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Electrical impedance of methane flat flame

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Electrical Impedance of Methane Flat Flame

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THESIS

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Dr. Robert L. McConnell

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As part of an ongoing effort to improve emissions and increase efficiency of natural gas fired turbines, this work was undertaken to determine if electrical impedance measurements of the flame are a direct indication of fuel/air ratio. Previous work measured electrical resistance of the combustion of gases in an atmospheric combustor. From this work, it was conjectured that the complex impedance might provide more information about the flame than using pure resistance. This thesis discusses the measurement of the complex electrical impedance of a Methane Flat Flame Burner. The data shows a relationship between the magnitude of the impedance and temperature, which relates directly to the fuel/air mixture. This work was supported in part by the National Energy Technology Laboratory (NETL).

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Keywords

Angular frequency	Electron transfer
Anion	Equivalence ratio
Argon Ionization Detector (AID)	Flame ionization
Auto-ignition	Flame ionization Detection (FID)
Bunsen burner	Flashback
Cation	Flat flame burner
Charge	Fuel/air ratio
Charge density	Galvanic voltage
Chemi-Ionization	Gas chromatography (GC)
Chromatography	Gas-Liquid chromatography (GLC)
Collision frequency	Ionization by collision
Conduction current	Ionization by transfer of excitation energy
Conductivity	Lean-blowoff
Convection current	mean free path
Coulomb force	Methane (CH ₄)
Coulomb logarithm	NO _x emission
Current density	Relative permittivity
Electric field	Soot
Electrical conductivity	Thermal Conductivity Detector (TCD)
Electrical impedance	Transmission line
Electrical resistance	Wavelength
Electrolytic current	

Symbols

Ω – electrical resistance and impedance (impedance is a complex number)

E – electric field

J – current density

I – current

σ – conductivity

S – surface area

N – charge density

q – charge

e – electron charge

u – velocity

ρ – charge density

μ – mobility

V – voltage

Z – impedance

R, r – resistance

x – reactance

ν – collision frequency

f – frequency

ω – angular frequency

M – mass

P – pressure

V – volume

n – molar density

R – ideal gas constant

k – Boltzmann's constant

T – temperature

d – diameter

λ – mean free path, or wavelength

N_A – Avogadro's number

ϵ – relative permittivity

eV – electron volt

C – Capacitance

L – Inductance

F – Fuel

A – Air

List of Acronyms

NETL – National Energy Technology Laboratory

DoE – Department of Energy

FID – Flame Ionization Detection

TCD – Thermal Conductivity Detector

AID – Argon Ionization Detector

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Chapter ONE

Introduction

Low emission natural gas burners are a focal point for many research laboratories. The National Energy Technology Laboratory (NETL) is continuously investigating methods for reducing emissions from such systems. One example of such a burner is the gas combustors used in a turbine. These gas combustors are typically operated at moderate to high *fuel/air ratio*, to avoid problems with *lean-blowoff*, *flashback*, and *auto ignition*. At these levels of fuel/air ratio, *soot* and *NO_x emissions* can be high. A new research initiative by NETL is concentrating on controlling the fuel/air and reducing the emissions of gas combustors.

Current research has suggested optical based control for measuring fuel/air ratio. For the optical equipment to properly work, optical access to the flame inside the combustion chamber must be given. Not only does this require special machining of the combustion tube, but also it poses a larger problem with pressurized combustors that require very thick walls to ensure pressure integrating during operation. Once access is gained to the flame through an optical window, measurements can be taken. However, the process of combustion causes the window to become dirty and the flame can no longer be viewed. There has also been work performed using fiber optics, but these still suffer from dirt on the sensing window [1].

NETL's focus has now shifted to determining if the *electrical conductivity* of the flame's gases can be related to the fuel/air ratio. In fact, recently published work has already been done demonstrating this relationship does exist [2]. If measuring conductivity can determine the fuel/air ratio of a combustor, the advantage of not requiring an optical window will be gained. The only modification of the combustor would be mounting the probes needed to make the measurements on the inside wall of the combustor and passing only data acquisition wires from these probes through the combustion wall.

This thesis documents the relationship of electrical properties of the flame with the fuel/air ratio. The fuel/air ratio is often normalized to a value known as the *equivalence ratio* (1-1) and is denoted by the Greek letter phi (ϕ).

$$\phi = \frac{F / A_{Actual}}{F / A_{Stoichiometric}} \quad (1-1)$$

The stoichiometric fuel/air ratio depends on the fuel composition. It is defined as a special case when there is just enough oxygen to convert all of the fuel into oxidized products [3]. The background needed to understand the history of flame measurements is given in Chapter 2. In Chapter 3, the discussion of the equipment used in this research is discussed. Chapter 4 introduces the theory behind the measurements and develops the calculated values for impedance versus frequency. To analyze this calculated data it is then compared to the measured data and discussed in Chapter 5. Finally, Chapter 6 includes the conclusion and future work in the ongoing research to support clean power generation.

Problem Statement

Can the complex *electrical impedance* of the flame be a better measure of fuel/air ratio or other combustion properties than pure *electrical resistance*? No previous research has been discovered relating the electrical properties of flame as a function of an applied frequency.

Chapter TWO

Background

The background of measuring flame properties extends back to the mid part of the 1900's. Much work was performed in the late 1950's and into the 1960's. The background information provided in this chapter will offer information on flame ionization and develop the proper background to discuss the theory of Flame Impedance. A more realistic and simpler approach to understanding a flame's properties during "real-time" operation is needed to make controlling a flame's combustion possible. Now that significant accomplishments in understanding a flame's combustion process have been made, research is leaning towards developing a simple measuring technique that could be utilized in the field to possibly control the combustion process. To understand the development of this new technique, an understanding of the history of *chromatography*, particularly *gas chromatography (GC)*, *flame ionization*, and *flame ionization detection (FID)* will be given. A brief history of chromatography and the development of gas chromatography are discussed in section 2.1. Flame ionization and the milestones of Flame Ionization Detection will be discussed in Section 2.2 and 2.3 respectively. Section 2.4 will provide a brief overview of electrical impedance. Section 2.5 and 2.6 will discuss the most recent research being developed, Flame Resistance and Flame Impedance.

2.1 History of Chromatography

The science of Chromatography extends into the late 19th century. However, by definition, chromatography is a naturally occurring event that takes place everyday.

Chromatography is the process of separation and identification of chemical components in a mixture[4]. For example, water running through a bed of rocks and soil; the water molecules will deposit parts of their molecular structures that cannot pass through certain regions of the rock or soil. This separation of the water molecule can be considered a natural form of Chromatography. From this simple example, it can be shown that the water is moving, known as the mobile phase and the rock/soil combination is static known as the stationary phase. In 1906, Ramsey separated mixtures of gases and vapors using absorbents [5]. The person denoted by many as the “father of Chromatography” and was the first to use the term Chromatography is Michael Tswett, a Russian Botanist. Tswett separated plant pigments by a process now known as ***Gas-Liquid Chromatography (GLC)***. The science of Chromatography has been around for quite sometime, but the birth of Gas Chromatography did not occur for almost another fifty years. Below is a chronological list of dates and those involved in the development of Chromatography. This is only a partial list, but it shows just how long Chromatography has been studied and improved over a century [6].

Date	Inventor	Milestone
1848	Way and Thompson	Recognized the phenomenon of ion exchange in solids.
1850-1900	Runge, Schoenbein, and Goepfelsroeder	Studied capillary analysis on paper.
1876	Lemberg	Illustrated the reversibility and stoichiometry of ion exchange in aluminum silicate minerals.
1892	Reed	First recorded column separation: tubes of kaolin used for separation of FeCl_3 from CuSO_4 .
1903-1906	Tswett	Invented chromatography with use of pure solvent to develop the chromatogram; devised nomenclature; used mild adsorbents to resolve chloroplast pigments.
1930-1932	Karrer, Kuhn, and Strain	Used activated lime, alumina and magnesia adsorbents.
1935	Holmes and Adams	Synthesized synthetic organic ion exchange resins.
1938	Reichstein	Introduced the liquid or flowing chromatogram, thus extending application of chromatography to colorless substances.
1938	Izmailov and Schraiber	Discussed the use of a thin layer of unbound alumina spread on a glass plate.
1939	Brown	First use of circular paper chromatography.
1940-1943	Tiselius	Devised frontal analysis and method of displacement development.
1941	Martin and Synge	Introduced column partition chromatography.
1944	Consden, Gordon, and Martin	First described paper partition chromatography.
1947-1950	Boyd, Tompkins, Spedding, Rieman, and others	Ion-exchange chromatography applied to various analytical problems.
1948	M. Lederer and Linstead	Applied paper chromatography to inorganic compounds.
1951	Kirchner	Introduced thin-layer chromatography as it is practiced today.
1952	James and Martin	Developed gas chromatography.
1956	Sober and Peterson	Prepared first ion-exchange celluloses.
1956	Lathe and Ruthvan	Used natural and modified starch molecular sieves for molecular weight estimation.
1959	Porath and Flodin	Introduced cross-linked dextran for molecular sieving.
1964	J. C. Moore	Gel permeation chromatography developed as a practical method.

Table 2-1: Brief History of Chromatography

Martin and Synge made suggestions for the use of GC in 1941. It was Martin and James that first published work on GC in 1952 and concluded how easy and simple it was to perform [7]. Not all compounds can be analyzed using GC. A compound must have certain volatile and thermal stability. Although the process of separating a molecule is relatively easy, the equipment to perform the analysis can get very complicated. The gas passes through columns in the GC. Each column will absorb different elements of the gas, while the remaining elements will pass

through. This process relates to the previously mentioned example with the water running through the bed of rocks. The rock carry out the role as the separating columns and the water is the product being separated. This example is more closely associated with Liquid Chromatography, but the same basic concept applies. The process of GC is a breakthrough in measuring the properties of a flame. Technology is now demanding the use of this knowledge to improve efficiency and control for many products that use a combustion chamber. The typical GC can separate and identify the components of a compound, but using such a system in an environment that requires fast response is virtually impossible. Soon after the development of Gas Chromatography, the study of flame ionization was introduced and the development of Flame Ionization Detection was conceived. The FID device can be used to understand a flame's properties by measuring its ionization. This will be discussed in more detail in the following sections.

2.2 Flame Ionization

A flame's ionization process is just one method to identify flame properties by gas chromatography. This research, known as Flame Ionization, is the study of flame properties that typically cannot be seen by the naked eye. Ionization occurs through many processes in the combustion of flames. The significant amount of ionization occurs by three main processes: ***Ionization by Collision***, ***Electron Transfer***, ***Ionization by Transfer of Excitation Energy***, and ***Chemi-Ionization***. Since the fuel burned in this experiment was 99.9% pure ***methane (CH₄)***, the chemical reactions will be an example of methane reactions with oxygen and other molecular structures.

2.2.1 Ionization by Collision

When molecules or electrons collide, ideally head-on, the energy exerted by the collision may be great enough to cause a reaction that results in ionization. In the case with Methane:

(collision of methane and oxygen molecules)

(collision of methane and a free electron)

It has been proven that in combustion systems the collision of electrons rather than molecules is a much greater source of ionization [8].

2.2.2 Electron Transfer

When the ionization potential is large between two molecules, an electron can be transferred between the molecules. This, of course, causes ionization.

This type of reaction is not a significant source of ionization, but its potential to occur exists

2.2.3 Chemi-ionization

The process of chemi-ionization is described by the term. This process is a direct result of the chemical rearrangement, which releases energy that leads to ionization. This type of ionization reaction is considered the most important in hydrocarbon flames [9].

2.3 Development of Flame Ionization Detection (FID)

With the onset of Gas Chromatography and the study of flame ionization, a device to measure such properties in a real-time environment was needed. Not too long after the introduction of GC, the Flame Ionization Detector was developed in 1958. After its release, it did not take long for the FID to become popular and research began to improve its design and performance. In the mid 1960s, FID became commercially available. Before the introduction of the Flame Ionization Detector, two other detectors had been invented and used. These were the flame emission detector that monitors the amount of visible light emitted and the flame conductivity detector, which measures the temperature of the luminescent cone above the flame to derive information about the compound. Neither of these detectors was reliable and both were not very sensitive to changes in the system. The FID proved to be the opposite; the FID can analyze 50 ppb of organic compounds with a standard deviation of only 5%. The most interesting discovery by the FID being that flame ionization only occurs once out of every 10^6 carbon atoms [10]. The development of such a device as the FID that can count this ionization is an outstanding achievement of technology.

2.3.1 History of the FID

Before the invention of the FID, chromatography was accomplished using what is known as columns. The separated parts of the compound appear as different colored rings on each column. This method is ideal for liquids, but does not work as well when analyzing gasses. As mentioned earlier, Martin and James were the first to discover a way to analyze gas at the British National Institute for Medical Research. Just like most initial accomplishments, the method used by Martin and James was too complicated and unrealistic for widespread use. Other detectors

mentioned earlier were also used before the introduction of the FID, but they all exhibited features undesired by the combustion community as being a viable measuring device for flame ionization.

The earliest commercial use of GC, utilized the thermal conductivity detector (TCD). In 1955, commercial units of the Gas Chromatograph were available with the TCD. The TCD was designed using a power supply, thermistors, and an amplifier (Figure 2.1). The TCD measures the changing temperature of the gas flowing around the sensor. Changes in the thermal conductivity of the gas would cause a temperature change, which was sensed by a change in resistance of the thermistors. The TCD used in Gas Chromatographs used two pairs of TCDs, arranged in a bridge type configuration (Figure 2.1). The largest downfall of the TCD is that it requires helium as the carrier gas and it was not very sensitive especially at low concentrations. Although many detectors require a particular type of carrier gas, the quantities of helium available outside the United States was very little, making the TCD expensive and virtually impossible to operate outside the United States. Worldwide acceptance of the TCD did not occur and other countries were using early versions of a hydrogen detector. Many of these detectors were also complicated to use.

Then in 1958, the *Argon Ionization Detector (AID)* and Flame Ionization Detector (FID) were invented almost simultaneously. It seemed as if these two detectors would compete for acceptance as the primary device to measure flame ionization.

Figure 2-1: Schematic Diagram of a Typical Thermal Conductivity Detector (TCD)

J.E. Lovelock, working for the British National Institute for Medical Research invented the AID. As its name indicates, this detector used argon as its carrier gas. W. G. Pye & Co. quickly commercialized the AID in 1958. It was introduced at the May 1958 International GC Symposium in Amsterdam, The Netherlands. The introduction of this high sensitivity detector excited the GC community and it was used as the primary ionization detector. After several years as the commercially available high sensitivity ionization detector, the AID was superseded by the FID [11].

2.3.2 Design of the FID

Shortly after the FID came to the commercial market, it became the most used ionization detector. The FID proved to have superior range, response, and sensitivity over any other detector built. The FID was actually developed in two separate places simultaneously in different areas of the world. In the mid 1960s, all the commercial equipment took on a similar

design utilizing the now, very accurate, FID. A cut away view of a typical FID is shown in Figure 2-2. This section will look into the different features of the FID design. The different features include the jet, airflow, carrier and hydrogen flow, exhaust flow, thermal control, ion collection, electrometer, igniters, and the polarity of the FID.

Figure 2-2: Typical Modern Flame Ionization Detector (FID)

The jet in an FID is very important. The size of the jet determines the gas velocity flowing out of the jet so that it matches the rate of diffusion in the flame. Matching the gas velocity and the rate of diffusion is very important in order to minimize thermal transfer or flow stability problems. The shape of the jet is also important. A square, rough edge jet may cause samples to condense before leaving the jet restricting the flow. To maximize the efficiency and accuracy of the jet, it should be centered in the FID and be smooth.

It is desired to have uniform and laminar flow along the sides of the FID. Airflow then becomes very important. Because of the complexity of diffusion flames and the FID construction, many FIDs require much more air and others require less to minimize the effects on the sides of the jets. For this reason, most FIDs introduce air into the system through a porous diffuser located well below the tip of the jet. This allows for complete control of the airflow.

The FID is a hydrogen ionization detection device. Just like the argon detector that required argon as the carrier gas, the FID requires hydrogen as the carrier gas. The flow of the hydrogen must be large enough to supply the sample with enough carrier gas, but also flow in such a way that it mixes thoroughly with the sample of fuel gas.

The exhaust flow in an FID is typically not very important, but does have some problems associated with it, if it is not properly maintained. If the exhaust particles are unable to leave the FID, they may fall back into the flame. These particles falling back into the flame will cause the FID to produce spikes in its readings. Also, silica from the silicon coated column bars may deposit onto the detector and cause a build up of electric charge. If the exhaust is too cool, it could condense and the water vapors run back into the detector causing erroneous measurements. The last item to mention about the exhaust flow is the importance of keeping the ambient outside air from traveling back into the exhaust exit.

Thermal control of the carrier gas is very important to keep any gases from condensing inside the FID. Also, it is a good practice to maintain the detector's body temperature. Variations in the detector's body temperature, will affect the detection mechanism. If the flame

from the jet heats any parts of the detector, the parts may emit electrons affecting the measurement of the FID. Other parts of the detector can cause electrical leakage and offset the current if not kept cool. The effects from thermal inefficiency of the FID can be reduced, but the effects most frequently reported are slight catalytic ionization and thermionic ionization. Readings that should have given positive peaks may produce negative peaks and vice versa.

Ion collection within the FID is somewhat simple. In a typical ionization environment, the smallest probe with electric field intensity of only 10 volts has enough sensitivity to collect all the ions produced in the combustion. The size of the probe limits the size of the sample that is burned. Samples larger than what the probes can collect will cause saturation of the ions. Also, recombination of negatively and positively charged particles occurs before the probes can detect them. To properly detect ionization in this setting, a probe with larger surface area and increased electric field intensity as high as 300 volts would be required. It is also important that the collector and jet must be electrically insulated with quality high temperature insulation. A leakage of $10^{12} \Omega$ will produce a magnitude of around 10nA of current at 100 volts. This does not seem like much, but in some detectors, sensitivities are on the pico-amp scale. Two types of insulators have been used in two separate designs. By removing the insulator from the hot part of the FID, fluorocarbon plastic can be used. Within the flame, high-purity ceramic can achieve the insulation required for the detector. It has been determined that fluorocarbon plastic has an insulation resistance of 10^{15} - $10^{18} \Omega$ and high-purity ceramic is approximately 10^{14} - $10^{16} \Omega$. These values are based on clean material, any surface contamination can cause decreased insulation performance.

The remaining two parts of a FID, the igniter and electrometer, are important, but due to improvements in technology, the commercially available equipment has taken over their controls automatically, and in the case of the igniter, it is more of a safety issue rather than a performance concern. An igniter inside the FID is much safer than trying to light the jet with a match. Fingers and lives are not lost by the initial combustion or by the potential 300 volts on the collection probes. The electrometer is just that, an electro – meter. It is capable of measuring the electric field produced by the collection of ions in the FID. An important feature of the FID is that the polarity of the potential does not make a difference in the measurement of ions [12].

2.4 Electrical Impedance

Electrical impedance may simply be thought of as the AC “resistance.” Impedance is a complex number usually expressed as “Z”. The impedance equals $r + jx$.

$$Z = r + jx \quad (\Omega) .$$

Z, the complex impedance (called simply “the impedance”)

r, the real part, known as the resistance (note that conductivity is simply 1/R),

x, the imaginary part, known as the reactance.

(Both parts are measured in units of ohms.)

So, if one knows the complex impedance, one also knows R (and by default calculation, conductivity) as a part of the impedance. The magnitude of the reactance is $X = \omega L$ or

$$X = 1/\omega C .$$

Where ω is the complex frequency in radians/sec and $\omega = 2\pi f$, where f = frequency in Hertz.

