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Development of an atmospheric pressure microwave induced plasma beam

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DEVELOPMENT OF AN ATMOSPHERIC PRESSURE MICROWAVE INDUCED PLASMA BEAM

A thesis submitted in fulfilment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

THE UNIVERSITY OF WOLLONGONG

by

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SCHOOL OF ELECTRICAL, COMPUTER AND TELECOMMUNICATIONS ENGINEERING

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ABSTRACT

Development of a device capable of producing a high power atmospheric pressure plasma beam has been one of the goals of researchers since the development of the magnetron. Until now, progress has been hampered for a variety of technical reasons not the least being materials limitations and the unavailability of suitable microwave generators. The work set forth in this dissertation describes the development of an efficient, atmospheric pressure, plasma beam applicator capable of sustained operation at powers in excess of 5 kW. Sustained operation at such high powers is accomplished through innovative cooling techniques. The operating parameters necessary to produce a stable plasma beam are elaborated upon, as are the physical properties of the plasma. Properties such as beam temperature, length and pressure are characterised as a function of the operating parameters of the system. Beam temperatures are determined using laser scattering techniques from which 2D temperature profiles of the beam are reconstructed.

The voltage standing wave ratio and complex impedance of the plasma are determined as a function of microwave power, discharge gas flow rate and state of tuning of the applicator for both cooled and non-cooled versions of the waveguide applicator. An electric circuit model of the plasma/applicator system is then derived from these measurements. Temperatures and impedances are compared to those reported in the literature for similarly generated microwave plasmas.

Application of a microwave plasma beam to welding and joining applications is totally absent from the literature. In this thesis, autogenous butt welding of sheet steel is
detailed and examination of the weld strength and weld microstructure as a function of microwave power, discharge gas flow rate and travel speed performed. Results indicate that welds performed using a microwave plasma beam are comparable in appearance and quality to those generated using gas tungsten arc welding techniques.
LIST OF PUBLICATIONS/CONFERENCE PROCEEDINGS

Title: Microwave Induced Plasma Jet Welding and Joining.
Authors: S. A. Gower and D. DoRego.

Title/Seminar: Modelling of a Microwave Plasma Jet.
Authors: S. A. Gower and F. J. Paoloni.

Seminar: A Microwave Induced Plasma Jet Welder (MIPJ).
Authors: S. A. Gower.

Seminar: Modelling of a Microwave Plasma Jet.
Authors: S. A. Gower and F. J. Paoloni.

Seminar: A Microwave Induced Plasma Jet Welder (MIPJ)
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Poster/Seminar: Microwave Induced Plasma Jet Welding (MIPJ).
Authors: S. A. Gower.

Seminar: Applications of a Microwave Induced Plasma Jet.
Authors: S. A. Gower.

Title: Microwave Induced Plasma Jet (MIPJ) Welding and Joining.
Authors: S. A. Gower.

Seminar: Microwave Induced Plasma Jet Welding and Joining.
Authors: S. A. Gower.
Venue: 2nd JWRI-CRC Technical Exchange, University of Wollongong, 11th of March, 1996.

Seminar: Microwave Induced Plasma Jet.
Authors: S. A. Gower.
Venue: WTIA Panel 14 meeting, CSIRO Lindfield, Sydney, April 1996.
Title: High Power Microwave Gas Plasma Generation.
Authors: S. A. Gower, D. McLean and F. J. Paoloni.
Venue: Australian Provisional Patent #PO0286, 6th of June, 1996.

Seminar: Microwave Induced Atmospheric Pressure Plasma Jet.
Authors: S. A. Gower, C. Montross and F. J. Paoloni.

Title/Seminar: Microwave Induced Plasma Jet for Welding.
Authors: S. A. Gower, D. DoRego and D. McLean.
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Seminar: Microwave Induced Plasma Jet Welding.
Authors: S. A. Gower.
Venue: Industrial Automation Research Centre Meeting, 5th of September, 1996.

Poster: Microwave Induced Plasma Jet Welding.
Authors: S. A. Gower and D. DoRego.
Venue: Post Graduate Research Student Open Day, 17th of September, 1996.
Title: Microwave Induced Plasma Jet Welding of Sheet Steel.

Authors: S. A. Gower, D. DoRego and A. Basu.

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CHAPTER 1. LITERATURE REVIEW.

1.1 Introduction.

The aim of the research reported in this thesis was to construct a microwave induced plasma applicator capable of welding sheet steel. This brief imposed several restrictions or requirements on the final design. These requirements were to produce: i) a well collimated beam with a diameter as small as possible, ii) a plasma beam with sufficient power to rapidly melt steel, iii) a discharge gas flow rate low enough to ensure molten metal was not ejected from the weld pool, iv) the ability to shape the cross section of the plasma beam.

To that end, this literature review gives an overview of the work published concerning microwave discharges generated using coaxial and cavity applicators. Although it is difficult to directly compare results from different authors due to the myriad of different applicator designs, the modes of excitation as well as operation and plasma parameters are discussed. The plasma/applicator system is covered as well as applications to industry, science and space research. The object is to review the literature concerning generation of plasmas using microwaves at atmospheric pressures and at microwave frequencies of 915 MHz and 2450 MHz. A brief description of cavity modes for cylindrical and rectangular cavities is given as a background to the discussion.

1.2 Review of Microwave Cavity Theory.

Transmission lines and waveguides are used to efficiently propagate electromagnetic energy, whereas a resonator in any electrical system is an energy storage device [1].
Hence a resonator is equivalent to a resonant circuit element. At low frequencies, a capacitor and an inductor are used to form a resonant circuit, Figure 1a. To make this combination resonate at higher frequencies, the inductance and capacitance must be reduced, as in Figure 1b. To reduce the inductance still further, parallel straps are used as in Figure 1c. The limiting case is the completely enclosed rectangular box or cavity resonator shown in Figure 1d. In this geometry, the maximum voltage is produced between the centre of the top and bottom plates.

![Simple LC circuits](image-a)
![Quasi cavity](image-b)
![Enclosed cavity](image-c)

Figure 1. Evolution of a cavity resonator from a simple LC circuit, [1]

The $\text{TE}_{mnp}$ modes for a cavity resonator can be found in any elementary text and are given below [2]. The expressions for electric and magnetic fields were derived from Figure 2 with the $z$ axis designated as the “direction of propagation”. The existence of perfectly conducting end walls at $z=0$ and $z=d$ leads to the formation of standing waves, i.e. no wave propagates within the cavity. The TE standing wave pattern within the cavity is designated by the $mnp$ subscript where $m$ refers to variations of the fields in the $x$ direction, $n$ in the $y$ direction and $p$ in the $z$ direction.
Figure 2. Coordinate system and dimensions used for TE mode field derivation [3].

\[
E_x = \frac{j\omega \mu n\pi}{k^2} \frac{m\pi x}{b} H_0 \cos\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \sin\left(\frac{pxz}{d}\right) e^{j\omega t}
\]

\[
E_y = -\frac{j\omega \mu n\pi}{k^2} \frac{m\pi x}{b} H_0 \sin\left(\frac{m\pi x}{a}\right) \cos\left(\frac{n\pi y}{b}\right) \sin\left(\frac{pxz}{d}\right) e^{j\omega t}
\]

\[
H_x = -\frac{1}{k^2} \frac{m\pi}{a} \frac{p\pi}{d} H_0 \sin\left(\frac{m\pi x}{a}\right) \cos\left(\frac{n\pi y}{b}\right) \cos\left(\frac{pxz}{d}\right) e^{j\omega t}
\]

\[
H_y = -\frac{1}{k^2} \frac{n\pi}{b} \frac{p\pi}{d} H_0 \cos\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \cos\left(\frac{pxz}{d}\right) e^{j\omega t}
\]

\[
H_z = H_0 \cos\left(\frac{m\pi x}{a}\right) \cos\left(\frac{n\pi y}{b}\right) \sin\left(\frac{pxz}{d}\right) e^{j\omega t}
\]
where

\[ k^2 = \left( \frac{m \pi}{a} \right)^2 + \left( \frac{n \pi}{b} \right)^2 \]

The resonant frequency of the cavity is given by

\[ \omega_{mn} = \frac{1}{\sqrt{\mu \varepsilon}} \sqrt{\left( \frac{m}{a} \right)^2 + \left( \frac{n}{b} \right)^2 + \left( \frac{p}{d} \right)^2} \]

The preceding equations represent the electric and magnetic field components for microwaves contained to a general rectangular cavity. However, this discussion is confined to the dominant or TE101 mode as this mode represents the most desirable condition for a microwave plasma applicator since the maximum electric field strength is located along the central axis of the cavity as seen in Figure 3. For the TE101 mode, these equations reduce to three non zero field components:

\[ E_y = -j \omega \mu H_0 \frac{a}{\pi} \sin \left( \frac{\pi x}{a} \right) \sin \left( \frac{\pi z}{d} \right) e^{j \omega t} \]
Examining these three equations, we see that the electric field has a maxima for \( x = a/2 \) and \( z = d/2 \), is in the \( y \) direction and becomes zero at the side walls as required by perfect conductors [3]. The magnetic field lines lie in the \( x-z \) plane and surround the vertical displacement current resulting from the time rate of change of \( E_y \). There are equal and opposite charges on the top and bottom walls because of the normal electric field ending there. A current flows between the top and bottom, becoming vertical in the side walls. This is analogous to a conventional resonant circuit, with the top and bottom acting as capacitor plates and the side walls as the current path between them. This brings us full circle to Figure 1 and the evolution of a cavity resonator from an LC circuit. The TE101 mode may be excited by a coaxially fed microwave probe inserted in the centre region of the top or bottom face where \( E_y \) is a maximum or by a loop to couple to the maximum \( H_x \) placed inside the front or back face. The best location for the probe or loop depends on the impedance matching requirements of the microwave circuit of which the resonator is a part. To couple microwave energy from a waveguide to the cavity, a hole or iris at an appropriate location in the cavity wall is necessary. The field in the waveguide must have a favourable component to excite the desired mode in the cavity resonator.
In a manner similar to the construction of a rectangular resonator, a cylindrical resonator is formed from a section of circular waveguide with electrically conducting end plates [3]. For simplicity, consider the TM01 mode in a circular waveguide of radius $a$ at cutoff so that there is no variation in the $z$ direction. The vertical electric field has a maximum at the centre and dies off to zero at the conducting side walls. A circumferential magnetic field surrounds the displacement current represented by the time varying electric field. Neither component varies in the axial or circumferential direction. Equal and opposite charges exist on the two end plates and a vertical current flows in the side walls. The field components are shown diagrammatically in Figure 4 and are given by:

$$E_z = E_0 J_0(kr)$$

$$H_\phi = \frac{jE_0}{\eta} J_1(kr)$$
\[ k = \frac{p_{i1}}{a} = \frac{2.405}{a} \]

where the resonant frequency is

\[ \omega_0 = \frac{k}{\sqrt{\mu \varepsilon}} = \frac{2.405}{a \sqrt{\mu \varepsilon}} \]

Note that for a TM010 cavity the resonant frequency is a function of radius only and does not depend on the length \( z \). Also, the electric field strength is uniform over the entire length of the cavity which is important for generating long plasma columns.

![Figure 4. Sections through a cylindrical cavity showing TM010 field patterns [3].](image)
1.3 A Chronology of Applicator Development.

