below a large plane surface of the substance where the power density of a perpendicularly impinging forward propagating plane electromagnetic wave has decayed by 1/e from the surface value (1/e=1/2.718..≈37%).

$$d_p = \frac{\lambda_o}{2\pi}\sqrt{\frac{2}{\varepsilon'\left[(1+\tan^2\delta)^{\frac{1}{2}}-1\right]}} \qquad (2.5)$$

where

d_p	is the field penetration depth (cm)		
ϵ'	relative permittivity;	λ_o	wavelength in free space (cm)

Owing to the interaction of the dipole moment with the electric field, a polar substance has a dielectric constant which is larger than that of a non-polar material. The dielectric constant of a polar material is strongly dependent upon various physical parameters such as temperature, pressure and frequency of applied field (Grant et al., 1978). For a polar substance the relative permittivity ϵ' (dielectric constant) decreases with increasing frequency as the motion of molecular dipoles is unable to keep up with the changes in direction of the

electric field. Accompanying this fall in permittivity is an absorption of energy by the medium from the field. All biological molecules are polar therefore they are likely to respond well to electromagnetic stimulation.

2.3.1. RF Heating

In alternating current, the direction of flow is constantly being reversed. The number of times that the current changes direction per second is called the frequency, and it is measured in Hertz (Hz).

Frequency, f = 1/T cycles per second = Hertz = 1 s^{-1}; T = period (time units)

$$f = \frac{v}{\lambda}; \quad \lambda = \frac{v}{f}; \quad \omega = 2\pi f \tag{2.6}$$

where v = velocity, λ = wavelength, ω = angular frequency.

And

$$v = \frac{c_0}{\sqrt{\varepsilon'\mu'}} \tag{2.7}$$

where c_0 = velocity of light in free space = 300,000 km/s; ϵ' and μ' in air is approximately 1. The wavelength = $\lambda = 300/f$; where λ is in m, and f is in MHz.

The principle of selective dielectric heating is best seen by examining the general expressions for time rate of temperature rise and power dissipation in a dielectric, as follows:

$$\frac{dT}{dt} = 0.239 \times 10^{-6} \frac{P}{c\rho} \tag{2.8}$$

$$P = 2\pi f E^2 \varepsilon_o \varepsilon'' \tag{2.9}$$

Which yields the following equation since $\epsilon_o = 8.85 \times 10^{-12}$ F/m.

$$P = 55.61 f E^2 \varepsilon''_r \times 10^{-12} \tag{2.10}$$

where dT/dt is expressed in °C/s, P is expressed in W/m^3, c represents the specific heat of the dielectric material (J/kg·K), ρ is its density (kg/m^3), f is the frequency (Hz), E is the rms value of the dielectric loss factor (V/m), and ϵ_r'' is the imaginary part of the complex relative permittivity, $\epsilon^* = \epsilon'_r - j\epsilon_r''$.

Because the heating rate (dT/dt) depends on the variable P, and on c and ρ, which are fixed for any given substance and condition, the variables that influence the value of P, the power dissipation per unit volume, will be important in determining differential heating of components of a mixture. If a mixture of materials is subjected to dielectric heating by high-frequency or microwave electric fields, the relative power absorption will depend upon the relative values of E and ϵ''_r for each of the materials in the mixture (Nelson, 1985).

Too high a value of ϵ'' will result in a small skin depth, which annuls the desirable volumetric heating effect. On the other hand, too low an ϵ'' renders the material practically transparent to the incoming energy. Experience has shown that materials with an effective loss factor in the range $10^2 < \epsilon'' < 2$ will be suitable for processing with this form of energy (Metaxas, 1988). Therefore, a knowledge of the dielectric properties is very important when assessing the feasibility of heating a given material (Table 2.2). Selective polar or ionic additions to a low-loss host material can enhance its effective loss and render it suitable for dielectric processing. It is sometimes possible to modify a low loss factor material, without significantly altering its other properties, with a small amount of high loss factor additive, such as carbon black added to natural rubber, or sodium chloride to urea-formaldehyde glues (UIE, 1992).

2.3.2. Material Properties

Potential applications of RF cover a great number of dielectric materials containing ions and polar molecules. The alternating electric field in RF forces the displacement of ions leading to small localized electric currents where the material heats up from the Joule effect (Bialod and Marchand, 1986), and the interaction with polar molecules (common to microwave) through relaxation. With sinusoidal alternating currents the polarisation is a function of the relative position of the two opposite charges.

Table 2.2: Loss factor, ϵ'' for some common materials (UIE, 1992; Nelson,1973).

Material	27.12 MHz	2450 MHz
Pork fat	51	2.7
Pork meat	420	18
Fruit	275	15.5
Raw carrot	319	13
Polyethylene	<0.1	0.001
Ice (-20°C)	0.2	0.1
Salt water	900	19.6
Pure water	0.4	10.7
Wheat	0.4	0.2

If the polarisation is in phase with the electric field (δ=0 at low frequency), the potential has a quadrature loss (90°) with respect to the intensity. The active power is zero while in relaxation mode, the polarization assumes a δ lag with the excitation electric field: the source supplies an active power of $VI \cos(\pi/2 - \delta)$. The material reacts as a condenser with loss factor δ (Figure 2.1).

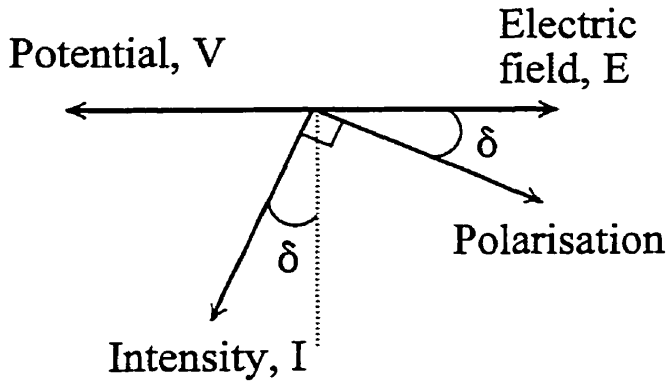

Figure 2.1: Fresnel diagram representing the relative phases.

The absorption of electromagnetic waves by biological materials is highly dependent on the frequency. The amount of energy absorbed at a particular frequency is dependent on the dielectric parameters of the material and the size and dimensions with respect to wavelength. In the low frequency range, a biological tissue is almost non-absorbent to RF

energy and the reflection coefficient is high. The absorbed energy in the RF region probably varies from 0.01 to 10% (of incident energy) from 300 kHz to 300 MHz, respectively. Thus, when a sample has dimensions much smaller than the wavelength, most of the energy is transmitted around the sample. At higher frequencies (microwave), the cross-sectional area of the exposed subject is comparable to, or greater than the wavelength, the reflection coefficient has a value ~ 60%.

There are considerable differences in the electrical and thermal response of foods to microwave and radio-frequency fields, which depends on aspects of chemical composition, physical structure, and geometry of the product and the mechanism or dominant mode of energy transfer from the electromagnetic field to the product (Mudgett, 1985). By Industrial, Scientific and Medical regulation (ISM), dielectric heating applications are assigned to a limited number of frequencies in RF 13.56, 27.12 and 40.68 MHz, and microwave frequencies of 915, 2450, 5800 and 24225 MHz. Although the use of 915 MHz is permitted in North and South America, most of the commercially available microwave food processing equipment is designed for operation at 2450 MHz. This reflects manufacturing emphasis on the development of home microwave ovens. Parenthetically, field penetration depths may be considerably greater at 915 and 27.12 MHz.

The dielectric properties of food materials may be determined in frequency intervals from direct current to optical frequencies by various measuring techniques. Lumped circuit methods may be used to determine complex permittivity over the frequency range from zero to approximately 200 MHz. At frequencies from 10 MHz, the capacitance and dissipation factor of samples are generally measured by a capacitance bridge. At frequencies from 10^4 to 10^8 Hz, resonant circuits with fixed inductors and variable capacitors may be used, with resonance indicated by voltmeter deflection. Resonance methods also measure the material's capacitance. But the loss component is obtained from the width of the resonance curve, determined by either susceptance or frequency variation of the material. Dielectric constants are obtained by either method from their relationship with the material's capacitance (Mudgett, 1985).

The choice of processing frequency for a particular unit operation may be critical

because the dielectric behaviour and heating characteristics of foods vary with frequency and temperature in patterns which are significantly affected by moisture and salt contents. Ionic losses for a particular product are much higher and dipole losses are much lower at 915 MHz than at 2450 MHz and vice versa. At higher ISM microwave frequencies (5800 MHz), dipole losses for most products are much greater and ionic losses become negligible. In contrast, ionic losses are increasingly greater as frequency decreases at sub-microwave frequencies, and dipole losses for free-water become negligible. The effects of frequency variation in the radio-frequency region on the dielectric constant are negligible because of the dielectric constant of water in this region is close to its static value.

The dielectric properties of semisolid food products are primarily determined by their chemical composition in terms of moisture, salts and solid contents and to a much lesser extent, by effects of physical structure. Moisture and dissolved salts are the major determinants of dielectric activity in the liquid phase of such products as modified by volumetric exclusion effects of an inert solids-phase containing colloidal or undissolved lipid, proteins, carbohydrate, ash, or bound water. In general, natural semisolid food materials may be considered in groups of low (fruits and vegetables), intermediate (vegetables and meats), and high (meats and fish) conductivity with limited penetration depths at microwave frequencies. Processed foods with added salt have much higher liquid-phase conductivities and therefore much lower field-penetration depths at frequencies in the microwave region, or in other words, most of the energy in such products is absorbed by "skin effects" close to the surface (Mudgett, 1985).

Liquid or semi-solid foods containing suspended phases with greatly different properties from their continuous phase can be considered as heterogeneous products. Dielectric behaviour of one phase that is essentially different from another phase results in differential heating rates of the phases. Differential heating rates in real food products are seen to depend on phase properties that differ to some extent from those of the idealized systems. Generally, in products with electrically dissimilar phases and phase thicknesses close to their power penetration depths, the phase with the higher dielectric loss factor heats more rapidly, in spite of the impedance mismatch at the boundary between the phases (Mudgett,

1985).

2.4. RADIO-FREQUENCY HEATING APPLICATIONS

When it is appropriate (or necessary) for foods to be heated, High Temperature Short Time (HTST) treatments generally deliver products of a superior quality (Harlfinger, 1992; Rosenberg and Bögl, 1987). For this reason, electromagnetic energy, with its rapid heating potential, may offer a competitive edge in agricultural and food applications.

2.4.1. Thermal Treatment of Food Products

Research in RF technology has stated the possibility of sterilizing or pasteurizing a food product at time-temperature values much lower than those now required using conventional heating techniques. Conceivably, the benefit of using RF energy comes from a potential selective killing effect on microorganisms other than that attributable to a heating effect or a targeted localised heating of the microorganisms. The literature on this topic is quite diverse and somewhat variable and, at times, contradictory in nature.

Beckwith and Olsen (1931) reported significant reductions in the numbers of *Saccharomyces ellipsoideus* and other yeast suspension irradiated with RF for 15 min. Temperatures of the irradiated suspensions were not allowed to exceed 39°C. Fabian and Graham (1933) treated broth suspensions of *Escherichia coli* with 7.5, 10, and 15 MHz RF energy in a combination condenser-cooler apparatus which maintained the medium at about 19°C by circulation of cold water in the jacket of the condenser. They found that destruction of the bacteria occurred at the three frequencies with lethal effect greatest at 10 MHz. About 88% destruction of *E. coli* occurred after 8 h of treatment. Fleming (1944) irradiated *E. coli* with RF energy of various frequencies from 11 to 350 MHz. A 10-W power input was used and the time of exposure for all treatments was 1 min. Maximum temperature reached during any treatment was 30°C. All frequencies tested had a lethal effect on the bacteria with the greatest effect, about 98% destruction, occurring at approximately 60 MHz. Nyrop (1946)

applied RF energy of 10-100 kHz to *E. coli* in broth suspensions. He used electrodes in close contact with the broth medium. He observed that 99.6% kill was achieved with a field strength of 205 V/cm in 5 s. and 99.8% kill in 10 s. exposure. Brown and Morrison (1954) studied the effect of RF energy at 50Hz, 190 kHz, 25 MHz on *E. coli*. The bacteria were irradiated in nutrient broth by means of a capsule electrode assembly. Their initial experiments disclosed many instances of destruction of *E. coli*. They found, however, that a thermal effect was responsible as temperatures in the capsule reached 55 °C. They repeated their earlier work and concluded there was no significant killing effect in most treatments unless the final temperature exceeded about 50 °C.

If the RF energy has a synergistic effect with heat on the microorganism, a greater killing effect than that determined in a water bath study should be observed (Carroll and Lopez 1969). The general consensus from literature is that the only lethal effect on *S. cerevisiae*, *E. coli*, and *B. subtilis* attributable to the RF treatment is a thermal one and there is no synergistic effect of heat and RF energy on these microorganisms.

If heat can be generated faster in the microbial cell than in the suspension medium, the cell might be destroyed thermally at a comparatively low heating rate of the suspension medium. This possibility is dependent upon the chemical composition of the suspension medium and of the microbial cells. Since most microbial cells bear an electrical charge, usually negative, there exists the possibility of mechanically disrupting the cell by causing it to oscillate rapidly in the high-frequency field. If these oscillations are rapid enough, or of a large enough displacement, or both, the elastic limits of the cell structure might be exceeded, thus causing the cell to rupture and die (Carroll and Lopez, 1969). If RF energy of a given frequency is selectively absorbed by certain critical organic molecules of the microbial cell such as an essential protein or DNA molecules, these molecules could be irreversibly denatured and the microorganisms rendered non-viable at low-heating levels of the suspension medium. Whether or not this possibility occurs, it may depend on what happens at the molecular level. Very little is known concerning the effects of RF energy on molecules other than water. An investigation into determining a RF frequency at which DNA molecules resonate could prove especially fruitful. If such a resonance frequency exists, the application

of RF energy of sufficient intensity at this frequency might cause either a direct, physical change in the configuration of the molecule, or the energy could be dissipated mainly as heat (Carroll and Lopez, 1969).

Food Pasteurizing

Research was conducted on the electrical heating of fat/muscle layers of ham for pasteurizing with capacitive dielectric heating up to 100 MHz (Bengtsson et al., 1970). The bacteriological examination was made by surface sampling, plating on ATP-agar and incubating at 30°C for 3-4 days. A limited study of the bacterial flora present was made with total counts (Bengtsson et al., 1970). Heat generation was considerably higher in unsalted pork than in ham with 3% salt content, while the difference was only slight between 3 and 6% salt content. Power efficiency was higher at 60 MHz than at 35MHz. Size of the air gap was critical to power efficiency and had to be small. Temperature distribution in the ham was improved by using lean hams of uniform salt content, by increasing the frequency from 35 to 60 MHz and by good thermal insulation of the moulds. Horizontal layers of fat were always overheated, while vertical layers (perpendicular to the electrode) and embedded balls or cylinders of fat were not (Bengtsson et al., 1970). Significantly lower juice losses were obtained with RF-processing than in hot water processing and treatment time was less than half. Sensory evaluation showed a general tendency towards better quality of RF-processed hams, particularly for juiciness.

Microbiological examination after prolonged storage showed considerably higher total counts for RF-processed hams, indicating a need for higher final temperatures or supplemental heat treatment. Total counts decreased with increasing salt content and final water temperature, and in one of the runs, where salt content was 5% and final temperature above 75°C in the immersion water, bacterial counts were very low (Bengtsson et al., 1970).

Dielectric pasteurization of lean hams at 60 MHz resulted in acceptable temperature distribution and substantially reduced heat treatment time and juice losses with indications of an advantage in sensory quality. On the other hand, the shortened heat treatment, in combination with a lower surface temperature than in conventional hot water processing, gave

a higher surface infection. The higher surface infection of RF-processed hams is probably a direct result of the lower and shorter surface heat treatment. After processing, only spore-forming bacteria were found indicating that the heat treatment was sufficient to kill vegetative cells.

In comparison, at 2450 MHz with 454 g ham, considerably higher power density in the ham and shorter heat treatment time could be used than at 60 MHz with higher power efficiency. At the same time, surface temperatures reached were considerably higher than at the lower frequency, and juice loss was roughly comparable to that in hot water processing at 85°C (Bengtsson et al. 1970).

RF Heating of Sausages

The dielectric properties of sausage emulsions were tentatively assessed by reflection measurements in a coaxial waveguide partially filled with sausage emulsion in the range 10 to 300 MHz (Houben et al., 1991). Estimations of the penetration depths have showed that, for heating large diameter items, electromagnetic energy approximately in the 10 to 100 MHz range would be the best choice, with the 27 MHz ISM approved band, ideal for avoiding radio interference.

Stationary heating tests with sausage emulsions at varying formulations stuffed in tubes made of different materials were performed at 27 MHz by Houben et al. (1991) in a heating unit consisting of a cylindrical borosilicate glass tube through which a sausage emulsion was passed. The rapid heating rates resulted in considerably reduced Cook values (Cook values represent integrated heating times at a reference temperature (80 to 113°C) with respect to physical and chemical changes of product quality) as compared to conventional heating methods (Houben et al., 1991). Sausage products heated well and had a good appearance without release or loss of moisture and fat. Temperatures in the pasteurization region (~80°C), could easily be reached, yielding promising results.

RF Heating for Tempering

A French RF and MW equipment manufacturer, Sairem (Bernard, 1997), has worked

with the fish industry to develop RF-tempering techniques in the fish processing sector. The 50Ω technology for fish tempering is improving the productivity and lowering the manufacturing costs while promoting the development of more innovative products for the benefit of the fish industry and its consumers.

2.4.2. Seed Treatment

Problems with poorly or slowly germinating seeds have plagued growers of numerous plant species in agricultural production of field crops, horticultural crops, ornamental, nursery materials for landscaping, and forest trees. Particular success was achieved in the treatment of alfalfa seed and that of some other small-seeded legumes that exhibited impermeable-seed-coat problems (Nelson and Stetson, 1985).

In cultural production, the seed-coat impermeability problem is not one of seed viability, because hard seeds will eventually germinate and grow. Instead, the seed coat is impermeable to moisture, and hard seeds cannot be depended upon to germinate quickly when planted to produce an acceptable stand of the crop within a short initial period. Hard seeds that germinate later may result in seedlings that are too small to compete effectively with other vegetative growth (Nelson, 1976).

For many years, seedmen have used a process known as scarification to increase the permeability of seed coats in seed lots with high percentage of hard seed. This is an abrasive process that has a damaging effect on seed, and lots that have been mechanically scarified cannot be stored for the next season without high risk of serious deterioration in seed quality.

When a seed is exposed to RF fields of sufficiently high frequency and intensity, its temperature will rise due to dielectric heating, its germination will increase to some maximum as exposure increases, then, with continued increasing exposure, germination will decline (Nelson, 1976).

Direct comparison of 39 MHz and 2450 MHz exposures on germination of alfalfa seeds of three different varieties was made by Stetson and Nelson (1972). The two frequencies were equally effective for reducing hard-seed percentages and increasing germination when the resulting seed temperatures were comparable. The choice of operating

frequency for the treatment of alfalfa seed to improve germination seems to be of little consequence as far as the seed response is concerned. This choice is more likely determined by process requirements and economic factors (Nelson, 1976).

Moisture in seeds is always an important factor. In hard seeds like those that occur in alfalfa, the hilum operates as a hygroscopically activated valve, permitting moisture to escape from the seed but closing to prevent the seed from taking up moisture in a humid environment. When seeds are treated with RF energy, moisture content is important for two reasons. Since the dielectric loss factor of seeds increases with moisture content, their moisture content determines the rate at which they will absorb energy from the RF electric fields. Further, the temperatures that seeds can tolerate without loss of viability are dependent upon their moisture content (Nelson, 1976). RF treatment is more successful in lowering hard-seed percentages when moisture content is low. Also, the final seed temperatures produced by optimum treatment levels increases as moisture content decreases, ranging from 49°C for the highest moisture content to 100°C for extremely dry seed.

The most important temperature influence appears to be that of the final temperature to which the seed is raised by RF treatment. For seed lots of normal moisture content, about 6 to 7%, a treatment that results in a temperature of about 75°C is close to the optimum exposure for increasing germination by lowering hard-seed content. The maintenance of high quality in RF-treated seed lots for several years after treatment is an important advantage over mechanical scarification (Nelson and Stetson, 1985).

2.4.3. Grain Treatment

Nelson and Stetson (1974) studied treatments at 39 MHz and 2450 MHz to control rice weevils in wheat. Their results indicated that 39 MHz treatments were more effective with complete insect mortality at a treatment temperature of 40°C, whereas, 2450 MHz required a treatment temperature of 80°C to achieve complete mortality.

Fleurat-Lessard et al. (1979) have studied the biological effects of RF and MW on two common insects *Tenebrio molinor* and *Pieris brassicae*. Insect larvae and pupae exposed to high and ultra high frequencies with power densities under thermal lethal level showed

metabolic modifications and imaginal phenotypic abnormalities.

In an experiment by Nelson et al. (1981), dielectric heating at 42 and 2450 MHz was applied to whole soybeans. Chemical analyses revealed that dielectric heating of soybeans can be as effective as conventional steam roasting in reducing trypsin-inhibitor activity.

2.4.4. Wood Disinfestation

The pinewood nematode *Bursaphelenchus xylophilus* is a destructive pest of the pine forests of Japan, and may cause some mortality of stressed exotic pines in North America. Pinewood nematode infestations have been found in wood chips exported from North America and in green lumber and packing case wood from Canada. As a result of these interceptions and the pine wilt disease in Japan, the European Community Commission enacted regulations, including a kiln-dried or heat treatment requirement for all imported coniferous sawn wood in order to protect European forests from exotic tree pests.

Dwinell et al. (1994) conducted a study to evaluate a RF/vacuum dryer for the eradication of pinewood nematode in green sawn wood. The electromagnetic radiation was provided by a 10 kW-output radio-frequency generator operating at 13.56 MHz. Two parallel stacks, each comprised of 25 pieces of sawn pine lumber, 5 by 5 cm in cross section and 91 cm long, were treated in each run. In their first trial, a 1kV electrode voltage was applied for 15 h on wood having 24.3% moisture (dry basis), with 25 mm mercury vacuum. The maximum temperature reached was 43 °C in the geometric centre of the centre board, while the temperature of the surface board reached only 35-38 °C. After treatment, 63% of the boards yielded live nematodes. For their second trial, the dryer was operated for 26 h with an electrode voltage of 1.4 kV, and the maximum temperature reached was 50 °C in the geometric centre of the centre board. After the vacuum was turned off, the temperature recorded increased to 80 °C. The temperature of the surface boards never exceeded 39 °C. Nematode extraction revealed that the highest incidence of pinewood nematodes (20 to 36%), was in the end samples of the boards. The boards with live nematodes had an average wood mc of 13.5% whereas the mc of boards free of nematodes averaged 5.3%. In another trial, the vacuum was turned on only 1.5 h after the start of the drying cycle. The temperature first

rose to 75°C, and when the vacuum was applied, the wood temperature rapidly declined to about 30°C. By the end of the run, the wood temperature recorded at the geometric centre of the centre board had increased to 80°C, while surface boards had temperatures ranging 30-50°C. Live nematodes were not extracted from any of the boards and the final average moisture content was 6.6%. Dwinell and Carr (1991) operated parallel electrodes at 27.12 MHz where they were not able to kill the pinewood nematode in pine chips at temperatures below 48°C. Whether under vacuum or not, the eradication of the pinewood nematode in wood by radio waves appears to depend on temperature. Furthermore, above 46°C, nematode mortality is a function of time and temperature. Dwinell and Carr (1991) reported that no live nematodes were recovered from chips heated to 70°C. Dwinell et al. (1994) reported that nematodes were eradicated in boards where the wood temperature exceeded 48°C. This lethal temperature is about the same as that of a conventional steam heat treatment.

In an experiment by Pohleven et al. (1998), RF heating at 4.75 MHz was used to eradicate pine wood decay fungi. The eradication was dependent on the fungus species (*Coniophora p.*, *Lentinus l.*, and *Gloeophyllum t.*), temperature (75-90°C) and duration (4-12 min.) of exposure to RF. At low temperatures, the time of exposure had to be adequately longer.

2.4.5. Soil Disinfestation

The practice of disinfesting soils of pathogens is becoming more and more important for nursery purposes and bagged soil (Szmidt et al., 1989). Soil disinfestation may be accomplished principally by either heat or chemicals. Heat is employed mostly in greenhouses and nurseries where relatively small volumes of soil are required. In an experiment by Eglitis and Johnson (1970), they used a generator with 5.7 kW output, a plate voltage of 5.2 kV, and a frequency of 27.12 MHz. The soils studied were so severely contaminated with damping-off organisms that their use for greenhouse culture was impossible. Seedling survival was only 76% of the theoretical maximum in the least contaminated soil (a specially composted medium with a high organic base) and in five remaining untreated samples the average

seedling stand was only 17%. Seedling counts in the same soils irradiated for 5 min ranged between 86 to 92%. The soil temperature increased from ambient to between 96 and 101 °C at the end of the RF exposure. In two trials, it appeared that a 2 min treatment was inferior to the 5 min treatment, but even this interval improved the average seedling stand from 27 or less to 75-81%. At the conclusion of this experiment, the soil temperature had risen to 46-57 °C. There appeared to be no advantage in prolonging the energy exposure to 10 min (Eglitis and Johnson, 1970).

2.4.6. Soil Remediation

RF heating of contaminated soils offers a way of thermally desorbing organic contaminants for subsequent collection. Soils can be locally heated to high temperatures using RF electrodes, thus most organic contaminants can be desorbed, accelerating the release and transport out of the soil (Edelstein et al., 1994). Recent in situ tests using RF energy to vaporize hydrocarbons in contaminated soils have successfully removed up to 99% of hazardous chemicals. These vaporized contaminants are vented to a surface barrier and condensed to be recovered (Dev and Downey, 1988). Enhanced soil vapour extraction is very promising for in situ soil remediation (Bowder and Daniel, 1997).

2.4.7. Seed De-Germination

High frequency heating has also been suggested as a pre-treatment to kill the germination potential of seeds and weed seeds (Rodionova et al., 1990). De-germination treatments are of interest to bird seed producers and for nursery producers interested in limiting weed propagation (Barker and Craker, 1991; Pyon et al., 1997). RF treatments would offer an interesting alternative to steam-sterilization or high intensity treatments such as roasting. Lambert et al. (1950) conducted RF treatment (15 MHz) devitalization of wheat seeds. Their results indicated that a combination of high plate voltage (>2500 V) with a minimal treatment time of 4 min, successfully devitalized the seeds. Pyon et al. (1997) proposed that RF radiation offers an environmental friendly alternative in weed management practices.

2.4.8. Biomedical Applications

Tissue cells act as electrical conductors because of their electrolyte composition. A direct current causes cellular membrane depolarization in a tissue. If depolarization occurs in neuromuscular tissue, it results in excitation and shock of the tissue. In the body, an alternating current below 100 kHz, causes tissue ions to be pulled alternately to and fro because of the rapid reversal of current flow. If a very high frequency alternating current is applied (> 100 kHz), cellular ions change position to a small degree because of the rapidity of reversal in the direction of the current. Depolarization does not occur and there is no excitation or shock of the tissue. However, such a behaviour, imparts a degree of kinetic energy to the cells, and the ions become excited and collide with other particles. This kinetic energy raises the temperature of the cell so that the effect of very-high frequency alternating current on tissue is not electrical but thermal (Valleylab, 1993). With RF systems, several waveforms of current are available depending on the target application such as: Cutting, where a small spark is formed between the electrode and the tissue and it is the spark and the heat of the current passing through the tissue that does the cutting; fulguration where sparks of modulated current are used to coagulate and char tissue; or any other thermal effect (Valleylab, 1993). In today's medicine, RF has applications in cancer treatment, neurosurgery, catheter ablation, etc. Radio-frequency ablation promises a less invasive alternative to surgery for cancer and many types of tumors (Knight, 1998).

2.5. RADIO-FREQUENCY DRYING APPLICATIONS

The R&D work which has been undertaken so far in high frequency (HF) heating applications is constrained by the small size of the corresponding equipment manufacturing industry and the limited market demand, causing the investment costs to remain high. The present situation may change when more resources are dedicated to the study of the technique and its applications and when the size of the industry increases. However, there are some well known applications of RF energy to drying, especially wood, textile and veneer drying.

2.5.1. Drying of Latex, Veneer, and Resins

Carr (1993), conducted four drying and curing tests on convective heating only, RF heating only (27.12 MHz), preheating with RF oven followed by convective heating and convective heating followed by RF postheating of latex adhesive on carpet. RF heating lowered moisture content very rapidly to below the target value of 5%, requiring much shorter times than for a laboratory convection drying unit. RF drying time was also much lower than the 120 s typically needed in commercial convection ovens (< 50 s). In the case of pre-heating, the latex absorbed RF energy rapidly, and the moisture content dropped even with as low as 2 s of preheating. Movement of moisture from the interior of the material to the surface can increase the effectiveness of convective drying following dielectric heating. In the case of RF post-heating, since much of the moisture has been removed by the convection oven, the latex does not absorb the RF energy as readily as in preheating. Therefore, the drying rate is lower in RF postheating than RF preheating (Carr, 1993).

In a study conducted by Wilson (1989), RF heating (13.5 MHz) was effective in redistributing moisture throughout a bundle and throughout sheets within a bundle in veneer application. Where the veneer had pockets of high moisture content, moisture was distributed to areas of low moisture content (Wilson, 1989). Radio-frequency drying of wood veneer appears to be an attractive alternative to conventional drying practices for the forest products industry. Several significant features make such an installation attractive: a small floor-space requirement, small labour requirement, and no degradation of veneer and the consequent value loss that typically occurs in conventional drying practices. Additionally, the RF-dried veneer is of better quality for processing because moisture content is uniform throughout the sheet. Sufficient storage space is needed, however, to permit the veneer bundles to cool before making them into plywood (Wilson, 1989).

The overall results of Wilson's (1989) feasibility study showed RF drying to be a cost-effective alternative to traditional drying in primary driers. Given an investment of $1 M for equipment, spare parts, and associated storage space, plus an annual operating cost of $ 120 000, the calculated simple payback period (total cost+total savings) on the RF dryer was only 18 months (Wilson, 1989).

Palumbo et al. (1997) conducted a comparative study of microwave and radio-frequency curing of epoxy resins. Their study demonstrated that radio-frequencies are preferable to microwaves in the activation process of cross-linking reactions in epoxy networks.

2.5.2. Alfalfa Drying

Murphy et al. (1992) conducted experiments on RF drying (27 MHz) of alfalfa. In their opinion, a short calculation suffices to confirm that the large-scale drying of alfalfa by RF dielectric heating alone is not economically viable at current energy costs. To dry alfalfa from 80% to 12% moisture content requires the removal of 3.5kg water per 1.0kg of dried alfalfa. Assuming that the water removed is free water, that the alfalfa is initially at 20°C and that the water is vaporized at 100°C, the energy required is 8.8MJ, or 2.4kWh. Typically, the efficiency of RF ovens (the ratio of RF energy absorbed to mains input energy) is about 50-60 %, so 4.9 kWh of input energy would be required to produce 1kg of dried alfalfa. At a rate of 4¢ per kWh, the energy costs alone would amount to $200 per t of dried alfalfa, which is more than the current market value of about $US 150 per t (Murphy et al., 1992). It is clear that the only economically feasible application of RF power to the drying of alfalfa is as a supplementary rather than a major power source. Since RF power is, as a rule, preferentially absorbed in regions of higher moisture content, it was hypothesized that the addition of RF power could lead to more even drying (Murphy et al., 1992).

The application of RF power increases the drying rate significantly for a fixed forced-air temperature, although the magnitude of the increase decreases with time. The power coupled decreases with time since the dielectric loss factor of the alfalfa load decreases as the moisture content decreases. Comparison of the results obtained using forced-air only and RF only, and comparison of the results obtained using RF in combination with forced air at different temperatures, suggests that the alfalfa is more evenly dried when the relative contribution of the RF power is minimized. These results are somewhat surprising, since RF power is typically preferentially absorbed in regions of high dielectric loss factor, which corresponds to regions of high moisture content (Murphy et al., 1992).

2.5.3. Grain Drying

In the process of RF-drying, the choice of operating frequency and intensity of the field depends, on the one hand, on the electro-physical parameters of the material ϵ and tan δ and, on the other hand, on the given technological requirements (permissible temperature of heating the grain, speed of drying and economic efficiency). All these requirements are contradictory and a compromise solution of this question is needed if the optimum conditions of drying are to be created. Use of a higher frequency of the field leads to a more intensive evaporation of moisture and to a reduction in the drying period, but if the grain is overheated, wrinkling, cracking, and swelling may occur, which results in a deterioration of the seed and commercial quality of the grain. Knipper (1959), on the basis of experimental data, established the relationship between the specific energy and field frequency for drying grain when it is required to ensure the preservation of its seed quality.

Experience has shown that at a high frequency (10-15 MHz) and field intensity, drying may be affected within 20-25 min, but the seed quality deteriorates. At a lower frequency (1-5 MHz) or field intensity, the seed quality of the grain is preserved but the drying period is increased to 40-60 min. As with conventional hot-air drying, there is a limit of heating intensity in high-frequency heating beyond which the seed quality deteriorates. In hot-air drying, this limit is reached when the temperature of the drying medium is about 80-90°C. In high frequency drying, a specific power loss $P_{spec} \approx 0.3\text{-}0.4$ W/cm^3 represents that limit. A valuable merit of high frequency drying of grain is the absence of a drying medium with a high temperature, and the good uniformity of drying throughout the entire grain mass (Knipper, 1959).

2.5.4. Food Drying

RF drying, with regards to food, has mainly been used for post-bake drying of cookies and crackers, and pasta (UIE, 1992; Mermelstein, 1998). Cookies and crackers, fresh out of the oven, have a non uniform moisture distribution which may yield to cracking during handling. RF heating can help even out the moisture distribution after baking, by targeting the remaining moisture pockets.

2.5.5. Wood Drying

In RF wood drying, since the average dielectric constant (ϵ') for water is about 20 times larger than that of dry cell-wall for the same frequency range (10 - 30 MHz) and temperature, water will heat at a much more rapid rate than wood. Water is therefore selectively heated internally more than the surrounding cell-wall material thus eliminating the slow conduction from the surface to the core of the lumber that occurs in conventional kiln drying processes.

When an RF field is combined with low ambient pressures, high temperature and pressure gradients can develop in both the longitudinal and transverse lumber direction. Since both types of gradients will develop toward the same direction, i.e. from the centre of the board to the ends and surface, moisture will be driven out rapidly in both liquid and gas phase during the initial stages of drying. The steep gradients will also increase the rate of bound water diffusion at moisture contents below the fibre saturation point (Avramidis and Liu, 1994).

In laboratory trials conducted by Avramidis and Liu (1994), the middle temperature (T_c) of cedar increased from ambient to about 55°C and 105°C in 7 h at 0.6 and 1 kV electrode voltage, respectively, 13.56 MHz frequency and 2.7 kPa absolute pressure. After the initial rise, the T_c at 1 kV remained constant until the end of the drying run, whereas the T_c at 0.6 kV after a short plateau, slowly increased to approximately 105°C in about 12 h. The total drying time at 0.6 kV was 24 h from an initial moisture content of 38% to a final moisture content of 15%. Whereas with 1 kV, the total drying time was reduced to 14 h. It is interesting to note that the same cedar will normally require more than 25 days of drying time in a conventional "heat and vent" kiln for the same initial and final moisture content levels whereas western hemlock requires approximately 15 days.

Flow of vapour takes place primarily in the longitudinal direction which for softwoods can be 500 to 80000 times greater compared to tangential and 15 to 50000 times greater compared to radial permeability. The thickness of the specimens did not affect the total drying times. Both 25.4cm thick cedar and hemlock specimens required approximately the same amount of drying time from the same initial moisture to a final moisture content of 15%,

when compared to 9.1 cm thick specimens. This is because the bulk of the moisture flow from the middle parts of lumber takes place in the longitudinal direction (Avramidis and Liu, 1994).

2.5.6. Textile Drying

The Textile Industry is a major consumer of energy. Preparation, dyeing and finishing areas of textile manufacturing consume as much as 60% of the total energy required to produce textile goods. About 70-90% of this energy is consumed in repeated drying of wet fabric. Drying is conventionally done in steam boxes, tenters and tumble dryers which have overall energy efficiency of about 30%. RF drying, has found its application in the area of removal of this residual moisture with efficiency of about 50-60%. The advantage of RF heating is that the wetter areas of the fabric are heated preferentially giving a self-limiting advantage to RF drying (Pai et al., 1989). In materials such as open width fabrics, the spacing between the RF electrodes must be small. In such case the stray-field electrode system is recommended.

2.6. SUMMARY

From the literature, we can sum up the advantages and disadvantages of RF in the following manner.

2.6.1. Advantages of RF

1) Overcomes many heat transfer problems as water is preferentially heated;
2) Reduction in overall drying operating costs of 20-50%;
3) A considerable decrease of in-process time;
4) Acts as a moisture levelling process;
5) High overall energy efficiency;
6) No over-drying or over heating;

7) Low maintenance costs;

8) Investment return rate of 2-3 years;

9) Provides preferential heating of wet spots;

10) Effective in removing low moisture levels.

2.6.2. Disadvantages of RF

1) High initial capital costs ($ 2000-5000/kW capacity);

2) Subject to the fluctuations of electrical costs;

3) Skilled labour is required;

4) All generators and applicators must be properly shielded;

5) Unit must be tuned properly by a skilled technician.

CHAPTER III - THEORETICAL ASPECTS AND APPLICATOR DESIGN

3.1. ABSTRACT

Radio-frequency methods have been used for decades in through-heating of non-conductive materials. RF methods appear to be promising for many heating and drying processes but there is still a need for more engineering design data related to the design of the applicators and the performance of these systems before costly prototypes are built. Energy, temperature, and breakdown (electrical discharges) phenomena may limit the plant throughput, and the effect produced by the high frequency (HF) field parameters need to be examined with regard to their effects on the resulting heating.

3.2. RF TECHNOLOGY

3.2.1. Applicators

In a basic RF system, triode valves are primarily used to generate the high frequency energy in a resonant circuit, called the tank circuit. The latter takes the form of a cavity or is made up of lump elements. Traditionally, the system operates as a Class C self-excited oscillator with an inductive loop situated close to the tank circuit to transfer the energy to the applicator. For maximum transfer of energy to the loaded applicator the impedance matching between the tank circuit and the applicator is crucial.

Triode valves operating under Class C conditions form the basis of the majority of the radio frequency power source. The energy from the radio-frequency or magnetron oscillators is transferred to specially constructed resonant electrode arrays or cavities, called applicators, which house the material to be processed. At microwave frequencies, the most popular applicator is a multimode resonant cavity, similar in construction but much larger than its domestic counterpart. In addition, single-mode resonant applicators as well as nonresonant

waveguide or horn-type devices have been used (Metaxas, 1988). At large powers, the resonant circuit of the radio-frequency source forms a cavity (referred to as the tank), the dimensions of which determine the frequency of operation. Basic radio-frequency applicators are presented in Figure 3.1 and comprise of parallel plates (throughfield applicator) for bulk loads, rodded strayfield applicators for thin planar dielectrics and stagger-through field rodded applicators, which establish both axial and lateral electric fields within materials of medium thickness (Metaxas, 1988).

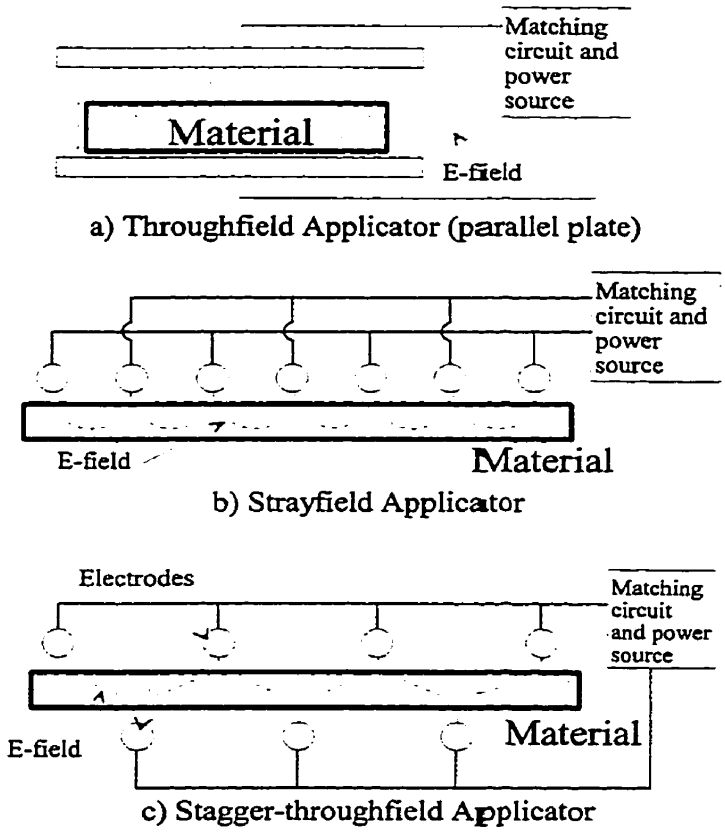

Figure 3.1: Electrode configurations for RF applicators: a) Throughfield applicator; b) Strayfield applicator; and c) Stagger-throughfield applicator (Metaxas, 1988).

Practical Electric Capacitor

In practice an electric capacitor is made up of two adjacent conductors separated by

an insulator or dielectric:

$$V = V_1 - V_2 \tag{3.1}$$

where the potential V is expressed in Volts, and V_1 and V_2 are the potentials of the two adjacent conductors.

The potential difference between the two conductors increases linearly with the charge transfer Q where:

$$Q = C(V_1 - V_2) = CV \tag{3.2}$$

The capacitance C depends upon the conductor's geometry, size and the dielectric constant of the insulating material. For a plate capacitor:

$$C = \varepsilon \varepsilon_o \frac{A}{d} \tag{3.3}$$

where C is the capacitance expressed in Farads; A is the surface area of the plate in m^2; d is the distance between the plates in m, ϵ is the relative complex permittivity (F/m), and ϵ_0 is the absolute permittivity of vacuum (F/m).

The electric field (in V/m) is uniform between the plates except for the "fringe and edge effects" (Figure 3.2).

$$E = \frac{V}{d} \tag{3.4}$$

where d is the distance between plates (m). The capacitance increases with increased area and decreased plate distance.

Experimental evidence has demonstrated that the electric field concentrates on the corner of the cylindrical material in a parallel plate configuration. This is explained by the fact that at the corners, there are conflicting boundary conditions that are satisfied by field concentration (Roussy and Pearce, 1995).

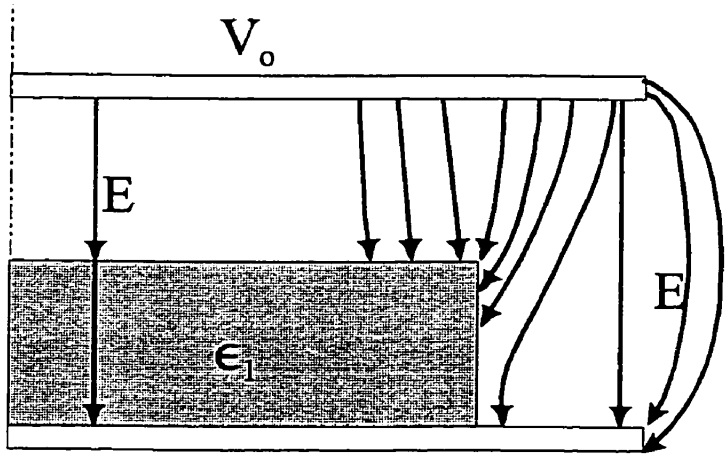

Figure 3.2: Sketch of the electric field concentrations at the corner of a cylindrical shaped material between parallel plates (Roussy and Pearce, 1995).

Understanding the Impedance

In order to continue further and to understand an RF system, we must first remember some basics of electric circuits. A RF system is usually well defined by a circuit including a resistance, an inductance and a capacitance, commonly referred to as an RLC circuit. Consider the series circuit shown in Figure 3.3.

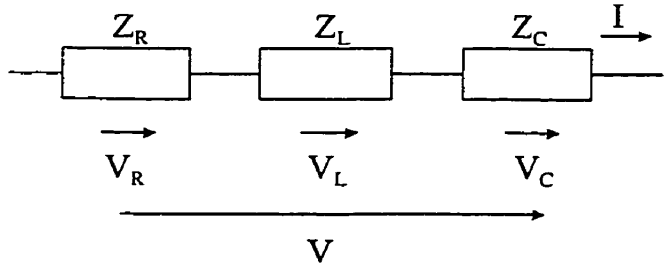

Figure 3.3: RLC series circuit.

The impedance is a constant of proportionality between voltages and currents. Impedances can be combined in series and parallel just as resistances.

$$V_R = RI \tag{3.5}$$

$$V_L = j\omega LI \tag{3.6}$$

$$V_C = -j\frac{1}{\omega C}I = \frac{I}{j\omega C} \tag{3.7}$$

In a series arrangement, the voltage across the circuit is the sum of individual component voltage.

$$V = RI + j\omega LI + \frac{1}{j\omega C}I = (R + j\omega L + \frac{1}{j\omega C})I \tag{3.8}$$

Where R, jωL, and 1/jωC are referred to as the impedances of the individual elements. Where

$$Z_R = R; \quad Z_L = j\omega L; \quad Z_C = \frac{1}{j\omega C} \tag{3.9}$$

and the total impedance Z for the series RLC circuit is:

$$Z = R + j\omega L + \frac{1}{j\omega C} \tag{3.10}$$

3.2.2. Electrode System: What Occurs between RF Electrodes

An RF electric field is created by an RF voltage gradient, using electrodes connected to an RF voltage source. The electric field distribution in the space between the electrodes depends on their shape, and on the dielectric properties of the product to be heated.

Using parallel flat plates, completely filled with a homogeneous material, the resulting electric field is homogeneous except close to the edges. In such conditions, the voltage applied on the electrodes is equal to the electric field's value between the electrodes multiplied by the distance from one electrode to the other. As an example, a 100 kV/m electric field between 10 cm spaced electrodes needs 10 kV RF voltage. To give an order of magnitude, this 100 kV/m electric field, at 27 MHz, in a material with a loss factor of 0.2 will cause a 6 W/cm^3 heat power generation in the material, and a corresponding heating rate around 1° to 2°C per s. Even higher heating rates may be obtained, in more lossy materials,

or by increasing the electric field value. But in the latter case, the upper limit will be the electrical breakdown strength of the material: 3000 kV/m in clean dry air, 100 to 500 kV/m in most of the materials to be heated (UIE, 1992). When the field strength E reaches a value of about 3 kV per mm (3×10^6 V/m) in dry air, the air molecules become ionized and corona discharges occur, accompanied by a hissing sound and a bluish glow around the conductor (Elgerd, 1977).

What happens when there is an air gap between the heated product and the electrodes? There are two homogeneous electric field distributions, in each medium, but the corresponding values are not independent: the electric field in the air is equal to the electric field in the product multiplied by its dielectric constant (usual values for food dielectric constant are from 2 to 15). The voltage applied is then the sum of two voltages: one creates the electric field through the product, and the other through the air. In most applications with a flat plate configuration, there often exists the presence of an air gap between the product and the top electrode. The configuration, shown in Figure 3.4, is equivalent to two electrode system in series, with a virtual electrode separating the air and the product at an intermediate voltage. For example, assuming that the dielectric constant is equal to 15, a 30 kV/m electric field in the material implies a 450 kV/m electric field in the air gap. The field in the air is always higher than in the product. The voltage is 2250 V in the product (30 kV/m × 0.075m), and 2250 V in the air (450 kV/m × 0.005m) for a total of 4500 V applied to the electrodes (Figure 3.4). This is why in practice, air gaps should be minimized to limit energy wastage.

In a simplified picture of dielectric heating, a regular slab of homogeneous material at a uniform temperature is placed between parallel electrodes; no heat exchange with the surroundings takes place. When an alternating electromagnetic field is applied to the electrodes, the resulting field in the slab is uniform, and the energy absorbed, and therefore the temperature rise is the same at all points in the material (Sanders, 1966).

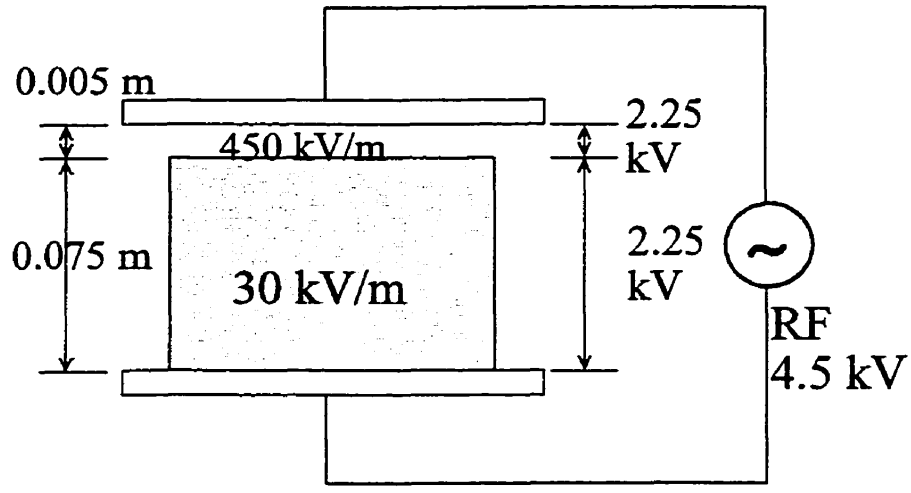

Figure 3.4: Effect of an air gap.

In practice, however, three main factors disturb this situation:

1) the block may not be an exact parallelepiped;

2) the material may consist of two or more components, e.g., fat and lean, pastry and filling...;

3) temperature gradient resulting from above two factors will cause uneven power absorption further increasing temperature differences.

Runaway heating takes place when the warmest parts take more and more of the available power at the expense of the coldest parts. In most applications of dielectric heating to food, runaway heating is unavoidable if contact with both electrodes is maintained. In practice, an airgap is introduced between the top electrode and the upper surface of the material being heated (Sanders, 1966). A part of the voltage appears in this gap, the amount depends on the relative heights of the gap and of the material and on the dielectric properties of the material. In a series arrangement, there is no effect on the relative power absorption by the two constituents as the current through both is identical (Figure 3.5). In a parallel arrangement, the voltage across the two constituents is no longer identical. The voltage and the power absorption are decreased to the greatest extent in the material of highest conductivity. An air gap of one-tenth the height of the material reduces the voltage across the material to 5-48% of that across the plates.

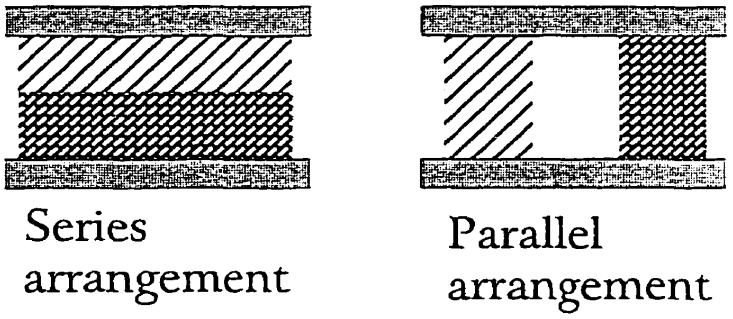

Figure 3.5: Series and parallel arrangement between flat electrodes.

It is this difference which makes possible a continuous process where different materials are present between the electrodes at the same time (Sanders, 1966).

3.2.3. The Standardized 50 Ω RF Technology

The 50Ω technology uses a fixed frequency quartz oscillator with subsequent amplification through a vacuum amplifier. This technology is gaining popularity, although more expensive than a class C oscillator, it offers superior frequency stability and better compliance with new stringent EMC regulations coming into force due to the overwhelming use of radio-frequencies for telecommunication purposes.

The standardized 50Ω technology is schematically presented in Figure 3.6. It is composed of 1) a generator with an adjustable output power in a standard load with 50 Ω impedance; 2) standard coaxial lines with characteristic impedance of 50 Ω to carry the RF power; 3) matching boxes using adjustable capacitors or inductors located between the coaxial line and the applicator; and 4) on-line measurement of the incident and reflected RF powers.

The applicator is the part of the RF installation in which the product is heated by the electric field. The electrodes are connected to the RF voltage via bus bars. The shape of the electrodes depends on the shape of the product, and on the desired temperature distribution in it. Three well-known types of electrode configurations are employed: through field plates, stray field electrode systems, and staggered through-field electrode systems as presented

earlier in Figure 3.1.

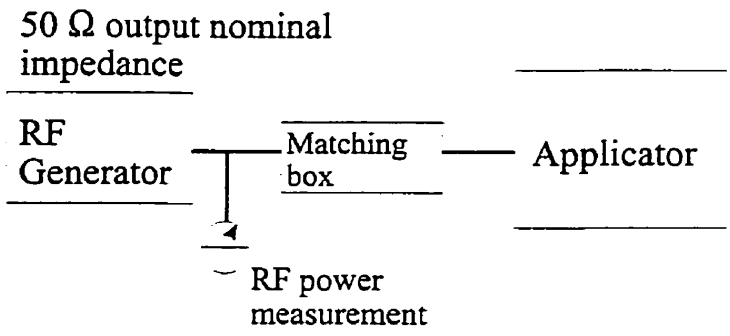

Figure 3.6: Schematic of a 50Ω output impedance RF system (Marchand and Meunier, 1990).

In a general way, an optimized design is obtained if the air gaps between electrodes and product are minimal (useless voltages); if the parasitic capacitances are minimal (useless electric field and reactive power); and if the feeding conductors are as short and wide as possible (useless inductances and power losses). For stray-field or staggered through-field systems, the diameter of the electrodes and the distance between two successive electrodes may have a big influence on the behaviour of the applicator. In some cases, it is useful to do a pre-tuning of the applicator, using inductances connected parallel to the electrodes (Marchand and Meunier, 1990).

The RF impedance of the applicator is essential to be known. It can be measured using a network analyser. This impedance obviously depends on the dielectric properties of the heated product. The temperature and moisture content of the product may change during the heating cycle. So, even without any variation of the electrode configuration, the impedance of the applicator may deviate from its nominal value. The matching box acts as an impedance balancer. At the nominal operating frequency, the impedance of the applicator must be changed, through the matching box to the nominal output impedance of the generator, 50 Ω. In order to minimize the parasitic power losses, the matching device must use only reactive components, as capacitors and inductances.

To match the impedances of the load to that of the generator, additional units of

electrical capacitance or inductance must be placed either in series or parallel, or in a combination of both, with the load. The physical dimensions of such components vary with frequency, and therefore, the selected frequency for a given heating application must be chosen to provide matching impedance components of practical physical size. It is often required to adjust these matching impedances to compensate for changes of load impedance with different materials to be heated or different masses of the same material. In general, as the size of the mass to be heated goes up, the optimum frequency goes down (Cable, 1954).

For optimum utilization of the equipment, the load impedance must be matched to the output impedance of the generator and any impedance introduced by the leads carrying the energy to the load must be considered as load impedance. Every unit length of leads which is between the generator and the electrodes, has a given amount of electrical inductance and capacitance along with resistance, and these properties limit and divert the high frequency current which performs the heating operation. The electrical impedance of the load circuit must be matched to the output impedance of the high-frequency generator, and this is generally accomplished by the use of a tuning network at the load, with the load impedance making up a section of the tuning network. The simplest form of such a network is a single variable inductance placed in series or parallel electrically with the load electrodes (Cable, 1954).

3.3. APPLICATOR DESIGN

3.3.1. Basics

The electrodes themselves carry relatively small amounts of current, therefore are not heated to any great extent by the current losses in them. Electrically, they can be made from thin sheets of good electrical conducting material, such as copper, silver, aluminum or brass. The thickness of the plates and the manner of support are dictated to a large degree by the mechanical requirements for supporting the electrodes and maintaining their relative positions, both with respect to each other and to the material being heated. It is also important that their spacing with other parts of the electrical circuit be maintained constant, since all air spaces

between the high voltage electrode and the electrically grounded parts represent capacitances at the frequencies employed for dielectric heating which go to make up the overall high frequency circuit, and must be maintained constant (Cable, 1954). One electrode is usually maintained at ground potential and if that is the case, no particular care must be taken to insulate it from other parts of the circuit. The high-voltage electrode must be mounted on insulators, commonly known as "stand-off" insulators, which prevent it from becoming grounded and thus permit the two electrodes to be operated at a high potential difference, a requisite for dielectric heating.