Thus, if one measures complex impedance and obtains the magnitude and angle, by simple complex number calculation, one can derive r and all the other values of C or L if the frequency is known [13].

2.5 Flame Resistance Research

Research began with Professor Roy Nutter, West Virginia University Computer Engineering Professor. Nutter performed DC voltage analysis in a stationary combustor. Experiments were conducted by applying a DC field to the combustion chamber through copper electrodes mounted in three places. Two were mounted on either side of the combustion chamber and the other, known as a shield electrode mounted at the fuel/air nozzle. From these electrodes, voltage and current measurements were taken as the fuel/air ratio was changed. Figure 2-3 shows the setup configuration of the electrodes.

Figure 2-3: Quartz Combustor Tube showing Top, Bottom, and Shield Electrodes

From this work, Nutter concluded that the measured resistance of the combustor is related to the equivalence ratio of the fuel. By knowing the fuel flow or air flow, the equivalence ratio can be deduced from the resistance measurement of the flame. Nutter also concluded that the noise present in the collected data reflects the turbulent flow of the fuel in the combustor [14].

2.6 Flame Impedance Research

From the discussion of electrical impedance earlier, resistance is the real part of impedance, $Z = r + jx$, and the previous work of resistance measurements by Nutter does not include the jx part that makes impedance complex. This is often referred to as the imaginary part of the impedance. From the previous resistance research, it was proposed that the phase, or imaginary, part of impedance may contain further information about the relationship between electrical properties of the flame and the equivalence ratio. Work began to investigate this possibility. No former work had been published relating the electrical impedance to the equivalence ratio of a flame. To make these initial measurements much simpler, a flat flame burner was implemented, due to its controllable and constant flame structure. The flat flame burner will be discussed in detail in the next section about the equipment used for data acquisition. Also, in the previous research on resistance, data was collected by hand and then plotted using computer software. Because this method leads to potential collection errors, a device that could collect voltage and current measurements automatically at a given frequency was needed. To accomplish this the Solartron Gain-Phase Analyzer, model 1260, was bought for the purpose of data collection. The Solartron Analyzer also was capable of communicating with a connected computer. With the Z-Plot software provided by Solartron, it was possible to control the analyzer and view the collected data much easier. When connected to the system, the

instrument collected voltage and current data. The software was able to utilize this data and automatically plot the impedance versus the applied frequency. With this equipment, an initiative was possible that brought a completely new development in thermal measuring equipment to enable measurement near the flame at high temperatures. This new equipment brought also added complications to the overall system and each problem will be discussed in more detail in the Equipment and Theory chapter of this thesis.

Chapter THREE

Experimental Setup

The experimental setup and design consists of a *flat flame burner*, the design of high temperature probes, and an impedance analyzer. The experiment began by designing probes that were to be placed near the flame front. The environment that the probes were exposed to required the design of the probes to meet some basic specifications. The functions of the instrument utilized in the data collection were then learned.

This chapter will focus on the three parts of the experiment mentioned previously. Section 3.1 will discuss the flat flame burner. The advantages of using the flat flame burner and an overview of its operation will be given. In section 3.2, the probe configuration that resulted in the best data will be discussed. Finally, the Solartron impedance analyzer used for the data collection will be reviewed in section 3.3.

3.1 Flat Flame Burner

The flat flame burner has aided research of flame properties tremendously by allowing research to be done using its one-dimensional flame. From its name, the flame above the burner is “flat”. Most are familiar with the *Bunsen burner* and its associated conical flame structure (Figure 3-1). The cone-like flame has flame regions known as the inner flame zone and the outer

flame zone that can be visually seen as blue and yellow respectively. The problem with making flame measurements on a Bunsen burner is the location of the probes. A measurement in the inner flame zone would differ greatly from a measurement in the outer flame zone, where the temperature differences alone would cause dissimilar results. Also, the Bunsen burner has no form of flame stabilization. When making a measurement, the slightest air movement would cause the conical flame to fluctuate. To prevent this fluctuation, a flame shield that would allow access to the flame for probe implementation would be required, complicating the design.

Figure 3-1: Bunsen Burner

There have been two flat burners designed. The two burners can be described as either cooled or uncooled burner. The uncooled burner that was designed by Powling requires much more control of stream velocities and flame velocities [15]. These velocities are important to keep the flame flat. The cooled burner designed by Botha and Spalding controls the velocities using a cooled porous disk on the face of the burner. For these two burners, the flame is stabilized using an extra gas around the flame such as Nitrogen. The cooled burner is more widely used than the uncooled burner, and this section will only concentrate on the details of the cooled burner used to collect the impedance data for this research. The burner used was a water-

cooled burner from McKenna Products (Figure 3-2). A cutaway view of the McKenna Flat Flame Burner is shown in Figure 3-3. The probes seen in Figure 3-2 are the first set of probes designed for data collection. This probe design resulted in very noisy data and its design was aborted.

Figure 3-2a: Flat Flame Burner and Probes

Figure 3-2b: McKenna Flat Flame Burner

To maintain a flat flame, the approaching stream velocity must equal the flame velocity. For the uncooled burner by Powling, these velocities must be controlled using flow controllers. By using the cooled burner, the gas as it approaches the surface of the burner transfers heat to the burner. The burner's temperature rises slightly, but temperature of the burned gas is reduced. This reduction in temperature reduces the flame speed and the flat flame equalizes slightly above the burner surface. As the flame burns above the burner surface enough energy is lost to balance the flame speed with the stream velocity creating a stable flat flame insensitive to the mixture flow rate. The advantage this burner provides is a one-dimensional flame [16]. This is discussed in more detail in the theory section, but it allows an assumption that the conduction of the electric field intensity and current density are also homogenous. Homogenous is defined as

constant over a given area, so the current density and electric field intensity is constant over the cross sectional area assumed [17]. This will be discussed further in the Theory chapter.

Finally, for the burner to stabilize the flame even further, a nitrogen jacket around the periphery of the flame can be used. However, with the final setup used in this research it was not needed.

Figure 3-3: Cutaway View of McKenna Flat Flame Burner

3.2 Probe Development

Several probe designs were built and tested throughout the research of measuring the flame impedance. The probe designs were built to be able to:

1. Handle extreme temperatures,

2. Be electrically shielded from outside electrical interference,
3. And, be precisely located relative to the flame.

Copper wire for the probe itself has too low of a melting temperature for use in the flame. Since RF frequencies will be used to make measurements, electrically shielded measurement cable was used to interconnect the probes and the measurement equipment. Heat conduction from the probe tips could not injure the cables.

Initially, platinum was believed to be the ideal material for extreme temperatures. Platinum is resistant to corrosion at high temperatures, but posed a large galvanic voltage when connected to copper. In addition, Hartwell Calcote recommended not using Platinum because it “is a catalyst for combustion and the tips overheat”. He also stated that:

“Tungsten is bad because of oxidation and it emits electrons when heated.” He also said, “60% platinum and 40% rhodium makes a good electrode. Ni-chrome is pretty good.”

There was additionally little choice but to use copper core shielded cable to interface from the probes to the impedance analyzer. The material for the probes must interface well with copper. It should lie close to copper’s galvanic properties to avoid galvanic corrosion. This corrosion will be discussed in more detail in the Theory Chapter, Section 4.2, but it causes added resistance to the system. A copper ring was used around the burner periphery for one contact with the flame. This ring was large to provide adequate surface area to cool of the copper. The second probe was one of the original probes and was made from inconel. This second probe resided in the hottest part of the flame and was oriented in the direction of the flame flow. A sketch of this configuration is shown in Figure 3-4a. A picture of the actual setup is shown in Figure 3-4b.

Figure 3-4a: Sketch of Burner Setup

Figure 3-4b: Probe Configuration Actually Used

The probe configuration used to conclude the results of this research was not designed as well as they could have been, especially the copper electrode around the flame. The method in which the inconel probe was designed allowed for possible cross measurement between the ceramic beads on the end of the probe. In Figure 3-4b the very tip of the probe are two little hollow pieces of copper that the inconel probe was positioned in. As the flame burns, reactions take place throughout the entire gas stream as it exhausts away from the burner. If other reactions were measured from spaces between the ceramic beads, the analyzer would record an improper value for the impedance.

The burner face, made of aluminum and other metals, was earth grounded. The impedance measurements used in for this research required that the copper strip and the probe not to be connected to earth ground. To keep the copper electrode from touching the burner face, a ceramic pad was placed under the ring. Although this isolated the electrode from ground, the ceramic pad affected the flame's ability to contact the copper electrode. The burning flame, had to burn around the ceramic pad to make contact with the copper electrode. Perturbations in the

flame from the ceramic pad had an affect on the outcome of the data. The testing facility that the flat flame burner was mounted on was completely made of metal fixtures, so there was no location to physically mount the copper electrode. The slightest movement of the electrode would change variables of the setup. With improved probes, many of the questions that arise from the position of the inconel probe and copper electrode would be eliminated by controlling distances using translation tables.

3.3 Instrumentation

The instrumentation used to collect the impedance data was the Solartron model 1260 Impedance Gain-Phase Analyzer (Figure 3-5). This equipment was compared to other models and was chosen based on its ability to automatically perform data acquisition of impedance.

Features of the Solartron 1260 Impedance Gain-Phase Analyzer include:

- Frequency range 10 μ Hz to 32MHz
- Noise rejection features
- Sweep tests of amplitude, frequency, or bias
- Real-time data acquisition through GPIB port to a computer
- Data output configurable to user specified values
- Output includes RS 423, GPIB, data storage device
- Adjustments can be made while measurements are being taken
- Device learning program to recall series of commands
- Self test capabilities
- Local control or remote control

Figure 3-5: Solartron 1260 Impedance Gain-Phase Analyzer

The analyzer was equipped with a generator output, generator input, and two sets of voltage input terminals. All of the interfacing to the Solartron must be done through shielded coaxial cable. It was very important to keep the length of the cables between the analyzer and the test setup as short as possible. Longer cables add capacitance to the measurement particularly to the generator input and the LO input of the voltage terminals. To measure in-circuit impedance, connections were made to the Solartron using the generator output and input and the first set (V1) inputs (Figure 3-6) [18]. Once the cables were attached to the analyzer, proper connections to the probes were made through coaxial splitters (Figure 3-7).

Figure 3-6: Solartron Basic Configuration to Measure In-circuit Impedance

Figure 3-7: System Configuration with Solartron Analyzer, Burner, and Probe Setup

Z-plot software for Windows was utilized to communicate to the Solartron. This software made it easier to set up the measurement equipment, collect the data, and preview the data. The software was installed on a laptop computer and communicated with the analyzer through the GPIB port and a PCMICA data acquisition card.

Before collecting data in the flame, calibration of the equipment and verification of DC resistance was performed using resistors across the probes. This confirmed the order of magnitude of the data collected from the impedance meter.

The Z-plot for Windows manual provides an overview of the capabilities of the analyzer. Chapter 8 of the manual summarizes the setup experiments. Eight basic frequency response experiments may be configured from the main Z-plot window.

The first two experimental procedures produce a frequency spectrum	
Control E: Sweep Frequency	A frequency spectrum is measured while using a constant DC potential and AC amplitude
Control I: Sweep Frequency	A frequency spectrum is measured while using a constant DC current and AC amplitude
The third and fourth experimental procedures use a constant frequency and produce a voltage spectrum	
Control E: Sweep DC Potential	The applied DC potential (voltage bias) is varied while the frequency and AC amplitude are kept constant
Control E: Sweep AC Amplitude	The applied voltage waveform is varied in amplitude while the frequency and DC potential are kept constant
The fifth and sixth types of experimental procedures use a constant frequency and produce a current spectrum	
Control I: Sweep DC Current	The applied DC current (current bias) is varied while the frequency and AC amplitude are kept constant
Control I: Sweep AC Amplitude	The applied current waveform is varied in amplitude while the frequency and DC current are kept constant
The seventh and eighth experimental procedures apply a constant Frequency, DC Polarization and AC amplitude over time	
Control E: Vs. Time	The Frequency and DC potential voltage and AC amplitude are constant. The system is monitored for changes over time
Control I: Vs. Time	The Frequency and DC current and AC amplitude are constant. The system is monitored for changes over time

Table 3-1: List of Possible Test Configurations for Solarton Analyzer

For the flame impedance research, the AC response of the system using the first two experimental procedures (“Control E” and “Control I”) was investigated because they give impedance as a function of frequency. Both experimental procedures were tried. Results were much more clear using the Control I: Sweep Frequency rather than Control E: Sweep Frequency.

The “Control E” holds the applied voltage (E) constant while varying the applied current. The “Control E” experiment yielded noisy results. The available current measurements for this instrument fall at the edge of the measurable specifications for the applied voltages in this mode for impedances of the order required for the flame (very high).

The “Control I” measurement holds the applied current (I) constant while varying the voltage. Measurements of the voltage are then within measurement specifications at these very high impedances. The equation $|Z| = \frac{V}{I}$ means that for a large Z, the changes in V make more sense than changes in I. Therefore, holding the current (I) constant results in better measurements for these large magnitudes of impedance. The results of this research used the Control I method.

The software also allows monitoring of certain variables within a system. The monitor feature is different depending on the type of sweep used. Since the Control I sweep was used, the monitor function options are as follows:

*If **Monitor – Off** is used, the AC voltage amplitude at the generator output is determined by the **AC Amplitude** value. Note: Because of parasitic losses in cables, the test fixture, and the current measurement circuits, the amplitude applied to the device may be smaller than the value selected.*

***Monitor – V1** activates a feedback loop to adjust the AC amplitude at the generator output in order to produce the **AC Target** at the V1 analyzer input. The amplitude at the generator output will never exceed the **AC Limit** value. The **Error Limit** specifies how close the feedback loop must be to be considered acceptable. If the **Error Limit** is exceeded, an Error 84 signal will be produced. This does not necessarily indicate that the data is invalid, but rather that the amplitude at V1 was not exactly the desired value*

***Monitor I** – activates a feedback loop to adjust the AC amplitude (voltage) at the generator output in order to produce the **AC Target** at the I (current) analyzer input. The amplitude at the generator output will never exceed the **AC Limit** value. The **Error Limit** specifies how close the feedback loop must be to be considered acceptable. If the **Error Limit** is exceeded, an Error 84 signal will be produced. This does not necessarily indicate that the data is invalid, but rather that the amplitude at the I Input was not exactly the desired value.*

The above description is from the Z-plot manual and all the bold face words are parameters that can be set depending on the particular monitor mode set in software. One of the goals of this experiment was to try to back up the DC results from the atmospheric combustor, so it was decided to use the **Monitor – V1** mode to maintain 3 volts at the input, a similar condition used in taking the DC measurements. So, **AC Target** was set to 3 volts. As will be shown in the results, sweeps were taken from 0.1 Hz to 1 MHz. All attempts to generate results from frequencies greater than 1 MHz were unsuccessful, so frequencies below 1 MHz were primarily used for these experiments. Of this frequency range, only values below 1 kHz show valid data. This will be discussed in more detail in the results and conclusion. The data above 1 MHz continues the same fashion as the data between 1 kHz and 1 MHz. The data converges to the same value as the “No Flame” data.

The Solartron had one limitation that affects the data. The analyzer has a large percent error associated with it at high impedance (above $1\text{M}\Omega$) (Figure 3-7). Below $1\text{M}\Omega$, the analyzer only has a 1% error, however, at impedances greater than $1\text{M}\Omega$, the analyzer has a 10% error. This seriously limits the data collection. It will be shown in the Results that the magnitude of the data in the laboratory experiments is smaller than the calculated data. This error associated can explain the separation of experimental data with the theoretical data. This is discussed in more detail in the Chapter Five [19].

Figure 3-8: Solartron 1260 accuracy

3.4 Data Analysis

The Z-plot software used to collect the data was capable of graphing the magnitude of the impedance and the angle as function of the frequency. The software records the collected data to a filename.z file. This file was a space delimited file and can be analyzed using most spreadsheet software programs capable of opening space delimited files. The data collection was performed on site at the Morgantown, WV DoE/NETL facility. In order to analyze the data outside the NETL facility, the files were saved and Microsoft Excel was used to reopen the data. The Z-plot file only recorded the real part (r or $Z'(a)$ in the software), and the imaginary part (x , or $Z'(b)$ in the software) of the impedance. Microsoft Excel was used to recombine the real part and imaginary part into the complex form, $r + jx$, and then it was possible to extract the magnitude and angle. Then these values were plotted versus frequency and graphs similar to those generated by the Z-plot software were obtained.

Chapter FOUR

Theory

Theory of impedance measurements of a flat flame using an AC generated signal is discussed below. The theory presented in this chapter is based on basic electromagnetic fields and waves. Many assumptions have been made to develop this theory, since no previous research results have been discovered relating to flame impedance and the motion of current when an AC electric field is applied. Section 4.1 discusses the theory of the flame as a conductor and its properties. In this section, the theory behind the impedance of the flame will also be introduced. Boundary conditions and capacitance are introduced in section 4.2. Section 4.3 discusses the equipment setup and how it relates to a transmission line problem. The chapter will also address the assumed parameters and the theoretical results from the calculations performed in the earlier parts of this chapter. The comparison of the calculated results to the experimental results taken in the lab will be covered in the next chapter.

4.1 The flame as a Conductor

The flame between the two collection points can be assumed to be a conductor. Initial calculation assumed that the conductor is isotropic. Isotropic simply means that the applied *electric field* (E) and the *current density* (J) have the same value and direction [20]. To make

this assumption, the probe materials and conductor must be considered as good conductors. Analyzing this in terms of vector representation, the current density would need to strike the contacting surface between the probe and the flame at a 90° angle. Figure 4-1 shows the assumption that has been made in the calculations of current density. Figure 4-2 shows a possible scenario for the movement of J and E . To analyze what is really happening would require an extensive knowledge of the flame structure. More knowledge of the flame structure would also result in valuable information about the homogeneity of the area in question. The location of the flame's secondary reaction is unknown, but the probe tips were designed small enough to avoid problems with cross measurement of other sources such as secondary flame reactions. Analysis of this region using standard electrical and electromagnetic relationships will be discussed before discussing the overall system.

Figure 4-1: Isotropic J and E

Figure 4-2: Anisotropic J and E

4.1.1 Current

There are three main types of electric currents caused by the motion of free electrons. Dominant in the flame is **conduction current**. The other two types are **electrolytic currents**, (inside a solution by a process known as electrolysis) and **convection current**, (caused by motion of electrons and/or ions in a vacuum) [21].

Conduction currents unlike electrolytic currents and convection currents are solely based on the crystalline structure that makes up a solid material. From the study of Chemistry and the structure of an atom it is known that the atom consists of a positively charged nuclei surrounded by electrons. These electrons form what are known as shells around the nuclei. Figure 4-3 shows a representation of a single CHO^* molecule, the most important radical in the conduction of electric current. A radical, denoted by the star, is a molecule with unpaired electrons and is extremely reactive [22]. If an electron becomes free from one of its shells, the molecule becomes a positively charged ion, known as a **cation** (CHO^+). Likewise, if a free electron attaches to the neutrally charged ion, it becomes an **anion**, (CHO^-) [23]. Typically in flame ionization, the CHO^* molecule will lose an electron during chemi-ionization as discussed in section 2.2.3. The electrons on the outer shells are not held to the atom as strongly as the other electrons on the closer shells to the nuclei. In an atom any given shell has a maximum number of electrons that can occupy it, Having too many electrons will cause the left over electrons to attach to the next shell, but not having enough will leave holes for a free electron to fill. The further away from the nuclei an electron attaches, the less energy it takes to free the electron from the atom. This transfer of electrons is conduction. The outer shell, known as the valence shell, holds the electrons used in conduction. When no probes are present in the flame,

conduction occurs, but by applying an electric field, the conduction of electrons becomes organized between the field points. This organization will then cause a current through the conductor.