Research into ultra high frequency discharges in gases evolved from the development of high power magnetrons used for radar purposes during the Second World War. Equipment designed at the General Electric Research Laboratory, shown in Figure 5 and reported on by Cobine and Wilbur [4], consisted of a coaxial applicator which produced a torch like flame at atmospheric pressure from 1 kW developmental magnetrons operating in the frequency range of 500-1100 MHz. The microwave energy was coupled into a cavity which was then coupled to a coaxial section terminating in the plasma torch. Tuning of the cavity was achieved by means of a tuning rod and the coaxial section was adjustable to allow matching to the torch. The plasma gas flowed out axially along the coaxial section. The torch was initiated by touching the inner conductor with a carbon rod or a piece of insulated wire. Once the plasma was established, the system was impedance matched by adjusting the length of the coaxial section and the depth of penetration of the tuning slug. The efficiency of the torch varied by as much as 60% depending on the plasma forming gas used and the discharge tip had to be water cooled to prevent erosion. Plasma parameters were determined using a 5.0 kW magnetron though it is not specified what the applicator arrangement was for these tests.
In 1965, Fehsenfeld et al examined six microwave discharge cavities operating at 2450 MHz for use as spectroscopic light sources. The cavity assignments and characteristics are given in Table 1. Medical diathermy units operating at 2450 MHz and having a maximum output power of 125 W supplied the CW microwave power for the cavities. These units were inexpensive and uncomplicated compared to government surplus radar equipment. All of the cavities were designed to produce discharges in a 13 mm O.D. quartz tube.

Cavity 1, Figure 6, was the earliest cavity used and consisted of a tapered waveguide section with a slot cut into the narrow portion. The best operating characteristics were obtained when the ionisation chamber was placed midway along the slot near the edge. Coupling was achieved by an adjustable probe.
<table>
<thead>
<tr>
<th>Cavity</th>
<th>Electrical Configuration</th>
<th>Estimated frequency range (MHz)</th>
<th>Coupling adjustment</th>
<th>Removable from glass discharge system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tapered rectangular TE103</td>
<td>2.45</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2a</td>
<td>Foreshortened 3/4 wave coaxial</td>
<td>2.3-2.6</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2b</td>
<td>Foreshortened 3/4 coaxial</td>
<td>2.3-2.6</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Foreshortened 1/4 wave radial</td>
<td>2.3-2.6</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Coaxial termination</td>
<td>0.5-4.5</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>Foreshortened 1/4 wave coaxial</td>
<td>2.0-3.0</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 1. The cavities examined by Fehsenfeld et al [5], 1965.

In cavity 2a, Figure 7, the discharge is struck in the gap between the hollow inner cylinders through which the ionisation chamber eccentrically slips. Cavity tuning is achieved by adjusting the gap distance between the varying inner cylinders. A hose fitting on the coaxial connector allows for cooling air to be blown through the cavity to prevent overheating of the ionisation chamber. A hole in the outer cylinder allows for spectroscopic studies to be performed [7, 8, 9, 10].

Cavity 2b, Figure 8, is identical to 2a except for an addition of an extra matching element. In cavity 2b, tuning is achieved by simultaneously adjusting the gap distance and stud penetration. Cavity 3, Figure 9, is a foreshortened radial line where magnetic
field coupling to the cavity is achieved via a large inductive loop. Air cooling of the cavity is required to prevent the ionisation chamber from melting. The positioning of the ionisation chamber hole was by trial and error to produce the most intense discharge.

In cavity 4 coupling is achieved via a matching stub located on the coaxial connector. Supplementary coupling is achieved by adjustment of the shaped probe, see Figure 10. Again air cooling of the ionisation chamber is necessary. Fehsenfeld draws attention to the fact that this is not a resonant cavity in the sense of the other discharge cavities. He goes on to say that the other cavities were designed to resonate at 2450 MHz and perform over a limited band about this frequency whereas cavity 4 worked well over a bandwidth greater than 1000 MHz.

Cavity 5, Figure 11, is a resonant cavity whose resonant frequency is adjusted by means of a tuning stub and coupling by means of an adjustable slider. Cooling air for the ionisation chamber is forced through a tube located in the body of the cavity.

Figure 6. The tapered waveguide applicator of Fehsenfeld [5], 1965.
Figure 7. The foreshortened 3/4 wave coaxial applicator of Fehsenfeld [5], 1965.

Figure 8. The foreshortened 3/4 coaxial applicator of Fehsenfeld [5], 1965.
Figure 9. The foreshortened 1/4 wave radial applicator of Fehsenfeld [5], 1965.

Figure 10. The coaxial termination applicator of Fehsenfeld [5], 1965.
The two important things to note about all of these cavities is that they are coaxially fed and that supplementary cooling of the ionisation chamber is necessary. In order to increase the microwave power available for plasma generation, microwaves need to be fed to the plasma cavity via waveguides. This overcomes the power handling limits of coaxial cables. This is not necessarily an issue in the research lab but can be a problem in an industrial environment where high levels of microwave power are needed for applications such as welding of steel [11]. Swift describes a plasma torch [12] that is coaxially fed and operates at power levels up to 2.5 kW. The unit operates at 2450 MHz and is not based on a resonant cavity design but that of a coaxial applicator, Figure 12.
The output of the magnetron is fed via a rigid 50 ohm coaxial line to the plasma torch via a slotted line. Impedance matching of the plasma flame to the 50 ohm line is accomplished by tuning the bridges in the two stub sections. A stream of cooling water flows through the inner conductor of the matching element to cool the tip which screws in and is interchangeable. The plasma gas flows axially along the inner conductor to the tip in a similar manner to the electronic torch of Cobine and Wilbur [4]. The principal difference between these two torches is the matching elements. Similarly though, the plasma was initiated by an insulated rod with a pointed tungsten end which was placed on the tip of the torch to produce the initiating spark.

A waveguide to coaxial transition, Figure 13, was the basis of the microwave discharge system described by Murayama [13]. 400 W, 2469 MHz microwave energy was fed to the coaxial waveguide via a rectangular waveguide. The discharge was generated on the open end of the coaxial section where a water-cooled aluminium electrode was placed.
on the tip of the inner conductor. Argon was used as the plasma forming gas and the discharge was matched to the source by insertion of an inductive iris 63 mm from the central axis of the coaxial waveguide. The discharge system was used for determination of plasma parameters with the plasma being seeded with hydrogen, calcium and sodium to facilitate the process.

Figure 13. Waveguide configuration of the discharge generator of Murayama [13], 1968.

Work performed by Arata et al from 1973 to 1975 led to a series of four reports titled “High Power Microwave Plasma Beam as a Heat Source”. In Report 1 [14], subtitled “Microwave Plasmatron in Nitrogen Gas”, Arata et al used the arrangement given in Figure 14 to deliver 3 kW at 2450 MHz of microwave power to a coaxial applicator via rectangular waveguide.
Figure 14. Schematic layout of the "Microwave Plasmatron" as described by Arata et al [14], 1973.

The applicator was similar in design to that of the authors Swift, Murayama and Cobine, the main difference being the method of delivery of the microwave power. To facilitate the delivery of high microwave powers it was necessary to move from coaxial cable to hollow rectangular waveguide. The applicator consisted of a coaxial waveguide section with two tuning plungers. The discharge gas was fed axially with flow rates from 30 to 200 litres per minute and a water cooled tungsten tip was placed on the end of the inner conductor from which the discharge was initiated. A 200 mm long quartz tube was positioned at the exit side of the discharge to obtain a stable axial flow of the gases. Nitrogen and nitrogen with 5% hydrogen were used as the principal plasma forming gases. Air, carbon dioxide, argon, and argon with 2-10% hydrogen were also used. The discharge system was used to investigate a high power atmospheric plasma beam as a new type of practical heat source.
In Report 2, subtitled “Characteristics of 30 kW Plasmatron” [15], Arata et al examined a 30 kW, 915 MHz plasma beam where the configuration of the plasmatron was changed to the rectangular waveguide type in order to make the plasma axis parallel to the electric lines of force.

Figure 15. Cross sectional front view of the 30 kW plasmatron as described by Arata et al [15], 1973.

Figure 15 gives the cross sectional front view of the plasmatron in detail. The main part of the plasmatron was a water-cooled rectangular cavity resonator with dimensions 180x60x340 mm. A 40 mm I.D. Pyrex tube was inserted through the upper and lower broad walls of the waveguide through which a tangential gas flow was introduced with flow rates of 100-600 l/min. The protruding Pyrex tube was covered with water-cooled copper cylinders to limit light emission and microwave leakage. The plasma was ignited by inserting a tungsten wire into the Pyrex tube and sub matching was performed.
by adjusting a tuning plunger at the end of the plasmatron. The primary matching mechanism was an E-H tuner upstream from the plasmatron.

In Report 3 [16] by Arata et al the energy absorption processes of the 30 kW plasmatron are examined. The plasmatron design is the same as that for Report 2 except for the addition of a calorimetric power measurement system. Report 4 [17] describes the first attempt at utilising an atmospheric microwave plasma beam for an industrial application. Figure 16 gives a cross sectional front view of the plasmatron whereas Figure 17 is a schematic diagram of the cutting system used by Arata et al. The dimensions of the cavity were changed from those used in Reports 2 and 3 to a value of 250x30x300 mm. The Pyrex tube was also replaced by a boron nitride ceramic tube of diameter 10 mm to which several types of nozzle tips were inserted on the exit side of the gas flow. This tube was sometimes water cooled to measure the heat loss to the walls. The direct power loss to the cooling water was ascertained to be negligible once the plasma was ignited. The stand-off distance between the workpiece and the nozzle was set at 4 mm. The thickness of the mild steel workpieces was 3, 4 and 6 mm and the cutting velocity was varied up to 750 mm/min. The gas flow rate was varied from 100-400 l/min. The results of this work were that the "strong temperature decay in the large gas flows gave unfavourable results" and that "studies of the turbulent flow should be performed in detail to reform the applicability of this type of plasma beam for cutting or welding". By this admission, the applicator of Arata [16] failed to meet the third design requirement as set out in Section 1.1.
Figure 16. Cross sectional front view of the 30 kW plasmatron used for cutting as described by Arata et al [16], 1975.

Figure 17. Schematic diagram of the cutting system described by Arata et al [17], 1975.
In 1974, Asmussen et al [18] examined a cylindrical, variable length cavity operating at 2.45 GHz and 1.3 kW. Asmussen’s cavity, shown in Figure 18, consisted of a 1.25 cm I.D. quartz tube located on the axis of a 10.15 cm water cooled cylindrical cavity. The quartz tube could be forced-air cooled when necessary. Small holes were cut into the exterior walls of the cavity providing coaxial ports required for microwave diagnostic measurements. Depending on the cavity mode excited, two adjustable loop coupling antennae located in the side of the cavity, allowed the RF energy to be introduced into the cavity. The cavity was tuned by means of a plunger that acted as a movable wall in the plasma cavity system. RF energy is fed to the system coaxially and argon was used as the discharge gas.

![Figure 18. Cylindrical resonant cavity of Asmussen [18], 1974.](image)

A cavity with the shape of a pillbox, as described by Beenakker [19], has found applications in optical and atomic emission spectroscopy (OES and AES respectively) and is represented schematically in Figure 19. The cavity consisted of a copper cylindrical wall of I.D. 93 mm with a fixed bottom and a removable lid. The height of
the wall was chosen to be 10 mm. The ionisation chamber extends through the centre of
the cavity and is made of silica with a 1.45 mm I.D. Microwave power is fed into the
cavity by a coupling loop and tuning is achieved by adjusting either of the tuning screws
mounted in the cavity bottom or wall. Holes in the cylindrical wall were used for
viewing and cooling purposes. Microwave power input to the system was continuously
variable between 20 and 200W. The discharge was initiated by a Tesla coil or
spontaneously. Data given for the conditions necessary for spontaneous ignition seem
strange in as much as the ionisation potential of helium is greater than that for argon
implying that spontaneous ignition is more likely to occur in argon. The author claims
improved functionality through the ability to generate stable plasmas in both argon and
helium at atmospheric pressure and no background molecular spectra. Helium plasmas
are desirable in chromatography because organic compounds are almost completely
atomised by the plasma [19].