The high voltage lead from the tank circuit to the electrode can be a short stub extending through the top of the oscillator, thus making the electrical connections extremely simple. Access to the electrodes can be through a door on the side of the cabinet or through a hinged cover on the top of the cabinet. When this latter type of construction is used, the upper electrode which is operated at ground potential is usually fastened to the hinged lid, and moves out of the way as the cover is raised, permitting the bottom electrode to be fully exposed and available for convenient loading and unloading (Cable, 1954). Care must be taken to see that the access doors and hinged covers of such an installation make good electrical contact with the frame along all edges, and sufficient bonding must be maintained across points in the link mechanism to provide ample electrical conductivity to carry the current which will flow between the electrodes.

As is the case with any components mounted in close proximity to the electrodes, care must be taken to see that the presence of metal does not distort or shield the dielectric field between the electrodes. For example if a manifold connected to a blower for vapour removal is to run along the side of the electrodes and to provide an air stream across the electrode area, this manifold must be made of an electrically non-conducting material; if it were not, the field would be concentrated in the spaces above and below the manifold where it is nearest to the electrode. The manifold will assume a potential above ground in accordance with the values of the electrical capacitance distributed between the manifold and the electrodes, and therefore, care must be taken to insulate the manifold from the blower and blower motor so that the high-frequency energy does not damage the components.

On the other hand, there is always the possibility of locating such components with relationship to the electrodes so that the field is not affected by their presence. If sufficient clearance is maintained between the manifold and the high potential electrodes and leads, the manifold can be constructed from metal without fear and can be grounded solidly to the cabinet frame to ensure that all high-frequency picked up from stray fields will be bled off to ground. The rule of thumb for minimum spacing is to space all metallic objects away from the electrodes by at least the distance equivalent to the electrode separation, since the stray-field which emanates from the side of the electrode area attenuates rapidly at this distance. Thus, if the electrode spacing was 10 cm, no metallic parts would be placed within 10 cm of either electrode.

In any dielectric-heating application or installation, importance is given to the material used for supporting or retaining the work during the heating cycle since it can draw heat away from the work to such an extent that the method is unsuccessful, or distort the field to such a degree that the nonuniformity of the heat pattern is intolerable.

For the containment of the system, the problem is one of reducing its radiating qualities. There are two general approaches to reducing the radiation from the equipment:

1) Arranging the components of the equipment from both mechanical and electrical standpoint in such a manner as to make the radiation a minimum and;

2) Allowing the equipment to radiate as it will, and enclosing the entire installation in an electromagnetic shield which confines the radiation within its limits.

Both procedures are finding use, but the former should be investigated to its fullest extent before shielding is resorted to, since it is both costly and cumbersome to achieve, especially if the installation is large.

There are many things that can be done to reduce the radiation from the equipment. First of all, the oscillator itself should be totally enclosed in a metal cabinet, preferably aluminum or some high conductivity metal, since the high frequency energy within the oscillator cabinet can escape to the surrounding atmosphere through any space not

metallically shielded. The electric circuit made up by the sides of the cabinet should be of high conductivity, and maintained at ground potential. Doors on the cabinet for instance, should be electrically connected to the frame at numerous points around the opening, instead of a single connection which would be considered ample grounding under normal conditions.

Water service connections to the equipment, necessary whenever water-cooled tubes are used, must be properly grounded, to prevent high-frequency energy from escaping through the water inlet to drain and so provide an antenna which will radiate the energy off into the surroundings. Instrument wiring, especially where meters and relays are located remotely from the oscillator, must be shielded to prevent pick-up of radio-frequency energy wherever such wiring passes through a high-frequency field. This also holds true of control wiring and any other mechanical or electrical device that extends from the high-frequency section of the oscillator through the cabinet into the outside surrounding space. In other words any metallic object exposed to the high-frequency field must be shielded and the shield grounded at the point where it leaves the cabinet. When the electrodes are self-contained, care must be taken to prevent radiation. The access door to the electrodes must be grounded to the frame and again it should be stressed that a single ground point is insufficient. The electrode section must be well enclosed in a solid sheet of metal or mesh screen and the access door must completely shield the opening when closed. The electrode cabinet should be considered as the oscillator cabinet from a radiation standpoint and all points that provide an opening to the surrounding atmosphere should be covered with metal sheet of screening when the unit is in operation.

3.3.2. Arcing Problems

At the frequencies used in radio frequency heating (13.56 MHz or 27.12 MHz) higher electric field amplitudes are developed in the load and applicator compared to microwaves systems of the same power densities. Consequently the likelihood of atmospheric arcs, localized overheating, micro-arcs or corona discharges occurring in the applicator or any voids within the material being processed is higher. These effects lower the breakdown potential, further increasing the possibility of an electrical discharge occurring, which can

result in considerable damage to both equipment and material product (Clee and Metaxas, 1994). Additionally if the material has regions with high moisture content the possibility exists of extremely sharp corners at the boundary of a void inducing the formation of micro-arcs within the material due to an enhancement of the electric field at the apex of a corner.

The use of a spectrum analyser has indicated to Clee and Metaxas (1993) that just prior to the formation of an arc in the applicator/material assembly, the resonant frequency of the tank circuit begins to increase. This increase occurs regardless of the type of discharge observed in the applicator, whether an internal micro-arc or external discharge across the electrodes. With increased loading the applicator reflects an appreciable reactance into the tank circuit which alters the effective inductance of the tank circuit and hence the resonant frequency. Just prior to an observable micro-arc in a void of the sample, the resonant frequency (from 13.56 MHz) of the tank circuit can be observed to rapidly increase to 13.76 MHz and above, representing a change of over 2% of the fundamental. This change in the resonant frequency is around four times the maximum change associated with normal variations due to loading effects. This micro-arc results in a discharge to the upper electrode in the applicator by which time the frequency spectrum becomes unstable (Clee and Metaxas, 1994).

During the build up of ionization just prior to an electrical discharge, the frequency of the RF oscillator increases rapidly. This is followed by a change in the output from the phase locked loop which triggers the oscilloscope. Similarly the output from the operational amplifier increases and its variation is stored by the oscilloscope. The change in output voltage from the operational amplifier δV, is directly proportional to the increase in frequency, δf, of the generator, meanwhile the rise time δt, of the output gives an indication of the time required for the frequency shift and is proportional to the arc development time (Clee and Metaxas, 1994). Even at low RF power levels (around 2 MWm^{-3}) electrical discharges in a loaded applicator can frequently occur, particularly for materials with very high moisture levels ($\geq$100% dry basis).

An high speed photography study conducted by Clee and Metaxas (1994), revealed that in all situations when an arc discharge occurred, flashing over the material to the

electrode, it was preceded by micro-arcs inside or on the surface of the material. In some cases these micro-arcs were so short lived they could not be observed without the high speed camera; on the other hand some could last for several seconds. These micro-arcs can propagate and cause overheating, burning and subsequent scorching of the material. This creates further sites for micro-arcs which continue to grow until eventually they break through the surface and an electrical discharge to an adjacent electrode occurs. Research has shown that at relatively low power levels and mean moisture contents the possibility of arcing is still quite high.

3.3.3. How to Tune an RF System

The extent to which power is absorbed by the material, rather than dissipated by ohmic heating of the metal components of the applicator circuit, is determined by the so-called "Q-factor" of the applicator. The Q-factor of a circuit is defined as:

$$Q - factor = 2\pi \times \frac{Peak\ energy\ stored\ in\ the\ circuit}{Energy\ dissipated\ in\ the\ circuit\ per\ cycle} \qquad (3.11)$$

A large unloaded Q-factor means that little energy is absorbed by the metal components while a small loaded Q-factor means that the material is capable of absorbing the energy. For high efficiencies of a system, the unloaded Q-factor should be large (300 -1000) and the loaded Q-factor should be small (30-100), (Perkin, 1983). In the case of our own applicator design we have an unloaded Q-factor of 330 and a loaded Q-factor ranging from 30 to 90 depending on the material tested.

With a network analyser connected to the applicator, by injecting a low power signal into it via a launching loop and connecting a receiving loop through the other end of the applicator, its resonant frequency, unloaded and loaded Q-factors can be readily measured. Once the applicator/material assembly has been designed to operate at the required frequency, it is then inductively connected to the tank circuit. The two circuits must be optimally coupled in order to transfer maximum energy to the processed material. It is at this stage that a network analyser becomes of paramount importance in assessing the performance of the two

coupled circuits.

The Q-factors and resonant frequencies of the tank and the applicator circuits must be measured when they are completely isolated from one another, as the impedance reflected into the tank by the applicator is effective in changing the resonant frequency and Q-factor of the tank. In any new application and applicator design, the coupling factors between tank/applicator and tank/launching loop are not known and are selected by trial and error.

Whether the tank circuit takes the form of a metallic box or consists of lump elements, the basic optimisation procedures do not change. The launching loop, of inductance L, consists of a copper coil connected to an N-type 50Ω connector, which in turn is connected to the network analyser via an S-parameter test set. During the optimisation stage, the tank is excited with a low power swept frequency signal from the network analyser. This sets up an electromagnetic field distribution, in the tank, which is similar to that established under high power operation. The signal reflected back into the S-parameter test set is then processed by the network analyser to calculate the complex reflection coefficient and impedance. The impedance loci can be plotted on a Smith Chart format. The launching loop has a normalized reactance of $j\omega L/Z_o$ on the Smith Chart, where Z_o is the characteristic impedance of the system (50Ω in this case). The value of $j\omega L/Z_o$ does not affect the profile of the impedance measured by the network analyser, only its position on the Smith Chart.

During operation, the radio frequency energy is generated in the tank circuit at an angular frequency ω_{or}. This frequency is fixed and can only be changed by altering the values of the parameters of the tank. A proportion of the power generated in the tank is coupled into the applicator via the mutual inductance M'. As in the tank circuit, the resonant frequency of the applicator is defined by the values of its discrete circuit elements, i.e. capacitance, C_a, and inductance, L_a. The value of L_a is set by the particular shape of the applicator. The value of C_a is a function of many parameters which include electrode type, dimensions and spacing, combined with the dielectric properties of the material being processed. As the electrode separation d varies, the applicator capacitance changes which in turn alters the applicator's angular frequency (Metaxas and Clee, 1993).

The applicator/material impedance is represented by: $Z_a = R_a\{1 + jx'\}$. The combined

system can be represented by an "equivalent" circuit. The parameters R_e and L_e are the equivalent resistance and inductance, respectively, and are functions of the angular frequency of operation ω, and are defined by the following:

$$R_e = R_t \left\{1 + \frac{k_{at}^2 Q_a Q_t}{(1 + x'^2)}\right\}\left(\frac{\omega}{\omega_{oa}}\right)\left(\frac{\omega}{\omega_{ot}}\right) \tag{3.12}$$

and

$$L_e = L_t\left\{1 - (\omega / \omega_{oa})\frac{x' k_{at}^2 Q_a}{(1 + x'^2)}\right\} \tag{3.13}$$

$$k_{at} = \frac{M}{\sqrt{L_a L_t}} \tag{3.14}$$

where:

k_{at} is the coupling factor between the tank circuit and the applicator. Q_a, Q_t, ω_{oa}, *and* ω_{ot} are the respective Q-factors and resonant angular frequencies of the applicator and tank circuits and x' is a function of ω and the discrete circuit elements that form the applicator.

The equivalent circuit has the following resonant angular frequency, Q-factor and impedance:

$$\omega_e = (C_t L_e)^{-1/2} \tag{3.15}$$

$$Q_e = \frac{\omega_e L_e}{R_e} \tag{3.16}$$

$$Z_e = R_e(1 + jx) \tag{3.17}$$

where x is a function of all the circuit elements in the applicator/tank combined circuit. The impedance across the launching/ coupling loop as seen by the network analyser is given by:

$$Z_{na} = R + (j\omega L) + \frac{\omega^2 M^2}{Z_t} \tag{3.18}$$

In the Smith Chart, the impedance locus of the tank is a large circle displaced from the R/Z_o axis by $+j\omega L/Z_o$, the normalised impedance of the launching coil. If there is sufficiently large detuning, the smaller circle is outside the visual range of the frequency sweep and cannot be seen. At this point very little interaction takes place between the applicator and the tank circuit. Similarly, the return loss responses show a large disparity in magnitude, with that of the tank circuit being far bigger indicating that the oscillations are confined within the tank circuit and very little energy is transferred to the applicator.

3.3.4. Fine Tuning of Applicator's Impedance

For a given application, the upper electrode may require to be moved vertically to accommodate for sample size or shape, thus varying the resonant frequency of the combined applicator/material assembly. New reflection measurements need to be made with the network analyser for both the empty applicator and for the applicator containing different loads. As the resonant frequency of the applicator is brought closer to that of the tank by varying the electrode separation the applicator locus is observed to increase while that of the tank circuit decreases. A critical position is reached when the applicator resonant frequency is approximately equal to the tank resonant frequency and the two loci appear to coincide. At this stage the return loss responses are approximately of equal magnitude and separated by only about 0.6 MHz (Metaxas and Clee, 1993). In industrial applicators such frequency shifts must be kept to a minimum in order that the generator does not radiate energy outside the prescribed frequency limits.

When the applicator is coupled to the output stage of the power unit, the working parameters will hardly change as long as no material is inserted in the applicator. The dynamic impedance and the Q-factor maintain therefore their high values, a condition which can be referred to as standing condition for the high power unit. While in this condition, the power generated in the tank circuit is quite small and accounts for losses in the system. With

the material inserted through the applicator and the latter adjusted to be tuned to the frequency of the tank circuit, effective interaction will take place between the two resonant circuits. Now we can understand the way in which the material affects the operation of the high power generator by effectively lowering its dynamic impedance, on account of the increased overall resistance in the tank circuit. The output power depends directly on the operating parameters, such as the peak anode voltage and current flow (Metaxas, 1987).

The behaviour of the tuning circuits can be represented by a simplified circuit shown in Figure 3.7. For an unloaded circuit, the value of Q_a is large, typically 100's, whereas when loaded with the material to be heated, Q_a falls to a lower value, typically 10's, with the precise value dependent on the dielectric properties of the loading material.

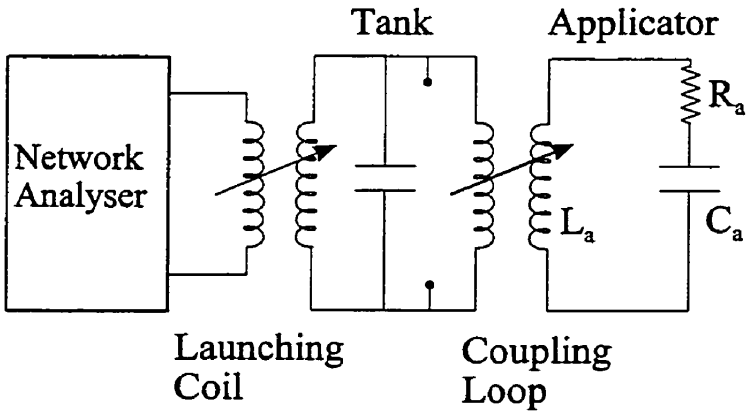

Figure 3.7: Simplified circuit to represent the generator and the applicator circuits (Perkin, 1987).

The impedance data are plotted on a Smith Chart (Figure 3.8). The impedance across the terminals of a simple parallel resonant circuit, as the frequency is swept slightly above or below the resonant frequency, is a circle symmetrically placed about the horizontal axis of the Smith Chart which represents the position of zero reactance. The resonant frequency and dynamic impedance are found from the point where the circle cuts the horizontal axis. Prior to coupling and matching the applicator (with the material inserted in it) to the radio-frequency power unit through its tank circuit, it must be ensured that the applicator/material assembly exhibits a frequency response compatible with the output response of the power

unit. The frequency response of the applicator/material assembly is extremely difficult to predict theoretically and a method is needed through which it can be rapidly measured and adjusted to lie within the required band for high power operation. This can be achieved by carrying out transmission measurements using a network analyser (Metaxas, 1985).

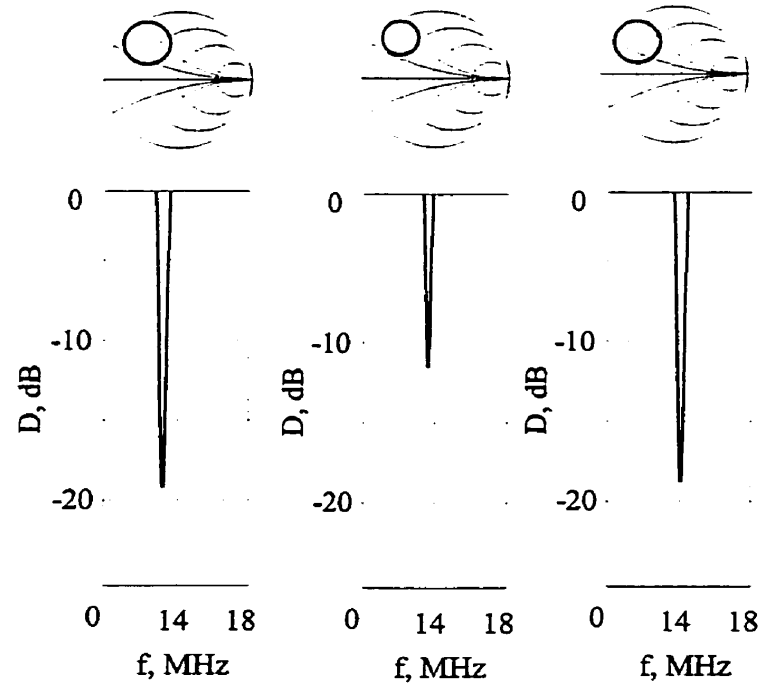

Figure 3.8: Typical impedance loci and return loss D measured from the Network Analyser for f_1 = 13.56 MHz (Neophytou and Metaxas, 1997).

Once the resonance response, bandwidths and Q-factors of the isolated applicator have been measured, it is necessary to examine the characteristics of the loaded applicator when coupled to the tank circuit and to assess not only the resonance response and the effects of any parasitic oscillatory circuits through transmission type of measurements, but also to closely examine the impedance matching performance of the two coupled circuits.

This latter requirement is achieved through reflection measurements using the network analyser. A swept frequency signal from a network analyser is coupled directly to the applicator via another loop, called the launching loop (Figure 3.9).

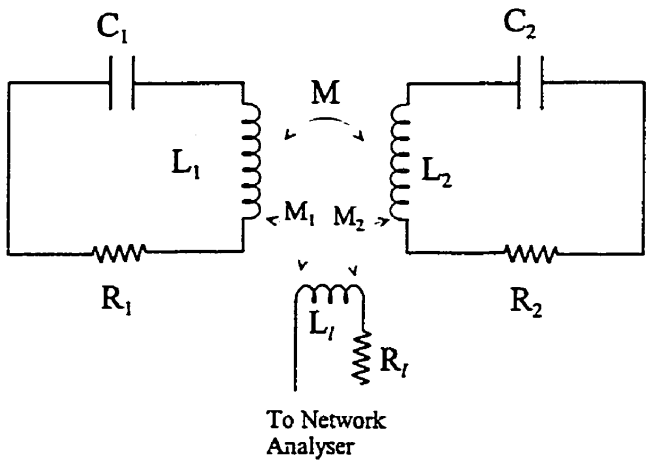

Figure 3.9: Equivalent circuit for matching the tank and applicator with a launching loop from the Network Analyser.

This is a single turn loop connected to a 50 Ω coaxial adapter, which is, in turn, connected to the transmission/reflection test set forming the output stage of the network analyser. The output from this loop is fed back into the network analyser in order to process and display the transmitted signal. This method affords a visual display of the applicator resonance response, and through such responses the corresponding bandwidths and overall tuning range are rapidly obtained. The Q_o factor varies with the electrode separation d. As d increases, Q_o decreases and tends towards a constant value. With a material inserted between the applicator electrodes, the network analyser response shifts to a lower frequency and becomes broader (bandwidth increase).

Not all the energy which is delivered to the applicator is utilized for raising the temperature of the product. Some power is dissipated in the metallic electrodes, and some is radiated (Metaxas, 1985).

The impedance locus of Z_{NA} as shown on the Smith chart (Figure 3.8), is a single circle which reduces as f_2 gets closer to f_1, when optimum matching occurs. When the mutual inductance of the coil-tank M_1 increases the circle increases in size. The return loss D has a single minimum. The minimum value decreases as optimum matching is approached. When M_1 increases the peak decreases. Figure 3.8 shows the effects for a particular system

configuration where the tank circuit maintains a resonant frequency of 13.56 MHz (Neophytou and Metaxas, 1997).

3.4. DESIGN OF OUR SYSTEM

3.4.1. Radio Frequency or Microwaves?

A most intriguing perennial question is which of the four principal frequencies, 13.56, 27.12, 915, 2450 MHz, would be best to adopt for a particular application? - Some recommendations may apply: 1) Since the dielectric-properties of the material to be processed vary as a function of frequency along with temperature and moisture content as variables, they should point to a specific frequency range; 2) For large scale end processing applications of materials, radio frequency with its longer wavelength is less prone to standing waves and resulting non-uniform heating; 3) Moisture levelling is more effective at radio-frequency for wet planar materials in drying applications; 4) If drying needs to be carried out under vacuum to reduce the boiling point, as could be the case with some temperature-sensitive materials, microwave energy is preferred since the likelihood of arcing is much smaller.

There is another reason why certain frequencies are better suited for loads of given dimensions; at certain frequencies, there is the formation of standing waves where the wave is reflected, reinforcing the original wave. If a set of electrodes were designed so that their length was equal to a half or quarter wavelength at a given frequency, standing waves would be set up along the electrodes, and instead of all points on the electrode receiving full voltage during a complete cycle, the voltage would be a maximum at one point and zero at another. Since the heating effect in dielectric heating is proportional to the square of the voltage, this would mean that a large variation in heating would take place across the electrodes and the uniformity of heating inherent in dielectric heating would paradoxically be absent. Thus it is important to choose a frequency for a given heating application which will prevent the formation of standing waves.

Our design is based on the standardized 50 Ω system (Appendix A) as described by Bialod and Marchand (1986) and schematically presented in Figure 3.6. Design methods are necessary for the promotion of new applications in the agri-food sectors. RF is cheaper and more durable than microwave. However in both cases the investment costs are high and are a function of the installed power, thus it is necessary to maximize the choice of required power. Power transfer to the material must be optimized while losses of energy in the systems must be minimized. The nominal impedance of a generator is the load impedance corresponding to optimal operation of the generator. In a standardized RF system, this impedance has been set to 50 Ω. The impedance of the applicator depends on its design features and on the characteristics of the load. The impedance of the applicator is likely to change and the impedance brought back to the matching box will no longer be 50 Ω. A fraction of the emitted or incident power from the generator is reflected from the end of the transmission line. The superposing of the two waves produces a system of stationary waves (overloads). If the perturbation is great, the generator is equipped with a safety system which switches off the power. A measure of active incident and reflected power is supplied by means of a simple coaxial connection.

To prevent overheating, the matching box with its variable condensers is continuously water cooled. The matching box is a passive quadri-pole which transforms impedances. It consists of two adjustable condensers which bring the impedance of the loaded applicator to match with the standard designed impedance of the generator.

3.4.2. Our Electrical Design

In our design the generator operates at the frequency of 27.12 MHz and its maximum power output is 600 W for a maximum applied voltage around 5 kV. The surface of application is approximately 60 cm^2 (0.00636 m^2) for a holding container of 9 cm in diameter, and 8 cm deep. So what is the impedance of the load, its capacitance and its resistance when the treated material is wheat and it fills the separation between the electrodes?

To understand from an electrical point of view, the system can be represented as a

circuit having a capacitance, and an electrical resistance in parallel. The value of the capacitance is given by:

$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \tag{3.19}$$

where ϵ_o = permittivity of free space (10^{-9} /36 π, F/m);

ϵ_r = dielectric constant of the material (Table 3.1)

A = surface area of the material in the field (m^2)

d = thickness of the load (m).

$$C = \frac{1}{36\pi}\frac{10^{-9}(4)(0.00636)}{0.08} = 2.81\times 10^{-12}\ F \tag{3.20}$$

Table 3.1: Some wheat properties at 27.12 MHz.

Loss factor	0.3
Volume	0.0006 m^3
Mass	0.2 kg
ϵ_r	4

The value of the resistance can be calculated from equation 3.21.

$$R = \frac{1}{\omega\ C(\tan\delta)} \tag{3.21}$$

Where ω is the pulsating of the electric field: $\omega = 2\ \pi f = 2\pi \times 27.12 \times 10^6 = 170.4 \times 10^6$ and tan δ is the loss factor.

$$R = \frac{1}{(170.4\times 10^6)(2.81\times 10^{-12})(0.3)} = 6961.50\,\Omega \tag{3.22}$$

And the impedance of the load is given by:

$$\frac{1}{Z} = \frac{1}{R} + j\omega\ C \tag{3.23}$$

thus

$$Z = \frac{R}{1 + j\omega\ CR} \tag{3.24}$$

$$Z = \frac{6961}{1 + j(170.4 \times 10^6 \times 2.81 \times 10^{-12} \times 6961)} = \frac{6961}{1 + 3.33j} \tag{3.25}$$

$$Z = \frac{6961}{(1 + 3.33j)} \frac{(1 - 3.33j)}{(1 - 3.33j)} = \frac{6961(1 - 3.33j)}{1 + 3.33j - 3.33j + 11}$$

$$Z = \frac{6961(1 - 3.33j)}{12} = 580 - 1931.7j = 2017\ \Omega \tag{3.26}$$

The total load can be represented by a capacitance of value C and a resistance of value R placed in parallel as expressed in equation 3.23.

Thus

$$\frac{1}{Z} = \frac{1}{R} + j\omega\ C = \frac{1}{580 - 1931.7j} \frac{(580 + 1931.7j)}{(580 + 1931.7j)} \tag{3.27}$$
$$= 0.0001426 + 0.0004749j$$

and the resistance of the load is:

$$R = \frac{1}{0.0001426} = 7012.63\ \Omega \tag{3.28}$$

and the capacitance of the load is $\omega C = 0.0004749$

$$C = \frac{0.0004749}{170.4 \times 10^6} = 2.787 \times 10^{-12}\ F \tag{3.29}$$

The inductance of the bus bar is obtained from the LC circuit: $LC\omega^2 = 1$, thus

$$L = \frac{1}{C\omega^2} = \frac{1}{2.787 \times 10^{-12}(170.4 \cdot 10^6)^2} = 0.0000124\ H = 0.0124\mu H \tag{3.30}$$

3.4.3. Our Applicator Design

The materials chosen for the construction of the chamber are more or less arbitrary; the principal requirements being that they are good conductors (for the purpose of electromagnetic shielding of RF chamber) at the selected operating frequency and resistant to processing chemicals and temperatures. Enclosure in a metal walled compartment increased electrical safety and isolated the RF radiation produced around the electrodes from the outside environment. It is generally accepted that a level of radiation equivalent to that emanated from the human body in a normal sedentary state (100 W/m^2) is safe for permanent exposure.

The applicator design is schematically presented in Figure 3.10, a photograph of the full system is presented in Figure 3.11 along with its schematic presentation in Figure 3.12. The electrodes are square in shape to ensure adequate temperature distribution in the product mass contained in cylindrical shaped Teflon or borosilicate glass containers. The electrode configuration chosen is the standard parallel plate system (Figure 3.10). The lower electrode was chosen as the high voltage one since the electrodes are mounted directly over the matching box, thus making the connection as short as possible. The electrodes are connected to the RF voltage via thin silver plated copper strips. Access to the electrodes was then made simple through a hinged cover on the top of the cabinet. Electrode spacing was ensured with Teflon columns.

The radiating qualities of the installation were limited by ensuring the containment of the applicator in a metal cabinet enclosure maintained at ground potential.

The cabinet enclosure consisted of a metal mesh screen which provides ample metallic shield. When the system was in operation, the cabinet was connected to the frame at numerous points around the opening to ensure proper grounding under high voltage conditions.

The RF impedance of the applicator was measured using a network analyzer. This impedance allowed the tuning of the matching box which acts as an impedance regulator. The matching box is a passive quadri-pole, in place to control the impedance matching of the system. In our set-up, it consists of two tunable capacitors and one fixed resistor coil. The purpose of the

matching box is to bring back any impedance between the applicator's load to match the standard impedance of the generator, in our case, 50 Ω.

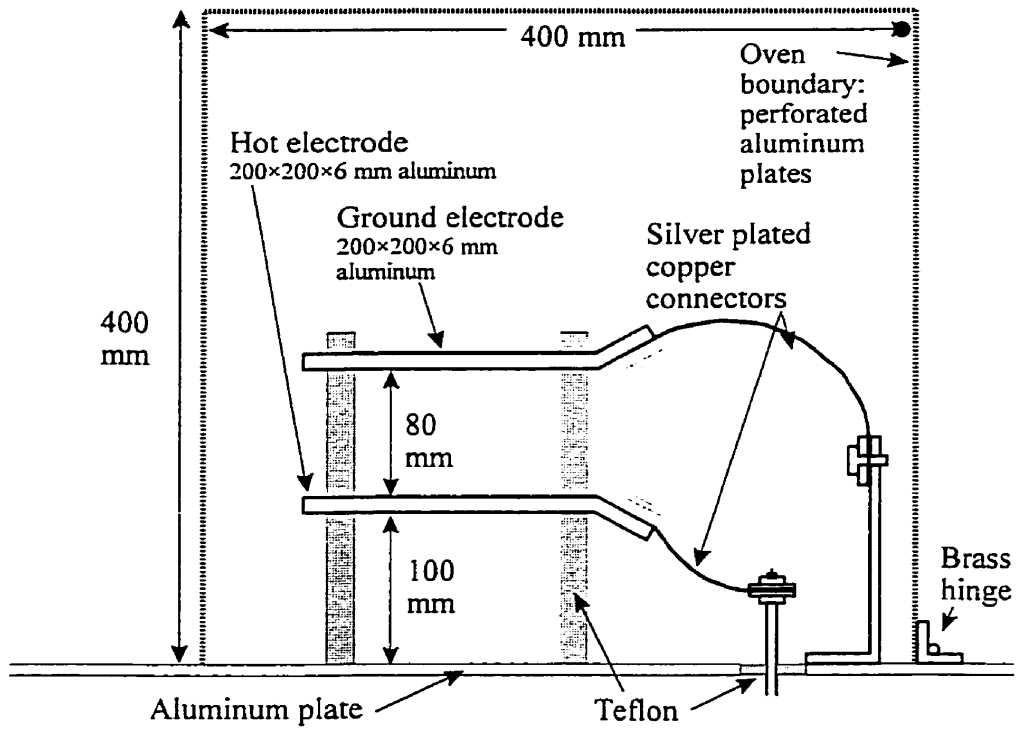

Figure 3.10: Schematic view of the designed applicator.

Our matching network is composed of automatically controlled tuning with motorized variable capacitors with phase and amplitude discriminators. The active incident and reflected powers between the generator and the matching box are measured using simple couplings on the coaxial cable and the readings are made from monitors placed on the generator control board. The control board of the matching box corrects automatically the impedance tuning of the system. To prevent thermal overload, the matching box is cooled by cold water circulation through the fixed resistor coil.

Figure 3.11: Photograph of the applicator and RF system.

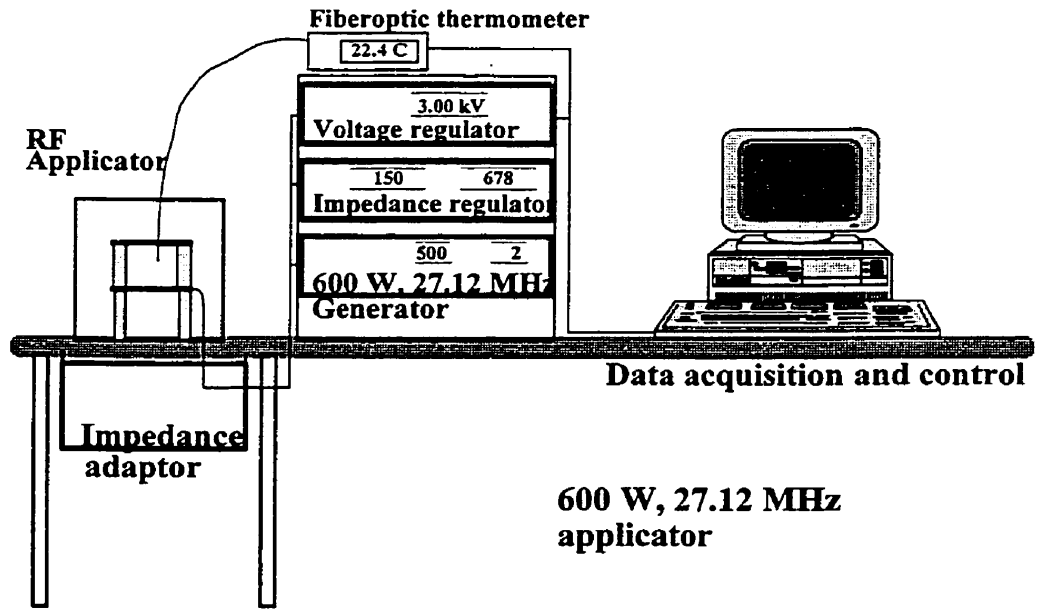

Figure 3.12. Schematic view of complete RF system.

In our preliminary trials, vapour given-off by the heating process was condensating on the top electrode and the dripping water drops were causing flash overs in the air gap between the electrodes, charring the material at its surface. To rectify this problem a small blower was mounted on the cabinet enclosure to circulate an air stream across the electrodes, during the heating cycle, which helped to carry the vapour away.

3.4.4. Step-by-Step Design Considerations

Let's now look at our design considerations. For our set-up we first looked at the size of generator which would be required. For that we first determined the size of samples we would be interested in treating. On average our treatments would vary between 50 and up to 300 g. For rapid effective thermal treatment you would need to have from 0.1 up to 1 W/g of effective power applied on the produce. In an RF set-up you could usually expect to have 60 to 70% efficiency in power transfer from the generator to the produce. Thus to have a factor of safety we assumed a transfer efficiency of 60%. Therefore the power of the generator that we required was found accordingly:

$$\text{Generator (W)} = \frac{1\frac{W}{g} \times 300g}{0.6} = 500\,W \tag{3.31}$$

Therefore a 600 W RF generator was purchased from the French microwave company SAIREM.

Then we had to consider the applicator design. The design was to be consistent with the size of our samples. There are a few rules to follow when designing an RF applicator: 1) The electrodes should not be designed so that their length equals a half or a quarter of the wavelength (λ).

$$\lambda = \frac{\text{speed of light}}{\text{frequency}} = \frac{30 \times 10^9\ cm/s}{27.12 \times 10^6\ cycles/s} = 1106\,cm/cycle = 11m \tag{3.32}$$

Our electrodes are 0.2 m × 0.2 m in dimensions, which is well below the half or the quarter of the wavelength. Otherwise, standing waves would be set up along the electrodes, and

instead of all points of the electrode receiving full voltage during a complete cycle, the voltage would be a maximum at one point and zero at another. Since the heating effect in dielectric heating is proportional to the square of the voltage, this would mean that a large variation in heating would take place across the electrodes and the uniformity of dielectric heating would be missing.

2) The electrode must carry a high voltage electric field. Electrically they can be made from thin sheets of good electrical conducting material, such as copper, silver, aluminum or brass. In our set up we chose aluminum for its ease of handling and its light weight.

3) The bottom electrode was chosen as the high voltage electrode in order to minimize the length of the connection to the generator. Furthermore the impedance adaptor was then positioned just below the applicator, here again to facilitate the connection. The high voltage electrode is mounted on Teflon columns to prevent the high voltage electrode from becoming grounded. The spacing between the electrode and the grounded metallic support plate must be greater than the electrode spacing in order to avoid interference. It was thus set at 10 cm since the electrode spacing was set at 8 cm. The electrode spacing is fixed in order to maintain the capacitance of the applicator constant. The contact leads of both electrodes were made of thin copper strips. The copper strips were silver plated in order to optimize electrical conductivity. The connections, for both the high voltage and the ground electrode, were made through the width of the electrode, in order to ensure ample electrical conductivity.

4) The electrodes were designed to prevent the formation of corona discharge and the resultant ionization of the surrounding air and the subsequent arc-over to ground. Sharp corners are prone to brush discharges. Thin electrodes, even when perfectly rounded at the edges still have relatively sharp corners and thus are liable to corona discharge when energized at high frequency voltage. Therefore it is recommended to have a minimum practical thickness of 6 mm or thicker. The corners of the 6 mm thick electrodes were

trimmed with a large radius and the surface was polished.

5) The electrode applicator was then enclosed in a cabinet which acts as a hinged cover for access to the electrode assembly for loading and unloading of the material. Here again the cover clearance from the electrodes must be greater than the electrode spacing, and in our case it was greater than 10 cm on all sides. Also good electrical contact must be ensured along all edges of the frame in order to provide ample electrical grounding and thus ensure maximum potential differences between the electrodes.

6) A small blower has been mounted on the applicator cabinet to pass an air stream across the electrodes to carry water vapour away from the electrodes. Water vapour may cause flash overs between the electrodes or between the high voltage electrode and the material being heated. Since the blower is grounded to the cabinet and it is placed at a good enough distance from the electrodes, its presence does not cause interferences with the dielectric heating process.

7) Once the applicator was designed, we needed to calculate the impedance of the applicator in order to choose an adequate impedance adaptor to transform the applicator impedance to the nominal value of the generator which is standardized to 50 Ω. This was achieved with the help of the company manufacturing the RF generator and impedance adaptor (SAIREM, France) and with a Network Analyzer which was borrowed from the Hydro-Quebec research laboratories (LTEE-Shawinigan, Quebec).

The impedance adaptor comes equipped with two variable capacitors mounted in parallel. The initial matching of impedance between the applicator and the generator is done by simply designing a resistive coil (mounted in parallel or in series with the two variable capacitors) so that when the applicator is filled with a material, you have enough latitude for adjustment with the two variable capacitors which adjust the impedance in both magnitude and in phase (with a variability from 0 to 1000 pF). This is a trial and error process by which you place different resistive coils in the circuit along with the fixed capacitors until you get

an optimal reading of the capacitance with your network analyzer. The resistive coil is simply a brass pipe made into a spiral coil (in our case 5 spires). The number of spires will determine its resistance which will have different effects on the total impedance of the electrical RC (resistive, capacitive) circuit.

The RF generator:

The RF power generator is a free running oscillator circuit coupled to a triode valve which is fed by a high voltage power source (220 V). The oscillator circuit produces the oscillations which are sustained by the triode valve. The output power from the generator is indicated and adjusted by a potentiometer placed on the front of the generator. There are two galvanometers located on the front of the generator. One displays the incident power supplied by the generator and the other one displays the reflected power which comes back to the generator when the power is not adequately absorbed by the load in the applicator. If the amount of reflected power is too great, the life of the generator will be significantly reduced. The generator is thus equipped with a safety feature that automatically shuts off the generator when reflected power is above 10 % of the incident power.

The generator can be operated manually with a series of switches and a potentiometer for adjusting the power. The generator can also be operated by remote control (computer control) via a cannon plug driven by set signals (0-10V).

The output impedance of the generator has been set by the manufacturer to $Z = 50 + 0j$ that is 50 Ω. In order to maximize the energy transfer between the power source and the applicator, the impedance of the applicator must match that of the generator. The matching is done by the impedance adaptor, placed between the generator and the applicator.

The impedance adaptor:

This is also referred to as the matching box or the matching network. The details of the matching network are schematically presented in Appendix B. The matching box acts as an impedance balancer. At the nominal operating frequency, the impedance of the applicator must be changed through the matching box, to the nominal output impedance of the generator

(50-Ω). As the impedance of the applicator may vary around its nominal value (because different materials are processed or because the moisture content varies during the process, etc.), at least two reactive components of the matching box must be adjustable during the heating process. Since variable inductances are difficult to realize for high-power applications, variable capacitors are used. The matching box of our system is composed of two variable capacitors (which can vary from 0 to 1000 pF) and one fixed resistive coil. The capacitors are variable and are controlled by a matching box controller or impedance regulator (see photographs in Appendix B). The wide range of variability obtainable from the variable capacitors allows for use of the RF equipment with a multitude of different materials while assuring that the impedance of the applicator will remain matched to that of the generator, thus ensuring maximal power transfer from the generator to the material. The first variable capacitor is referred to the module or load matching to modulate to 50Ω and the second variable capacitor is referred to phase matching to monitor changes in phase (θ).

The impedance regulator:

The impedance regulator is the electric control of the matching box (see photograph in Appendix B). It controls the variations of the capacitors in order to maintain the impedance of the system at 50Ω. The regulator has an automatic feed-back, called the discriminator, connected to the applicator, which detects any fault in module tuning ($\neq$ 50Ω) and in phase tuning ($\neq 0°$) and takes immediate action with the variable capacitors in order to optimize and correct the faulty match. With this automatic impedance regulator, reflected power is minimized and power transfer is maximized.

The fiberoptic temperature measurement system:

The temperature measurement system is composed of optical fiber sensor probes which are transparent to electromagnetic interferences in comparison to traditional sensors. The probes can be directly inserted in the material to be heated. They have rapid response time (0.25 s) and the measurements can easily be interfaced to a data acquisition system by the means of an analog output (0-20 mA) and RS-232 communication interface (see

Appendix C for details).

The voltage regulator:

The voltage regulator is directly connected to the high voltage electrode of the applicator via a silver plated connector. This allows the accurate measurement of the voltage at the electrode level. Knowing the voltage at the electrodes allows for the calculation of the energy being absorbed by the material. The voltage regulator can be used simply as a measuring tool and it can also be used to control the voltage at the electrode during the period of a process. The voltage control can be achieved manually or via remote control with (0 - 10V) signals to the computerized control system.

The data-acquisition and control system (computer based):

The generator, the voltage regulator, the impedance regulator, the fiberoptic sensor are all connected to a data acquisition card which collects inputs in either mA or V. The inputs are sent to a data acquisition software which transfers, through mathematical correlations programmed by the user, the analogous inputs into observed values of:

* Incident and reflected power of the generator (W);
* Module and phase capacitor variations of the matching network (pF);
* Electrode voltage (V);
* Temperature inside the product mass (°C); etc.

The computer can be used as a control system in response to the data collected to take corrective measures in the RF treatment with respect to electrode voltage, and shut-off time.

3.5. IMPROVING COUPLING

3.5.1. Ionic Conductivity to Improve Coupling

Relatively little is known about the mechanisms of interaction in foods or their biochemical constituents at low frequencies. Ideal processing frequencies for specific unit operations may well vary with the processing objective because the dielectric behaviour of

food varies so widely with temperature and chemical composition in specific frequency ranges. At microwave frequencies, dipole losses in high and intermediate moisture foods are dominant at low temperatures while ionic losses become increasingly dominant at higher temperatures, where penetration depths become increasingly large. At frequencies below the microwave region, conductive migration effects associated with electrophoresis of dissolved salts in ionic solutions become increasingly more pronounced because of an inverse relationship between ionic loss and frequency (Mudgett, 1994).

At submicrowave frequencies, interfacial or space charge polarization mechanisms may be seen, which involve interactions between the field and charges bound or trapped within the material. Interfacial or space charge polarization effects may make some contributions to the dielectric behaviour of foods at radio-frequencies because of bound water and surface charge effects in the megahertz region. Such effects are not significant in food processing at submicrowave frequencies, because they are overpowered by ionic conductivity losses.

Dissolved salts depress the dielectric constant and elevate the dielectric loss with respect to the behaviour of pure water. Depression of the dielectric constant results from the binding of free water molecules by counter-ions of dissolved salts in aqueous solution. Elevation of dielectric loss in aqueous ionic solutions results from the addition of conductive charge carriers (dissolved salts) that are able to migrate by electrophoresis in directions opposite to the polarity of the applied field. The effects of increasing temperature at constant concentration are to increasingly depress the dielectric constant and elevate the dielectric loss of the ionic solution.

However you often get combined effects of dipole rotation and conductive (ionic) charge migration. These effects vary inversely with temperature; that is, the dipole loss component of an ionic solution decreases, and its ionic loss component increases with increasing temperature and vice versa (Mudgett, 1994).

The dielectric properties of structural, suspended, or bound food constituents classified in proximate analysis as moisture, carbohydrate, lipid, protein, or ash contents are similar to those for a variety of inorganic and organic solids that are dielectrically inert

compared with dielectrically active fluids like water or aqueous ions. Many liquid and semi-solid food products may be considered mixtures of dielectrically inert solids and dielectrically active fluids which are not chemically or electrically interactive. The inert phase is considered suspended in the active phase or vice-versa. The effects of moisture content are particularly important in the microwave region and for most practical purposes, are negligible at radio-frequencies.

3.5.2. Ionic Conductivity Testing

Trials were conducted to study the effects of increased ionic conductivity on the behaviour of the RF heating system, the energy coupling and the temperature increase. Wheat samples of 215 g were first treated with additions of various quantities of salt (from 0 to 50 g). With these trials, heating results were erratic and no conclusion could be derived from the ionic conduction effects. It is likely that with the simple addition of salt to the wheat seeds, all the salt crystals accumulated at the bottom of the container creating large gradients. Changes had to be made to the salt application procedure. We then tried to mix the wheat seeds with salt water to help increase the homogeneity of the salted wheat. However, here again, we had erratic results, likely caused by the increase in moisture content of the wheat and the inability, to some extent, of the wheat seeds to absorb the water due to the osmotic pressure of the salted solution which was evidenced by the presence of free water in the container even after an equalizing period of 48 h. It was then decided to opt for another method to achieve a more uniform spread of the salt over the mass of wheat seeds. The wheat seeds were thus sprayed with an olive oil aerosol to make the seeds sticky. Numerous quantities of salts were stirred in with the wheat kernels. This method allowed for an even distribution of the salt crystals over the surface of the wheat kernels. This method yielded the best results with uniform heating throughout the seed mass. For the experiment, it was decided that 215 g samples of wheat would be oil sprayed, stirred with 0, 5g, 10g, and 25g of salt and RF treated at 400 W output power for 3 min. and the tests would be repeated three

times. The statistical analysis of the data is presented in Appendix D. The average results of

the three replicates are presented in Figures 3.13-3.16. The temperature increase with time is presented in Figure 3.13, and it appears that the temperature increased with an increase in salt content with the maximum final temperature reached with the highest, 25 g, addition of salt. The increase in temperature was however not statistically significant ($p=0.9361$). The increase in the phase value of the matching box is presented in Figure 3.14. The phase value increased as it adjusted to couple the impedance of the circuit with increasing temperature over time. The salt addition had an effect on the phase adjustment with a significant increase with an increase in salt content again here with the most pronounce effect with the highest salt addition. The decrease in load value of the matching box with increasing temperature over time is presented in Figure 3.15. The salt addition marked a significant decrease in the load value. The Voltage decrease with temperature as affected by the salt content is presented in Figure 3.16. There was a significant effect on the voltage caused by the increase in salt content from 0 to 25 g ($p=0.0035$). The phase and load values of the matching box are excellent indicators of the dielectric behaviour of the material being heated. As we could theoretically predict, the dielectric properties were affected by the increased ionic conductivity which can clearly be noted with the necessary changes in impedance matching with both modulation and phase changes.

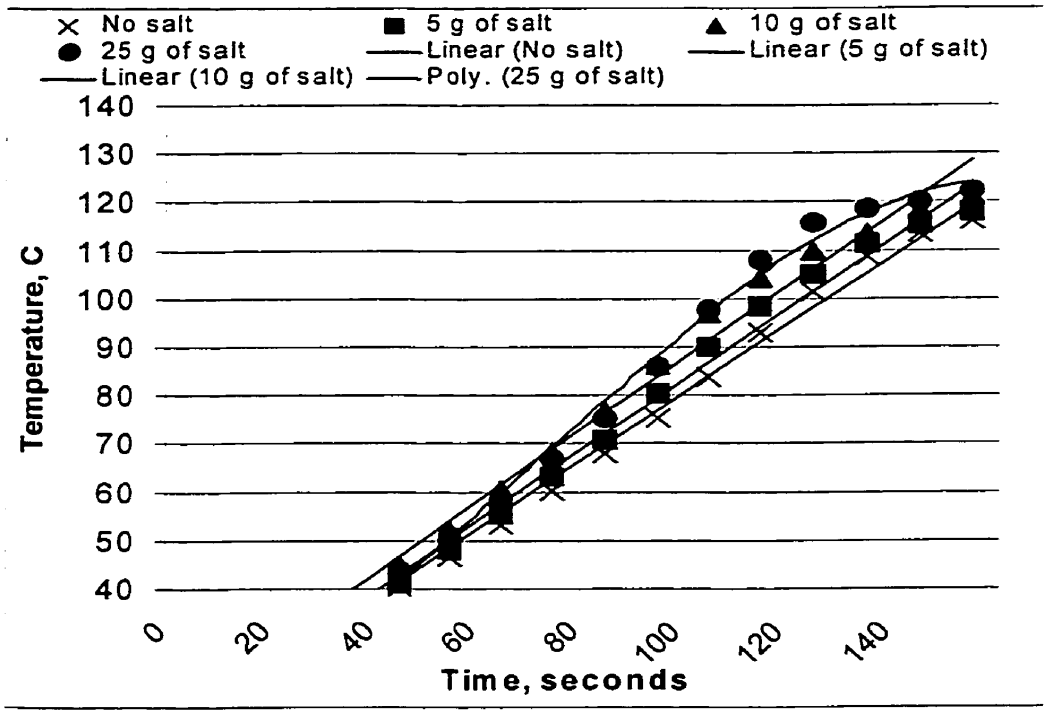

Figure 3.13: Temperature increase of wheat seeds under constant RF power with increasing salt content.

Least square fits were found to model the temperature behaviour of the wheat seeds with increasing salt content. In Figure 3.13, linear fits were found for samples containing no salt, 5 g of salt, and 10 g of salt. For 25 g of salt a polynomial regression matched better the data. The regressions expressing temperature (T, °C) increase with time (t, s) are as follows:

For wheat samples (215g) without salt (R^2=0.9957):

$$T = 7.088t + 5.9986 \tag{3.33}$$

For wheat samples (215g) with 5 g of salt (R^2= 0.9946)

$$T = 7.3494t + 6.0273 \tag{3.34}$$

For wheat samples (215g) with 10 g of salt (R^2=0.9918)

$$T = 7.4512t + 9.3564 \tag{3.35}$$

For wheat samples (215g) with 25 g of salt (R^2=0.9962)

$$T = -0.0451t^3 + 1.0976t^2 + 0.6647t + 16.912 \tag{3.36}$$

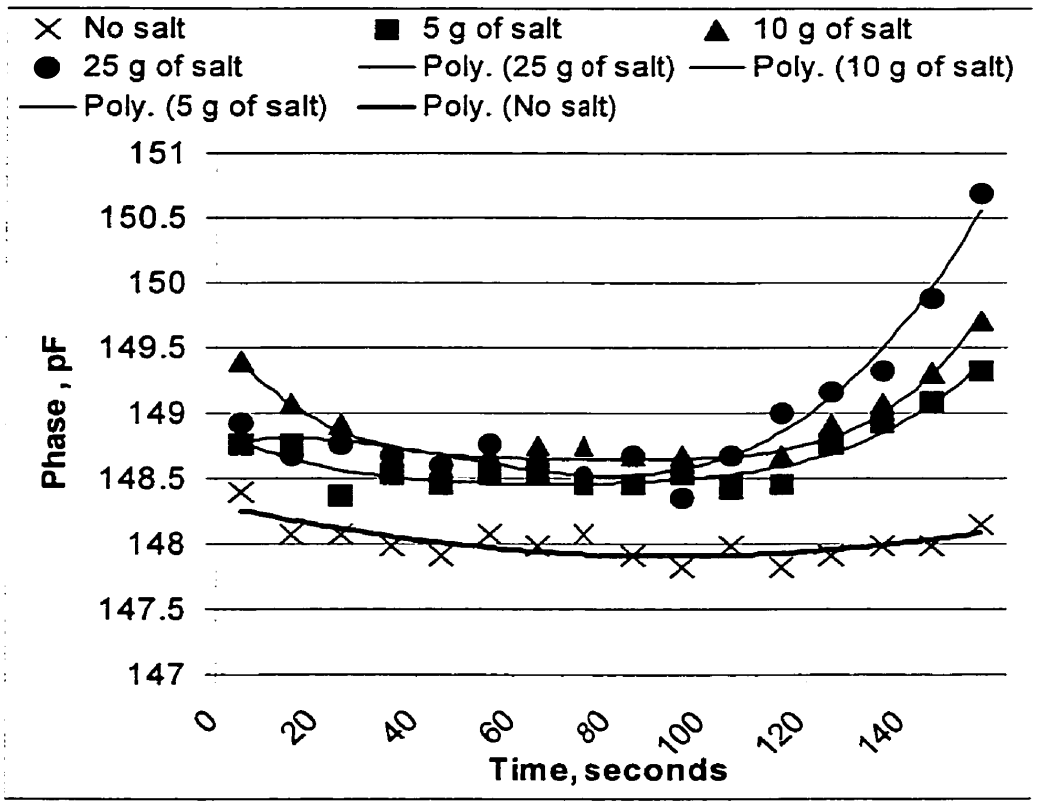

Figure 3.14: Variations of the matching box phase values with increasing salt contents under constant RF power for 3 min.

In Figure 3.14, polynomial regressions matched best the phase changes with time as a function of salt content. The regressions expressing phase variations (Phase, pF) with time (t, s) are as follows:

For wheat samples (215g) without salt (R^2=0.7513):

$$Phase = 0.0046t^2 - 0.0889t + 148.34 \tag{3.37}$$

For wheat samples with 5 g of salt (R^2=0.9042):

$$Phase = 0.0001t^4 - 0.0034t^3 + 0.0413t^2 - 0.236t + 148.98 \tag{3.38}$$

For wheat samples with 10 g of salt (R^2=0.9351):

$$Phase = 0.0003t^4 - 0.009t^3 + 0.1096t^2 - 0.5978t + 149.89 \tag{3.39}$$

For wheat samples with 25 g of salt (R^2=0.9596):

$$Phase = 0.0021t^3 - 0.0333t^2 + 0.1079t + 148.71 \tag{3.40}$$

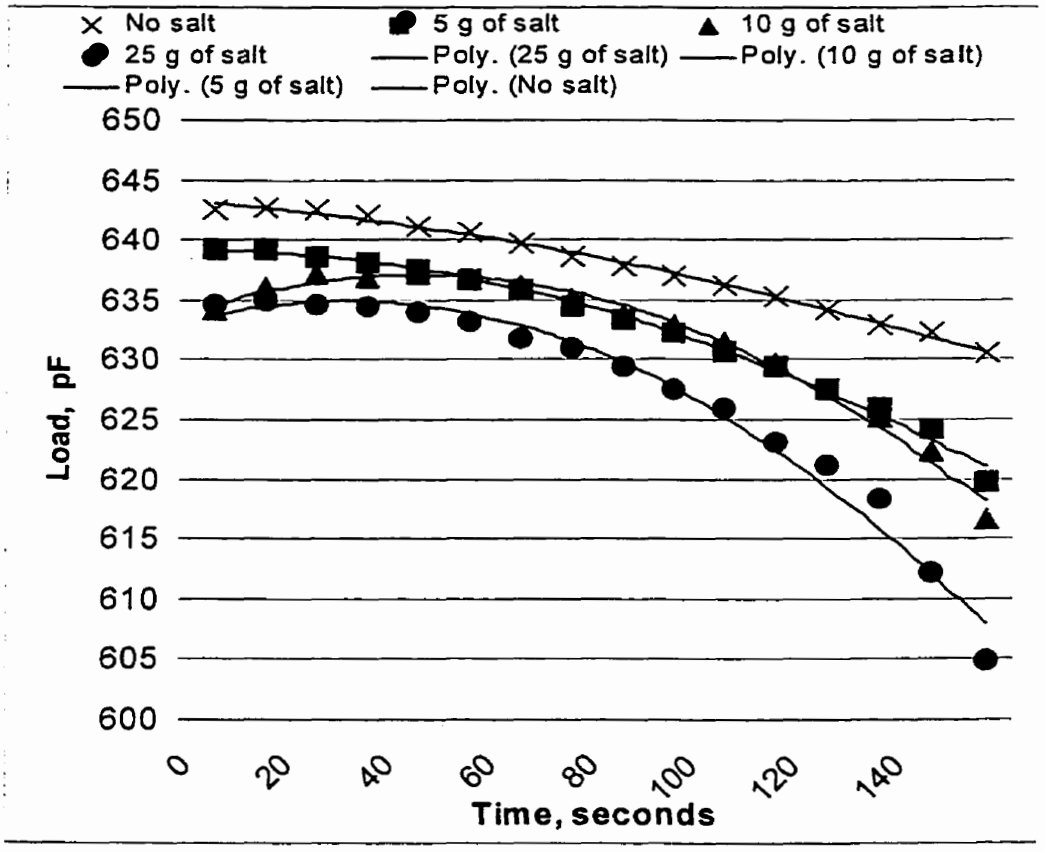

Figure 3.15: Variations of matching box load values (pF) with increasing salt contents under constant RF power for 3 min.