Figure 4-3: CHO* Molecule

Using simple proven electromagnetic properties, it can be shown that the total amount of current through an arbitrary *surface*, S , is the flux of the current density, J , vector through S ,

$$I = \int_S J \cdot ds = JS \quad (\text{A}) . \quad (4-1)$$

4.1.2 Current Density

From equation 4-1 the current through the flame depends on the current density (J) integrated across the entire surface. Current density can be defined as the product of the number of charge carriers N per unit volume, the charge of each carrier q and the velocity u of the carriers,

$$J = (N)(q)(u) \quad (\text{A} / \text{m}^2). \quad (4-2)$$

In equation 4-2 the product of Nq is charge per unit volume, often written as $\rho = Nq$ and equation 4-2 can be written as

$$J = \rho u \quad (\text{A} / \text{m}^2). \quad (4-3)$$

The velocity at which any given charge travels is directly proportional to the electric field intensity (E) by a constant of the medium known as electron mobility μ_e ,

$$u = -\mu_e E \quad (\text{m / s}). \quad (4-4)$$

Substituting equation 4-4 into 4-3 yields,

$$J = \sigma E \quad (\text{A / m}^2), \quad (4-5)$$

where $\sigma = -\rho_e \mu_e$. This constant is a parameter of the medium known as **conductivity**.

Conductivity is used to relate materials and their ability to conduct. The units of conductivity are ampere per volt-meter (A/V * m) or siemens per meter (S/m), where ampere per volt (A/V) equals a siemen (S). This parameter is the basis of the theory behind flame impedance.

4.1.3 Impedance

Before deriving the conductivity of a flame, the impedance as a function of the conductivity will be given. The impedance of the flame can be theorized by looking at a particular section or surface of the flame, between the collection points. The theory of the impedance of a homogeneous material with constant cross section begins with a vector representation of **ohm's law**.

$$\bar{V} = \bar{I} \bar{Z}. \quad (4-6)$$

where V, I, and Z are all AC electrical properties of the applied field. Using the same relation shows the voltage across the material is

$$\begin{aligned} \bar{V} &= \bar{E} \ell \\ \text{or} \\ \bar{E} &= \frac{\bar{V}}{\ell}. \end{aligned} \quad (4-7)$$

It was shown earlier that the total current through the conductor is

$$\bar{I} = \int_S \bar{J} \cdot d\mathbf{s} = \bar{J}S$$

or

$$\bar{J} = \frac{\bar{I}}{S} \quad (4-8)$$

Substituting equation 4-7 and 4-8 into equation 4-5 yields

$$\frac{I}{S} = \sigma \frac{\bar{V}}{\ell}$$

or

(4-9)

$$\bar{V} = \left(\frac{\ell}{\sigma S} \right) \bar{I} = Z \bar{I}$$

Solving equation 4-9 for the impedance of a homogenous material with constant cross sectional area is

$$Z = \frac{\ell}{\sigma S} \quad (\Omega) [24]. \quad (4-10)$$

4.1.4 Conductivity

From equation 4-10, the length (ℓ) and surface area (S) are constants of the medium. In order to have complex impedance (Z) dependant upon the frequency, the conductivity must also be complex and dependant upon the frequency. The complex conductivity will take the form of $\sigma = \sigma_x - j\sigma_y$. It has been proven that the conductivity of species k is

$$\sigma_k = \frac{N_k q^2 (v_k - j\omega)}{M_k (v_k^2 + \omega^2)} \quad (\text{S/m}). \quad (4-11)$$

Species k becomes the electrons and CHO^+ molecules that ionize to produce the conductivity.

In the flame, conductivity applies to electrons as well as ions. The total conductivity then becomes the sum of the conductivities of all the species. From the conductivity equation

$\sigma = \sigma_x - j\sigma_y$ [24, 25], it is much easier to write the individual components of conductivity as

$$\sigma_x = \sum_k \frac{N_k q^2 v_k}{M_k (v_k^2 + \omega^2)} \quad \sigma_y = \sum_k \frac{N_k q^2 \omega}{M_k (v_k^2 + \omega^2)} . \quad (4-12a \text{ \& } b)$$

In equations 4-11 and 4-12 N is the **charge density**, q is the **charge**, ω is the **angular frequency** equal to $2\pi f$, M is the **mass** of the species, and v is the **collision frequency** [25].

4.1.5 Collision Frequency

The mass and charge of CHO^+ and free electrons are constants, however the collision frequency and charge density are not. The collision frequency can be calculated by dividing the average velocity by the mean free path,

$$v_k = \frac{\bar{v}}{\lambda} \quad (1/s) . \quad (4-13)$$

The mean free path is derived from Kinetic theory using the ideal gas law $PV = nRT$, the diameter of the molecules (d), and Avogadro's number (N_A). The **mean free path** represents a typical distance that a particle would move between collisions based on a particle's probability of undergoing interactions with other particles in a medium. Equation 4-14 shows the mean free path derived from the properties of the molecules and the system [26],

$$\lambda = 4.5 \times 10^{13} \frac{T^2}{q_i^2 n_i \ln \Lambda} \quad (\text{cm}) . \quad (4-14)$$

The interesting part of equation 4-14 is that the mean free path is proportional to the temperature of the system. The temperature of the burner will depend on the equivalence ratio.

As equivalence ratio is increased, the temperature also increases. The numbers in Table 4-1 are based on typical numbers measured by experimentation in the past.

The average velocity is based on **Maxwell's Speed Distribution** of an ideal gas [27]. Shown in Figure 4-4, is the Maxwell Speed Distribution for molecules. Equations 4-15 describe the most important parts of the distribution. The most important equation is 4-15(b), which calculates the average molecular speed, or average velocity of a molecule.

Figure 4-4: Maxwell's Speed Distribution

$$v_p = \sqrt{\frac{2RT}{M}}, \quad \bar{v} = \sqrt{\frac{8RT}{\pi M}}, \quad v_{rms} = \sqrt{\frac{3RT}{M}} \quad (\text{m/s}). \quad 4-15 \text{ a, b, \&c)}$$

Substituting equation 4-15b and 4-14 into 4-13, after verifying proper units, equation for collision frequency is calculated (electron-ion, electron-electron, and ion-ion),

$$v_{ei} = 1.5 \times 10^{-6} \frac{q_i^2 n_i \ln \Lambda}{T_e^{3/2}} \quad (1/\text{s}), \quad (4-16)$$

$$v_{ee} = 3 \times 10^{-6} \frac{q_i^2 n_i \ln \Lambda}{T_e^{3/2}} \quad (1/\text{s}), \quad (4-17)$$

$$v_{ii} = q_i^4 \left(\frac{m_e}{m_i} \right)^{1/2} \left(\frac{T_e}{T_i} \right)^{3/2} v_{ee} \quad (1/s) . \quad (4-18)$$

The collision frequency is a function of the variable denoted as $\ln \Lambda$. This is called the **Coulomb logarithm**, computed from the Maxwell's distribution function and it represents the maximum impact parameter [28]. The coulomb logarithm is derived from the **Coulomb force** between two particles. Typical values for the Coulomb force are given in Table 4-1. Notice that for low temperature plasmas the coulomb logarithm is around 10. Since the flat flame burner is can be considered a low temperature plasma, below 0.2 eV, the Coulomb logarithm can be assumed to be 9 [29].

KT _e (eV)	n (m ⁻³)	Ln Λ	
0.2	10 ¹⁵	9.1	(Q-machine)
2	10 ¹⁷	10.2	(lab plasma)
100	10 ¹⁹	13.7	(typical torus)
10 ⁴	10 ²¹	16.0	(fusion reactor)
10 ³	10 ²⁷	6.8	(laser plasma)

Table 4-1: Typical values of the Coulomb logarithm

4.2 Boundary Conditions of the Conductors

In experimental measurements, boundaries between unlike components must be considered. In this system, there exist two boundary conditions. The first boundary being the connection of the copper wire coaxial cable used from the Solartron with the inconel used for the probes. The effects of this junction are minimal and will be discussed 4.2.1. In section 4.2.2, the junction between the inconel probe and the flame will be discussed. The junction between the probes and flame is very important because it may introduce extra capacitance into the system measurement.

4.2.1 Galvanic Effects from Dissimilar Metals

A junction between dissimilar metals creates what is known as a *galvanic voltage* at the junction. This erroneous voltage will affect the voltage applied at the probe tip. To help pick metals with similar galvanic levels, the scientific community uses a published list known as the galvanic series [30]. The top of the list is the least noble and therefore has the lowest resistance to galvanic effects. The galvanic series is given in Appendix A-1 and it can be seen that platinum is the most noble of these materials, which implies it will be the most resistant to galvanic effects. This does not mean that galvanic effects will not exist. If platinum is introduced to a dissimilar metal, for example copper, and moisture is present, the large differences in the galvanic levels of copper and platinum will cause a galvanic voltage. Just as in this example, there was little choice but to use copper core shielded cable to interface from the probe(s) to the impedance analyzer. The material for the probes then must interface well with copper. As mentioned earlier, looking at what materials were readily available and how they associated with copper according to the galvanic series, inconel proved superior. Since inconel fell close to copper in galvanic series and the moisture present in the up stream of the burner was minimal, the effect from galvanic voltages was negligible.

4.2.2 Boundary Conditions in the Flames

The boundaries at the flame between the inconel probe and the copper electrode by far are the most important to consider. If the probe is protruding into the flame in such a way as to create cold gas around the tip, a capacitor is created between the actual flame itself and the probe. The physical properties of a capacitor are two conduction plates separated by a dielectric material. The probe tip can be considered one conductor and the flame can represent the other

conductor. The ideal dielectric between these two conductors is air. There can be some debate as to whether air is the only substance between the probes and the flame. To prove the effects on the probes at the flame front, this assumption will be sufficient. Also, because the flame and copper electrode have differences in electrical conductivity, the boundary also can affect the measurements. Figure 4-5 is a representation of the probe, flame and copper electrode.

Figure 4-5: The Flame Boundaries Act as a Parallel Plate Capacitor

Consider the probe to flame boundary. The largest effect is the capacitance this boundary may add to the readings by the Solartron. Figure 4-6 is a basic parallel capacitor where each conductor has an equal surface area S , and the plates are separated by a distance d . If the boundary between the probe and the flame is considered as a parallel plate capacitor, then the capacitance is

$$C = \epsilon \frac{S}{d} \quad (\text{F}) [31]. \quad (4-17)$$

where ϵ is the *relative permittivity* of the medium between the probe and the flame, which is assumed to be air. The relative permittivity ϵ of air is $1/36\pi \times 10^{-9}$ (F/m). The space between the probe and the flame depends on the amount the probe is protruding into the flame front. The further the probe extends, the more air gap that will be created until the tip is completely in the flame, in which case the gap would remain constant.

Figure 4-6: Simple Parallel Capacitor and its Analogy to the System

In the beginning of this chapter, an assumption was made that the flame is considered homogenous, meaning the current density and the applied electric field both flow smoothly across the medium. The assumption is that the inconel probe, flame, and copper electrode are all good conducting media. At each boundary where the flame meets either the inconel or the copper electrode, the direction or the path that the current travels may be affected. For calculation purposes, Figure 4-1 represents what has been assumed, but because of unlike conductivities of the inconel, flame, and copper electrode, Figure 4-2 is more realistic. At the boundary between the metal and the flame, the current is striking the boundary at some angle to the surface. In an ideal conductor, the current density will strike the boundary perpendicular to the surface. As mentioned in the last chapter about the experiment, the equipment was setup to hold the voltage across the probe and copper electrode at 3 volts. At times during experiments,

an error would occur informing that the Solartron could not hold the voltage at the desired level. The boundary conditions between the inconel probe, flame, and copper electrode may be the cause of such an error.

4.3 Transmission Line

When looking at the overall system from the Solartron Impedance Analyzer to the probes, the system is setup similar to a simple *transmission line* problem. Figure 4-7 shows this system as a transmission line. Transmission lines are excellent devices to carry power from a source, or transmitter, to a load. The most commonly used transmission line is the coaxial cable. Coaxial cable is constructed with a center conductor, dielectric material, an outer conductor, and insulation. An important part of transmission line theory is the characteristic impedance of the line. How well the load impedance “matches” the transmission line and the transmission line matching the impedance of the transmitting device will affect the performance of the coaxial cable. If given certain parameters, it is possible to calculate the load impedance from the reflected wave. However, because the frequencies used for the analysis of the flame, this method of theorizing the load impedance cannot be used. In transmission line theory, it is accepted that if the length of the transmission line divided by the *wavelength*, $\frac{\ell}{\lambda}$, is smaller than 0.01 then the effects from the transmission line may be ignored [32]. As it will be shown in the experimental plots, the frequencies that will be used are less than 1 kHz. At these frequencies $\frac{\ell}{\lambda}$ is very small. In conclusion, the transmission line effects from this system are negligible.

Figure 4-7: Transmission Line layout of analyzer and load

Chapter FIVE

Results

This Chapter will discuss the experiments performed in the laboratory on the flat flame. The theoretical data will be presented separately and then compared to the data collected in the laboratory. Many experimental tests were performed to collect the data in this chapter. Details from each of experimental tests performed and the results from those tests will be discussed in Section 5.1. Furthermore, the theoretical results and some of the problems that arose with calculations of the theoretical data will be presented in Section 5.2. Finally, in Section 5.3, comparison of the experimental data with the theoretical data will be given that will lead to a conclusion on this research.

5.1 Experimental Results

The Solartron Analyzer is capable of performing many different tests based on the configuration of the equipment. The Solartron was set up to duplicate the previous research measurements on electrical resistance using smaller voltage magnitudes. To calculate the electrical impedance instead of the electrical resistance an AC applied voltage will replace the DC voltage used for the resistance measurements. After much trial and error, the current settings of the equipment were optimized based on the resulting data. Much of the early data contained

noise and was inconclusive. After modifying the test procedures of the analyzer, settings were reached that resulted in adequate data to discuss. As mentioned in Chapter Three, the Control I method was employed to measure the Impedance of the flame.

Six data sets were collected that shows conclusive data (Table 5-1). The first three data sets are discussed in Section 5-1. The three remaining sets were performed to investigate the effects of the distance between the inconel probe and copper electrode. This data is mentioned in an Addendum following the Appendix. Along with this data came many questions that still need to be answered to further this research and will be discussed in more detail in the conclusion in Chapter six.

Code (Date)	Description
101601	Manually Averaged Data
102301	Frequency Sweeps
102501	Time Sweeps
110901	Smallest Distance Between Collection Points
111301	Greatest Distance Between Collection Points
111501	Middle Distance Between Collection Points

Table 5-1: Summary of Conclusive Data Sets

The first of these experiments, the manually averaged data, utilized a special feature of the Solartron Analyzer. Under the “Measure” menu of the Z-Plot for Windows software, an option can be used called “Variable” to analyze the system at a given set of specifications and at one frequency. Data was collected at intervals of 0.1, 1, 10, 100, 1k, 10k, 100k, and 1M Hz. The AC amplitude of the Analyzer was set to 3.00 volts, similar to what was used in the DC measurements. By setting the generator to the frequencies above, and monitoring the data displayed on the screen, values were manually averaged and both magnitude of the impedance ($|Z|$) and theta (θ) were recorded (Appendix B-1). These recorded values were plotted against the

applied frequency (Figure 5-1 & 5-2 respectively). This data is labeled with code 101601 data, corresponding to the date at which it was taken

The second experiment, labeled 102301, used the Solartron Analyzer to sweep through a range of frequencies from 0.1 – 1MHz. As the analyzer swept through the frequencies, it recorded the values of the real ($Z'_{(a)}$) and the imaginary ($Z''_{(b)}$) parts of the impedance data (Appendix B-2). From this experiment, the data then was analyzed using Microsoft Excel and values for the magnitude of the impedance $|Z|$ and angle theta (θ) were calculated and plotted (Figure 5-3 & 5-4).

Figure 5-3: 102301 - $|Z|$ vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different equivalence ratios
October 23, 2001

Figure 5-4: 102301 - theta vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different equivalence ratios
October 23, 2001

All the data exhibits similar trends. However, the 102501 and 101601 data is very similar. The 101601 and 102501 data sets are common in that they both are averaged data. Also, the magnitude is greater than the data in the 102301 data. This brings up an interesting idea, that the Solartron may have some inherent losses when operating under the Control I vs. Frequency method. The flame structure must also be considered. As the frequency is changed, allowing the flame to stabilize and the ionization to react to the change in frequency would be more beneficial than quickly sweeping through frequencies. Also, at frequencies above 1 kHz, the magnitude of the impedance converges to the same value as the “No Flame” condition. This can be seen throughout the experiments performed. Below 1 kHz, there is a distinct separation of the data based on the equivalence ratio.

5.2 Theoretical Results

Now that the experimental results have been considered, the theoretical results can be calculated and compared to those taken in the laboratory. Using the theory presented in Chapter Four, calculations were made on the impedance of the flame. Equation 4-10 shows that the impedance ($r + jx$) is a function of the conductor length and surface area. A surface area, similar to that shown in Figure 4-1 was assumed. This area was based on the diameter of the inconel probe used and the distance between the probe and the copper shield around the flame (Figure 5-7). The diameter of the probe was measured to be 0.085 inches and was an estimated distance of 0.75 inches from the copper shield. Units used in calculations are in the cgs (centimeters, grams, seconds) measurement system. The remaining constants of the systems and molecules (Table 5-2) were all known values based on Physics and Chemistry.

Figure 5-7: Assumed Flame Conductor Area

Conductor Parameters	Value	Units
length	1.905	centimeters
diameter	0.2159	centimeters
radius	0.10795	centimeters
System Parameters		
Pressure	1	atm
Surface Area	1.365323302	square centimeters
Volume	6.97E-02	cubic centimeters
Gas Constant	951866.7399	cubic centimeters*atm/ mol*eV
Avrogodro's #	6.02E+23	atoms/mole
Coulomb logarithm	10	
Molecular Parameters		
CHO* Diameter	1.00E-08	centimeters
CHO* Mass	29	amu
CHO+ Charge State	1.00E+00	
CHO+ Charge	4.80E-10	esu
e- Diameter	1.00E-16	centimeters
e-Mass	0.0005	amu
e- Charge	-4.80E-10	esu

Table 5-2: System Parameters and Units

From Chapter Four, many complicated equations were introduced. Many of these equations were based on parameters of the system or the molecules. The equations can be further summarized by combining all of the constants. Also, by combining the equations into equation 4-10, electrical impedance can be summarized into one equation,

$$Z = \frac{\ell}{\sigma S} \quad (\Omega) \quad (5-1)$$

and

$$\sigma_k = C \frac{(v_k - j\omega)}{(v_k^2 + \omega^2)} \quad (\text{S/m}), \quad (5-2)$$

where $C = \frac{n_k e^2}{M_k}$ and the conductivity becomes a function of the collision frequency and applied

angular frequency ($2\pi f$). The collision frequency, v_k , then becomes a function of the species'

temperature, electron or ion, which is assumed to be the same for this research and will be denoted below with the variable T,

$$\nu_k = \frac{\bar{v}}{\lambda} \quad (\text{Hz}). \quad (5-3)$$

Substituting Equations 4-14 and 4-15b into Equation 5-3, collision frequencies for electrons and ions become,

$$\nu_{ee} = K_e T^{-3/2} \text{ and } \nu_{ii} = K_i A^{-1/2} T^{-3/2} \quad (\text{Hz}), \quad (5-4)$$

where K_e and K_i are constants of the system.