Figure 19. The microwave cavity of Beenakker [19] for OES applications, 1976.
An atmospheric microwave discharge source known as a “Surfatron” was reported by Moisan et al [20] in 1979. The device shown in axial cross section in Figure 20, is not a resonant cavity but rather can be considered as a length of a coaxial transmission line. It comprises two essential parts, the coupler and the excitation structure. The coupler is constructed from a semi rigid coaxial cable terminated by a standard N-type coaxial connector. An anodised aluminium plate is attached to the inner conductor and the height or penetration depth of the plate relative to the inner coaxial tube determines the coupling capacity. Minimising the reflected power is achieved by adjusting the height of this plate. The research used 915 MHz, 700 W continuously variable microwave power and for powers above 200 W, the surfatron was externally water-cooled.

Figure 20. The microwave surfatron of Moisan et al [20], 1979.

A small argon torch based on the surfatron is given in Figure 21. Small aluminium wires, 1 mm were welded with this small torch. Other applications suggested by the authors for the surfatron are as an excitation source for microsamples in OES analysis,
as a spectroscopic light source for ultra violet study at pressures up to one atmosphere or modified and used as a small welding torch.

Bloyet and Leprince [21, 22] were granted two US patents dealing with a plasma generator. The embodiment of both patents is identical, only the claims being different. The plasma generator represented in Figure 22, is a hybrid coaxial/re-entrant cavity design. Microwave energy is fed coaxially to a cylindrical re-entrant cavity. A hollow metallic tube is passed coaxially through the centre of the cavity on the end of which the plasma is generated and through which the discharge gas is passed. Ignition of the plasma is accomplished by striking a spark between the end of the inner conductor and a metallic rod brought into close proximity. The cavity was fed with 2450 MHz microwave energy with power continuously varied from 15 to 500 W. The authors' stress that this is not a resonant cavity confined to operation over a very limited frequency range but a cavity with an operating bandwidth of order of 20% about the
nominal operating frequency. Matching is accomplished by adjusting the penetration of a threaded rod located in the outer wall of the cavity.

Figure 22. Hybrid cavity design of Bloyet and Leprince [21, 22], 1984-86.

Moisan et al reported on a high power surface wave launcher [23] dubbed a "waveguide surfatron". It consisted of both waveguide and coaxial line elements as seen in Figure 23. The microwave power is supplied from a generator to a rectangular waveguide section terminated by a movable short circuit plunger. The coaxial section is attached perpendicularly to the wall of the waveguide and its inner conductor extends into the waveguide as a sleeve around the ionisation chamber forming a circular gap in the immediate vicinity of the opposite wall. The waveguide surfatron design was first proposed by Chaker et al [24] and has two matching mechanisms to effectively couple microwave energy to the plasma column. Microwave powers up to 1.3 kW were tested using this device with forced-air cooling of the ionisation chamber necessary for
microwave powers greater than 200 W. The I.D. and O.D. of the fused silica ionisation chamber used was 10 and 47 mm respectively.

Figure 23. The waveguide surfatron of Moisan et al [23], 1987.

A TM010 resonant cavity was proposed by D. J. Helfritch et al for destruction of hazardous wastes such as chlorinated hydrocarbons [25]. The article has very little detail but gives the diagram shown in Figure 24. The cavity was constructed such that a steel rod could be inserted into the cavity volume to allow for fine tuning to achieve resonance. The author neglects to mention ignition methods or give any cross sectional diagrams to indicate gas and waste flows. There is a claim of 1 kW of reflected power for a forward power of 6 kW to achieve a plasma temperature of 4000 K but again, no details are given. Both air and steam were used as the process gas.
Research done at the University of Tokyo by Mitsuda et al [26] led to the development of a microwave plasma torch for diamond synthesis applications. A schematic diagram of their microwave plasma jet apparatus is shown in Figure 25. The apparatus consisted of a waveguide to coaxial transition connected to an air tight chamber. The plasma was initiated on the centre water cooled copper electrode of the coaxial waveguide and the substrate mounted on a temperature controlled sample holder. Microwave power was continuously variable from 2 to 5 kW at a frequency of 2450 MHz. As the intention of the work was diamond synthesis, an argon-hydrogen-methane mix was used as the discharge gas. The researchers reported deposition rates of 30 μm per hour for substrate temperatures up to 1600 K.
Figure 25. Diamond synthesis apparatus of Mitsuda et al [26], 1989.

Figure 26. The axisymmetric microwave field and plasma generator of Gaudreau [27], 1989.
In 1989, Gaudreau et al [27] were granted a US patent for a microwave plasma generator which is claimed to create an axisymmetric microwave field and plasma. The device shown schematically in Figure 26, is essentially identical to that of Moisan’s et al [23]. The apparatus consists of a rectangular waveguide section through which a conductive rod passes transversely and coaxially into a circular output waveguide. There are matching elements on both the rectangular and circular waveguide sections. The plasma apparatus is then mounted on a vacuum chamber in which experiments are performed.

A microwave heating type plasma jet using a resonant cavity was investigated by Tahara et al [28]. The subject of the research was a microwave plasma jet for space propulsion that competes against the most widely used catalytic hydrazine thruster for attitude control of artificial satellites. The device, shown schematically in Figure 27, consisted of an aluminium TM011 resonant cavity and a 20 mm I.D. quartz ionisation chamber located axially along the cylinder. Both the cavity and the ionisation chamber were forced-air cooled. Matching was achieved by adjustment of a movable end wall. The discharge gas was helium and microwave powers of 520 W at 2450 MHz were used. Thrust was measured by the deflection of a target and thrust performance was evaluated. The results obtained show that the thruster of Tahara et al [28] competes well against the most widely used catalytic hydrazine thrusters for attitude control of artificial satellites [29].
J. J Sullivan describes a resonant cavity design that requires no tuning mechanism and is more stable in the US Patent # 4965540 [30]. The cavity was based on a cylindrical re-entrant design and the ionisation chamber extends axially though the centre of the cavity as shown in Figure 28. Microwave power at 2450 MHz is fed coaxially to the cavity via a coupling loop mounted through the cavity side wall. The claim of no tuning mechanism relies on a low Q for the cavity and the coupling loop. The low Q for the cavity is due to the increased conductance of a shorter plasma and that of the coupler due to its lower reactance. A modification to the cavity is also proposed that allows for liquid cooling to enable operation at higher powers. The modification consists of two liquid cooled plates that attach to the top and bottom faces of the applicator and a system of sealing rings and tubes to allow the coolant to circulate around a portion of the ionisation chamber. The principal function of the cavity is as a spectroscopic light source. No mention is given in the patent document of the microwave power level or the discharge gas flow rates used.
A comparison of microwave induced plasma sources was performed by Forbes et al in JAAS [31]. The four cavities compared were a Folded coaxial, a Straight coaxial, an Enhanced Beenakker TM010 and a Strip line source. The Folded coaxial cavity is a modified surfatron-like structure and is shown in Figure 29. The folded coaxial line is formed by the inner and outer walls of the tube (Figure 29-5) and is slightly shorter than a quarter wavelength. The tapered tip coaxial conductor couples energy to the plasma through the concentrating gap. Microwaves enter the cavity in a region where the local electric field strength is a maximum. The second resonator placed at the output plane is to reflect radiated microwaves back into the cavity. The discharge is maintained in a quartz tube of I.D. 1 mm x O.D. 6 mm and is located axially within the cylindrical cavity.
The Straight coaxial cavity shown in Figure 30, is 3/4 of a wavelength long and also has a secondary resonator attached to attenuate both coaxial and surface mode propagation outside the cavity. Coupling is accomplished by an adjustable depth antenna and tuning by a movable plunger on the rear of the cavity.
The Beenakker cavity, shown previously in Figure 19, was modified to obtain a higher coupling coefficient. This was achieved by the addition to the antenna of a movable plate as used in the surfatron [20]. This eliminated the need for additional tuning at the coupling loop and conventional frequency tuning could be achieved with a single screw. The enhanced Beenakker cavity is shown in Figure 31.

![Figure 31. The Enhanced Beenakker cavity as examined by Forbes et al [31], 1991.](image)

A schematic diagram of a strip line source is shown in Figure 32. The ionisation chamber crosses the strip and is located at a region of maximum electric field strength one quarter wavelength from the rear wall. At the other end of the strip, an adjustable plate antenna couples microwave energy between a coaxial connector and the strip. A capacitive tuner for adjusting the resonant frequency is located on the opposite side of the strip with the strip being 3/4 of an electrical wavelength long. The plasmas were initiated by inserting a nichrome wire attached to a small insulating rod into the ionisation chamber. All four cavities described by Forbes are for OES applications and
are coaxially fed. The operating parameters for the cavities included a maximum microwave power of 120 W and plasma gas flow rates up to 2.1 litres per minute.

![Diagram of a microwave source](image)

Figure 32. The Strip Line source as examined by Forbes et al [31], 1991.

Burns and Boss described techniques to improve the impedance match of a microwave source to a TM010 cavity plasma [32] for OES applications. Their cavity, shown in Figure 33, was milled from aluminium and had three 8 mm diameter quartz tuning rods inserted through the cylinder walls at positions, 1 mm above, 1 mm below and from the opposite side, normal to the plasma tube. A slot was cut in the cavity lid to allow insertion of a coupling probe. The reflected power was minimised by traversing the coupling probe along the slot and supplementary tuning was achieved by adjusting the insertion depths of the three quartz tubes. Argon was the discharge gas with flow rates up to 7 litres per minute and the maximum microwave power used was 50 W. This power was fed coaxially to the cavity. The probe tips were brass and were sheathed in a dielectric to increase the local electric field strength. By improving the impedance match of the generator to the plasma, the authors' techniques extend the efficient
operating range of the microwave induced plasma and improve the detection limits and sensitivities for a given amount or concentration of analyte.

![Diagram of TM010 cavity of Burns and Boss [32], 1991.](image)

To overcome reported limitations such as the stability (and excitation capability) of the resulting plasma being perturbed by small quantities of introduced foreign materials, Jin et al [33] proposed the microwave plasma torch shown in Figure 34. The plasma torch is similar in construction to the surfatron of Moisan [20], but has the ability to slide the coupling antenna assembly along the length of the ionisation chamber. The ionisation chamber is a concentric arrangement in which the plasma gas flows through the outer tube and the carrier gas and sample flows along the inner. Microwave power is fed coaxially and is continuously variable between 0 and 500 W at 2450 MHz. The torch is designed for AES applications and detection limits of 1-50 ng/ml are claimed for most of the elements studied.
Matusiewicz [34] also examined a rectangular resonant cavity for AES applications. A schematic diagram of the rectangular cavity design is given in Figure 35 and has been designed in the form of a rectangular box resonator with a height of 18 mm. The resonant cavity is coupled via an inductive window or iris and resonates in a TE101 mode. The iris is adjustable and enables coupling of the cavity to the source under different operating conditions. Adjustment of the resonant frequency of the cavity is attained by use of a movable plunger that acts as one of the walls of the cavity. The distance between the antenna and the iris has been chosen to achieve maximum stability of the cavity/magnetron system. Boron nitride was employed for the ionisation chamber due to other ceramic tubes failing for microwave powers greater than 150 W. The ionisation chamber was located centrally within the rectangular cavity and had an O.D. and I.D. of 6.3 mm and 2.0 mm respectively. The plasma was ignited by a one second burst from a piezoelectric plasma ignition device. The operating conditions for argon, helium, nitrogen, air and oxygen plasmas were investigated and the researchers claim to be the first to generate an oxygen plasma. Discharge gas flow rates of 0-2 litres per minute were used and the highest power plasma generated was 500 W at 2450 MHz.
The author claims superiority over the Beenakker cavity [19] in terms of electrical and mechanical integrity, ease of tuning and extremely wide range of resonance and coupling adjustments as well as excellent resistance to cavity detuning caused by changes in plasma density with the introduction of wet aerosols.

![Diagram of microwave detector and plasma cavity](image)

Figure 35. The rectangular cavity of Matusiewicz [34], 1992.

