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THE USE OF ELECTRICAL PROPERTIES MEASURED AT RADIO FREQUENCIES FOR PAN BOILING & BRIX CONTROL

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Abstract

The theory and development of a probe measuring electrical properties at radio frequencies for use in sugar processing is discussed. Basic relationships between the physical properties and the reactance and resistance of massecuites and syrups are given. It is shown that the new system is less sensitive to encrustation than conductivity measurements and can be used in high purity boilings. Relationships developed enable the generation of different signals with a microprocessor, representing various combinations of mother liquor brix and crystal content. Experiences and results are detailed in the use of radio frequency probes for the control of continuous and batch pans, as well as evaporator syrup brix.

Introduction

In the past, conductivity measurements have been used to control all boilings in raw sugar factories. This measurement generally works well for 'B' and 'C' boilings, but is not satisfctory for 'A' boilings and is ineffective for high grade white sugar boilings.

With the recent introduction of continuous pans for boiling 'A' sugars in raw sugar factories in South Africa, a need for a better measurement of massecuite conditions in the pan became apparent[5-7].

Measurements of massecuite characteristics using changes in electrical properties at radio frequencies have been described by Reichard *et al*[1,2] and Moller[3,4].

This paper describes the theoretical background and the development of a measurement probe using radio frequencies. The probe, referred to as an RF probe, was developed primarily for use in controlling continuous pans boiling 'A' sugars, but has applications in batch boilings of all purities and brix control, some of which are also described.

Theory of radio frequency measurement

Referring to Figure 1, the complex impedance, Z, of material measured at radio frequencies by the probe can be considered to be made up of a parallel resistance, Rm and a parallel capacitance, Cm. Rm is equivalent to the electrical conductivity of the massecuite at radio frequencies, including dielectric losses. Cm is the capacitance across the probe and is directly proportional to the dielectric constant of the material surrounding the probe.

This capacitance Cm, may be converted to a capacitive reactance Xm, given by:

Xm = $1/(2\pi f\mathrm{Cm})$, where:-
Xm = Reactance (Ohms)
f = Frequency of Measurement (Hz)
Cm = Massecuite Capacitance (Farads).

Parallel resistance and reactance, Rm and Xm, may be converted to an equivalent series resistance and reactance, designated Rs and Xs. This series combination is measured directly with an RF probe and these results use to calculate Rm and Xm, which cannot be directly measured.

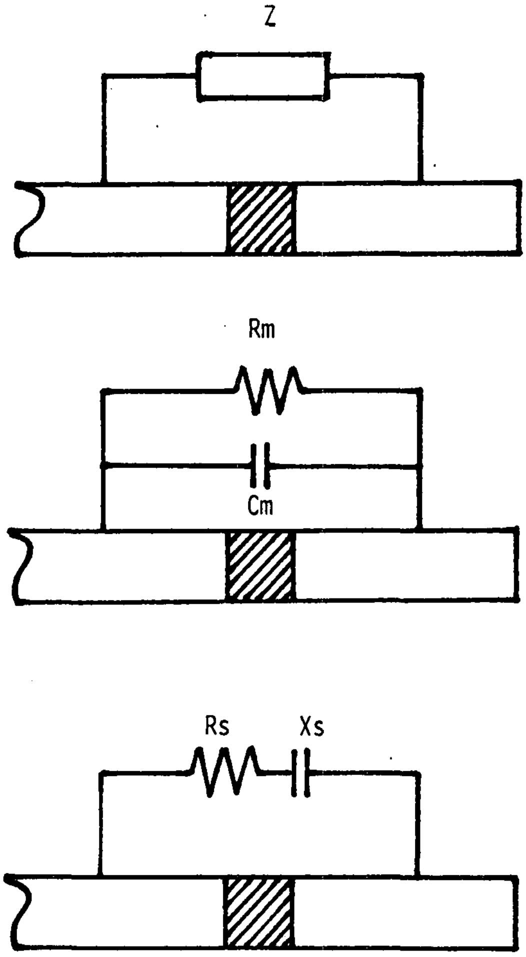

FIGURE 1 Representation of the impedance between the two measuring sections of an RF Probe

It can be shown that the relationships between Rm, Xm and Rs, Xs are as follows:

$$\mathrm{Rs} = \mathrm{Rm\,Xm^2/(Xm^2 + Rm^2)} \qquad \text{........ (1)}$$

$$\mathrm{Xs} = \mathrm{Rm^2\,Xm/(Xm^2 + Rm^2)} \qquad \text{........ (2)}$$

The impedance across the electrode can now be expressed as:-

$$\mathrm{Z} = \mathrm{Rs} - j\mathrm{Xs}, \text{ where } j = \sqrt{-1} \qquad \text{........ (3)}$$

If in the probe measuring circuit a variable inductance with a reactance, X1, is connected in series, then the impedance measured is:

$$\mathrm{Z} = \mathrm{Rs} - j\mathrm{Xs} + j\mathrm{X1} \qquad \text{........ (4)}$$

By adjusting this variable inductance, a value of X1 = Xs may be obtained which cancels out the series capacitance of the material around the probe. Under these conditions, Z = Rs.

Instead of varying X1, one could install a fixed inductor and a variable capacitor Xt, in series, as shown in Figure 2.

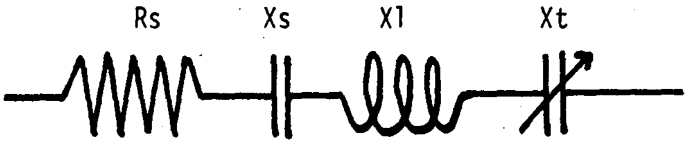

FIGURE 2 Circuit for setting Rs = Z by setting X1 = Xs + Xt

The measured impedance is then:-

$$Z = Rs + jX1 - j(Xs + Xt) \quad \quad (5)$$

where Xt is the reactance of the variable tuning capacitor. As the probe and tuning circuit is tuned through resonance by adjusting the variable capacitor, the following relationship between Z and probe tuning is obtained:-