In Figure 3.15, polynomial regressions matched best the load value changes with time. The regressions expressing load variations (Phase, pF) with time (t, s) are as follows:

For wheat samples (215g) without salt (R^2=0.9954):

$$Load = -0.0302t^2 - 0.3182t + 643.41 \quad (3.41)$$

For wheat samples (215g) with 5g of salt (R^2=0.9938):

$$Load = -0.0744t^2 + 0.0565t + 639.17 \quad (3.42)$$

For wheat samples (215g) with 10g of salt (R^2=0.9896):

$$Load = -0.1549t^2 + 1.5319t + 633.27 \quad (3.43)$$

For wheat samples (215g) with 25g of salt (R^2=0.9807):

$$Load = -0.174t^2 + 1.2394t + 632.7 \quad (3.44)$$

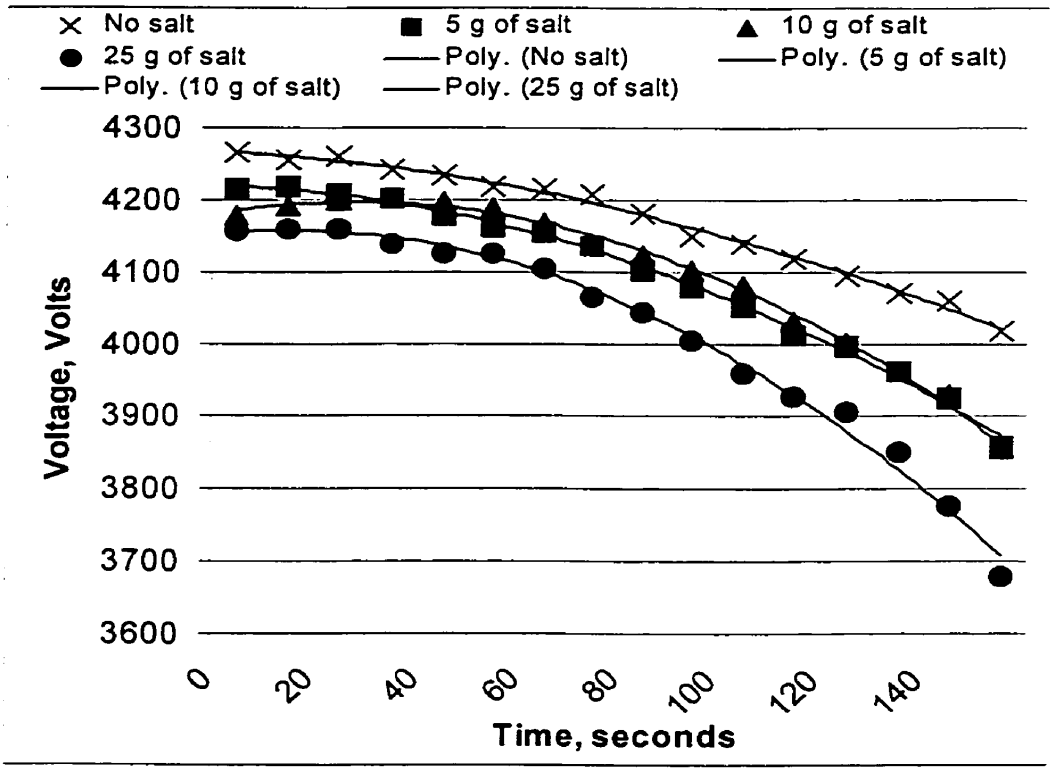

Figure 3.16: Voltage decrease with 3 min. of constant RF power and increasing salt content.

In Figure 3.16, polynomial regressions matched best the voltage decrease with time. The regressions expressing voltage decrease (V, volts) with time (t, s) are as follows:

For wheat samples (215g) without salt (R^2=0.9925):

$$V = -0.7889t^2 - 2.9613t + 4269.5 \tag{3.45}$$

For wheat samples (215g) with 5 g of salt (R^2=0.9962):

$$V = -1.2977t^2 - 0.9668t + 4221.1 \tag{3.46}$$

For wheat samples (215g) with 10 g of salt (R^2=0.9954):

$$V = -2.061t^2 + 13.602t + 4174 \tag{3.47}$$

For wheat samples (215g) with 25 g of salt (R^2=0.9921):

$$V = -2.2726t^2 + 8.911t + 4148.5 \tag{3.48}$$

3.6. SUMMARY

The two important conditions which must be met in order to successfully operate an RF dielectric heater are (a) the equipment should operate in a stable manner at one frequency within a very narrow frequency band, and (b) it should be possible to vary the power drawn from the generator, from a standby value up to its full rated output, while maintaining a perfect impedance matching between the applicator and the generator.

The development of new applications of RF heating requires targeted equipment design, specific fine tuning of the applicator design, high tech tools and highly skilled technicians. These boundaries are perhaps the reason why few applications have successfully been developed to reach the market place.

CHAPTER IV - RADIO-FREQUENCY SEED TREATMENT

4.1. ABSTRACT

Wheat-seed infection by a fungus such as *Fusarium graminearum* can considerably lower the seed germination and the quality of the harvest. It is thus important to treat the seeds to reduce the incidence of the fungus. Fungicidal and thermal treatments are traditional methods of seed treatment.

Radio-frequency (RF) heating, like microwave heating, is a rapid volumetric heating process which helps to reduce thermal damage to the seed. The advantage of RF over microwaves is that the electromagnetic wavelength is longer thus it has a greater depth of penetration allowing for the treatment of larger quantities in the target of potential commercial applications.

This study was conducted to determine the combined effect of different levels of RF power, temperature, and moisture content on the quality of seed-grade wheat infected by a fungus, and seed-grade soybean with a view to improving germination. For wheat seeds, the results indicate that all variables have a significant effect on the mortality of the fungus and the seed vigour. With higher electromagnetic power, higher temperature (90°C) and higher moisture content (14%), the fungus mortality is significantly increased, with a fungal vigour of less than 0.1, and the germination quality of the seeds is decreased to a seed vigour below 0.3. There appears to be, however, an optimal treatment for which the fungus mortality is maximized while conserving 70 to 80% of the seed germination quality. For soybean seeds, only treatments of low RF intensity (60°C) were successful in improving seed vigour for low moisture seeds especially at lowest moisture content typically found in stored seeds.

4.2. INTRODUCTION

Seed treatments are used on many crop seeds for a variety of purposes. The greatest use of seed treatments has been to provide an inexpensive insurance against rooting of the seeds by fungi and other pests. Increasingly, commercial seed producers are beginning to view seed treatments as a means to substantially increase the value of the seed and to improve plant growth and productivity (Taylor and Harman, 1990).

Interest in the possibility of controlling pests with high frequency electric energy dates back to over 60 years (Beckwith and Olsen, 1931; Fabian and Graham, 1933; Fleming, 1944; and Nyrop, 1946). Concern about the health hazards of chemical pesticides in the 1950's and 1960's, has stimulated further studies on the possible uses of radio-frequency (RF) and microwave energy for controlling pests that attack grain during storage (Brown and Morrison, 1954; Whitney et al., 1961; Carroll and Lopez, 1969; and Eglitis and Johnson, 1970). Although past research has shown some promising results with the use of dielectric heating in pest control and for improving seed quality, and has shown potential to overcome concerns about the use of chemical pesticides, still today new dielectric techniques have not found their way into practical use (Nelson, 1996).

The objectives of this work were thus to:

1) Evaluate the potential of RF energy, at 27.12 MHz, to disinfect seed-quality wheat infected with *Fusarium graminearum* while maintaining the germination quality;

2) Determine the potential of RF treatments to improve soybean seed germination and seed vigour, since there has been evidence in past research by Nelson's team (Nelson and Stetson, 1985; and Nelson, 1976), that dielectric heating may improve the germination potential of seeds having an impermeable seed coat.

4.2.1. Mechanisms of Seed Germination

Germination is the series of events which cause a dry dormant seed, in response to water uptake, to show a rise in metabolic activity and to initiate the formation of a seedling

from the embryo. A typical seed has three fundamental parts as can be seen in Figure 4.1. 1) a seed coat; 2) a storage area called the endosperm and; and 3) a dormant embryo (Mayer and Mayber, 1989).

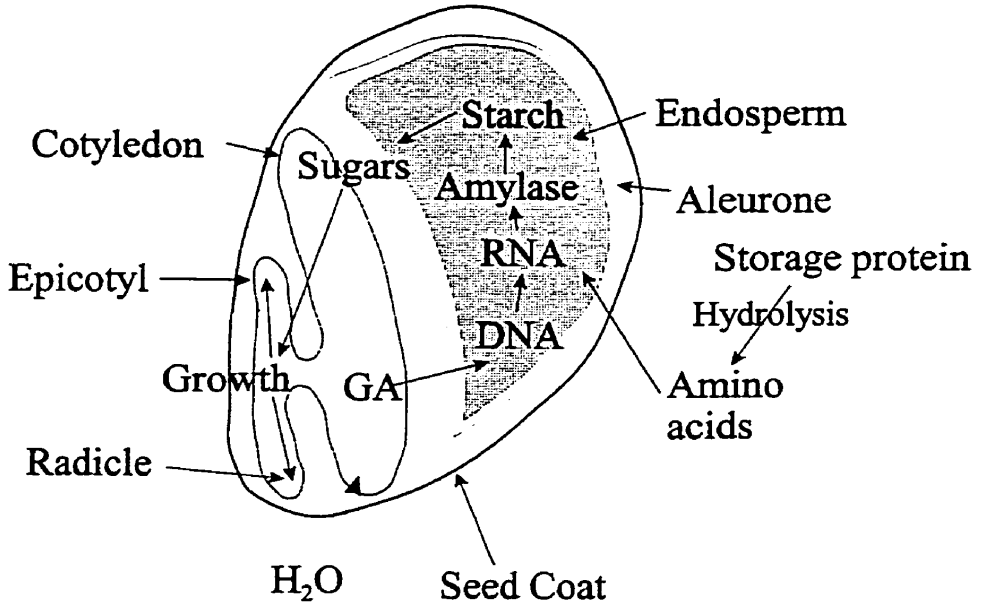

Figure 4.1: Typical mechanisms involved in the germination of a seed.

The seed coat is impermeable and it requires to be weakened in order to allow the water absorption needed to activate the embryo's metabolism and the start of growth. The physical weakening of the seed coat is called scarification. Mechanical scarification is needed in the cases of seeds having a thick seed coat like legume seeds. Once there is an opening in the seed coat, the seed will start imbibing water to feed the embryo.

The embryo is composed of three parts:1) the cotyledon (one if a monocot or two in the case of a dicot); 2) the epicotyl (which will become the shoot); 3) the radicle (which will become the root).

The endosperm of the seed is composed in majority of a starch storage area with a covering layer known as the aleurone layer which is made of cells which store protein in abundance. Thus the first step in seed germination is the absorption of water. The water

penetrates the seed coat and softens the hard dry tissues of the seed. The water taken-up will cause the grain to swell up. The water then activates the biochemistry of the dormant embryo. The water coming into the seed and embryo dissolves a chemical which is produced in the cotyledon of the embryo. This chemical is called gibberellic acid (GA in Figure 4.1). It is a plant hormone. The dissolved gibberellic acid is transported with the water through the rest of the seed's tissues through the endosperm starchy flesh until it reaches the aleurone layer. The gibberellic acid then crosses into the cytoplasm of the aleurone cells where it activates the DNA which in turn sends the instructions for the survival of the plant. The information in the DNA is transcribed to an RNA messenger which carries on to the process of protein synthesis. The protein synthesis is made possible by the restructuring of the existing amino acids from the protein of the aleurone layer. The protein being made is called amylase. This is a protein of great importance due to its enzymatic properties. The amylase produced is then transported from the aleurone cells into the endosperm. In the endosperm, the amylase accelerates the hydrolysis of starch into its component sugars. The released sugars are then transported from the endosperm to the embryo. The cotyledon acts as the sugar transfer area of the grain. Once the cotyledon has stocked up on sugar, the embryo uses the sugar as fuel and building blocks for growth leading to the emergence of the radicle and epicotyl. Germination is said to have occurred when growth of the radicle bursts the seed coat and protrudes as a young root (Mayer and Mayber, 1989).

There are multiple factors which will influence the successful germination of a seed. Those are principally, light, moisture and temperature conditions. Water is essential to germination. Too little or too much can retard germination, reduce vigour or injure the seeds.

Seed Embryo

It appears, from the mechanisms of seed germination that the embryo is the part of the seed where the major role is played with respect to initiation of the process through water absorption and through plant growth via the radicle and epicotyl which feed on the sugar reserves accumulated in the cotyledon. In the context of RF treatment of seeds it will be interesting to find out if there are structural damages occurring at the embryo level, especially

at the surface of the seed which would allow for the easier uptake of water into the cotyledon (the determination of cracks is the subject of Chapter V). In our preliminary research as well as in the literature, it has been found that an RF treatment can significantly improve seed germination and vigour. Where vigour is a parameter evaluating the strength of the plant shortly after germination (length of root and shoot).

Seeds subjected to an RF field heat up as they absorb energy from the electromagnetic field. The rate of energy absorbed per unit volume of seeds can be expressed as:

$$P = 2\pi f E^2 \varepsilon_o \varepsilon'' \tag{4.1}$$

where P is the power in W/m^3, f is the frequency in MHz, E is the rms electric field intensity in V/m and ϵ_o is the permittivity of free space and ϵ'' is the dielectric loss factor of the seeds.

The dielectric loss factor, the imaginary component of the relative complex permittivity, $\epsilon_r = \epsilon_r' - j\epsilon_r''$, is a characteristic of the seed that depends upon its composition. The seed, as seen in Figure 4.1, is composed of various chemical components which will most likely have an effect on the spatial variability of the dielectric property of the seed. So far there has not been any measurement made (by us or in the literature) on the dielectric property of the various parts of a seed. Rather, the measurement of dielectric properties has been made on powdered grains or on bulk samples of grains. Thus the values that are available are for the seed as a whole and not for parts of a seed. If we take the example of wheat, the primary component of the seed is starch which makes up the composition of the endosperm, then the composition of the embryo is mostly protein and to a lesser extent, oil. It is likely that there are differences in the dielectric properties at various locations through a seed especially between the embryo and the endosperm which have significant differences in composition. According to the composition of both parts, the assumption that can be made is that the embryo has a greater dielectric loss factor than the endosperm, so the seed probably absorbs a greater amount of energy at the level of the embryo. However, the seed is of relatively smaller size and the selective heating at some location due to its higher dielectric loss factor may be of little consequence due to rapid dispersion of that heat through the entire volume of the seed over the period of a treatment. Results from our analysis of stress crack

development in seeds (Chapter V) will help us to determine if there is selective heating in any parts of the seeds. It will be interesting to know if it occurs in the embryo, which may help explain why the RF treatment may enhance seed germination as it was the case in some of our experiments, and for other researchers.

4.2.2. Germination Improvement

In cultural production, the seed-coat impermeability can present a problem for farmers and seed-men. This problem is not one of seed viability, because the seeds may eventually germinate and grow. Instead, the seed coat is impermeable to moisture, and the seeds cannot be depended upon to germinate quickly when planted to produce an acceptable stand of the crop.

For many years, seed-men have used a process known as scarification to increase the permeability of seed coats in seed lots with high percentage of hard seed. Scarification is an abrasive process that may damage the seed, and increase the risk of infection and serious deterioration in seed quality (Nelson and Stetson, 1985). Hard seeds have a high occurrence in legume seeds and they are often found in soybean depending on cultivar, moisture stress and defoliation before harvest (Heatherly and Kenty, 1995; and Vieiro et al., 1992). Hard seed phenomenon has been reported for many species such as soybean, cowpea, alfalfa, clover, etc. (Saio, 1976). The seed coat of these species are hard, making them impermeable to moisture requiring scarification through weathering or abrasion to allow the uptake of moisture essential for germination. Scarification can be achieved through mechanical means, freeze-thaw cycles, thermal treatments such as hot air or steam, however, scarification in general may be injurious to the quality of the seeds (Hall et al., 1993).

When seed is exposed to RF energy of sufficiently high frequency and intensity, its temperature will rise due to dielectric heating. If samples of a given seed lot that contains an appreciable portion of hard seed are subjected to a sequence of exposures of increasing duration, germination will increase to some maximum as exposure and temperature increase, then, with continued increasing exposure, germination will decline (Nelson, 1976; Nelson and Stetson, 1985).

Direct comparisons of 39 MHz and 2450 MHz exposures on germination of alfalfa seed of three different varieties were studied by Nelson (1976). The two frequencies were equally effective for reducing hard-seed percentages and increasing germination when the resulting seed temperatures were comparable (Nelson, 1976). Thus, RF treatment for lowering hard-seed contents in seed lots promises advantages compared to mechanical scarification, which damages the quality of seed when it is held in storage.

4.2.3. Control of Seed-borne Diseases

Seeds are an essential component of world trade and are distributed nationally and globally, destined to grow crops, which themselves are consumed. Approximately 90% of all food crops in the world are propagated by seeds (Maude, 1996). Seeds are also the carrier of pathogens (fungi, bacteria, viruses, etc.), which are transmitted when the host seeds are sown.

For more than 50 years, seed-borne pathogens of cereals were effectively controlled by the routine use of organo-mercury fungicides. In response to concerns over the toxicity and persistence of mercury in the environment, environmental agencies have prohibited the use of mercury in agriculture. Today, other chemicals are used, however the increasing health and environmental concerns are likely to lead to their prohibition as is the case for methyl bromide.

One of the requirements of certified seed is that the minimum germination should be at least 85% in the case of Canada #1 wheat seeds and at least 90% in the case of Canada #1 soybean seeds (Canada Seeds Act, 1967). The presence of a fungal disease such as *Fusarium spp.* may have an effect on the certification, as the disease will reduce germination and field emergence (Gilbert and Tekauz, 1995).

High levels of *Fusarium* are associated with cool wet weather. The fungus attacks the pericarp and aleurone layer and penetrates cell walls quickly to enter the endosperm where it digests storage protein and starch. *Fusarium spp.* are known to have an effect on germination in wheat seed and it is probable that it is through the control of this pathogen that the seed treatment effect is mediated. *Fusarium graminearum, F. culmorum* and *F.*

crookwellense are closely related species that produce mycotoxins such as deoxynivalenol or nivalenol and zearalenone. These fungi cause fusarium head blight in small grains and gibberella ear rot in maize. *F. graminearum* is regarded as the most virulent although all three species can cause epidemics (Miller, 1994). The mycotoxins produced by *Fusarium* species are known to cause alimentary toxic ailments to mammals. Dietary exposure to these mycotoxins can lead to an increased susceptibility to other microbial infections. Pigs and other monogastric animals including humans appear to display the greatest susceptibility to these toxins (Sweeney and Dobson, 1998).

Monitoring of the disease can be done either by preharvest or postharvest control. Preharvest control is accomplished by i) selection of disease free seed and production areas; and ii) adequate cultural practices. The adequate cultural practices include planting disease free seeds, treating with antibiotics, using fungicides and pesticides, avoiding over irrigation, considering crop rotation and monitoring the possible disease vectors. Postharvest control methods should only be considered when preharvest control measures have failed since it is recommended to prevent the occurrence of the disease rather than to eradicate an already present infection or infestation (Schumann, 1991). There exists nonetheless methods that may help upgrade the phytosanitary quality of the seeds after harvest. Those are, i) surface disinfectant by chemical seed treatment; and ii) hot-water or heat treatment.

Heat disinfection of grain using high temperatures has the benefits of being a very effective, rapid, no residue method. However, it offers no medium-long term protection, and its potential to be used to disinfect grain has yet to be implemented.

Heat treatments have been investigated for a number of seeds such as hot water treatment of rice (Ventura and Garrity, 1987), dry heat treatment of pepper seeds (Rast and Stijger, 1987), lettuce seeds (Drew and Brocklehurst, 1985) and sorghum seeds (More et al., 1992). Microwave treatment of seeds has also been investigated (Bhaskara-Reddy et al., 1995; Stephenson et al., 1996). Results have shown that thermal electromagnetic treatments can effectively eliminate the contaminants with various levels of seed damage.

Results have all indicated that safe treatments were a function of the temperature, the exposure period, the storage conditions, cultivar resistance and pathogen heat resistance. In

any case, complete elimination of the disease or pathogen had an adverse effect on the germination and viability of the treated seeds.

4.2.4. Selective RF Heating

In theory, when a mixture of materials, for example, grain and insects, is exposed to an RF field, one material may absorb energy at a higher rate than the other, providing a selective or differential heating condition. The heating rate of each material would then depend on the frequency and intensity of the field, and on the loss factor, specific heat and density of each material.

If selective heating of pests in relation to the grain they infest were possible, dielectric heating would offer an advantage over conventional heating for stored-grain pest control. In a situation where the dielectric loss factor for the pests and the grain are different, the electric field intensities in the pests and the grain might also differ, offering a great potential for selective heating (Nelson et al., 1966).

Heating by radio-frequency has been used successfully for the eradication of certain internally borne bacteria, fungi and viruses from seeds, and provides a residue-free effective means of controlling a number of diseases (Seaman and Wallen, 1967). Sublethal exposures of certain seeds to RF fields have been found to stimulate germination and to reduce the incidence of hard seeds (Nelson, 1976). In experimentations conducted by Fleurat-Lessard et al. (1979; 1989), there seems to be a true potential of RF heating in the disinfestation of grain, cereal and flour with targeted thermal shock.

In an experiment by Nelson and Stetson (1974), electric fields at 39 and 2450 MHz were tested to control rice weevils in wheat. It was found that 39 MHz exposures were much more effective than were 2450 MHz exposures in killing the insects. Complete mortality was achieved at 39 MHz by exposures that produced grain temperatures of 40 °C, whereas higher temperatures were required with 2450 MHz. In recent studies, concentrating on the dielectric property measurement in the RF and microwave electromagnetic spectrum, Nelson et al. (1998) state that their permittivity data indicate no advantage of frequencies up to 20 GHz for potential control of stored-grain insects with no apparent selective heating.

4.3. MATERIALS AND METHODS

All treatment tests were conducted with the RF-system designed for this study as described in Chapter III.

4.3.1. Germination and Seed Vigour Testing

Germination is most commonly used to determine seed viability. Seed vigour is defined as those seed properties which determine the potential for rapid uniform emergence and development of normal seedlings under a wide range of field conditions.

The paper towel test was employed for evaluating seed vigour. Germination paper, cut to a size of 20 cm wide by 30 cm long was used. Two layers were put together and soaked in a large dish filled with distilled water. Fifty seeds were then scattered evenly over the surface of the paper leaving a margin of 2 cm from the edges except 4 cm from the bottom. Another sheet of paper was soaked in water and placed on top. The assembly was then rolled up in a loosely packed cylinder held together at the top by a tape bearing the treatment number so that each roll was clearly identified. Each roll was placed upright in a beaker in which 1 cm of water was maintained. Two rolls were prepared from each set of seeds. After 7 days at 20°C, the percentage of normal seedlings was counted along with radical and hypocotyl length.

A conventional vigour index for each seedlot was established by multiplying percent normal germination by millimetres of hypocotyl and radical length as seen in equation 4.2 (Abdul-Baki and Anderson, 1973).

$$\textit{Vigour Index} = \%\ \textit{Germination} \times (\textit{Hypocotyl} + \textit{radical}) \qquad (4.2)$$

A vigour ratio was then calculated by dividing the sample vigour index by the vigour index of the control (untreated sample). The vigour index of the control sample was therefore equal to 1.

4.3.2. Method of Fungal Detection

Assessment of seed infection was conducted with Potato Dextrose Broth and Agar, supplemented with Penta-chloro-nitro-benzene (PCNB 1.5 g/L: a fungicide which prevents the growth of other saprophytic fungi)) and Chloramphenicol (0.1 g/L). The agar medium was prepared by mixing the agar powder with an appropriate quantity of water, and additives. The mixture was sterilized in an autoclave for 20 min. and cooled to approximately 50°C. This mixture was carefully poured into petri dishes by lifting the lid just enough to pour in the growth media in order to avoid contamination. The closed petri were allowed to cool and solidify for 20 min. after which they were ready for use. Following the RF treatments, 100 seeds from each sample were sown in petri plates (25/plates). The seeds were individually placed on the agar surface with a disinfected forceps. The plates were incubated at 20°C for 4 days. *Fusarium spp.* colonies consist of fluffy yellow to pink or coral-coloured mycelium. Seeds associated with the mycelium were considered infected.

4.3.3. Experimental Design

Wheat seeds were obtained in late fall from the college farm. The field was chosen because it was infected with *Fusarium graminearum*. The infection level was around 40%. The weather conditions prior to harvest had been dry for a long period, thus the seeds which were harvested had a moisture content around 10-11%. The seeds were harvested by hand to minimize damage. After harvest the seeds were laid out on trays and set to dry under forced air ventilation at room temperature, until the wheat reached a moisture content of 8%. The wheat was then separated in three batches: one to be kept at 8% moisture, one to be brought up to 10% and the last one to be brought up to 14% moisture content by the addition of pre-determined amounts of distilled water. Once the desired moisture contents were obtained, the three different batches of seeds were stored separately in sealed containers kept in refrigerated storage until use. All samples were left to reach room temperature before use.

Fifty gram samples were placed in 50 mL Pyrex beakers for treatment in the RF applicator. Two fiberoptic probes (Nortech Fibronic, Quebec) were placed in the wheat mass at two different locations (top middle, and bottom middle) to monitor the product

temperature during treatment. The samples were subjected to 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11 W/g of applied power and brought to temperatures of 60, 70, 80, and 90°C. Each treated sample was divided in three, where one part was used for moisture determination, one part was used for fungal disease determination and the last part was used for germination testing. In all cases, the results were compared with control (untreated) values.

In the case of germination improvement by RF treatment, soybean seeds (cv. Maple Glen having 13.3% m.c.), commercially procured, were used for the study. Samples (200 g) were placed in 500 mL Teflon beakers for treatment in the RF applicator. The samples were subjected to RF treatments upto 60, 70 and 80°C, for 5, 10 or 15 min. at three different moisture contents of 13.3, 18.4, and 22.9%. Each treatment was replicated three times. Each treated sample was tested for germination and seed vigour.

4.4. RESULTS AND DISCUSSION

The temperature readings obtained from the two fiberoptic probes were not statistically different, thus the average of the two values was taken as the temperature of the grain mass. All results were analysed statistically using a statistical analysis software (SAS for Windows). The data was arranged in order to study the effect of moisture content and final temperature on the seed vigour in the case of soybeans and also of fungal vigour in the case of RF treated wheat seeds. The statistical analysis outputs are presented in Appendix E, and the results are referred to in the text.

4.4.1. Moisture Content

Moisture in seeds is always an important factor. The hilum operates as a hygroscopically activated valve, permitting moisture to escape from the seed but closing to prevent the seed from taking up moisture in a humid environment. When seeds are treated with RF energy, the moisture content is important because their dielectric loss factor increases with moisture content, therefore their moisture content determines, in large part, the rate at

which they will absorb energy from the RF electric fields. Also, the temperatures that seeds can tolerate without loss of viability are dependent upon their moisture content. For seeds of low moisture content, about 8%, a treatment that results in a temperature of about 75-85 °C is close to the maximum exposure for maintaining germination quality and achieving appreciable levels of pest mortality. On the other hand, at higher moisture content, around 14%, the final temperature should not exceed a maximum of 65-75 °C.

Wheat seeds

Effects of moisture content on RF-treated wheat seeds are presented in Figures 4.2 and 4.3. Seeds having higher moisture levels are more susceptible to heat damage and reduction of seed vigour, even at relatively low temperatures. The maximum treatment temperature for wheat seeds having 14% m.c. is 60°C, 70°C for wheat seeds having 10% m.c., and 80°C for 8% m.c. wheat seeds. In Figure 4.2, polynomial least square fits were matched to the data to express the seed vigour ratio as a function of treatment temperature. For 8% mc wheat seeds, the seed vigour ratio (VR) is expressed as follows (R^2=0.9685):

$$VR = -0.0011T^2 + 0.1582T - 4.4703 \quad (4.3)$$

For 10% mc wheat seeds (R^2=0.9343):

$$VR = -0.0007T^2 + 0.0859T - 1.6148 \quad (4.4)$$

For 14% mc wheat seeds a linear regression fitted the data (R^2=0.9967):

$$VR = -0.0196T + 2.1765 \quad (4.5)$$

An inverse trend is seen in Figure 4.3, where highest fungal destruction was achieved at higher moisture content and the highest fungal survival was experienced at the lowest moisture content.

Soybean seeds

The germination percentage, vigour index and vigour ratio of RF-treated soybeans are

presented in Figures 4.4 to 4.7. Figure 4.4 presents germination percentage along with linear regressions expressing germination percentage as a function of RF treatment intensity (where P is expressed in W/g).

For 13.3% mc soybean seeds, the regression is as follows (R^2=0.7272):

$$Germ\% = -109.47\ P + 249.79 \tag{4.6}$$

For 18.4% mc soybean seeds, the regression is as follows (R^2=0.9328):

$$Germ\% = -139.35\ P + 231.4 \tag{4.7}$$

For 22.9% mc soybean seeds, the regression is as follows (R^2=0.9286)

$$Germ\% = -90.627\ P + 151.04 \tag{4.8}$$

The only RF-treatments which maintained the germination percentage are the treatment combinations at 60°C for low moisture soybeans (13.3% m.c.). Any other treatment combination and higher soybean moisture content had a detrimental effect on germination percentage and seed vigour with the worst results obtained for the soybean seeds with highest moisture content (22.9% m.c.). Improvement of vigour was obtained for both lower moisture contents (13.3 and 18.4% m.c.), for mild RF treatments at 60°C. All treatments were detrimental to vigour for soybeans of higher moisture content (Figures 4.5 to 4.7). The vigour ratio, which expresses the vigour as a function of the control values is presented in Figure 4.6, expressed as a function of RF power intensity and in Figure 4.7, expressed as a function of time-temperature combinations. The vigour ratio raised above 1, only for low moisture seeds (13.3% m.c.), and mild heat treatments (60°C).

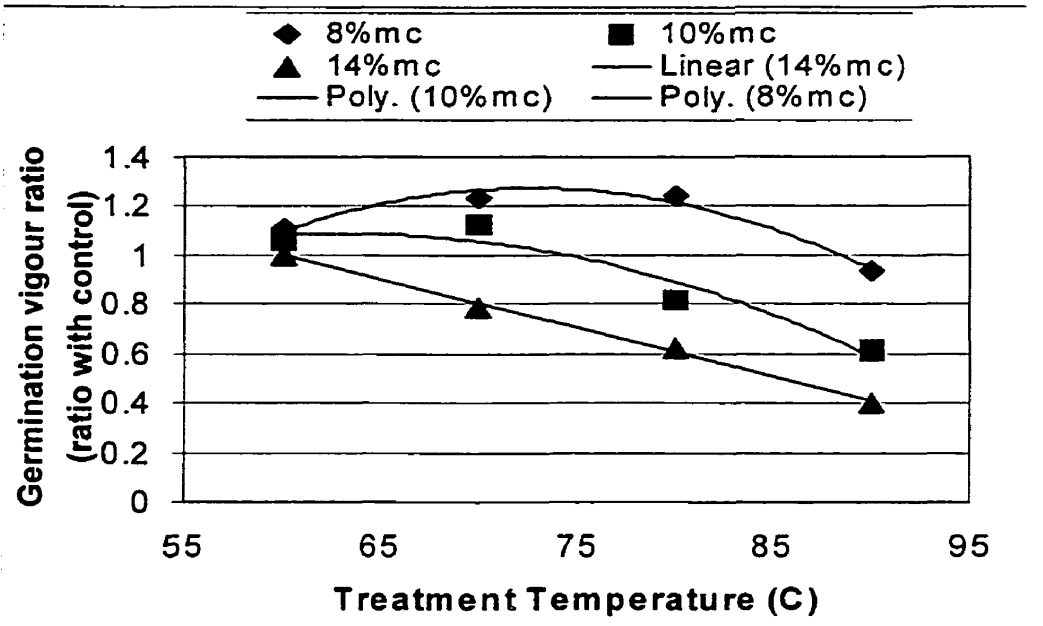

Figure 4.2: Ratio of seed vigour of RF treated wheat seeds graphically represented as a function of product temperature and initial seed moisture content.

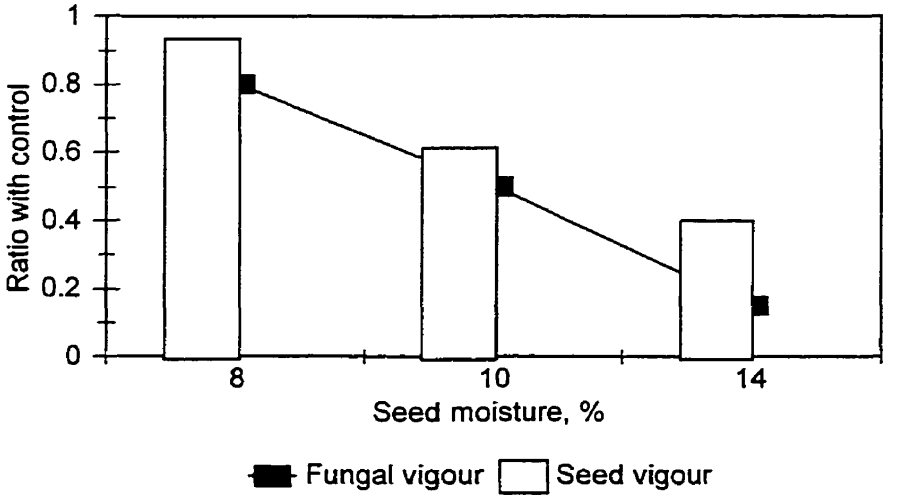

Figure 4.3: Ratio of seed and fungal vigour of RF-treated wheat seed expressed as a function of seed moisture content for a treatment temperature of 90°C.

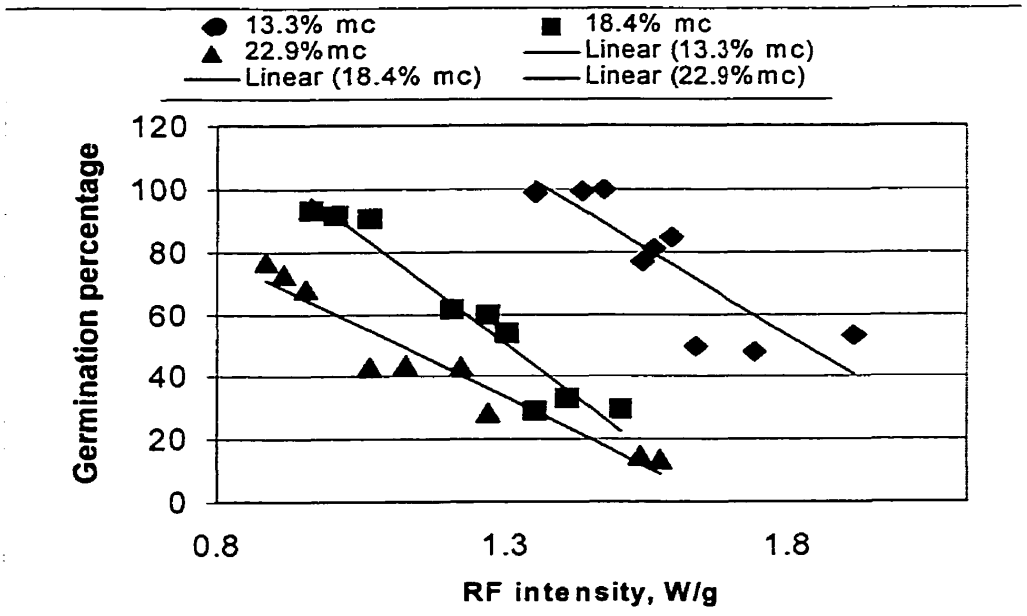

Figure 4.4: Germination percentage of RF treated soybean seeds, at three different initial moisture contents as a function of RF power intensity.

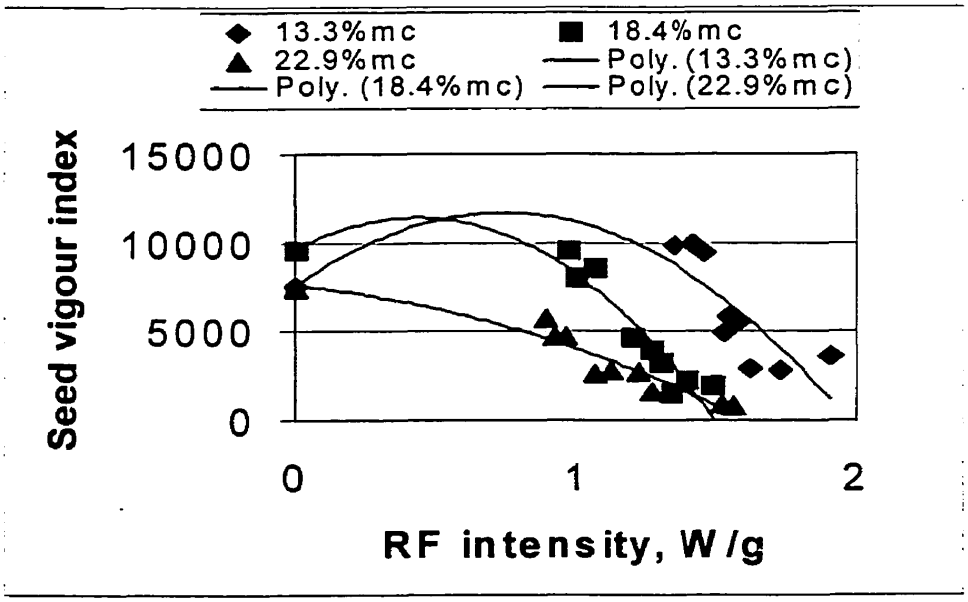

Figure 4.5: Seed vigour index of RF treated soybean seeds, at three different moisture contents as a function of RF power intensity.

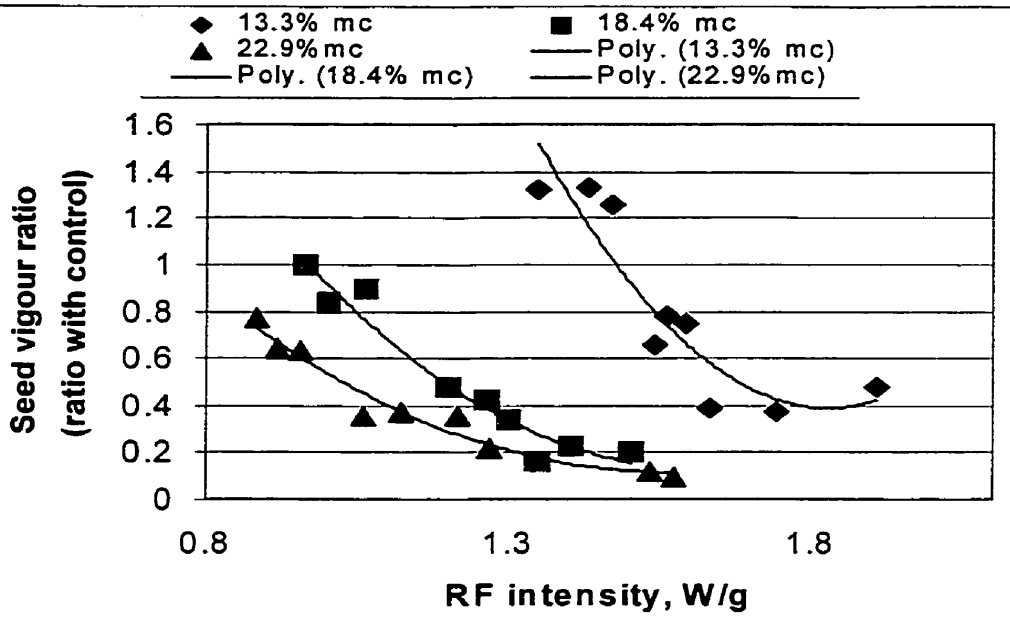

Figure 4.6: Seed vigour ratio of RF treated soybean seeds, at three different moisture contents as a function of RF power intensity.

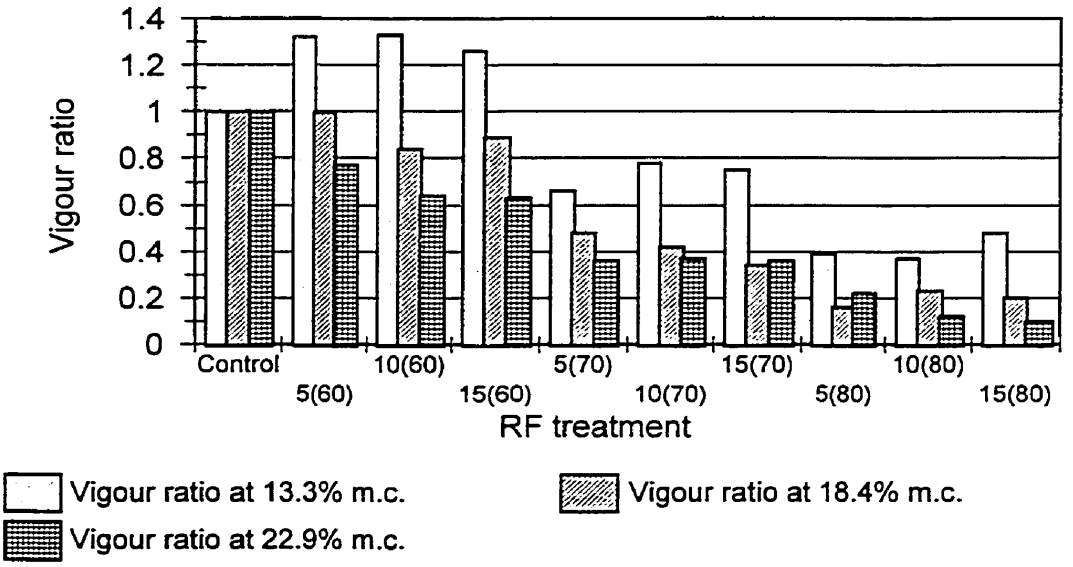

Figure 4.7: Seed vigour ratio of RF treated soybean seeds, at three different moisture contents as a function of RF treatment time-temperature combinations.

Figure 4.5 presents the polynomial regressions of Vigour Index expressed as a function of RF power intensity.

For 13.3%mc soybean seeds, the regression is as follows (R^2=0.6255):

$$Vigour\ Index = -7538.9\,P^2 + 11056\,P + 7635.9 \tag{4.9}$$

For 18.4%mc soybeans seeds, the regression is as follows (R^2=0.9026):

$$Vigour\ Index = -9754.6\,P^2 + 8266.4\,P + 9678.7 \tag{4.10}$$

For 22.9%mc soybean seeds, the regression is as follows (R^2=0.9127):

$$Vigour\ Index = -1805.8\,P^2 + 1777\,P + 7604.5 \tag{4.11}$$

Figure 4.6 presents the polynomial regressions of seed vigour ratio (ratio with control values) expressed as a function of RF power intensity.

For 13.3%mc soybean seeds, the regression is as follows (R^2=0.8453):

$$VR = 4.9856\,P^2 - 18.202\,P + 17.004 \tag{4.12}$$

For 18.4%mc soybean seeds, the regression is as follows (R^2=0.9525):

$$VR = 2.0786\,P^2 - 6.7202\,P + 5.5616 \tag{4.13}$$

For 22.9%mc soybean seeds, the regression is as follows (R^2=0.9576):

$$VR = 1.2743\,P^2 - 4.0215\,P + 3.2858 \tag{4.14}$$

4.4.2. Temperature

Soybean seeds

In the soybean experiment conducted, the degree of germination stimulation was highly correlated to the applied temperature, initial moisture content and treatment duration. Temperature and moisture content had significant impact on the germination quality, while treatment duration only had a significant impact when studied in combination with sample

moisture content (Appendix E). If we look at the results obtained for heat treatment of the low moisture soybean (13.3% m.c.), the RF treatment was successful in keeping the germination percentage and improving the seed vigour for treatments at 60°C of 5, 10 and 15 min. (Figure 4.7). Both temperatures of 70 and 80°C reduced the germination percentage, and seed vigour for all treatment combinations.

As can be seen, germination improvement was only achieved with low moisture seeds (13.3%) and low intensity RF treatments (60°C). This is an interesting result since treatment for seed germination improvement would likely be resorted to when the seeds are already at low moisture, taken out of storage. As expected, higher intensity RF treatments and higher moisture contents yielded lower germination and seed vigour due to thermal damage to the seed following pressure build-up from the moisture content attempting to escape the kernel.

Wheat seeds

Similarly, with wheat seeds, which do not experience hard seed problems, we obtained an improvement of the seed vigour with mild heat treatments as can be seen in Figure 4.2 where the seed vigour was significantly improved for low moisture wheat seeds at treatment temperatures of 60, 70 and 80°C.

The temperature influence appears to be that of the final temperature to which the seed is raised by RF treatment. Increasing the treatment temperature from 60 to 70, 80 and 90°C had a significant ($p<0.05$) effect on both the germination quality and the fungal vigour for the three seed moisture levels of wheat seeds. In addition to final seed temperature, it appears that the heating rate has a significant effect on seed germination as well as fungal vigour. Indeed, in Figure 4.8, we can see that with low applied power, the treatment requires 30 min. and leads to a little reduction in both germination and fungal vigour. On the other hand, with moderate power, the time is decreased to 15, 6, and 4 min. with a more appreciable decrease in fungal vigour and no decrease in germination quality (if not an increase in vigour with a stimulation of germination). The trends were similar for the three moisture levels, however only the results for seeds having 10% moisture content are presented here in Figures 4.8-4.11.

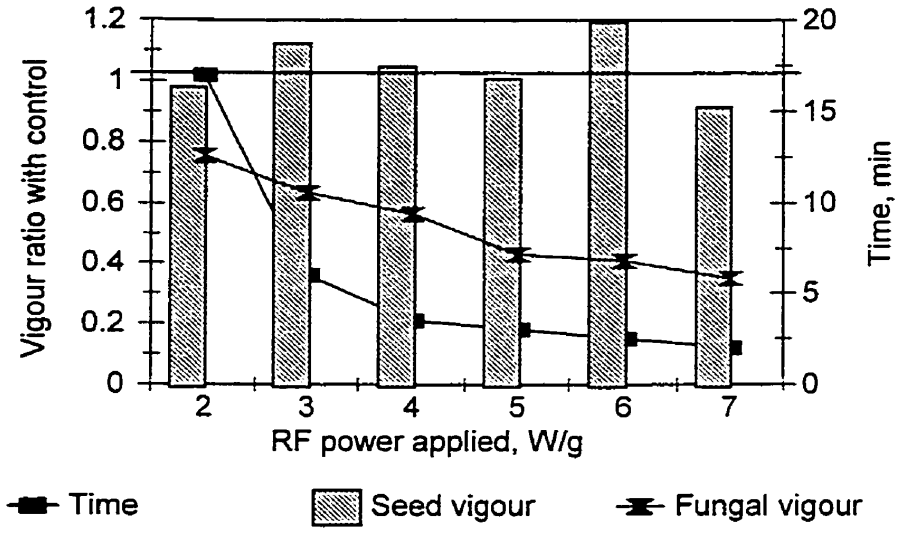

Figure 4.8: Seed vigour, fungal vigour and treatment time expressed as a function of applied power for a seed moisture content of 10% and seed temperature of 60°C.

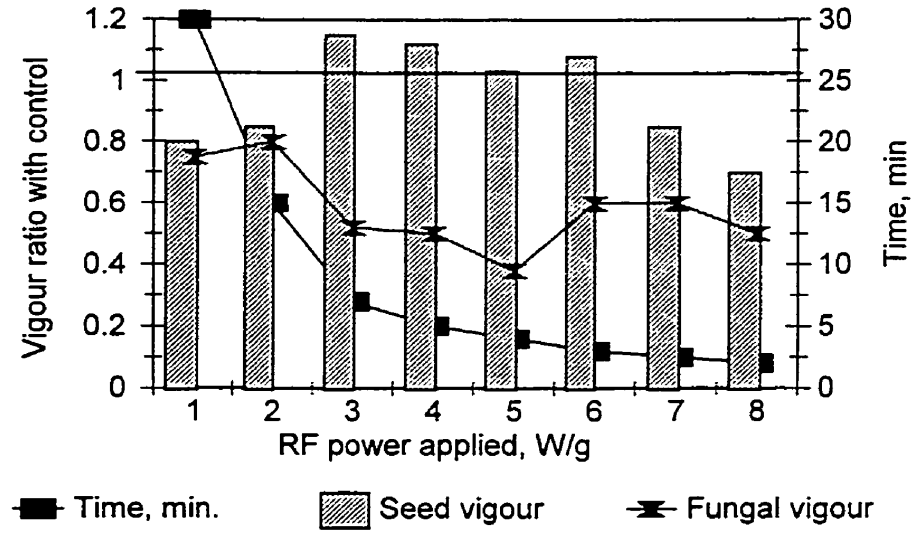

Figure 4.9: Seed vigour, fungal vigour and treatment time expressed as a function of applied power for a seed moisture content of 10% and seed temperature of 70°C.

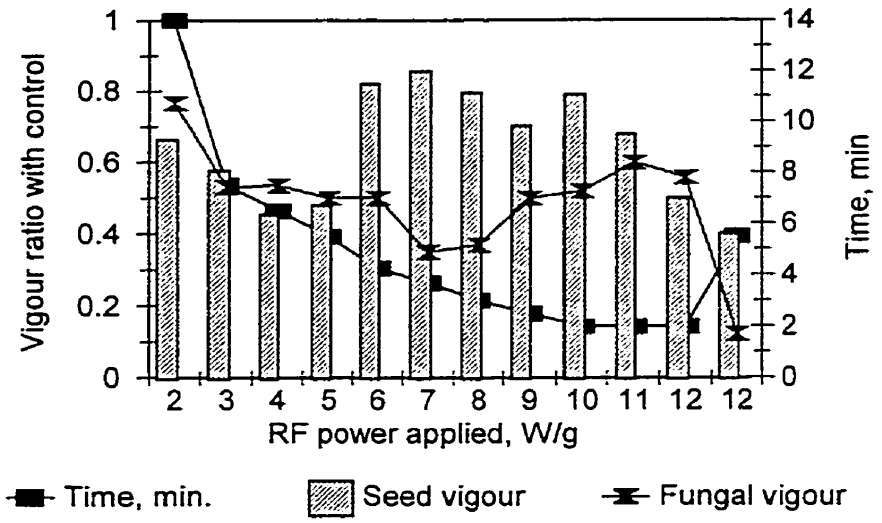

Figure 4.10: Seed vigour, fungal vigour and treatment time expressed as a function of applied power for a seed moisture content of 10% and seed temperature of 80°C.

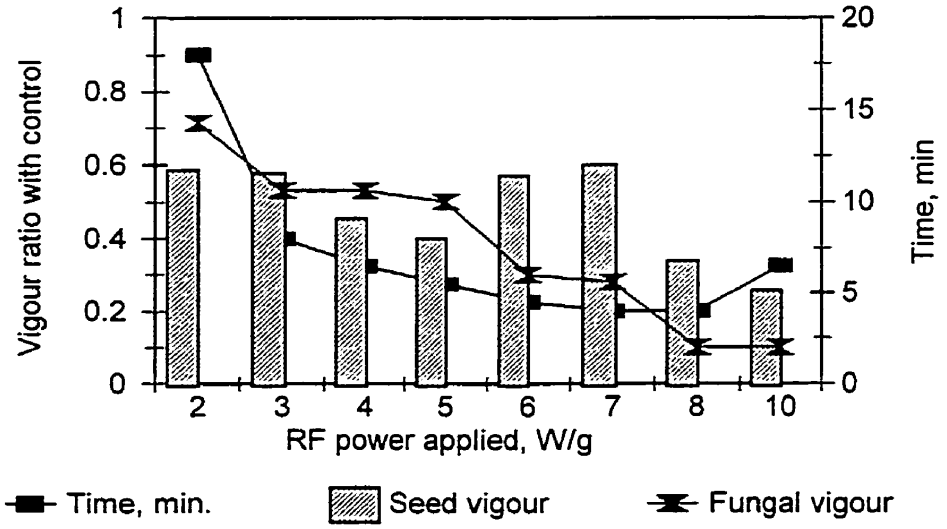

Figure 4.11: Seed vigour, fungal vigour and treatment time expressed as a function of applied power for a seed moisture content of 10% and seed temperature of 90°C.

The different final temperatures were obtained with electrode voltages varying from 2 to 5 kV. As mentioned above, the treatment times were significantly different from 30 min. at low voltage to 1-3 min. at high voltage. There appears to be a greater efficiency of moderate and high intensity treatments on pest mortality due to the more rapid elevation of temperature producing a higher degree of thermal shock. The study has shown that higher field intensities were more efficient than low intensities for wheat disinfection. The maximum permissible field intensity increases as moisture content of the grain decreases. It also depends on the length of exposure required. This can effectively be seen in Figure 4.10 at exposures of 12 W/g and 80°C, at 2 and 6 min. treatment times, you obtain a significant decrease in both seed and fungal vigour with an increase in residence time.

4.5. CONCLUSIONS

The results indicate that some level of control of seed-borne diseases may be achieved by RF treatment, but better RF control and more extensive knowledge of the electrical characteristics of both host tissues and pathogens are needed to enable less empirical selection of field intensities for utilization of possible differential heating or other effects.

It has been suggested that the production of heat is the only possible biological result of the absorption of radio waves, although lethal effects of RF treatment on bacteria in suspension at temperatures considerably below those capable of killing by external application have been reported in the past (Fleming, 1944; Seaman and Wallen, 1967; and Whitney et al. 1961). From our experiment we can only conclude that we achieved partial control of the fungus due to the lethal thermal treatment. We did not achieve selective heating of the fungus and we did not successfully eradicate the fungus while maintaining the germination quality of the seeds. At best, we reduced by 60 % the level of the *Fusarium* infection while maintaining the seed quality intact.

High heating rates are to be preferred, generally to minimize thermal energy loss from the pests to the host material. In our experiments, moderate power levels yielding moderate

temperature increase are recommended to offer a thermal shock with sufficient residence time to effectively eradicate the pest and yet not too high since it would destroy the seed germination quality. Since the loss factor of hygroscopic materials such as grain generally increases with increasing moisture content, their heating rates are higher when moisture content is greater. Generally high field intensities are more efficient in achieving pest mortality which was our case, with unfortunately a significant decrease in seed vigour.

Acceptable tolerance levels in radio-frequency treatment are determined by the purpose for which the treated material is to be used. Complete or partial eradication can in some cases be acceptable. With increasing restrictions on the use of agro-chemicals to control pathogens and pests in grain, physical treatments are presenting a potential alternative. Complete eradication by physical means may not be possible, however, it may bring the infection/disease below the threshold causing disease outbreaks of commercial significance. While high intensity treatments are recommended for pest control, lower intensity treatments are recommended for the improvement of seed germination. Soybean seed vigour ratio of 1.3 and higher can be achieved with mild 60 °C, 5 min. duration RF treatments. The maintenance of high quality in RF-treated seed lots, as well as the improvement of seed vigour are important advantages that RF-treatments can offer as an alternative to scarification for seed priming.