An International Patent submitted by Lucas and Lucas from The Welding Institute, proposes a method for generating a plasma suitable for welding applications [35]. Two applicator designs are proposed and both are coaxially fed and are based on a TM010 resonant cavity design. The first, shown schematically in Figure 36, consists of a cylindrical cavity with an insertable slug that is transformed into a re-entrant cavity as the slug is inserted. This increases the electric field strength in the region of the discharge cavity. This ceramic button like cavity was located at the exit opening of the resonant cavity, was circular in cross section and had a diameter of 7 mm and was 3 mm high. A tungsten electrode is mounted within the cavity and the plasma gas was fed to it.
via a conduit in the faceplate. A separate conduit feeds a supply of shielding gas for welding operations. Microwave powers of 500-1000 W are typically used with discharge gas flow rates of several litres per minute.

Figure 36. The re-entrant cavity design of Lucas and Lucas [35], 1992.

The second applicator, shown in Figure 37, consisted of a TM010 cavity in which a ionisation chamber was mounted axially. The ionisation chamber was fashioned from ceramic and had an I.D. of 3 mm. Matching to the cavity was accomplished by means of an insertable annulus that surrounded one end of the ionisation chamber. Both of the Lucas cavities were coaxially fed and neither have produced a weld of acceptable quality [36] due to failure of the ionisation chamber under high microwave power conditions.
Another application that can potentially gain from microwave induced plasma technology is that of electrothermal space propulsion. Power has examined [37] the role of microwaves in such an application and has constructed a TM011 operating at 915 MHz and 30 kW. The apparatus shown schematically in Figure 38, consists of resonant cylindrical cavity with microwave and discharge gas feeds. A 5.7 T superconducting magnet is included for implementation of a magnetic nozzle. The ionisation chamber is fashioned from quartz for use at low powers and from alumina or boron nitride at high powers. It has a 50 mm I.D. and is surrounded by a vacuum liner to minimise conductive and convective heat losses. The vacuum liner provides an evacuated annulus of 5 mm around the ionisation chamber. A moveable shorting wall or plunger provides tuning capabilities and can be translated over such a distance as to allow for tuning to TM011 or TM012 modes. At the time of writing, no plasmas had been generated and the experimental work was limited to operation with a water load in place of the cavity.
A liquid cooled quartz torch was constructed by Matusiewicz and Sturgeon [38] for use in the rectangular cavity of Matusiewicz [34]. The cavity remain unchanged except for the liquid cooled ionisation chamber shown in Figure 39. The torch was made entirely from quartz and consisted of two concentric tubes, a coolant inlet and outlet, as well as feeds for the discharge and analyte carrier gases. The carrier gas was introduced through the inner tube while an outer gas flow was introduced approximately perpendicular to the nebuliser flow. The outer gas flow rate was controlled separately from the nebuliser gas flow rate. The coolant was fed through a capillary near the exit side of the ionisation chamber and flowed along the plasma region before exiting the torch. The coolants examined were Dimethyl polysiloxane, hydraulic fluid and automotive transmission fluid (with the latter being most desirable due to its low cost and wide availability) and a flow rate of 150 ml/min was sufficient to prevent erosion or etching of the ionisation chamber. Matusiewicz concludes by stating that “the fluid cooled torch enhances ionisation chamber lifetime and significantly decreases
erosion/ablation of the quartz tube surface, leading to a background emission spectrum that is comparatively free of Si lines and molecular SiO bands in the UV-VIS and a decreased continuum in the near IR [39].” The torch was ignited by inserting a section of tungsten wire attached to a non-conducting handle.

A waveguide based field applicator [40] was used by Moisan et al for large diameter plasma generation. The applicator consisted of a slotted antenna array bent into a cylinder about an axis parallel to the slotted wall. This array is then housed within a cylindrical chamber with flanges that acted as endplates as seen in Figure 40. Microwaves were fed to the cavity via a tapered waveguide section and tuning was accomplished using a standard waveguide plunger. The ionisation chamber was made from quartz and was forced-air cooled with argon and helium being used as the discharge gases. The microwave power supplied to the cavity was continuously variable up to 1 kW at a frequency of 2.45 GHz.
1.4 Determination of Plasma Parameters.

Cobine and Wilbur [4] recorded an electron temperature ranging from $7.85 \times 10^4$ K at the tip to $13.4 \times 10^4$ K near the inner electrode for a 350W atmospheric pressure discharge in nitrogen. The measurements were obtained by means of a thin walled nickel tube (2.3 mm O.D., 0.76 mm wall) cooled by a strong stream of air passing through it. The probe was located on the axis of the discharge and passed through the discharge at right angles. The potential of the probe was measured relative to the inner conductor. The authors report that reducing the power level by one half did not appreciably affect the electron temperature ($14.8 \times 10^4$) and the results generated are “at least of the correct order of magnitude”. The authors also make an estimation of the “flame temperature” of between 1870-3740 K using buoyancy methods. This involves measuring the upward deflection of a horizontally directed flame to determine the trajectory from which an estimation of the temperature can be made. The plasma impedance was also measured
for a microwave power of 3.75 kW at 915 MHz and is given in Table 1. No measure of
the electron density was performed.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Gas Velocity (m/sec)</th>
<th>Impedance (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.432</td>
<td>5-41.5j</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.432</td>
<td>4-51.5j</td>
</tr>
<tr>
<td>Air</td>
<td>0.432</td>
<td>4-47.0j</td>
</tr>
<tr>
<td>Air</td>
<td>0.762</td>
<td>4-51.5j</td>
</tr>
</tbody>
</table>

Table 2. Plasma impedance data of Cobine and Wilbur [4], 1951.

In Murayama’s [13] argon plasma, hydrogen and calcium served as probe elements for
the measurement of electron density and gas temperature, respectively, and sodium as a
seed for increasing electron density. The excitation temperature, $T_{ex}$, the electron
density, $n_e$, the ionisation temperature, $T_i$, and the gas temperature, $T_g$, were measured
at operating powers of 50, 200 and 400 W and are tabulated in Table 3 and Table 4.
The discharge was set on the axis of an optical system and the image of the discharge
focused on the entrance slit of a 1 m Ebert monochromator with 8.3 Å/mm first order
dispersion. Measurements were made on the electrode spot, on the axis of the central
core of the plasma and in the plasma mantle. The gas temperature of the plasma was
measured in the plasma mantle using Doppler broadening and is given in Table 5. The
plasma was not in local thermodynamic equilibrium (LTE) anywhere in close vicinity to
the electrode at the powers investigated. At distances between 1 and 3 mm from the
electrode, the non seeded plasma approached LTE with increasing power whilst the
seeded plasma deviated from LTE. Murayama interprets the deviation from LTE at lower powers in the nonseeded plasma as being due to the inhomogeneity of the plasma.

<table>
<thead>
<tr>
<th></th>
<th>Electrode Spot</th>
<th>Electrode Spot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non seeded</td>
<td>Non seeded</td>
</tr>
<tr>
<td>50 W</td>
<td>200 W</td>
<td>400 W</td>
</tr>
<tr>
<td>$T_e$ (K)</td>
<td>7900±100</td>
<td>7500±90</td>
</tr>
<tr>
<td>$T_i$ (K)</td>
<td>7000±50</td>
<td>6900±70</td>
</tr>
<tr>
<td>$n_e$ (10^{14} \text{ cm}^{-3})$</td>
<td>3.1±0.3</td>
<td>2.4±0.3</td>
</tr>
</tbody>
</table>

Table 3. Electrode spot plasma parameters as measured by Murayama [13], 1968.

<table>
<thead>
<tr>
<th></th>
<th>Central Core Axis</th>
<th>Central Core Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non seeded</td>
<td>Non seeded</td>
</tr>
<tr>
<td>50 W</td>
<td>200 W</td>
<td>400 W</td>
</tr>
<tr>
<td>$T_e$ (K)</td>
<td>7900±100</td>
<td>6900±90</td>
</tr>
<tr>
<td>$T_i$ (K)</td>
<td>7400±70</td>
<td>6800±200</td>
</tr>
<tr>
<td>$n_e$ (10^{14} \text{ cm}^{-3})$</td>
<td>6.1±0.7</td>
<td>2.0±0.6</td>
</tr>
</tbody>
</table>

Table 4. Central core axis plasma parameters as measured by Murayama [13], 1968.
Table 5. Parameters of the plasma mantle as measured by Murayama [13], 1968.

<table>
<thead>
<tr>
<th></th>
<th>Non seeded</th>
<th>Non seeded</th>
<th>Seeded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200 W</td>
<td>400 W</td>
<td>200 W</td>
</tr>
<tr>
<td>$T_s$ (K)</td>
<td>4500±900</td>
<td>4600±1000</td>
<td>6200±1200</td>
</tr>
<tr>
<td>$T_e$ (K)</td>
<td>NA</td>
<td>NA</td>
<td>6200±80</td>
</tr>
<tr>
<td>$n_e$ ($10^{11}$ cm$^{-3}$)</td>
<td>NA</td>
<td>NA</td>
<td>5.0±2.2</td>
</tr>
</tbody>
</table>

Arata et al [14] also used a 1 m Ebert monochromator with 8.3 Å/mm first order dispersion to measure the parameters of a 3 kW, 2450 MHz plasma. The electron density of the plasma beam was obtained by measuring the Stark effect on the hydrogen Balmer line. The discharge gas was nitrogen with 5% hydrogen and flows were varied between 30 and 200 litres per minute. The plasma temperature was estimated using the Saha-Eggert equation with the assumption of LTE. The plasma temperature and electron density are given as a function of axial distance and transmitted power in Figure 41 and Figure 42 respectively. The temperature and density as given in Figure 41 increases rapidly and attains a maximum value of $T=6700$ K, $N_e=7E13$ cm$^{-3}$ at $z=5$ mm and then decreases moderately with axial distance.
Figure 41. Plasma temperature and electron density as a function of axial distance, Arata et al [14], 1973.

The plasma temperature and density increases nearly proportionally with power for power levels >0.8 kW. The plasma temperature is given as a function of radial distance and discharge gas flow rate for a 1.5 kW and 1.71 kW plasma respectively, in Figure 43 and Figure 44. As can be seen from these Figures, the plasma temperature is almost constant for flow rates up to 200 l/min and the temperature decreases with radial distance as would be expected. A standing wave meter in the rectangular waveguide was used to measure the plasma impedance. Figure 45 and Figure 46 show the effect of the plasma impedance on the transmitted power and discharge gas flow rate.
Figure 42. Plasma temperature and electron density as a function of transmitted power, Arata et al [14], 1973.

Figure 43. Plasma temperature as a function of radial distance, Arata et al [14], 1973.
Figure 44. Plasma temperature as a function of discharge gas flow rate, Arata et al [14], 1973.

Figure 45. Plasma impedance as a function of transmitted power, Arata et al [14], 1973.
Figure 46. Plasma impedance as a function of discharge gas flow rate, Arata et al [14], 1973.

Arata et al also examined the plasma properties of a 30 kW, 915 MHz plasmatron [16] using spectroscopic methods. Plasma densities were again measured from Stark broadening of the hydrogen Balmer line for various conditions by mixing various percentages of hydrogen to the nitrogen (or argon) discharge gas. Assuming LTE the temperature was then determined from the Saha equation. Good agreement was obtained with plasma temperatures determined by measuring the relative intensity ratio of hydrogen Balmer lines. Figure 47 shows there is little dependence of plasma temperature or density on incident microwave power for a ionisation chamber diameter of 40 mm. The temperature and density are about 6400 K and 1E14 cm\(^3\) for incident powers between 10 and 25 kW. By reducing the ionisation chamber diameter to 20 mm, the dependence of temperature and density on microwave power becomes more pronounced as shown in Figure 48.
The tendency of increasing temperature and density with decreasing ionisation chamber diameter is shown in Figure 49 and Figure 50 for nitrogen and argon as the discharge gases. This tendency supports the notion that a microwave plasma welder should be based around a small diameter ionisation chamber. A 20 mm ionisation chamber produced temperatures of about 6700 K and 7700 K in nitrogen and argon with
microwave powers of 10.3 kW. Figure 51 shows there is no dependence of the plasma parameters on discharge gas flow rate. By varying the gas flow rate between 80 and 300 litres per minute, the plasma temperature and density remained relatively constant at 6750 K and 3E14 cm$^3$ respectively.