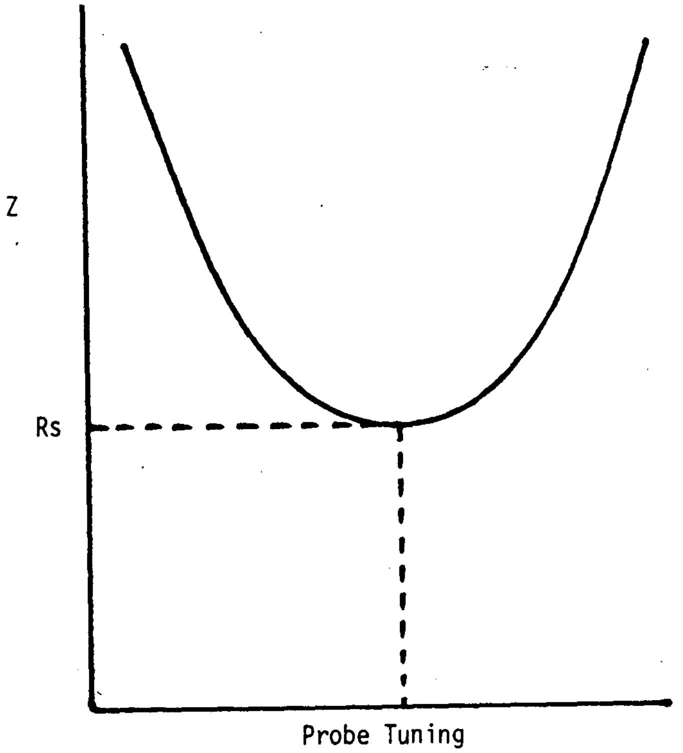

FIGURE 3 Relationship between impedance Z and probe tuning

The minimum value of Z is equivalent to Rs. Any changes in Xs can be compensated for by an adjustment in probe tuning Xt, to keep

$jX1 - j(Xs + Xt) = 0$

If the tuning is carried out automatically to keep the system in resonance, then continuous measurements of Rs and Xs can be obtained.

A probe has been developed which gives an output signal equivalent to Z and which has facilities for continuously varying the tuning by means of an electrical input signal. This probe, when connected to a microprocessor-based controller or analogue controller (which are programmed or designed to continuously vary the tuning to keep the probe and tuning circuit in resonance), is able to provide signals representative of Rs and Xs. If a microprocessor controller is used, this may be programmed to extract absolute values of Rs and Xs and calculate values of Rm and Cm, which may be used individually or in various combinations for control. The development of this probe is now described.

Probe development

Physical Construction

Referring to Figure 4, the wetted part of the probe consists of a stainless steel tube carrying an inner conductor connected to a solid stainless steel section. A Teflon insulator is used to separate these two sections and O-rings are provided for sealing. The probe body is designed with cooling fins to reduce the amount of heat conducted to the box containing the electronics mounted on the end of the probe. The probe is designed so that it can be pulled straight out from the wall of the pan for cleaning after loosening a locking screw.

The measurement path through the massecuite is from the end section of the probe to the tubular section, which represents the shortest electrical path. The idea of the tubular extension is to get the measurement section of the probe well into the massecuite and away from the wall of the pan.

Calibration is done by connecting a simulator between the end and tubular section.