CHAPTER V - STRESS CRACK ANALYSIS OF RF TREATED SEED-QUALITY WHEAT

5.1. ABSTRACT

Radio-frequency heat treatment of wheat was studied to identify the relationship between heating conditions and grain quality categorized in terms of kernel viability (germination percentage and vigour) and structural damage (stress cracks). Definite effects from heating intensity have been found and attributed to the stress cracks developed inside wheat kernels under certain combinations of kernel moisture content, temperature and absorbed power. These cracks were visualized by soft x-ray photography and quantified by a damage index that provides a numerical notation for the cracks. A clear relation among the parameters consisting of heating intensity, stress cracks and grain quality has been found which justifies the use of damage indices for selecting optimum parameters in highly intense processes such as dielectric heating for grain drying or thermal treatment.

5.2. INTRODUCTION

For more than 50 years, seed-borne pathogens of cereals were effectively controlled by use of organo-mercury fungicides. In response to concerns over the toxicity and persistence of mercury in the environment, environmental agencies have prohibited the use of mercury in agriculture. Today, other chemicals are used; however the increasing health concerns and the increased incidence of fungicide resistant races of many seed-borne pathogens will soon lead to the prohibition of other chemicals. An interesting alternative may reside in the thermal disinfection of grain using radio-frequency high temperatures, with the benefits of being an effective, rapid, no residue method. However, it offers no residual

protection, and its potential for disinfection of grain destined for export, where markets demand non-chemical treatments, requires further investigation. Grain quality after treatment is also an important issue to consider as it significantly impacts on the industry for storage and export potential.

Interest in the possibility of controlling pests with high frequency electric energy dates back to more than 60 years (Fabian and Graham, 1933; Nyrop, 1946). Concern about the health hazards of chemical pesticides since the 1950's has stimulated further studies on the possible uses of radio-frequency (RF) and microwave energy for controlling stored-grain and stored-product pests (Brown and Morrison, 1954; Seaman and Wallen, 1967; Nelson *et al.*, 1996; 1998). There also seems to be a notable advantage in reducing the percentage of hard seed in seed lots with the use of RF thermal treatments, for seeds experiencing hard seed problems such as alfalfa, clover or soybean. Indeed research has shown that there exist treatment combinations which effectively improve seed germination in seed lots experiencing hard seed problems (Nelson and Stetson, 1985). The ability of water to absorb electromagnetic energy generated at radio and microwave frequencies offers a means of rapidly transferring heat throughout the volume of the moist material. Hence, the temperature of the material is rapidly raised. Heating with electromagnetic field heating may be used to our advantage in final stages of drying or in thermal treatments, where conventional means are slow, energy intensive, and somewhat inefficient. Radio-frequency heating, with its deep penetration capacity, enables heating of thick product layers with a good potential in industrial applications.

It appears that thermal phyto-sanitary methods have mostly been restrained due to the narrow window between the effective destruction of the pathogen and the risk of damaging the seeds (Maude, 1996). Thermal treatments have a great potential for seed disease control. However, precise temperature control and a better understanding of the kinetics behind pathogen thermal kill and seed heat damage are required. Although heat damage to grain has been investigated by several researchers (Ghaly and Sutherland, 1984; Gunasekaran *et al.*, 1985; Jaquette *et al.*, 1996) specific and more detailed information is needed on heat damage

from dielectric heating. The temperature tolerance of both the host material (grain or seeds) and the pathogens or insects depend on their individual characteristics (cultivar, developmental stage, etc.), but in general the temperature should not exceed 75 °C to preserve the germination of the seeds, but should be greater than 65 °C in order to obtain complete pest inactivation (Maude, 1996).

5.2.1. Heat Damage to Grain

A high intensity thermal treatment creates both temperature and moisture gradients within the wet material. These gradients may cause tensile stresses thus generating internal cracks and/or external (visible) fissures, when the local tension exceeds the ultimate strength of the material. Cracking is detrimental to grain quality since affected kernels are more susceptible to mould, exhibit enhanced loss of dry substance during storage and may disintegrate during transportation. Cracked grains are generally of lower quality, which constrains their marketability. The destructive effect of cracks is of prime importance for seed quality grains because of reduced germination and vigour.

The anatomy of the grain kernel comprises mainly the pericarp, seed coat, aleurone layer, germ and endosperm. Considering this anatomy, the cracking mechanisms are based on a pressure build-up. The hypothesis is that the endosperm is made principally of thin walled cells filled with protoplasm and starch granules which have a lower resistance to moisture transfer than the nonporous pericarp and aleurone layer (Gunasekaran *et al.*, 1985; Kudra *et al.*, 1993). Therefore, the water vapour generated inside the kernels due to heating starts to accumulate within the endosperm. This results in a pressure gradient which leads to pericarp tension and possibly to cracking. This is probably enhanced in dielectric heating where the volumetric heat generation may result in localized tensile stresses. Furthermore, due to the different composition of various sections of a kernel, it is likely that they possess different dielectric properties, leading to different levels of energy absorbtion. This may influence the location of cracks within a kernel (endosperm versus embryo) affecting the seed viability and quality in different ways than traditional heating methods. The germ or embryo,

embedded in the endosperm tissue, consists of oil and protein and very little starch. The outer portion of the germ is separate from the endosperm through the scutellum. This structural discontinuity helps prevent the propagation of cracks in the germ region of the kernel.

5.2.2. Structural Damage Determination

The conventional method for determining structural damage is the candling procedure, where shining or fluorescent light is passed through the kernel while holding the germ side toward the light source. This method requires time and effort and tends to lose accuracy due to fatigue of the human eye.

Computer vision systems have been developed (Gunasekaran *et al.* 1987, Reid *et al.*, 1991, etc.) for the automated detection of stress cracks in kernels. Those systems usually consist of four stages: image acquisition, positioning, edge detection and algorithm transform. These systems have good algorithm performance, however they have poor performance in edge detection and differentiation (Gunasekaran *et al.* 1987, Reid *et al.*, 1991). Another system of computer vision that has been successfully developed is the frequency domain image analysis system using Fourier Transform for inspection of stress cracks (Han *et al.*, 1996). With this system, stress crack recognition is somewhat improved by contrast enhancement followed by edge enhancement with an edge elimination algorithm.

An advanced laboratory method allowing for direct detection of structural changes in a material is Magnetic Resonance Imaging (MRI). MRI techniques involve the manipulation of several magnetic field gradients oriented at right angles to each other resulting in spatial encoding of signals and further information about their position. Zeng *et al.* (1996) have developed MRI techniques for non-destructive and non-invasive study of seed cracking. Proton density images and transient moisture distribution profiles have been obtained using MRI. When available, MRI can be an excellent tool for studying the kinetics of crack formation and moisture movement in grain kernels.

Devahastin et al. (1998) developed a colorimetric method to quantify mechanical damage in grain. The method consists of scanning for the absorbance peak of a specific dye

to adjust the reading wavelength of a spectrophotometer. The dye is then used to soak the damaged grain samples which are later analysed by spectrophotometry.

There also exists a less sophisticated technique of measurement both in equipment and procedure, when compared to MRI, based on the statistical analysis of X-ray photograms of grain kernels. Moreover, X-ray photography is much cheaper than nuclear magnetic resonance, scanning microscopy or laser technology. This method is the one chosen for this experiment, since we have proven its efficacy in our laboratory and it is available for our use (Kudra *et al.*, 1996). The method was refined for the purpose of this study with computer automation.

5.3. MATERIALS AND METHODS

5.3.1. System for Analysis of X-ray Images of Wheat Grains

Wheat grain is one of the most valuable plant materials containing high proportions of nutritional components. Unfortunately, during harvesting and post-harvesting processing, it is subjected to damages both of mechanical and thermal nature. These damages, which are frequently difficult to notice by a naked eye, can cause detrimental effects on the physical and biological properties of grains. Damaged kernels absorb moisture more intensively and have lower mechanical strength than the undamaged kernels (e.g., they crumble easily). Thus, careful choice of the parameters which characterise grain processing technology is of major importance if losses due to low quality of this cereal are to be minimised. This aim, however, can only be achieved if objective and precise methods for identification of internal grain structure are available.

One of the techniques which provides high quality visualisation of the internal kernel structure is the soft X-ray photography. This technique is particularly useful in detecting internal damages of the photographed kernels since the X-rays are absorbed to the different extent by damaged and undamaged endosperm (Niewczas et al., 1995; Pecen, 1994; and

Woźniak, 1995). Moreover, X-raying of kernels is non-destructive and is considerably cheaper than other more sophisticated imaging techniques like Magnetic Resonance Imaging (MRI), scanning microscopy or laser technology. It has to be stressed, however, that sole visualisation of the kernels, irrespectively of the technique used, does not provide quantitative evaluation of the overall quality of the kernel, e.g., geometrical parameters of grain internal features, their quantity and distribution within the structure etc. In order to carry out accurate grain quality assessment, specialised image processing and analysis methods need to be employed for detection, measurement, and interpretation of kernel X-ray images. For several years, already, image processing techniques have become particularly attractive because they can be implemented cost effectively on desktop computers. These techniques offer a new powerful tool which, in the case of grain quality analysis, can bring considerable improvements in terms of analysis quality, shorter processing time and lower number of skilled technicians involved. Moreover, determination of some important features of grain images, too cumbersome for analysis with the use of "manual" methods, can be achieved.

Program Description

Major parts of a computerised system specially developed for analysis of wheat grain kernels are visualised in Figure 5.1. The soft X-ray apparatus ELEKTRONIKA Model 25 of Russian make was used for grain X-raying (Figure 5.2).

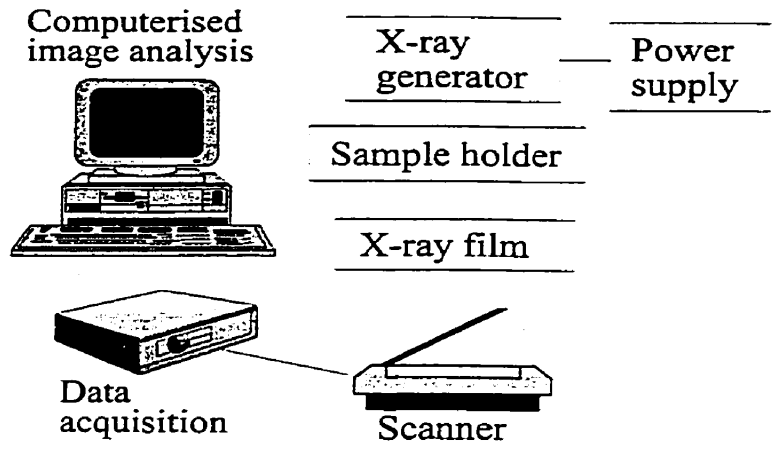

Figure 5.1: Schematic diagram of the X-Ray photometry system.

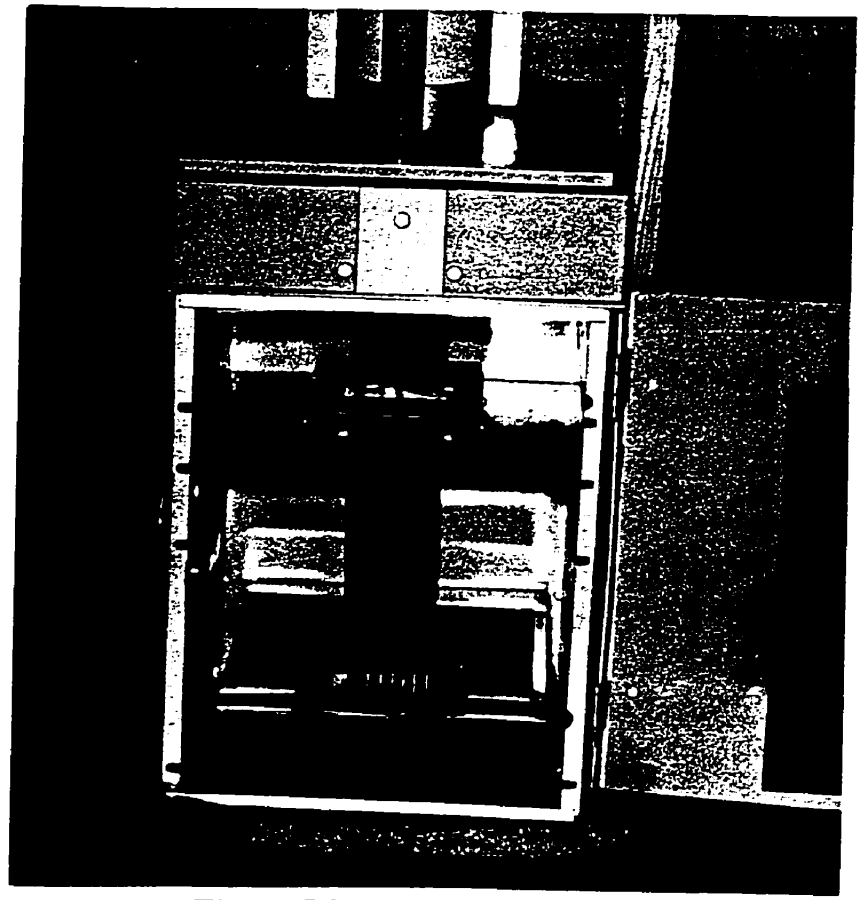

Figure 5.2: X-ray chamber.

The 'ELECTRONIKA 25' is a compact, short focal length unit equipped with a 2kW X-ray tube. The X-ray tube voltages and currents range from 10 to 25 kV and from 30 to 80 mA respectively, and can be set at a required level. The X-ray apparatus allows image magnification of up to 10 times. The image is recorded on KODAK X-ray film in the 13x18 cm format. Each X-ray exposition lasts exactly one minute. Precise timing of the expositions is critical for obtaining good quality pictures in which the image contrast is maintained at the same level for comparison. For each X-ray exposition, 12 grain kernels were evenly positioned (groove down) on a sample holder. The images of grains are obtained in the form of photograms of size 18 x 13 in which the grains are magnified 5 times. The photos are then scanned by a Hewlett-Packard table photo-scanner ScanJet 4C equipped with a transparency adapter. The scanner provides 400 dots per inch (dpi) scanning resolution and 8-bit grey scale image digitisation. It produces files in the Windows Bitmap graphics format which are transferred to an IBM-PC compatible computer. The X-raying and photo-scanning procedure provides a sufficient resolution (both spatial and grey scale) for reflecting distinct features important for accurate characterisation of kernel damages. A single grain kernel is depicted approximately by 10000 image picture elements (pixels) each assuming one of 256 discrete grey values (with 0 corresponding to black, and 255 to white).

Quantification of grain cracks is the most difficult problem in grain quality evaluation. This is due to a rich variety of damage types the kernel can suffer from. Some of the damages are well defined (usually perpendicular to the groove) whereas others can form a network of tiny narrow cracks running in arbitrary directions and crossing each other.

Irrespective of the above mentioned problems in quantitative assessment of grain quality a number of measures (damage indices) were proposed for this task (Chowdhury, 1976). Some of these measures termed Positional Damage Indices (PDI) have been worked out to take into account not only the extent of the damage but also the position it occurs relative to the germ (Grzesiuk and Kulka, 1988). Another method for grain quality evaluation was proposed which accounts both for the localisation and the severity of the damage (Niewczas, 1991; Niewczas, 1994; and Strumillo, 1996). This method relies on

superimposing a rectangular grid onto the area of the grain image and evaluating endosperm quality in each of the grain image zones. The number of rows and columns defining the number of analysis zones can vary according to the requirements. Each of the analysis zone is assigned its corresponding weight characterising its position and importance in the grain kernel (e.g., for projection A, see Figure 5.3, larger weights are assigned to zones nearest to the germ). Also, each zone is given "a mark" reflecting the damage severity. Different types of damage indices can be defined depending on distribution of weights in the grid, e.g., overall index (all weights equal to 1), positional index (accounting for damage localisation), mixed indices, etc.

The software package, called GRAINS (Strumillo, 1996), was developed for aiding the analysis required for evaluation of endosperm cracks, grain structure, computations of geometrical and statistical parameters of grain images and generating report files with analysis results. GRAINS is a menu driven program and works on IBM-PC compatible machines in Windows programming environment (Windows 95).

The program window, as it appears once the program is started, can be seen in Figure 5.3. The main menu bar contains names of the pull-down menus grouping all commands available in the program. The main command groups are: **FILE, PLOTS, IMAGE, DOCUMENT, WINDOW**, and **HELP**.

The **FILE** menu, following the Windows programming conventions, groups commands for manipulating data files, of which **GRAINS** contains commands for loading image files, opening new documents, and storing analysis data.

The **PLOTS** menu is activated once an image window is opened in the **GRAINS** workplace and contains commands for detecting boundaries of grain kernels and commands for generating plots based on the image information, such as projections, image brightness profile plots and image scaling procedures (for scaling image objects to their real size units).

The **IMAGE** menu groups commands for changing attributes of the displayed grey-scale X-ray image in order to make it most convenient for user visual inspection, i.e., image colouring, choice of colour palette, and image contrast/brightness manipulation.

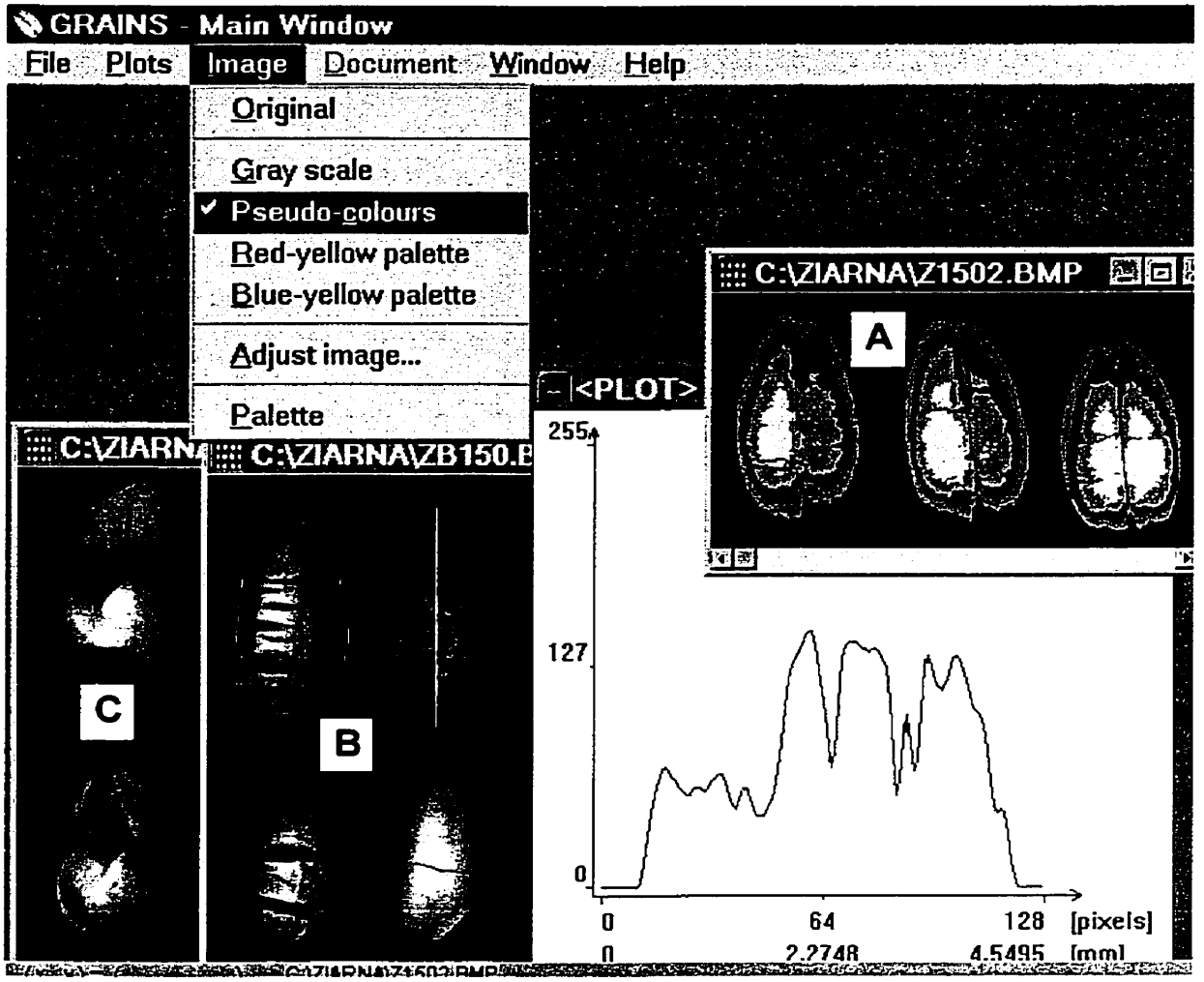

Figure 5.3: A view of the program window including three kernel projections (A, B, and C).

The **DOCUMENT** menu contains key program commands associated with kernel analysis, i.e., measurements of main geometrical and statistical parameters of individual kernels, inspection and evaluation of grain internal structure quality, and commands for editing the document window where the analysis results are stored.

WINDOW and **HELP** menus, available in **GRAINS**, offer standard functions similar to other programs working in the Windows environment.

Complete analysis of an individual grain kernel, using commands available in **GRAINS**, can be split up into the three following stages:

1) detection of grain boundary in an image;

2) calculations of main geometrical and statistical parameters of the grain image object; and

3) computations of damage indices.

GRAINS supports procedures for display and analysis of grain kernels scanned in three different projections termed A, B, and C. Figure 5.3 shows the program window with the **PLOTS** menu activated and a number of pre-loaded image windows each containing different grains projections. The procedure of detecting grain boundary, for projection A, relies on pointing, with a mouse driven cursor, the terminating points of the grain groove (for B, C projections indication of any point lying in the proximity of kernel centre will suffice). Each of this pointing scheme (commands **CONTOUR** A, B, C respectively in the **PLOTS** menu) initiates a procedure for automatic detection of the kernel boundary.

A special contour extraction technique called active contour model (or snake) has been employed for detection of grain boundaries. The reason for this, is that image regions representing grain boundaries are poorly defined (non-uniform brightness, kernel-fragmentation). Snake is a clever contour finding method originally proposed by Kass et al., (1988) and, recently, Szczypiński and Strumillo (1996). Figure 5.3 illustrates an example of contours (closed white curves) indicating boundaries of grain image objects obtained with the use of the snake algorithm. Note also the displayed brightness profile window containing an image brightness plot corresponding to a user-defined line fragment positioned in the area of

the B-projected kernel.

Geometrical and statistical parameters of image grain objects can be determined. Figure 5.4 views results of such an analysis, initiated with the **INSERT GRAINS** command, along with a list of the **DOCUMENT** menu group. Analysis results of each single kernel are inserted into the **DOCUMENT** window. These results are structured as follows.

First, there is a number of text lines with labelling information and comments provided by the program user as shown in the Figure 5.4. On the right-hand side, a list of geometrical parameters and their computed values are displayed. Further below, histogram and cumulative histogram diagrams corresponding to the image area marked in white are plotted. Finally, in the lower right-hand corner of the **DOCUMENT** window values of the computed statistical parameters of the analysed image fragment are listed out.

The most important feature of **GRAINS** package is that it provides means for aiding calculations of kernel damage indices according to the method proposed by Niewczas (1991; and 1994). This program function is initiated with the **ANALYSE** cracks command from the **DOCUMENT** menu. At the start a program window called **CRACKS** is displayed (see Figure 5.5). In the left-hand part of this window an enlarged view of the analysed kernel is displayed (i.e., in one of the supported projections A, B, or C). The right-hand part of the **CRACKS** window contains different groups of text fields, radio and other control buttons enabling control of damage index calculation procedure. A rectangular grid is super-imposed onto the enlarged kernel image. The number of rows and columns of this grid is user-defined and monitored by the program. Note, in the upper left hand corner of each grid cell there is a digit displayed. This is the "mark" (integers from 0-9) the user can assign to the corresponding kernel rectangular fragment which reflects its damage state, with 0 indicating no damages and 9 reserved for severe damage.

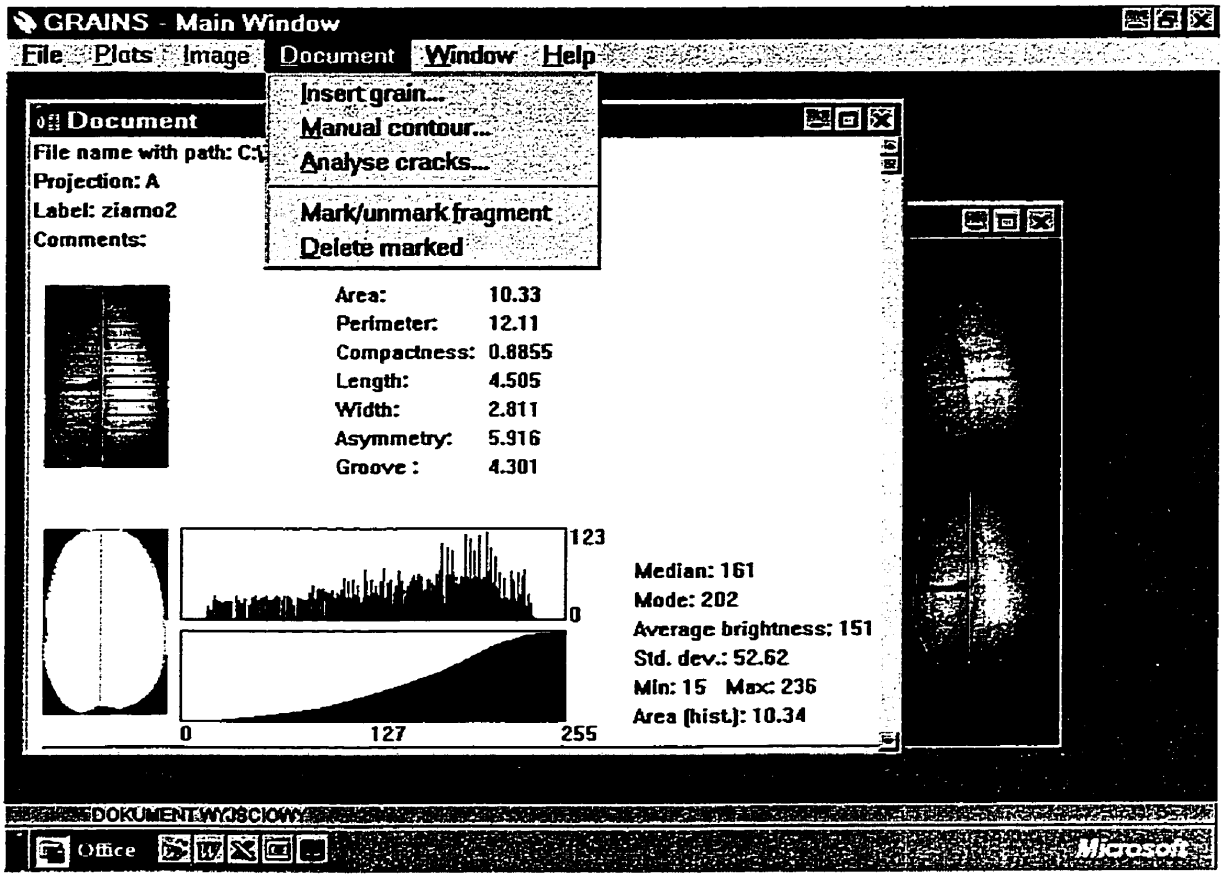

Figure 5.4: A view of the program window with geometrical and statistical parameters.

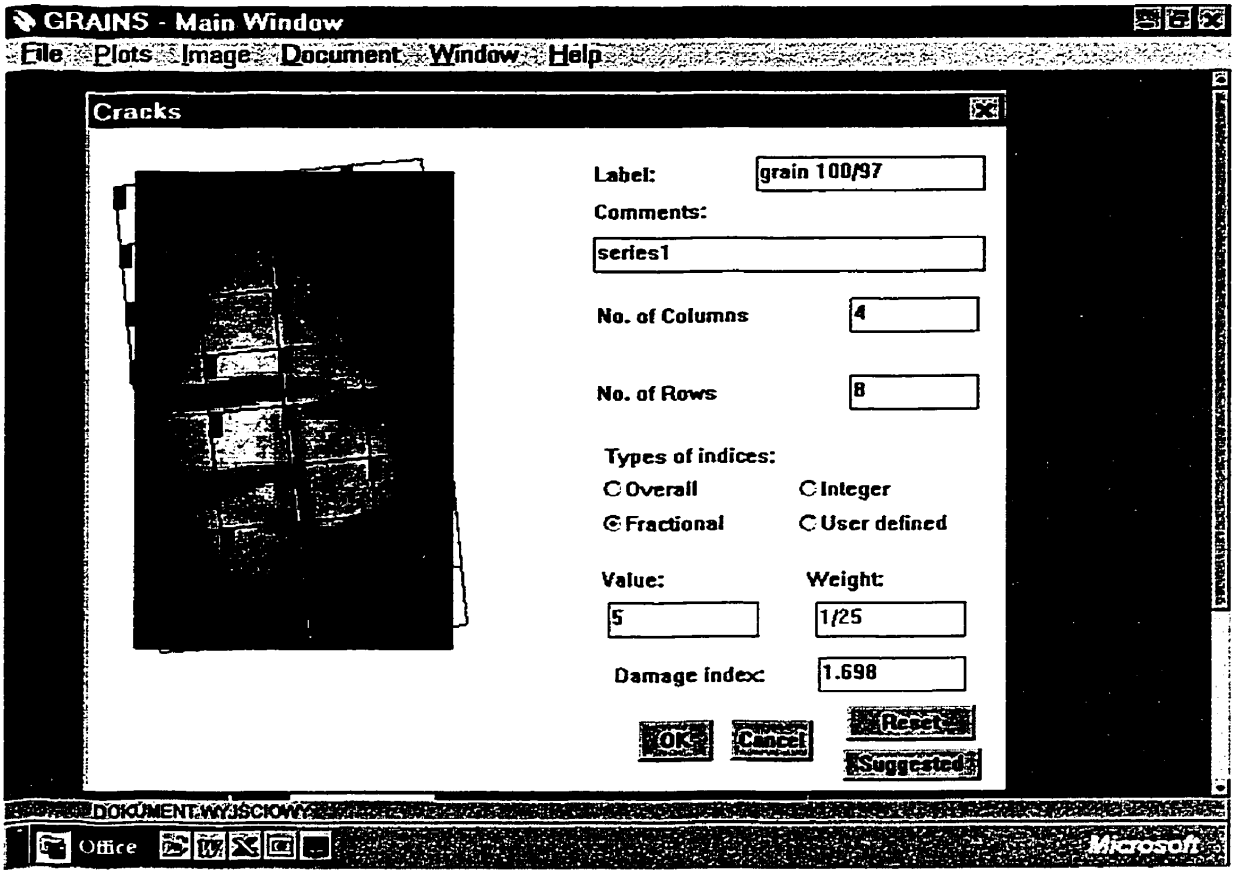

Figure 5.5: View of a window presenting cracks.

Calculations of four types of damage indices are supported by the program procedure. Choice of the particular index is available by picking one of the respective radio buttons located in the right-hand side of the **CRACKS** window. Damage index type is specified by pre-assigning specific weight values to each row of the analysing grid. For the **OVERALL** damage index all weights are equal to one. The other possibility is to choose these weights arbitrarily according to user preferences.

The remaining two types of indices, available in the program, are the positional indices, which assign a weight to the position of the damage in proportion to the distance they appear from grain germ. The closer the position of the damage to the germ the larger the weight (i.e., the relative importance) of this damage.

The final values of the positional damage indices (PDI) are calculated according to the following formula (Niewczas, 1991; and 1994):

$$PDI = \sum_{i} \sum_{j} w_i \, b_{ij} \tag{5.1}$$

where i,j are the co-ordinates of grid rows and columns respectively, w_i is the weight value assigned to the i-th grid row, and b_{ij} is the user marked kernel damage at grid co-ordinate ij.

Completion of the grain damage evaluation procedure inserts automatically the computed PDIs and the user marked pattern of kernel damages into the program **DOCUMENT** window. All the data inserted into the **DOCUMENT** window can be stored as disk files.

5.3.2. Experimental Procedure

Seed-grade wheat cv. Roma from Poland was used in preliminary trials in September 1996 and cv. Pollet from Canada was used in the full experimental design study in January 1997. The grain was stored in a cold room at 4°C until required for testing. The effects of radio-frequency thermal treatments, on the development of heat stress cracks within the grain kernels, were determined according to the following experimental design:

Cv. Roma:

1) Three moisture contents of 13.5, 17 and 22%; The initial moisture content of the wheat was 13.5% (w.b.). The samples of 17 and 22% moisture were brought to those levels by adding to the grain mass the required amount of distilled water. Moisture levelling was ensured over 72 h storage at 4 °C with thorough mixing. Prior to RF thermal treatment, the wheat samples were left to equilibrate to room temperature in sealed containers. The moisture content was determined by the convection oven method (ASAE Standard S352.2) at 130 °C for 24 h with sample sizes of at least 10 g. The percentage moisture was obtained by dividing the loss in mass by the mass of the original sample and multiplied by 100;

2) Three seed temperatures of 60, 70 and 80 °C corresponding to three different RF power intensities for each moisture content;

3) Three treatment times of 5, 10 and 15 min.

The results are illustrated in terms of treatment temperature and time combinations (for example 5, 60 °C as the treatment lasted 5 min at 60 °C).

Approximately 30 g of each treated sample was used for germination testing and the remainder was used for the X-ray analysis and computation of a general average crack index.

Cv. Pollet:

1) Three moisture contents of 15, 20 and 25%; The initial moisture content of the wheat was 15% (w.b.). The samples of 20 and 25% moisture were brought to those levels by adding to the grain mass the required amount of distilled water. Moisture levelling was ensured over 72 h storage at 4 °C with thorough mixing. Prior to RF thermal treatment, the wheat samples were left to equilibrate to room temperature in sealed containers. Moisture content was determined following ASAE standards;

2) Three treatment temperatures of 60, 70 and 80 °C corresponding to three different

RF power intensities for each moisture content;

3) Three treatment times of 5, 10 and 15 min.

The results are illustrated in terms of treatment power intensities (W/g) as calculated using equation (2.10) or as treatment temperature and time combinations (for example 5(60) for 5 min treatment at 60 °C).

Approximately 30 g of each treated sample was used for germination testing while the remainder was used for the X-ray analysis of the wheat seeds to determine average damage index and the positional characteristics of cracking from RF thermal processing.

5.3.3. Germination and Seed Vigour Testing

Germination testing is most commonly used to determine seed viability. The seed vigour is defined as those seed properties which determine the potential for rapid uniform emergence and development of normal seedlings under a wide range of field conditions. The paper towel test is one of the oldest methods employed for evaluating seed vigour (Abdul-Baki and Anderson, 1973). The germination paper was cut to a size of 25 cm wide by 25 cm long. Two layers put together were soaked in a large dish filled with distilled water. Fifty seeds were then scattered evenly over the surface of the paper leaving a margin of 2 cm from the edges except 4 cm from the bottom. Another sheet of paper was soaked in water and placed on top. The assembly was then rolled up in a loosely packed cylinder held together at the top by a tape bearing the treatment number so that each roll was clearly identified. Then each roll was placed upright in a beaker in which water was maintained at 1 cm from the bottom to keep, via capillarity, the towels wet. Two rolls were prepared per sample. After 7 days at 20 °C, the percentage of normal seedlings was counted along with radical and hypocotyl length. A conventional vigour index for each seedlot was established by multiplying percent normal germination by millimetres of hypocotyl and radical length as seen in equation 5.2 (Abdul-Baki and Anderson, 1973).

$$\textit{Vigour Index} = \%\ \textit{Germination} \times (\textit{Hypocotyl} + \textit{radical}) \qquad (5.2)$$

A vigour ratio was then calculated by dividing the sample vigour index by the vigour index

of the control (untreated sample). The vigour index of the control sample was therefore equal to 1.

5.3.4. X-ray Photography

Crack detection was obtained by a compact short-focus soft X-ray apparatus (Figures 5.1 and 5.2 as described in section 5.3.1) which provides images at magnifications ranging from 2× to 10×. With this apparatus, the kernels were selected at random from a sample and were exposed for one minute to soft X-rays issuing from a source operating at 15 kV. The X-rays are absorbed differently by damaged and undamaged endosperm, giving distinct images of cracks and an outline of germ against the background of the endosperm (Kudra *et al.*, 1996). The negative of the image obtained was then optically magnified 40× and analysed by dividing the image of each kernel into sectors, identifying the sectors with visual cracks and determining the damage index of the endosperm (refer to section 5.3.1 for more details).

Roma wheat

Kernels of same size were selected from each sample. Each sample was represented by 10 sets of 12 kernels. The digitized images consisted of 262144 pixels arranged in 512 lines, each line consisting of 512 pixels, where every point (pixel) is a number ranging from 0 to 255. The number is an indicator of the grey level, where 0 corresponds to black and 255 to white. The delineation of phase boundary and cracks and fissures was carried by a grey-level threshold. Each of the kernel images was divided into 3 horizontal zones perpendicular to the groove differentiating 6 sectors of the kernel. Zones with cracks or without cracks were given a value of 1 or 0, respectively. The computer program then computed a simple average index of the cracks referred to as the summary index (IS) which is equal to the sum of partial values. The summary index thus ranges from 0 (kernel with no apparent cracks) to 6 (kernel having cracks in each of the six zones). The summary index was compiled along with the germination percentage and vigour results to correlate the radio-frequency treatment combinations with the maintenance of seed quality.

Pollet Wheat

The wheat kernels (cv. Pollet) were X-ray analysed following the same procedure as described above, except that the analysis was further refined to obtain a positional index. Like for Roma wheat, a summary index was first derived from the X-rayed photographs of the seeds. The "overall damage index" indicates the extent of grain destruction but does not account for crack localization which may be critical for seed quality if the germ is affected. A "positional index" (IP), adapted to the quantification in the form of a binary index, can provide more explicit information of crack location. Because the germ occupies approximately 1/3 of the length of a wheat kernel, its picture was divided into three horizontal zones of equal width (Figure 5.6). Following the idea of a "weighted distribution", each zone was assigned with a corresponding weight in a binary system (2^i with i = 0, 1, and 2). Thus the zone opposite to the germ was weighed by 1, the central zone by 2 and the zone with the germ by 4 (Figure 5.6). In this way, eight possible categories of damage were distinguished ranging from 0 (no visible crack) to 7 (cracks identified in all sectors). For Pollet wheat, the summary index (IS), the positional index (IP), germination percentage and seed vigour were compiled and correlated with the RF treatment combinations.

5.4. RESULTS AND DISCUSSION

5.4.1. Roma Wheat

Results of seed quality evaluation from the summary index (IS) and seed vigour index are presented in Figures 5.7-5.11. Although the damage index for an individual kernel is of discrete nature, the average values of multiplicity of kernels from the same run (in our case 12 kernels), approach normal distribution which allows for the interpretation of the experimental data by statistical means. For this experiment, the data were analysed by analysis of variance using a statistical analysis software (see the SAS output in Appendix F).

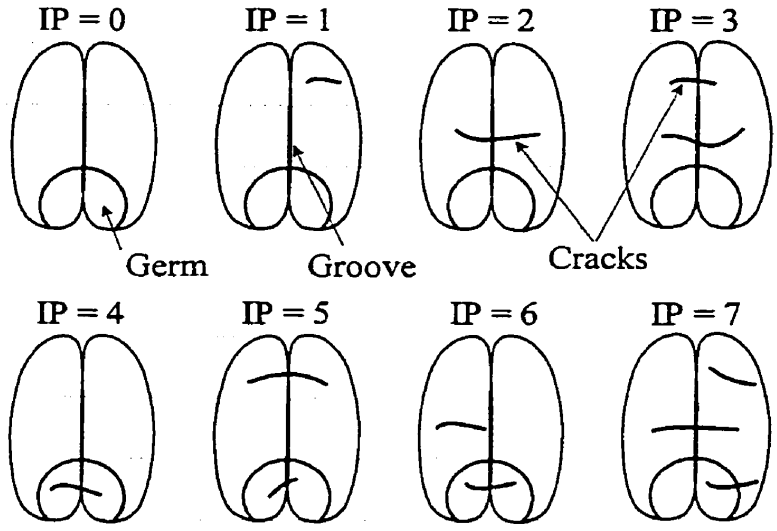

Figure 5.6: Positional damage index (IP) from 0 to 7.

The analysis of variance for the average index took into account the different moisture, temperature and time treatments. Treatments were also combined to compare main effects.

Figures 5.7, 5.8 and 5.9 present a summary of the results obtained for wheat seeds having 13.5, 17 and 22% moisture contents, respectively. The three graphs clearly indicate a decrease of seed vigour with an increase in RF treatment intensity along with a related increase in the damage summary index with an increase in the average number of cracks. Also, the moisture content had a distinct effect on the development of cracks with a significantly higher damage summary index with increasing moisture content, even with the control non-treated samples. The water absorption alone, involved in the process of raising the initial moisture content of the seeds, was the cause of a significant increase in the damage summary index of the control samples for wheat seeds of 13.5, 17 and 22% mc.

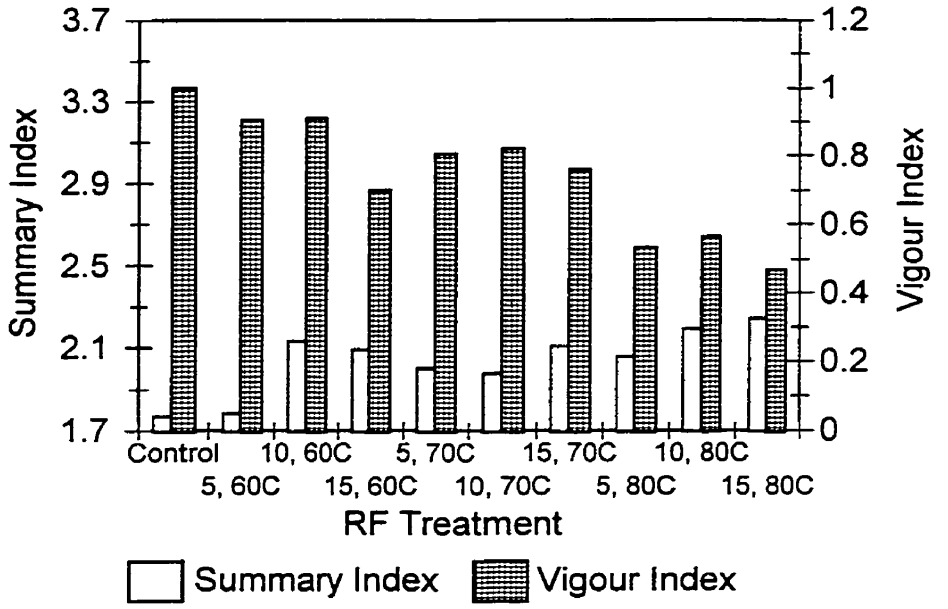

Figure 5.7: Summary Index and Seed Vigour Index of Roma wheat seeds (13.5% m.c.), with different RF treatment combinations (where 5, 60C is a 5 min treatment at 60°C).

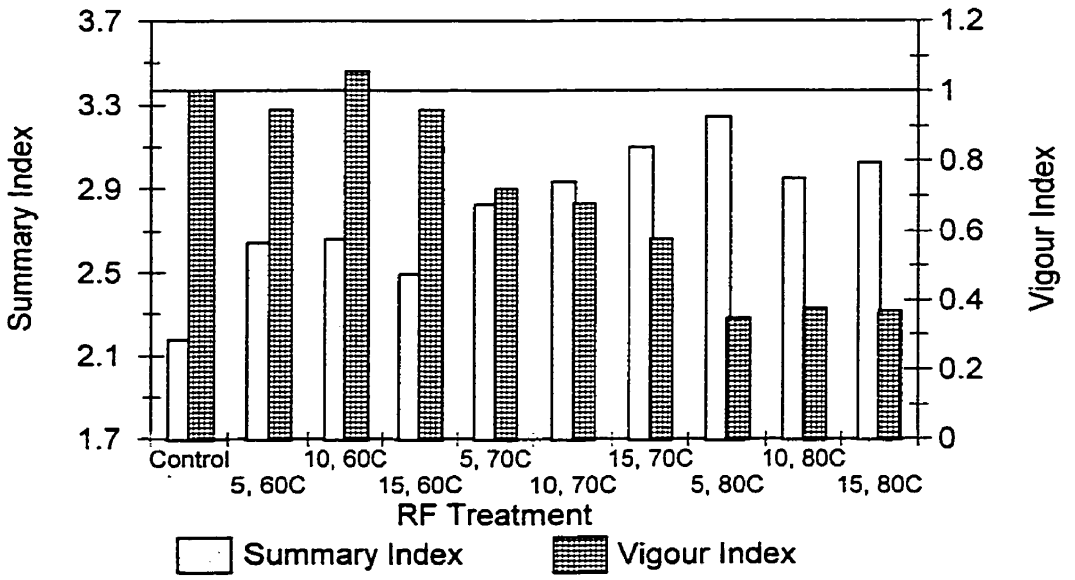

Figure 5.8: Summary Index and Seed Vigour Index of Roma wheat seeds (17% m.c.), with different RF treatment combinations.

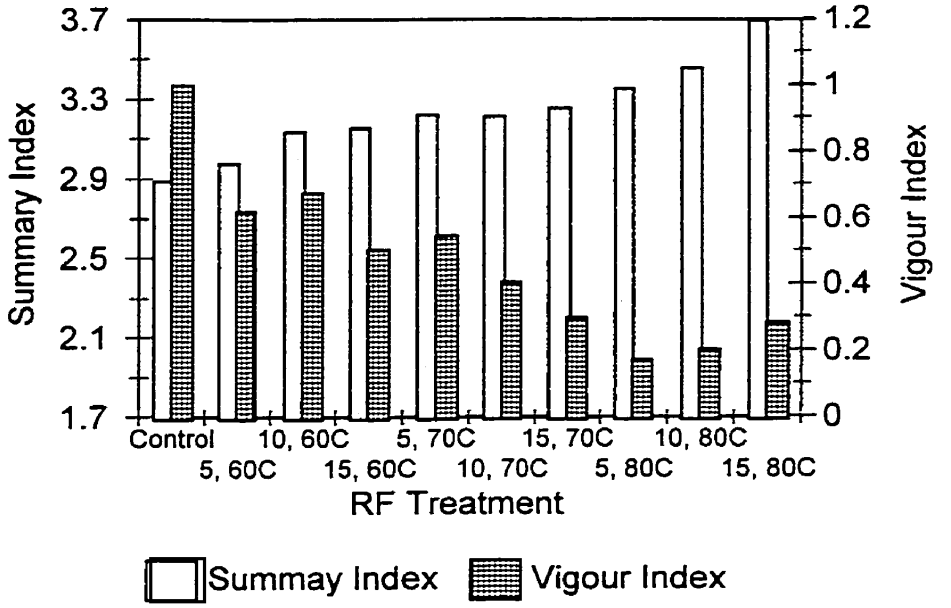

Figure 5.9: Summary Index and Seed Vigour Index of Roma wheat seeds (22% m.c.), with different RF treatment combinations.

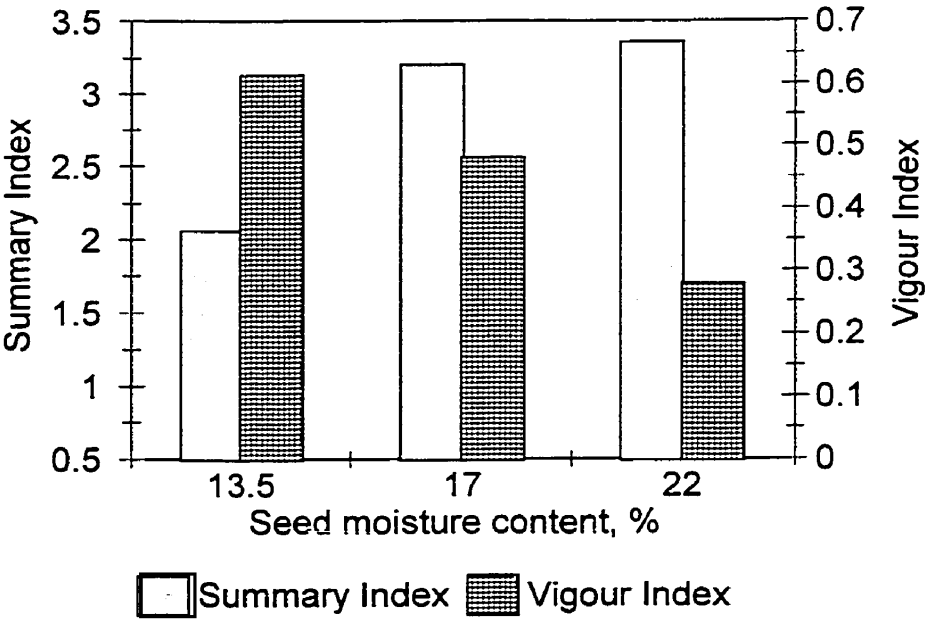

Figure 5.10: Summary Index and Seed Vigour Index as affected by the moisture content of Roma wheat seeds (RF treatment of 5 min at 80°C).

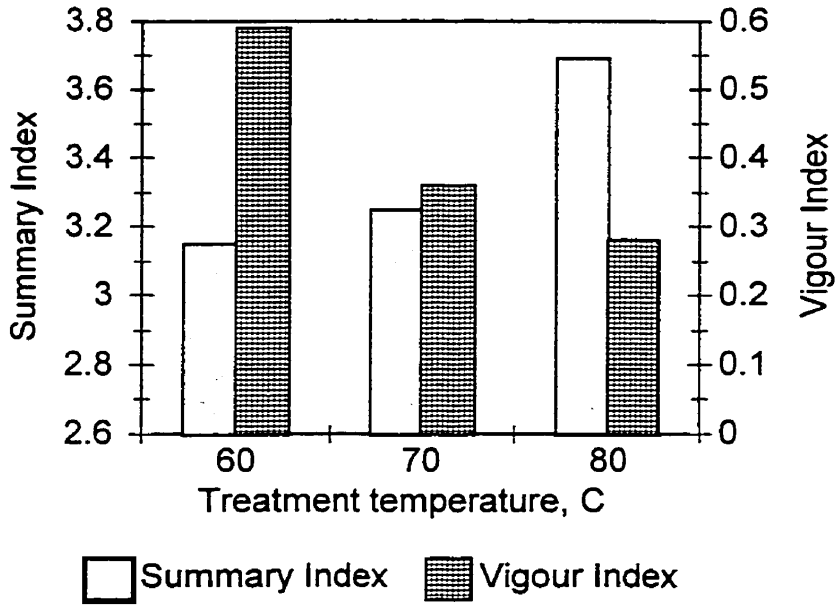

Figure 5.11: Summary Index and Seed Vigour Index as affected by the treatment temperature of Roma wheat seeds (RF treatment of 15 min at 22% m.c.).

All results were analysed statistically and they indicate that there is a significant difference ($p<0.001$) in seed quality (both seed vigour and damage indices) with varying moisture content. Figure 5.10 presents, as an example, the results obtained for an RF treatment of 5 min at grain temperatures of 80°C. With increasing moisture content from 13.5% to 17% and 22% there is a significant increase in stress cracks with a linear decrease in seed vigour by 39% up to 72%.

This product response was expected since at higher moisture content there is an improvement of the RF power absorption in the grain mass. The higher moisture content coupled with greater volumetric heat generation contributed to higher pressure gradients in the kernels leading to higher crack formation at higher moisture content.

Figure 5.11 presents the effect of RF treatment temperature on the quality of the seeds. There is an increase in the damage index with an increase in temperature. It is statistically significant ($p<0.05$) between 60°C and 80°C as well as between 70°C and 80°C.

The increase in damage of the seeds between 60°C and 70°C is however not statistically significant. The decrease in seed vigour with an increase in treatment temperature is statistically significant ($p<0.01$) for the three temperatures tested. For the variation in treatment times the results for both the damage index and the seed vigour show great variability with no specific trend. The reason for this behaviour is not yet explained.

5.4.2. Pollet Wheat

Results for germination percentage, positional and summary damage index (IP and IS) are presented in Figures 5.12 to 5.14 for Pollet wheat of 15.3%, 20.8% and 25.9% m.c. respectively and summarized in Figure 5.15 for all moisture contents. All data were analyzed

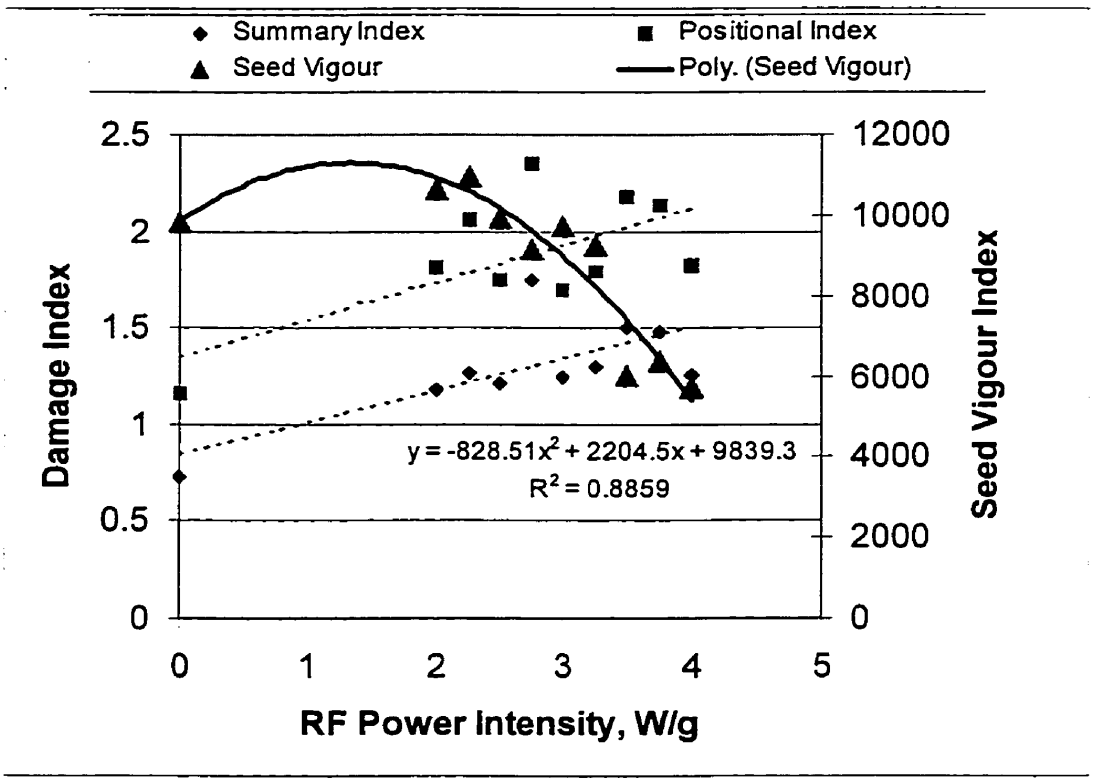

Figure 5.12: Seed vigour, positional and summary damage index of RF treated Pollet wheat seeds at 15.3% moisture content.

via statistical means, and the results are presented in Appendix F.