Figure 49. Effect of tube diameter on plasma parameters for nitrogen gas, Arata et al [16], 1973.
Figure 50. Effect of tube diameter on plasma parameters for argon gas, Arata et al [16], 1973.

Figure 51. Effect of discharge gas flow rate on plasma parameters, Arata et al [16], 1973.
Figure 52. Temperature dependence on incident power and nozzle diameter, Arata et al [17], 1975.

Figure 53. Temperature dependence on gas flow rate and nozzle diameter, Arata et al [17], 1975.
Arata et al [17] also examined the plasma temperature as a function of incident power for various nozzle diameters, Figure 52 and gas flow rates for various nozzles, Figure 53. In each case, the temperature is greater for a smaller nozzle diameter as would be expected from thermodynamic principals.

1.5 Summary of Literature Review.

Applicators for generating microwave plasmas can be broadly separated into two groups. These are coaxial and cavity applicators. The coaxial applicators were first used in the early 1950's and were generally low power devices that were coaxially fed microwave power. In order to minimise degradation of the centre conductor or discharge tip, materials such as copper and tungsten were used in conjunction with water cooling techniques. This kept the tip cool enough so that erosion did not occur. To generate plasmas with higher powers, it was necessary to use metallic waveguides to deliver the microwave power instead of coaxial cables. The result was an applicator that required a waveguide to coaxial transition and is well illustrated by Figure 13.

Coaxial cables however, have some benefits over waveguides, such as flexibility of the cable and reduced bulk. Bulk is especially important as the microwave frequency is reduced. For example, at 2450 MHz, a TE10 waveguide has internal dimensions of 43 x 86 mm whereas at 915 MHz, these dimensions increase to 120 x 240 mm. Coaxial cables capable of carrying very high microwave powers are now available and are being used in the generation of microwave plasmas [37]. Though these cables are not small, they are still flexible. The cable used by Power [37] measured 12.5 cm in diameter and was rated at 32 kW of CW microwave power at 915 MHz. The cut-off frequency was 960 MHz and the attenuation was less than 0.05 dB over a 5 m length. Using such a
high power rated cable should allow the generation of a microwave plasma using the coaxial techniques described in Section 1.3. These techniques do not require the ionisation chamber used in cavity applicators. The ionisation chamber is prone to failure due to absorption of microwave energy with increasing temperature but does produce a collimated plasma beam essential for applications such as high quality welding.

The first resonant cavity applicators were coaxially fed devices for operation at low powers [5]. As the power input to these devices was increased beyond a few hundred Watts it became necessary to provide supplementary cooling of the ionisation chamber to prevent tube failure. Many researchers [5, 18, 19, 23, 28, 40] used forced-air cooling techniques to extend the life of their ionisation chambers. Arata et al [17] used water cooling techniques to show that the plasma heat loss to the walls of a 20 mm ionisation chamber was negligible due to the helical flow of gas producing a virtual cold wall. Sullivan makes reference to water cooling in Reference [30]. In his design the annulus of water surrounds only part of the ionisation chamber and is a mere 0.1 mm thick. He goes on to say that water coolant can be replaced by air flow if desired. The implication here is that water cooling is not necessary in his design though it may just be a case of operating at low enough powers to ensure the ionisation chamber is in no danger of failing. No information is given on operating parameters in the patent text. In fact not all designs require supplementary cooling of the ionisation chamber as shown in Reference [16]. If the I.D. is large enough then a gas wall can be formed that limits the contact of the plasma with the walls of the ionisation chamber. Unfortunately, a large I.D. also means a large diameter plasma which is not desirable for welding studies. To overcome the large diameter plasma a nozzle arrangement can be used [17].
serves two functions; firstly it reduces the diameter of the plasma beam and secondly it can increase the plasma temperature by adiabatic compression. Both are desirable properties for optimal welding performance. Nozzles also have some undesirable side effects when it comes to welding. The nozzle erodes with time due to contact with the plasma and the erosion products contaminate the welding process. Also, as the nozzle erodes, the plasma exit orifice increases in size leading to reduction in weld quality from a larger heat affected zone.

Resonant cavity applicators can be subdivided into various groups. These are rectangular, cylindrical, waveguide and waveguide field applicators. The literature seems to favour cylindrical cavities possibly due to the ability to have a plasma greater in length than a quarter wavelength though this may not be desirable for all applications. The waveguide field applicator of Moisan et al [40] appears to be unique in the literature and has applications in large area plasma generation. Throughout the literature there has been a correlation between ionisation chamber diameter and microwave power, i.e. high microwave powers are associated with tubes of large I.D. Those cooling techniques in the literature have dealt with large diameter ionisation chambers and high powers or with low powers and small diameter tubes. Plasma operation with small diameter ionisation chambers and high microwave powers have not been examined due mainly to the difficulty in maintaining a high temperature plasma in contact with the walls of the ionisation chamber without failure.

Plasma parameters have been measured for both coaxially generated [4, 13] and cavity generated plasmas [14, 16, 17]. For the three coaxially generated plasmas reviewed, the maximum microwave powers used were 350 W with a nitrogen discharge gas flow
velocity of approximately 1 m/s, 1.8 kW with nitrogen gas flow rates of up to 200 l/min, and 400 W with argon gas flow rates of 11 g/min (~ 9 litres/min). For cavity generated plasmas, microwave powers of up to 20 kW were used with nitrogen discharge gas flow rates from 80 to 300 l/min. None of the temperature measurement methods used a direct means of measuring temperature. Instead, assumptions about the state of the plasma were made and then temperatures determined using these assumptions. The assumption was that the plasma was in a state of local thermodynamic equilibrium allowing temperatures to be determined from densities using the Saha-Eggert equation. The temperatures derived were generally between 5000 to 8000 K regardless of the applicator used or the microwave frequency or power level. In some cases [4, 13], the temperatures recorded were spot temperatures and are not indicative of the thermal profile of the plasma. There has also been no systematic investigation to fully quantify plasma parameters over the complete operating range of applicator variables.

1.6 Conclusion.

This literature survey enumerates applicator development since the late 1940’s and has examined the ways in which a plasma can be generated using microwaves. Though it does not cover all the work done by all researchers, it does cover all major applicator types and important advances in the science of generating microwave plasmas at atmospheric pressure. Those applicators designed to operate at reduced pressures are not covered nor are those that use methods other than microwaves for plasma generation as they are outside the scope of this thesis.
Applications for microwave induced plasmas are diverse and research for use as a heat source or in space propulsion is detailed. By far the most interest for microwave induced plasma applications comes from the spectroscopy community. Microwaves are capable of generating high power, inert, stable and luminous plasmas at atmospheric pressure. Inert gases are preferable to molecular gases because of the absence of a background molecular spectrum. Using a large diameter ionisation chamber (or cooling of the tube) also leads to reduced atomic and molecular emission since ablation of the tube walls does not occur from contact with the plasma thereby increasing sensitivity and reducing detection limits.

As mentioned in the introduction, a microwave induced plasma applicator capable of welding sheet steel requires: i) a well collimated beam with a diameter as small as possible, ii) a plasma beam with sufficient power to rapidly melt steel, iii) a discharge gas flow rate low enough to ensure molten metal is not ejected from the weld pool, iv) and the ability to shape the cross section of the plasma beam. A small diameter, well collimated beam can be most easily produced by use of a ionisation chamber that has a small inside diameter. This translates to using a cavity applicator, as there is no provision for a ionisation chamber in a coaxial design. To rapidly melt steel, high microwave powers are necessary. Table 6 gives ionisation chamber I.D. and the microwave power regime for those references cited in Section 1.3 that require a ionisation chamber. As can be seen from this Table, high microwave powers combined with small diameter ionisation chambers are virtually absent from the literature. It is this area of research that this thesis embodies as well as application of microwave induced plasmas to welding of sheet steel. The applicator must be able to operate efficiently at low discharge gas flow rates and have the ability to change the shape of the
cross section of the plasma beam. To date, all plasma beams reported in the literature are of circular cross section. The ability to shape the plasma beam is advantageous when it comes to welding because one applicator can serve the purpose of preheating the metal, melting and heat treatment of the weld in one pass. A similar method employed currently in industry is known as multi cathode TIG (tungsten inert gas). Here, separate TIG cathodes (and power supplies) provide, preheating, melting and heat treatment functions. Both The Welding Institute (TWI) England and the Japanese Welding Research Institute (JWRI) in Japan have examined microwave generated plasmas as a heat source for cutting applications [35, 17]. Neither however, have published any data on welding research using microwave plasmas. TWI have been limited to low powers due to ionisation chamber failure [36] and JWRI possibly by the high gas flow rates necessary to sustain the plasma in their applicator. As previously mentioned, high gas flow rates expel the metal from the weld zone once it has become molten so instead of welding a cutting action is initiated.

Application of microwave plasmas to welding and small diameter ionisation chambers combined with high microwave powers are not covered in the literature. As such there has been no systematic investigation to quantify plasma parameters or weld quality over the range of applicator variables. This thesis will rectify these deficiencies.
<table>
<thead>
<tr>
<th>Tube I.D. (mm)</th>
<th>Power (kW)</th>
<th>Low P &lt; 0.5</th>
<th>Medium 0.5 &lt; P &lt; 1.5</th>
<th>High P &gt; 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small &lt; 5 mm</td>
<td></td>
<td>19, 28, 31, 32, 34, 35</td>
<td>35, 38</td>
<td></td>
</tr>
<tr>
<td>Medium 5 &lt; d &lt; 10 mm</td>
<td></td>
<td>20, 23</td>
<td>20, 23</td>
<td>17</td>
</tr>
<tr>
<td>Large &gt; 10 mm</td>
<td></td>
<td>5, 18</td>
<td>18</td>
<td>15, 16, 37</td>
</tr>
</tbody>
</table>

Table 6. Ionisation chamber diameter and microwave power for selected references.
CHAPTER 2. EXPERIMENTAL DESIGN, EQUIPMENT AND PROCEDURES.

2.1 Introduction.

The goal of this thesis was to develop a microwave generated plasma device that could produce a beam of plasma capable of welding sheet steel using off the shelf components where possible. This chapter describes the componentry used to generate and measure microwave radiation. It also describes the ancillary equipment used in the course of experimentation but does not cover the design of the plasma beam applicator. This is left for Chapter 3. Figure 54 represents diagrammatically those components of the experimental apparatus that are detailed in Chapters 2 and 3.

Figure 54. Diagrammatic representation of experimental apparatus.
Also covered in this chapter is the experimental procedure required for prolonged and safe operation of the microwave equipment. In the interest of safety and due to the extreme voltages and high microwave powers used, it was occasionally necessary for some procedures to be performed in conjunction with another doctoral student. It is made clear in the text where data has been generated collaboratively.

2.2 Pulsed Power Supply.

The first microwave power supply used was constructed in-house by the Microwave Applications Research Centre, a wholly owned company of the University of Wollongong. It was rated at approximately 1.5 kW and produced microwave power pulsed at the line frequency of 50 Hz. This was satisfactory for preliminary experimentation but it became quite clear that continuous power was necessary to prevent the plasma from extinguishing and then re-igniting 50 times per second. This is important since the plasma was first initiated by use of a conducting wire inserted into the high electric field region of the applicator. If the plasma then extinguishes, the wire needs to be re-inserted so that the wire becomes a consumable and/or contaminant since it must be left in place for continued plasma generation.