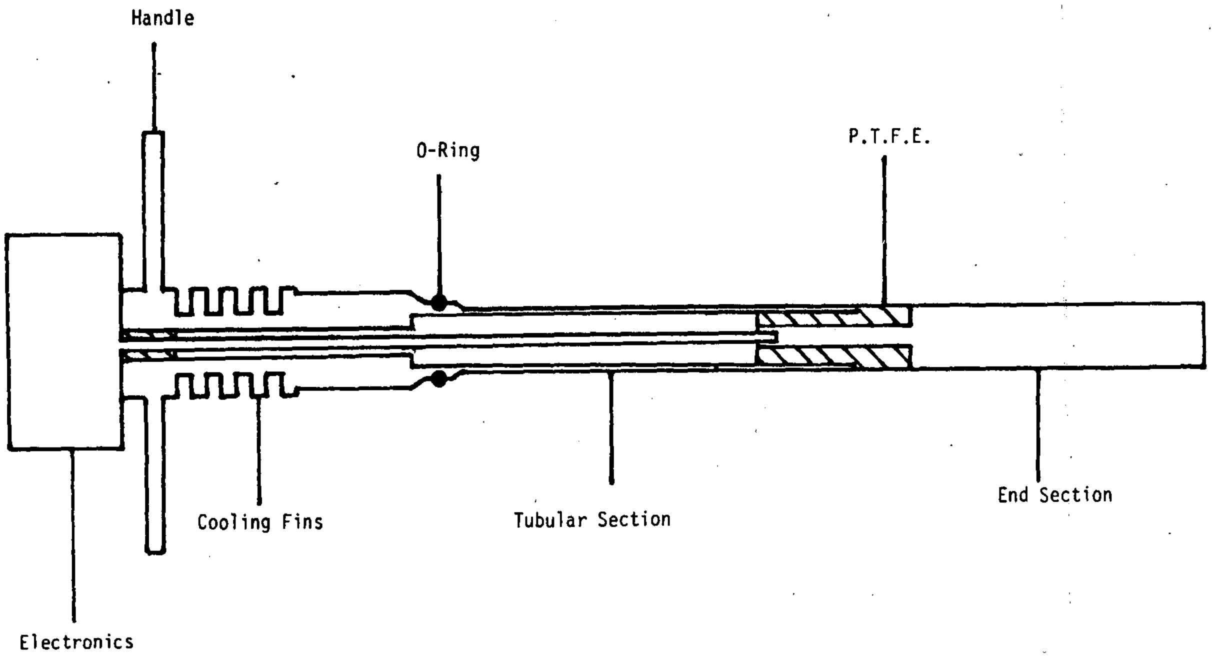

FIGURE 4 Sketch of the RF Probe as currently in use

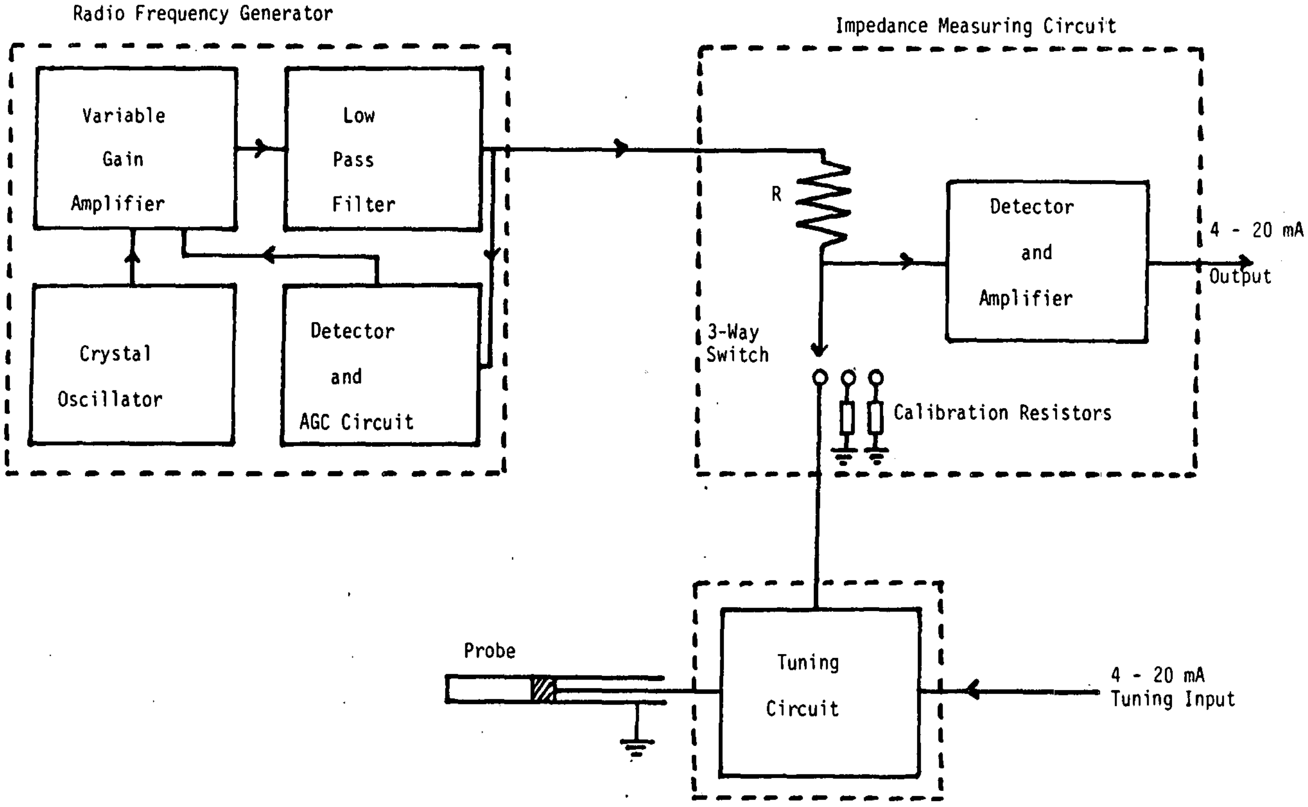

FIGURE 5 Lay-out of the RF Probe electronics

Measurement Circuit

Refferring to Figure 5, the RF probe electronics consist of 3 sections:

The Radio Frequency Generator Section: The purpose of this section is to generate a radio frequency signal of constant frequency and amplitude. This consists of a crystal oscillator feeding a variable gain amplifier, the output of which is passed through a low pass filter to remove undesirable harmonics.

The output amplitude is controlled by a detector and automatic gain control circuit.

The Impedance Measuring Circuit: The output from the radio frequency generator section feeds a voltage divider consisting of resistor R and the probe and tuning circuit. The voltage across the probe and tuning circuit is converted to a 4–20 mA instrumentation signal. Span and zero adjustments are provided to facilitate calibration of the measurement circuit and a switch is provided where fixed resistors can be substituted for the probe and tuning circuit during calibration.

Probe & Tuning Circuit: The tuning circuit contains a fixed inductor and various combinations of varicapdiodes and fixed capacitors, which form part of a series-tuned circuit together with the probe. A 4-20 mA input signal is used to vary the tuning of the circuit. In addition, there are span and zero adjustments used for calibration of the probe-tuning range.

The probe circuit board is usually mounted on the end of the probe, but in hostile environments, e.g. when there is excessive steam or if the electronics would be subjected to temperatures in excess of 60°C, the electronics are mounted remote from the probe. A ½ or 1 wavelength length of low loss coaxial cable is then used to couple the probe circuit to the probe. This does, however, result in changes in calibration.

The probe can be used in two different ways:

With Fixed Tuning: In this mode, the probe requires a preset 4–20 mA signal and the output from the probe can be fed directly into a controller. Under these conditions, the output will vary according to massecuite impedance. The response obtained from the instrument is dependent on where the fixed tuning is set in relation to the resonance curve. Referring to Figure 6, there are three possibilities where the fixed tuning may be set:

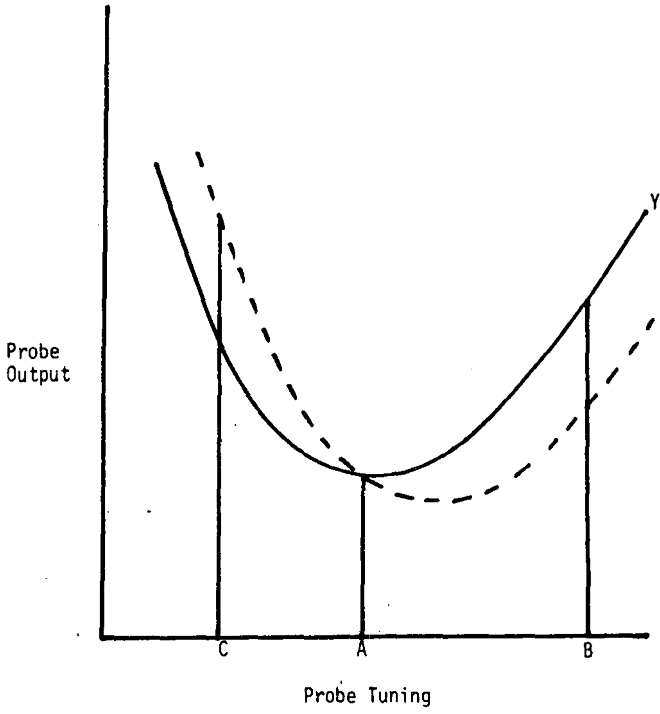

FIGURE 6 Impedance versus probe tuning for two different massecuite conditions

A At the minimum output point, i.e. with the probe and tuning circuit at resonance.

B On the side of the curve where the probe and tuning circuit exhibits inductive reactance.

C On the side of the curve where the probe and tuning circuit exhibits capacitive reactance.

In all three positions, the probe will respond to changes in capacitance and resistance of the massecuite, but the relative sensitivity to each will vary.

This is illustrated in Figure 6, where the change in output is shown for two different massecuite conditions, Y and Z.

With Automatic Tuning: If continuous outputs of massecuite series resistance and capacitance are required, the probe may be connected to a microprocessor programmed to make continuous adjustments to the tuning, keeping the probe and tuning circuit in resonance. The microprocessor can be programmed to extract absolute values of series resistance and capacitance by reference to calibration tables in the unit. From these values, parallel capacitance and resistance may be calculated and any required combination of these used for control. A Yokogawa single loop programmable controller has been successfully used to perform these functions, as well as controlling pan feed according to the signal obtained.