It is clearly seen in Figure 5.12 that, with seeds of low moisture content (15.3% m.c.) and moderate RF treatments (less than 3 W/g corresponding to treatments of 60 and 70°C and treatment times of 5, 10 and 15 min), the seed vigour is high with germination percentage maintained at the acceptable level of 85%, while the level of structural damage is kept low with a Summary Index around 1.5 and a Positional Index around 2 indicating structural damage in the endosperm region of the kernel. At higher RF intensity (80°C) the seed vigour is decreased considerably with germination percentage in the vicinity of 60 %, while the damage indices, both IS and IP remained the same around 1.5 and 2, respectively. With higher moisture contents, of 20.8% and 25.9%, as seen in Figures 5.13 and 5.14, the damage to the seeds is greatly increased with an increase in RF treatment intensity and caused by the

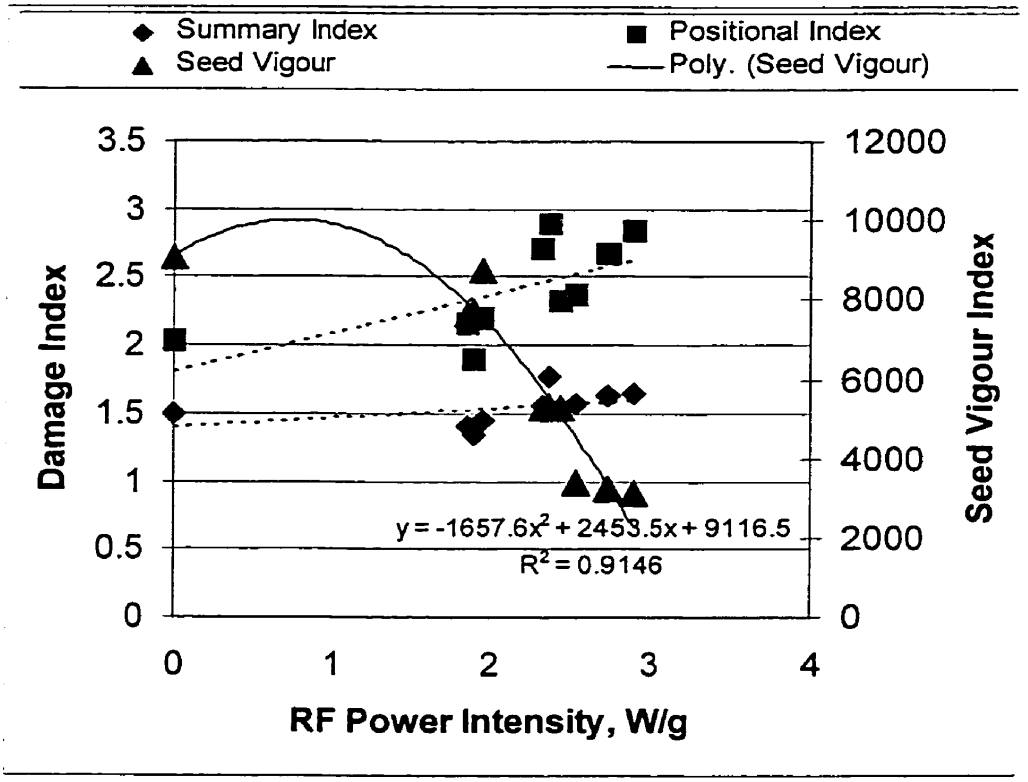

Figure 5.13: Seed vigour, positional and summary damage index of RF treated Pollet wheat seeds at 20.8% moisture content.

addition of water, added to increase the moisture content of the seeds.

Even with the lowest RF treatment (2 W/g corresponding to 5 min at 60°C), the seed vigour decreased by some 15% and the germination percentage dropped from 92 to 79 percent germination for wheat seeds of 20.8% m.c. The summary index did not show a significant increase with an increase in RF-treatment intensity, however, the positional index showed an increasing trend to reach an IP value of 3 at the maximal RF intensity treatment. An IP of 3 indicates the presence of damage throughout the endosperm. In the case of high moisture seeds (25.9% m.c.), the damaging effect of the RF-treatments were even more pronounced. Indeed, as can be seen in Figure 5.14, the summary index increased up to 2 for the control as a result of the moisture addition affecting considerably the initial quality of the grain. With RF-treatments, the summary index increased to 2.5. The positional index increased to 3 for the control and up to 4.2 after RF-treatment. A positional index of 4 and up indicates that there is structural damage which occurred in the embryo or germ of the seed leading to a loss in seed viability and germination. With the mildest RF-treatment (1.5 W/g or 60°C for 5 min), the seed vigour dropped by 40% corresponding to a germination percentage drop from 90% down to 55%. Values of positional index for the three moisture contents tested are summarized in Figure 5.15. We can clearly see that the most damage to the embryo was obtained with high moisture wheat seeds with IP values of 3.5 to 4.2. There was a high variability in the results. Nevertheless, the results were consistent enough to yield upward trends with an increase in RF-treatment intensity. Our results did not however, indicate that a decrease in seed germination is caused by the presence of cracks in the embryo. Nonetheless, an increase in structural damage did yield a decrease in germination percentage directly related to an increase in RF-treatment intensity.

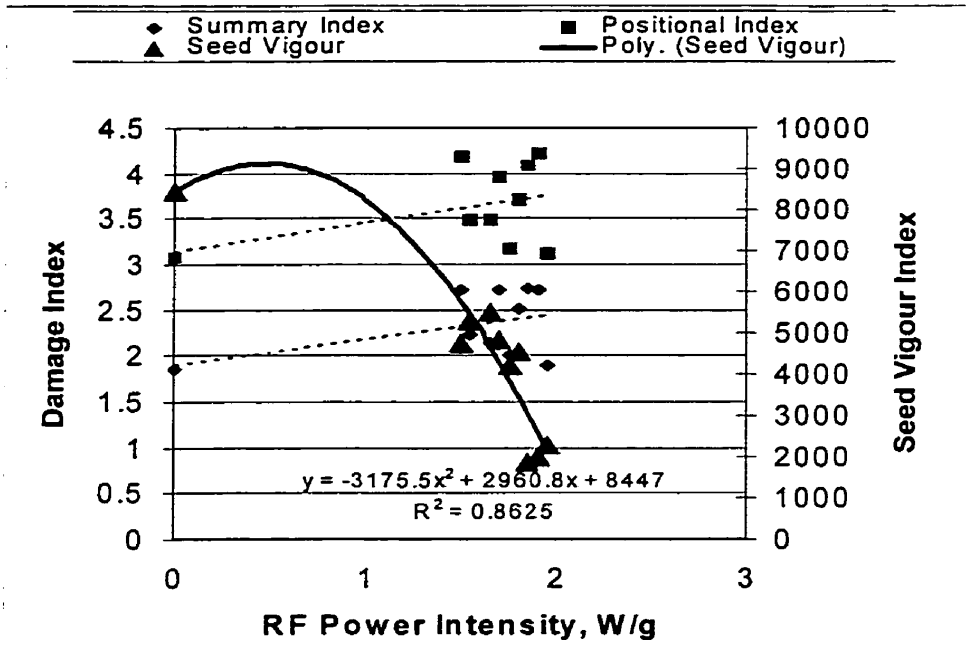

Figure 5.14: Seed vigour, positional and summary damage index of RF treated Pollet wheat seeds at 25.9% moisture content.

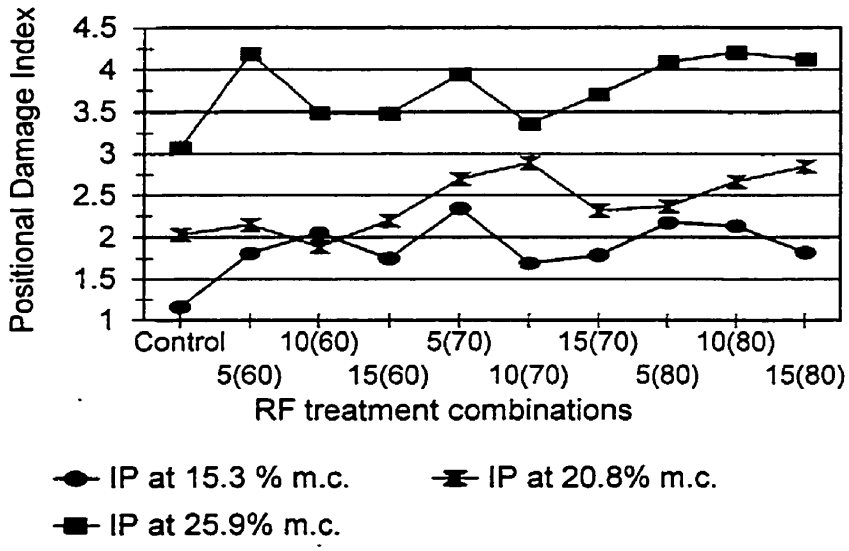

Figure 5.15: Positional damage index of RF treated wheat seeds (cv. Pollet) at three moisture contents.

5.5. CONCLUSION

The determination of crack formation and seed vigour after RF thermal treatment are practical tools for the determination of optimum dielectric heating parameters in the phytosanitary treatment or dielectric drying of seeds. Our preliminary results have shown that there is a significant effect of treatment combinations (temperature and time; and moisture content) on the germination and quality of the seeds. Thermotherapy only allows for a very narrow window of operating conditions for both thermal efficiency and conservation of seed quality. It is through the understanding of the heating kinetics and the damage kinetics that we may succeed in the development of efficient dielectric heating technologies for agri-food purposes. This research has successfully established correlations between moisture content, heating temperatures and treatment times with seed quality. There is a significant increase in crack development in seeds with an increase in moisture content, RF treatment temperature and RF treatment residence time. Our results have presented an average or overall damage index which indicates the extent of grain damage and a positional damage index which takes account of crack localisation which can be important for assessing grain quality.

It is likely that the kernel possesses varying dielectric properties at the embryo and the endosperm level due to their differences in composition where the latter is starchy whereas the embryo is mostly made of protein. However, our research has not permitted us to conclude on any preferential heating within the grain kernel as indicated by cracks localisation.

A complete X-ray image analysis system for aiding in quality assessment of wheat kernels has been presented. Analysis procedures are based on computer image processing techniques applied to X-ray images of grains. These techniques proved viable in the task of kernel quality evaluation in many respects. They are precise, objective, relatively cheap and yield fast throughput.

CHAPTER VI - RF TREATMENT FOR READY-TO-EAT FRESH CARROTS

6.1. ABSTRACT

This study was conducted to determine the potential of an RF thermal treatment to improve and extend the storability of vacuum packaged carrot sticks stored at 5-6°C. The results have shown that it is possible to treat carrot sticks to 60°C in less than 2 min in a parallel plate RF-applicator, and thus reduce the initial total microbial load. The RF treatments were compared to chlorinated water dipping, and hot water dipping. All storage trials from 0 to 14 days at 6°C, have indicated that the reduction of the initial microbial load alone, does not maintain the quality of carrot sticks for 14 days, since at this point the microbial loads in all cases studied were higher than 3×10^6. Nonetheless, the quality evaluation of the RF treated samples was greater than for either the control samples (chlorinated water) or hot-water treated carrot samples. The RF-treatments maintained colour, the vacuum of the packages, and the excellent taste of the carrot sticks, which was not the case for control and hot-water treated carrots.

6.2. INTRODUCTION

6.2.1. The Problem

A Québec Company, specializing in the preparation and commercialisation of fresh vegetables, offers a package of 35 g of vacuum packed carrot sticks. At the present time, the processing technology of the Company allows them to maintain a fresh-like quality of the product for a 14-day period when the product is maintained in refrigerated storage at temperatures between 1 and 3°C. It is however almost impossible to ensure that these temperatures will be maintained during transit, distribution and retail display. In fact, it is

often seen that such products will be subjected to temperatures greater than 5 °C. In these conditions, the microbial activity and the respiratory activity (anaerobic under vacuum) increase considerably. This leads to bulging of the packaging and a significantly reduced shelf-life. The company producing these prepared carrots is therefore looking for a processing step which would allow them to maintain the quality of their carrot sticks, vacuum packed, and stored for 14 days at 5-6°C.

For this reason, a study was conducted to evaluate the potential of a mild dielectric heating treatment as a means to solve the problem. The proposed mild dielectric thermal treatment could possibly reduce the microbial load as well as reduce the enzymatic activity, while minimizing the impact of heat on the sensory properties of fresh-like minimally processed (MP) carrot sticks. Microorganisms are an important factor to consider in dealing with MP fresh fruits and vegetables because microbial spoilage has economic consequences of importance but most importantly because consumer safety is at risk with food borne illness (Brackett, 1994).

Although other traditional methods of heating could have been selected for this study, (hot water, hot air, hot steam, etc.), radio-frequency (RF) heating was selected. Radio-frequency heating is little used in the agri-food sectors; however, it possesses specific particularities in comparison with other heat transfer modes. Indeed, in RF heating, the energy is absorbed directly within the material, the heating is rapid and uniform throughout the material, and the technology is relatively simple to adapt to an existing processing line. In order to evaluate the potential of RF technology for the preparation of minimally processed fresh-like carrot sticks, it is necessary to define, in laboratory trials, the real potential of the technology, to study the design of the applicator, and to determine the operating parameter of the process such as, treatment temperature, residence times, power densities, etc., and all their effects on product quality and shelf-life enhancement.

6.3. OBJECTIVES

The objectives of this study were to validate the development of a processing methodology for the RF thermal treatment of minimally processed, fresh-like carrot sticks, that would permit to successfully store them in vacuum packages for a period of 14 days at 5-6°C while minimizing the impact of RF-heating on product quality and organoleptic properties.

6.4. LITERATURE REVIEW

6.4.1. Preservation Techniques for Minimally Processed Fresh Vegetables

Over the last few years, the per capita consumption of fresh vegetables has increased significantly over the consumption of processed vegetables such as canned vegetables. The consumers perceive that fresh vegetables are more nutritional than processed vegetables. In the United States, it is the industry of minimally processed fruits and vegetables which has gained the greatest popularity from the consumers especially with ready-made mixed vegetables salads, sticks and cubes of celery and carrots, broccoli and cauliflower florets, and onions slices (Garg et al., 1990).

Minimally processed (MP) fresh fruits and vegetables are fresh raw fruits or vegetables processed in order to supply a ready-to-eat or ready-to-use product. The fruits or vegetables are usually trimmed, peeled, cut, washed and sometimes disinfected. The products are packaged in sealed pouches, or in plastic trays sealed with polymeric films. A shelf-life of several days under refrigeration is necessary for feasible transport and retail of final products. MP fruits and vegetables can be used as ingredients for cooked dishes, but in many instances they are consumed raw. Much developmental work is being carried in response to strong consumer demand for new types of like-fresh quality convenience foods. The purpose of minimally processed refrigerated foods is to deliver to the consumer a like-fresh fruit or vegetable product with an extended shelf-life and at the same time ensure food safety and

maintain sound nutritional sensory quality.

MP fruits and vegetables are respiring tissues where the respiration is greatly increased by cutting, slicing, heat treatments and preservatives. Their main features are (1) the presence of cut surfaces and damaged plant tissues, (2) minimal processing that cannot ensure sterility or microbial stability of the product, (3) active metabolism of the plant tissue, and (4) confinement of the product. Therefore, microorganisms are likely to proliferate on the product, but their behavior may be influenced by plant tissue metabolism and by modified atmosphere created by the combined effects of product respiration and packaging film permeability. Contamination by foodborne pathogens and their multiplication during storage could also be of concern, particularly because most MP fruits and vegetables are consumed without any heat treatment.

Mesophilic bacteria counts on plate count agar from MP fruits and vegetables are highly variable and range from 10^3 to 10^9 colony forming units $(CFU)g^{-1}$. The product quality is often acceptable, despite such high counts. Raw vegetables are already heavily contaminated when they enter the processing chain. Analyses at different stages of processing have shown that the end product is frequently less contaminated than the raw vegetable (Nguyen-the and Carlin, 1994) .

Spoilage of MP carrots has been characterized by exudation and production of off-odours or off-flavours on slices or shredded carrots. Spoilage development is usually in sink with the growth of microorganisms but does not necessarily mean that all spoilage is of microbial origin. The development of microorganisms and the decrease in quality score is not linear. In many instances, total bacterial counts at the end of the storage are unrelated to sample quality. Indeed, in shredded carrots, total counts of mesophilic flora were similar in spoiled samples and in samples with good appearance (Nguyen-the and Carlin, 1994).

Storage temperature will also have an important effect on spoilage. In MP products, two factors should be taken into account to explain the effect of temperature in addition to its direct action on growth rate: (1) storage temperature determines the respiration rate of the product, and, therefore, changes the gaseous atmosphere in the package, which may influence the behaviour of micro-organisms; (2) temperature may also influence the rate of senescence

of the processed fruit or vegetable, thus modifying the environment for microorganisms.

Prevention and control of MP fruits and vegetables spoilage can be achieved through a number of handling methods. Principally, chlorine is widely used for the disinfection of whole fruits and vegetables. The efficiency of decontamination depends on the product as is the case for dipping in water containing 300 ppm free chlorine which reduced total microbial counts from 1.10^6 CFU g^{-1} to 3.10^3 CFU g^{-1} on lettuce but had little effect on carrots (Nguyen-the and Carlin 1994). Traditionally the chlorine treatment should not exceed 200 ppm (Wiley, 1994).

Fresh carrots are minimally processed by abrasive peelers and washed to remove cellular fluids to produce carrot sticks, baby whole peeled carrots and grated carrots. Cutting accelerates respiration, causes mechanical damage and softens plant tissue. Cut tissues have lower barriers to gas diffusion. Cut products must be taken to 4 °C immediately after cutting. The shelf-life and acceptability for packaged minimally processed carrots is limited due to a white discoloration that develops on abraded surface, bulging of the packaging and spoilage during storage. Cutting also allows for juices to leak from inner tissues and these juices contain nutrients that can be used by micro-organisms to sustain their growth. To remediate to that, the ideal treatment would inactivate enzymes involved in the development of surface discoloration, while maintaining a fresh aspect, flavour, texture and microbiological quality of the product. Preservation methods to extend shelf-life of MP carrots can utilize many of the classic procedures to preserve food either individually or in combinations. These methods include heat preservation utilizing mild heat treatments with rapid cooling; chemical preservation, including acidulants, antioxidants, chlorine, anti-microbials; gas and controlled atmospheres; refrigeration; irradiation; and in some cases moisture reduction (Wiley, 1994). A steam treatment is commonly used to inactivate enzymes in fresh vegetables to improve storage quality. The enzyme inactivation may prevent the accumulation of isocoumarin a bitter compound, affecting the flavour, found in carrots. Isocoumarin is synthesized in response to ethylene production which occurs during storage in sealed packages (Howard et al., 1994). Heat preservation is one of the oldest forms of preservation known to man, and has potential to provide barriers to reduce microorganisms and inhibit enzyme activity. The

problem is that heat is associated with destruction of flavour, texture, colour and nutritional quality.

In an experiment by Howard et al., (1994), a steam treatment effectively retarded development of surface discoloration on minimally processed carrot sticks. Steam control appeared to retard enzymatic metabolism. However, steam treated samples developed off odours and a mucilaginous material accumulated on the carrot surface after 10 days. Softening was also apparent in steam treated samples during storage. No decay, off odors or textural changes were detected in non-treated samples. Steam treatment may reduce levels of competitive microflora which in turn allows the proliferation of spoilage pathogens. Steam inactivation of the phenylpropanoid (enzymatic) metabolism may have promoted decay by reducing the resistance of the carrot tissue to microbial attack.

Packaging or storage conditions that would inhibit bacterial spoilage of prepared vegetables could increase the shelf-life and saleability of the product. To prevent anaerobiosis, and the consequent production of off-flavours and discoloration of the product, some packers perforate the overwrap, and while this assists the maintenance of a partial aerobic atmosphere within the pack, it can cause excessive water loss with wilting and drying of the product as a result.

In an attempt to provide the consumer with convenience (450g) prepackaged ready-to-use- vegetables, with greater than 1 week shelf-life, some local producers have introduced vacuum packaging combined with chilled distribution. A study conducted by Buick and Damoglou (1987) consisted of a comparison of the microbial development on vacuum and non-vacuum packaged sliced carrots, and a determination of whether vacuum packaging was an advantage when allocating a shelf-life to the product. Vacuum packaging of carrots reduced the rate of increase and the final numbers of aerobic flora compared to non vacuum packaged carrots. When carrots were subjected to vacuum packaging, the population changed to become more microaerophilic and fermentative in nature. The predominant microorganism present after vacuum pack storage was *Leuconostoc* spp., an organism commonly isolated from fermenting vegetable material. These organisms form a slimy covering on the spoiled product. Non-vacuum packaged carrots resulted in the initial predominant organisms *Erwinia*

spp. remaining as the main spoilage species.

As expected, anaerobic respiration and the consequent production of carbon dioxide caused a reduction of the vacuum in the vacuum packaged samples upon storage. The time taken for this gas production to become sufficiently noticeable to render the pack unsaleable decreased with increase in storage temperature. At 15°C storage the pack was loose after 2 days, at 10°C after 4 days and at 4°C the packs were loosening after 8 days.

The principal disadvantage in trying to establish modified atmosphere storage conditions to prolong the shelf-life of consumer ready vegetables in retail packs is that the vegetables are still alive and respiring, and consequently, the packs used must be capable of allowing sufficient oxygen to reach the vegetables while permitting sufficient dissipation of the carbon dioxide produced to avoid excessively modified atmospheres. We must take account of the fact that the respiration of whole carrots increases from 9 to 12 cm^3 CO_2 $kg^{-1}h^{-1}$ after peeling, at 10°C (Buick and Damoglou, 1987).

Vacuum packaging is widely used in the retail meat industry where respiration of the product is not a problem. Low storage temperature and reduced oxygen levels can reduce the respiration rates of vegetable material but the conditions must be adequate since the storage of a food material under low oxygen or anaerobic conditions inevitably leads to concern regarding the growth of anaerobic food poisoning microorganisms, in particular *Clostridium botulinum*. However, even under conditions of temperature abuse, the product would be unsaleable due to respiratory by-products and other microbial spoilage before Clostridial growth and toxin production became a problem.

The atmosphere in the film bags can be allowed to drop down to 0.5% O_2 and increase up to 10% for CO_2 without detrimental consequences on shelf-life and quality of the carrots provided the temperature is kept near 0°C (Izumi et al., 1996). At temperatures above 5°C, low O_2 may promote the growth of lactic acid bacteria. However, lactic acid bacteria can be used as a protective culture to provide preservation against food pathogens such as *Listeria* (Kelly et al., 1998). Werlein (1998) demonstrated that at low temperatures (1-2°C), sous-vide packaging of carrots yields higher quality carrots up to 21 days of storage.

Loss of firmness and off flavour in MP carrots are associated with high CO_2 levels and

low O_2 levels; high number of lactic acid bacteria and yeasts; and production of ethanol, acetic and lactic acids (lactic acid fermentation). Typically, *Leuconostoc mesentoroides* is the lactic acid bacteria isolated from MP carrots. Furthermore, MP carrots stored in a CO_2 enriched environment produce an exudate of electrolytes, nutrients and sugars. The exudate provides an excellent medium for microbial growth. However, leakage is reduced in CA containing 10% CO_2 and 10%O_2 rather than in air by reducing the physiological activity. Polypropylene (40μm thick) commonly used is not permeable enough to both O_2 and CO_2 to ensure good preservation of the commodity (Varoquaux and Wiley, 1994). Use of highly permeable films (>2000 $ml \cdot m^{-2} \cdot atm^{-1} \cdot day^{-1}$) results in better conditions for the commodity. Of course there is a downside to this, it leads to higher respiration rates and induces faster consumption of carbohydrates and thus a loss in palatability which can be minimized by lowering temperatures (~2°C). Furthermore, carrot cultivars also have an important role in their suitability for ready-to-use processing. Some carrot cultivars are more susceptible to increasing CO_2 and decreasing O_2, leading to rapid spoilage (Varoquaux and Wiley, 1994). Physiological damage to many fresh produce items such as cauliflower, celery and carrot can occur at CO_2 concentrations in excess of 2-6%. Anaerobiosis is evidenced by the appearance of off-flavours and off-odours. Polymeric films of reasonably high permeability to O_2 and CO_2 should be used with MP fruits and vegetables (Schlimme and Rooney, 1994).

Polymeric membranes generally exhibit a high resistance to the diffusion of water vapour. Maintenance of high relative humidity is essential to the development of defence mechanisms. High RH maintains the turgor of fruits and vegetables but it may cause condensation on the commodity favouring microbial growth. Excessive RH may also lead to the exudation of cellular sap.

Optimization of ready to use processing:

- Careful handling to limit bruising;
- Reduced initial microbial loads (through washing);
- Optimal draining of wash waters to avoid conditions favouring microbial growth;
- Optimal MA packaging to slow senescence, enzyme activity, and microbial growth while

not triggering the anaerobic metabolism.

It is a combination of the right set of hurdles which will lead to the best minimally processed product.

6.4.2. Mild Heat Treatments for the Conservation of Fresh Fruits and Vegetables

Mild heat treatments to reduce or eliminate pathogens offer an alternative means to control the quality deterioration of fresh fruits and vegetables. These mild heat treatments consist of subjecting the products to temperatures of 50 to 60°C for periods of time not exceeding 3 to 5 min (Barkai-Golan and Philips, 1991). Studies have shown that most fruits and vegetables tolerate well these conditions while they allow to reduce significantly the pathogens present on the produce (Barkai-Golan and Philips, 1991; Couey, 1989)

Generally the means of applying those mild heat treatments are, hot air, hot water and steam. The easiest conditioning treatment is through the use of water since it offers a greater flexibility and easiest control (Barkai-Golan and Philips, 1991).

No mention on the use of dielectric heating (either microwave or radio-frequency) for the thermal conditioning of fresh fruits and vegetables has been found in the literature.

6.4.3. Carrot Cultivar

Carrots exists in a great number of cultivars which all vary in their properties (shape, colour, sweetness, etc.). In North America, we prefer the elongated varieties (Imperator type), while in Europe the Chanteney, and the Nantais, rounder in nature, are preferred. Imperator type carrots are long and narrow and best when consumed shortly after harvest and not processed. On the other hand, the Nantais type is a cultivar which behaves very well in fresh-like processing. From cultivar characteristics, the Nantais type of carrots should be adopted as the cultivar of choice for minimally processing applications (Villeneuve and Leteinturier,1992).

6.4.4. Dielectric Heating

The development of industrial application of dielectric heating must carefully take

account of the advantages and the technological limitations and the specific properties and characteristics of the product of interest. The technology certainly has limitations in its high capital initial investment (5 to 10 times that of traditional/fossil fuel heating systems) and in its moderate energy conversion between the generator and the product (between 40 and 65%). Nonetheless, the technology possesses advantages of interest with potential for development in the agri-food sectors, namely that: the product heats up from within; that certain components may be heated selectively depending on their properties; only the product is heated, not the air or the oven; and large power densities can be transmitted (Marchand and Meunier, 1990).

The commercial use of RF in the agri-food sectors is not widespread. When RF is adopted, it is usually integrated in a conventional process in order to optimize efficiency while reducing initial investment cost. In the agri-food sectors we can find applications of RF heating for dehydration of crackers, tobacco drying and pasta drying.

6.5. MATERIALS AND METHODS

Trials were thus conducted to develop and validate an RF conditioning treatment allowing minimally processed carrot sticks of quality to be stored for 14 days at 5-6 °C.

6.5.1. Methods

The carrots used in these trials were either provided by the processing company or prepared, in our laboratory, from fresh carrots purchased at the supermarket. The carrot samples obtained from the company were already prepared into sticks and were delivered in 2-kg vacuum packed bags. For the samples prepared from fresh carrots, the carrots were peeled by hand and cut into 100mm long sticks. The carrots used were all from the elongated "Imperator" cultivar.

For all trials, the heat treatments were applied to samples of 100 g of prepared carrots. After treatment, the samples were immediately cooled in iced chlorinated (100 ppm) water

baths, and surface dried with paper towel. The 100g samples were subsequently sub-divided in 25g samples and vacuum packed in commercially purchased plastic bags (Polypropylene plastic films, DELI*1, Emballage Godin CDR, Vanier, QC). The packed carrot sticks were then identified and stored for 7 and/or 14 days in a refrigerated storage room maintained at 5-6°C. Each treatment was replicated three times. A Multivac (A300) packaging unit was used to vacuum pack the carrots and seal the bags.

Control samples were used in all cases as a reference point for the study of the performance of the treatment combinations. The control samples were prepared and packaged the same way as the treated samples.

The experiment targeted the evaluation of the importance of many factors such as material thickness between the electrodes, the duration of the treatment, the power density, and a salt water (5000 ppm NaCl) pre-treatment. The salt water pre-treatment was studied to determine if it could improve the impedance matching between the RF generator and the carrot sticks in the applicator, since ionic conduction is an important mechanism involved in energy transfer into heat at electromagnetic frequencies in the radio range (as demonstrated in Chapter III).

Thermal treatments with hot water were also conducted as a means of comparison between RF and a standard. For these trials, the samples were prepared in the same manner, with a preliminary dip in cold chlorinated water, patted dried with paper towel, and immersed in a bath of boiling water until the samples reached the desired internal temperature. Once the temperature was reached, the samples were then dipped in iced chlorinated water, patted dried and subdivided in 25g samples, vacuum packed and stored for 7 and 14 days in refrigerated storage. All results were analyzed statistically. The SAS output is presented in Appendix G.

6.5.2. RF Treatments

During the thermal RF treatments, the 100g samples were placed on a Teflon sample holder between the electrodes of the applicator. The power densities from the generator were between 5 and 6 $W \cdot g^{-1}$, the maximum output power of our equipment. The heat treatments

were interrupted when the desired temperatures were reached or when the treatment time exceeded 5 min. After treatment the samples were cooled in iced chlorinated (100 ppm) water, patted dried, subdivided, vacuum packed and stored in a refrigerated unit. The RF heating unit used for this experiment is described in Chapter III.

6.5.3. Evaluation of Sensory and Microbial Quality

The initial and final quality of the prepared and treated carrot sticks was determined with the following criteria: total plate counts, appearance, colour, texture, odour and taste. The total plate counts are expressed in colony forming units per gram (CFU/g) of product, while a scale of 1 (worse) to 5 (best) was used to quantify the quality parameters of appearance, colour, texture, odour and taste. Due to lack of time, the microbial analysis was contracted out to an external laboratory (Analex Inc., Laval, QC).

6.6. RESULTS AND DISCUSSION

6.6.1. RF Thermal Treatments of Carrot Sticks in a Thin Layer (1-2 cm thick)

The first series of tests were conducted on carrot sticks prepared and provided by the company interested in the development of this treatment. These trials were conducted by placing the carrot sticks, on a Teflon holder, in a thin layer between the electrodes (Figure 6.1).

The thin layer trials were first chosen since this configuration would be best suited for the commercial installations of the company. During the trials, the samples were all handled in the manner described earlier, treated, cooled, patted dried, subdivided, packed and stored. The target temperature to reach was 60 °C.

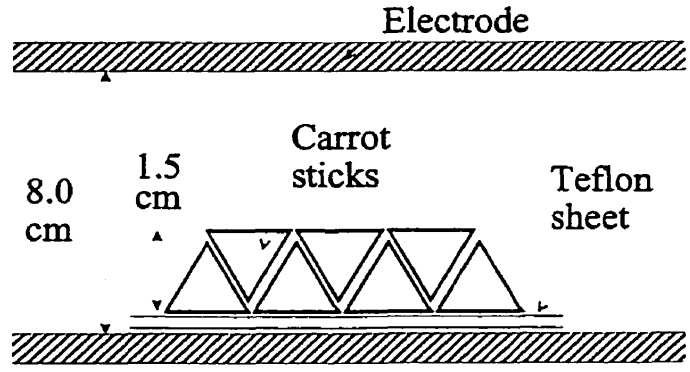

Figure 6.1: Carrot sticks placed in a thin layer between the electrodes.

At first the results indicated that the coupling of the RF energy with the carrots was not optimal and much of the energy was being lost through the matching network and monitored via the increase in temperature of the system's cooling water. Indeed, matching of the impedance was difficult and reached the physical limits of the equipment. The heating rate observed were at best of the order of 6°C/min increase and it took close to 5 min for the carrot samples to reach 40°C. Furthermore, a lot a variability was experienced in coupling for every sample. Due to the problems experienced with these trials and the fact that the target temperatures were not met within 5 min treatments, the samples were not analysed for their microbial quality. The samples were nonetheless stored at 6°C for a storage period of 7 days.

The analysis of the sensory quality of the samples, after 7 days of storage, showed that more than half of the RF-treated carrots were improper for consumption while all the control samples were of good sensory quality.

Following those disappointing results, modifications had to be made to improve the coupling between the generator and the samples in the applicator. Surely, a thin layer of material is not appropriate with the equipment that we have.

6.6.2. RF Thermal Treatments of Carrot Sticks in a 4 to 5 cm Thick Layer

To improve the RF coupling, the layer of carrot sticks in the applicator was increased from 1-2 cm to 4-5 cm (Figure 6.2).

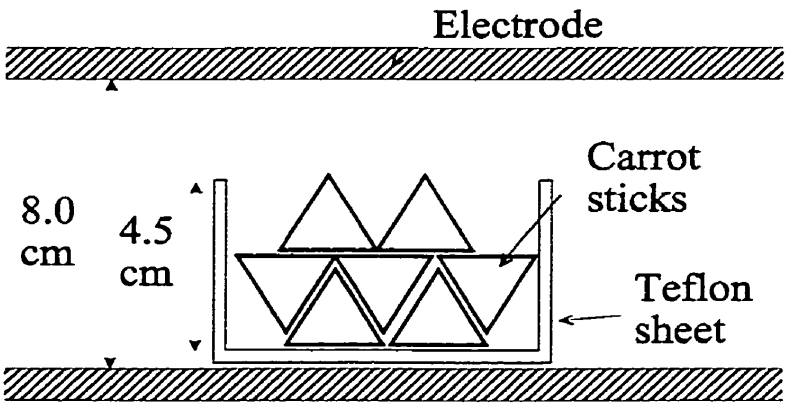

Figure 6.2: Carrot sticks placed in a 4.5 cm layer between the electrodes.

During these trials, the heating times required to reach the target temperature of 60°C varied from 2 to 7 min. The increase in the thickness of the layer of carrots did not increase enough the coupling to allow for adequate energy absorption by the carrots. This poor coupling once again lead to high variability in heating rates and long treatment times. The samples were cooled after treatment and processed as prescribed before storage at 6°C for 7 and 14 days.

After 7 days of storage, the sensory quality (appearance, texture, colour, odour and taste) of all carrot samples, treated and non-treated, was excellent. However, the sensory quality of the control samples was in general a little superior to the RF-treated samples. The total plate counts indicated that all samples (treated and non-treated) had counts higher than 3×10^6 CFU/g.

After 14 days of storage, the quality of all samples was not acceptable. The bags had started to inflate from the product's respiration, and the sticks had a slimy exudate covering them or were surrounded by free water collected in the bags. Furthermore, an off-odour

(either acid, rancid, fermented and sulfurous) was detectable upon opening the bags. For these reasons, these samples were not analysed for total plate counts.

During these trials, burning marks were observed sporadically on the edges of a few sticks RF-treated. These marks were likely caused by arcing occurring between the product edges and the electrodes. Incidents of arcing were detected by the data-acquisition system with the disruption of impedance matching evidenced by the phase and module readings of the variable capacitors. These burning marks were black and did not have more than 5 mm × 1 mm dimensions. Adjustments were made to attempt to limit these occurrences, such as changes to the product configuration, reduction off the applied voltage, etc. However, even a reduction in applied voltage did not solve this problem.

6.6.3. Effects of Different Processing Steps on the Quality of RF-treated Carrot Sticks

These trials were conducted on fresh carrots from the United States purchased and prepared on site (peeled and cut) just prior to treatment and packaging. These trials were conducted to estimate the relative importance of the processing steps and treatments on the quality of the final product. The treatments were applied in a cumulative fashion in the following manner: a dip in cold chlorinated water (100 ppm), a dip in salt water (5000 ppm NaCl) to improve the energy coupling, a RF thermal treatment (6 $W \cdot g^{-1}$ in a thin layer), and a cooling step in iced chlorinated water (100 ppm). After treatment, the regular procedure was followed to pack and store the samples for 7 and 14 days at 6°C.

The dipping of the carrot sticks in salt water did not increase the coupling of the impedance and did not improve the transfer of energy to the sticks. Indeed it took close to 5 min for the temperature to rise to 35-40°C. Furthermore the dipping in a salt water solution increased the incidence of burning on the edges of the sticks with a concentration of the energy on the salted surface of the edges.

The microbial analysis indicated a cumulative effect of the treatments on the total plate counts after 7 days of storage (Table 6.1). After 14 days of storage, there was no detectable cumulative effect of the treatments as the total plate counts were all greater than 3×10^6 CFU/g. The sensory evaluation of the quality of samples stored for 14 days indicated that all

were acceptable. In general, all packages maintained their appearance with good vacuum. The quality scores (5 = best and 1 = worse) obtained for the appearance of the RF-treated packaged product, its colour, its odour, texture and its taste were respectively 4.0, 4.2, 4.0, 4.2 and 4.25. No sign of mould, rot or decay was visible on the samples. On the other hand, the control samples all had a dryer appearance with whitening at the edges of the sticks in comparison to the nice orange colour of the RF treated samples. Some traces of burning were also found on a few RF-treated samples.

Table 6.1: Total plate counts for the carrot sticks.

Description of treatment	Total plate counts (CFU/g) Duration of storage		
	0 d	7 d	14 d
Control, chlorinated water (100 ppm)	2 735	$2\ (10)^6$	$> 3\ (10)^6$
Chlorinated water (100 ppm) + salt water (5 000 ppm)	1 025	$1{,}9\ (10)^6$	$> 3\ (10)^6$
Chlorinated water (100 ppm) + salt water (5 000 ppm) + RF (6 $W \cdot g^{-1}$) + chlorinated water (100 ppm)	215	$1{,}0\ (10)^6$	$> 3\ (10)^6$

Note: Values are means of two readings.

6.6.4. Effects of RF Treatment Times and Hot Water Treatment on Carrot Quality

Series of tests were conducted to determine the effect of RF treatment time and hot water treatment on the quality of the end product. In order to optimise the energy coupling, the carrots were placed in a thick layer of 6.5 cm (Figure 6.3). The carrots used for this series of tests were prepared on site from fresh carrots.

For the RF treatments, the carrot sticks were brought to 60°C and maintained at that temperature for residence times of 0, 1 and 3 min. After treatment the samples were precooled in iced chlorinated water (100 ppm), patted dried, subdivided into 25g samples, vacuum packed and stored at 6°C for 7 and 14 days.

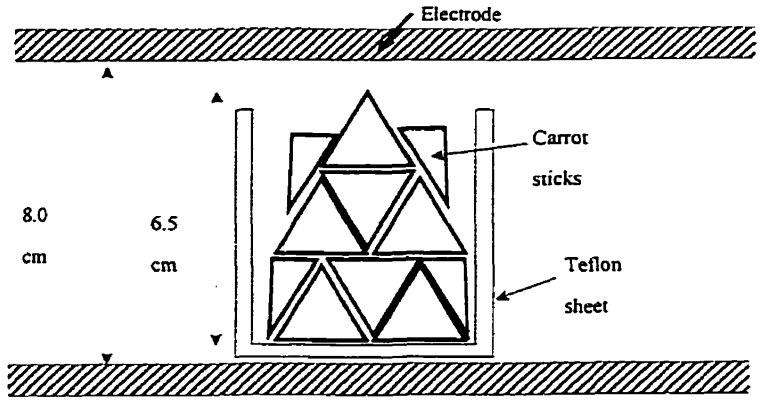

Figure 6.3: Carrot sticks placed in a thick 6.5 cm layer between the electrodes.

The new layout of the product in a thick layer considerably improved the energy coupling between the generator and the product. Indeed, with this layout, it only took from 80 to 140 s to bring the internal temperature of the carrot sticks to 60°C. The subsequent intermittent operation of the generator allowed to maintain this temperature for residence times of 1 and 3 min.

The microbial analysis yielded a cumulative effect of the treatments on the total plate counts (Table 6.2), up to 1 min residence time. The 3 min residence time did not improve the microbial count reduction any further due to overheating which lead to product deterioration. After 7 days of storage, the total counts had significantly increased with the greatest increases with the control samples.

After 14 days of storage, the difference between RF-treated and untreated disappeared and all counts were higher than $(10)^6$ CFU/g. The sensory evaluation of samples stored for 14 days indicated that all treated samples were acceptable with the exception of the hot water treated samples (Table 6.3). It was noted that the packaging of a number of control samples was bulging while the packaging had kept its tight vacuum in the case of RF-treated samples.

The control samples had a dry appearance with whitening edges and they experienced a loss in flavour. The RF-treated samples maintained their bright orange colour and their excellent taste. However, some signs of overheating and burning were noticeable on the edges of some RF-treated carrot sticks.

Table 6.2: Total plate counts of 6.5 cm stacked carrots sticks stored for 0, 7 and 14 days at 6 °C.

Description of treatment	Total plate counts (CFU/g) Duration of storage		
	0 d	7 d	14 d
Control, chlorinated water (100ppm)	70	$1,5 \times 10^6$	2.3×10^6
Chlorinated water (100ppm) + RF (6 W/g) + 0 min residence + chlorinated water (100ppm)	40	55 000	$> 3 \times 10^6$
Chlorinated water (100ppm) + RF (6 W/g) + 1 min residence + chlorinated water (100ppm)	25	16 500	2.4×10^6
Chlorinated water (100ppm) + RF (6 W/g) + 3 min residence + chlorinated water (100ppm)	25	150 000	$> 3 \times 10^6$
Hot water + pre-cooling in chlorinated water (100ppm)	< 10	n/a	$> 3 \times 10^6$

Note: The values are means of two readings.

Similarly, 100 g samples were dipped in boiling water until their internal temperature reached 60°C. Following treatment all samples were pre-cooled by dipping in an iced chlorinated water bath (100 ppm), patted dry, subdivided in 25 g samples and vacuum packed to be stored for 14 days at 6°C. For hot water treated samples, it took from 55 to 80 s to reach the target temperature. The initial charge of the prepared carrots (after peeling and cutting) were close to $2\ (10)^5$ CFU/g for total plate counts. The dipping in chlorinated water (100 ppm) allowed a considerable reduction of the total counts down to 70 CFU/g. The RF treatment was effective since it permitted a further reduction of total counts to 40 and 25 CFU/g.

Table 6.3: Sensory evaluation of 6.5 cm stacked carrots after 14 days of storage at 6°C.

Description of treatment	Sensory evaluation				
	Appearance	Colour	Odour	Texture	Taste
Control, chlorinated water (100ppm)	4	3.5	3.5	4	3.25
Chlorinated water (100 ppm) + RF (6 W/g) + 0 min residence + chlorinated water (100 ppm)	5	5	5	4.75	5
Chlorinated water (100 ppm) + RF (6 W/g) + 1 min residence + chlorinated water (100 ppm)	4.5	5	5	4.5	4.5
Chlorinated water (100 ppm) + RF (6 W/g) + 3 min residence + chlorinated water (100 ppm)	4.5	5	5	5	5
Hot water + pre-cooling in chlorinated water (100ppm)	1.3	4	2.7	2.5	1

Note: The values are means of two readings.

The best treatment was no doubt the hot water treatment since it allowed to bring down the total plate count to less than 10 CFU/g. In contrast with RF, in hot water dipping the heat was transferred from the outside of the stick to the inside of the stick. The measured temperature which controlled the treatment trials was the internal temperature, therefore it is likely that for hot water treatment the surface temperature was greater than the target temperature leading to a greater impact on the mortality rate of the microorganisms which are present in greater number at the surface of the product.

After 14 days of storage, all samples had total plate counts greater than 10^6 CFU/g, excessive amounts for ready-to-eat foods. These results indicate that a product shelf-life of 14 days at 6°C is not solely dependent on the control of the microbial count for vacuum packed produce.

These results indicate that the proposed heat treatment is not recommended as a sole treatment to improve the storability and food safety of minimally processed ready-to-eat carrot sticks. Rather, RF treatment should be considered as a part of an integrated approach,

including proper packaging, and adequate refrigeration.

6.7. SYNTHESIS AND CONCLUSION

The laboratory trials have demonstrated that it is possible to thermally treat carrot sticks with RF energy in less than 2 min to reduce the microbial charge before packaging while minimizing, to some degree, the detrimental effects on the sensory quality of the fresh-like product. The storage trials have indicated that the fact of reducing the initial microbial charge does not permit to extend the storage life of carrot sticks to 14 days at above optimal temperatures (5-6°C). Although the thermal process did succeed in reducing the microbial counts, the complete processing line may have been inappropriate for the type of end product of interest. Indeed, for minimally processed carrots, vacuum packaging may be more detrimental to the product than microbial decay itself.

Vacuum packaging does not provide the complete answer to retail vegetable packaging since prolonged anaerobic storage can lead to the production of ethanol and acetaldehyde causing browning and off flavours in the produce (Buick and Damoglou, 1987).

Ready-to-use carrot sticks packaged in polymeric films have a shelf-life of 6-7 days at 4°C and deteriorate rapidly at 10°C. Lactic acid bacteria identified as *Leuconostoc* spp., play an important role in the spoilage process. The onset of spoilage is detected by the increase in the amount of exudate released by the carrot strips. This is closely related to softening and the development of off flavours. Generally, a minimum shelf-life of about 7 days is required for domestic consumption, and 7 - 15 days for overseas consumption but preferably longer.

The main factors limiting shelf-life in minimally processed vegetables are enzymatic browning, white surface discolouration, microbial spoilage, senescence due to respiration and ethylene production and degradation in nutritional value, texture and flavours. Mechanical injury such as cutting, trimming and peeling, results in metabolic activation manifested in increased respiration rate, and in some cases, ethylene production. For damaged plant tissue

(peeled, cut and grated), the respiration averages 3 to 7 times that of intact tissue (Reyes, 1996). Generally, the shelf-life of raw and minimally processed vegetables is inversely proportional to the respiration rate.

In terms of packaging, the increase in the metabolism of minimally processed vegetables results in rapid consumption of oxygen in the package's headspace. Hence, polymeric films with higher oxygen transmission rate, would likely be preferable, in order to prevent the development of anaerobic conditions which can be conducive to the growth of pathogenic organisms and anaerobic fermentation.

In our experiment we used a polypropylene film which is a high barrier plastic which may have been detrimental to the quality of the carrot sticks, especially at storage temperatures greater than 5°C.

In the United States, one of the most important player in the production of ready-made salads and prepared fresh vegetables is the Dole Food Company Inc., where over 150 million kg of fresh vegetables are minimally processed every year. It is interesting to note that the Dole company only uses freshly harvested vegetables having the highest quality and immediately pre-cooled. Dole utilises a process of triple action washing with ice cold and chlorinated water. Following washing the vegetables are dried by centrifugal forces. The use of very cold, chlorinated, wash waters, along with the spin drying, are important processing steps to reduce the microbial loads and to reduce the rate of senescence of the vegetables. After that, the vegetables are rapidly carried by belt conveyors to a packaging line where they are weighed, and packed in various size bags. The packed vegetables are then stored and transported in refrigerated units until their final destination. The Dole Company insists that, through the distribution line, its products be kept at 1 - 4°C to ensure its product's quality and shelf-life (Anon. 1996).

CHAPTER VII - RF PASTEURIZATION OF HAM TO ENHANCE SHELF-LIFE IN VACUUM PACKAGING

7.1. ABSTRACT

Radio-frequency heating at 27.12 MHz was studied for the pasteurization of prepared samples of ham. The ham samples were brought to internal temperatures of 75 and 85°C, by radio-frequency heating, in 5 min and kept at those temperatures for an additional 5 min. The ham samples were then vacuum-packed in three different plastic films and stored at 4°C for 1 to 28 days. All samples were examined for drip loss, colour change, quality attributes such as off odours and sliminess, and total bacterial surface counts. The study indicates that radio-frequency heating can improve the storability of re-packed hams by reducing the bacterial load, reducing drip loss during storage and maintaining an overall greater product quality and acceptance.

7.2. INTRODUCTION

Today, an increasing percentage of hams are being sliced and merchandised in transparent oxygen-barrier vacuum pouches. Microbial control in this type of ham is dependent on the combination of high salt content, low moisture, nitrites, low oxygen, initial quality and refrigeration. However, more often than not, poor refrigeration of the retail display case, presents a health hazard, especially that the prepared vacuum-packed ham products are destined to be consumed without heat treatment (Ng et al., 1997). To prevent the outgrowth of food pathogens such as *Listeria*, it is necessary to prevent contamination of the food materials during preparation and packaging and perhaps shorten the rather long "shelf-life best before dates" of packaged meat products (Beumer et al., 1996).

Vacuum packaging is the most widely used packaging technique for cooked and

cured meats (Eustace, 1981; Andersen et al., 1988, Holley et al., 1996). Several investigations on the improvement of the shelf-life of cooked meat products have shown that low-oxygen atmospheres increase the shelf-life of meat products. Indeed, this environment restricts the growth of normal aerobic spoilage organisms. In general the shelf-life of sliced vacuum-packed ham is 18-20 days at a storage temperature of 4 °C (Kotzekidou and Bloukas, 1996). Recently, bacterial preparations used as protective cultures have shown promise to extend the shelf-life of certain meat products. Protective cultures are micro-organisms that can suppress the growth of food poisoning organisms present on the product. Inhibition of the growth of undesirable micro-organisms can take place in a number of ways such as the competition of nutrients, the production of organic acids, etc.

The use of pasteurization temperatures for processing of cured meats in relatively impermeable casings can yield products with a chilled shelf-life of about 16 weeks. Immediately following heat processing, these meats contain few viable bacteria but subsequent handling during slicing and repackaging at the consumer outlet permits the introduction of bacteria capable of low-temperature spoilage (Holley et al., 1996). In general, slicing and repackaging yields growth of Homo and Hetero- fermentative lactic acid bacteria (Holley, 1997). The use of low oxygen transmission rate packaging films (<50 cm^3 O_2 m^{-2} per 24 h atm^{-1}) retards the growth of undesirable, early spoilage organisms. Carbon dioxide is a powerful antimicrobial agent, however, lactic acid bacteria are unaffected by its action and rapidly become the dominant bacterial group in packs of processed meats held at chill temperatures (Holley et al., 1996). In a survey (1989-1990), the Québec Department of Agriculture Fisheries and Food found that retail sliced and vacuum-packed delicatessen meats frequently (56-58%) had in excess of 10^7 bacteria g^{-1} (lactic acid bacteria).

Interest in the possibility of controlling pests with high frequency electric energy dates back to over 60 years (Fabian and Graham, 1933; Fleming, 1944; Nyrop, 1946; Brown and Morrison, 1954; Carroll and Lopez, 1969). Concern about the health hazards of chemical pesticides and food safety has stimulated further studies on the possible uses of radio-frequency (RF) and microwave energy for pasteurization and food safety (Bengtsson et al, 1970; Rosenberg and Bögl, 1987; Mudgett, 1988; Houben et al., 1991; Thom and

Yeow, 1994). Although past research has shown some promising results on the use of dielectric heating for pest control, many food applications have not yet found their way into practical use.

The objective of this work was thus to evaluate the potential of RF energy to pasteurize ham pieces, vacuum-packed and stored under refrigeration for up to 28 days, in order to improve shelf-life and product quality and safety at the retail outlet.

7.2.1. Microbial Inactivation

The kinetics of microbial inactivation are related to time-temperature conditions within the product (Mudgett, 1988). Thermal resistance is characterized by the D-value and the Z-value.

$$D = \frac{2.303}{k_i} \tag{7.1}$$

and

$$Z = 2.303RT\frac{T_o}{E_A} \tag{7.2}$$

where D-value is the time to reduce the levels of some constituent by an order of magnitude (one log cycle, at the reference temperature) and the Z-value is the temperature difference needed to increase or decrease the D-value by one order of magnitude.

The thermal inactivation rate k_i (min^{-1}) is found as:

$$k_i = k_o \; Exp\,[E_A(T - T_o) / RTT_o] \tag{7.3}$$

Where T_o is a reference temperature (K), E_A is the activation energy (kJ/mole), R is the universal gas constant (kJ/mole-K), and T is the process temperature (K). In past research (Magnus et al, 1986 and Reichert et al., 1979), D- and Z-values have been determined for *Enterococcus faecium and E. faecalis* the most thermo-resistant microorganisms are found in large quantities in salted meats, especially ham. Consequently, these organisms are chosen as the reference microorganisms for the pasteurization of ham which are defined accordingly

with the following parameters at 70°C: Z = 10°C and D_{70} = 2.93 min (Reichert et al., 1979).

From this information, we chose to treat our ham at 75 and 85°C for 10 min. The duration of the treatment, 10 min, was chosen arbitrarily. The time of the treatment at the chosen temperature had to be above 3 min to ensure proper microbial inactivation (D_{70}=2.93) Since it took us less than 5 min to reach the desired temperature, the holding time was set to 5 min, which is more than the D_{70} value of 2.93 min. Higher temperatures were chosen to ensure adequate thermal inactivation since with RF heating, the internal temperature is higher than the surface temperature where most microorganisms are located.

7.2.2. Dielectric Heating

When the load is correctly tuned for the given output frequency and impedance of the generator, an appreciable voltage can be built up across the electrodes. This voltage is the important factor of dielectric heating since the quantity of heat generated within the load varies as the square of the impressed voltage.

If a mass of insulating material having a definite dimension is considered, the power will be given by:

$$Power = 55.63\, E^2\, f\, \varepsilon''_r \times 10^{-12} \qquad (7.4)$$

Power is expressed in W/m^3

E is the rms electric field intensity, V/m

f is the frequency, Hz

ϵ''_r is the loss factor.

The voltage is limited by the dielectric strength of the material which is a measure of its ability to withstand a voltage gradient across a unit cross section.

The investment cost is high and directly related to the power installed. It is thus very important to optimize the choice of power required and the use of the available power. Therefore energy transfer must be excellent between the generator and the product to achieve a 60% efficiency of the system (energy absorbed by the product). For the system, this implies that the power which is not transmitted from the generator to the product, must be

less than 10% of the incident power. This lost energy can be in the form of reflected power to the generator and heat loss in the distribution system.

From an overlook of the RF technology for dielectric heating, its use in industry is not widely spread although its usefulness has been demonstrated in the wood drying, wood gluing, textile, baking, and medical industries. The R&D work which has been undertaken so far in dielectric heating applications is constrained by the small size of the corresponding equipment manufacturing industry and the limited market demand, causing the investment costs to remain high. The present situation may change when more resources are dedicated to the study of the technique and its applications and when the size of the industry increases. For new applications, the design and installation of radio frequency equipment consists in the development of equipment specific to the needs of the product and of the application. Each new equipment is considered as a prototype requiring extensive testing which is translated into prohibitive investment costs and industrial risks. This is why extensive research is required in the laboratory to establish product-RF field behaviour to promote the industrial use of the technology.

7.3. MATERIALS AND METHODS

7.3.1. RF Heating

The RF system designed and described in Chapter 3 was used in this experiment. The size and shape of the ham samples was chosen in order to minimize the air gap between the electrodes. Cylindrical shaped ham samples were chosen for this experiment with 2.5 cm diameter and 7.5 cm length.

The electric potential at the electrodes was measured by voltage sensor composed of a silver connector attached to the hot electrode (bottom electrode). This sensor sends a reading of the applied voltage via a coaxial cable connected to a regulator and electronic indicator. In most applications with a flat plate configuration, there exists the presence of an air gap between the product and the top electrode. The configuration, shown in Figure

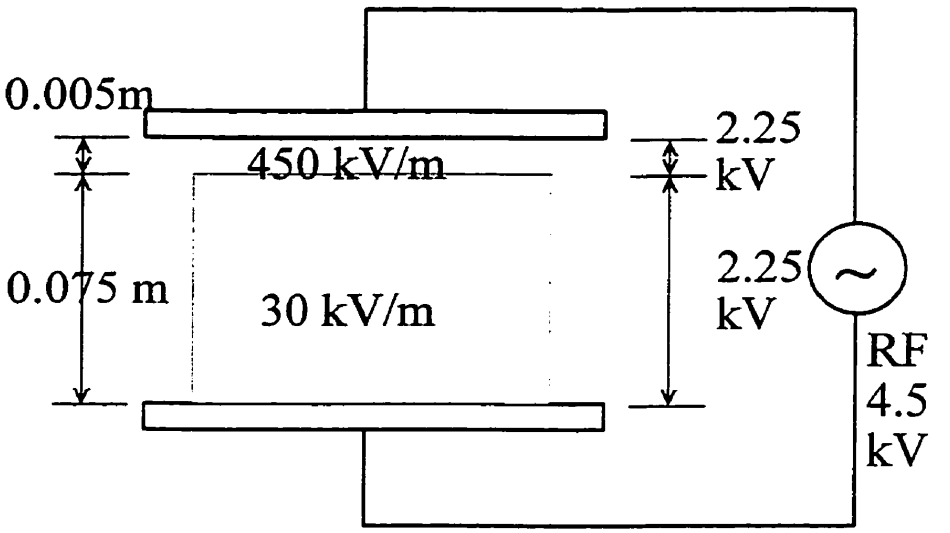

Figure 7.1: Effect of an air gap.

7.1, is equivalent to two electrode system in series, with a virtual electrode separating the air and the product at an intermediate voltage. There are two homogeneous electric field distributions, in each medium, but the corresponding values are not independent: The electric field in the air is equal to the electric field in the product multiplied by its dielectric constant.

Knowing this we can then determine the electric field in the product studied and follow up with the determination of the power absorbed by the material using the following equation which in practice is the same as equation (7.4) given before:

$$P = 2\pi f E^2 \varepsilon_o \varepsilon'' \tag{7.5}$$

where P is the power density, W/m^3;

f is the applied frequency in Hz;

E is the electric field strength in the material, V/m;

ϵ_o is the permittivity of free space (8.85×10^{-12} F/m) and

ϵ" is the loss factor of the material (assumed to be 50 from Nelson (1973)).