The shock wave from the expanding plasma front created a moderately loud bang when the plasma was first initiated. At 50 Hz, the 50 bangs per second were so noisy that the shock front could be quite plainly seen on an oscilloscope fitted with a microphone. The noise was completely eradicated by using continuous microwave power.
2.3 Continuous Wave Power Supply.

Conventional power supplies [41], used to drive high power continuous wave or CW magnetrons, utilise a step-up transformer with its secondary high voltage output connected to rectifiers to provide the dc high voltage for the magnetron. Although the ideal power supply would provide a current source, present conventional design provides a voltage source applied to the magnetron. In order to control the microwave output power with a voltage source applied to the magnetron, it is necessary to adjust the magnitude of the current in its electromagnet.

Funding was obtained to purchase a Spellman High Voltage Corporation MG10 switched mode 10 kW magnetron power supply. Along with the power supply, a National YJ1600 6 kW water cooled magnetron, launcher and circulator were purchased.

To evaluate power supply and magnetron operating conditions, filament current, anode voltage, anode current as well as output power of the power supply were all monitored. To evaluate the performance of the system, hour meters were implemented to log magnetron hours as well as power supply high voltage hours.

Spellman [41] claims that high frequency, 20 kHz, resonant invertor technology provides the following benefits over conventional magnetron supplies;

- A true current source for the magnetron allows direct control of the magnetron output power and provides inherent current limiting capability during a fault condition.
• Low output ripple current is obtained without the need for the energy storage filter components that could damage the magnetron in case of an arc or fault condition. No large values of capacitance or inductance are used.

• Reduced line frequency ripple is achieved through fast responding current feedback circuits.

• The output power can be shut down in less that 30 microseconds after a fault signal is received and then reapplied according to a pre-set programme. The fast response prevents magnetron damage when signals are applied from fault monitor circuits such as (π-1) or arc detectors.

• The output power can be controlled through a remote interface. Inputs may be derived from external sources such as temperature probes or a directional coupler/detector that provides an indication of excessive reflected power.

• Size and weight reduction of the power supply (by a factor of five) is achieved because high frequency invertor technology allows the use of small and light magnetic components.

• Magnetron stress is minimised through automatic ramping of the anode voltage and current.

• Remote and local control of the output powers are programmable, e.g. through a PLC.

2.4 Circulator.

A circulator or isolator is a three port microwave device that is used to prevent reflected microwaves from coupling to the magnetron antenna. In operation, magnetised ferrites in the circulator employ Faraday rotation to couple microwaves incident on port 1 to
Reflected microwaves incident on port 2 are then coupled to a water load via port 3. An excellent description of microwave-ferrite interactions and devices can be found in Ramo, Whinnery and Van Duzer [42]. The circulator used is shown schematically in Figure 55.

![Figure 55](image)

Figure 55. Schematic diagram of the circulator used.

### 2.5 Dual Directional Coupler.

The dual directional coupler used was a rigid waveguide type, shown schematically in Figure 56. Dual directional couplers are 4 port devices used to measure forward and reflected powers. The design used two waveguide sections crossed at 90 degrees with two radiating slots separated by a quarter waveguide wavelength. Microwaves incident on port 1 are coupled to ports 2, 3 and 4. The waves, being 90 degrees out of phase in the secondary waveguide, add constructively to yield a signal at port 3 and destructively giving no signal at port 4. By symmetry, waves incident on port 2 yield a signal at port 4 but none at port 3. The signal coupled to the secondary waveguide section was attenuated by 39 dB.
2.6 Three Stub Tuner.

A stub tuner is an impedance matching device used to transform the impedance of the load to match that of the source. If the impedances are matched then maximum power is transferred to the load since there are no reflections from the load, i.e. the VSWR=1 where VSWR is defined as the voltage standing wave ratio. The method of impedance matching of a single stub can be used to match any arbitrary, non zero, finite load impedance to the characteristic impedance of a waveguide [43]. However, the single stub method requires that the stub be inserted into the waveguide at a specific point, which varies as the load impedance or the operating frequency is changed. This requirement often presents practical difficulties since the specified insertion point may occur at an undesirable location from a mechanical viewpoint or, more importantly, the impedance of the plasma changes with each operating condition. An alternative method to single stub impedance matching is to use two or more short circuited stubs inserted into the waveguide at fixed, though not specific, locations as shown in Figure 57. A triple or three stub tuner allows a greater range of impedances to be matched than a two stub tuner. Engineering drawings of the three-stub tuner can be found in Appendix A.
2.7 Slotted Waveguide Section.

The slotted section used consisted of a length of waveguide with a calibrated non-radiating slot machined along the centre of the broadwall as shown in Figure 58. An antenna or probe slides along the slot and senses the resultant standing wave pattern of the microwaves. By measuring the standing wave ratio and the position of the voltage maxima and minima the load impedance can be determined. A detailed discussion of standing wave ratio is given in Section 4.2.
2.8 Power Meter.

Two Hewlett-Packard power meters, models 435A and 435B, with power sensing heads, model 8481A, were used for all power measurements. These were calibrated by Hewlett-Packard during the course of experimentation to ensure accuracy. With 69 dB attenuation, the power meters were capable of sensing microwave powers between 25 W and 800 kW FSD though in reality, the attenuators would fail at these power levels. The maximum power measured by the meters was 6.25 kW.

2.9 Microwave Leakage Meter.

Stray microwave radiation was measured using Holaday Industries, model 1501, microwave survey meter. This device was calibrated for 2450 MHz and could detect microwave radiation down to levels of 0.1 mW/cm². In accordance with the guidelines for occupational limits, microwave exposure was kept below 2 mW/cm².

2.10 Welding Table and Controller.

The welding table was constructed in-house and was driven by an RS Components stepper motor and control electronics via a 1.0 mm pitch lead screw to give a maximum translation rate of approximately 150 mm/min. The lead screw was later replaced by a high lead, 47 mm pitch, screw that gave a maximum translation rate of 7.0 m/min. This replacement was necessary as preliminary welding trials determined that the translation rate needed to be increased to run with microwave power levels exceeding 2 kW. The table can be adjusted in three dimensions allowing for the greatest flexibility when it comes to welding non uniform samples. The workpieces are held in place by a variety
of clamping jaws and are butted together in preparation for autogenous welding. Sample stand-off distance can be varied by 50 mm and table travel is 250 mm. Control of the table was accomplished via software written in-house using the virtual instrument application “Visual Designer”. A photograph of the welding table can be seen in Figure 59 and engineering drawings in Appendix B.

![Figure 59. Photograph of the welding table used.](image)

### 2.11 Experimental Procedure.

The individual microwave hardware elements are connected as shown in Figure 54. When attaching microwave waveguide components together, it is necessary to ensure the flange plates are securely fastened and the waveguides correctly aligned. Reflections can occur from waveguide discontinuities due to poor alignment and
microwave leakage from improperly fastened flange plates, both of which contribute to unnecessary experimental errors. In general, the slotted waveguide section was only used during experimentation to determine cavity and/or plasma properties. It was not used, for example, during welding trials.

When applying microwave power for an experiment, it was necessary to increase the power slowly. Ramping the microwave power serves to prolong magnetron life. This is important because a magnetron is an electron tube and therefore, classified as a consumable by the manufacturer.

2.12 Conclusion.

Equipment able to provide the continuous power levels necessary for practical welding was not available commercially. However, the equipment detailed in this chapter was developed to allow for generation, monitoring and detection of microwave radiation using commercially available and purpose built equipment. Efficient coupling of the microwave energy to the load is accomplished by insertion of matching elements into the microwave network. A purpose built welding table and instrumentation as well as monitoring software and hardware were also constructed to facilitate welding studies.
CHAPTER 3. APPLICATOR DEVELOPMENT.

3.1 Introduction.

This chapter deals with applicator design and development. Theoretical considerations, experimental results and efficiencies for rectangular and as well as cylindrical cavities are covered. A complete set of cavities with diameters of 60 to 90 mm in increments of 2 mm were constructed to determine the optimum diameter for a cylindrical applicator. These cavities were then tested at high power and at low power using a network analyser. Also detailed in the chapter is the development of the waveguide applicator from the test of concept design to the applicator used for welding trials. Matching with irises, efficiencies, cooling jacket experiments and materials selection for the waveguide applicator are also included here. In all instances, microwave power was delivered to the applicator via WR340 waveguide. This waveguide has internal dimensions of 43 x 86 mm and microwaves propagate within the waveguide in the fundamental or TE10 mode. To generate a plasma, the discharge gas flow rate was set between 2 and 10 litres/minute. Microwave power was then delivered to the cavity and the plasma ignited by a momentary insertion of an insulated tungsten wire into the ionisation chamber.

3.2 Cylindrical Cavity Design.

The resonant frequency of a cylindrical resonator is determined purely by the radius of the cylinder. As shown in Chapter 1, the angular frequency is given by;
\[ \omega_0 = \frac{k}{\sqrt{\mu \varepsilon}} = \frac{2.405}{a\sqrt{\mu \varepsilon}} \]

Where \( \mu \) and \( \varepsilon \) are the permeability and permittivity of the material contained within the cavity and \( a \) is the radial dimension.

For an air filled cavity resonating at 2450 MHz, the above relation gives a cylindrical cavity radius of \( a = 46.8 \) mm. Note that this dimension only applies for an empty cavity. With the addition of a ceramic ionisation chamber and plasma, the resonant radius will change for a fixed driving frequency of 2450 MHz.

To experimentally determine the internal diameter of a cylindrical cavity, containing a plasma and dielectric load, resonating at 2450 MHz in the TM010 mode, the following experiment was devised:

a) Firstly, the VSWR and load impedance phase was determined for a set of operating conditions, e.g. discharge gas flow rate of 5 litres/minute, a microwave power of 1.5 kW and a fixed cavity diameter. (The numerical value of VSWR is the square root of the ratio of the voltage maxima to voltage minima as measured from the standing wave pattern of the microwaves in the waveguide. This pattern was measured using the slotted section and HP power meters given in Section 2.7 and Section 2.8 respectively).

b) A section of 2.5 mm diameter brass tubing was then cut to such a length as to give an identical VSWR and load impedance phase when examining the S21 parameters.
on a network analyser. The S21 parameter is the ratio of the amplitude of the wave leaving port 2 to the wave entering port 1. The rationale for using the brass tube to mimic the plasma is based on the fact that the plasma behaves as a partially conducting medium since it has some degree of ionisation. This is well illustrated by examining the standing wave pattern for the waveguide applicator shown in Figure 60. Extrapolating either curve to zero on the standing wave scale gives a near minimum in the electric field strength, which is consistent with the boundary conditions of $E=0$ on a conductor.

c) The length of brass tubing was then inserted into the ionisation chamber of a cavity modelled from polystyrene and aluminium tape to simulate the plasma. Ideally, when examined on the network analyser the resonant frequency of the cavity with the dielectric and the simulated plasma would be 2450 MHz. If this was not the case, a new cavity with a different inside diameter, hopefully giving the desired resonant frequency, could be quickly constructed. This method of rapid prototyping was relatively easy to do using polystyrene models wrapped in aluminium tape. A photograph of a selection of polystyrene models can be seen in Figure 61.
Figure 60. Standing wave pattern about the ionisation chamber for a waveguide applicator. Forward CW microwave power = 360 W. Note: Graph in region -80 to 0 scaled down by a factor of 10.

Figure 61. Rapid prototyping polystyrene models used to model plasma/cavity system.
The network analyser used, a Hewlett-Packard model 8753C with model 85046A S parameter test set, is designed for low power applications and so could not simulate the change in effective dielectric constant of the applicator system with the change in temperature associated with high power operation. As such, it was not known if each of the polystyrene models would be capable of initiating and sustaining a plasma. Therefore, a new experiment was devised to accommodate the elevated temperatures of the applicator system when operating at high powers.