An analogue circuit board has been developed which is far cheaper and provides output signals equivalent to series resistance and series capacitance. This is presently being evaluated on a high grade batch pan in a raw sugar factory.

Experimental Details & Results

Maidstone 'A' Continuous Pan

Initial tests on a prototype radio frequency probe were carried out at Maidstone in one compartment of a continuous 'A' pan late in the 1983/84 season. These tests indicated that the measurement obtained was superior to that obtained from existing conductivity transmitters. The following season, RF probes were installed in all compartments of the Maidstone 'A' continuous pan. During this season, the following unforeseen problems were encountered:

Mechanical: The physical strength of these probes was inadequate and probes were bent by forces in the pan. Sealing of the box housing the electronics was inefficient, allowing ingress of moisture.

Electronic: Severe problems were experienced with changes in calibration due to temperature effects on electronic components.

Measurement: With these probes, measurement was between a P.T.F.E. covered cylindrical rod which protruded about 400 mm into the pan and the pan wall. It was found that stagnant massecuite against the wall of the pan often resulted in measurements not representative of the material in the pan, giving poor control.

Calibration: Calibration of these RF probes proved to be a problem, as the probes were P.T.F.E. covered, preventing use of a simulator on the probe.

A new probe was then designed to overcome the above problems. As experience had shown that P.T.F.E. coating did not prevent sugar encrustation on the probes, it was dispensed with in favour of uncoated stainless steel. This had the advantage of allowing workshop calibration using a simulator. These probes have been described earlier and illustrated in Figure 4.

These new probes were installed at the start of the 1985/86 season. The probes were interfaced with a G.E.C. Gem 80 microprocessor system, which was used to continuously vary the tuning and extract a signal equivalent to Rs for control purposes. This signal responded well to changes in crystal content and tests showed that good control of mother liquor brix was obtained.

Crystal content profiles were measured daily using a Gilette meter and adjustments made to controller settings where necessary. During this season, Maidstone achieved a record season average 'A' exhaustion of 64,92, at one of the lowest 'A' massecuite purities recorded of 83,10. No major problems have been experienced with these probes since installation.

Syrup Brix Measurement

An RF probe was fitted onto the outlet syrup line from one of the last effect evaporators at Maidstone to measure syrup brix leaving the vessel. The probe was operated with fixed tuning adjusted to the side of the resonance curve which gave the greatest sensitivity. The output of the probe, together with the output of a nuclear density meter installed on the same line, were recorded. For the duration of these tests the evaporator was on manual control and consequently large variations in brix were obtained. In order to assess the possible effects of scaling on the RF probe electrode, the nuclear density meter output was plotted against RF probe output on the first day of operation and again after one week of operation. These results are shown in Figure 7.

The measurement from the RF probe was then used to control brix. Routine laboratory analyses showed that good control was obtained, with very little shift in calibration over a period of three weeks. These tests showed that radio frequency measurements can be used in place of a nuclear density meter for evaporator brix control and radio frequency probes are now being installed on both sets of evaporators at Maidstone, to replace the existing system utilising level transmitters.

Control of Refinery white batch pans

A radio frequency probe has been adapted to fit a white sugar batch pan at Hulett Refinery. This, coupled to a Yokogawa single loop programmable controller, is used to give continuous output measurements of series capacitance, which has been shown to be closely related to crystal content. It has been found that this measurement enables seeding point to be accurately determined, since the measurement also varies with liquor brix. Once crystal content has been established in the pan, variations in mother liquor brix are small and hence changes in crystal content predominate in affecting the series capacitance.

As a trial, the pan has been fully automated, with an additional Yokogawa SLPC to control the entire boiling cycle and absolute pressure. The radio frequency probe used here has the electronics separated from the probe by means of a 1 wavelength length of coaxial cable, since temperatures under the pan are in excess of 80°C. The probe has proved very reliable in this application and the only problem experienced has been a shift in calibration due to ingress of moisture into the coaxial cable, which was remedied by replacing with a higher grade cable and improved sealing. Experiments are still in progress to optimise boiling profiles and some of the results of automatic boiling versus manual boiling are shown in Table 1.

These tests have shown that reliable measurements can be obtained from an RF probe in a Refinery white pan, which can be used to control the boiling.