In conclusion, the theoretical data shows that the flame's impedance is largely a function of the flame's temperature. This can be seen in Equation 5-4. The ionization depends on the collision between electrons and ions and this collision is completely dependent upon the energy of the molecules governed by the temperature of the flame. This collision frequency will change the value of conductivity and impedance. Collision frequency is typically a difficult value to estimate in a flame, due to the random elastic and inelastic collisions of electrons and ions. The reaction frequently considered the most important for ionization is the chemi-ionization of CHO^* , discussed in Chapter Two, Section 2.2. Other ions are created in smaller quantities, but are not taken into account in the calculations. Given information about the collision frequency of a system, the electrical impedance can be summarized as,

$$Z = \frac{\ell(\nu_k^2 + \omega^2)}{SC(\nu_k - j\omega)} \quad (\Omega), \quad (5-5)$$

where ℓ is the length of the conductor, S is the surface area, C is the conductivity constant introduced in equation 5-2, ν_k is the collision frequency as a function of temperature, and ω is the

applied angular frequency. Calculations of the theoretical impedance $|Z|$ and theta θ were made and plotted against the same frequencies used in the experimental sweeps (Figure 5-8 & 5-9).

Figure 5-9: Theoretical theta Vs. Frequency

5.3 A comparison (Experimental Vs. Theoretical)

Like most research, the theoretical results do not match the experimental results.

Although this research is no different, the experimental and theoretical data do exhibit similar characteristics. This Section will discuss the similarities of the data and present possible theories why the experimental and theoretical data do not match exactly.

Consider the experimental data of impedances $|Z|$ Vs. Frequency (Figure 5-1, 5-3, & 5-4), as the frequency is increased above 1 kHz, the impedance begins to decline, but the calculated data remains constant over the broad range of frequencies. From this it can be concluded that at frequencies above 1 kHz, the system exhibits extreme amounts of loss. In the theta vs. Frequency plots (Figure 5-2, 5-4, 5-6) the angle is -90° , which suggest a capacitive load at the higher frequencies. The probes used for data collection are exposed to not only the chemi-

ionization of the flame, but also the recombination of the electrons and other species in the different parts of the flame zone. It has been suggested by Jimmy Thornton, NETL employee, that in the higher frequencies, other species offer other paths for conduction between the probes resulting in lower impedances.

Looking at the magnitudes of the real part of the impedance in the experimental and theoretical data shows the largest discrepancy (Figure 5-10 & 5-11). Figure 5-10 shows the experimental and the theoretical data plotted on the same graph for a single equivalence ratio (0.9). The remaining equivalence ratios were all similar to this example. The magnitude of the experimental data ranges from the between $10^6 \Omega - 10^9 \Omega$. However, the calculated data is approximately $10^{11} \Omega$. Also, the experimental data is spread over a broader range of impedances than the theoretical data. Considering the analytical values used in the theoretical calculations, the charge density of electrons and ions do not change much. It is believed that a much greater change in the densities exists in the flame. This change in the charge density will limit the amount of ions or electrons created during ionization and affect the overall impedance.

Figure 5-10: Theoretical and Experimental $|Z|$ vs. Frequency
Frequency data at equivalence ratio of 0.9 using
October 26, 2001

Figure 5-11: Theoretical and Experimental theta vs. Frequency
Frequency data at equivalence ratio of 0.9 using

In the laboratory, it was noticed that the magnitude of the impedance measured by the Solartron had a direct relationship to the equivalence ratio of the fuel. As seen in the data in Section 5-1, the impedance becomes lower as the equivalence ratio is increased. The calculated data shows the same trend, only to conclude that the impedance appears to have a direct relationship of the equivalence ratio.

Chapter SIX

Conclusion

This research investigated the complex electrical impedance of a Methane flat burner flame, to determine if electrical impedance can provide information about the flame itself. Three electrical probe configurations were considered. The first design did not provide conclusive data and generated data with considerable noise. The second design, could not handle the extreme temperatures of the flame and as a result, the insulation on the shielded cable melted causing a short circuit. The third design produced the results presented in this thesis. It was constructed from a piece of copper and one of the inconel probes used for the first design. The copper was positioned in a circular fashion around the flame and the inconel probe was mounted above the flame, within the reaction zone. Several experiments were performed using Solartron Impedance Gain-Phase Analyzer.

6.1 Solartron Impedance Losses

When analyzing data in a “real time” environment, two things must be considered. The first is that the equipment gives the system being analyzed proper time to react to the changes in the applied frequency and secondly has the capability to analyze a system very quickly. The question arises as what is quick enough, but not too quick. A collection scheme too slow will miss critical data, however a collection scheme too fast may not allow the system to stabilize

before making a measurement. This was shown in the difference between the averaged data and the frequency sweep data. At 1kHz, the Solartron is very accurate for Impedances in the range of $1 - 1 \text{ M}\Omega$ with only 1% error. Outside $1 \text{ M}\Omega$, the percent error is greater than 10%. Although the measurements did not appear to be noisy at the high impedance, the experimental data recorded was considerably less than the theoretical data. It can be concluded that the Solartron added inherent losses to the data at these large values of impedance.

6.2 Research Conclusion

The impedance of a methane flat flame burner seems to be related to the equivalence ratio from the collision frequency and the applied angular frequency. This is confirmed by the experimental data and the theoretical data that was presented in Chapter Five. Although the magnitudes of the experimental data and the theoretical data do not match, a similar trend is noticeable. The data is conclusive at lower frequency and shows that the electrical equivalence of the flame is an RC circuit (Figure 6-1). At frequencies above 1 kHz the data is similar to that at the “No Flame” conditions. It can be concluded from this that at higher frequencies the capacitance of air dominates the data. This is shown in experimental data in Chapter Five as frequency increases above 1 kHz all the data converges and no separation of the data exists.

Figure 6-1: Flame Electrical Equivalence

6.3 Future Work

1. As mentioned in Section 6.1, the Solartron has limitations for high impedances. A alvanostat can be added to the analyzer to scale the input to an amount that can be accurately measured.
2. The time that the analyzer collects data on a particular frequency could be increased to eliminate problems with early measurements.
3. As the applied frequency changes, how does that affect the impedance measurement and does there exist a delay time to allow the ionization to reorganize with respect to the new applied field?
4. Although the probe design works well, the ceramic used as an insulator may not insulate at the higher temperatures. Only pure ceramic would allow for a perfect insulation of the probe. Otherwise the metal contaminates could conduct electricity as temperatures increase.
5. The mounting of the probes could be improved so that the movement of the system is minimal during and between data collection times. The data collected with a rigid system would be more conclusive when distance is known to be constant. This rigid system should also include eliminating the ceramic padding underneath the copper electrode. As mentioned before the ceramic padding cause perturbations in the flame and is affecting the outcome of the data.

Appendix A-1: Galvanic Series

Noble, cathodic end

Platinum
Gold
Graphite
Titanium
Silver
Hastelloy C
18-8 austenitic stainless steels (passive condition)
Iron-chromium alloys (passive condition)

Inconel (passive)

Nickel
Monel
Cupronickel alloys
Bronzes

Copper

Brasses

Inconel (active)

Nickel (active)
Tin
Lead
18-8 Austenitic stainless steels (active)
13% Chromium stainless steel (active)
Cast iron
Mild steel and iron
Cadmium
Aluminum alloys
Zinc
Magnesium and magnesium alloys

Active, anodic end

Appendix B-1: 101601 - Manually Averaged Data

$ Z $		0.6	0.7	0.8	0.9	1.0	No Flame
Frequency (Hz)	1.00E+06	1.98E+05	1.66E+05	2.08E+05	2.06E+05	2.00E+05	1.63E+05
	1.00E+05	1.40E+06	1.32E+06	1.45E+06	1.62E+06	1.61E+06	1.48E+06
	1.00E+04	1.07E+07	1.17E+07	1.37E+07	1.28E+07	9.62E+06	1.61E+07
	1.00E+03	6.32E+07	8.45E+07	7.68E+07	6.32E+07	4.06E+07	2.19E+08
	1.00E+02	1.82E+08	8.41E+07	4.15E+07	2.22E+07	1.21E+07	1.27E+09
	1.00E+01	1.79E+08	4.07E+07	1.92E+07	1.07E+07	6.60E+06	1.07E+09
	1.00E+00	2.13E+08	4.00E+07	1.82E+07	1.00E+07	6.14E+06	1.70E+09
	1.00E-01	2.32E+08	4.08E+07	1.86E+07	9.80E+06	6.40E+06	1.31E+09

theta		0.6	0.7	0.8	0.9	1.0	No Flame
Frequency (Hz)	1.00E+06	-76.89	-77.62	-77.64	-77.05	-75.1	-78.25
	1.00E+05	-89.02	-93.4	-91.47	-89.11	-84.4	-102
	1.00E+04	-71.74	-77.97	-78.32	-72.04	-65.5	-96
	1.00E+03	-61.02	-62.6	-60.06	-58.02	-55.9	-103.2
	1.00E+02	-39.27	-11.73	-3.96	-0.78	-0.68	-88.5
	1.00E+01	-10.11	-1.018	0.323	0.74	0.79	-30.14
	1.00E+00	-6.402	-0.82	-0.34	-0.38	-0.37	-128.1
	1.00E-01	-5.184	0.017	0.009	-0.09	0.08	-167.2

Appendix B-2: 102301 - Frequency Sweep Data

$\phi = 0.6$

ZPlotW Data File: Version 2.2													
Raw Data													
Sweep Frequency: Control Current													
Date: 10-23-2001 Time: 12:12:32													
Open Circuit Potential (V): 0													
C:\SAI\ZData\Flat Burner\102301\1k-1M,nonull,0.6,unknown,monitor,V1,Copperstirp1.z													
Frequency													
4	2	0	1	1000000	1000								
31													
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)	
1.00E+06	3.00E+00	0.00E+00	1.40E+01	3.67E+04	-1.48E+05	0.00E+00	4	0	36670-148300j	152766.4	-1.32839	-76.1111	
7.94E+05	3.00E+00	0.00E+00	3.97E+01	3.81E+04	-1.53E+05	0.00E+00	4	0	38088-152800j	157475.5	-1.32651	-76.0033	
6.31E+05	3.00E+00	0.00E+00	6.73E+01	4.31E+04	-1.90E+05	0.00E+00	4	0	43087-190170j	194990	-1.34799	-77.234	
5.01E+05	3.00E+00	0.00E+00	9.31E+01	1.92E+04	-2.62E+05	0.00E+00	4	0	19166-262250j	262949.4	-1.49784	-85.8201	
3.98E+05	3.00E+00	0.00E+00	1.19E+02	-1.46E+04	-3.13E+05	0.00E+00	4	0	-14586-313380j	313719.3	-1.61731	-92.6649	
3.16E+05	3.00E+00	0.00E+00	1.45E+02	8.03E+03	-4.61E+05	0.00E+00	4	0	8031.9-461000j	461070	-1.55338	-89.0018	
2.51E+05	3.00E+00	0.00E+00	1.70E+02	1.04E+04	-4.87E+05	0.00E+00	4	0	10403-487070j	487181.1	-1.54944	-88.7764	
2.00E+05	3.00E+00	0.00E+00	1.96E+02	6.71E+04	-6.63E+05	0.00E+00	4	0	67106-663000j	666387.4	-1.46992	-84.2205	
1.58E+05	3.00E+00	0.00E+00	2.22E+02	1.23E+04	-7.25E+05	0.00E+00	4	0	12280-724600j	724704	-1.55385	-89.0291	
1.26E+05	3.00E+00	0.00E+00	2.48E+02	-1.89E+04	-1.06E+06	0.00E+00	4	0	-18856-1058300j	1058468	-1.58861	-91.0207	
1.00E+05	3.00E+00	0.00E+00	2.74E+02	1.38E+05	-1.24E+06	0.00E+00	4	0	137750-1243300j	1250908	-1.46045	-83.6778	
7.94E+04	3.00E+00	0.00E+00	3.00E+02	-6.64E+04	-1.39E+06	0.00E+00	4	0	-66371-1391300j	1392882	-1.61846	-92.7312	
6.31E+04	3.00E+00	0.00E+00	3.28E+02	1.96E+05	-2.14E+06	0.00E+00	4	0	196120-2138000j	2146976	-1.47932	-84.7589	
5.01E+04	3.00E+00	0.00E+00	3.54E+02	6.03E+05	-2.37E+06	0.00E+00	4	0	602540-2366900j	2442390	-1.32152	-75.7176	
3.98E+04	3.00E+00	0.00E+00	3.80E+02	6.01E+05	-3.06E+06	0.00E+00	4	0	600780-3057900j	3116358	-1.3768	-78.8848	
3.16E+04	3.00E+00	0.00E+00	4.06E+02	7.49E+05	-3.53E+06	0.00E+00	4	0	748590-3527400j	3605959	-1.36168	-78.0184	
2.51E+04	3.00E+00	0.00E+00	4.32E+02	1.28E+06	-4.27E+06	0.00E+00	4	0	1282100-4271400j	4459668	-1.27919	-73.2924	
2.00E+04	3.00E+00	0.00E+00	4.58E+02	1.39E+06	-5.31E+06	0.00E+00	4	0	1387900-5305700j	5484225	-1.31494	-75.3407	
1.58E+04	3.00E+00	0.00E+00	4.84E+02	2.07E+06	-6.57E+06	0.00E+00	4	0	2072900-6570400j	6889635	-1.26519	-72.49	
1.26E+04	3.00E+00	0.00E+00	5.10E+02	2.22E+06	-7.67E+06	0.00E+00	4	0	2218800-7666300j	7980929	-1.28907	-73.8584	
1.00E+04	3.00E+00	0.00E+00	5.36E+02	2.67E+06	-9.64E+06	0.00E+00	4	0	2669900-9640400j	10003283	-1.30062	-74.52	
7.94E+03	3.00E+00	0.00E+00	5.62E+02	3.94E+06	-1.13E+07	0.00E+00	4	0	3936200-11254000j	11922508	-1.23434	-70.7222	

6.31E+03	3.00E+00	0.00E+00	5.88E+02	5.10E+06	-1.33E+07	0.00E+00	4	0	5104700-13312000j	14257184	-1.20462	-69.0199
5.01E+03	3.00E+00	0.00E+00	6.14E+02	6.44E+06	-1.57E+07	0.00E+00	4	0	6440800-15674000j	16945742	-1.18091	-67.6611
3.98E+03	3.00E+00	0.00E+00	6.40E+02	8.03E+06	-1.83E+07	0.00E+00	4	0	8025000-18302000j	19984089	-1.15757	-66.3237
3.16E+03	3.00E+00	0.00E+00	6.66E+02	1.01E+07	-2.19E+07	0.00E+00	4	0	10071000-21893000j	24098309	-1.13965	-65.2971
2.51E+03	3.00E+00	0.00E+00	6.92E+02	1.21E+07	-2.62E+07	0.00E+00	4	0	12144000-26198000j	28875802	-1.13673	-65.1301
2.00E+03	3.00E+00	0.00E+00	7.18E+02	1.53E+07	-3.07E+07	0.00E+00	4	0	15275000-30739000j	34325089	-1.10961	-63.576
1.58E+03	3.00E+00	0.00E+00	7.44E+02	1.85E+07	-3.56E+07	0.00E+00	4	0	18517000-35578000j	40108271	-1.09091	-62.5047
1.26E+03	3.00E+00	0.00E+00	7.70E+02	2.26E+07	-4.28E+07	0.00E+00	4	0	22550000-42803000j	48379741	-1.08591	-62.2183
1.00E+03	3.00E+00	0.00E+00	1.42E+01	2.85E+07	-5.04E+07	0.00E+00	4	0	28549000-50351000j	57881505	-1.055	-60.4468
7.94E+02	3.00E+00	0.00E+00	4.03E+01	3.46E+07	-5.73E+07	0.00E+00	4	0	34560000-57329000j	66940330	-1.02829	-58.9169
6.31E+02	3.00E+00	0.00E+00	6.20E+01	4.11E+07	-6.63E+07	0.00E+00	1	0	41085000-66337000j	78029320	-1.01628	-58.2285
5.01E+02	3.00E+00	0.00E+00	8.38E+01	4.80E+07	-7.17E+07	0.00E+00	1	0	48019000-71733000j	86321768	-0.98089	-56.2011
3.98E+02	3.00E+00	0.00E+00	1.06E+02	5.56E+07	-7.59E+07	0.00E+00	1	0	55583000-75905000j	94079960	-0.93874	-53.7858
3.16E+02	3.00E+00	0.00E+00	1.27E+02	6.45E+07	-8.03E+07	0.00E+00	1	0	64509000-80315000j	1.03E+08	-0.89411	-51.2286
2.51E+02	3.00E+00	0.00E+00	1.51E+02	7.40E+07	-8.10E+07	0.00E+00	0	0	73998000-81022000j	1.1E+08	-0.83068	-47.5943
2.00E+02	3.00E+00	0.00E+00	1.72E+02	8.45E+07	-7.86E+07	0.00E+00	0	0	84459000-78568000j	1.15E+08	-0.74928	-42.9305
1.58E+02	3.00E+00	0.00E+00	1.94E+02	9.54E+07	-7.25E+07	0.00E+00	0	0	95421000-72489000j	1.2E+08	-0.64966	-37.223
1.26E+02	3.00E+00	0.00E+00	2.16E+02	1.03E+08	-6.36E+07	0.00E+00	0	10	103440000-63627000j	1.21E+08	-0.55146	-31.5961
1.00E+02	3.00E+00	0.00E+00	2.33E+02	9.52E+07	-3.47E+07	0.00E+00	1	0	95243000-34739000j	1.01E+08	-0.34975	-20.039
7.94E+01	3.00E+00	0.00E+00	2.55E+02	8.31E+07	-1.79E+07	0.00E+00	1	0	83066000-17919000j	84976767	-0.21246	-12.1733
6.31E+01	3.00E+00	0.00E+00	2.77E+02	7.73E+07	-1.05E+07	0.00E+00	1	0	77301000-10527000j	78014501	-0.13535	-7.75495
5.01E+01	3.00E+00	0.00E+00	2.98E+02	7.01E+07	-5.44E+06	0.00E+00	1	0	70090000-5443500j	70301065	-0.07751	-4.44093
3.98E+01	3.00E+00	0.00E+00	3.20E+02	5.96E+07	-1.51E+06	0.00E+00	1	0	59632000-1507900j	59651062	-0.02528	-1.44852
3.16E+01	3.00E+00	0.00E+00	3.42E+02	5.99E+07	-9.77E+05	0.00E+00	1	0	59869000-977490j	59876979	-0.01633	-0.93539
2.51E+01	3.00E+00	0.00E+00	3.64E+02	5.57E+07	-4.89E+04	0.00E+00	1	0	55678000-48915j	55678021	-0.00088	-0.05034
2.00E+01	3.00E+00	0.00E+00	3.85E+02	5.17E+07	6.64E+04	0.00E+00	1	0	51668000+66429j	51668043	0.001286	0.073665
1.58E+01	3.00E+00	0.00E+00	4.07E+02	4.89E+07	-4.60E+04	0.00E+00	1	0	48945000-45969j	48945022	-0.00094	-0.05381
1.26E+01	3.00E+00	0.00E+00	4.29E+02	4.66E+07	-3.31E+05	0.00E+00	1	0	46569000-331170j	46570178	-0.00711	-0.40745
1.00E+01	3.00E+00	0.00E+00	4.50E+02	4.10E+07	-4.45E+05	0.00E+00	1	0	40955000-445490j	40957423	-0.01088	-0.62321
7.94E+00	3.00E+00	0.00E+00	4.72E+02	3.83E+07	-5.93E+05	0.00E+00	1	0	38284000-592530j	38288585	-0.01548	-0.88671
6.31E+00	3.00E+00	0.00E+00	4.94E+02	3.70E+07	-8.16E+05	0.00E+00	1	0	37037000-816190j	37045992	-0.02203	-1.26243
5.01E+00	3.00E+00	0.00E+00	5.16E+02	3.39E+07	-8.13E+05	0.00E+00	1	0	33858000-812640j	33867751	-0.024	-1.37492
3.98E+00	3.00E+00	0.00E+00	5.38E+02	3.41E+07	-9.45E+05	0.00E+00	1	0	34137000-945450j	34150090	-0.02769	-1.58644
3.16E+00	3.00E+00	0.00E+00	5.60E+02	3.08E+07	-8.30E+05	0.00E+00	1	0	30820000-829810j	30831169	-0.02692	-1.54228
2.51E+00	3.00E+00	0.00E+00	5.82E+02	2.15E+07	-3.32E+05	0.00E+00	1	0	21529000-331580j	21531553	-0.0154	-0.88237
2.00E+00	3.00E+00	0.00E+00	6.04E+02	3.86E+07	-1.16E+06	0.00E+00	1	0	38604000-1158400j	38621376	-0.03	-1.71877
1.58E+00	3.00E+00	0.00E+00	6.26E+02	3.61E+07	-8.93E+05	0.00E+00	1	0	36120000-892820j	36131033	-0.02471	-1.41596
1.26E+00	3.00E+00	0.00E+00	6.48E+02	3.69E+07	-8.70E+05	0.00E+00	1	0	36899000-870400j	36909264	-0.02358	-1.35128