7.3.2. Sample Preparation

Hams were purchased from a local market. All hams were selected from the same manufacturer (Maple Leaf, La Mère Michel ham). The hams had a minimum of 17 percent protein content, low in fat, and had a homogeneous appearance. All hams utilized for the experiment had more than 6 weeks manufacturer's best before date prior to being used for RF pasteurizing, vacuum packaging and storing, in order to ensure uniform initial quality.

Each ham produced on average 9 cored samples for treatment. The cored samples had 2.5 cm diameters and 7.5 cm lengths. The samples each weighed approximately 30 g. The samples were prepared on a disinfected surface using disinfected cutting tools (knife and core borer). Each sample was then placed on a disinfected sample holder, upright in the RF cavity to be treated. A hole was punched in each sample to allow the insertion of a temperature sensor. All working surfaces were washed before each treatment and treated with 77% ethanol.

The RF treatments consisted of 10 min treatments at 75 and 85 °C. Once heat treated, the ham samples were placed in sterile plastic bags subsequently vacuum sealed (Cryovac vacuum sealer). Three different plastic packaging films were chosen for this study. All films were selected for their moderate-to-low O_2 permeability. A double layer film composed of a Nylon film (Dartek N-201, DuPont Canada) and a polyethylene film (Sclairfilm A-322, DuPont Canada); a polypropylene film, PP (Cryovac, Canada) and a high density polyethylene film, PE (Cryovac, Canada). Manufacturer's specifications are given in Table 7.1. Moisture and gas transmission rate of the plastic packaging materials used were not tested in these experiments.

Table 7.1: Manufacturer's specifications of the packaging films.

	Moisture permeability $g/m^2/24$ h	Oxygen permeability (at 20 °C) $cc/m^2/24$ h
1) High Density Polyethylene[1]	15-20	2500
2) Nylon/Polyethylene[2]	295	60
3) Polypropylene[1]	6-10	26

[1] Cryovac Canada,
[2] DuPont Canada

Once vacuum sealed, the ham samples were stored in refrigerated storage for 1 (control), 7, 14, 21 and 28 days. Storage for 28-days was only conducted for ham samples RF-treated to 85°C. Each treatment was replicated three times for a total of 81 samples treated with radio frequency along with three controls for each plastics for the 5 storage

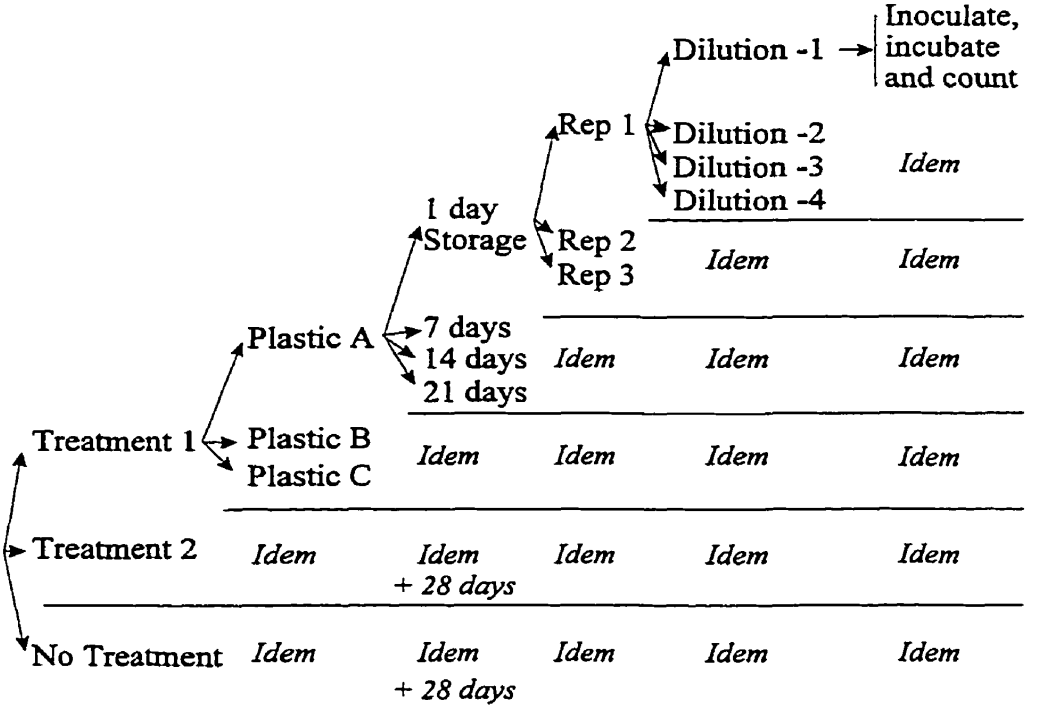

Figure 7.2: Experimental design for RF treated ham.

periods studied for an additional 45 ham samples and a total of 126 samples for this study. The experimental design is presented in Figure 7.2.

The drip loss from both the treatments and the storage combinations was calculated for each sample. At the completion of each storage period, the wrapped samples were individually weighed, and the ham samples were aseptically removed from the package to be analyzed (colour measurement, sensory quality attributes, and microbiological analysis). The empty packages were weighed, dried and reweighed to determine the mass of water released from the ham samples. The percent drip loss was then obtained by difference:

$$\% \; drip \; loss = \frac{mass \; of \; water}{mass \; ham \; sample} \times 100 \qquad (7.6)$$

The surface colour of the ham samples was measured using a Chromameter (Minolta) using the Hunter Lab Color System: L is the lightness variable, a and b are the chromaticity coordinates. The total color difference is measured in the lab colour system by the following equation: Color difference = $(\Delta L^2 + \Delta a^2 + \Delta b^2)^{0.5}$.

The quality of the samples was evaluated on the basis of their appearance in the package, off-odour, sliminess, and appearance of the ham pieces out of package. Taste evaluation was not conducted in view of the potential health risk.

The pH was not monitored throughout the experiment, since other research has shown that for test periods less than one month there is no significant change in pH of vacuum packaged meats (Korkeala et al.,1987; and Holley et al., 1996). However, the pH was measured (with a hand-held Omron Ph-meter) after 40 days of storage and although there was no statistically significant change in pH there was a definite trend showing a decrease in pH, a decrease however not sufficient to prevent microbial spoilage.

7.3.3. Microbiological Sample Preparation

Samples from the ham packages were prepared by aseptically cutting 10 g from the tip and surface of the ham cores. The 10-g sample was placed in a sterile Stomacher bag with 90 ml of sterile 0.1% peptone in distilled water and mixed for 60 s at high speed in a Stomacher. Necessary decimal dilutions were made in sterile 0.1% peptone water (10^{-1}, 10^{-2}, 10^{-3} and 10^{-4}). Pre-poured duplicate Petri plates were inoculated with 100μL dilutions by spread plating on plate count agar (Difco) and incubating at 35°C for 48 h (Roberts et al., 1995).

After incubation, all colonies were counted on plates containing 300 or fewer colonies. The plates containing fewer than 300 colonies at a given dilution were used to calculate the number of colony forming units per gram of test sample (Roberts et al., 1995):

$$N = C / \{V(n_1 + 0.1n_2)d\} \qquad (7.7)$$

where:

C is the sum of colonies on all plates counted;

V is the volume applied to each plate;

n_1 is the number of plates counted at first dilution;

n_2 is the number of plates counted at second dilution;

d is the dilution from which first count was obtained.

7.3.4. Statistical Analysis

The data collected for total plate counts, colour, and drip loss were analyzed statistically by a 2-factor arrangement in a completely randomized design. The factors were plastic film packages (PP, PE and Nylon) and RF treatment temperatures (75 and 85 °C). The SAS output is presented in Appendix H.

7.4. RESULTS

The first few sample trials indicated that there was a high incidence of arcing in cases where there was fat pockets on the edges of the ham cores. Furthermore, there was high chances of scorching or browning of the edges of the ham samples. This can be explained with the schematic presented in Figure 7.3.

Experimental evidence has demonstrated that the electric field concentrates on the corner of the cylindrical material in a parallel plate configuration. This is because, at the corner there are conflicting boundary conditions that are satisfied by field concentration (Roussy and Pearce, 1995).

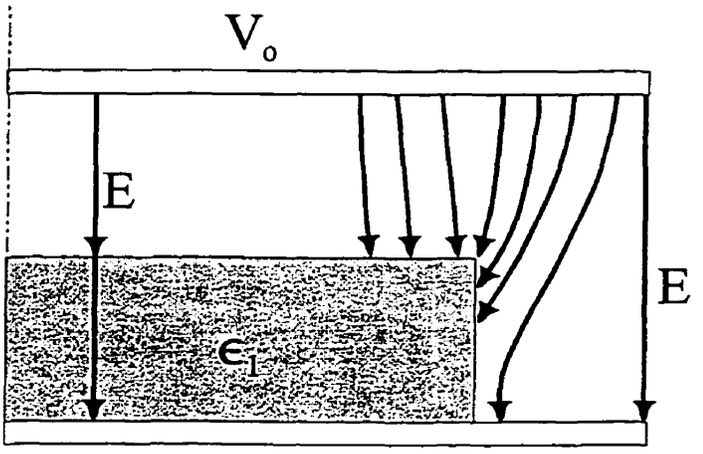

Figure 7.3: Sketch of the electric field concentrations at the corner of a cylindrical shaped material between parallel plates (Roussy and Pearce, 1995).

Typical temperature increase and RF incident power from the generator for the RF treatments studied, are presented in Figures 7.4 and 7.5 for treatments at 75 and 85°C, respectively.

Although up to 600 W was generated by the RF-power source, for ham samples of 30-35 g, only approximately 1 to 2 W/g of material was actually absorbed by the material. Indeed, from equations 7.4 and 7.5, we can calculate the power absorbed by the material. Since there was an airgap of 0.5 cm at the top of the ham sample below the top electrode, there was an important loss of energy through the system. This airgap was necessary due to the presence of arcing between the electrodes when the ham sample was in contact with the grounded electrode. This loss of energy dissipated in the matching box where the water cooling system was registering increases in temperature of up to 8°C.

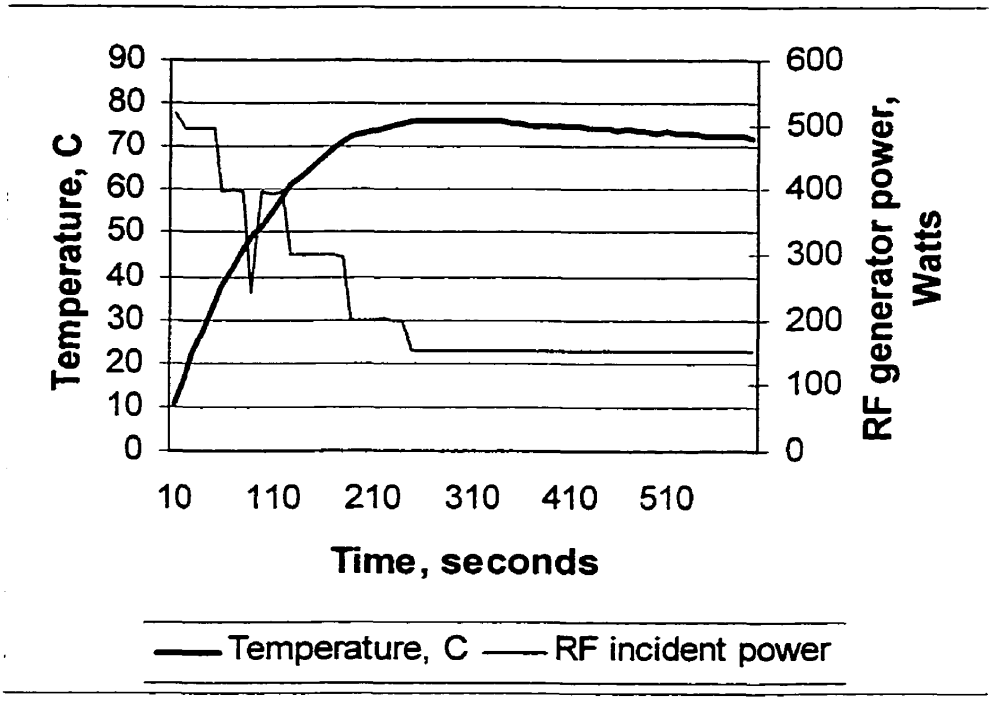

Figure 7.4: Typical temperature rise and incident RF power for ham treated to 75°C.

For treatments at 75 °C, with the measurement of the electrode voltage monitored by our data-acquisition system, the power absorbed by the material was on average around 1.07 W/g, and for treatments at 85 °C, the power absorbed by the material was on average around 1.83 W/g. We can see in Figures 7.4 and 7.5, that the target temperature was reached within the first 5 min (around 4 min), and the temperature was maintained at the set value for an additional 5 min for a total treatment duration of 10 min.

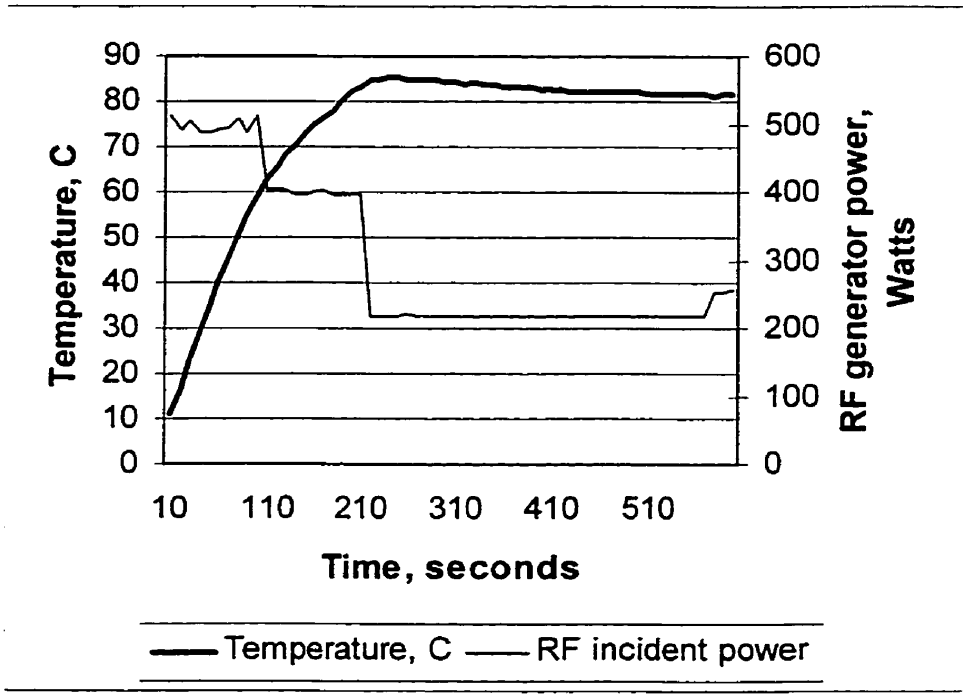

Figure 7.5: Typical temperature rise and incident RF power for ham treated to 85°C.

The results of the microbiological study (total plate counts) are presented in Figures 7.6 to 7.10. The effects of the different packaging materials on the colony forming units (CFU) per gram of ham are presented in Figure 7.6, for RF-treatments at 75 °C and in Figure 7.7, for RF-treatments at 85 °C. The packaging material had little effect on the CFU/g for the first three weeks of storage. The statistical analysis of the results did not show a significant difference in the microbial counts affected by the different plastic films with the exception of the 28-day results which yielded that the polypropylene (PP) films had a slower increase in the total counts towards the end of the storage period. The PP film maintained the CFU below 10^7.

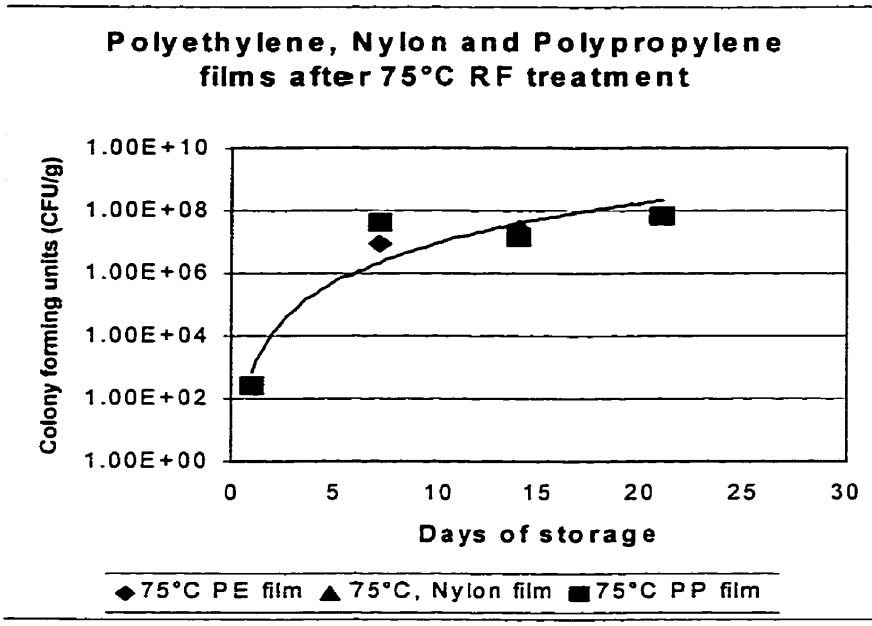

Figure 7.6: Effect of the types of plastic membrane on the resulting total microbial counts over 1 to 21 days of storage after RF treatments at 75°C.

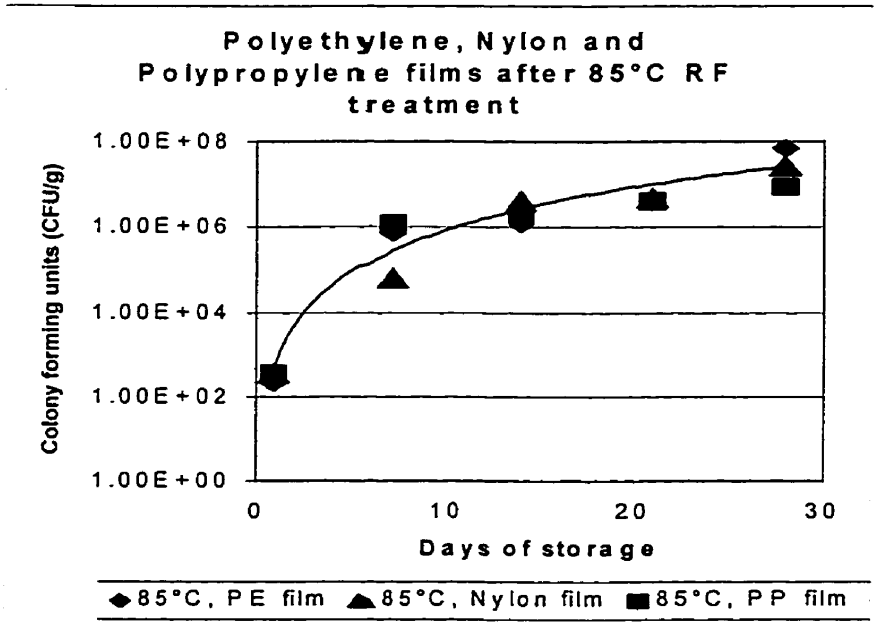

Figure 7.7: Effect of the types of plastic membrane on the resulting total microbial counts over 1 to 28 days of storage after RF treatments at 85°C.

As the statistical analysis demonstrates (Appendix H) the microbial counts were significantly influenced by the treatment temperatures of 75 or 85°C ($p<0.0001$) and by the numbers of days in storage ($p<0.0001$). There was no significant difference in total microbial counts which can be attributed to the different plastic membranes.

The total microbial counts can be predicted with a power regression model as a function of storage time in days (d). The power regression models for ham RF-treated at 75°C and 85°C, regardless of the type of plastic packaging, are graphically presented in Figures 7.6 and 7.7, yielding the following equations for 75°C RF-treated ham ($R^2=0.9058$):

$$Microbial\ Count = 671.11\, d^{4.1601} \tag{7.8}$$

and for 85°C RF-treated ham ($R^2=0.9776$):

$$Microbial\ Count = 423.39\, d^{3.3106} \tag{7.9}$$

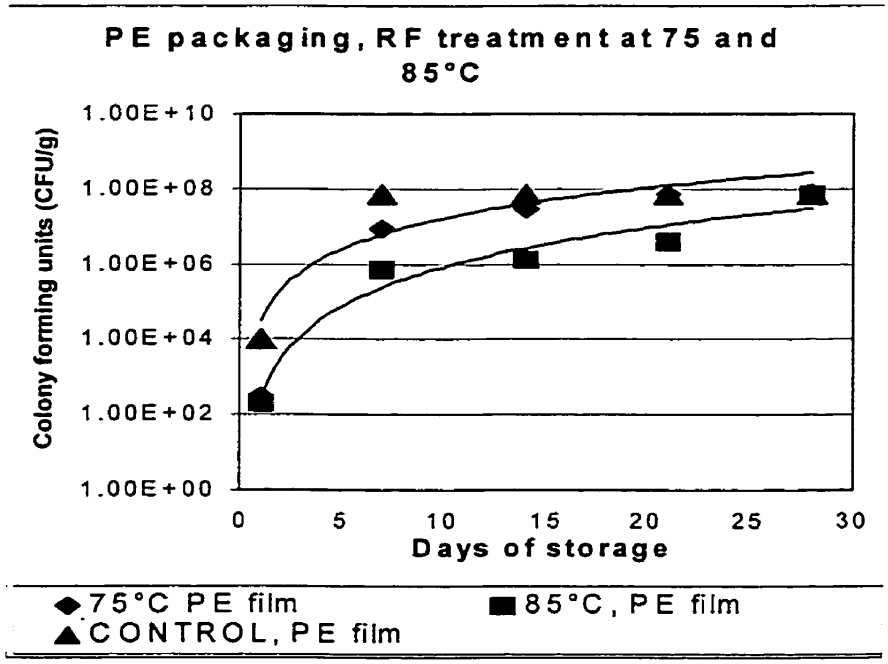

Figure 7.8: Microbial counts for RF-treated ham at 75 and 85°C compared to control samples, vacuum packed in Polyethylene film.

The microbial counts of RF-treated ham samples at 75 and 85°C vacuum packaged in PE film are presented in Figure 7.8. The analysis of the results indicates that there is a significant difference in microbial counts between control samples and ham sample RF-treated at 75°C and 85°C up to 21 days of storage. After 21 days, the control and RF-treated (75°C) ham samples had total microbial counts exceeding the set limit of our dilutions (a limit of 7×10^7 CFU/g) which does not allow us to differentiate between the results. However, the RF-treated samples at 85°C maintained total counts significantly lower until 21 days of storage, and below the target set limit of 10^7. The PE film failed to maintain the CFU of RF-treated ham (85°C) below 3×10^7, beyond 21 days of storage. The RF treatment significantly reduced the CFU/g throughout the storage period tested when compared to non-treated samples. The control samples reached CFU/g well above 7×10^7 after 21 days of storage and had a CFU/g of 2.5×10^7 after only 7 days. Treatments at 75°C failed to improve the microbial safety past 14 days for all types of packaging materials, hence they were not stored past 21 days. Here again the microbial counts can be modeled with a power regression expressing microbial counts (CFU/g) as a function of days of storage for PE plastic.
For control (non-treated) ham vacuum packed in PE film the power regression yields (R^2=0.8471):

$$Microbial\ Count = 31094\ d^{2.7187} \tag{7.10}$$

and for 85°C RF-treated ham stored in PE film the power regression yields (R^2=0.9613):

$$Microbial\ Count = 263.02\ d^{3.4909} \tag{7.11}$$

Total microbial counts for RF-treated ham at 85°C and vacuum packed in Nylon film are presented in Figure 7.9. The RF treatment significantly maintained the total counts lower than for the control samples throughout the storage period of 28 days with the RF-treated ham still having an acceptable level of microorganisms according to tolerable limits ($<3 \times 10^7$ CFU/g).

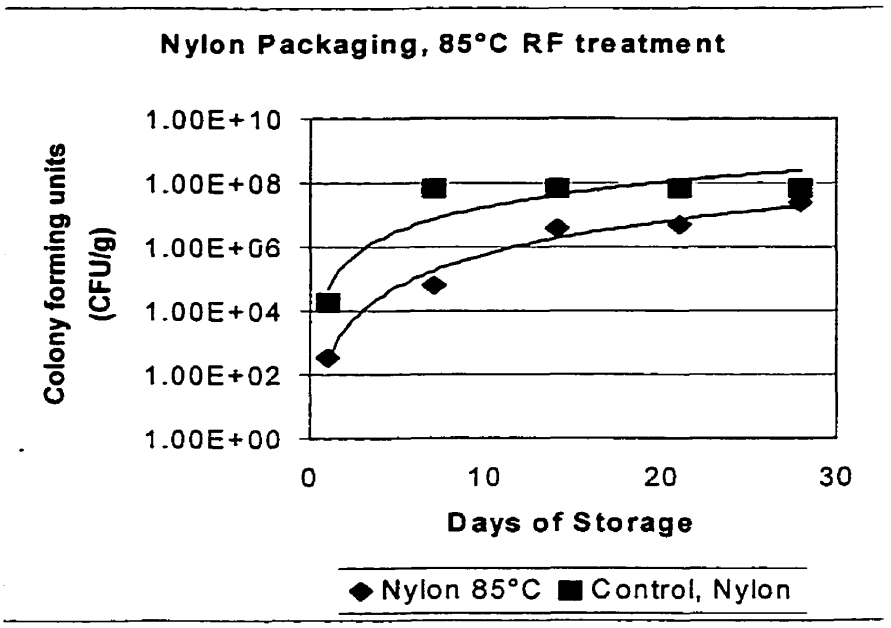

Figure 7.9: Microbial counts for RF-treated ham at 85°C compared to control samples, vacuum packed in Nylon film.

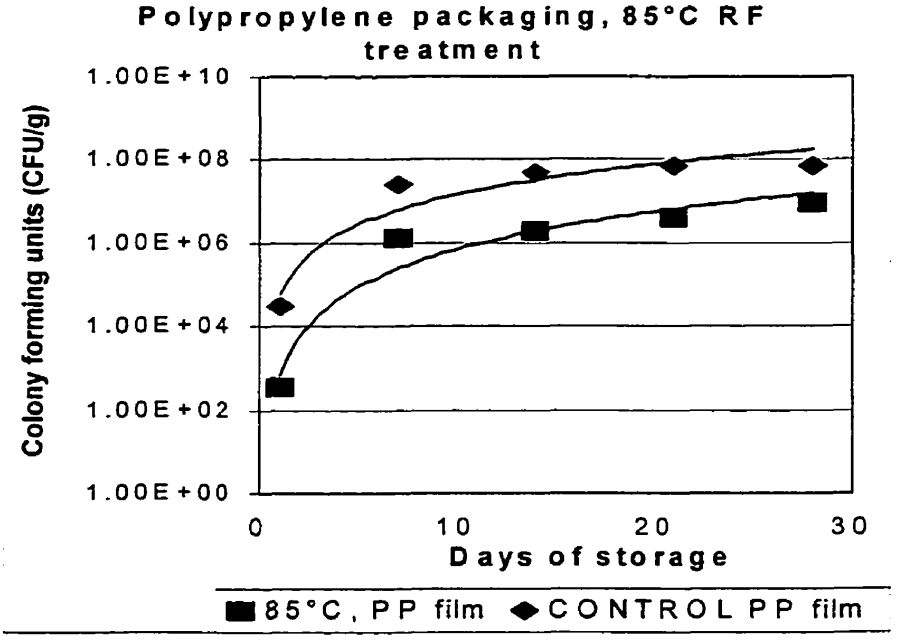

Figure 7.10: Microbial counts for RF-treated ham at 85°C compared to control samples, vacuum packed in Polypropylene film.

Here again the microbial counts can be modeled with a power regression expressing microbial counts (CFU/g) as a function of days of storage for Nylon plastic packaging. For control (non-treated) ham vacuum packed in Nylon film the power regression yields (R^2=0.8471):

$$Microbial\ Count = 53536\, d^{2.5273} \tag{7.12}$$

and for 85 °C RF-treated ham stored in Nylon film, the power regression yields (R^2=0.9754):

$$Microbial\ Count = 273.13\, d^{3.3425} \tag{7.13}$$

The microbial counts for RF-treated ham at 85 °C and vacuum packed in polypropylene film are presented in Figure 7.10. Here again, the RF treatment significantly maintained the total counts lower than for the control throughout the storage period with final total counts being the lowest of all treatments below 1×10^7. Polypropylene packaging offered the best long term protection against the development of micro-organisms in vacuum packaging due to its low oxygen permeability.
For control (non-treated) ham vacuum packed in PP film the power regression yields (R^2=0.9230):

$$Microbial\ Count = 57736\, d^{2.4072} \tag{7.14}$$

and for 85 °C RF-treated ham stored in PP film, the power regression yields (R^2=0.9452):

$$Microbial\ Count = 679.79\, d^{3.0019} \tag{7.15}$$

Results of the colour measurements and appearance, odour and sliminess evaluation are given in Table 7.2. The colour measurements with the Minolta Chromameter did not yield any trend or variations in colour parameters (L, a, and b) which could be correlated to treatment combinations. There was no statistically detectable difference in colour from all samples (Appendix H). There was however a detectable difference in colour made during the evaluation of the samples, with ham samples stored for 28 days in PE film. On these samples there was a noticeable whitish discoloration of the edges. Otherwise, with respect

to colour, all other samples, control and RF-treated, remained appetizing including the ham samples which experienced some level of scorching and browning from the RF-field.

The results of the quality assessment, presented in Table 7.2, indicate that the quality of the samples was maintained for all treatment combinations until 21 days of storage, except for the control in PE and Nylon films where a slight off-odour was perceived from the samples. In the polypropylene film, the quality of the sample was maintained for both RF-treated and control for up to 21 days. For the 28-days storage, the quality of the samples were maintained for RF-treated (85°C) ham packed in Nylon and Polypropylene. A strong acidic off-odour developed in all non-treated sample packages in PE and Nylon after 28 days. RF-treated (85°C) ham samples had a good overall appearance except for PE packed samples which experienced a light discoloration and a light acidic off-odour. No sample experienced the development of a slimy film on its surface.

Drip losses are presented in Figures 7.11-7.14. Significantly lower drip losses were obtained with RF-processing than with non-treated samples. From visual inspection of the ham samples, the RF treatments dried the surface of the ham samples which may have helped to reduce the tendency to experience drip losses during packaged storage when compared to their control counterpart. The type of packaging material also influenced significantly the drip loss from the ham samples as can be seen in Figure 7.14 and in the SAS output in Appendix H ($p<0.0001$). The highest drip losses were experienced with the polypropylene vacuum packed ham since polypropylene film had the lowest moisture permeability characteristic of all packaging used. This high free water content in the packages did not influence the quality of the samples with respect to microbial counts and overall quality since, PP packed ham samples had the best results overall with lowest microbial counts after 28 days and best sample quality with respect to appearance and odour.

Drip losses were maintained constant throughout the storage period for RF-treated samples stored in Polyethylene and Nylon films, whereas the samples stored in Polypropylene film and all control samples (in all types of bags) had drip losses increasing with the increase in storage time with a significant effect of time ($p<0.0001$).

Table 7.2: Colour measurements, appearance, odour and sliminess.

	Treatment	Hunter Colour			Appearance, odour, sliminess
		L	a	b	Comments
1 day PE	75°C RF	53.65	15.06	6.63	Good overall
	85°C RF	63.33	12.74	8.11	Good overall
	Control	60.94	12.38	6.12	Good overall
1 day Nylon	75°C RF	53.43	15.64	6.60	Good overall
	85°C RF	58.29	14.06	7.13	Good overall
	Control	59.69	13.64	6.37	Good overall
1 day PP	75°C RF	59.20	11.35	5.85	Good overall
	85°C RF	56.11	15.24	7.13	Good overall
	Control	57.65	13.96	6.19	Good overall
7-days PE	75°C RF	52.29	13.83	6.98	Good overall
	85°C RF	56.45	11.12	5.69	Good overall
	Control	60.82	13.14	6.54	Good overall
7-days Nylon	75°C RF	49.32	16.59	6.59	Good overall
	85°C RF	56.72	12.24	5.96	Good overall
	Control	61.04	13.08	6.58	Good overall
7-days PP	75°C RF	59.06	13.26	6.71	Good overall
	85°C RF	55.28	14.61	6.91	Good overall
	Control	63.72	10.99	6.86	Good overall
14-days PE	75°C RF	56.09	12.95	6.20	Good overall
	85°C RF	52.96	14.91	7.33	Good overall
	Control	57.88	12.77	5.95	Good overall
14-days Nylon	75°C RF	49.95	16.75	6.90	Good overall
	85°C RF	54.14	15.31	7.01	Good overall
	Control	56.13	13.45	6	Good overall
14-days PP	75°C RF	55.86	14.02	6.75	Good overall
	85°C RF	55.33	13.94	6.8	Good overall
	Control	56.76	13.43	6.45	Good overall, small loss vacuum, watery
21-days PE	75°C RF	58.27	13.06	6.81	Good overall,
	85°C RF	57.89	11.67	6.45	Good overall,
	Control	60.78	11.38	6.13	Good overall, small loss vacuum, off odour
21-days Nylon	75°C RF	59.25	12.8	6.72	Good overall
	85°C RF	52.99	13.96	5.95	Good overall
	Control	58.37	12.85	5.8	Good overall, slight off odour
21-days PP	75°C RF	59.21	12.76	6.77	Good overall
	85°C RF	50.59	14.42	5.82	Good overall
	Control	59.42	11.89	6.25	Good, loss of vacuum, water accumulation
28-days PE	85°C RF	58.67	9.89	6.47	Good overall, light white discoloration
	Control	59.21	12.89	7.64	Good appearance with strong off-odour
28-days Nylon	85°C RF	59.18	12.32	7.3	Good overall
	Control	59	13.49	6.78	Strong off-odour with loose package
28-days PP	85°C RF	53.38	14.45	6.43	Good overall, watery accumulation
	Control	53.33	15.21	7.06	Soft texture, loose package, off-odour, watery

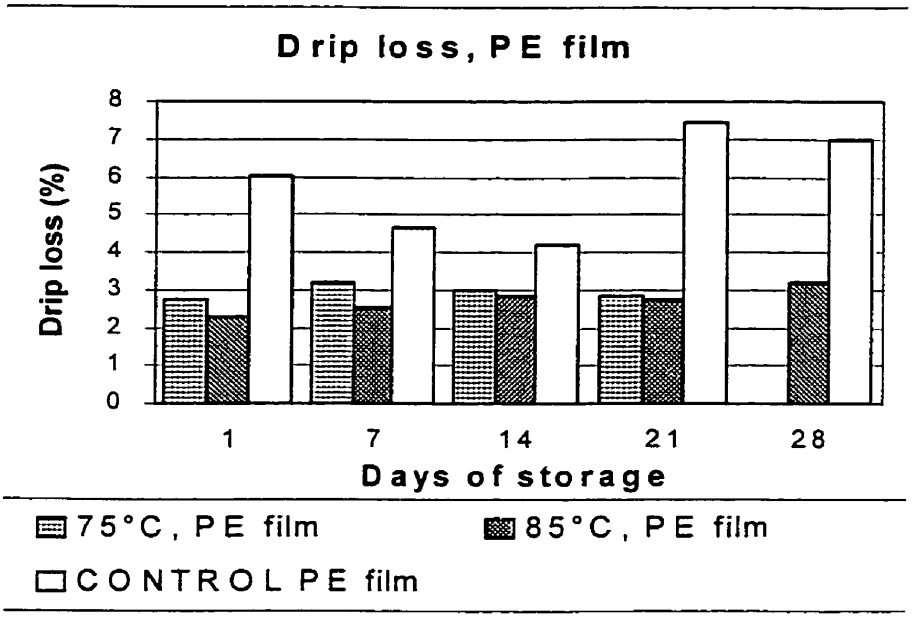

Figure 7.11: Percent drip loss of RF-treated and control ham vacuum packed in Polyethylene film

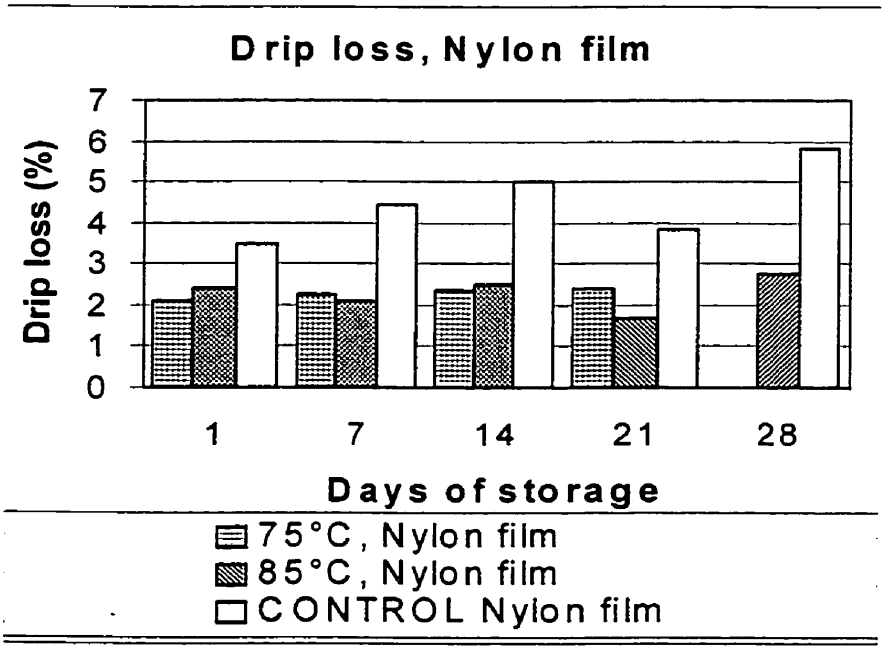

Figure 7.12: Percent drip loss of RF-treated and control ham vacuum packed in Nylon plastic film.

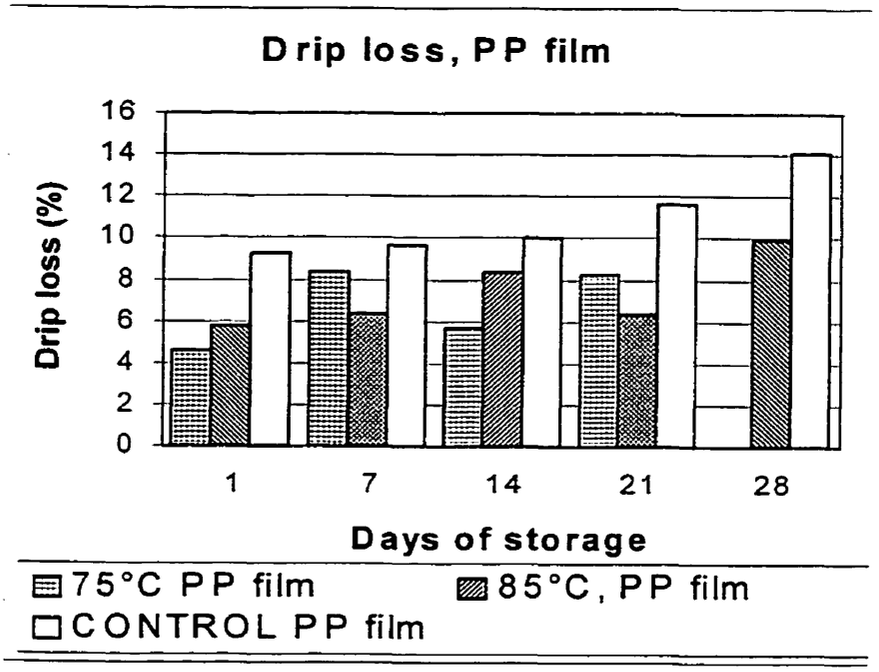

Figure 7.13: Percent drip loss of RF-treated and control ham vacuum packed in Polypropylene plastic film.

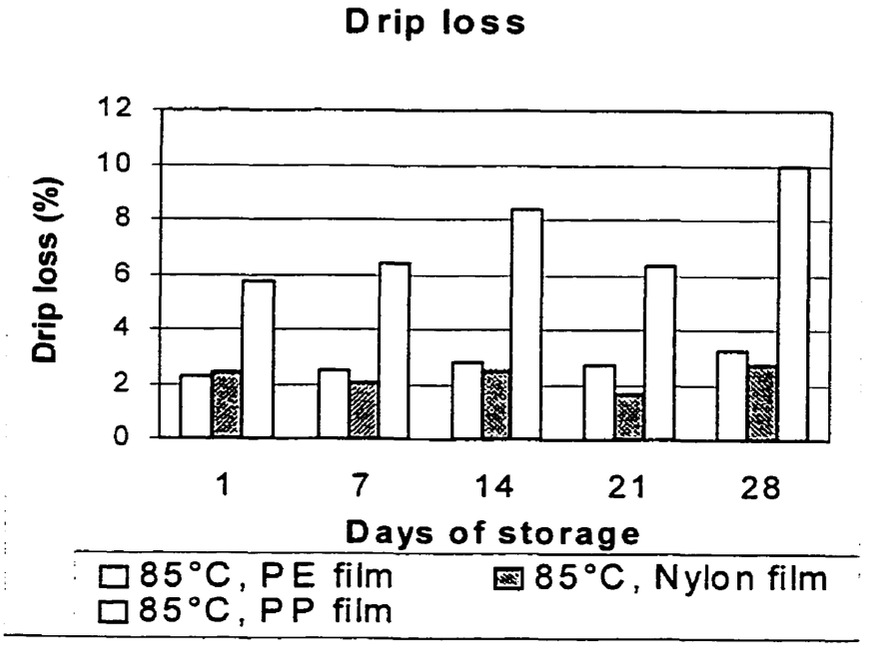

Figure 7.14: Percent drip loss of RF-treated ham (85°C) in three different plastic films under vacuum.

7.5. DISCUSSION AND CONCLUSION

High initial numbers of bacteria are normally associated with shorter shelf-lives, but cooked cured meats may be slightly different when packed in the anaerobic environment of a gas impermeable vacuum package where curing salts and low O_2 interact to facilitate the dominance by lactic acid bacteria during refrigerated storage. Growth of lactic acid bacteria can protect vacuum packed processed meats from the growth of pathogenic bacteria through the production of anti-microbial compounds (Holley et al., 1996).

The vacuum packed ham stored at refrigerated temperatures have significant sensory appeal even when the dominant lactic acid bacteria reach numbers in excess of 10^8 g^{-1}. It is evident that, when the O_2 permeability of the packaging film is higher, consumer-detectable spoilage takes place at lower numbers of bacteria. Spoilage of these products cannot be related easily to the number of bacteria present because of the localization of bacterial growth at product surfaces and because the dominating lactic acid bacteria are non-proteolytic, fermentative types with low spoilage potential under anaerobic refrigerated storage conditions.

Vacuum-packed processed meats, are a special category of product where the declaration of a maximum for bacterial numbers can be impractical because these products are essentially the result of an acceptable lactic acid bacteria food fermentation, (leading to the exclusion of bacterial pathogens) provided that refrigerated conditions and vacuum (low O_2) conditions are maintained.

In view of our results, it is clear that the type of organisms which develop in these products during refrigerated storage would be more important to predict shelf-life, rather than just the total number of bacteria which developed. In vacuum packs, the number of lactic acid bacteria are frequently very high (> 8 log CFU/g) before signs of spoilage become visible as was the case in this study. Nonetheless, RF-heating at 85°C did help reduce the total number of bacteria and it helped maintain the ham quality for 28 days in high barrier plastic films (Nylon, Polypropylene and Polyethylene) under vacuum and refrigeration.

CHAPTER VIII - SUMMARY AND CONTRIBUTIONS TO KNOWLEDGE

8.1. SUMMARY

Radio-frequency heating has been used in a few industrial processes for many years. It has a number of advantages over other processes such as the volumetric dissipation of energy and the ability to level out moisture gradients. However, it also has some limitations, mainly technical and economical. It is generally true to say that RF techniques have only been justified in processes involving material of high value or that cannot be processed by other means.

The future of RF heating surely lies within applications in drying and in "cooking" or pasteurizing of cooked food products, rather than in the treatment of fresh-like or heat sensitive materials for phytosanitary and pasteurizing purposes. Although RF heating is rapid, in comparison with conventional means of heating such as air, steam or water, it is not rapid enough to efficiently thermal treat without a detrimental effect on the quality of the commodity, whether it is the viability of seeds or the quality of fresh foods.

Globalization of worldwide markets with all the varying sanitary control and regulations for stocks of feed and foodstuffs are emphasizing the importance of physical methods to protect, in an environmental friendly way, our agricultural and food products. The growing public concern about the health hazards associated with pesticides and chemical preservatives has intensified the research for alternative means and methods of handling.

To increase the interest in the use of microwave and radio frequency power in industrial applications, the price ratio of a kWh of fossil fuel to a kWh of electricity must favour electricity. Currently, the ratio is 1:4 and as high as 1:10 in the case of gas. Only with a decrease in electricity costs or with the promotion of the long term advantages of clean energy sources (electric power from renewable resources such as wind, hydro and solar power), can the future of industrial applications of microwave and high frequency heating be assured (Van Loock, 1997a). Furthermore, pollution of our atmosphere as a result of fossil

fuel combustion raises the threat of global warming and signals the beginning of the end of the fossil fuel era as we know it today.

The investment costs of microwave and radio-frequency for industrial applications are still quite prohibitive. However, the increasing demand for cleaner and more energy efficient processing technologies will force the capital costs to go down in the near future. Van Loock (1997b), summarized the investment cost for different techniques (Table 8.1)

Table 8.1: Investment cost and energy consumption for different sources of heat (Van Loock, 1997b).

Technique	Investment Cost US $/kg·h	Energy Consumption specific electric consumption kWh/kg
Mechanical	50	0.1
Convection	250	0.2
Infrared	25	1.2
Heat pump	500	0.3
High frequency	1500	1.75
Microwaves	2500	1.75
915 MHz	2000	1.5

Under adequate conditions, RF-heating can allow rapid heating throughout a material without temperature gradient provided that the equipment has been optimally designed for the material being processed, that the electric field is homogeneous (proper applicator design with adequate electrode configuration) and that the sample is homogeneous. In practice this is difficult to achieve, especially if the RF system designed is meant for laboratory research destined to work with a variety of different products and commodities. However, for any designed RF system destined for a targeted processing plant, it is likely that all operating parameters can be optimized so that operations can be stabilized rendering the development of any application worth the while.

Product niches are calling for radio-frequency and microwave applications. For example, pasteurization of ready-meals by microwave or radio-frequency may not be able to produce better product than other preservation methods but the potential is there for a broad spectrum of shelf stable products of very high quality, convenience, and high market value that consumers want. Further research is needed for controlling processes and assuring

proper product safety.

8.2. CONTRIBUTION TO KNOWLEDGE

The work presented here has made an original contribution to the body of knowledge surrounding the development of applications of radio-frequency heating in the agricultural and food sectors. The main contributions are:

1) The design considerations of RF-applicators have been identified and summarized for the benefit of future potential applications' development.
2) The impact of increased ionic conductivity on the improvement of power coupling in an RF applicator was investigated. The addition of table salt to wheat kernels can improve the energy transfer from the RF generator to the loaded applicator. The impact of salt addition on product temperature, RF power matching and electrode voltage behaviour has been reported.
3) The potential of RF heating for disinfecting wheat seed infected with *Fusarium graminearum* was investigated. Results are presented relating decreased fungal vigour with maintenance of seed germination vigour.
4) RF thermal treatment was investigated with impermeable coat soybean seeds to determine the treatment potential for seed priming and reducing hard seed incidence.
5) X-ray analysis of RF-treated wheat seeds was conducted to better understand the process of crack development related to RF treatment intensity and loss of germination.
6) RF-treatment of carrots was investigated as a means of improving the shelf life of minimally processed ready to eat carrot sticks. Although the experiment carried out did not improve the shelf life, the RF-treatments did show that it was possible to rapidly (less than 2 minutes) heat treat carrot sticks, to reduce the initial microbial load, and to improve the overall appearance of stored carrot sticks.
7) RF-treatment of ham was investigated as a potential means of processing ready to eat ham, prior to vacuum packaging for the retail outlet. The investigation has demonstrated that an RF treatment can effectively reduce the initial microbial load prior to

packaging. However, a thermal treatment alone may not be sufficient to ensure the long term quality and safety of ready-to eat produce. Packaging material, temperature of storage, handling practices, etc., are all important components involved in product shelf-life.

8.3. FUTURE WORK

Although a temperature treatment can function efficiently in the laboratory, it may not operate commercially as expected because of problems related to scale. These problems are acute for heat treatments because heat treatments are short and they may leave areas of lower temperature where the intended thermal inactivation will not have been successful. Future work in this area should certainly investigate the larger scale potential and feasibility. On the other hand, RF may not be the most suitable frequency range for microbial inactivation purposes alone, but rather as a complimentary source of heat in many thermal applications. Future research work would certainly gain from investigating conventional thermal processes and their re-design to implement RF energy as a supplemental source of heat.

There is a growing interest from the food industry for mild heat treatment methods that can offer sufficient heat to ensure microbiological safety and mild enough to maintain product quality. Process optimization and automated control of RF techniques are potential candidates for these mild heat industrial applications.

The future promises abundant electric power from renewable sources (hydro-power, wind-power, solar power, etc.), which will favour the use of electro-technologies in processing. Essential basic research must be carried to develop various applications of microwaves and radio-frequency in thermal processing of agricultural and food products to ensure market growth, competitiveness and the abundance of fresh, safe and high quality produce. Any technology which may extend shelf life and product safety is worth investigating further.

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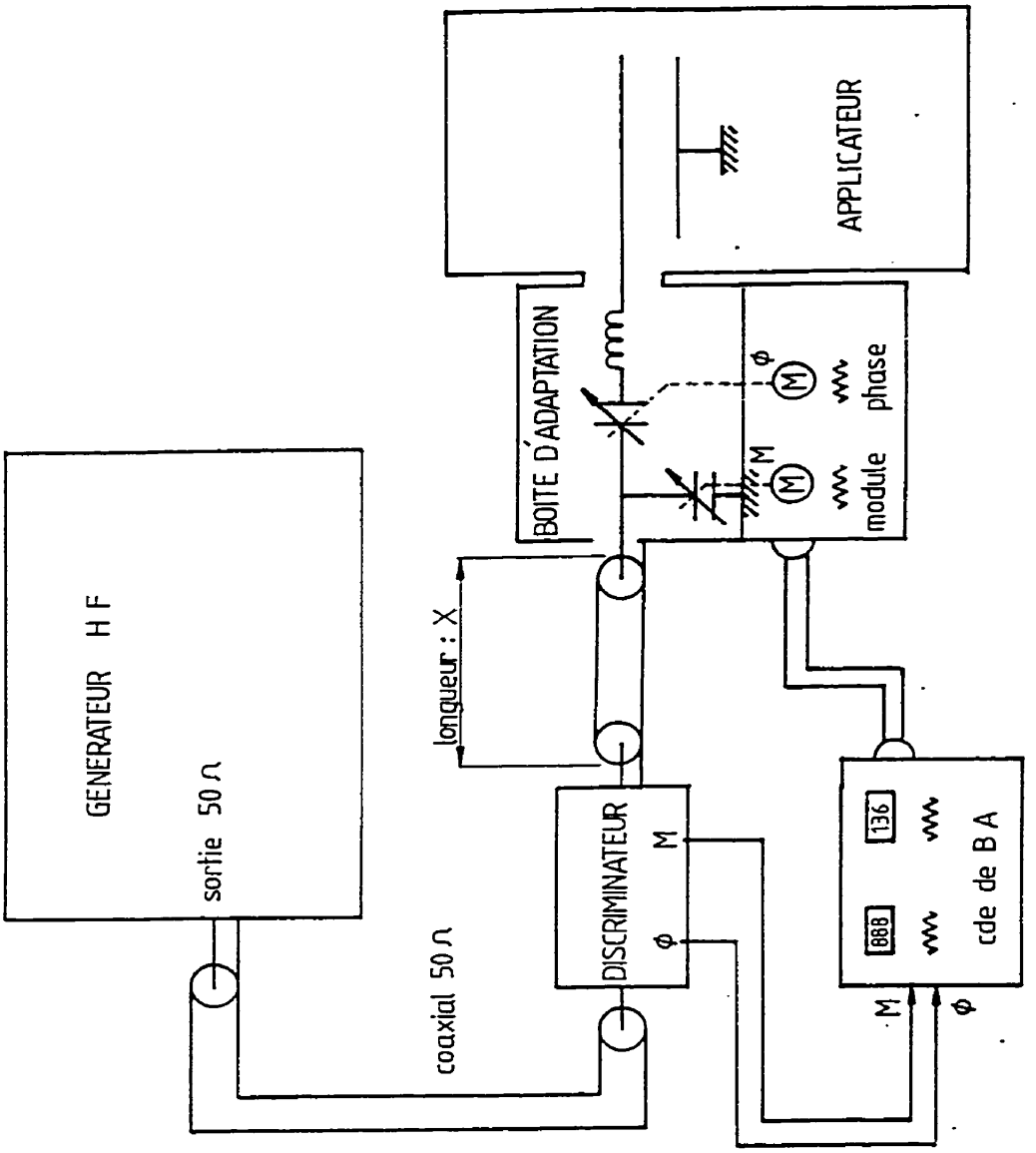
APPENDIX A

Schematic of 50 Ω installation from SAIREM

Appendix A: 50 Ω RF installation from SAIREM.