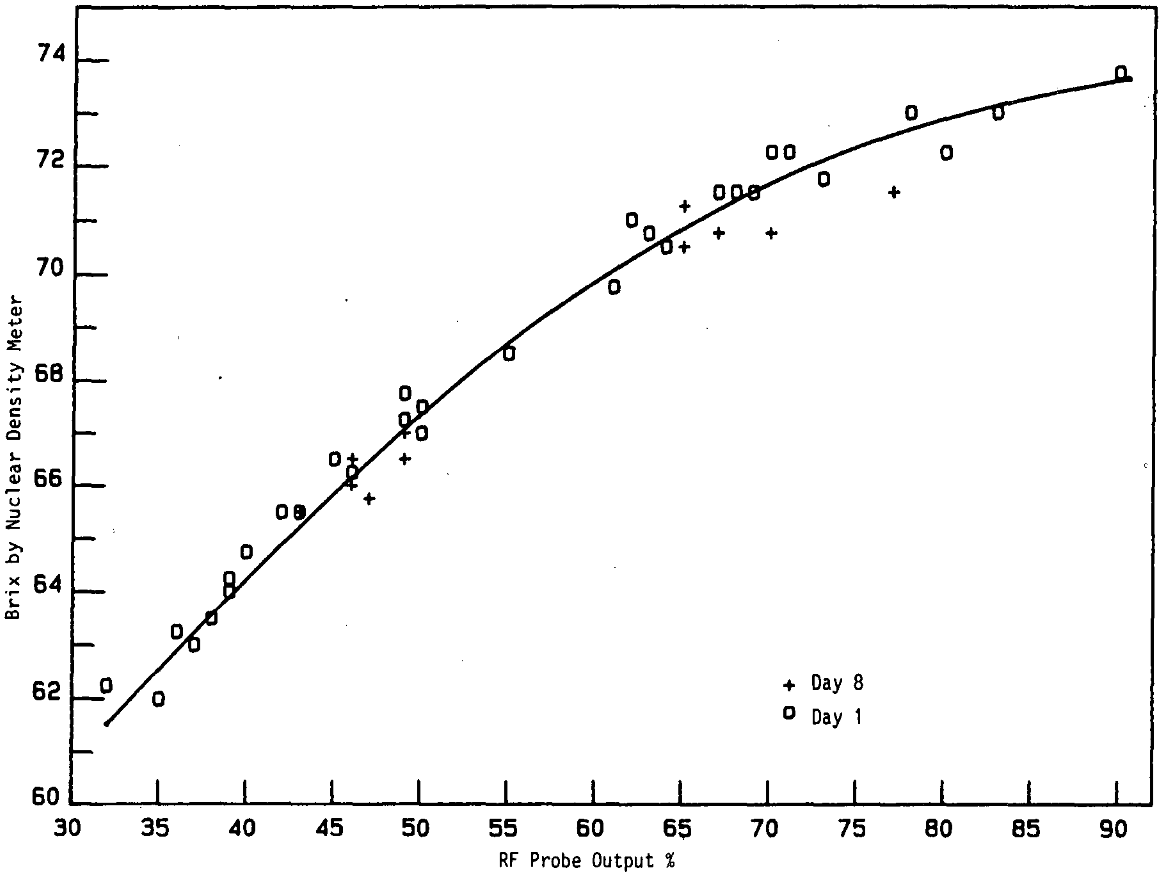

FIGURE 7 Brix as measured by a nuclear density meter versus RF Probe output

Table 1
Sugar quality from manual and automatic boilings
(No. 2 pan - Hulett Refinery)

	No. of Samples	Conglomerate count	MA	CV
Manual	8	77	565	37
Automatic	25	71	633	31

Laboratory Experimental Work

Initial tests were carried out using a prototype probe operating at 45 MHz, fitted to a 20 ℓ laboratory vacuum pan boiling 'A' massecuites.

Series resistance and capacitance were determined in this instance by manually varying probe tuning, and plotting a resonance curve for each measurement. Later, this resonance curve was matched by connecting a simulator consisting of a variable capacitor in series with a variable resistor, across the probe. The capacitor and resistor were adjusted to match the resonance curves previously determined and the values of the capacitor and resistor were then measured, giving Rs and Xs. These tests showed a strong correlation between crystal content and series resistance, as shown in Figure 8.

A boiling was also done in this pan on Refinery fine liquor and an excellent correlation between crystal content and both parallel and series capacitance was obtained. The result for parallel capacitance is shown in Figure 9.

Subsequently, the pan was fitted with an improved RF probe operating at 27 MHz, conductivity probe, massecuite temperature probe and boiling point elevation measurement.

The RF probe was connected to a Yokogawa SLPC, which was programmed to extract signals representative of series resistance and series capacitance. These two signals, together with all the other measurements, were put onto a recorder.

A series of tests were carried out on syrups and massecuites to determine the effect of temperature, ash, purity, brix and crystal content on the RF measurements. During some of these tests, every effort was made to hold all variables constant, except the one under investigation which was varied over as large a range as possible. Earlier experimental work had been confined to boiling massecuites, where many parameters showed only small variations, e.g. mother liquor brix, purity and temperature and a strong degree of inter-correlation was also present.

The ranges covered in this work were:–

Massecuite/Syrup Temperature	40°C - 90°C
Mother Liquor/Syrup Brix	64 - 85
Mother Liquor/Syrup Purity	63 - 85
Ash %	4,3 - 8,8
Crystal Content %	0 - 43

Multi-linear regressions over the 153 data sets obtained gave the following results:–

$$\mathrm{Ln}\left(\frac{1}{\mathrm{Rs}}\right) = -4{,}103 - 0{,}0994\ \mathrm{MLBX} + 0{,}0490\ \mathrm{Ash}\ \% - 0{,}0182\ \mathrm{XTAL}\ \% + 7{,}295\ \mathrm{Ln}\left(\frac{T + 273}{100}\right) \qquad r^2 = 0{,}990 \qquad \ldots\ (6)$$

$$\mathrm{Ln}\left(\frac{1}{\mathrm{Xs}}\right) = -8{,}044 - 0{,}144\ \mathrm{MLBX} + 0{,}0367\ \mathrm{Ash}\ \% - 0{,}0159\ \mathrm{XTAL}\ \% + 13{,}893\ \mathrm{Ln}\left(\frac{T + 273}{100}\right) \qquad r^2 = 0{,}955 \qquad \ldots\ (7)$$