1.00E+00	3.00E+00	0.00E+00	6.70E+02	3.55E+07	-5.48E+05	0.00E+00	1	0		35485000-548450j	35489238	-0.01545	-0.88548
7.94E-01	3.00E+00	0.00E+00	6.93E+02	3.01E+07	-2.47E+05	0.00E+00	1	0		30077000-246670j	30078011	-0.0082	-0.46989
6.31E-01	3.00E+00	0.00E+00	7.16E+02	3.04E+07	-3.92E+05	0.00E+00	1	0		30432000-391660j	30434520	-0.01287	-0.73736
5.01E-01	3.00E+00	0.00E+00	7.40E+02	3.15E+07	-3.95E+05	0.00E+00	1	0		31472000-395370j	31474483	-0.01256	-0.71975
3.98E-01	3.00E+00	0.00E+00	7.63E+02	3.21E+07	3.69E+04	0.00E+00	1	0		32143000+36860j	32143021	0.001147	0.065704
3.16E-01	3.00E+00	0.00E+00	7.87E+02	3.19E+07	-1.84E+05	0.00E+00	1	0		31872000-183580j	31872529	-0.00576	-0.33002
2.51E-01	3.00E+00	0.00E+00	8.12E+02	3.23E+07	1.30E+05	0.00E+00	1	0		32332000+129530j	32332259	0.004006	0.22954
2.00E-01	3.00E+00	0.00E+00	8.35E+02	3.31E+07	-8.32E+03	0.00E+00	1	0		33051000-8315.6j	33051001	-0.00025	-0.01442
1.58E-01	3.00E+00	0.00E+00	8.59E+02	3.14E+07	-4.70E+05	0.00E+00	1	1		31375000-470400j	31378526	-0.01499	-0.85896
1.26E-01	3.00E+00	0.00E+00	8.80E+02	3.87E+07	4.24E+05	0.00E+00	1	0		38691000+424060j	38693324	0.01096	0.627946
1.00E-01	3.00E+00	0.00E+00	9.08E+02	3.57E+07	-2.75E+05	0.00E+00	1	0		35673000-274590j	35674057	-0.0077	-0.44102

$\phi = 0.7$

ZPlotW Data File: Version 2.2													
Raw Data													
Sweep Frequency: Control Current													
Date: 10-23-2001 Time: 09:49:29													
Open Circuit Potential (V): 0													
C:\SAI\ZData\Flat Burner\102301\0.1-1M,nonull,0.7,unknown,monitor,V1,Copperstrip1													
Frequency													
4	2	0	1	1000000	0.1								
71													
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)	
1.00E+06	3.00E+00	0.00E+00	1.39E+01	4.01E+04	-1.43E+05	0.00E+00	4	0	40108-142840j	148364.1	-1.29706	-74.3158	
7.94E+05	3.00E+00	0.00E+00	3.96E+01	3.90E+04	-1.78E+05	0.00E+00	4	0	39032-177700j	181936.2	-1.35458	-77.6117	
6.31E+05	3.00E+00	0.00E+00	7.60E+01	-6.35E+03	-2.25E+05	0.00E+00	4	0	-6347.5-225420j	225509.4	-1.59895	-91.6129	
5.01E+05	3.00E+00	0.00E+00	1.02E+02	-2.75E+04	-1.97E+05	0.00E+00	4	0	-27539-197060j	198975	-1.70965	-97.9555	
3.98E+05	3.00E+00	0.00E+00	1.28E+02	-5.22E+04	-2.31E+05	0.00E+00	4	0	-52167-231070j	236885.5	-1.79284	-102.722	
3.16E+05	3.00E+00	0.00E+00	1.53E+02	-7.26E+04	-5.26E+05	0.00E+00	4	0	-72553-526000j	530980.2	-1.70786	-97.8534	
2.51E+05	3.00E+00	0.00E+00	1.79E+02	-6.08E+05	2.40E+05	0.00E+00	4	0	-607640+239810j	653249.7	2.7657	158.4629	
2.00E+05	3.00E+00	0.00E+00	2.05E+02	1.39E+05	-8.55E+05	0.00E+00	4	0	138810-854610j	865809.7	-1.40978	-80.7743	
1.58E+05	3.00E+00	0.00E+00	2.33E+02	2.53E+05	-1.09E+06	0.00E+00	4	0	252990-1085800j	1114884	-1.34188	-76.8842	
1.26E+05	3.00E+00	0.00E+00	2.59E+02	3.01E+05	-1.96E+06	0.00E+00	4	0	300860-1963600j	1986515	-1.41876	-81.289	
1.00E+05	3.00E+00	0.00E+00	2.85E+02	2.41E+05	-1.99E+06	0.00E+00	4	0	240560-1986600j	2001112	-1.45029	-83.0956	
7.94E+04	3.00E+00	0.00E+00	3.11E+02	-1.82E+05	-2.59E+06	0.00E+00	4	0	-182280-2587200j	2593613	-1.64113	-94.0301	
6.31E+04	3.00E+00	0.00E+00	3.39E+02	2.76E+05	-2.07E+06	0.00E+00	4	0	275560-2066800j	2085089	-1.43825	-82.4057	
5.01E+04	3.00E+00	0.00E+00	3.65E+02	3.36E+05	-2.57E+06	0.00E+00	4	0	335990-2572900j	2594745	-1.44094	-82.56	

3.98E+04	3.00E+00	0.00E+00	3.91E+02	2.91E+05	-3.16E+06	0.00E+00	4	0	291270-3157200j	3170607	-1.4788	-84.7291
3.16E+04	3.00E+00	0.00E+00	4.17E+02	4.54E+05	-3.59E+06	0.00E+00	4	0	454270-3593000j	3621603	-1.44503	-82.7942
2.51E+04	3.00E+00	0.00E+00	4.43E+02	7.20E+05	-4.91E+06	0.00E+00	4	0	719760-4910500j	4962969	-1.42526	-81.6612
2.00E+04	3.00E+00	0.00E+00	4.69E+02	3.34E+05	-5.71E+06	0.00E+00	4	0	334440-5709700j	5719486	-1.51229	-86.6478
1.58E+04	3.00E+00	0.00E+00	4.95E+02	6.61E+05	-7.53E+06	0.00E+00	4	0	660690-7526000j	7554945	-1.48323	-84.983
1.26E+04	3.00E+00	0.00E+00	5.21E+02	8.14E+05	-9.27E+06	0.00E+00	4	0	814480-9266100j	9301827	-1.48312	-84.9767
1.00E+04	3.00E+00	0.00E+00	5.47E+02	1.39E+06	-1.13E+07	0.00E+00	4	0	1393000-11294000j	11379582	-1.44808	-82.9687
7.94E+03	3.00E+00	0.00E+00	5.73E+02	1.47E+06	-1.40E+07	0.00E+00	4	0	1468400-14021000j	14097682	-1.46645	-84.0213
6.31E+03	3.00E+00	0.00E+00	5.99E+02	1.88E+06	-1.71E+07	0.00E+00	4	0	1882500-17088000j	17191380	-1.46107	-83.7134
5.01E+03	3.00E+00	0.00E+00	6.25E+02	1.80E+06	-2.25E+07	0.00E+00	4	0	1798500-22456000j	22527906	-1.49088	-85.421
3.98E+03	3.00E+00	0.00E+00	6.51E+02	3.53E+06	-2.76E+07	0.00E+00	4	0	3526200-27582000j	27806489	-1.44364	-82.7146
3.16E+03	3.00E+00	0.00E+00	6.77E+02	4.35E+06	-3.47E+07	0.00E+00	4	0	4354800-34685000j	34957310	-1.4459	-82.8438
2.51E+03	3.00E+00	0.00E+00	7.03E+02	1.12E+07	-4.19E+07	0.00E+00	4	0	11221000-41916000j	43391957	-1.30923	-75.0132
2.00E+03	3.00E+00	0.00E+00	7.29E+02	1.27E+07	-4.91E+07	0.00E+00	4	0	12721000-49100000j	50721138	-1.31729	-75.475
1.58E+03	3.00E+00	0.00E+00	7.55E+02	2.11E+07	-6.02E+07	0.00E+00	4	0	21071000-60182000j	63764098	-1.23401	-70.7038
1.26E+03	3.00E+00	0.00E+00	7.81E+02	2.88E+07	-6.79E+07	0.00E+00	4	0	28829000-67938000j	73801647	-1.16948	-67.0064
1.00E+03	3.00E+00	0.00E+00	8.07E+02	3.73E+07	-7.69E+07	0.00E+00	4	0	37263000-76947000j	85494865	-1.11981	-64.1606
7.94E+02	3.00E+00	0.00E+00	8.33E+02	4.68E+07	-8.75E+07	0.00E+00	4	0	46840000-87532000j	99276566	-1.07945	-61.8479
6.31E+02	3.00E+00	0.00E+00	8.55E+02	6.09E+07	-8.85E+07	0.00E+00	1	0	60931000-88509000j	1.07E+08	-0.96789	-55.4559
5.01E+02	3.00E+00	0.00E+00	8.76E+02	6.83E+07	-6.66E+07	0.00E+00	1	0	68255000-66596000j	95361272	-0.7731	-44.2952
3.98E+02	3.00E+00	0.00E+00	8.98E+02	7.10E+07	-5.48E+07	0.00E+00	1	0	70999000-54800000j	89687781	-0.65733	-37.6625
3.16E+02	3.00E+00	0.00E+00	9.20E+02	7.20E+07	-4.36E+07	0.00E+00	1	0	72020000-43649000j	84214699	-0.54487	-31.2187
2.51E+02	3.00E+00	0.00E+00	9.43E+02	6.89E+07	-3.02E+07	0.00E+00	0	0	68937000-30204000j	75263481	-0.41295	-23.6601
2.00E+02	3.00E+00	0.00E+00	9.65E+02	5.91E+07	-1.64E+07	0.00E+00	0	0	59078000-16383000j	61307526	-0.27051	-15.4993
1.58E+02	3.00E+00	0.00E+00	9.87E+02	8.03E+07	-2.30E+07	0.00E+00	0	0	80271000-22966000j	83491740	-0.27866	-15.9661
1.26E+02	3.00E+00	0.00E+00	1.01E+03	5.51E+07	-7.02E+06	0.00E+00	1	0	55089000-7015200j	55533872	-0.12666	-7.25716
1.00E+02	3.00E+00	0.00E+00	1.03E+03	4.82E+07	-3.21E+06	0.00E+00	1	0	48153000-3211400j	48259968	-0.06659	-3.8155
7.94E+01	3.00E+00	0.00E+00	1.05E+03	3.65E+07	-1.88E+05	0.00E+00	1	0	36482000-187760j	36482483	-0.00515	-0.29488
6.31E+01	3.00E+00	0.00E+00	1.07E+03	2.36E+07	1.14E+06	0.00E+00	1	0	23628000+1142200j	23655591	0.048303	2.767578
5.01E+01	3.00E+00	0.00E+00	1.10E+03	2.84E+07	1.13E+06	0.00E+00	1	0	28426000+1126700j	28448320	0.039616	2.269802
3.98E+01	3.00E+00	0.00E+00	1.12E+03	2.45E+07	1.29E+06	0.00E+00	1	0	24480000+1285900j	24513750	0.05248	3.006903
3.16E+01	3.00E+00	0.00E+00	1.14E+03	1.91E+07	1.14E+06	0.00E+00	1	0	19074000+1135800j	19107787	0.059477	3.407769
2.51E+01	3.00E+00	0.00E+00	1.16E+03	1.76E+07	9.89E+05	0.00E+00	1	0	17592000+988700j	17619761	0.056143	3.216735
2.00E+01	3.00E+00	0.00E+00	1.18E+03	1.69E+07	8.00E+05	0.00E+00	1	0	16888000+800250j	16906950	0.04735	2.712972
1.58E+01	3.00E+00	0.00E+00	1.20E+03	1.79E+07	6.05E+05	0.00E+00	1	0	17873000+605000j	17883237	0.033837	1.938719
1.26E+01	3.00E+00	0.00E+00	1.22E+03	1.75E+07	4.53E+05	0.00E+00	1	0	17543000+453090j	17548850	0.025822	1.479472
1.00E+01	3.00E+00	0.00E+00	1.24E+03	2.22E+07	1.93E+05	0.00E+00	1	0	22154000+193010j	22154841	0.008712	0.499159
7.94E+00	3.00E+00	0.00E+00	1.26E+03	1.95E+07	2.90E+04	0.00E+00	1	0	19489000+29020j	19489022	0.001489	0.085316

6.31E+00	3.00E+00	0.00E+00	1.29E+03	1.93E+07	-7.52E+04	0.00E+00	1	0	19297000-75166j	19297146	-0.0039	-0.22318
5.01E+00	3.00E+00	0.00E+00	1.31E+03	2.36E+07	-3.34E+05	0.00E+00	1	0	23637000-334450j	23639366	-0.01415	-0.81065
3.98E+00	3.00E+00	0.00E+00	1.33E+03	2.15E+07	-3.34E+05	0.00E+00	1	0	21455000-333920j	21457598	-0.01556	-0.89166
3.16E+00	3.00E+00	0.00E+00	1.35E+03	2.35E+07	-4.50E+05	0.00E+00	1	0	23540000-450240j	23544305	-0.01912	-1.09574
2.51E+00	3.00E+00	0.00E+00	1.37E+03	1.79E+07	-2.33E+05	0.00E+00	1	0	17879000-233240j	17880521	-0.01304	-0.74741
2.00E+00	3.00E+00	0.00E+00	1.40E+03	1.32E+07	-7.64E+04	0.00E+00	1	0	13226000-76405j	13226221	-0.00578	-0.33099
1.58E+00	3.00E+00	0.00E+00	1.42E+03	1.55E+07	-1.40E+05	0.00E+00	1	0	15531000-139820j	15531629	-0.009	-0.5158
1.26E+00	3.00E+00	0.00E+00	1.44E+03	1.36E+07	-1.08E+05	0.00E+00	1	0	13575000-107930j	13575429	-0.00795	-0.45553
1.00E+00	3.00E+00	0.00E+00	1.46E+03	1.72E+07	-2.12E+05	0.00E+00	1	0	17236000-211920j	17237303	-0.01229	-0.70443
7.94E-01	3.00E+00	0.00E+00	1.49E+03	1.77E+07	-1.06E+05	0.00E+00	1	0	17738000-105750j	17738315	-0.00596	-0.34158
6.31E-01	3.00E+00	0.00E+00	1.51E+03	1.59E+07	-6.99E+04	0.00E+00	1	0	15910000-69937j	15910154	-0.0044	-0.25186
5.01E-01	3.00E+00	0.00E+00	1.53E+03	1.43E+07	-1.65E+04	0.00E+00	1	0	14311000-16464j	14311009	-0.00115	-0.06592
3.98E-01	3.00E+00	0.00E+00	1.56E+03	1.46E+07	-2.89E+04	0.00E+00	1	0	14593000-28878j	14593029	-0.00198	-0.11338
3.16E-01	3.00E+00	0.00E+00	1.58E+03	1.96E+07	-1.17E+05	0.00E+00	1	0	19603000-117210j	19603350	-0.00598	-0.34258
2.51E-01	3.00E+00	0.00E+00	1.61E+03	7.39E+06	-8.35E+04	0.00E+00	1	0	7385200-83503j	7385672	-0.01131	-0.6478
2.00E-01	3.00E+00	0.00E+00	1.63E+03	3.53E+06	-6.97E+03	0.00E+00	1	0	3532600-6971j	3532607	-0.00197	-0.11306
1.58E-01	3.00E+00	0.00E+00	1.65E+03	1.36E+07	-3.01E+04	0.00E+00	1	0	13571000-30126j	13571033	-0.00222	-0.12719
1.26E-01	3.00E+00	0.00E+00	1.68E+03	1.61E+07	1.12E+05	0.00E+00	1	0	16114000+111760j	16114388	0.006935	0.397373
1.00E-01	3.00E+00	0.00E+00	1.71E+03	1.33E+07	-1.14E+04	0.00E+00	1	0	13264000-11439j	13264005	-0.00086	-0.04941

 $\phi = 0.8$

ZPlotW Data File: Version 2.2												
Raw Data												
Sweep Frequency: Control Current												
Date: 10-23-2001 Time: 10:20:18												
Open Circuit Potential (V): 0												
C:\SAI\ZData\Flat Burner\102301\0.1-1M,nonnull,0.8,unknown,monitor,V1,Copperstrip1												
Frequency												
4	2	0	1	1000000	0.1							
71												
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)
1.00E+06	3.00E+00	0.00E+00	1.39E+01	2.74E+04	-1.55E+05	0.00E+00	4	0	27449-155430j	157835.1	-1.396	-79.9848
7.94E+05	3.00E+00	0.00E+00	3.96E+01	3.79E+04	-1.72E+05	0.00E+00	4	0	37891-171780j	175909.3	-1.35369	-77.561
6.31E+05	3.00E+00	0.00E+00	6.73E+01	6.50E+04	-2.01E+05	0.00E+00	4	0	65038-201070j	211327	-1.25796	-72.0757
5.01E+05	3.00E+00	0.00E+00	9.30E+01	-1.21E+03	-2.50E+05	0.00E+00	4	0	-1211.1-250400j	250402.9	-1.57563	-90.2771
3.98E+05	3.00E+00	0.00E+00	1.19E+02	7.71E+03	-3.30E+05	0.00E+00	4	0	7708.5-330330j	330419.9	-1.54746	-88.6632
3.16E+05	3.00E+00	0.00E+00	1.45E+02	3.90E+04	-4.83E+05	0.00E+00	4	0	38962-483440j	485007.5	-1.49038	-85.3923