SYNOPTIQUE
INSTALLATION H F 50 Ω

Modifications
a
b
c

SAIREM
22, avenue Albert Einstein
b.p. 6043
69604 VILLEURBANNE CEDEX
tél. 78.94.02.30

Matière : | ech:

Client: STANDARD

Date: 06-90

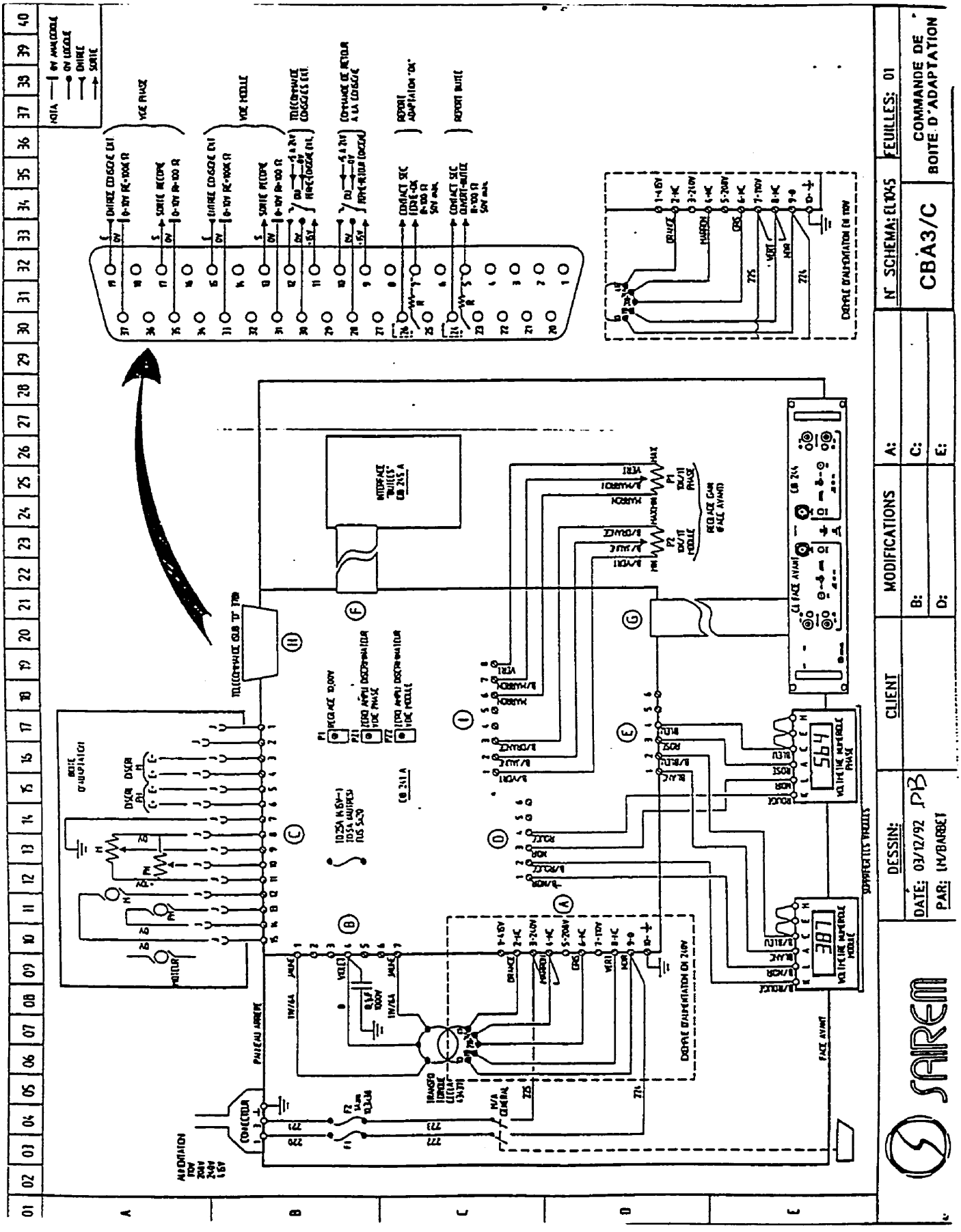
Dessin: PIATKO

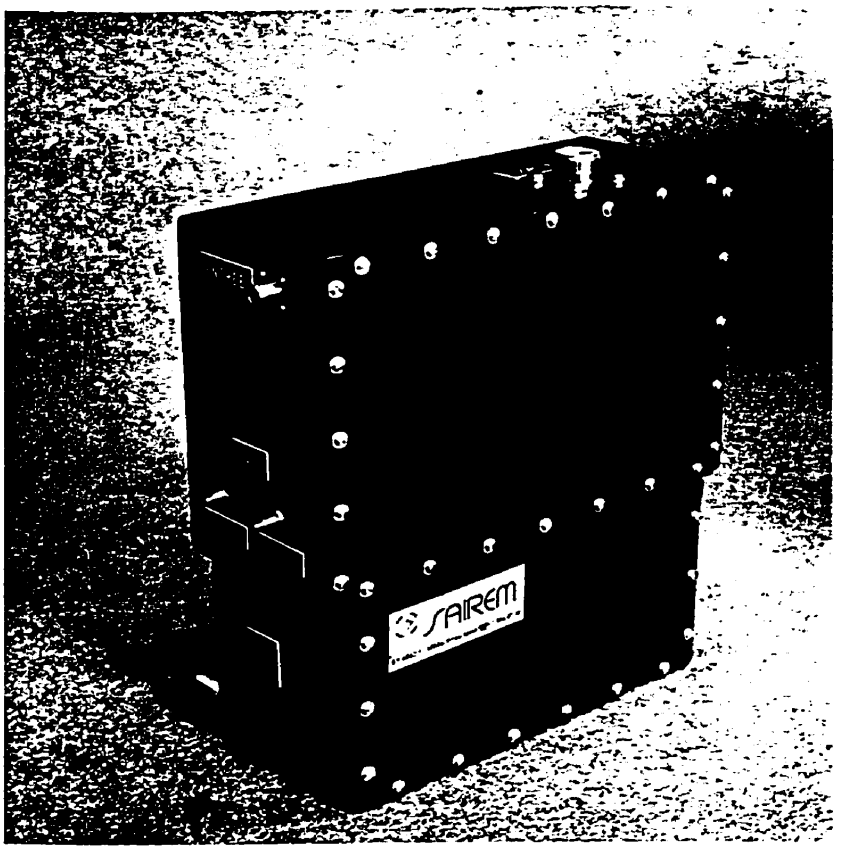
APPENDIX B

- Schematic of Matching Network System

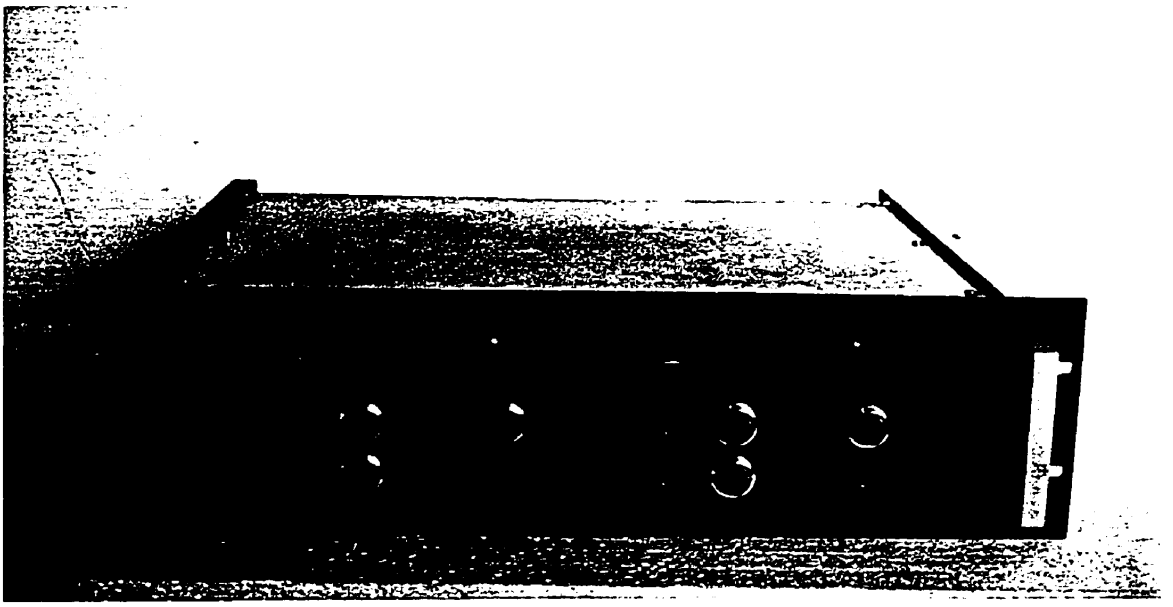
- Photographs of matching box and control

Appendix B: Matching Network.





Photograph of Matching Box

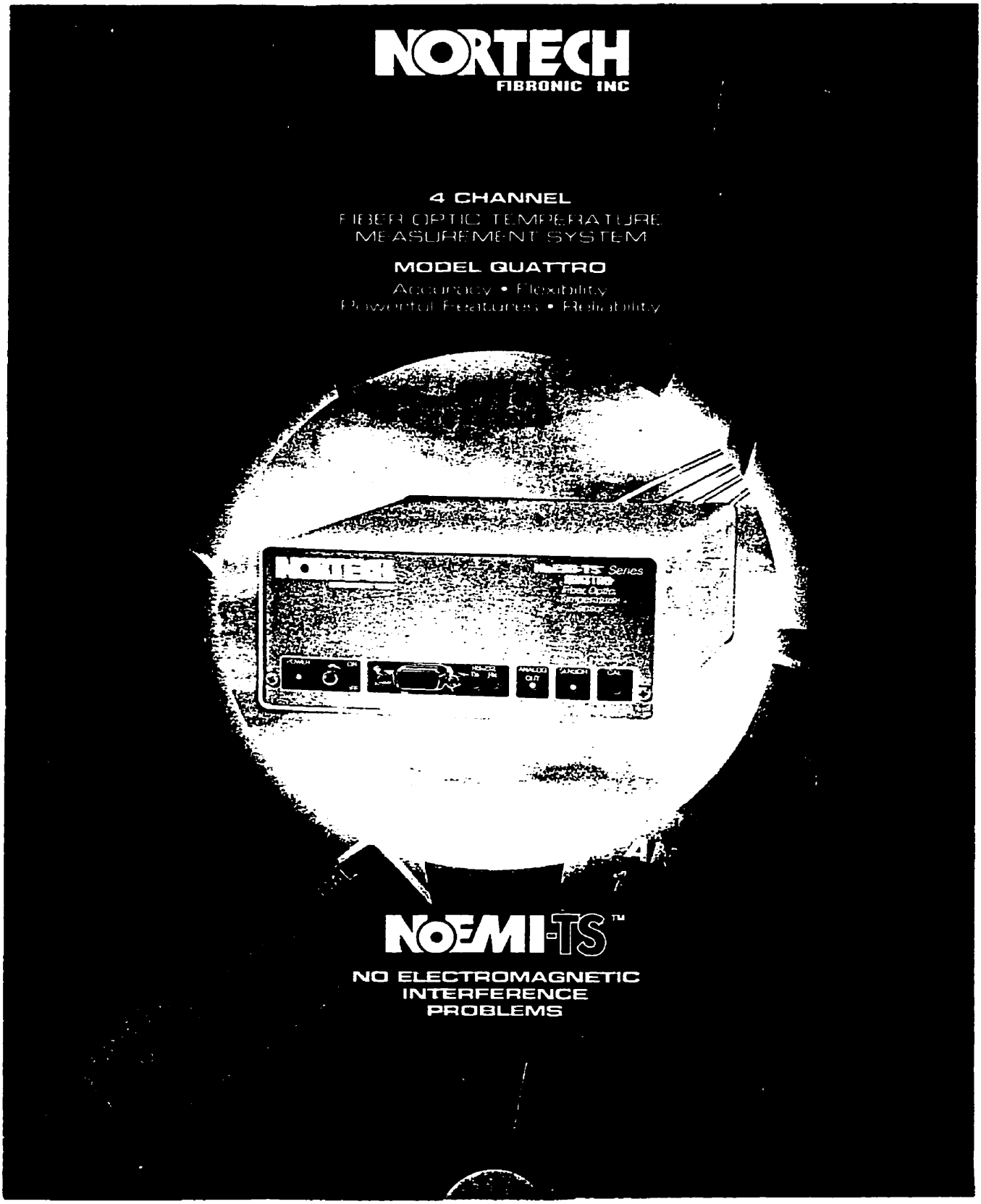


Photograph of Matching Box Control

APPENDIX C

Fiberoptic temperature measurement system and specifications

Appendix C: Fiberoptic temperature measurement system by Nortech Fibronic Inc.



Appendix C: Specifications of the Fiberoptic temperature measurement system.

NoEMI-TS Product Specifications

NoEMI-TS Transducer Product Specifications

Resolution	0,1°C
Accuracy	The greater of 1°C or 1% of reading plus 0.003 °C per meter of fiber
Temperature Range	-60° to 250°C (probe dependent)
Number of channels	1
Response time	Typically 0.5 to 1.0 second (probe configuration dependent)
Unit	User selection of °C or °F
Operating temperature	0° to 50°C
Storage temperature	-20° to 60°C
Local display*	Display of channel number and temperature readings as well as various user information.
Power	15 to 24VDC (see note below, front panel item #10)
Size	228L x 140W x 65D mm
Weight	1.2 kg
Standard interface	RS-232C Analog output* (4-20mA**, 0-20mA**, 2-10V, 0-10V, 0-5V or 1-5V)
Sensor	Dielectric epoxy tipped optical fiber

NoEMI-TS Quattro Product Specifications

Resolution	0,1°C
Accuracy	The greater of 1°C or 1% of reading plus 0.003 °C per meter of fiber
Temperature Range	-60° to 250°C (probe dependent)
Number of channels	4
Response time	Typically 0.5 to 1.0 second per enabled channel (probe configuration dependent)
Unit	User selection of °C or °F
Operating temperature	0° to 50°C
Storage temperature	-20° to 60°C
Local display*	Display of channel number and temperature readings as well as various user information.
Power	15 to 24VDC (see note below, front panel item #10)
Size	228L x 140W x 65D mm
Weight	1.3 kg
Standard interface	RS-232C Analog output* (4-20mA**, 0-20mA**, 2-10V, 0-10V, 0-5V or 1-5V)
Sensor	Dielectric epoxy tipped optical fiber

*: Selection must be made at time of order.
**: Note that the 20 mA analog output options are self-powered type interfaces (by opposition to loop-powered type interfaces), and thus do not require any external supply.

APPENDIX D

SAS output for analysis of salt addition to wheat kernels

Appendix D: Statistical analysis of salt addition

ANALYSIS OF IONIC CONDUCTION WITH SALT

OBS	S	V	T
1	1	4265.11	16.160
2	1	4255.56	21.637
3	1	4261.28	27.487
4	1	4242.30	34.270
5	1	4232.89	40.263
6	1	4217.94	46.747
7	1	4216.10	53.313
8	1	4208.53	60.223
9	1	4182.36	67.840
10	1	4149.17	75.453
11	1	4138.13	83.770
12	1	4118.20	92.937
13	1	4092.78	101.453
14	1	4071.26	108.843
15	1	4060.48	113.567
16	1	4016.30	115.980
17	2	4215.42	15.530
18	2	4217.33	21.523
19	2	4207.94	27.893
20	2	4202.38	34.227
21	2	4178.14	41.093
22	2	4163.36	48.140
23	2	4154.19	55.487
24	2	4135.81	63.217
25	2	4103.10	71.007
26	2	4077.92	80.357
27	2	4052.86	89.917
28	2	4012.23	98.280
29	2	3996.48	105.100
30	2	3961.77	111.157
31	2	3925.70	115.207
32	2	3859.98	117.820
33	3	4177.88	17.403
34	3	4192.89	24.160
35	3	4198.34	30.973
36	3	4202.07	37.660
37	3	4196.53	44.710
38	3	4189.02	52.307
39	3	4168.61	60.463
40	3	4139.38	68.173
41	3	4122.90	76.690
42	3	4101.39	86.187
43	3	4081.74	96.880
44	3	4031.76	104.473
45	3	4001.85	109.913
46	3	3960.67	113.567
47	3	3929.89	118.160
48	3	3855.72	121.343
49	4	4157.58	15.720
50	4	4161.27	22.903
51	4	4161.28	29.840
52	4	4139.23	36.763
53	4	4126.44	43.777
54	4	4124.64	50.873
55	4	4104.64	58.503
56	4	4065.09	66.703
57	4	4043.74	75.183
58	4	4003.21	86.020
59	4	3959.79	97.733
60	4	3927.18	108.120
61	4	3905.13	115.837

OBS	S	V	T
62	4	3851.34	118.630
63	4	3777.47	120.233
64	4	3680.14	122.470

ANALYSIS OF IONIC CONDUCTION WITH SALT Temperature effect

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
S	4	1 2 3 4
V	64	3925.7 4103.1 3927.18 3996.48 4001.85 4031.76 4052.86 4060.48 4065.09 4071.26 4077.92 4081.74 4124.64 4161.28 4177.88 4202.07 4208.53 4217.33 4255.56 3680.137 3777.467 3851.337 3855.717 3859.977 3905.133 3929.887 3959.787 3960.667 3961.767 4003.213 4012.233 4016.297 4043.743 4092.777 4101.387 4104.643 4118.203 4122.903 4126.443 4135.813 4138.133 4139.233 4139.383 4149.167 4154.187 4157.577 4161.267 4163.357 4168.607 4178.143 4182.363 4189.017 4192.887 4196.533 4198.343 4202.377 4207.943 4215.423 4216.103 4217.937 4232.887 4242.297 4261.283 4265.107
T	63	105.1 15.53 15.72 16.16 24.16 29.84 34.27 37.66 44.71 48.14 67.84 76.69 83.77 86.02 96.88 98.28 108.12 115.98 117.82 118.16 118.63 122.47 101.4533 104.4733 108.8433 109.9133 111.1567 113.5667 115.2067 115.8367 120.2333 121.3433 17.40333 21.52333 21.63667 22.90333 27.48667 27.89333 30.97333 34.22667 36.76333 40.26333 41.09333 43.77667 46.74667 50.87333 52.30667 53.31333 55.48667 58.50333 60.22333 60.46333 63.21667 66.70333 68.17333 71.00667 75.18333 75.45333 80.35667 86.18667 89.91667 92.93667 97.73333

Number of observations in data set = 64

ANALYSIS OF IONIC CONDUCTION WITH SALT Temperature effect

Analysis of Variance Procedure

Dependent Variable: T

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	528.3666360	176.1222120	0.14	0.9361
Error	60	75827.1021084	1263.7850351		
Corrected Total	63	76355.4687444			

R-Square	C.V.	Root MSE	T Mean
0.006920	50.69179	35.54975	70.12922

Source	DF	Anova SS	Mean Square	F Value	Pr > F
S	3	528.3666360	176.1222120	0.14	0.9361

ANALYSIS OF IONIC CONDUCTION WITH SALT Temperature effect

Analysis of Variance Procedure

T tests (LSD) for variable: T

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 60 MSE= 1263.785
Critical Value of T= 2.00
Least Significant Difference= 25.141

Means with the same letter are not significantly different.

T Grouping	Mean	N	S
A	73.08	16	4
A	72.69	16	3
A	68.50	16	2
A	66.25	16	1

ANALYSIS OF IONIC CONDUCTION WITH SALT Temperature effect

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: T

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 60 MSE= 1263.785

Number of Means	2	3	4
Critical Range	25.14	26.45	27.31

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	S
A	73.08	16	4
A	72.69	16	3
A	68.50	16	2
A	66.25	16	1

ANALYSIS OF IONIC CONDUCTION WITH SALT Voltage effect

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
S	4	1 2 3 4
V	64	3925.7 4103.1 3927.18 3996.48 4001.85 4031.76 4052.86 4060.48 4065.09 4071.26 4077.92 4081.74 4124.64 4161.28 4177.88 4202.07 4208.53 4217.33 4255.56 3680.137 3777.467 3851.337 3855.717 3859.977 3905.133 3929.887 3959.787 3960.667 3961.767 4003.213 4012.233 4016.297 4043.743 4092.777 4101.387 4104.643 4118.203 4122.903 4126.443 4135.813 4138.133 4139.233 4139.383 4149.167 4154.187 4157.577 4161.267 4163.357 4168.607 4178.143 4182.363 4189.017 4192.887 4196.533 4198.343 4202.377 4207.943 4215.423 4216.103 4217.937 4232.887 4242.297 4261.283 4265.107
T	63	105.1 15.53 15.72 16.16 24.16 29.84 34.27 37.66 44.71 48.14 67.84 76.69 83.77 86.02 96.88 98.28 108.12 115.98 117.82 118.16 118.63 122.47 101.4533 104.4733 108.8433 109.9133 111.1567 113.5667 115.2067 115.8367 120.2333 121.3433 17.40333 21.52333 21.63667 22.90333 27.48667 27.89333 30.97333 34.22667 36.76333 40.26333 41.09333 43.77667 46.74667 50.87333 52.30667 53.31333 55.48667 58.50333 60.22333 60.46333 63.21667 66.70333 68.17333 71.00667 75.18333 75.45333 80.35667 86.18667 89.91667 92.93667 97.73333

Number of observations in data set = 64

ANALYSIS OF IONIC CONDUCTION WITH SALT Voltage effect

Analysis of Variance Procedure

Dependent Variable: V

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	202029.8856	67343.2952	5.05	0.0035
Error	60	799871.2397	13331.1873		
Corrected Total	63	1001901.1253			

R-Square	C.V.	Root MSE	V Mean
0.201647	2.821150	115.4608	4092.684

Source	DF	Anova SS	Mean Square	F Value	Pr > F
S	3	202029.8856	67343.2952	5.05	0.0035

ANALYSIS OF IONIC CONDUCTION WITH SALT Voltage effect

Analysis of Variance Procedure

T tests (LSD) for variable: V

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 60 MSE= 13331.19
Critical Value of T= 2.00
Least Significant Difference= 81.655

Means with the same letter are not significantly different.

T Grouping	Mean	N	S
A	4170.52	16	1
A	4096.91	16	3
B A	4091.54	16	2
B			
B	4011.76	16	4

ANALYSIS OF IONIC CONDUCTION WITH SALT Voltage effect

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: V

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 60 MSE= 13331.19

Number of Means	2	3	4
Critical Range	81.66	85.90	88.70

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	S
A	4170.52	16	1
B A	4096.91	16	3
B A	4091.54	16	2
B	4011.76	16	4

ANALYSIS OF IONIC CONDUCTION WITH SALT Phase and Load effect

OBS	S	P	L
1	1	148.390	642.507
2	1	148.070	642.733
3	1	148.070	642.507
4	1	147.990	642.053
5	1	147.910	641.140
6	1	148.070	640.683
7	1	147.990	639.777
8	1	148.070	638.647
9	1	147.913	637.743
10	1	147.830	637.067
11	1	147.990	636.167
12	1	147.830	635.270
13	1	147.910	634.150
14	1	147.990	632.990
15	1	147.990	632.277
16	1	148.150	630.460
17	2	148.770	639.260
18	2	148.770	639.260
19	2	148.370	638.580
20	2	148.530	638.127
21	2	148.450	637.450
22	2	148.530	636.773
23	2	148.530	635.877
24	2	148.450	634.530
25	2	148.450	633.413
26	2	148.530	632.257
27	2	148.450	630.743
28	2	148.450	629.413
29	2	148.770	627.560
30	2	148.930	625.980
31	2	149.090	624.143
32	2	149.330	619.710
33	3	149.390	634.200
34	3	149.070	636.037
35	3	148.910	637.160
36	3	148.670	636.937
37	3	148.590	637.160
38	3	148.670	636.710
39	3	148.750	636.263
40	3	148.750	635.140
41	3	148.670	633.710
42	3	148.670	632.957
43	3	148.430	631.440
44	3	148.670	629.673
45	3	148.910	627.607
46	3	149.070	625.107
47	3	149.310	622.287
48	3	149.710	616.640
49	4	148.920	634.717
50	4	148.680	634.940
51	4	148.760	634.717
52	4	148.680	634.493
53	4	148.600	634.047
54	4	148.760	633.153
55	4	148.600	631.727
56	4	148.520	630.970
57	4	148.680	629.377
58	4	148.360	627.523
59	4	148.680	625.940
60	4	149.000	623.057
61	4	149.160	621.227

OBS	S	P	L
62	4	149.320	618.380
63	4	149.880	612.223
64	4	150.687	604.907

ANALYSIS OF IONIC CONDUCTION WITH SALT Phase effect

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
S	4	1 2 3 4
P	34	149 148.6 147.83 147.91 147.99 148.07 148.15 148.36 148.37 148.39 148.43 148.45 148.52 148.53 148.59 148.67 148.68 148.75 148.76 148.77 148.91 148.92 148.93 149.07 149.09 149.16 149.31 149.32 149.33 149.39 149.71 149.88 147.9133 150.6867
L	60	634.2 616.64 618.38 619.71 625.94 625.98 627.56 630.46 630.97 631.44 632.99 633.71 634.15 634.53 634.94 635.14 635.27 636.71 637.16 637.45 638.58 639.26 641.14 604.9067 612.2233 621.2267 622.2867 623.0567 624.1433 625.1067 627.5233 627.6067 629.3767 629.4133 629.6733 630.7433 631.7267 632.2567 632.2767 632.9567 633.1533 633.4133 634.0467 634.4933 634.7167 635.8767 636.0367 636.1667 636.2633 636.7733 636.9367 637.0667 637.7433 638.1267 638.6467 639.7767 640.6833 642.0533 642.5067 642.7333

Number of observations in data set = 64

ANALYSIS OF IONIC CONDUCTION WITH SALT Phase effect

Analysis of Variance Procedure

Dependent Variable: P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	8.92783992	2.97594664	21.40	0.0001
Error	60	8.34210729	0.13903512		
Corrected Total	63	17.26994722			

R-Square	C.V.	Root MSE	P Mean
0.516958	0.250880	0.372874	148.6264

Source	DF	Anova SS	Mean Square	F Value	Pr > F
S	3	8.92783992	2.97594664	21.40	0.0001

ANALYSIS OF IONIC CONDUCTION WITH SALT Phase effect

Analysis of Variance Procedure

T tests (LSD) for variable: P

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 60 MSE= 0.139035
Critical Value of T= 2.00
Least Significant Difference= 0.2637

Means with the same letter are not significantly different.

T Grouping		Mean	N	S
	A	148.9554	16	4
	A			
B	A	148.8900	16	3
B				
B		148.6500	16	2
	C	148.0102	16	1

ANALYSIS OF IONIC CONDUCTION WITH SALT Phase effect

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: P

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 60 MSE= 0.139035

Number of Means	2	3	4
Critical Range	.2637	.2774	.2864

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	S
	A	148.9554	16	4
B	A	148.8900	16	3
B		148.6500	16	2
	C	148.0102	16	1

ANALYSIS OF IONIC CONDUCTION WITH SALT Load effect

Analysis of Variance Procedure

Dependent Variable: L

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	961.1883809	320.3961270	7.60	0.0002
Error	60	2528.3864481	42.1397741		
Corrected Total	63	3489.5748290			

R-Square	C.V.	Root MSE	L Mean
0.275446	1.026589	6.491516	632.3386

Source	DF	Anova SS	Mean Square	F Value	Pr > F
S	3	961.1883809	320.3961270	7.60	0.0002

ANALYSIS OF IONIC CONDUCTION WITH SALT Load effect

Analysis of Variance Procedure

T tests (LSD) for variable: L

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 60 MSE= 42.13977
Critical Value of T= 2.00
Least Significant Difference= 4.5909

Means with the same letter are not significantly different.

T Grouping	Mean	N	S
A	637.886	16	1
B	632.692	16	2
B	631.814	16	3
C	626.962	16	4

ANALYSIS OF IONIC CONDUCTION WITH SALT Load effect

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: L

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 60 MSE= 42.13977

Number of Means	2	3	4
Critical Range	4.591	4.829	4.987

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	S
A	637.886	16	1
B	632.692	16	2
B	631.814	16	3
C	626.962	16	4

APPENDIX E

- SAS output for analysis of RF disinfection of wheat seeds

- SAS output for analysis of RF priming of soybean seeds

ANALYSIS OF COVARIANCE for RANDOMIZED COMPLETE BLOCK DESIGN
WHEAT DISINFECTION EXPERIMENT

OBS	R	T	X	Y
1	50	65	0.9800	1.163
2	50	70	0.8130	0.755
3	50	80	0.7931	0.750
4	100	65	0.8088	0.500
5	100	70	0.6640	0.767
6	100	80	0.5858	0.714
7	150	65	1.0858	0.796
8	150	70	1.1246	0.408
9	150	80	0.5775	0.531
10	200	65	1.0476	0.612
11	200	70	0.6302	0.674
12	200	80	0.4545	0.535
13	250	65	0.8570	0.563
14	250	70	0.7539	0.500
15	250	80	0.4806	0.560
16	300	65	0.7325	0.488
17	300	70	0.8194	0.673
18	300	80	0.8210	0.530
19	350	65	0.9958	0.633
20	350	70	0.7300	0.744
21	350	80	0.7400	0.674
22	400	65	0.9136	0.429
23	400	70	0.7953	0.571
24	400	80	0.6700	0.347
25	450	65	0.7953	0.744
26	450	70	0.6889	0.571
27	450	80	0.5365	0.184
28	500	65	1.1957	0.327
29	500	70	0.6146	0.306
30	500	80	0.4015	0.286
31	550	65	0.7195	1.000
32	550	70	0.6875	0.656
33	550	80	0.5084	0.558

General Linear Models Procedure
Class Level Information

Class	Levels	Values
R	11	50 100 150 200 250 300 350 400 450 500 550
T	3	65 70 80

Number of observations in data set = 33

General Linear Models Procedure

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	13	0.84055192	0.06465784	2.80	0.0203
Error	19	0.43803196	0.02305431		
Corrected Total	32	1.27858388			

R-Square	C.V.	Root MSE	Y Mean
0.657409	25.63100	0.151836	0.592394

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X	1	0.05227673	0.05227673	2.27	0.1486
R	10	0.69440410	0.06944041	3.01	0.0186
T	2	0.09387109	0.04693555	2.04	0.1581

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X	1	0.01303828	0.01303828	0.57	0.4612
R	10	0.72456648	0.07245665	3.14	0.0153
T	2	0.09387109	0.04693555	2.04	0.1581

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
T1 VS T2	0.08716182	1.15	0.2655	0.07596927
T2 VS T3	0.11584547	1.54	0.1405	0.07531423
T1 VS T3	0.20300729	2.00	0.0601	0.10154034

Parameter		Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
INTERCEPT		0.7476781092 B	5.00	0.0001	0.14958595
X		-.1816263348	-0.75	0.4612	0.24151532
R	50	0.1919389276 B	1.42	0.1720	0.13522196
	100	-.0689970363 B	-0.55	0.5859	0.12450881
	150	-.1068436743 B	-0.75	0.4625	0.14248965
	200	-.1178684160 B	-0.94	0.3583	0.12519764
	250	-.1863385341 B	-1.49	0.1518	0.12478192
	300	-.1466353173 B	-1.13	0.2710	0.12932931
	350	-.0210109551 B	-0.16	0.8749	0.13165455
	400	-.2609387313 B	-2.02	0.0582	0.12946770
	450	-.2319582490 B	-1.87	0.0775	0.12426345
	500	-.4137219848 B	-3.28	0.0040	0.12624945
	550	0.0000000000 B	.	.	.
T	65	0.2030072857 B	2.00	0.0601	0.10154034
	70	0.1158454683 B	1.54	0.1405	0.07531423
	80	0.0000000000 B	.	.	.

NOTE: The X'X matrix has been found to be singular and a generalized inverse was used to solve the normal equations. Estimates followed by the letter 'B' are biased, and are not unique estimators of the parameters.

ANALYSIS OF COVARIANCE

General Linear Models Procedure

Level of R	N	Y Mean	Y SD	X Mean	X SD
50	3	0.88933333	0.23701547	0.86203333	0.10264552
100	3	0.66033333	0.14135888	0.68620000	0.11314539
150	3	0.57833333	0.19828347	0.92930000	0.30528477
200	3	0.60700000	0.06963476	0.71076667	0.30464757
250	3	0.54100000	0.03553871	0.69716667	0.19450769
300	3	0.56366667	0.09698625	0.79096667	0.05063994
350	3	0.68366667	0.05612783	0.82193333	0.15065594
400	3	0.44900000	0.11333137	0.79296667	0.12181676
450	3	0.49966667	0.28673391	0.67356667	0.13007957
500	3	0.30633333	0.02050203	0.73726667	0.41106416
550	3	0.73800000	0.23212927	0.63846667	0.11377172

Level of T	N	Y Mean	Y SD	X Mean	X SD
65	11	0.65954545	0.25020686	0.92105455	0.15375217
70	11	0.60227273	0.14883420	0.75649091	0.14100888
80	11	0.51536364	0.17750677	0.59717273	0.14089011

ANALYSIS OF COVARIANCE

General Linear Models Procedure
Least Squares Means

R	Y LSMEAN	Std Err LSMEAN	Pr > |T| HO:LSMEAN=0	LSMEAN Number
50	0.90818505	0.09117657	0.0001	1
100	0.64724908	0.08937272	0.0001	2
150	0.60940244	0.09691026	0.0001	3
200	0.59837770	0.08840942	0.0001	4
250	0.52990758	0.08889507	0.0001	5
300	0.56961080	0.08801844	0.0001	6
350	0.69523516	0.08900230	0.0001	7
400	0.45530739	0.08806314	0.0001	8
450	0.48428787	0.09001646	0.0001	9
500	0.30252413	0.08780904	0.0027	10
550	0.71624612	0.09231219	0.0001	11

T for H0: LSMEAN(i)=LSMEAN(j) / Pr > |T|

i/j	1	2	3	4	5	6	7
1	.	1.991185	2.389613	2.397058	2.905103	2.705208	1.712481
		0.0610	0.0274	0.0270	0.0091	0.0140	0.1031
2	-1.99118	.	0.275903	0.393756	0.946285	0.613597	-0.3742
	0.0610		0.7856	0.6981	0.3559	0.5468	0.7124
3	-2.38961	-0.2759	.	0.081822	0.584258	0.309911	-0.67768
	0.0274	0.7856		0.9356	0.5659	0.7600	0.5061
4	-2.39706	-0.39376	-0.08182	.	0.552101	0.229259	-0.76357
	0.0270	0.6981	0.9356		0.5873	0.8211	0.4545
5	-2.9051	-0.94629	-0.58426	-0.5521	.	-0.31504	-1.29584
	0.0091	0.3559	0.5659	0.5873		0.7562	0.2106
6	-2.70521	-0.6136	-0.30991	-0.22926	0.315038	.	-1.01147
	0.0140	0.5468	0.7600	0.8211	0.7562		0.3245
7	-1.71248	0.374205	0.67768	0.763572	1.295838	1.011474	.
	0.1031	0.7124	0.5061	0.4545	0.2106	0.3245	
8	-3.62038	-1.5158	-1.20131	-1.13952	-0.59153	-0.92199	-1.93223
	0.0018	0.1460	0.2444	0.2687	0.5611	0.3681	0.0684
9	-3.20974	-1.31408	-0.90331	-0.91787	-0.36759	-0.67091	-1.63463
	0.0046	0.2045	0.3777	0.3702	0.7172	0.5104	0.1186
10	-4.74717	-2.76697	-2.31842	-2.38324	-1.82855	-2.14268	-3.12546
	0.0001	0.0123	0.0317	0.0278	0.0832	0.0453	0.0056
11	-1.41944	0.554154	0.749835	0.941459	1.493314	1.133813	0.159592
	0.1720	0.5859	0.4625	0.3583	0.1518	0.2710	0.8749

T for H0: LSMEAN(i)=LSMEAN(j) / Pr > |T|

i/j	8	9	10	11
1	3.620382	3.209741	4.747174	1.419436
	0.0018	0.0046	0.0001	0.1720
2	1.515801	1.314081	2.766965	-0.55415
	0.1460	0.2045	0.0123	0.5859
3	1.201315	0.903307	2.318421	-0.74983
	0.2444	0.3777	0.0317	0.4625
4	1.139517	0.917865	2.383243	-0.94146
	0.2687	0.3702	0.0278	0.3583
5	0.591527	0.36759	1.828552	-1.49331
	0.5611	0.7172	0.0832	0.1518
6	0.921988	0.67091	2.142684	-1.13381
	0.3681	0.5104	0.0453	0.2710
7	1.932234	1.634635	3.12546	-0.15959
	0.0684	0.1186	0.0056	0.8749
8	.	-0.22768	1.22519	-2.01547
		0.8223	0.2355	0.0582

ANALYSIS OF COVARIANCE

General Linear Models Procedure
Least Squares Means

Least Squares Means for effect R
T for H0: LSMEAN(i)=LSMEAN(j) / Pr > |T|

Dependent Variable: Y

i/j	8	9	10	11
9	0.227684	.	1.454984	-1.86667
	0.8223		0.1620	0.0775
10	-1.22519	-1.45498	.	-3.27702
	0.2355	0.1620		0.0040
11	2.015474	1.866665	3.27702	.
	0.0582	0.0775	0.0040	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

T	Y LSMEAN	Std Err LSMEAN	Pr > |T| H0:LSMEAN=0	LSMEAN Number
65	0.68911697	0.06034977	0.0001	1
70	0.60195516	0.04578237	0.0001	2
80	0.48610969	0.06007547	0.0001	3

T for H0: LSMEAN(i)=LSMEAN(j) / Pr > |T|

i/j	1	2	3
1	.	1.14733	1.999277
		0.2655	0.0601
2	-1.14733	.	1.538162
	0.2655		0.1405
3	-1.99928	-1.53816	.
	0.0601	0.1405	

NOTE: To ensure overall protection level, only probabilities associated with pre-planned comparisons should be used.

ANALYSIS OF SOYBEAN RESULTS

OBS	M	T	X	V
1	13.3	60	5	1.21
2	13.3	60	5	1.34
3	13.3	60	5	1.40
4	13.3	60	10	1.31
5	13.3	60	10	1.25
6	13.3	60	10	1.42
7	13.3	60	15	1.25
8	13.3	60	15	1.17
9	13.3	60	15	1.35
10	13.3	70	5	0.90
11	13.3	70	5	0.66
12	13.3	70	5	0.42
13	13.3	70	10	0.59
14	13.3	70	10	0.95
15	13.3	70	10	0.80
16	13.3	70	15	0.74
17	13.3	70	15	0.76
18	13.3	70	15	0.74
19	13.3	80	5	0.37
20	13.3	80	5	0.35
21	13.3	80	5	0.46
22	13.3	80	10	0.33
23	13.3	80	10	0.40
24	13.3	80	10	0.39
25	13.3	80	15	0.47
26	13.3	80	15	0.57
27	13.3	80	15	0.40
28	18.4	60	5	1.16
29	18.4	60	5	1.08
30	18.4	60	5	0.75
31	18.4	60	10	0.96
32	18.4	60	10	0.79
33	18.4	60	10	0.78
34	18.4	60	15	0.94
35	18.4	60	15	0.75
36	18.4	60	15	1.00
37	18.4	70	5	0.42
38	18.4	70	5	0.51
39	18.4	70	5	0.51
40	18.4	70	10	0.43
41	18.4	70	10	0.37
42	18.4	70	10	0.45
43	18.4	70	15	0.41
44	18.4	70	15	0.34
45	18.4	70	15	0.27
46	18.4	80	5	0.15
47	18.4	80	5	0.14
48	18.4	80	5	0.18
49	18.4	80	10	0.26
50	18.4	80	10	0.17
51	18.4	80	10	0.26
52	18.4	80	15	0.17
53	18.4	80	15	0.14
54	18.4	80	15	0.29
55	22.9	60	5	0.69
56	22.9	60	5	0.73
57	22.9	60	5	0.89
58	22.9	60	10	0.60
59	22.9	60	10	0.72
60	22.9	60	10	0.60
61	22.9	60	15	0.71

ANALYSIS OF SOYBEAN RESULTS

OBS	M	T	X	V
62	22.9	60	15	0.71
63	22.9	60	15	0.49
64	22.9	70	5	0.29
65	22.9	70	5	0.34
66	22.9	70	5	0.44
67	22.9	70	10	0.64
68	22.9	70	10	0.44
69	22.9	70	10	0.34
70	22.9	70	15	0.32
71	22.9	70	15	0.45
72	22.9	70	15	0.31
73	22.9	80	5	0.29
74	22.9	80	5	0.18
75	22.9	80	5	0.18
76	22.9	80	10	0.06
77	22.9	80	10	0.15
78	22.9	80	10	0.16
79	22.9	80	15	0.11
80	22.9	80	15	0.13
81	22.9	80	15	0.07

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
M	3	13.3 18.4 22.9
T	3	60 70 80
X	3	5 10 15
V	60	1 0.4 0.6 0.8 0.9 1.4 0.06 0.07 0.11 0.13 0.14 0.15 0.16 0.17 0.18 0.26 0.27 0.29 0.31 0.32 0.33 0.34 0.35 0.37 0.39 0.41 0.42 0.43 0.44 0.45 0.46 0.47 0.49 0.51 0.57 0.59 0.64 0.66 0.69 0.71 0.72 0.73 0.74 0.75 0.76 0.78 0.79 0.89 0.94 0.95 0.96 1.08 1.16 1.17 1.21 1.25 1.31 1.34 1.35 1.42

Number of observations in data set = 81

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

Dependent Variable: V

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	26	9.97043210	0.38347816	34.95	0.0001
Error	54	0.59253333	0.01097284		
Corrected Total	80	10.56296543			

R-Square	C.V.	Root MSE	V Mean
0.943905	18.16108	0.104751	0.576790

Source	DF	Anova SS	Mean Square	F Value	Pr > F
M	2	2.42362469	1.21181235	110.44	0.0001
T	2	7.00780988	3.50390494	319.33	0.0001
X	2	0.01790617	0.00895309	0.82	0.4476
M*T	4	0.33097531	0.08274383	7.54	0.0001
M*T*X	12	0.12513333	0.01042778	0.95	0.5059
T*X	4	0.06498272	0.01624568	1.48	0.2209

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

T tests (LSD) for variable: V

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 54 MSE= 0.010973
Critical Value of T= 2.00
Least Significant Difference= 0.0572

Means with the same letter are not significantly different.

T Grouping	Mean	N	M
A	0.81481	27	13.3
B	0.50667	27	18.4
C	0.40889	27	22.9

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: V

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 54 MSE= 0.010973

Number of Means	2	3
Critical Range	.05716	.06012

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	M
A	0.81481	27	13.3
B	0.50667	27	18.4
C	0.40889	27	22.9

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

T tests (LSD) for variable: V

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 54 MSE= 0.010973
Critical Value of T= 2.00
Least Significant Difference= 0.0572

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	0.96481	27	60
B	0.51259	27	70
C	0.25296	27	80

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: V

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 54 MSE= 0.010973

Number of Means	2	3
Critical Range	.05716	.06012

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	T
A	0.96481	27	60
B	0.51259	27	70
C	0.25296	27	80

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

T tests (LSD) for variable: V

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 54 MSE= 0.010973
Critical Value of T= 2.00
Least Significant Difference= 0.0572

Means with the same letter are not significantly different.

T Grouping	Mean	N	X
A	0.59407	27	5
A			
A	0.57852	27	10
A			
A	0.55778	27	15

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

Duncan's Multiple Range Test for variable: V

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 54 MSE= 0.010973

Number of Means	2	3
Critical Range	.05716	.06012

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	X
A	0.59407	27	5
A			
A	0.57852	27	10
A			
A	0.55778	27	15

Level of M	Level of T	N	V Mean	V SD
13.3	60	9	1.30000000	0.08558621
13.3	70	9	0.72888889	0.15964370
13.3	80	9	0.41555556	0.07384293
18.4	60	9	0.91222222	0.15221513
18.4	70	9	0.41222222	0.07758508
18.4	80	9	0.19555556	0.05811865
22.9	60	9	0.68222222	0.11121800
22.9	70	9	0.39666667	0.11011358
22.9	80	9	0.14777778	0.06887993

Level of M	Level of T	Level of X	N	V Mean	V SD
13.3	60	5	3	1.31666667	0.09712535
13.3	60	10	3	1.32666667	0.08621678
13.3	60	15	3	1.25666667	0.09018500
13.3	70	5	3	0.66000000	0.24000000
13.3	70	10	3	0.78000000	0.18083141
13.3	70	15	3	0.74666667	0.01154701
13.3	80	5	3	0.39333333	0.05859465
13.3	80	10	3	0.37333333	0.03785939
13.3	80	15	3	0.48000000	0.08544004
18.4	60	5	3	0.99666667	0.21733231
18.4	60	10	3	0.84333333	0.10115994
18.4	60	15	3	0.89666667	0.13051181
18.4	70	5	3	0.48000000	0.05196152
18.4	70	10	3	0.41666667	0.04163332
18.4	70	15	3	0.34000000	0.07000000
18.4	80	5	3	0.15666667	0.02081666
18.4	80	10	3	0.23000000	0.05196152
18.4	80	15	3	0.20000000	0.07937254
22.9	60	5	3	0.77000000	0.10583005
22.9	60	10	3	0.64000000	0.06928203
22.9	60	15	3	0.63666667	0.12701706
22.9	70	5	3	0.35666667	0.07637626

ANALYSIS OF SOYBEAN RESULTS

Analysis of Variance Procedure

Level of M	Level of T	Level of X	N	V Mean	V SD
22.9	70	10	3	0.47333333	0.15275252
22.9	70	15	3	0.36000000	0.07810250
22.9	80	5	3	0.21666667	0.06350853
22.9	80	10	3	0.12333333	0.05507571
22.9	80	15	3	0.10333333	0.03055050

Level of T	Level of X	N	V Mean	V SD
60	5	9	1.02777778	0.27119079
60	10	9	0.93666667	0.31452345
60	15	9	0.93000000	0.28814059
70	5	9	0.49888889	0.18435322
70	10	9	0.55666667	0.20760539
70	15	9	0.48222222	0.20541286
80	5	9	0.25555556	0.11544600
80	10	9	0.24222222	0.11659522
80	15	9	0.26111111	0.17982244

APPENDIX F

- SAS output for analysis of X-ray cracks of Roma wheat

- SAS output for analysis of X-ray cracks of Pollet wheat

ANALYSIS OF VARIANCE, IS VALUES ROMA WHEAT

One-Way Analysis of Variance

Data: ANAL.aIS

Level codes: ANAL.treatment

Labels: ANAL.code

Means plot: Tukey Confidence level: 95 Range test: Tukey

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	83.635165	29	2.8839712	15.459	.0000
Within groups	50.368860	270	.1865513		
Total (corrected)	134.00403	299			

0 missing value(s) have been excluded.

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Table of means for ANAL.aIS by ANAL.treatment

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Tukey HSD intervals for mean	
abc	10	2.1749900	.1664151	.1365838	1.8089340	2.5410460
a1	10	2.6416600	.1309128	.1365838	2.2756040	3.0077160
a2	10	2.6583300	.1631365	.1365838	2.2922740	3.0243860
a3	10	2.4916700	.1293715	.1365838	2.1256140	2.8577260
b1	10	2.8249900	.1391377	.1365838	2.4589340	3.1910460
b2	10	2.9333300	.1409827	.1365838	2.5672740	3.2993860
b3	10	3.0999900	.1277777	.1365838	2.7339340	3.4660460
c1	10	3.2416600	.0760218	.1365838	2.8756040	3.6077160
c2	10	2.9500100	.1333338	.1365838	2.5839540	3.3160660
c3	10	3.0250100	.1459611	.1365838	2.6589540	3.3910660
def	10	3.2166700	.2180874	.1365838	2.8506140	3.5827260
d1	10	3.2500000	.1619741	.1365838	2.8839440	3.6160560
d2	10	3.1333300	.1070115	.1365838	2.7672740	3.4993860
d3	10	2.8833300	.1166644	.1365838	2.5172740	3.2493860
e1	10	3.2083300	.1412282	.1365838	2.8422740	3.5743860
e2	10	3.1500000	.1354020	.1365838	2.7839440	3.5160560
e3	10	2.9750100	.1248755	.1365838	2.6089540	3.3410660
f1	10	3.6916700	.1314998	.1365838	3.3256140	4.0577260
f2	10	3.1583300	.0981671	.1365838	2.7922740	3.5243860
f3	10	3.1583400	.1299580	.1365838	2.7922840	3.5243960
ghi	10	1.9750000	.1349726	.1365838	1.6089440	2.3410560
g1	10	2.1083500	.1624670	.1365838	1.7422940	2.4744060
g2	10	2.1333300	.1133112	.1365838	1.7672740	2.4993860
g3	10	2.0916700	.1311462	.1365838	1.7256140	2.4577260
h1	10	2.0083500	.1100290	.1365838	1.6422940	2.3744060
h2	10	1.7666700	.0849832	.1365838	1.4006140	2.1327260
h3	10	1.7833200	.1304067	.1365838	1.4172640	2.1493760
i1	10	2.0583300	.1496124	.1365838	1.6922740	2.4243860
i2	10	2.2416600	.1451125	.1365838	1.8756040	2.6077160
i3	10	2.1916700	.1416627	.1365838	1.8256140	2.5577260
Total	300	2.6741667	.0249367	.0249367	2.6073343	2.7409990

Analysis of Variance for ANAL.aIS - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:ANAL.moisture	68.277042	2	34.138521	182.998	.0000
B:ANAL.combin	6.589879	9	.732209	3.925	.0001
INTERACTIONS					
AB	8.7682445	18	.4871247	2.611	.0005
RESIDUAL	50.368860	270	.1865513		
TOTAL (CORRECTED)	134.00403	299			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

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Table of Least Squares Means for ANAL.aIS

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	300	2.6741667	.0249367	2.6250607	2.7232726
A:ANAL.moisture					
13.5	100	2.0358350	.0431916	1.9507810	2.1208890
17	100	2.8041640	.0431916	2.7191100	2.8892180
22	100	3.1825010	.0431916	3.0974470	3.2675550
B:ANAL.combin					
Control	30	2.4555533	.0788567	2.3002668	2.6108399
60 C * 5 min	30	2.6666700	.0788567	2.5113834	2.8219566
60 C * 10 min	30	2.6416633	.0788567	2.4863768	2.7969499
60 C * 15 min	30	2.4888900	.0788567	2.3336034	2.6441766
70 C * 5 min	30	2.6805567	.0788567	2.5252701	2.8358432
70 C * 10 min	30	2.6166667	.0788567	2.4613801	2.7719532
70 C * 15 min	30	2.6194400	.0788567	2.4641534	2.7747266
80 C * 5 min	30	2.9972200	.0788567	2.8419334	3.1525066
80 C * 10 min	30	2.7833333	.0788567	2.6280468	2.9386199
80 C * 15 min	30	2.7916733	.0788567	2.6363868	2.9469599
AB					
13.5 Control	10	1.9750000	.1365838	1.7060358	2.2439642
13.5 60 C * 5 min	10	2.1083500	.1365838	1.8393858	2.3773142
13.5 60 C * 10 min	10	2.1333300	.1365838	1.8643658	2.4022942
13.5 60 C * 15 min	10	2.0916700	.1365838	1.8227058	2.3606342
13.5 70 C * 5 min	10	2.0083500	.1365838	1.7393858	2.2773142
13.5 70 C * 10 min	10	1.7666700	.1365838	1.4977058	2.0356342
13.5 70 C * 15 min	10	1.7833200	.1365838	1.5143558	2.0522842
13.5 80 C * 5 min	10	2.0583300	.1365838	1.7893658	2.3272942
13.5 80 C * 10 min	10	2.2416600	.1365838	1.9726958	2.5106242
13.5 80 C * 15 min	10	2.1916700	.1365838	1.9227058	2.4606342
17 Control	10	2.1749900	.1365838	1.9060258	2.4439542
17 60 C * 5 min	10	2.6416600	.1365838	2.3726958	2.9106242
17 60 C * 10 min	10	2.6583300	.1365838	2.3893658	2.9272942
17 60 C * 15 min	10	2.4916700	.1365838	2.2227058	2.7606342
17 70 C * 5 min	10	2.8249900	.1365838	2.5560258	3.0939542
17 70 C * 10 min	10	2.9333300	.1365838	2.6643658	3.2022942
17 70 C * 15 min	10	3.0999900	.1365838	2.8310258	3.3689542
17 80 C * 5 min	10	3.2416600	.1365838	2.9726958	3.5106242
17 80 C * 10 min	10	2.9500100	.1365838	2.6810458	3.2189742
17 80 C * 15 min	10	3.0250100	.1365838	2.7560458	3.2939742
22 Control	10	3.2166700	.1365838	2.9477058	3.4856342
22 60 C * 5 min	10	3.2500000	.1365838	2.9810358	3.5189642
22 60 C * 10 min	10	3.1333300	.1365838	2.8643658	3.4022942
22 60 C * 15 min	10	2.8833300	.1365838	2.6143658	3.1522942
22 70 C * 5 min	10	3.2083300	.1365838	2.9393658	3.4772942
22 70 C * 10 min	10	3.1500000	.1365838	2.8810358	3.4189642
22 70 C * 15 min	10	2.9750100	.1365838	2.7060458	3.2439742
22 80 C * 5 min	10	3.6916700	.1365838	3.4227058	3.9606342
22 80 C * 10 min	10	3.1583300	.1365838	2.8893658	3.4272942
22 80 C * 15 min	10	3.1583400	.1365838	2.8893758	3.4273042

Multiple range analysis for ANAL.aIS by ANAL.moisture

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
13.5	100	2.0358350	X
17	100	2.8041640	X
22	100	3.1825010	X

contrast	difference	+/-	limits	
13.5 - 17	-0.76833		0.14395	*
13.5 - 22	-1.14667		0.14395	*
17 - 22	-0.37834		0.14395	*

* denotes a statistically significant difference.

Multiple range analysis for ANAL.aIS by ANAL.combin

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
Control	30	2.4555533	X
60 C * 1	30	2.4888900	X
70 C * 1	30	2.6166667	X
70 C * 1	30	2.6194400	X
60 C * 1	30	2.6416633	XX
60 C *	30	2.6666700	XX
70 C *	30	2.6805567	XX
80 C * 1	30	2.7833333	XX
80 C * 1	30	2.7916733	XX
80 C *	30	2.9972200	X

contrast	difference	+/-	limits	
Control - 60 C * 5 min	-0.21112		0.35579	
Control - 60 C * 10 min	-0.18611		0.35579	
Control - 60 C * 15 min	-0.03334		0.35579	
Control - 70 C * 5 min	-0.22500		0.35579	
Control - 70 C * 10 min	-0.16111		0.35579	
Control - 70 C * 15 min	-0.16389		0.35579	
Control - 80 C * 5 min	-0.54167		0.35579	*
Control - 80 C * 10 min	-0.32778		0.35579	
Control - 80 C * 15 min	-0.33612		0.35579	
60 C * 5 min - 60 C * 10 min	0.02501		0.35579	
60 C * 5 min - 60 C * 15 min	0.17778		0.35579	
60 C * 5 min - 70 C * 5 min	-0.01389		0.35579	
60 C * 5 min - 70 C * 10 min	0.05000		0.35579	
60 C * 5 min - 70 C * 15 min	0.04723		0.35579	
60 C * 5 min - 80 C * 5 min	-0.33055		0.35579	
60 C * 5 min - 80 C * 10 min	-0.11666		0.35579	
60 C * 5 min - 80 C * 15 min	-0.12500		0.35579	
60 C * 10 min - 60 C * 15 min	0.15277		0.35579	
60 C * 10 min - 70 C * 5 min	-0.03889		0.35579	
60 C * 10 min - 70 C * 10 min	0.02500		0.35579	
60 C * 10 min - 70 C * 15 min	0.02222		0.35579	
60 C * 10 min - 80 C * 5 min	-0.35556		0.35579	
60 C * 10 min - 80 C * 10 min	-0.14167		0.35579	
60 C * 10 min - 80 C * 15 min	-0.15001		0.35579	
60 C * 15 min - 70 C * 5 min	-0.19167		0.35579	
60 C * 15 min - 70 C * 10 min	-0.12778		0.35579	
60 C * 15 min - 70 C * 15 min	-0.13055		0.35579	
60 C * 15 min - 80 C * 5 min	-0.50833		0.35579	*
60 C * 15 min - 80 C * 10 min	-0.29444		0.35579	
60 C * 15 min - 80 C * 15 min	-0.30278		0.35579	
70 C * 5 min - 70 C * 10 min	0.06389		0.35579	
70 C * 5 min - 70 C * 15 min	0.06112		0.35579	
70 C * 5 min - 80 C * 5 min	-0.31666		0.35579	
70 C * 5 min - 80 C * 10 min	-0.10278		0.35579	
70 C * 5 min - 80 C * 15 min	-0.11112		0.35579	
70 C * 10 min - 70 C * 15 min	-0.00277		0.35579	
70 C * 10 min - 80 C * 5 min	-0.38055		0.35579	*
70 C * 10 min - 80 C * 10 min	-0.16667		0.35579	
70 C * 10 min - 80 C * 15 min	-0.17501		0.35579	
70 C * 15 min - 80 C * 5 min	-0.37778		0.35579	*

* denotes a statistically significant difference.

Multiple range analysis for ANAL.aIS by ANAL.combin

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
70 C * 15 min - 80 C * 10 min		-0.16389	0.35579
70 C * 15 min - 80 C * 15 min		-0.17223	0.35579
80 C * 5 min - 80 C * 10 min		0.21389	0.35579
80 C * 5 min - 80 C * 15 min		0.20555	0.35579
80 C * 10 min - 80 C * 15 min		-0.00834	0.35579

* denotes a statistically significant difference.

ANALYSIS OF VARIANCE, IS VALUES, ROMA WHEAT

Tue Feb 18 1997 04:09:03 PM

Analysis of Variance for ANAL.aIS - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:ANAL.moisture	54.511162	2	27.255581	143.174	.0000
B:ANAL.object	5.075258	3	1.691753	8.887	.0000
INTERACTIONS					
AB	5.8259490	6	.9709915	5.101	.0001
RESIDUAL	54.825777	288	.1903673		
TOTAL (CORRECTED)	134.00403	299			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Tue Feb 18 1997 04:09:31 PM

Table of Least Squares Means for ANAL.aIS

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	300	2.6377311	.0281638	2.5822860	2.6931763
A:ANAL.moisture					
13.5	100	2.0256958	.0487811	1.9296620	2.1217297
17	100	2.6993017	.0487811	2.6032678	2.7953355
22	100	3.1881958	.0487811	3.0921620	3.2842297
B:ANAL.object					
Cont	30	2.4555533	.0796591	2.2987307	2.6123759
60 C	90	2.5990744	.0459912	2.5085329	2.6896160
70 C	90	2.6388878	.0459912	2.5483462	2.7294293
80 C	90	2.8574089	.0459912	2.7668673	2.9479505
AB					
13.5 Cont	10	1.9750000	.1379736	1.7033753	2.2466247
13.5 60 C	30	2.1111167	.0796591	1.9542941	2.2679393
13.5 70 C	30	1.8527800	.0796591	1.6959574	2.0096026
13.5 80 C	30	2.1638867	.0796591	2.0070641	2.3207093
17 Cont	10	2.1749900	.1379736	1.9033653	2.4466147
17 60 C	30	2.5972200	.0796591	2.4403974	2.7540426
17 70 C	30	2.9527700	.0796591	2.7959474	3.1095926
17 80 C	30	3.0722267	.0796591	2.9154041	3.2290493
22 Cont	10	3.2166700	.1379736	2.9450453	3.4882947
22 60 C	30	3.0888867	.0796591	2.9320641	3.2457093
22 70 C	30	3.1111133	.0796591	2.9542907	3.2679359
22 80 C	30	3.3361133	.0796591	3.1792907	3.4929359

Multiple range analysis for ANAL.aIS by ANAL.moisture

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
13.5	100	2.0256958	X
17	100	2.6993017	X
22	100	3.1881958	X

contrast	difference	+/-	limits	
13.5 - 17	-0.67361		0.16252	*
13.5 - 22	-1.16250		0.16252	*
17 - 22	-0.48889		0.16252	*

* denotes a statistically significant difference.