The four steps in the new experiment were:

a) Two cylindrical applicators were constructed from aluminium bar with outside diameters of 100 mm and internal diameters of 50 and 60 mm. The first was 60 mm long and the second 100 mm. The 100 mm long cavity is shown photographically in Figure 62.

b) These applicators were then used to generate high power plasmas. Quartz and then boron nitride were used as the ionisation chambers whilst using argon and then nitrogen as the discharge gas.

c) The resonant frequency of the applicator was then determined using the network analyser under three different conditions; empty, with ionisation chamber and with ionisation chamber and simulated plasma.

d) The inside diameter of the applicator was then increased by 2 mm and the process of high power and network analyser tests repeated. This was repeated until the I.D.'s of the 60 and 100 mm long cavities reached 76 and 92 mm respectively. The work on the 60 mm long cavity was performed by Duarte DoRego, a research student from the Department of Mechanical Engineering at the University of Wollongong, and is included here for completeness.
Figure 63 shows the resonance characteristics of the 100 mm cylindrical cavity as a function of internal diameter for the following conditions: empty, loaded with boron nitride dielectric and loaded with boron nitride dielectric and simulated plasma. Also represented for interest on the graph is the theoretical frequency for an empty cavity resonating in the TM010 mode. Quite clearly, the theoretical values bear no resemblance to the experimentally measured values. The main reason for this may be an inappropriate coupling mechanism between the waveguide and the cavity. Since the mode excited within a cylindrical cavity is critically dependent on the coupling mechanism, one needs to carefully choose the coupling method to generate the required field pattern. Instead of using a rectangular to cylindrical waveguide transition, an inductive loop could have been used to couple energy to the cavity. This may have produced the correct field pattern but would necessitate the use of coaxial cable to
deliver the microwave energy. This situation would be at odds with the goal of producing a practical welding tool.

Another likely reason for the discrepancy between the measured and theoretical resonance values, for the empty cavity case, is due to the effective coupling aperture changing with each increase in diameter. The increase in the effective coupling aperture occurred because the cylindrical cavity was attached to the end of a section of 43 by 86 mm waveguide. Only after the I.D. of the cavity increased beyond 86 mm did the aperture dimensions remain constant. It is hard to know what effect this had on the resonance data generated but regardless, it was another source of experimental error and being outside the scope of this thesis, was not investigated further.

As the diameter of the cavity increased, different modes within the cavity became dominant and as such, appear as discontinuities in the plots in Figure 63. If nothing else, this data serves to show just how difficult it is to determine the optimal dimensions for a dielectric loaded cylindrical cavity resonator.
Table 7 contains the cavity diameter/plasma data for both the 60 mm and 100 mm long cavities. This data was generated using CW microwave power up to 2 kW with a triple stub tuner used to match the load presented by the plasma/cavity system to the source. The boron nitride used for the ionisation chamber was not pure and so has a higher loss factor than the pure material. The greater the loss factor of a material, the more readily it will absorb microwave energy. For example, distilled water has a loss factor of 76.7 [44], pure boron nitride has a loss factor of 0.00075 and quartz 0.0002 at 3000MHz. This higher loss factor meant the tube heated through the absorption of microwave energy and provided an electron source for plasma initiation (Figure 64 shows a photograph of an impure boron nitride ionisation chamber that has failed due to oxidation). The quartz tube was essentially transparent to microwaves and could not initiate a plasma since it did not heat up. This is verified by experimental results given
in Table 7. The fact that a plasma could not be initiated in the quartz ionisation chamber suggests that a plasma cannot be initiated purely from dielectric breakdown of the discharge gas but needs initiating through some secondary mechanism such as thermionic emission of electrons from the heated ionisation chamber, or from the spark generated on the tip of a tungsten wire inserted into the cavity. This point is important since it was initially thought that it might be possible to design an applicator that would spontaneously initiate a plasma. From Table 7, it is also evident that it is easier to generate an argon plasma than a plasma from nitrogen gas. This is consistent with the ionisation energy of argon being lower than for nitrogen gas. However, the situation is complicated since nitrogen gas is a diatomic molecule that can absorb energy in both vibrational and rotational modes.

There was no attempt to determine the heat capacity or temperature of the plasma during these experiments so it is not clear which internal diameter allowed the cavity to resonate at 2450 MHz, thereby providing the “hottest” plasma. The fact that the plasma could be easily generated for diameters of 88 and 78 mm, with nitrogen and argon as the discharge gas respectively, implies that the plasmas generated from these two gases have different properties and so behave differently.
As it happens, the I.D. of the cavity is only critical if there are no matching elements in the microwave network since a reasonable match for most I.D.'s was obtained by using a stub tuner arrangement. The maximum efficiency obtained for a cylindrical cavity was about 60% where the efficiency is defined as:

\[
\text{Efficiency} = \frac{\text{Forward Power} - \text{Reflected Power}}{\text{Forward Power}}
\]

It should be noted that there was no mechanism for fine tuning the resonant frequency of these cavities and this may well be the reason for the relatively low efficiency recorded.
<table>
<thead>
<tr>
<th>I.D.</th>
<th>60 MM CAVITY</th>
<th>100 MM CAVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BN</td>
<td>BN</td>
</tr>
<tr>
<td>50</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>52</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>54</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>56</td>
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</tr>
<tr>
<td>60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62</td>
<td>Y</td>
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</tr>
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</tr>
<tr>
<td>72</td>
<td>-</td>
<td>N</td>
</tr>
<tr>
<td>74</td>
<td>Y</td>
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</tr>
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<td>76</td>
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<td>Y</td>
</tr>
<tr>
<td>92</td>
<td>N</td>
<td>Y</td>
</tr>
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</table>
Table 7. Cylindrical cavity internal diameter/plasma data.

3.3 Rectangular Cavity Design.

A rectangular cavity with dimensions of 43x45x45 mm was constructed from aluminium and had two fine tuning stubs. The first stub was aligned parallel with the broadwall of the attached waveguide and was positioned mid wall. The second was aligned parallel with the short-wall of the attached waveguide as shown in Figure 65. This cavity is similar in design to that of Matusiewicz [34] in as much as the cavity is attached to a section of standard waveguide and has smaller dimensions than that of the waveguide. However, the method of tuning is different as an inductive iris is not used in the design detailed here.
The dimensions for this cavity were determined from measurements taken from the cylindrical cavity case whilst a plasma was being generated and fine tuned using the network analyser. It was not possible to generate a plasma with this configuration at any power level or with any ionisation chamber or gas. The principal reason for this is that the dimensions of the cavity are below cutoff and hence the microwaves do not propagate into the cavity with sufficient power to create and maintain a plasma. Figure 66 is a network analyser plot of the rectangular cavity showing the resonance characteristics both for an empty cavity and for the cavity with a boron nitride ionisation chamber. The cavity was tuned to resonate at 2450 MHz whilst empty by use of the two tuning stubs and then the resonance data recorded. The ionisation chamber was then placed in the cavity and the resonance data recorded again. As can be quite clearly seen from Figure 66, the resonant frequency of the cavity has dropped by just under 100 MHz and the attenuation by 15 dB with the insertion of the dielectric. When the plasma is initiated, the resonant frequency will change again. As previously mentioned, it was not possible to generate a plasma when the cavity was tuned to 2450 MHz with the ionisation chamber in place.
Figure 66. Resonance characteristics of the rectangular applicator. N.B. x-axis units are Frequency (100 MHz/division) and y-axis units are Attenuation (10 dB/division).

3.4 Waveguide Cavity Design.

A schematic diagram of the rectangular waveguide applicator is given in Figure 67. As can be seen from the diagram, the applicator is a section of waveguide fitted with a sliding short circuit, or movable tuning plunger, with the ionisation chamber passing centrally through the broadwall of the waveguide.

Figure 67. Schematic diagram of the WR340 waveguide applicator
Microwaves enter the cavity via an aperture or iris and are reflected from the plunger at the rear of the cavity where boundary conditions require the electric field to be zero. The plasma is easiest to initiate when the superposition of forward travelling and reflected waves produce a maxima centred on the ionisation chamber. Once the plasma has been initiated, the plunger position is adjusted to give a minimum of reflected power. The adjustment means that the conditions necessary for matching efficiently to, and maintaining a plasma are different from those necessary to initiate one. This agrees with theory since the resonant frequency of a cavity will change when any dielectric, such as a plasma, is added. Figure 68 shows the change in standing wave pattern for a waveguide applicator with and without a plasma. The $\pi$ phase change in the standing wave pattern is due to a change in sign of the load impedance, i.e. the resonance point has been passed.

Figure 68. Standing wave pattern for the waveguide applicator both with and without plasma. Forward CW microwave power = 2.0 kW.
A series of irises was constructed in an attempt to obtain a better match between the microwave source and the load. However, because the load is dynamic in nature, a unique iris would be necessary to match the load to the source for each operating condition. Although achievable, this is far from desirable.

<table>
<thead>
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<th>No Iris (86X43 MM)</th>
<th>Forward Power (W)</th>
<th>Reflected Power (W)</th>
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</thead>
<tbody>
<tr>
<td>With Plasma</td>
<td>2200</td>
<td>~ 0</td>
</tr>
<tr>
<td>Without Plasma</td>
<td>1500</td>
<td>1400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Resonant Iris (28.6 X 14.24 MM)</th>
<th>Forward Power (W)</th>
<th>Reflected Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Plasma</td>
<td>2100</td>
<td>1200</td>
</tr>
<tr>
<td>Without Plasma</td>
<td>2000</td>
<td>1100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonant Iris (61.5X5 MM)</th>
<th>Forward Power (W)</th>
<th>Reflected Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Plasma</td>
<td>4000</td>
<td>~ 0</td>
</tr>
<tr>
<td>Without Plasma</td>
<td>1350</td>
<td>1250</td>
</tr>
</tbody>
</table>

Table 8. Forward and reflected power for a selection of irises.

Table 8 gives the forward and reflected power for three of the irises constructed both when generating a plasma, and when no plasma was present. The dimensions for the non-resonant iris and resonant irises were 28.6 x 14.24 mm and 61 x 5 mm respectively. A resonant iris can be used to match a load to a waveguide much like an LC circuit can be used to extract maximum power out of a 50Hz power system. That is, they
resonantly remove reactance and transform resistance to matched values. By its nature, the waveguide cavity represents a complex frequency dependent load, the reactance of which will be essentially much the same as if the cavity was unloaded. However, the resistive component will depend greatly on the load. It should be possible to minimise reflection of incident microwave energy by selecting an appropriate iris that cancels the reactive component. In doing so the resistive component will be modified. As can be readily seen from Table 8, an iris is not necessary as the waveguide applicator is well matched without one. For this reason, and the fact that a separate iris would be necessary for each operating condition due to the dynamic nature of the load, it was decided to proceed without an iris and as such this avenue of investigation was abandoned.

The waveguide applicator shown in Figure 67 operated routinely with efficiencies of 98% without the need for a matching aperture or iris. The data presented in Figure 69 is for an argon discharge gas with a flow rate of 7.5 litres/min and 600 W CW microwave power. The peak efficiency represented here is approximately 98.5%. It is evident from this Figure just how critical the tuning plunger position is on the matching characteristics. The ability to match the load so effectively to the source for any operating condition means the coupling aperture can be dispensed with altogether. Although this applicator design proved successful in generating and sustaining a microwave plasma, it was limited in functionality to sustained operation below 700 W of CW microwave power. This threshold could be increased to approximately 1 kW of CW power if the ionisation chamber was forced-air cooled. Sustained operation above these power levels led to the failure of the ionisation chamber due to the effects of thermal runaway or oxidation. Thermal runaway is a positive feedback condition
whereby the ability of the ceramic ionisation chamber to absorb microwave energy increases with temperature. As the ionisation chamber heats due to contact with the plasma, it becomes more electrically conducting and absorbs more microwave energy, which increases the temperature of the tube even further. The result is that the ionisation chamber eventually heats until the melting point is reached and then fails.