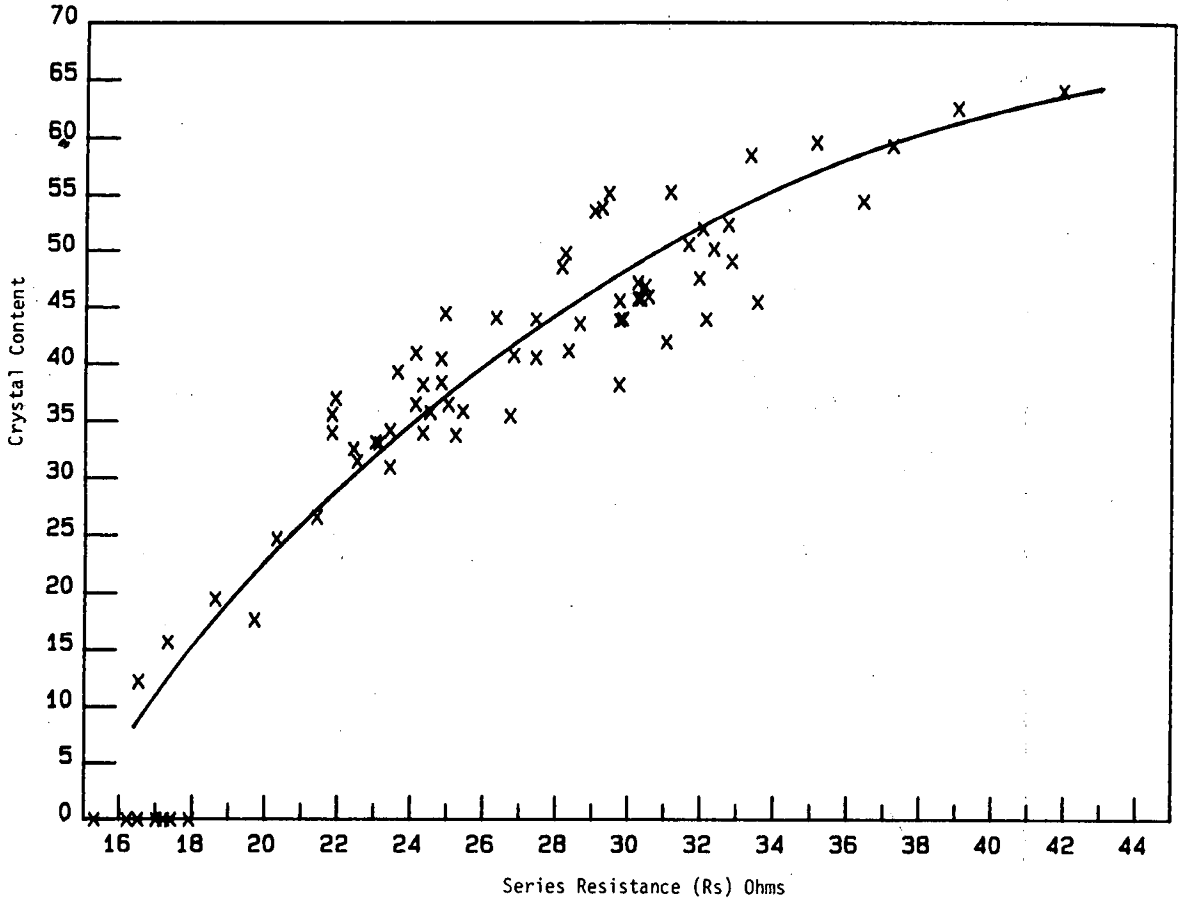

FIGURE 8 Relationship between crystal content & series resistance measured at 45 MHz

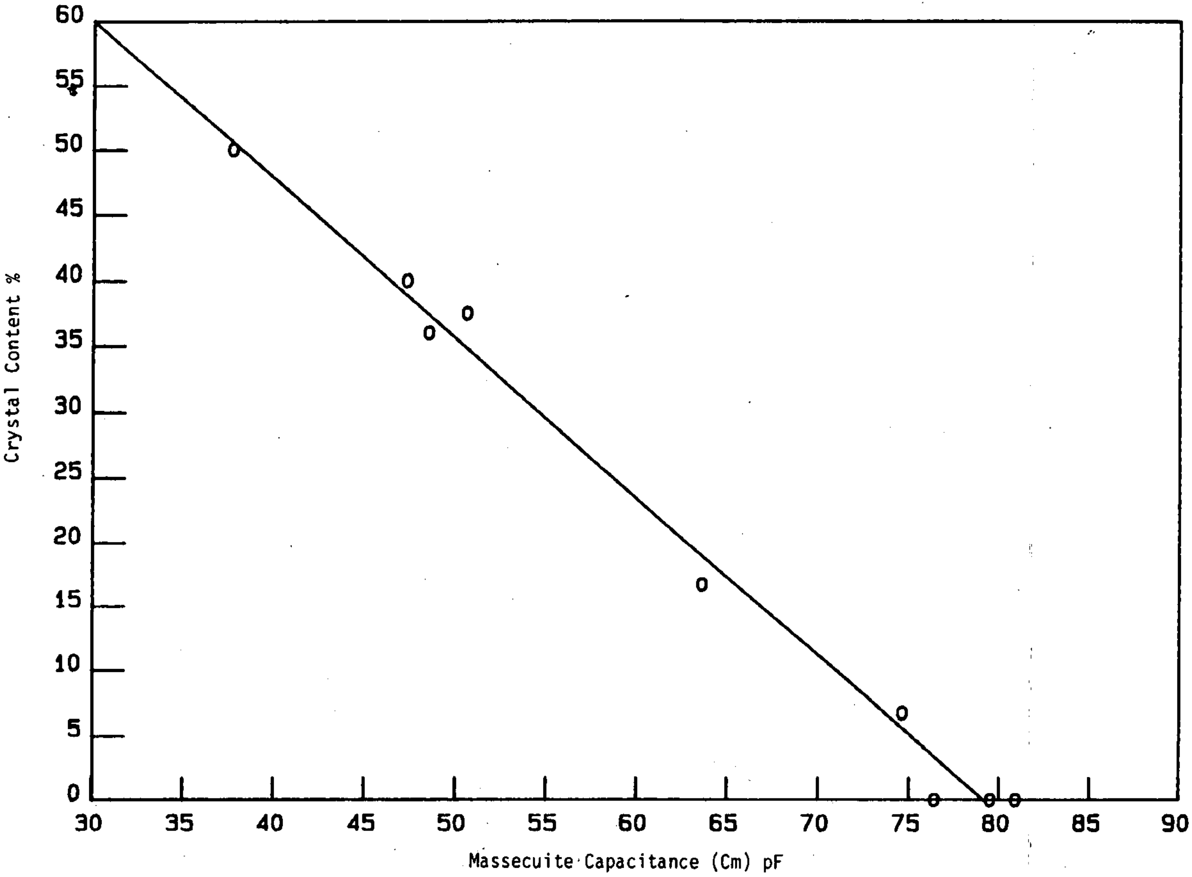

FIGURE 9 Relationship between crystal content & massecuite capacitance for high purity massecuites at 45 MHz

$$\ln\left(\frac{1}{Rm}\right) = -5{,}170 - 0{,}118\ MLBX + 0{,}0423\ Ash\ \% - 0{,}0165\ XTAL\ \% + 9{,}168\ \ln\left(\frac{T + 273}{100}\right) \qquad r^2 = 0{,}974 \quad \ldots\ldots (8)$$

$$\ln(Cm) = 7{,}456 - 0{,}0740\ MLBX + 0{,}0547\ Ash\ \% - 0{,}0188\ XTAL\ \% + 2{,}566\ \ln\left(\frac{T + 273}{100}\right) \qquad r^2 = 0{,}950 \quad \ldots\ldots (9)$$

$$\ln\left(\frac{1}{R}\right) = -9{,}010 - 0{,}111\ MLBX + 0{,}0256\ Ash\ \% - 0{,}0149\ XTAL\ \% + 10{,}219\ \ln\left(\frac{T + 273}{100}\right) \qquad r^2 = 0{,}973. \quad \ldots\ldots (10)$$

In the above equations:-

MLBX = Mother liquor brix or syrup brix
Ash % = Ash % mother liquor or syrup
XTAL % = Crystal content %
T = Temperature (°C)
Rs = Series resistance (Ohms)
Xs = Series capacitive reactance (Ohms)
Rm = Parallel resistance (Ohms)
Cm = Parallel capacitance (Picofarads)
R = Resistance measured by conductivity (Ohms).