2.51E+05	3.00E+00	0.00E+00	1.70E+02	-2.09E+04	-5.37E+05	0.00E+00	4	0	-20924-537170j	537577.4	-1.60973	-92.2307
2.00E+05	3.00E+00	0.00E+00	1.96E+02	-1.12E+04	-6.91E+05	0.00E+00	4	0	-11185-691250j	691340.5	-1.58698	-90.927
1.58E+05	3.00E+00	0.00E+00	2.22E+02	-7.47E+04	-8.32E+05	0.00E+00	4	0	-74733-832320j	835668.4	-1.66034	-95.1308
1.26E+05	3.00E+00	0.00E+00	2.48E+02	9.06E+04	-1.32E+06	0.00E+00	4	0	90564-1322000j	1325098	-1.5024	-86.0811
1.00E+05	3.00E+00	0.00E+00	2.74E+02	-1.05E+05	-1.21E+06	0.00E+00	4	0	-105480-1209200j	1213792	-1.65781	-94.9854
7.94E+04	3.00E+00	0.00E+00	3.00E+02	-4.06E+05	-1.48E+06	0.00E+00	4	0	-406380-1483200j	1537864	-1.83822	-105.322
6.31E+04	3.00E+00	0.00E+00	3.28E+02	1.40E+05	-1.95E+06	0.00E+00	4	0	139990-1949200j	1954221	-1.4991	-85.8921
5.01E+04	3.00E+00	0.00E+00	3.54E+02	1.33E+05	-2.30E+06	0.00E+00	4	0	132800-2300200j	2304030	-1.51313	-86.6957
3.98E+04	3.00E+00	0.00E+00	3.80E+02	8.46E+05	-3.59E+06	0.00E+00	4	0	846300-3593200j	3691519	-1.33948	-76.7468
3.16E+04	3.00E+00	0.00E+00	4.06E+02	5.20E+05	-3.72E+06	0.00E+00	4	0	519580-3720600j	3756704	-1.43204	-82.0501
2.51E+04	3.00E+00	0.00E+00	4.32E+02	4.13E+05	-4.99E+06	0.00E+00	4	0	412630-4987200j	5004241	-1.48825	-85.2702
2.00E+04	3.00E+00	0.00E+00	4.58E+02	6.15E+05	-6.15E+06	0.00E+00	4	0	614500-6146500j	6177141	-1.47115	-84.2908
1.58E+04	3.00E+00	0.00E+00	4.84E+02	-2.74E+05	-7.24E+06	0.00E+00	4	0	-274090-7240100j	7245286	-1.60864	-92.168
1.26E+04	3.00E+00	0.00E+00	5.10E+02	9.43E+05	-9.53E+06	0.00E+00	4	0	942640-9534600j	9581084	-1.47225	-84.3538
1.00E+04	3.00E+00	0.00E+00	5.36E+02	2.55E+05	-1.28E+07	0.00E+00	4	0	254750-12831000j	12833529	-1.55094	-88.8626
7.94E+03	3.00E+00	0.00E+00	5.62E+02	1.37E+06	-1.51E+07	0.00E+00	4	0	1367000-15068000j	15129881	-1.48032	-84.8162
6.31E+03	3.00E+00	0.00E+00	5.88E+02	2.82E+06	-1.91E+07	0.00E+00	4	0	2818900-19060000j	19267325	-1.42396	-81.5872
5.01E+03	3.00E+00	0.00E+00	6.14E+02	3.65E+06	-2.44E+07	0.00E+00	4	0	3653500-24353000j	24625529	-1.42188	-81.468
3.98E+03	3.00E+00	0.00E+00	6.40E+02	6.14E+06	-2.96E+07	0.00E+00	4	0	6141100-29607000j	30237188	-1.36628	-78.2818
3.16E+03	3.00E+00	0.00E+00	6.66E+02	9.49E+06	-3.56E+07	0.00E+00	4	0	9488600-35614000j	36856350	-1.31042	-75.0813
2.51E+03	3.00E+00	0.00E+00	6.92E+02	1.39E+07	-4.15E+07	0.00E+00	4	0	13917000-41465000j	43738188	-1.24698	-71.4466
2.00E+03	3.00E+00	0.00E+00	7.18E+02	1.92E+07	-4.99E+07	0.00E+00	4	0	19229000-49896000j	53473033	-1.20296	-68.9243
1.58E+03	3.00E+00	0.00E+00	7.44E+02	2.60E+07	-5.51E+07	0.00E+00	4	0	25972000-55120000j	60932415	-1.13046	-64.7706
1.26E+03	3.00E+00	0.00E+00	7.70E+02	3.29E+07	-6.19E+07	0.00E+00	4	0	32914000-61908000j	70113707	-1.08214	-62.0022
1.00E+03	3.00E+00	0.00E+00	7.96E+02	3.83E+07	-7.07E+07	0.00E+00	4	0	38341000-70707000j	80433278	-1.07392	-61.5312
7.94E+02	3.00E+00	0.00E+00	8.22E+02	4.64E+07	-8.16E+07	0.00E+00	4	0	46359000-81552000j	93807705	-1.05389	-60.3835
6.31E+02	3.00E+00	0.00E+00	8.44E+02	5.50E+07	-9.02E+07	0.00E+00	1	0	54979000-90199000j	1.06E+08	-1.0234	-58.6364
5.01E+02	3.00E+00	0.00E+00	8.65E+02	6.91E+07	-6.72E+07	0.00E+00	1	0	69107000-67152000j	96359579	-0.77105	-44.178
3.98E+02	3.00E+00	0.00E+00	8.87E+02	6.90E+07	-5.05E+07	0.00E+00	1	0	69003000-50543000j	85533671	-0.63219	-36.2219
3.16E+02	3.00E+00	0.00E+00	9.09E+02	7.07E+07	-3.95E+07	0.00E+00	1	0	70695000-39483000j	80973393	-0.50934	-29.1833
2.51E+02	3.00E+00	0.00E+00	9.32E+02	6.55E+07	-2.55E+07	0.00E+00	0	0	65529000-25521000j	70323334	-0.37139	-21.279
2.00E+02	3.00E+00	0.00E+00	9.54E+02	5.53E+07	-1.31E+07	0.00E+00	0	0	55340000-13099000j	56869143	-0.23242	-13.3168
1.58E+02	3.00E+00	0.00E+00	9.76E+02	4.16E+07	-4.88E+06	0.00E+00	0	0	41609000-4876900j	41893831	-0.11668	-6.68501
1.26E+02	3.00E+00	0.00E+00	9.97E+02	3.05E+07	-9.33E+05	0.00E+00	0	0	30451000-933040j	30465291	-0.03063	-1.75503
1.00E+02	3.00E+00	0.00E+00	1.02E+03	2.31E+07	5.16E+05	0.00E+00	1	0	23112000+516030j	23117760	0.022324	1.279051
7.94E+01	3.00E+00	0.00E+00	1.04E+03	1.94E+07	9.66E+05	0.00E+00	1	0	19381000+965720j	19405045	0.049787	2.852585
6.31E+01	3.00E+00	0.00E+00	1.06E+03	1.67E+07	1.10E+06	0.00E+00	1	0	16727000+1103100j	16763334	0.065852	3.773037
5.01E+01	3.00E+00	0.00E+00	1.08E+03	1.48E+07	1.06E+06	0.00E+00	1	0	14780000+1061800j	14818091	0.071717	4.109088

3.98E+01	3.00E+00	0.00E+00	1.11E+03	1.37E+07	9.91E+05	0.00E+00	1	0	13668000+990660j	13703855	0.072354	4.145563
3.16E+01	3.00E+00	0.00E+00	1.13E+03	1.29E+07	8.92E+05	0.00E+00	1	0	12932000+891770j	12962711	0.068849	3.94478
2.51E+01	3.00E+00	0.00E+00	1.15E+03	1.16E+07	7.29E+05	0.00E+00	1	0	11637000+729030j	11659814	0.062566	3.584758
2.00E+01	3.00E+00	0.00E+00	1.17E+03	1.11E+07	5.86E+05	0.00E+00	1	0	11085000+585770j	11100466	0.052794	3.024895
1.58E+01	3.00E+00	0.00E+00	1.19E+03	1.19E+07	4.88E+05	0.00E+00	1	0	11853000+487800j	11863033	0.041131	2.356629
1.26E+01	3.00E+00	0.00E+00	1.21E+03	9.78E+06	3.30E+05	0.00E+00	1	0	9778300+329510j	9783850	0.033685	1.930028
1.00E+01	3.00E+00	0.00E+00	1.24E+03	9.22E+06	2.39E+05	0.00E+00	1	0	9223900+239370j	9227005	0.025945	1.486553
7.94E+00	3.00E+00	0.00E+00	1.26E+03	8.93E+06	1.43E+05	0.00E+00	1	0	8930200+142500j	8931337	0.015956	0.914196
6.31E+00	3.00E+00	0.00E+00	1.28E+03	8.57E+06	8.08E+04	0.00E+00	1	0	8565600+80833j	8565981	0.009437	0.54068
5.01E+00	3.00E+00	0.00E+00	1.30E+03	8.44E+06	4.30E+04	0.00E+00	1	0	8438900+43001j	8439010	0.005096	0.291952
3.98E+00	3.00E+00	0.00E+00	1.32E+03	8.07E+06	1.58E+04	0.00E+00	1	0	8074500+15812j	8074515	0.001958	0.1122
3.16E+00	3.00E+00	0.00E+00	1.35E+03	8.37E+06	-1.99E+04	0.00E+00	1	0	8373800-19933j	8373824	-0.00238	-0.13639
2.51E+00	3.00E+00	0.00E+00	1.37E+03	8.29E+06	-2.77E+04	0.00E+00	1	0	8293000-27695j	8293046	-0.00334	-0.19134
2.00E+00	3.00E+00	0.00E+00	1.39E+03	8.85E+06	-2.96E+04	0.00E+00	1	0	8851900-29637j	8851950	-0.00335	-0.19183
1.58E+00	3.00E+00	0.00E+00	1.41E+03	8.69E+06	-1.72E+04	0.00E+00	1	0	8693700-17184j	8693717	-0.00198	-0.11325
1.26E+00	3.00E+00	0.00E+00	1.43E+03	8.15E+06	-2.50E+04	0.00E+00	1	0	8147800-24964j	8147838	-0.00306	-0.17555
1.00E+00	3.00E+00	0.00E+00	1.46E+03	8.08E+06	-3.98E+04	0.00E+00	1	0	8084600-39779j	8084698	-0.00492	-0.28191
7.94E-01	3.00E+00	0.00E+00	1.48E+03	1.17E+07	-4.16E+04	0.00E+00	1	0	11735000-41635j	11735074	-0.00355	-0.20328
6.31E-01	3.00E+00	0.00E+00	1.50E+03	9.50E+06	-8.78E+03	0.00E+00	1	0	9499500-8783.7j	9499504	-0.00092	-0.05298
5.01E-01	3.00E+00	0.00E+00	1.53E+03	8.71E+06	-3.34E+04	0.00E+00	1	0	8711200-33386j	8711264	-0.00383	-0.21959
3.98E-01	3.00E+00	0.00E+00	1.55E+03	7.70E+06	6.36E+03	0.00E+00	1	0	7704500+6362.3j	7704503	0.000826	0.047314
3.16E-01	3.00E+00	0.00E+00	1.57E+03	7.49E+06	6.81E+03	0.00E+00	1	0	7494000+6814.3j	7494003	0.000909	0.052099
2.51E-01	3.00E+00	0.00E+00	1.60E+03	7.34E+06	-1.99E+03	0.00E+00	1	0	7335600-1994j	7335600	-0.00027	-0.01557
2.00E-01	3.00E+00	0.00E+00	1.62E+03	7.40E+06	1.13E+04	0.00E+00	1	0	7395400+11296j	7395409	0.001527	0.087516
1.58E-01	3.00E+00	0.00E+00	1.65E+03	1.13E+07	-1.59E+04	0.00E+00	1	0	11266000-15858j	11266011	-0.00141	-0.08065
1.26E-01	3.00E+00	0.00E+00	1.67E+03	9.60E+06	-2.95E+04	0.00E+00	1	0	9604900-29541j	9604945	-0.00308	-0.17622
1.00E-01	3.00E+00	0.00E+00	1.70E+03	7.82E+06	4.39E+04	0.00E+00	1	0	7816400+43876j	7816523	0.005613	0.321617

$\phi = 0.9$

ZPlotW Data File: Version 2.2												
Raw Data												
Sweep Frequency: Control Current												
Date: 10-23-2001 Time: 10:50:24												
Open Circuit Potential (V): 0												
C:\SAI\ZData\Flat Burner\102301\0.1-1M,nonull,0.9,unknown,monitor,V1,Copperstrip1												
Frequency												
4	2	0	1	1000000	0.1							

71													
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)	
1.00E+06	3.00E+00	0.00E+00	1.39E+01	-1.58E+03	-1.24E+05	0.00E+00	4	0	-1578.8-123520j	123530.1	-1.58358	-90.7323	
7.94E+05	3.00E+00	0.00E+00	3.97E+01	4.34E+04	-1.81E+05	0.00E+00	4	0	43397-181220j	186343.7	-1.33575	-76.5329	
6.31E+05	3.00E+00	0.00E+00	6.72E+01	-1.51E+04	-2.00E+05	0.00E+00	4	0	-15116-200420j	200989.2	-1.64608	-94.3132	
5.01E+05	3.00E+00	0.00E+00	9.30E+01	4.15E+04	-2.67E+05	0.00E+00	4	0	41486-267210j	270411.3	-1.41677	-81.1749	
3.98E+05	3.00E+00	0.00E+00	1.19E+02	6.91E+04	-3.86E+05	0.00E+00	4	0	69099-385960j	392096.7	-1.39364	-79.8498	
3.16E+05	3.00E+00	0.00E+00	1.45E+02	-6.80E+04	-3.38E+05	0.00E+00	4	0	-68026-338250j	345022.6	-1.76926	-101.371	
2.51E+05	3.00E+00	0.00E+00	1.70E+02	-6.07E+03	-5.70E+05	0.00E+00	4	0	-6068.1-570450j	570482.3	-1.58143	-90.6095	
2.00E+05	3.00E+00	0.00E+00	1.96E+02	-1.87E+04	-6.33E+05	0.00E+00	4	0	-18690-633430j	633705.7	-1.60029	-91.6901	
1.58E+05	3.00E+00	0.00E+00	2.26E+02	-4.60E+04	-8.15E+05	0.00E+00	4	0	-46049-814540j	815840.6	-1.62727	-93.2357	
1.26E+05	3.00E+00	0.00E+00	2.52E+02	6.79E+04	-1.14E+06	0.00E+00	4	0	67937-1137000j	1139028	-1.51112	-86.5806	
1.00E+05	3.00E+00	0.00E+00	2.78E+02	-8.53E+03	-1.17E+06	0.00E+00	4	0	-8526.5-1171900j	1171931	-1.57807	-90.4169	
7.94E+04	3.00E+00	0.00E+00	3.03E+02	-1.27E+05	-1.47E+06	0.00E+00	4	0	-126610-1472900j	1478332	-1.65655	-94.913	
6.31E+04	3.00E+00	0.00E+00	3.32E+02	4.03E+05	-2.10E+06	0.00E+00	4	0	403230-2100500j	2138854	-1.38114	-79.1332	
5.01E+04	3.00E+00	0.00E+00	3.58E+02	4.02E+05	-2.99E+06	0.00E+00	4	0	402450-2993000j	3019936	-1.43713	-82.3417	
3.98E+04	3.00E+00	0.00E+00	3.84E+02	2.19E+05	-3.48E+06	0.00E+00	4	0	219030-3475700j	3482595	-1.50786	-86.3941	
3.16E+04	3.00E+00	0.00E+00	4.13E+02	3.52E+05	-4.34E+06	0.00E+00	4	0	351570-4337700j	4351924	-1.48992	-85.3663	
2.51E+04	3.00E+00	0.00E+00	4.39E+02	7.44E+04	-5.06E+06	0.00E+00	4	0	74443-5061300j	5061847	-1.55609	-89.1573	
2.00E+04	3.00E+00	0.00E+00	4.65E+02	8.40E+05	-6.41E+06	0.00E+00	4	0	840340-6410100j	6464948	-1.44044	-82.5313	
1.58E+04	3.00E+00	0.00E+00	4.91E+02	1.07E+06	-8.37E+06	0.00E+00	4	0	1068300-8366400j	8434329	-1.44379	-82.7233	
1.26E+04	3.00E+00	0.00E+00	5.17E+02	1.83E+06	-1.06E+07	0.00E+00	4	1	1831100-10603000j	10759951	-1.39979	-80.2019	
1.00E+04	3.00E+00	0.00E+00	5.39E+02	2.83E+06	-1.29E+07	0.00E+00	4	0	2829100-12878000j	13185094	-1.35455	-77.6098	
7.94E+03	3.00E+00	0.00E+00	5.65E+02	3.65E+06	-1.55E+07	0.00E+00	4	0	3654000-15495000j	15920011	-1.33921	-76.731	
6.31E+03	3.00E+00	0.00E+00	5.91E+02	6.19E+06	-1.86E+07	0.00E+00	4	0	6193100-18630000j	19632407	-1.24986	-71.6118	
5.01E+03	3.00E+00	0.00E+00	6.17E+02	8.04E+06	-2.12E+07	0.00E+00	4	0	8039200-21178000j	22652515	-1.208	-69.2132	
3.98E+03	3.00E+00	0.00E+00	6.43E+02	1.28E+07	-2.46E+07	0.00E+00	4	0	12820000-24614000j	27752503	-1.09061	-62.4876	
3.16E+03	3.00E+00	0.00E+00	6.69E+02	1.53E+07	-2.71E+07	0.00E+00	4	0	15326000-27076000j	31112635	-1.05572	-60.4886	
2.51E+03	3.00E+00	0.00E+00	6.95E+02	1.89E+07	-3.05E+07	0.00E+00	4	0	18948000-30486000j	35894608	-1.0147	-58.1378	
2.00E+03	3.00E+00	0.00E+00	7.21E+02	2.31E+07	-3.33E+07	0.00E+00	4	0	23050000-33342000j	40533831	-0.96592	-55.3431	
1.58E+03	3.00E+00	0.00E+00	7.47E+02	2.63E+07	-3.63E+07	0.00E+00	4	0	26289000-36309000j	44826945	-0.94412	-54.0941	
1.26E+03	3.00E+00	0.00E+00	7.73E+02	3.11E+07	-4.41E+07	0.00E+00	4	0	31068000-44107000j	53950422	-0.95714	-54.84	
1.00E+03	3.00E+00	0.00E+00	7.99E+02	3.39E+07	-4.72E+07	0.00E+00	4	0	33895000-47224000j	58128970	-0.94826	-54.3311	
7.94E+02	3.00E+00	0.00E+00	8.25E+02	3.90E+07	-5.64E+07	0.00E+00	4	0	38986000-56373000j	68540669	-0.96575	-55.3333	
6.31E+02	3.00E+00	0.00E+00	8.47E+02	4.48E+07	-6.30E+07	0.00E+00	1	0	44799000-62959000j	77270862	-0.95236	-54.5659	
5.01E+02	3.00E+00	0.00E+00	8.69E+02	4.93E+07	-4.02E+07	0.00E+00	1	0	49289000-40227000j	63620885	-0.68451	-39.2195	
3.98E+02	3.00E+00	0.00E+00	8.91E+02	4.92E+07	-2.94E+07	0.00E+00	1	0	49157000-29368000j	57261593	-0.53853	-30.8555	
3.16E+02	3.00E+00	0.00E+00	9.12E+02	4.65E+07	-2.03E+07	0.00E+00	1	0	46515000-20291000j	50748102	-0.41134	-23.568	