Multiple range analysis for ANAL.aIS by ANAL.object

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
Cont	30	2.4555533	X
60 C	90	2.5990744	X
70 C	90	2.6388878	X
80 C	90	2.8574089	X

contrast	difference	+/-	limits	
Cont - 60 C	-0.14352		0.23768	
Cont - 70 C	-0.18333		0.23768	
Cont - 80 C	-0.40186		0.23768	*
60 C - 70 C	-0.03981		0.16807	
60 C - 80 C	-0.25833		0.16807	*
70 C - 80 C	-0.21852		0.16807	*

* denotes a statistically significant difference.

Analysis of Variance for ANAL.aIS - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:ANAL.moisture	54.511162	2	27.255581	132.994	.0000
B:ANAL.objtim	2.623977	3	.874659	4.268	.0057
INTERACTIONS					
AB	4.0808293	6	.6801382	3.319	.0036
RESIDUAL	59.022177	288	.2049381		
TOTAL (CORRECTED)	134.00403	299			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table of Least Squares Means for ANAL.aIS

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	300	2.6377311	.0292217	2.5802032	2.6952591
A:ANAL.moisture					
13.5	100	2.0256958	.0506135	1.9260545	2.1253372
17	100	2.6993017	.0506135	2.5996603	2.7989430
22	100	3.1881958	.0506135	3.0885545	3.2878372
B:ANAL.objtim					
contr.	30	2.4555533	.0826515	2.2928397	2.6182669
5 min	90	2.7814822	.0477189	2.6875395	2.8754250
10 min	90	2.6805544	.0477189	2.5866117	2.7744972
15 min	90	2.6333344	.0477189	2.5393917	2.7272772
AB					
13.5 contr.	10	1.9750000	.1431566	1.6931718	2.2568282
13.5 5 min	30	2.0583433	.0826515	1.8956297	2.2210569
13.5 10 min	30	2.0472200	.0826515	1.8845064	2.2099336
13.5 15 min	30	2.0222200	.0826515	1.8595064	2.1849336
17 contr.	10	2.1749900	.1431566	1.8931618	2.4568182
17 5 min	30	2.9027700	.0826515	2.7400564	3.0654836
17 10 min	30	2.8472233	.0826515	2.6845097	3.0099369
17 15 min	30	2.8722233	.0826515	2.7095097	3.0349369
22 contr.	10	3.2166700	.1431566	2.9348418	3.4984982
22 5 min	30	3.3833333	.0826515	3.2206197	3.5460469
22 10 min	30	3.1472200	.0826515	2.9845064	3.3099336
22 15 min	30	3.0055600	.0826515	2.8428464	3.1682736

Multiple range analysis for ANAL.aIS by ANAL.moisture

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
13.5	100	2.0256958	X
17	100	2.6993017	X
22	100	3.1881958	X

contrast	difference	+/-	limits	
13.5 - 17	-0.67361		0.16863	*
13.5 - 22	-1.16250		0.16863	*
17 - 22	-0.48889		0.16863	*

* denotes a statistically significant difference.

Multiple range analysis for ANAL.aIS by ANAL.objtim

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
contr.	30	2.4555533	X
15 min	90	2.6333344	XX
10 min	90	2.6805544	XX
5 min	90	2.7814822	X

contrast	difference	+/-	limits	
contr. - 5 min	-0.32593		0.24661	*
contr. - 10 min	-0.22500		0.24661	
contr. - 15 min	-0.17778		0.24661	
5 min - 10 min	0.10093		0.17438	
5 min - 15 min	0.14815		0.17438	
10 min - 15 min	0.04722		0.17438	

* denotes a statistically significant difference.

row	treatm	mISabc	dISabc	mISdef	dISdef	mISghi	dISghi
1	XYZ	2.18	0.53	3.22	0.69	1.98	0.43
2	X1	2.64	0.41	3.25	0.51	2.11	0.51
3	X2	2.66	0.52	3.13	0.34	2.13	0.36
4	X3	2.49	0.41	2.88	0.37	2.09	0.41
5	Y1	2.83	0.44	3.21	0.45	2.01	0.35
6	Y2	2.93	0.45	3.15	0.43	1.77	0.27
7	Y3	3.10	0.40	2.98	0.39	1.78	0.41
8	Z1	3.24	0.24	3.69	0.42	2.06	0.47
9	Z2	2.95	0.42	3.16	0.31	2.24	0.46
10	Z3	3.03	0.46	3.16	0.41	2.19	0.45

Analysis of Variance for ANWAR.mIS - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:ANWAR.Moist	62.247061	2	31.123530	180.260	.0000
B:ANWAR.Temp	3.482198	2	1.741099	10.084	.0001
C:ANWAR.Time	1.030917	2	.515459	2.985	.0524
INTERACTIONS					
AB	2.9664716	4	.7416179	4.295	.0022
AC	1.2213518	4	.3053380	1.768	.1358
BC	.4837039	4	.1209260	.700	.5924
ABC	1.7209437	8	.2151180	1.246	.2730
RESIDUAL	41.956229	243	.1726594		
TOTAL (CORRECTED)	115.10888	269			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table of Least Squares Means for ANWAR.mIS

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	270	2.6984570	.0252879	2.6486345	2.7482796
A:ANWAR.Moist					
13.5	90	2.0425944	.0438000	1.9562993	2.1288896
17	90	2.8740722	.0438000	2.7877770	2.9603674
22	90	3.1787044	.0438000	3.0924093	3.2649996
B:ANWAR.Temp					
60	90	2.5990744	.0438000	2.5127793	2.6853696
70	90	2.6388878	.0438000	2.5525926	2.7251830
80	90	2.8574089	.0438000	2.7711137	2.9437041
C:ANWAR.Time					
5	90	2.7814822	.0438000	2.6951870	2.8677774
10	90	2.6805544	.0438000	2.5942593	2.7668496
15	90	2.6333344	.0438000	2.5470393	2.7196296
AB					
13.5 60	30	2.1111167	.0758638	1.9616490	2.2605843
13.5 70	30	1.8527800	.0758638	1.7033124	2.0022476
13.5 80	30	2.1638867	.0758638	2.0144190	2.3133543
17 60	30	2.5972200	.0758638	2.4477524	2.7466876
17 70	30	2.9527700	.0758638	2.8033024	3.1022376
17 80	30	3.0722267	.0758638	2.9227590	3.2216943
22 60	30	3.0888867	.0758638	2.9394190	3.2383543
22 70	30	3.1111133	.0758638	2.9616457	3.2605810
22 80	30	3.3361133	.0758638	3.1866457	3.4855810
AC					
13.5 5	30	2.0583433	.0758638	1.9088757	2.2078110
13.5 10	30	2.0472200	.0758638	1.8977524	2.1966876
13.5 15	30	2.0222200	.0758638	1.8727524	2.1716876
17 5	30	2.9027700	.0758638	2.7533024	3.0522376
17 10	30	2.8472233	.0758638	2.6977557	2.9966910
17 15	30	2.8722233	.0758638	2.7227557	3.0216910
22 5	30	3.3833333	.0758638	3.2338657	3.5328010
22 10	30	3.1472200	.0758638	2.9977524	3.2966876
22 15	30	3.0055600	.0758638	2.8560924	3.1550276
BC					
60 5	30	2.6666700	.0758638	2.5172024	2.8161376
60 10	30	2.6416633	.0758638	2.4921957	2.7911310
60 15	30	2.4888900	.0758638	2.3394224	2.6383576
70 5	30	2.6805567	.0758638	2.5310890	2.8300243
70 10	30	2.6166667	.0758638	2.4671990	2.7661343
70 15	30	2.6194400	.0758638	2.4699724	2.7689076
80 5	30	2.9972200	.0758638	2.8477524	3.1466876
80 10	30	2.7833333	.0758638	2.6338657	2.9328010
80 15	30	2.7916733	.0758638	2.6422057	2.9411410

Multiple range analysis for ANWAR.mIS by ANWAR.Moist

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
13.5	90	2.0425944	X
17	90	2.8740722	X
22	90	3.1787044	X

contrast	difference	+/-	limits	
13.5 - 17	-0.83148		0.14607	*
13.5 - 22	-1.13611		0.14607	*
17 - 22	-0.30463		0.14607	*

* denotes a statistically significant difference.

Multiple range analysis for ANWAR.mIS by ANWAR.Temp

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
60	90	2.5990744	X
70	90	2.6388878	X
80	90	2.8574089	X

contrast	difference	+/-	limits	
60 - 70	-0.03981		0.14607	
60 - 80	-0.25833		0.14607	*
70 - 80	-0.21852		0.14607	*

* denotes a statistically significant difference.

Multiple range analysis for ANWAR.mIS by ANWAR.Time

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
15	90	2.6333344	X
10	90	2.6805544	XX
5	90	2.7814822	X

contrast	difference	+/-	limits	
5 - 10	0.10093		0.14607	
5 - 15	0.14815		0.14607	*
10 - 15	0.04722		0.14607	

* denotes a statistically significant difference.

APPENDIX F

SAS output for analysis of X-ray cracks of Pollet wheat

ANALYSIS OF VARIANCE, IP VALUES

Analysis of Variance for aIP - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:moist	443.81481	2	221.90740	336.234	.0000
B:Temp	9.91332	2	4.95666	7.510	.0006
C:time	12.61005	2	6.30502	9.553	.0001
INTERACTIONS					
AB	11.693279	4	2.9233198	4.429	.0015
AC	12.100048	4	3.0250120	4.583	.0012
BC	8.592483	4	2.1481209	3.255	.0116
ABC	29.731794	8	3.7164743	5.631	.0000
RESIDUAL	516.76330	783	.6599787		
TOTAL (CORRECTED)	1045.2191	809			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table of Least Squares Means for AVERIP.aIP

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	810	2.7045432	.0285445	2.6484981	2.7605884
A:moist					
15	270	1.9527407	.0494405	1.8556677	2.0498138
20	270	2.4495926	.0494405	2.3525195	2.5466656
25	270	3.7112963	.0494405	3.6142232	3.8083694
B:Temp					
60	270	2.5590741	.0494405	2.4620010	2.6561471
70	270	2.7274074	.0494405	2.6303344	2.8244805
80	270	2.8271481	.0494405	2.7300751	2.9242212
C:time					
5	270	2.8645185	.0494405	2.7674455	2.9615916
10	270	2.6890370	.0494405	2.5919640	2.7861101
15	270	2.5600741	.0494405	2.4630010	2.6571471
AB					
15 60	90	1.8723333	.0856335	1.7041979	2.0404688
15 70	90	1.9415556	.0856335	1.7734201	2.1096910
15 80	90	2.0443333	.0856335	1.8761979	2.2124688
20 60	90	2.0805556	.0856335	1.9124201	2.2486910
20 70	90	2.6372222	.0856335	2.4690868	2.8053577
20 80	90	2.6310000	.0856335	2.4628645	2.7991355
25 60	90	3.7243333	.0856335	3.5561979	3.8924688
25 70	90	3.6034444	.0856335	3.4353090	3.7715799
25 80	90	3.8061111	.0856335	3.6379756	3.9742466
AC					
15 5	90	2.1117778	.0856335	1.9436423	2.2799132
15 10	90	1.9622222	.0856335	1.7940868	2.1303577
15 15	90	1.7842222	.0856335	1.6160868	1.9523577
20 5	90	2.4048889	.0856335	2.2367534	2.5730244
20 10	90	2.4842222	.0856335	2.3160868	2.6523577
20 15	90	2.4596667	.0856335	2.2915312	2.6278021
25 5	90	4.0768889	.0856335	3.9087534	4.2450244

25	10	90	3.6206667	.0856335	3.4525312	3.7888021
25	15	90	3.4363333	.0856335	3.2681979	3.6044688
BC						
60	5	90	2.7165556	.0856335	2.5484201	2.8846910
60	10	90	2.4825556	.0856335	2.3144201	2.6506910
60	15	90	2.4781111	.0856335	2.3099756	2.6462466
70	5	90	2.9992222	.0856335	2.8310868	3.1673577
70	10	90	2.5785556	.0856335	2.4104201	2.7466910
70	15	90	2.6044444	.0856335	2.4363090	2.7725799
80	5	90	2.8777778	.0856335	2.7096423	3.0459132
80	10	90	3.0060000	.0856335	2.8378645	3.1741355
80	15	90	2.5976667	.0856335	2.4295312	2.7658021

Multiple range analysis for aIP by moist

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
15	270	1.9527407	X
20	270	2.4495926	X
25	270	3.7112963	X

contrast	difference	+/-	limits	
15 - 20	-0.49685		0.16418	*
15 - 25	-1.75856		0.16418	*
20 - 25	-1.26170		0.16418	*

* denotes a statistically significant difference.

Multiple range analysis for aIP by Temp

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
60	270	2.5590741	X
70	270	2.7274074	X
80	270	2.8271481	X

contrast	difference	+/-	limits	
60 - 70	-0.16833		0.16418	*
60 - 80	-0.26807		0.16418	*
70 - 80	-0.09974		0.16418	

* denotes a statistically significant difference.

Multiple range analysis for aIP by time

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
15	270	2.5600741	X
10	270	2.6890370	X
5	270	2.8645185	X

contrast	difference	+/-	limits	
5 - 10	0.17548		0.16418	*
5 - 15	0.30444		0.16418	*
10 - 15	0.12896		0.16418	

* denotes a statistically significant difference.

APPENDIX F

ANALYSIS OF VARIANCE, IP VALUES, POLLET WHEAT

These analysis contains combined : Control Samples and all another Samples: J,K,L,...,P,Q,R.

Analysis of Variance for COMBINE.aIP - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:COMBINE.Moist	128.39038	2	64.195190	86.122	.0000
B:COMBINE.treatm	21.53414	1	21.534139	28.889	.0000
INTERACTIONS					
AB	1.3039793	2	.6519896	.875	.4174
RESIDUAL	644.02416	864	.7453983		
TOTAL (CORRECTED)	1146.1486	869			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table of Least Squares Means for COMBINE.aIP

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	870	2.3941049	.0577571	2.2807192	2.5074906
A:COMBINE.Moist					
15	290	1.5541204	.1000383	1.3577306	1.7505102
20	290	2.2372963	.1000383	2.0409065	2.4336861
25	290	3.3908981	.1000383	3.1945084	3.5872879
B:COMBINE.treatm					
TempXtime	810	2.7045432	.0303355	2.6449901	2.7640963
Control	60	2.0836667	.1114599	1.8648546	2.3024787
AB					
15 TempXtime (P,Q,R)	270	1.9527407	.0525427	1.8495918	2.0558897
15 Control PQR	20	1.1555000	.1930542	.7765065	1.5344935
20 TempXtime (M,N,O)	270	2.4495926	.0525427	2.3464436	2.5527416
20 Control MNO	20	2.0250000	.1930542	1.6460065	2.4039935
25 TempXtime (J,K,L)	270	3.7112963	.0525427	3.6081473	3.8144453
25 Control JKL	20	3.0705000	.1930542	2.6915065	3.4494935

Multiple range analysis for COMBINE.aIP by COMBINE.Moist

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
15	290	1.5541204	X
20	290	2.2372963	X
25	290	3.3908981	X

contrast	difference	+/-	limits	
15 - 20	-0.68318		0.33213	*
15 - 25	-1.83678		0.33213	*
20 - 25	-1.15360		0.33213	*

* denotes a statistically significant difference.

Multiple range analysis for COMBINE.aIP by COMBINE.treatm

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
Control	60	2.0836667	X
TempXtime	810	2.7045432	X

contrast	difference	+/-	limits
TempXtime - Control	0.62088		0.22671 *

* denotes a statistically significant difference.

IP VALUES FOR POLLET WHEAT

Level	Sample size	Average	Standard deviation	Coefficient of variation
J11	10	4.08300	0.67004	16.4105
J12	10	4.30900	0.52979	12.2949
J13	10	4.19300	0.70620	16.8423
J21	10	3.64100	0.72319	19.8625
J22	10	3.15900	0.87755	27.7794
J23	10	3.68300	0.76357	20.7324
J31	10	3.21800	0.91701	28.4963
J32	10	3.54100	0.69337	19.5813
J33	10	3.69200	0.64841	17.5627

Level	Sample size	Average	Standard deviation	Coefficient of variation
K11	10	4.52500	0.69479	15.3546
K12	10	4.48300	0.55970	12.4850
K13	10	2.82500	0.76176	26.9648
K21	10	2.97300	1.14826	38.6228
K22	10	2.82400	0.63684	22.5508
K23	10	3.68300	0.77620	21.0753
K31	10	3.50900	0.76884	21.9106
K32	10	3.73300	0.75178	20.1389
K33	10	3.87600	0.87833	22.6608

Level	Sample size	Average	Standard deviation	Coefficient of variation
L11	10	3.89100	0.85454	21.9619
L12	10	3.95000	0.83156	21.0521
L13	10	4.43300	0.59230	13.3612
L21	10	4.33200	0.65566	15.1352
L22	10	4.30000	0.39457	9.17615
L23	10	3.99100	0.73030	18.2988
L31	10	3.27500	0.87937	26.8510
L32	10	3.03300	0.77919	25.6904
L33	10	3.05000	0.45867	15.0383

Level	Sample size	Average	Standard deviation	Coefficient of variation
M11	10	2.23300	1.01004	45.2324
M12	10	2.25900	0.66857	29.5959
M13	10	1.94900	0.43442	22.2894
M21	10	1.90800	0.58093	30.4473
M22	10	1.79100	0.52431	29.2746
M23	10	1.97500	0.82542	41.7934
M31	10	2.00900	0.43021	21.4139
M32	10	2.00900	1.12522	56.0090
M33	10	2.59200	0.88820	34.2671

Level	Sample size	Average	Standard deviation	Coefficient of variation
N11	10	3.13400	0.65352	20.8527
N12	10	2.27600	0.59216	26.0174
N13	10	2.70100	0.69166	25.6074
N21	10	3.12600	0.75301	24.0887
N22	10	2.97500	1.36106	45.7500
N23	10	2.55800	0.73493	28.7308
N31	10	2.55700	0.79571	31.1189
N32	10	2.16600	0.94183	43.4826
N33	10	2.24200	0.53087	23.6782

Level	Sample size	Average	Standard deviation	Coefficient of variation
O11	10	2.30800	1.27250	55.1344
O12	10	2.06700	0.57875	27.9997
O13	10	2.71700	0.68039	25.0421
O21	10	3.15000	0.91914	29.1791
O22	10	2.45100	0.80507	32.8467
O23	10	2.42400	1.21312	50.0460
O31	10	2.57600	0.90228	35.0265
O32	10	3.34300	0.67077	20.0650
O33	10	2.64300	1.01961	38.5777

Level	Sample size	Average	Standard deviation	Coefficient of variation
P11	10	1.63300	0.65705	40.2356
P12	10	2.00800	0.57967	28.8680
P13	10	1.78200	0.43946	24.6613
P21	10	1.91900	0.74941	39.0519
P22	10	2.17500	0.83564	38.4202
P23	10	2.09200	0.81036	38.7362
P31	10	1.89200	0.97543	51.5555
P32	10	1.40000	0.53657	38.3267
P33	10	1.95000	0.94976	48.7057

Level	Sample size	Average	Standard deviation	Coefficient of variation
Q11	10	2.48300	0.58731	23.6533
Q12	10	2.43300	0.98615	40.5322
Q13	10	2.13300	0.54675	25.6329
Q21	10	1.88400	0.88750	47.1070
Q22	10	1.63400	0.97932	59.9340
Q23	10	1.55000	0.74358	47.9729
Q31	10	1.71600	0.86920	50.6529
Q32	10	1.75800	0.89126	50.6976
Q33	10	1.88300	0.54849	29.1287

Level	Sample size	Average	Standard deviation	Coefficient of variation
R11	10	1.90900	0.99196	51.9624
R12	10	2.56800	1.35010	52.5740
R13	10	2.05700	0.63388	30.8156
R21	10	2.42500	0.89967	37.0998
R22	10	1.92500	0.61032	31.7051
R23	10	2.05600	0.55540	27.0137
R31	10	2.16500	0.64894	29.9739
R32	10	1.77600	0.81704	46.0047
R33	10	1.51800	0.71476	47.0858

IP for J (1,2,3) Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	4.19500	0.62451	14.8871
10	30	3.49433	0.80045	22.9071
15	30	3.48367	0.76229	21.8820

IP for K Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	3.94433	1.03705	26.2922
10	30	3.16000	0.93131	29.4718
15	30	3.70600	0.78859	21.2787

IP for L Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	4.09133	0.78172	19.1066
10	30	4.20767	0.60968	14.4897
15	30	3.11933	0.71154	22.8105

IP for M Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.14700	0.73095	34.0453
10	30	1.89133	0.63834	33.7506
15	30	2.20333	0.87940	39.9121

IP for N Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.70367	0.71886	26.5884
10	30	2.88633	0.98904	34.2664
15	30	2.32167	0.76739	33.0535

IP for O Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.36400	0.90808	38.4131
10	30	2.67500	1.01827	38.0663
15	30	2.85400	0.91618	32.1016

IP for P Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.80767	0.56814	31.4295
10	30	2.06200	0.77882	37.7704
15	30	1.74733	0.85297	48.8155

IP for Q Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.34967	0.72549	30.8765
10	30	1.68933	0.85703	50.7317
15	30	1.78567	0.76129	42.6334

IP for R Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.17800	1.03837	47.6753
10	30	2.13533	0.71336	33.4076
15	30	1.81967	0.75470	41.4748

STATISTICS OF IP FOR ALL SETS: J,K,L,M,N,O,P,Q,R:

Variable:	aipj	aipk	aipl
Sample size	90	90	90
Average	3.72433	3.60344	3.80611
Standard deviation	0.798268	0.971949	0.852036
Coeff. of variation	21.4338	26.9728	22.386

Variable:	aipm	aipn	aipo
Sample size	90	90	90
Average	2.08056	2.63722	2.631
Standard deviation	0.75993	0.85731	0.959952
Coeff. of variation	36.5253	32.5081	36.4862

Variable:	aipp	aipq	aipr
Sample size	90	90	90
Average	1.87233	1.94156	2.04433
Standard deviation	0.747459	0.827924	0.85356
Coeff. of variation	39.9212	42.6423	41.7525

APPENDIX F

ANALYSIS OF VARIANCE, IS VALUES: POLLET WHEAT

These analalysis contains combined: Control Samples:
J,K,L,...,P,Q,R.

Analysis of Variance for COMBINE.aIS - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:COMBINE.Moist	44.870250	2	22.435125	51.615	.0000
B:COMBINE.treatm	8.396058	1	8.396058	19.316	.0000
INTERACTIONS					
AB	4.5822946	2	2.2911473	5.271	.0053
RESIDUAL	375.54742	864	.4346614		
TOTAL (CORRECTED)	575.31326	869			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table of Least Squares Means for COMBINE.aIS

Level	Count	Average	Stnd. Error	95 Percent Confidence for mean	
GRAND MEAN	870	1.5526759	.0441049	1.4660915	1.6392603
A:COMBINE.Moist					
15	290	1.0406759	.0763920	.8907074	1.1906445
20	290	1.4852500	.0763920	1.3352814	1.6352186
25	290	2.1321019	.0763920	1.9821333	2.2820704
B:COMBINE.treatm					
Temp*time	810	1.7465185	.0231650	1.7010422	1.7919949
Control	60	1.3588333	.0851138	1.1917426	1.5259241
AB					
15 Temp X time (P,Q,R)	270	1.3558519	.0401230	1.2770845	1.4346192
15 Control PQR	20	.7255000	.1474214	.4360903	1.0149097
20 Temp X time (M,N,O)	270	1.4780000	.0401230	1.3992327	1.5567673
20 Control MNO	20	1.4925000	.1474214	1.2030903	1.7819097
25 Temp*time (J,K,L)	270	2.4057037	.0401230	2.3269364	2.4844711
25 Control JKL	20	1.8585000	.1474214	1.5690903	2.1479097

Multiple range analysis for COMBINE.aIS by COMBINE.Moist

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
15	290	1.0406759	X
20	290	1.4852500	X
25	290	2.1321019	X

contrast	difference	+/-	limits	
15 - 20	-0.44457		0.25363	*
15 - 25	-1.09143		0.25363	*
20 - 25	-0.64685		0.25363	*

* denotes a statistically significant difference.

Multiple range analysis for COMBINE.aIS by COMBINE.treatm

Method: 95 Percent Tukey HSD

Level	Count	LS Mean	Homogeneous Groups
Control	60	1.3588333	X
TempXtime	810	1.7465185	X

contrast	difference	+/-	limits
Temp X time - Control	0.38769		0.17313 *

* denotes a statistically significant difference.

IS VALUES FOR POLLET WHEAT

Level	Sample size	Average	Standard deviation	Coefficient of variation
J11	10	2.79300	0.51504	18.4404
J12	10	2.75900	0.50718	18.3828
J13	10	2.61000	0.60882	23.3266
J21	10	2.24800	0.70383	31.3091
J22	10	2.21700	0.71231	32.1292
J23	10	2.21800	0.31902	14.3832
J31	10	1.84900	0.49626	26.8395
J32	10	2.26600	0.50151	22.1321
J33	10	2.29200	0.31999	13.9613

Level	Sample size	Average	Standard deviation	Coefficient of variation
K11	10	3.12300	0.65510	20.9766
K12	10	3.14900	0.48193	15.3042
K13	10	1.86800	0.57244	30.6444
K21	10	1.93400	0.93955	48.5808
K22	10	1.83400	0.38882	21.2007
K23	10	2.23300	0.66034	29.5718
K31	10	2.36600	0.58230	24.6111
K32	10	2.67600	0.55849	20.8705
K33	10	2.49200	0.57919	23.2420

Level	Sample size	Average	Standard deviation	Coefficient of variation
L11	10	2.53300	0.60592	23.9209
L12	10	2.72500	0.54848	20.1276
L13	10	2.96700	0.63802	21.5038
L21	10	2.77400	0.72832	26.2552
L22	10	2.77500	0.31440	11.3299
L23	10	2.58500	0.60665	23.4682
L31	10	2.01800	0.68944	34.1646
L32	10	1.85800	0.66173	35.6151
L33	10	1.79200	0.48989	27.3378

Level	Sample size	Average	Standard deviation	Coefficient of variation
M11	10	1.14300	0.52303	45.7591
M12	10	1.41700	0.48630	34.3192
M13	10	1.21600	0.39224	32.2562
M21	10	0.96700	0.32170	33.2677
M22	10	1.05800	0.40871	38.6300
M23	10	1.04100	0.41420	39.7891
M31	10	1.06600	0.23866	22.3886
M32	10	1.19100	0.70325	59.0473
M33	10	1.55800	0.52453	33.6667

Level	Sample size	Average	Standard deviation	Coefficient of variation
N11	10	1.85900	0.42715	22.9772
N12	10	1.25900	0.34962	27.7694
N13	10	1.56700	0.45882	29.2799
N21	10	2.00000	0.67505	33.7524
N22	10	1.72400	0.77250	44.8087
N23	10	1.63300	0.38664	23.6766
N31	10	1.56500	0.54750	34.9843
N32	10	1.26700	0.62375	49.2307
N33	10	1.81600	0.61145	33.6702

Level	Sample size	Average	Standard deviation	Coefficient of variation
O11	10	1.94200	1.23403	63.5445
O12	10	1.09200	0.40933	37.4844
O13	10	1.70800	0.42324	24.7796
O21	10	1.85100	0.62319	33.6677
O22	10	1.54100	0.57945	37.6024
O23	10	1.48400	0.70222	47.3195
O31	10	1.39200	0.62789	45.1067
O32	10	2.03300	0.49031	24.1174
O33	10	1.51600	0.72310	47.6978

Level	Sample size	Average	Standard deviation	Coefficient of variation
P11	10	1.16800	0.54303	46.4925
P12	10	1.28200	0.57283	44.6822
P13	10	1.08300	0.25460	23.5092
P21	10	1.21700	0.45903	37.7185
P22	10	1.37400	0.55788	40.6024
P23	10	1.23400	0.57357	46.4805
P31	10	1.35800	0.72711	53.5425
P32	10	0.97400	0.41302	42.4041
P33	10	1.30900	0.71016	54.2518

Level	Sample size	Average	Standard deviation	Coefficient of variation
Q11	10	1.77500	0.52148	29.3790
Q12	10	1.75000	0.83241	47.5664
Q13	10	1.72500	0.73162	42.4129
Q21	10	1.25800	0.66886	53.1685
Q22	10	1.27600	0.87165	68.3115
Q23	10	1.22400	0.77210	63.0800
Q31	10	1.25900	0.85245	67.7088
Q32	10	1.39200	0.79064	56.7986
Q33	10	1.24900	0.45427	36.3711

Level	Sample size	Average	Standard deviation	Coefficient of variation
R11	10	1.19900	0.62283	51.9460
R12	10	1.76700	1.19347	67.5424
R13	10	1.52600	0.49898	32.6986
R21	10	1.63400	0.68263	41.7766
R22	10	1.43300	0.43874	30.6167
R23	10	1.37600	0.43347	31.5019
R31	10	1.51600	0.50483	33.2998
R32	10	1.27400	0.65524	51.4316
R33	10	0.97600	0.60289	61.7711

IS for J (1,2,3) Level (time)	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.72067	0.53266	19.5782
10	30	2.22767	0.58566	26.2903
15	30	2.13567	0.47842	22.4015

IS FOR K Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.71333	0.82261	30.3174
10	30	2.00033	0.69708	34.8484
15	30	2.51133	0.56824	22.6272

IS FOR L Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	2.74167	0.60518	22.0736
10	30	2.71133	0.56371	20.7909
15	30	1.88933	0.60598	32.0735

IS FOR M Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.25867	0.46896	37.2584
10	30	1.02200	0.37258	36.4561
15	30	1.27167	0.54923	43.1894

IS FOR N Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.56167	0.47114	30.1691
10	30	1.78567	0.63103	35.3389
15	30	1.54933	0.61798	39.8867

IS for O Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.58067	0.84448	53.4257
10	30	1.62533	0.63613	39.1387
15	30	1.64700	0.66253	40.2265

IS for P Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.17767	0.46941	39.8590
10	30	1.27500	0.51884	40.6936
15	30	1.21367	0.63534	52.3485

IS for Q Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.75000	0.68263	39.0075
10	30	1.25267	0.74841	59.7457
15	30	1.30000	0.69854	53.7339

IS for R Level	Sample size	Average	Standard deviation	Coefficient of variation
5	30	1.49733	0.83412	55.7071
10	30	1.48100	0.52472	35.4303
15	30	1.25533	0.61286	48.8201

STATISTICS IS FOR ALL SETS: J,K,L,M,N,O,O,P,Q,R:

Variable:	aisj	aisk	aisl
Sample size	90	90	90
Average	2.36133	2.40833	2.44744
Standard deviation	0.587798	0.758347	0.707236
Coeff. of variation	24.8926	31.4885	28.8969

Variable:	aism	aisn	aiso
Sample size	90	90	90
Average	1.18411	1.63222	1.61767
Standard deviation	0.478015	0.581764	0.712763
Coeff. of variation	40.3691	35.6424	44.0612

Variable:	aisp	aisq	aisr
Sample size	90	90	90
Average	1.22211	1.43422	1.41122
Standard deviation	0.540993	0.737661	0.671669
Coeff. of variation	44.2671	51.4328	47.5948

APPENDIX G

SAS output for analysis of RF treatment of carrot sticks

APPENDIX G

PRINTOUT OF STATISTICAL ANALYSIS OF CARROTS

OBS	T	R	D	M	A	C	O	X	S
1	1	1	1	10	5.00	5.0	5.0	5.00	5.00
2	1	1	7	1300000	4.00	4.0	4.0	4.00	4.00
3	1	1	14	2300000	4.00	3.5	3.5	4.00	3.25
4	1	2	1	130	5.00	5.0	5.0	5.00	5.00
5	1	2	7	1700000	4.00	4.0	4.0	4.00	4.00
6	1	2	14	2100000	4.00	3.5	3.5	4.00	3.25
7	2	1	1	40	5.00	5.0	5.0	5.00	5.00
8	2	1	7	55000	5.00	5.0	5.0	5.00	5.00
9	2	1	14	3000000	5.00	5.0	5.0	4.75	5.00
10	2	2	1	200	5.00	5.0	5.0	5.00	5.00
11	2	2	7	65000	5.00	5.0	5.0	5.00	5.00
12	2	2	14	3000000	5.00	5.0	5.0	4.75	5.00
13	3	1	1	25	5.00	5.0	5.0	5.00	5.00
14	3	1	7	16500	4.75	5.0	5.0	4.75	5.00
15	3	1	14	2400000	4.50	5.0	5.0	4.50	4.50
16	3	2	1	55	5.00	5.0	5.0	5.00	5.00
17	3	2	7	12500	4.75	5.0	5.0	4.75	5.00
18	3	2	14	2000000	4.50	5.0	5.0	4.50	4.50
19	4	1	1	25	5.00	5.0	5.0	5.00	5.00
20	4	1	7	150000	4.75	5.0	5.0	5.00	5.00
21	4	1	14	3000000	4.50	5.0	5.0	5.00	5.00
22	4	2	1	20	5.00	5.0	5.0	5.00	5.00
23	4	2	7	120000	4.75	5.0	5.0	5.00	5.00
24	4	2	14	3000000	4.50	5.0	5.0	5.00	5.00
25	5	1	1	10	5.00	5.0	5.0	4.75	4.75
26	5	1	7	200000	3.80	3.8	3.5	4.00	2.00
27	5	1	14	3000000	1.30	4.0	2.7	2.50	0.00
28	5	2	1	10	5.00	5.0	5.0	4.75	4.75
29	5	2	7	180000	3.80	3.8	3.5	4.00	2.00
30	5	2	14	3000000	1.30	4.0	2.7	2.50	0.00

GLM ANALYSIS Microbial Count Effects

Class Level Information

Class	Levels	Values
T	5	1 2 3 4 5
R	2	1 2
D	3	1 7 14

Number of observations in data set = 30

GLM ANALYSIS Microbial Count Effects

Dependent Variable: M

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	4.69758E+13	3.35541E+12	416.97	0.0001
Error	15	1.20708E+11	8.04720E+09		
Corrected Total	29	4.70965E+13			

R-Square	C.V.	Root MSE	M Mean
0.997437	8.737731	89706.19	1026653

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	8.55398E+11	2.13850E+11	26.57	0.0001
D	2	4.18027E+13	2.09013E+13	2597.34	0.0001
T*D	8	4.31767E+12	5.39709E+11	67.07	0.0001

GLM ANALYSIS Microbial Count Effects

T tests (LSD) for variable: M

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 8.0472E9
Critical Value of T= 2.13
Least Significant Difference= 110392

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	1266702	6	1
B	1063337	6	5
B	1045008	6	4
B	1020040	6	2
C	738180	6	3

GLM ANALYSIS Microbial Count Effects

T tests (LSD) for variable: M

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 8.0472E9
Critical Value of T= 2.13
Least Significant Difference= 85509

Means with the same letter are not significantly different.

T Grouping	Mean	N	D
A	2680000	10	14
B	399900	10	7
C	60	10	1

Level of T	Level of D	N	M Mean	M SD
1	1	2	105.00	49.497
1	7	2	1600000.00	141421.356
1	14	2	2200000.00	141421.356
2	1	2	120.00	113.137
2	7	2	60000.00	7071.068
2	14	2	3000000.00	0.000
3	1	2	40.00	21.213
3	7	2	14500.00	2828.427
3	14	2	2200000.00	282842.712
4	1	2	22.50	3.536
4	7	2	135000.00	21213.203
4	14	2	3000000.00	0.000
5	1	2	10.00	0.000
5	7	2	190000.00	14142.136
5	14	2	3000000.00	0.000

GLM ANALYSIS Appearance effect

Dependent Variable: A

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	26.10200000	1.86442857	99999.99	0.0001
Error	15	0.00000000	0.00000000		
Corrected Total	29	26.10200000			

R-Square	C.V.	Root MSE	A Mean
1.000000	0	0	4.440000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	10.01533333	2.50383333	99999.99	0.0001
D	2	6.50400000	3.25200000	99999.99	0.0001
T*D	8	9.58266667	1.19783333	99999.99	0.0001

GLM ANALYSIS Appearance effect

T tests (LSD) for variable: A

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0
Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	5.000	6	2
B	4.750	6	3
C	4.750	6	4
D	4.333	6	1
E	3.367	6	5

GLM ANALYSIS Appearance Effect

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0
Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	D
A	5.000	10	1
B	4.460	10	7
C	3.860	10	14

GLM ANALYSIS Colour Effects

General Linear Models Procedure

Dependent Variable: C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	8.43466667	0.60247619	99999.99	0.0001
Error	15	0.00000000	0.00000000		
Corrected Total	29	8.43466667			

R-Square	C.V.	Root MSE	C Mean
1.000000	0	0	4.686667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	4.44800000	1.11200000	99999.99	0.0001
D	2	1.49066667	0.74533333	99999.99	0.0001
T*D	8	2.49600000	0.31200000	99999.99	0.0001

GLM ANALYSIS Colour Effects

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0
Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	5.000	6	3
B	5.000	6	2
C	5.000	6	4
D	4.267	6	5
E	4.167	6	1

GLM ANALYSIS Colour Effects

Duncan's Multiple Range Test for variable: C

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 15 MSE= 0
Number of Means 2 3 4 5
Critical Range 0 0 0 0

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	T
A	5.000	6	3
B	5.000	6	2
C	5.000	6	4
D	4.267	6	5
E	4.167	6	1

GLM ANALYSIS Colour Effects

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	D
A	5.000	10	1
B	4.560	10	7
C	4.500	10	14

GLM ANALYSIS Odour Effects

Dependent Variable: O

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	16.28800000	1.16342857	99999.99	0.0001
Error	15	0.00000000	0.00000000		
Corrected Total	29	16.28800000			

R-Square	C.V.	Root MSE	O Mean
1.000000	0	0	4.580000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	8.50133333	2.12533333	99999.99	0.0001
D	2	2.98400000	1.49200000	99999.99	0.0001
T*D	8	4.80266667	0.60033333	99999.99	0.0001

GLM ANALYSIS Odour Effects

T tests (LSD) for variable: O

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	5.000	6	3
B	5.000	6	2
C	5.000	6	4
D	4.167	6	1
E	3.733	6	5

GLM ANALYSIS Odour Effects

T tests (LSD) for variable: O

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

T Grouping	Mean	N	D
A	5.000	10	1
B	4.500	10	7
C	4.240	10	14

GLM ANALYSIS Texture Effects

Dependent Variable: X

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	13.30000000	0.95000000	99999.99	0.0001
Error	15	0.00000000	0.00000000		
Corrected Total	29	13.30000000			

R-Square	C.V.	Root MSE	X Mean
1.000000	0	0	4.550000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	6.38333333	1.59583333	99999.99	0.0001
D	2	3.20000000	1.60000000	99999.99	0.0001
T*D	8	3.71666667	0.46458333	99999.99	0.0001

GLM ANALYSIS Texture Effects

T tests (LSD) for variable: X

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	5.000	6	4
B	4.917	6	2
C	4.750	6	3
D	4.333	6	1
E	3.750	6	5

GLM ANALYSIS Texture Effects

T tests (LSD) for variable: X

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	D
A	4.950	10	1
B	4.550	10	7
C	4.150	10	14

GLM ANALYSIS Taste Effects

Dependent Variable: S

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	14	59.11666667	4.22261905	99999.99	0.0001
Error	15	0.00000000	0.00000000		
Corrected Total	29	59.11666667			

R-Square	C.V.	Root MSE	S Mean
1.000000	0	0	4.233333

Source	DF	Type I SS	Mean Square	F Value	Pr > F
T	4	32.95000000	8.23750000	99999.99	0.0001
D	2	9.81666667	4.90833333	99999.99	0.0001
T*D	8	16.35000000	2.04375000	99999.99	0.0001

GLM ANALYSIS Taste Effects

T tests (LSD) for variable: S

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 15 MSE= 0 Critical Value of T= 2.13
Least Significant Difference= 0

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	5.000	6	2
B	5.000	6	4
C	4.833	6	3
D	4.083	6	1
E	2.250	6	5

T tests (LSD) for variable: S

T Grouping	Mean	N	D
A	4.950	10	1
B	4.200	10	7
C	3.550	10	14

APPENDIX H

SAS output for analysis of RF treatment of ham

Appendix H: Statistical analysis of Ham Experiment

PRINTOUT OF STATISTICAL ANALYSIS OF HAM

OBS	R	T	P	X	D	C	L
1	1	70	1	1	1.66	909.00	52.295
2	2	70	1	1	2.44	0.00	49.795
3	3	70	1	1	4.12	0.00	58.845
4	1	80	1	1	2.94	90.91	61.745
5	2	80	1	1	2.09	182.00	66.305
6	3	80	1	1	1.88	364.00	61.945
7	1	70	2	1	1.65	91.00	53.200
8	2	70	2	1	2.31	546.00	54.940
9	3	70	2	1	2.20	137.00	52.145
10	1	80	2	1	2.27	410.00	55.830
11	2	80	2	1	2.83	320.00	59.475
12	3	80	2	1	2.13	2600.00	59.575
13	1	70	3	1	4.66	545.00	53.455
14	2	70	3	1	4.45	273.00	57.895
15	3	70	3	1	4.59	0.00	66.260
16	1	80	3	1	6.99	182.00	58.545
17	2	80	3	1	4.80	591.00	60.050
18	3	80	3	1	5.49	320.00	49.720
19	1	70	1	7	3.27	25000000.00	56.160
20	2	70	1	7	3.10	30600000.00	47.775
21	3	70	1	7	3.17	28000000.00	52.925
22	1	80	1	7	2.50	650000.00	60.100
23	2	80	1	7	2.43	250000.00	55.980
24	3	80	1	7	2.63	2900000.00	53.275
25	1	70	2	7	1.90	27300000.00	45.695
26	2	70	2	7	2.53	70000000.00	46.320
27	3	70	2	7	2.37	38000000.00	55.930
28	1	80	2	7	2.03	200000.00	57.350
29	2	80	2	7	1.80	90.00	57.175
30	3	80	2	7	2.37	180.00	55.625
31	1	70	3	7	8.00	26000000.00	61.055
32	2	70	3	7	8.90	70000000.00	57.500
33	3	70	3	7	8.10	38000000.00	58.610
34	1	80	3	7	6.40	1200000.00	53.840
35	2	80	3	7	5.90	1400000.00	60.260
36	3	80	3	7	6.83	1200000.00	51.735
37	1	70	1	14	3.17	10500000.00	58.095
38	2	70	1	14	2.82	5600000.00	55.995
39	3	70	1	14	2.92	11000000.00	54.165
40	1	80	1	14	1.82	5900000.00	50.220
41	2	80	1	14	3.61	5400000.00	54.735
42	3	80	1	14	3.04	960000.00	53.925
43	1	70	2	14	3.27	10000000.00	47.760
44	2	70	2	14	2.12	22000000.00	50.730
45	3	70	2	14	1.72	16000000.00	51.360
46	1	80	2	14	2.92	3400000.00	57.730
47	2	80	2	14	2.12	3100000.00	50.645
48	3	80	2	14	2.39	5700000.00	54.045
49	1	70	3	14	5.61	21000000.00	59.005
50	2	70	3	14	5.40	6400000.00	59.460
51	3	70	3	14	5.91	14000000.00	49.110
52	1	80	3	14	9.41	4400000.00	55.405
53	2	80	3	14	8.78	1000000.00	56.170
54	3	80	3	14	6.82	470000.00	54.400
55	1	70	1	21	2.93	70000000.00	56.155
56	2	70	1	21	2.53	70000000.00	57.710
57	3	70	1	21	3.07	70000000.00	60.935
58	1	80	1	21	2.74	700000.00	55.210
59	2	80	1	21	2.72	1130000.00	58.295
60	3	80	1	21	2.71	282000.00	60.175
61	1	70	2	21	2.78	70000000.00	60.720

62	2	70	2	21	2.42	70000000	59.570
63	3	70	2	21	1.96	70000000	57.445
64	1	80	2	21	1.79	69000	53.700
65	2	80	2	21	1.30	19700	54.525
66	3	80	2	21	1.97	140000	50.735
67	1	70	3	21	8.07	70000000	55.930
68	2	70	3	21	7.67	70000000	61.375
69	3	70	3	21	9.09	70000000	60.320
70	1	80	3	21	5.89	8600000	50.930
71	2	80	3	21	6.99	740000	51.470
72	3	80	3	21	6.20	3000000	49.360
73	1	80	1	28	3.66	70000000	56.300
74	2	80	1	28	2.98	70000000	60.795
75	3	80	1	28	2.98	70000000	58.915
76	1	80	2	28	2.65	16000000	59.490
77	2	80	2	28	2.22	28000000	59.220
78	3	80	2	28	3.34	35000000	58.825
79	1	80	3	28	10.10	8200000	49.840
80	2	80	3	28	10.30	10000000	53.415
81	3	80	3	28	9.32	8300000	56.895

GLM ANALYSIS of moisture loss

General Linear Models Procedure
Class Level Information

Class	Levels	Values
R	3	1 2 3
T	2	70 80
P	3	1 2 3
X	5	1 7 14 21 28

Number of observations in data set = 81

GLM ANALYSIS of moisture loss

General Linear Models Procedure

Dependent Variable: D

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	396.0291329	44.0032370	44.52	0.0001
Error	71	70.1818671	0.9884770		
Corrected Total	80	466.2110000			

R-Square	C.V.	Root MSE	D Mean
0.849463	24.55542	0.994222	4.048889

Source	DF	Type I SS	Mean Square	F Value	Pr > F
R	2	0.2294519	0.1147259	0.12	0.8906
T	1	0.4147200	0.4147200	0.42	0.5192
P	2	371.5880074	185.7940037	187.96	0.0001
X	4	23.7969536	5.9492384	6.02	0.0003

Source	DF	Type III SS	Mean Square	F Value	Pr > F
R	2	0.2294519	0.1147259	0.12	0.8906
T	1	0.3975347	0.3975347	0.40	0.5280
P	2	371.5880074	185.7940037	187.96	0.0001
X	4	23.7969536	5.9492384	6.02	0.0003

GLM ANALYSIS of moisture loss

General Linear Models Procedure

T tests (LSD) for variable: D

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 0.988477
Critical Value of T= 1.99
Least Significant Difference= 0.5395

Means with the same letter are not significantly different.

T Grouping	Mean	N	R
A	4.1141	27	1
A			
A	4.0489	27	3
A			
A	3.9837	27	2

GLM ANALYSIS of moisture loss

General Linear Models Procedure

Duncan's Multiple Range Test for variable: D

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 0.988477

Number of Means	2	3
Critical Range	.5395	.5677

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	R
A	4.1141	27	1
A			
A	4.0489	27	3
A			
A	3.9837	27	2

GLM ANALYSIS of moisture loss

General Linear Models Procedure

T tests (LSD) for variable: D

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 0.988477
Critical Value of T= 1.99
Least Significant Difference= 0.4433
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	4.1129	45	80
A			
A	3.9689	36	70

GLM ANALYSIS of moisture loss

General Linear Models Procedure

Duncan's Multiple Range Test for variable: D

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 0.988477
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Number of Means 2
Critical Range .4433

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	T
A	4.1129	45	80
A			
A	3.9689	36	70

GLM ANALYSIS of moisture loss

General Linear Models Procedure

T tests (LSD) for variable: D

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 0.988477
Critical Value of T= 1.99
Least Significant Difference= 0.5395

Means with the same letter are not significantly different.

T Grouping	Mean	N	P
A	7.0619	27	3
B	2.8122	27	1
C	2.2726	27	2

GLM ANALYSIS of moisture loss

Duncan's Multiple Range Test for variable: D

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 0.988477

Number of Means	2	3
Critical Range	.5395	.5677

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	P
A	7.0619	27	3
B	2.8122	27	1
C	2.2726	27	2

GLM ANALYSIS of moisture loss

General Linear Models Procedure

T tests (LSD) for variable: D

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 0.988477
Critical Value of T= 1.99
Least Significant Difference= 0.7239
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Means with the same letter are not significantly different.

T Grouping	Mean	N	X
A	5.2833	9	28
B	4.1239	18	7
B	4.1028	18	14
B	4.0461	18	21
C	3.3056	18	1

GLM ANALYSIS of moisture loss

General Linear Models Procedure

Duncan's Multiple Range Test for variable: D

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 0.988477
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Number of Means	2	3	4	5
Critical Range	.7239	.7616	.7866	.8048

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	X
A	5.2833	9	28
B	4.1239	18	7
B	4.1028	18	14
B	4.0461	18	21
C	3.3056	18	1

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure
Class Level Information

Class	Levels	Values
R	3	1 2 3
T	2	70 80
P	3	1 2 3
X	5	1 7 14 21 28

Number of observations in data set = 81

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

Dependent Variable: C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	3.15801E+16	3.50890E+15	11.53	0.0001
Error	71	2.15995E+16	3.04219E+14		
Corrected Total	80	5.31796E+16			

R-Square	C.V.	Root MSE	C Mean
0.593838	96.25764	17441867	18119982

Source	DF	Type I SS	Mean Square	F Value	Pr > F
R	2	1.40820E+14	7.04098E+13	0.23	0.7940
T	1	9.99417E+15	9.99417E+15	32.85	0.0001
P	2	2.45774E+14	1.22887E+14	0.40	0.6692
X	4	2.11993E+16	5.29983E+15	17.42	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
R	2	1.40820E+14	7.04098E+13	0.23	0.7940
T	1	1.52131E+16	1.52131E+16	50.01	0.0001
P	2	2.45774E+14	1.22887E+14	0.40	0.6692
X	4	2.11993E+16	5.29983E+15	17.42	0.0001

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 3.042E14
Critical Value of T= 1.99
Least Significant Difference= 9.47E6

Means with the same letter are not significantly different.

T Grouping	Mean	N	R
A	19838582	27	2
A	17887244	27	3
A	16634120	27	1

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

Duncan's Multiple Range Test for variable: C

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 3.042E14

Number of Means	2	3
Critical Range	9465404	9958796

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	R
A	19838582	27	2
A	17887244	27	3
A	16634120	27	1

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 3.042E14
Critical Value of T= 1.99
Least Significant Difference= 7.78E6
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	30538958	36	70
B	8184801	45	80

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

Duncan's Multiple Range Test for variable: C

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 3.042E14
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Number of Means 2
Critical Range 7776623

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	T
A	30538958	36	70
B	8184801	45	80

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 3.042E14
Critical Value of T= 1.99
Least Significant Difference= 9.47E6

Means with the same letter are not significantly different.

T Grouping	Mean	N	P
A	20328650	27	1
A	17960484	27	2
A	16070812	27	3

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

Duncan's Multiple Range Test for variable: C

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 3.042E14

Number of Means 2 3
Critical Range 9465404 9958796

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	P
A	20328650	27	1
A	17960484	27	2
A	16070812	27	3

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

T tests (LSD) for variable: C

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 3.042E14
Critical Value of T= 1.99
Least Significant Difference= 1.27E7
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Means with the same letter are not significantly different.

T Grouping		Mean	N	X
	A	35815594	18	21
	A	35055556	9	28
	B	20038904	18	7
C	B	8157222	18	14
C		420	18	1

GLM ANALYSIS of Microbial Counts

General Linear Models Procedure

Duncan's Multiple Range Test for variable: C

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 3.042E14
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Number of Means	2	3	4	5
Critical Range	12699172	13361127	13798933	14118311

Means with the same letter are not significantly different.

Duncan Grouping		Mean	N	X
	A	35815594	18	21
	A	35055556	9	28
	B	20038904	18	7
C	B	8157222	18	14
C		420	18	1

GLM ANALYSIS of ham colour

General Linear Models Procedure
Class Level Information

Class	Levels	Values
R	3	1 2 3
T	2	70 80
P	3	1 2 3
X	5	1 7 14 21 28

Number of observations in data set = 81

GLM ANALYSIS of ham colour

General Linear Models Procedure

Dependent Variable: L

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	191.2914341	21.2546038	1.17	0.3257
Error	71	1286.7258554	18.1228994		
Corrected Total	80	1478.0172895			

R-Square	C.V.	Root MSE	L Mean
0.129424	7.627962	4.257100	55.80914

Source	DF	Type I SS	Mean Square	F Value	Pr > F
R	2	8.8238321	4.4119160	0.24	0.7846
T	1	7.7986173	7.7986173	0.43	0.5140
P	2	45.9622247	22.9811123	1.27	0.2877
X	4	128.7067601	32.1766900	1.78	0.1433

Source	DF	Type III SS	Mean Square	F Value	Pr > F
R	2	8.8238321	4.4119160	0.24	0.7846
T	1	2.5556837	2.5556837	0.14	0.7084
P	2	45.9622247	22.9811123	1.27	0.2877
X	4	128.7067601	32.1766900	1.78	0.1433

GLM ANALYSIS of ham colour

General Linear Models Procedure

T tests (LSD) for variable: L

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 18.1229
Critical Value of T= 1.99
Least Significant Difference= 2.3103

Means with the same letter are not significantly different.

T Grouping	Mean	N	R
A	56.207	27	2
A	55.822	27	3
A	55.399	27	1

GLM ANALYSIS of ham colour

General Linear Models Procedure

Duncan's Multiple Range Test for variable: L

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 18.1229

Number of Means	2	3
Critical Range	2.310	2.431

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	R
A	56.207	27	2
A	55.822	27	3
A	55.399	27	1

GLM ANALYSIS of ham colour

General Linear Models Procedure

T tests (LSD) for variable: L

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 18.1229
Critical Value of T= 1.99
Least Significant Difference= 1.8981
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Means with the same letter are not significantly different.

T Grouping	Mean	N	T
A	56.0867	45	80
A	55.4622	36	70

GLM ANALYSIS of ham colour

Duncan's Multiple Range Test for variable: L

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 18.1229
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 40

Number of Means	2
Critical Range	1.898

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	T
A	56.0867	45	80
A	55.4622	36	70

GLM ANALYSIS of ham colour

General Linear Models Procedure

T tests (LSD) for variable: L

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 18.1229
Critical Value of T= 1.99
Least Significant Difference= 2.3103

Means with the same letter are not significantly different.

T Grouping	Mean	N	P
A	56.621	27	1
A	56.000	27	3
A	54.806	27	2

GLM ANALYSIS of ham colour

General Linear Models Procedure

Duncan's Multiple Range Test for variable: L

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 18.1229

Number of Means	2	3
Critical Range	2.310	2.431

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	P
A	56.621	27	1
A	56.000	27	3
A	54.806	27	2

GLM ANALYSIS of ham colour

T tests (LSD) for variable: L

NOTE: This test controls the type I comparisonwise error rate not the experimentwise error rate.

Alpha= 0.05 df= 71 MSE= 18.1229
Critical Value of T= 1.99
Least Significant Difference= 3.0995
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Means with the same letter are not significantly different.

T Grouping		Mean	N	X
	A	57.334	18	1
B	A	57.077	9	28
B	A	56.364	18	21
B	A	54.851	18	7
B		54.053	18	14

GLM ANALYSIS of ham colour

General Linear Models Procedure

Duncan's Multiple Range Test for variable: L

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 71 MSE= 18.1229
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 15

Number of Means	2	3	4	5
Critical Range	3.100	3.261	3.368	3.446

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	X
A	57.334	18	1
A	57.077	9	28
A	56.364	18	21
A	54.851	18	7
A	54.053	18	14