A correlation matrix on all data where crystal content was >0, gave the following results:-

	Rs	Xs	Rm	Cm	R
MLBX	0,73	0,81	0,80	−0,60	0,85
XTAL %	0,87	0,66	0,73	−0,93	0,74

In 'A' boilings, it is desirable to control crystal content since this is the primary factor determining exhaustion. The Rs signal which has been used at Maidstone is superior to the conductivity signal in this respect, since it shows a higher correlation with crystal content. The fact that the correlation is only 0,87 is due to interference by temperature, brix and ash effects, as shown in the multi-linear regressions.

The improvement in Rs compared to the commonly used conductivity signal R, for control purposes can be seen by looking at their relationships with crystal content, given by Figures 10 and 11.

The correlation matrix shows that Cm (massecuite capacitance) has a better correlation with crystal content than either Rs or R. This signal is calculated from the measured values of Rs and Xs. Referring to the multi-linear regressions, in the case of Cm the effect of crystal content is greater relative to temperature and mother liquor brix. This explains the better correlation of Cm with crystal content and indicates that Cm should be a better signal for control than Rs, as illustrated in Figure 12.

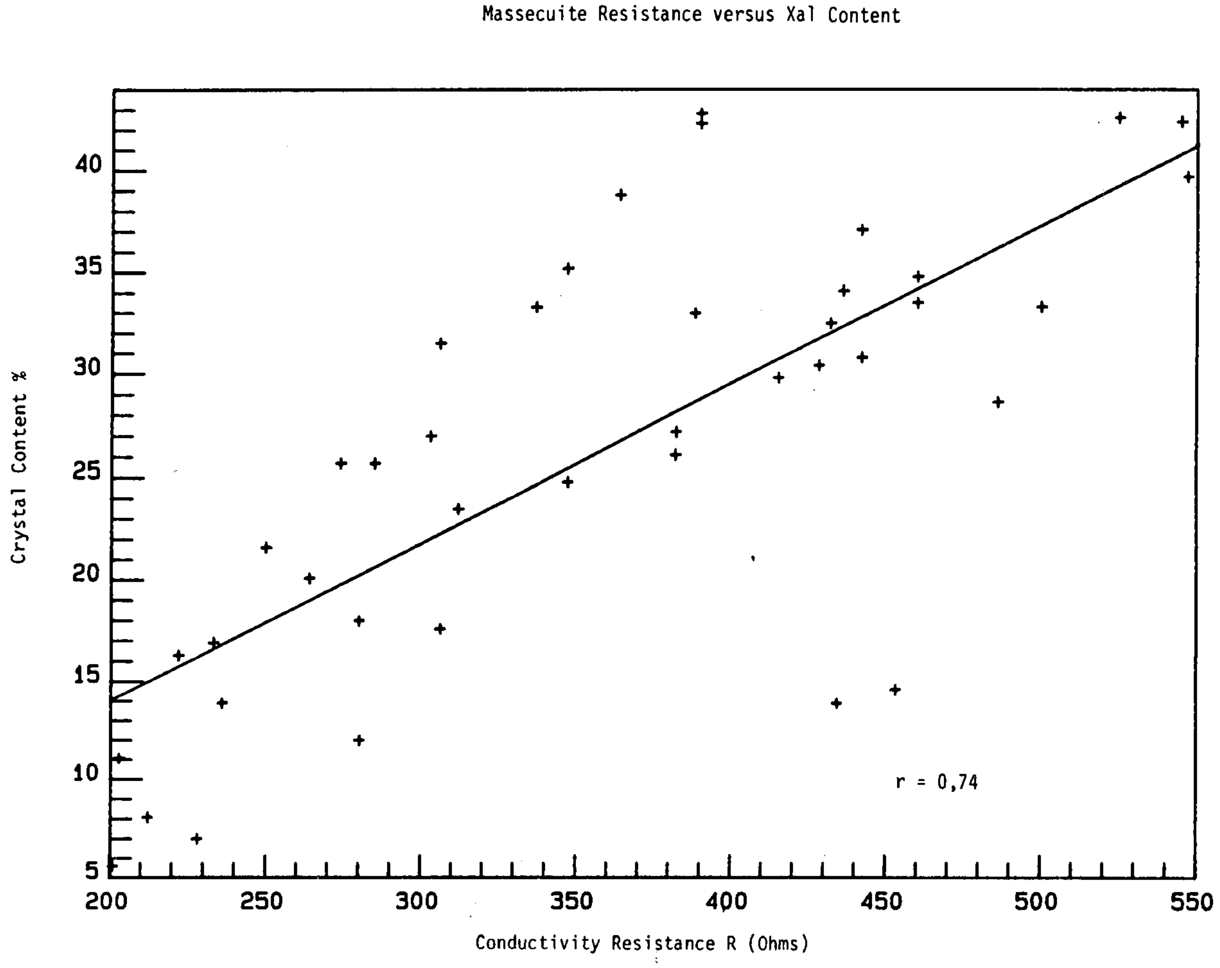

FIGURE 10 The relationship between crystal content and massecuite resistance measured by conductivity