2.51E+02	3.00E+00	0.00E+00	9.36E+02	3.96E+07	-1.16E+07	0.00E+00	0	0	39615000-11550000j	41264400	-0.28369	-16.2544
2.00E+02	3.00E+00	0.00E+00	9.57E+02	3.53E+07	-6.12E+06	0.00E+00	0	0	35260000-6120500j	35787262	-0.17187	-9.84739
1.58E+02	3.00E+00	0.00E+00	9.79E+02	2.54E+07	-1.81E+06	0.00E+00	0	0	25369000-1806100j	25433210	-0.07107	-4.0722
1.26E+02	3.00E+00	0.00E+00	1.00E+03	1.75E+07	9.75E+04	0.00E+00	0	0	17547000+97485j	17547271	0.005556	0.318312
1.00E+02	3.00E+00	0.00E+00	1.02E+03	1.36E+07	6.44E+05	0.00E+00	1	0	13611000+643850j	13626220	0.047268	2.708281
7.94E+01	3.00E+00	0.00E+00	1.04E+03	1.10E+07	7.64E+05	0.00E+00	1	0	10965000+763620j	10991558	0.069529	3.983737
6.31E+01	3.00E+00	0.00E+00	1.07E+03	1.04E+07	8.15E+05	0.00E+00	1	0	10375000+814630j	10406933	0.078358	4.489571
5.01E+01	3.00E+00	0.00E+00	1.09E+03	9.10E+06	7.17E+05	0.00E+00	1	0	9096900+717350j	9125140	0.078694	4.508816
3.98E+01	3.00E+00	0.00E+00	1.11E+03	8.22E+06	6.52E+05	0.00E+00	1	0	8221100+652150j	8246926	0.079161	4.535568
3.16E+01	3.00E+00	0.00E+00	1.13E+03	7.47E+06	5.49E+05	0.00E+00	1	0	7465300+549480j	7485495	0.073472	4.209639
2.51E+01	3.00E+00	0.00E+00	1.15E+03	7.09E+06	4.66E+05	0.00E+00	1	0	7091800+465920j	7107089	0.065604	3.75884
2.00E+01	3.00E+00	0.00E+00	1.17E+03	6.67E+06	3.77E+05	0.00E+00	1	0	6666500+376820j	6677141	0.056464	3.235168
1.58E+01	3.00E+00	0.00E+00	1.20E+03	7.24E+06	3.23E+05	0.00E+00	1	0	7243600+322990j	7250797	0.04456	2.553111
1.26E+01	3.00E+00	0.00E+00	1.22E+03	6.26E+06	2.27E+05	0.00E+00	1	0	6259900+226970j	6264013	0.036242	2.076507
1.00E+01	3.00E+00	0.00E+00	1.24E+03	5.98E+06	1.63E+05	0.00E+00	1	0	5976900+162590j	5979111	0.027196	1.558237
7.94E+00	3.00E+00	0.00E+00	1.26E+03	5.47E+06	1.09E+05	0.00E+00	1	0	5469300+108620j	5470378	0.019857	1.137741
6.31E+00	3.00E+00	0.00E+00	1.28E+03	5.35E+06	7.27E+04	0.00E+00	1	0	5350900+72662j	5351393	0.013579	0.777994
5.01E+00	3.00E+00	0.00E+00	1.31E+03	5.33E+06	3.73E+04	0.00E+00	1	0	5333200+37302j	5333330	0.006994	0.400737
3.98E+00	3.00E+00	0.00E+00	1.33E+03	5.22E+06	1.90E+04	0.00E+00	1	0	5218600+19015j	5218635	0.003644	0.208768
3.16E+00	3.00E+00	0.00E+00	1.35E+03	5.25E+06	5.83E+03	0.00E+00	1	0	5250800+5825.8j	5250803	0.00111	0.06357
2.51E+00	3.00E+00	0.00E+00	1.37E+03	5.20E+06	-3.14E+03	0.00E+00	1	0	5200800-3144.6j	5200801	-0.0006	-0.03464
2.00E+00	3.00E+00	0.00E+00	1.39E+03	5.12E+06	-7.25E+03	0.00E+00	1	0	5115600-7248.4j	5115605	-0.00142	-0.08118
1.58E+00	3.00E+00	0.00E+00	1.41E+03	5.05E+06	-1.61E+04	0.00E+00	1	0	5048200-16051j	5048226	-0.00318	-0.18217
1.26E+00	3.00E+00	0.00E+00	1.44E+03	5.81E+06	-1.46E+04	0.00E+00	1	0	5806400-14597j	5806418	-0.00251	-0.14404
1.00E+00	3.00E+00	0.00E+00	1.46E+03	5.37E+06	-1.39E+04	0.00E+00	1	0	5369300-13947j	5369318	-0.0026	-0.14883
7.94E-01	3.00E+00	0.00E+00	1.48E+03	4.89E+06	-1.05E+04	0.00E+00	1	0	4893100-10534j	4893111	-0.00215	-0.12335
6.31E-01	3.00E+00	0.00E+00	1.51E+03	4.90E+06	-5.94E+03	0.00E+00	1	0	4899500-5938.6j	4899504	-0.00121	-0.06945
5.01E-01	3.00E+00	0.00E+00	1.53E+03	4.83E+06	-1.19E+04	0.00E+00	1	0	4828200-11911j	4828215	-0.00247	-0.14135
3.98E-01	3.00E+00	0.00E+00	1.55E+03	4.82E+06	-1.03E+04	0.00E+00	1	0	4819700-10253j	4819711	-0.00213	-0.12189
3.16E-01	3.00E+00	0.00E+00	1.58E+03	4.67E+06	-6.91E+03	0.00E+00	1	0	4673100-6913.8j	4673105	-0.00148	-0.08477
2.51E-01	3.00E+00	0.00E+00	1.60E+03	4.83E+06	5.69E+03	0.00E+00	1	0	4828000+5692.6j	4828003	0.001179	0.067556
2.00E-01	3.00E+00	0.00E+00	1.62E+03	4.86E+06	-9.59E+03	0.00E+00	1	0	4861900-9594.7j	4861909	-0.00197	-0.11307
1.58E-01	3.00E+00	0.00E+00	1.65E+03	4.86E+06	9.66E+03	0.00E+00	1	0	4863200+9662j	4863210	0.001987	0.113833
1.26E-01	3.00E+00	0.00E+00	1.67E+03	4.81E+06	-1.00E+04	0.00E+00	1	0	4807000-10014j	4807010	-0.00208	-0.11936
1.00E-01	3.00E+00	0.00E+00	1.70E+03	4.70E+06	6.31E+03	0.00E+00	1	0	4696300+6312.5j	4696304	0.001344	0.077014

$\phi = 1.0$

ZPlotW Data File: Version 2.2												
Raw Data												
Sweep Frequency: Control Current												
Date: 10-23-2001 Time: 11:20:42												
Open Circuit Potential (V): 0												
C:\SAI\ZData\Flat Burner\102301\0.1-1M,nonull,01.0,unknown,monitor,V1,Copperstrip1												
Frequency												
4	2	0	1	1000000	0.1							
71												
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)
1.00E+06	3.00E+00	0.00E+00	1.39E+01	4.67E+04	-1.78E+05	0.00E+00	4	0	46652-178240j	184244.1	-1.3148	-75.3326
7.94E+05	3.00E+00	0.00E+00	3.96E+01	6.01E+04	-2.07E+05	0.00E+00	4	0	60140-207440j	215981.9	-1.28862	-73.8323
6.31E+05	3.00E+00	0.00E+00	6.72E+01	6.60E+04	-2.55E+05	0.00E+00	4	10	66004-254530j	262948.8	-1.31707	-75.4624
5.01E+05	3.00E+00	0.00E+00	8.86E+01	3.23E+04	-3.35E+05	0.00E+00	4	0	32301-335240j	336792.5	-1.47474	-84.4964
3.98E+05	3.00E+00	0.00E+00	1.14E+02	1.14E+04	-4.45E+05	0.00E+00	4	0	11399-445440j	445585.8	-1.54521	-88.5341
3.16E+05	3.00E+00	0.00E+00	1.40E+02	8.74E+04	-5.18E+05	0.00E+00	4	0	87370-518080j	525395.5	-1.40373	-80.4276
2.51E+05	3.00E+00	0.00E+00	1.66E+02	1.02E+04	-5.90E+05	0.00E+00	4	0	10163-590340j	590427.5	-1.55358	-89.0137
2.00E+05	3.00E+00	0.00E+00	1.92E+02	6.81E+04	-7.61E+05	0.00E+00	4	0	68095-760790j	763831.4	-1.48153	-84.8853
1.58E+05	3.00E+00	0.00E+00	2.21E+02	1.30E+05	-9.37E+05	0.00E+00	4	0	129740-936920j	945860.2	-1.4332	-82.1161
1.26E+05	3.00E+00	0.00E+00	2.46E+02	1.06E+05	-1.01E+06	0.00E+00	4	0	105970-1010200j	1015743	-1.46628	-84.0116
1.00E+05	3.00E+00	0.00E+00	2.72E+02	2.96E+05	-1.43E+06	0.00E+00	4	0	295640-1430900j	1461122	-1.36705	-78.3263
7.94E+04	3.00E+00	0.00E+00	2.98E+02	1.56E+05	-1.67E+06	0.00E+00	4	0	155520-1668900j	1676131	-1.47788	-84.6761
6.31E+04	3.00E+00	0.00E+00	3.27E+02	7.51E+05	-2.11E+06	0.00E+00	4	0	750870-2106600j	2236419	-1.2284	-70.3821
5.01E+04	3.00E+00	0.00E+00	3.53E+02	8.90E+05	-2.46E+06	0.00E+00	4	0	889900-2461500j	2617423	-1.22389	-70.1237
3.98E+04	3.00E+00	0.00E+00	3.79E+02	1.32E+06	-2.76E+06	0.00E+00	4	0	1323600-2763300j	3063943	-1.1241	-64.4059
3.16E+04	3.00E+00	0.00E+00	4.06E+02	1.49E+06	-3.55E+06	0.00E+00	4	0	1489200-3552000j	3851548	-1.1738	-67.2538
2.51E+04	3.00E+00	0.00E+00	4.32E+02	1.99E+06	-3.99E+06	0.00E+00	4	0	1986000-3994100j	4460609	-1.10936	-63.5619
2.00E+04	3.00E+00	0.00E+00	4.58E+02	2.77E+06	-4.90E+06	0.00E+00	4	0	2772800-4901200j	5631179	-1.05595	-60.5015
1.58E+04	3.00E+00	0.00E+00	4.84E+02	3.38E+06	-5.07E+06	0.00E+00	4	0	3382100-5067600j	6092550	-0.98229	-56.281
1.26E+04	3.00E+00	0.00E+00	5.10E+02	3.79E+06	-6.22E+06	0.00E+00	4	0	3791800-6224600j	7288580	-1.02367	-58.6517
1.00E+04	3.00E+00	0.00E+00	5.36E+02	5.02E+06	-7.04E+06	0.00E+00	4	0	5022700-7036100j	8644896	-0.95084	-54.479
7.94E+03	3.00E+00	0.00E+00	5.62E+02	5.89E+06	-7.64E+06	0.00E+00	4	0	5893400-7643000j	9651301	-0.91394	-52.3647
6.31E+03	3.00E+00	0.00E+00	5.88E+02	7.05E+06	-8.06E+06	0.00E+00	4	0	7046200-8062900j	10707908	-0.85259	-48.8497
5.01E+03	3.00E+00	0.00E+00	6.14E+02	8.11E+06	-8.78E+06	0.00E+00	4	0	8114800-8778200j	11954362	-0.82465	-47.2489
3.98E+03	3.00E+00	0.00E+00	6.40E+02	9.26E+06	-9.69E+06	0.00E+00	4	0	9258900-9689500j	13402001	-0.80812	-46.3018

3.16E+03	3.00E+00	0.00E+00	6.66E+02	1.04E+07	-1.06E+07	0.00E+00	4	0	10439000-10589000j	14869420	-0.79253	-45.4087
2.51E+03	3.00E+00	0.00E+00	6.92E+02	1.17E+07	-1.15E+07	0.00E+00	4	0	11695000-11510000j	16408934	-0.77743	-44.5432
2.00E+03	3.00E+00	0.00E+00	7.18E+02	1.27E+07	-1.22E+07	0.00E+00	4	0	12652000-12243000j	17605799	-0.76897	-44.0588
1.58E+03	3.00E+00	0.00E+00	7.44E+02	1.38E+07	-1.37E+07	0.00E+00	4	0	13789000-13707000j	19442695	-0.78242	-44.8291
1.26E+03	3.00E+00	0.00E+00	7.70E+02	1.47E+07	-1.53E+07	0.00E+00	4	0	14660000-15282000j	21176759	-0.80617	-46.1901
1.00E+03	3.00E+00	0.00E+00	7.96E+02	1.58E+07	-1.76E+07	0.00E+00	4	0	15838000-17575000j	23658463	-0.83734	-47.9759
7.94E+02	3.00E+00	0.00E+00	8.23E+02	1.70E+07	-2.02E+07	0.00E+00	4	0	16959000-20248000j	26411914	-0.87357	-50.0517
6.31E+02	3.00E+00	0.00E+00	8.44E+02	1.88E+07	-2.23E+07	0.00E+00	1	0	18767000-22334000j	29172039	-0.87197	-49.9601
5.01E+02	3.00E+00	0.00E+00	8.66E+02	1.75E+07	-1.18E+07	0.00E+00	1	0	17465000-11785000j	21069230	-0.5936	-34.0106
3.98E+02	3.00E+00	0.00E+00	8.88E+02	1.88E+07	-9.26E+06	0.00E+00	1	0	18752000-9255600j	20911806	-0.4585	-26.27
3.16E+02	3.00E+00	0.00E+00	9.09E+02	1.82E+07	-6.90E+06	0.00E+00	1	0	18162000-6897800j	19427761	-0.36297	-20.7964
2.51E+02	3.00E+00	0.00E+00	9.33E+02	1.52E+07	-3.92E+06	0.00E+00	0	0	15171000-3918100j	15668783	-0.25274	-14.4809
2.00E+02	3.00E+00	0.00E+00	9.54E+02	1.17E+07	-1.58E+06	0.00E+00	0	0	11682000-1575000j	11787695	-0.13401	-7.67848
1.58E+02	3.00E+00	0.00E+00	9.76E+02	8.34E+06	-3.38E+05	0.00E+00	0	0	8338300-338180j	8345155	-0.04054	-2.3225
1.26E+02	3.00E+00	0.00E+00	9.98E+02	6.14E+06	1.43E+05	0.00E+00	0	300	6142900+143250j	6144570	0.023315	1.335873
1.00E+02	3.00E+00	0.00E+00	1.02E+03	4.51E+06	2.39E+05	0.00E+00	1	0	4511200+238910j	4517522	0.05291	3.031512
7.94E+01	3.00E+00	0.00E+00	1.04E+03	3.76E+06	2.75E+05	0.00E+00	1	0	3764400+274890j	3774423	0.072894	4.17653
6.31E+01	3.00E+00	0.00E+00	1.06E+03	3.23E+06	2.62E+05	0.00E+00	1	0	3226500+262460j	3237157	0.081166	4.650492
5.01E+01	3.00E+00	0.00E+00	1.08E+03	2.91E+06	2.37E+05	0.00E+00	1	0	2905800+237260j	2915470	0.08147	4.667874
3.98E+01	3.00E+00	0.00E+00	1.10E+03	2.71E+06	2.16E+05	0.00E+00	1	0	2712900+216140j	2721496	0.079503	4.555202
3.16E+01	3.00E+00	0.00E+00	1.12E+03	2.40E+06	1.79E+05	0.00E+00	1	1	2398400+179300j	2405093	0.074619	4.275375
2.51E+01	3.00E+00	0.00E+00	1.14E+03	2.34E+06	1.52E+05	0.00E+00	1	0	2337700+152390j	2342662	0.065096	3.72972
2.00E+01	3.00E+00	0.00E+00	1.16E+03	2.03E+06	1.12E+05	0.00E+00	1	0	2026700+111560j	2029768	0.05499	3.150675
1.58E+01	3.00E+00	0.00E+00	1.18E+03	1.93E+06	8.93E+04	0.00E+00	1	0	1928500+89317j	1930567	0.046281	2.651715
1.26E+01	3.00E+00	0.00E+00	1.20E+03	1.81E+06	6.86E+04	0.00E+00	1	0	1814300+68636j	1815598	0.037813	2.166499
1.00E+01	3.00E+00	0.00E+00	1.22E+03	1.90E+06	5.35E+04	0.00E+00	1	0	1903300+53519j	1904052	0.028112	1.610679
7.94E+00	3.00E+00	0.00E+00	1.25E+03	1.83E+06	3.99E+04	0.00E+00	1	0	1834100+39858j	1834533	0.021728	1.244935
6.31E+00	3.00E+00	0.00E+00	1.27E+03	1.75E+06	2.55E+04	0.00E+00	1	0	1753400+25495j	1753585	0.014539	0.83304
5.01E+00	3.00E+00	0.00E+00	1.29E+03	1.79E+06	2.10E+04	0.00E+00	1	0	1790100+20958j	1790223	0.011707	0.670773
3.98E+00	3.00E+00	0.00E+00	1.31E+03	1.51E+06	1.28E+04	0.00E+00	1	0	1505300+12807j	1505354	0.008508	0.487457
3.16E+00	3.00E+00	0.00E+00	1.33E+03	1.61E+06	8.17E+03	0.00E+00	1	0	1606500+8173j	1606521	0.005087	0.291487
2.51E+00	3.00E+00	0.00E+00	1.36E+03	1.62E+06	5.93E+03	0.00E+00	1	0	1616600+5929.5j	1616611	0.003668	0.210153
2.00E+00	3.00E+00	0.00E+00	1.38E+03	1.67E+06	3.39E+03	0.00E+00	1	0	1671200+3392.3j	1671203	0.00203	0.116302
1.58E+00	3.00E+00	0.00E+00	1.40E+03	1.60E+06	2.38E+03	0.00E+00	1	0	1600700+2380.2j	1600702	0.001487	0.085197
1.26E+00	3.00E+00	0.00E+00	1.42E+03	1.52E+06	1.21E+03	0.00E+00	1	0	1523100+1207j	1523100	0.000792	0.045405
1.00E+00	3.00E+00	0.00E+00	1.44E+03	1.51E+06	-5.01E+02	0.00E+00	1	0	1514300-500.58j	1514300	-0.00033	-0.01894
7.94E-01	3.00E+00	0.00E+00	1.47E+03	1.67E+06	-9.59E+02	0.00E+00	1	0	1665800-959.35j	1665800	-0.00058	-0.033
6.31E-01	3.00E+00	0.00E+00	1.49E+03	1.62E+06	5.63E+03	0.00E+00	1	0	1621100+5625.9j	1621110	0.00347	0.19884

5.01E-01	3.00E+00	0.00E+00	1.51E+03	1.61E+06	-1.63E+02	0.00E+00	1	0	1614800-163.18j	1614800	-0.0001	-0.00579
3.98E-01	3.00E+00	0.00E+00	1.53E+03	1.57E+06	1.32E+03	0.00E+00	1	0	1572200+1315.3j	1572201	0.000837	0.047934
3.16E-01	3.00E+00	0.00E+00	1.56E+03	1.59E+06	3.40E+03	0.00E+00	1	0	1588800+3398.2j	1588804	0.002139	0.122547
2.51E-01	3.00E+00	0.00E+00	1.58E+03	1.55E+06	7.42E+03	0.00E+00	1	0	1553500+7423.6j	1553518	0.004779	0.273793
2.00E-01	3.00E+00	0.00E+00	1.61E+03	1.50E+06	1.41E+03	0.00E+00	1	0	1497900+1412.1j	1497901	0.000943	0.054014
1.58E-01	3.00E+00	0.00E+00	1.63E+03	1.49E+06	6.10E+03	0.00E+00	1	0	1487800+6096.2j	1487812	0.004097	0.234766
1.26E-01	3.00E+00	0.00E+00	1.66E+03	1.49E+06	5.58E+03	0.00E+00	1	0	1486400+5581.3j	1486410	0.003755	0.21514
1.00E-01	3.00E+00	0.00E+00	1.68E+03	1.50E+06	4.66E+03	0.00E+00	1	0	1502300+4663.8j	1502307	0.003104	0.177871

No Flame Data

ZPlotW Data File: Version 2.2												
Raw Data												
Sweep Frequency: Control Current												
Date: 10-23-2001 Time: 12:35:02												
Open Circuit Potential (V): 0												
C:\SAI\ZData\Flat Burner\102301\Open Circuit.z												
Frequency												
4	2	0	1	1000000	0.1							
71												
Freq(Hz)	Ampl	Bias	Time(Sec)	Z'(a)	Z''(b)	GD	Err	Range	r + jX	Z	theta (rad)	theta (deg)
1.00E+06	3.00E+00	0.00E+00	1.39E+01	3.87E+04	-1.51E+05	0.00E+00	4	0	38650-150860j	155732.3	-1.31999	-75.63
7.94E+05	3.00E+00	0.00E+00	3.96E+01	4.04E+04	-1.88E+05	0.00E+00	4	0	40445-187530j	191841.9	-1.35838	-77.8293
6.31E+05	3.00E+00	0.00E+00	6.72E+01	3.14E+04	-2.15E+05	0.00E+00	4	0	31369-214710j	216989.4	-1.42572	-81.6879
5.01E+05	3.00E+00	0.00E+00	9.30E+01	9.10E+03	-2.72E+05	0.00E+00	4	0	9100.3-271890j	272042.3	-1.53734	-88.083
3.98E+05	3.00E+00	0.00E+00	1.19E+02	5.50E+04	-4.41E+05	0.00E+00	4	0	54965-441200j	444610.6	-1.44685	-82.8986
3.16E+05	3.00E+00	0.00E+00	1.45E+02	8.76E+03	-4.31E+05	0.00E+00	4	0	8764.2-431220j	431309.1	-1.55047	-88.8357
2.51E+05	3.00E+00	0.00E+00	1.70E+02	3.49E+03	-5.44E+05	0.00E+00	4	0	3491.9-544340j	544351.2	-1.56438	-89.6325
2.00E+05	3.00E+00	0.00E+00	1.96E+02	4.09E+04	-7.17E+05	0.00E+00	4	0	40864-716640j	717804.1	-1.51384	-86.7364
1.58E+05	3.00E+00	0.00E+00	2.22E+02	-9.83E+04	-8.07E+05	0.00E+00	4	0	-98315-807030j	812996.5	-1.69202	-96.9457
1.26E+05	3.00E+00	0.00E+00	2.48E+02	-9.69E+04	-1.06E+06	0.00E+00	4	0	-96860-1063700j	1068101	-1.66161	-95.203
1.00E+05	3.00E+00	0.00E+00	2.74E+02	-1.53E+05	-1.16E+06	0.00E+00	4	0	-152870-1160900j	1170922	-1.70173	-97.5017
7.94E+04	3.00E+00	0.00E+00	3.00E+02	-2.69E+05	-1.55E+06	0.00E+00	4	0	-268690-1548700j	1571835	-1.74258	-99.8425
6.31E+04	3.00E+00	0.00E+00	3.28E+02	-7.07E+04	-2.25E+06	0.00E+00	4	0	-70690-2249000j	2250111	-1.60222	-91.8003
5.01E+04	3.00E+00	0.00E+00	3.54E+02	4.81E+05	-3.20E+06	0.00E+00	4	0	481230-3199000j	3234994	-1.42148	-81.4451
3.98E+04	3.00E+00	0.00E+00	3.80E+02	3.08E+04	-3.83E+06	0.00E+00	4	0	30793-3830500j	3830624	-1.56276	-89.5394

3.16E+04	3.00E+00	0.00E+00	4.06E+02	2.77E+05	-4.66E+06	0.00E+00	4	0	276860-4658000j	4666221	-1.51143	-86.5985
2.51E+04	3.00E+00	0.00E+00	4.32E+02	-3.76E+05	-6.13E+06	0.00E+00	4	0	-376230-6131000j	6142533	-1.63208	-93.5116
2.00E+04	3.00E+00	0.00E+00	4.58E+02	-1.28E+06	-7.72E+06	0.00E+00	4	0	-1279000-7715400j	7820693	-1.73507	-99.4125
1.58E+04	3.00E+00	0.00E+00	4.84E+02	-4.44E+05	-9.62E+06	0.00E+00	4	0	-443570-9624100j	9634317	-1.61685	-92.6389
1.26E+04	3.00E+00	0.00E+00	5.10E+02	-1.88E+06	-1.27E+07	0.00E+00	4	1	-1883000-12745000j	12883350	-1.71748	-98.4043
1.00E+04	3.00E+00	0.00E+00	5.32E+02	-1.95E+06	-1.46E+07	0.00E+00	4	0	-1950800-14604000j	14733718	-1.70359	-97.6085
7.94E+03	3.00E+00	0.00E+00	5.58E+02	-3.82E+06	-2.04E+07	0.00E+00	4	0	-3822400-20366000j	20721600	-1.75632	-100.63
6.31E+03	3.00E+00	0.00E+00	5.84E+02	-4.37E+06	-2.39E+07	0.00E+00	4	0	-4373100-23886000j	24283019	-1.75187	-100.375
5.01E+03	3.00E+00	0.00E+00	6.10E+02	-6.30E+06	-3.24E+07	0.00E+00	4	0	-6297800-32405000j	33011306	-1.76275	-100.998
3.98E+03	3.00E+00	0.00E+00	6.36E+02	-8.24E+06	-4.03E+07	0.00E+00	4	0	-8240600-40305000j	41138796	-1.77247	-101.555
3.16E+03	3.00E+00	0.00E+00	6.62E+02	-1.07E+07	-5.31E+07	0.00E+00	4	0	-10744000-53099000j	54175062	-1.77044	-101.439
2.51E+03	3.00E+00	0.00E+00	6.88E+02	-1.39E+07	-7.00E+07	0.00E+00	4	0	-13934000-70004000j	71377282	-1.76727	-101.257
2.00E+03	3.00E+00	0.00E+00	7.14E+02	-1.65E+07	-8.84E+07	0.00E+00	4	0	-16458000-88435000j	89953405	-1.75479	-100.542
1.58E+03	3.00E+00	0.00E+00	7.40E+02	-2.37E+07	-1.17E+08	0.00E+00	4	0	-23686000-117350000j	1.2E+08	-1.76996	-101.411
1.26E+03	3.00E+00	0.00E+00	7.66E+02	-3.58E+07	-1.57E+08	0.00E+00	4	0	-35756000-156740000j	1.61E+08	-1.79508	-102.851
1.00E+03	3.00E+00	0.00E+00	7.92E+02	-4.53E+07	-2.02E+08	0.00E+00	4	0	-45324000-201870000j	2.07E+08	-1.79165	-102.654
7.94E+02	3.00E+00	0.00E+00	8.18E+02	-6.66E+07	-2.69E+08	0.00E+00	4	0	-66608000-269420000j	2.78E+08	-1.81316	-103.887
6.31E+02	3.00E+00	0.00E+00	8.40E+02	-9.02E+07	-3.46E+08	0.00E+00	1	0	-90246000-346290000j	3.58E+08	-1.82573	-104.607
5.01E+02	3.00E+00	0.00E+00	8.61E+02	-9.43E+07	-4.19E+08	0.00E+00	1	0	-94332000-418690000j	4.29E+08	-1.7924	-102.697
3.98E+02	3.00E+00	0.00E+00	8.83E+02	-8.41E+07	-4.98E+08	0.00E+00	1	0	-84117000-498200000j	5.05E+08	-1.73806	-99.5835
3.16E+02	3.00E+00	0.00E+00	9.05E+02	-7.43E+07	-6.01E+08	0.00E+00	1	0	-74324000-600920000j	6.05E+08	-1.69386	-97.0507
2.51E+02	3.00E+00	0.00E+00	9.28E+02	-7.88E+07	-6.94E+08	0.00E+00	0	0	-78833000-693720000j	6.98E+08	-1.68395	-96.4832
2.00E+02	3.00E+00	0.00E+00	9.50E+02	-5.21E+07	-7.94E+08	0.00E+00	0	0	-52081000-793560000j	7.95E+08	-1.63633	-93.7549
1.58E+02	3.00E+00	0.00E+00	9.72E+02	-4.89E+06	-8.84E+08	0.00E+00	0	0	-4893500-883700000j	8.84E+08	-1.57633	-90.3173
1.26E+02	3.00E+00	0.00E+00	9.93E+02	7.97E+07	-9.84E+08	0.00E+00	0	0	79742000-984410000j	9.88E+08	-1.48997	-85.3689
1.00E+02	3.00E+00	0.00E+00	1.02E+03	2.51E+08	-1.05E+09	0.00E+00	1	0	250770000-1049600000j	1.08E+09	-1.33627	-76.5628

7.94E+01	3.00E+00	0.00E+00	1.04E+03	4.63E+08	-1.12E+09	0.00E+00	1	0	462600000-1124900000j	1.22E+09	-1.18064	-67.6457
6.31E+01	3.00E+00	0.00E+00	1.06E+03	6.55E+08	-1.24E+09	0.00E+00	1	0	655170000-1241500000j	1.4E+09	-1.08522	-62.1783
5.01E+01	3.00E+00	0.00E+00	1.08E+03	1.11E+09	-1.14E+09	0.00E+00	1	300	1108100000-1135300000j	1.59E+09	-0.79752	-45.6946
3.98E+01	3.00E+00	0.00E+00	1.10E+03	1.31E+09	-6.03E+08	0.00E+00	1	0	1312800000-603370000j	1.44E+09	-0.43081	-24.6838
3.16E+01	3.00E+00	0.00E+00	1.12E+03	1.15E+09	-2.41E+08	0.00E+00	1	0	1146200000-240880000j	1.17E+09	-0.20714	-11.8683
2.51E+01	3.00E+00	0.00E+00	1.14E+03	9.85E+08	-1.44E+08	0.00E+00	1	0	984760000-144210000j	9.95E+08	-0.14541	-8.33128
2.00E+01	3.00E+00	0.00E+00	1.16E+03	8.56E+08	-1.25E+08	0.00E+00	1	0	855670000-124720000j	8.65E+08	-0.14474	-8.29287
1.58E+01	3.00E+00	0.00E+00	1.18E+03	7.68E+08	-1.65E+08	0.00E+00	1	0	768270000-164950000j	7.86E+08	-0.21149	-12.1176
1.26E+01	3.00E+00	0.00E+00	1.21E+03	7.06E+08	-2.12E+08	0.00E+00	1	0	705930000-211570000j	7.37E+08	-0.29119	-16.6837
1.00E+01	3.00E+00	0.00E+00	1.23E+03	6.59E+08	-2.79E+08	0.00E+00	1	0	658750000-278920000j	7.15E+08	-0.40052	-22.9482
7.94E+00	3.00E+00	0.00E+00	1.25E+03	6.13E+08	-3.13E+08	0.00E+00	1	0	613000000-313360000j	6.88E+08	-0.47256	-27.0757
6.31E+00	3.00E+00	0.00E+00	1.27E+03	5.73E+08	-4.92E+08	0.00E+00	1	0	572970000-492480000j	7.56E+08	-0.71	-40.6798
5.01E+00	3.00E+00	0.00E+00	1.29E+03	5.67E+08	-5.73E+08	0.00E+00	1	0	567260000-573350000j	8.07E+08	-0.79074	-45.3059
3.98E+00	3.00E+00	0.00E+00	1.32E+03	5.09E+08	-7.33E+08	0.00E+00	1	0	509240000-732970000j	8.93E+08	-0.96359	-55.2099
3.16E+00	3.00E+00	0.00E+00	1.34E+03	4.53E+08	-9.44E+08	0.00E+00	1	0	453090000-943910000j	1.05E+09	-1.12326	-64.3583
2.51E+00	3.00E+00	0.00E+00	1.36E+03	4.33E+08	-1.08E+09	0.00E+00	1	0	433420000-1084000000j	1.17E+09	-1.19043	-68.2068
2.00E+00	3.00E+00	0.00E+00	1.38E+03	2.55E+08	-1.34E+09	0.00E+00	1	0	254580000-1337100000j	1.36E+09	-1.38265	-79.2201
1.58E+00	3.00E+00	0.00E+00	1.40E+03	1.58E+08	-1.96E+09	0.00E+00	1	0	157830000-1958800000j	1.97E+09	-1.4904	-85.3934
1.26E+00	3.00E+00	0.00E+00	1.43E+03	-9.60E+07	-2.07E+09	0.00E+00	1	0	-95996000-2074800000j	2.08E+09	-1.61703	-92.649
1.00E+00	3.00E+00	0.00E+00	1.45E+03	1.35E+08	-2.61E+09	0.00E+00	1	0	135330000-2605300000j	2.61E+09	-1.5189	-87.0265
7.94E-01	3.00E+00	0.00E+00	1.47E+03	-6.29E+07	-2.28E+09	0.00E+00	1	0	-62918000-2279100000j	2.28E+09	-1.5984	-91.5813
6.31E-01	3.00E+00	0.00E+00	1.49E+03	2.74E+09	-3.26E+09	0.00E+00	1	0	2735300000-3261800000j	4.26E+09	-0.87297	-50.0173

5.01E-01	3.00E+00	0.00E+00	1.52E+03	1.28E+09	-1.02E+09	0.00E+00	1	0	1283200000-1015800000j	1.64E+09	-0.66961	-38.3657
3.98E-01	3.00E+00	0.00E+00	1.54E+03	1.45E+09	-6.61E+08	0.00E+00	1	0	1446300000-660590000j	1.59E+09	-0.42845	-24.5483
3.16E-01	3.00E+00	0.00E+00	1.56E+03	1.25E+08	-7.36E+06	0.00E+00	1	0	125110000-7359800j	1.25E+08	-0.05876	-3.36664
2.51E-01	3.00E+00	0.00E+00	1.59E+03	1.51E+08	3.14E+06	0.00E+00	1	0	151230000+3135100j	1.51E+08	0.020728	1.18761
2.00E-01	3.00E+00	0.00E+00	1.61E+03	1.64E+08	-4.09E+06	0.00E+00	1	0	164020000-4088300j	1.64E+08	-0.02492	-1.42784
1.58E-01	3.00E+00	0.00E+00	1.64E+03	1.71E+08	-5.88E+06	0.00E+00	1	0	170700000-5875200j	1.71E+08	-0.0344	-1.97124
1.26E-01	3.00E+00	0.00E+00	1.66E+03	1.28E+08	-4.95E+06	0.00E+00	1	0	128360000-4947100j	1.28E+08	-0.03852	-2.20713
1.00E-01	3.00E+00	0.00E+00	1.69E+03	1.17E+08	-1.21E+07	0.00E+00	1	0	116640000-12058000j	1.17E+08	-0.10301	-5.90215

Appendix B-3: 102501 - Time Sweep Data

Z		0.6	0.7	0.8	0.9	1	No Flame
Frequency (Hz)	1.00E+06	1.73E+05	1.77E+05	1.55E+05	1.68E+05	1.57E+05	1.38E+05
	1.00E+05	1.42E+06	1.36E+06	1.28E+06	1.50E+06	1.32E+06	1.29E+06
	1.00E+04	4.79E+06	1.35E+07	3.49E+06	3.27E+06	2.56E+06	4.61E+06
	1.00E+03	3.68E+07	8.10E+07	1.31E+07	9.66E+06	6.39E+06	5.25E+07
	1.00E+02	1.82E+08	7.40E+07	2.52E+07	2.15E+07	1.28E+07	7.88E+08
	1.00E+01	1.77E+08	3.43E+07	1.87E+07	1.05E+07	6.74E+06	7.06E+08
	1.00E+00	2.22E+08	3.02E+07	1.79E+07	9.92E+06	6.41E+06	1.12E+09
	1.00E-01	2.23E+08	2.96E+07	1.82E+07	1.00E+07	6.43E+06	1.01E+09

Z		0.6	0.7	0.8	0.9	1	No Flame
Frequency (Hz)	1.00E+06	-78.39738887	-77.591932	-76.90852431	-77.45227	-77.0666517	-79.918886
	1.00E+05	-70.91818636	-88.7601	-64.81955773	-60.31415	-57.9012166	-69.496335
	1.00E+04	-48.58293028	-74.445526	-23.55730011	-16.67422	-11.3180268	-58.418928
	1.00E+03	-69.77923983	-59.898238	-31.87439719	-24.10436	-18.9557358	-95.722869
	1.00E+02	-43.83886026	-9.84416	-1.816142326	-0.356059	0.16420816	-83.857634
	1.00E+01	-12.83777829	-0.4512931	0.370435136	0.7973966	0.76601972	-31.429477
	1.00E+00	-7.325190754	-0.6783613	-0.567178959	-0.410727	-0.12113368	-146.01241
	1.00E-01	-5.717479492	-0.1553461	-0.4898914	-0.57528	-0.41321634	-103.40726

Appendix C-1: Investigation of Collision Frequency

$$v_e = 10^{11} \quad v_i = 10^8$$

$$v_e = 10^{12} \quad v_i = 1$$

$$v_e = 10^9 \quad v_i = 1$$

$$v_e = 10^6 v_i = 1$$

$$v_e = 10^3 v_i = 1$$

$$v_e = 100 v_i = 1$$

$$v_e = 10 \quad v_i = 1$$

$$v_e = 1 \quad v_i = 1$$

$$v_e = 1 \quad v_i = 10$$

$$v_e = 1 \quad v_i = 100$$

$$v_e = 1 \quad v_i = 10^3$$

$$v_e = 1 \quad v_i = 10^6$$

$$v_e = 1 \quad v_i = 10^9$$

$$v_e = 1 \quad v_i = 10^{12}$$

Addendum

Towards the end of the research, data was collected by separating the probe from the copper electrode at a known distance. As shown earlier, the setup used for data collection was not ideal. Data was taken with approximated distances of 3/16", 1/2", and 3/4". The data shows that there appears to be a connection between impedance and the distance between the probe and copper electrode. Although a conclusion can be drawn from this data, the experimental environment was not ideal. This addendum will only document the findings of this experiment, and further research should be done to valid its conclusion. The data was collected using the Control I vs. Frequency Sweep of the Solartron in a similar fashion as the previous data was collected.

Figure A-2: 110901 - theta vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
November 9th, 2001

Figure A-3: 111301 - |Z| vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
November 13, 2001

Also, in two of the data sets, 111301 and 111501, the theta is mostly inductive. However, if the data is shifted by 180° , then it fits the same trend that has been shown in the previous data. Not only can a conclusion be drawn about the distance between the probe and copper electrode, but also it can be induced that the further away the probe and copper electrode are, an inductance appears in the data. Instead of measuring an RC circuit, the flame looks more like an RLC circuit.

Figure A-5: 111301 - Shifted theta vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
November 13, 2001

Figure A-6: 111501 - $|Z|$ vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
November 15, 2001

Figure A-7: 111501 - theta Vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
November 15, 2001

Figure A-8: 111501 - Shifted theta vs. Frequency
frequency sweep from 0.1 Hz - 30 MHz at different f/a ratios not using Nitrogen Jacket
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