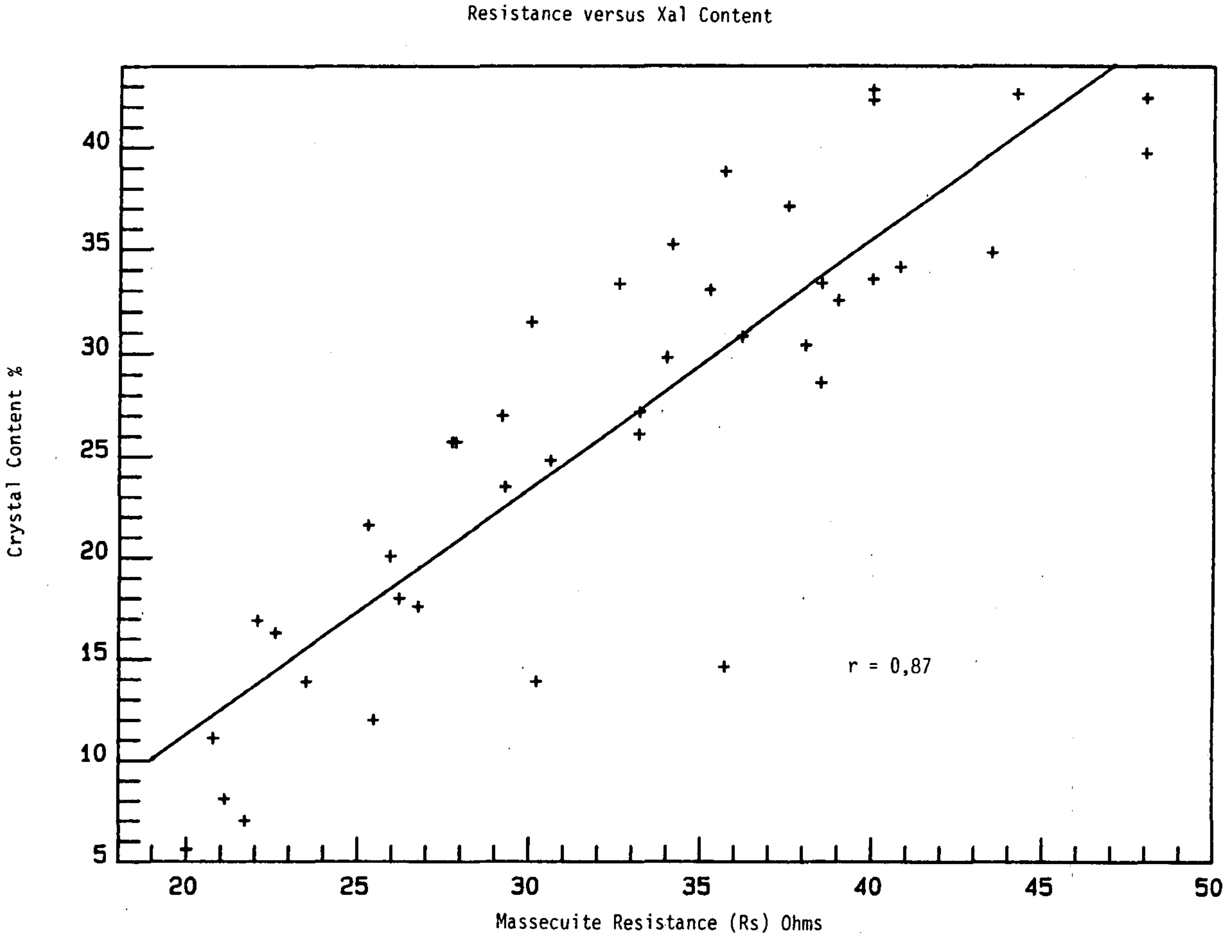

FIGURE 11 The relationship between crystal content & series massecuite resistance at 27 MHz

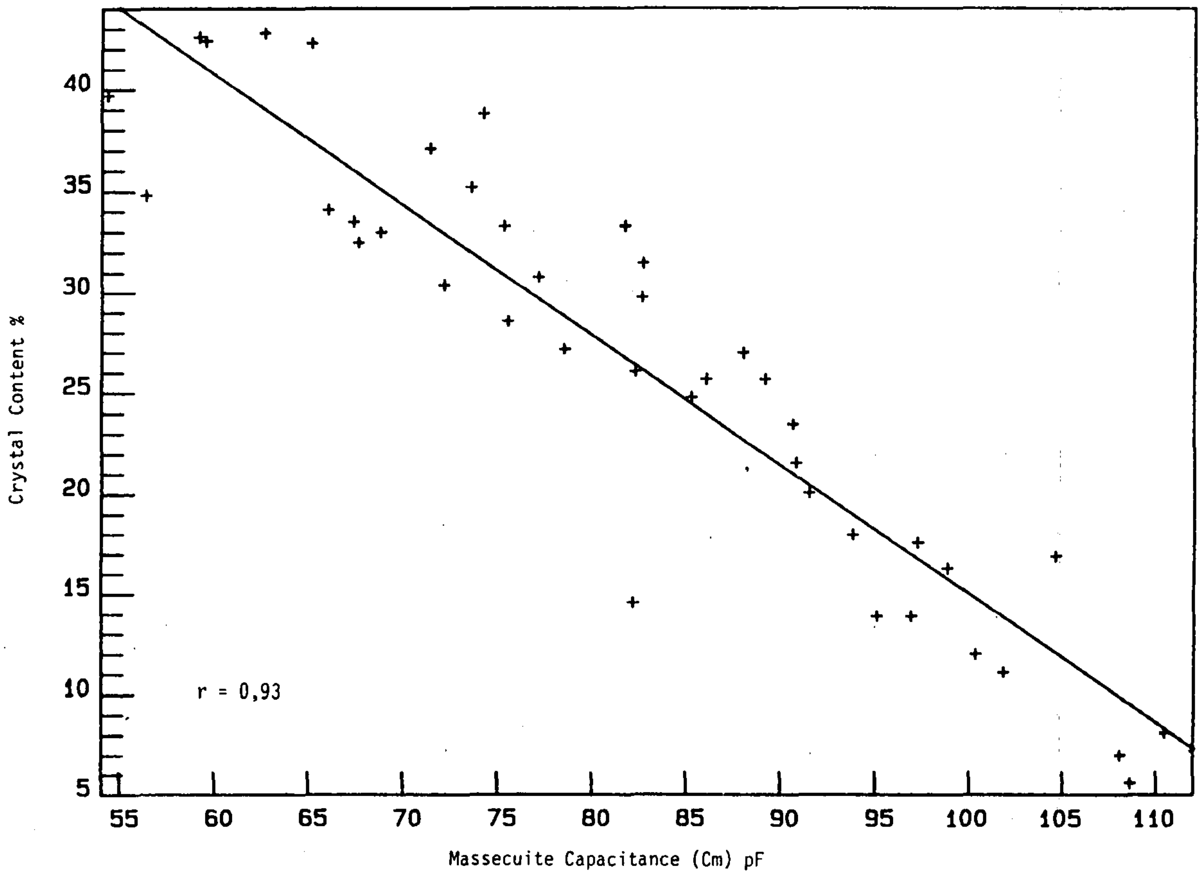

FIGURE 12 The relationship between crystal content & massecuite capacitance at 27 MHz

Further work is being done on the data already obtained to find the optimum combination of Rs and Xs for the best correlations with crystal content and mother liquor brix.

Conclusions

A measurement system using radio frequencies has been developed which can be used on all grades of boilings, including high grade Refinery products. It can also be used for syrup or molasses brix control.

It has advantages over the commonly used conductivity signal as it is less affected by scaling and sugar encrustation and hence, requires less frequent cleaning. It can also be used on higher grade boilings, where conductivity becomes ineffective due to low soluble ash levels.

The RF probe used for brix control shows considerable cost savings over alternative systems, i.e. nuclear density meters or refractometers.

A unique feature of this measuring system, when used with a microprocessor, is the ability to measure two different parameters simultaneously, allowing an optimum control signal to be derived, e.g. crystal content or mother liquor brix.

The measuring system as described in this paper has been patented.

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