![Graph of Percentage reflected power and VSWR as a function of sliding short position.](image)

Figure 69. Percentage reflected power and VSWR as a function of sliding short position.

### 3.5 Water-Cooled Waveguide Cavity Design.

To overcome the problem of thermal runaway, a more efficient mechanism for heat removal was required. The opportunity arose [45] to discuss the cooling methods of Arata et al [16] with Professor Shoji Miyake from the Japanese Welding Research Institute. Though the cooling methods employed in the research of Arata were for determining the heat loss through the walls of the ionisation chamber, using calorimetric methods, it was reasoned that a similar method could be used to remove the heat from
the ionisation chamber thereby preventing thermal runaway. It was uncertain whether such a manner could be employed since the applicator design and more importantly, the ionisation chamber I.D., were different from those of Arata. As mentioned in Section 1.3, a helical gas flow in the ionisation chamber (10 mm I.D.) of Arata produced a cold gas wall that prevented the plasma from coming into contact with the ionisation chamber. As the ultimate goal of this research was to produce an applicator capable of welding sheet steel, the 10 mm I.D. ionisation chamber of Arata would be far from desirable. In addition, it would be extremely unlikely that one could create a helical flow of gas inside a ionisation chamber with an I.D. of only 1 – 3 mm and so produce the cold gas wall.

![Diagram of waveguide applicator](image)

Figure 70. Water cooled waveguide applicator.

The waveguide applicator was modified to determine whether it was possible to initiate and sustain a plasma inside an annulus of water. The modifications are reflected in Figure 70 (compare Figure 67). For the initial experiment CW microwave power was varied between 0.3 and 1.6 kW and the argon discharge gas flow rate set at 7.5 l/min. Pyrex was used for the ionisation chamber and had dimensions of 3.44 x 5.10 mm (I.D.
x O.D.). The water-jacket tube had dimensions of 6.24 x 8.10 mm (I.D. x O.D.), giving an annulus of water 0.57 mm thick surrounding the ionisation chamber. The water flow was started and then the plasma successfully initiated. The temperature of the cooling water increased as would be expected. If the water flow was stopped and then restarted after about 5 seconds, the ionisation chamber would shatter due to thermal shock. This did not occur when the ionisation chamber was quartz as thermally, quartz is very robust. This result, the ability to generate and sustain a plasma inside an annulus of water, is counterintuitive since water is such a good receptor of microwave energy and one would expect the electric field strength at the centre of the ionisation chamber would be insufficient to sustain the plasma. Indeed, the plasma is seen to diminish in intensity as the thickness of the water annulus is increased. Following the success of the initial experiment, it was decided to repeat the experiment with differing cooling water annulus thickness.

Table 9 gives the water-jacket and ionisation chamber diameters along with annulus thickness and the volume of water contained within the waveguide applicator. This data, except for row 2, was generated using a CW microwave power of 800 W and an argon plasma gas flow rate of 7.5 l/min. Row 2 was generated with microwave powers between 300 and 1600 W. As can be seen, it was possible to generate a plasma even when the ionisation chamber was surrounded by an annulus of water 4 mm thick. This plasma however, was somewhat diminished both in length and intensity compared to the plasma generated when no coolant was present.
Table 9. Experimental water-jacket thickness data.

The final design of the water cooled waveguide applicator was drawn from many elements of the experimental programme, not the least the success of the water cooled ionisation chamber, and needed to take into account the operational requirements necessary for welding sheet steel. The design, as given in Figure 71, employs a counter current coolant flow in which the coolant flows past the hottest part of the ionisation chamber first. The coolant enters through the bottom of the waveguide and travels along a small diameter brass tube before reaching the void between the coolant jacket and the outside of the ionisation chamber near the plasma exit orifice. The coolant then travels along the ionisation chamber and exits through a quick-fit connector at the top of the applicator. The other advantage of counter current cooling is that the water-jacket
fills from the bottom up, thereby minimising possible air voids. This is especially important if the annulus thickness, the distance between the O.D. of the ionisation chamber and the I.D. of the coolant or water-jacket, is small. The coolant is contained by Viton O-ring seals between the outside of the quartz coolant jacket and the applicator body. The coolant is prevented from leaking into the plasma region by a taper lock fit between the ends of the ionisation chamber and the applicator body. A compressive force is applied to the taper lock by an adjustable brass face-plate at the plasma exit orifice.

Figure 71. Final design of the water cooled waveguide applicator.

The discharge gas enters the applicator through a quick-fit connector and then passes through a constricting baffle before entering the ionisation chamber to be ionised and ejected as a plasma. The purpose of the constricting baffle is twofold. Firstly, the gas feed hole can be angled and offset to optimise gas flow dynamics within the ionisation chamber. And secondly, the small diameter gas feed hole ensures that the plasma only
flows out through the exit orifice and not back along the gas feed line. The plasma is initiated by a momentary insertion of the spring loaded initiating plunger into the waveguide. No microwave leakage occurs during this action because the plunger is in intimate contact with the applicator body which is at earth potential.

The ionisation chamber in the ultimate design was fashioned from pure boron nitride and had an I.D. and O.D. of 3 mm and 15 mm respectively. The coolant jacket was fashioned from quartz and had an I.D. and O.D. of 16 mm and 19 mm respectively. This gave an annulus thickness of 0.5 mm which was more than adequate for a 6 kW plasma when coolant flow rates were of the order of 0.5 litres/minute. An attempt to use alumina for the ionisation chamber in this design was abandoned because the tube would shatter due to thermal shock whenever the plasma was initiated. Figure 72 and Figure 73 show the dismantled applicator with elements of the cooling system. Specifically, in Figure 72 the alumina ionisation chamber and cooling jacket are visible as are the coolant feed, gas manifold and associated brass componentry. Figure 73 shows the general arrangement of the applicator without the top plate, ionisation chamber and gas feed system. The tuning plunger is clearly visible, as is the water feed line and microwave transparent window. The applicator sits atop an atmospheric control vessel of I.D. 400 mm. This vessel houses the welding table and allows welding in a controlled atmosphere or at reduced pressure. It also has a viewing window to monitor welding progress.
Figure 72. Photograph of the waveguide applicator cooling system components.

Figure 73. Photograph of dismantled applicator with welding vessel.
Figure 74. Photograph of assembled waveguide applicator with welding vessel.

Figure 75. Photograph of the waveguide applicator operating at 5.25 kW.
Close-up detail of the assembled applicator without the welding vessel can be seen in Figure 75. This photograph shows the applicator generating a 5.25 kW plasma beam with an argon discharge gas flow rate of approximately 5 litres per minute. As can be seen from this photograph, the plasma beam is well collimated over a length in excess of 220 mm.

The efficiency of the water-cooled waveguide applicator was no different from that of the non cooled version. For example, it was possible to adjust the reflected power down to 10 W with a forward microwave power of 3 kW. This gives an efficiency in excess of 99.5%. It should be noted however that this efficiency does not take into account losses to the walls.

3.6 Conclusion.

Attempts at producing a cylindrical resonant cavity applicator suitable for materials welding and joining applications were unsuccessful. The use of rapid prototyping, a network analyser and high power tests showed that the maximum efficiency attainable for the investigated cavity design was only 60%. Rapid prototyping of the cavity involved sculpting the desired cavity from Polystyrene foam and then wrapping it in conducting aluminium tape. When examined using the network analyser, these prototypes behaved as machined aluminium cavities would but take a fraction of the time to construct. Being made from foam however, meant that operation was limited to low power tests only. The low power limitation meant that it was not possible to use the network analyser to model the cavity whilst generating a plasma. To overcome this, a method was developed whereby a small diameter brass tube was used to simulate the
plasma for the low power tests. The dimensions of the brass tube were selected such that it gave the same VSWR and load phase impedance when examined on the network analyser. Rapid prototyping of the cavity as well as simulation of the plasma by a brass insert allowed the electrical properties of the cavity to be determined at low powers.

High power tests were performed on a 100 mm long cavity fashioned from aluminium. The internal diameter of the cavity started at 60 mm and was increased in 2 mm steps until it reached 92 mm. For each of these increments a high power test was performed. Results of these measurements showed that it was possible to generate a plasma for each I.D. when using argon as the discharge gas. Results also showed that it was not possible to spontaneously generate a plasma in argon using a cylindrical cavity. The electric field strength of the microwaves in the cavity is insufficient to cause dielectric breakdown in argon and thus, a secondary mechanism is necessary to initiate the plasma. In the case of pulsed power and an impure boron nitride ionisation chamber, this mechanism was thermionic emission of electrons from the heated tube. For the case of CW microwave power and either quartz or pure boron nitride as the ionisation chamber, it was necessary to insert a length of tungsten wire into the ionisation chamber to initiate the plasma.

It was also not possible to generate a plasma in a rectangular cavity with dimensions 45 x 45 x 43 mm because the dimensions are below cut-off and thus, insufficient microwave energy penetrates the cavity to sustain a plasma. Previous attempts by researchers at producing high power plasmas in cavities with small diameter ionisation chambers have resulted in failure due to materials limitations. In effect, the ionisation chambers have melted due to thermal runaway. However, the task of designing,
building and testing a microwave plasma applicator that is suitable for welding and joining applications has been successfully completed using a waveguide applicator. The applicator is efficient, stable, operates at high powers and produces a highly collimated plasma beam and is shown operating at 5.25 kW in Figure 75. Routine efficiencies are greater than 98% without the use of a coupling aperture or iris and extended operation at microwave power levels of 6 kW is possible.

Previous to the development of this device, power levels for comparable applicators were limited to sustained operation below about 1 kW. The design detailed here is revolutionary in that it uses a small diameter, water cooled ionisation tube to produce a high power collimated beam. As shown in Table 6, a systematic investigation of these operating parameters is all but absent from the literature. Indeed, this is the first time that a high power plasma generated in a small diameter ionisation chamber has been demonstrated.
CHAPTER 4. CHARACTERISATION OF THE PLASMA/APPLICATOR SYSTEM.

4.1 Introduction.

Welding has been an accepted method for joining disparate samples for many years with welding techniques and parameters being optimised through trial and error methods. In essence, welding is still classified as a black art since many processes are not well understood. As the use of a microwave induced plasma beam as a welding tool is absent from the literature, much work at characterising the beams properties as a function of external parameters is necessary. This chapter deals with the characterisation of the plasma/applicator system. Specifically, the way the applicator responds to external variables such as power, gas flow rate, applicator tuning etc. is characterised as this information is essential to produce a device capable of consistent, high quality welding. To that end, the research covered can be broadly divided into two sections. The first deals with the electrical properties of the plasma and the second with determination of the physical parameters of the plasma such as length, pressure and temperature. The purpose of the applicator is to produce a well-collimated beam of plasma into which is deposited as much microwave power as possible to produce a practical welding tool. The amount of power deposited in the plasma is a measure of the efficiency of the applicator and can be determined by measuring the VSWR of the system. This means it is necessary to have a thorough understanding or knowledge of what governs, controls and characterises the VSWR so that the applicator can be operated at maximum efficiency.
Section 4.2 deals with the background theory of VSWR and how it relates to the microwave power travelling within the waveguide. Section 4.3 examines the VSWR of the non-cooled waveguide applicator, described in Section 3.4, as a function of the variables determining the operating characteristics of the plasma. It specifically covers microwave power, discharge gas flow rate and the state of tuning of the system. VSWR measurements on the slotted line also allow the plasma impedance to be determined, from which a simple electrical circuit model of the plasma/applicator system is developed, given in Section 4.4. Section 4.5 examines the real and imaginary impedance of the plasma as a function of the same variables that determine the operating characteristics of the plasma listed above.

Section 4.6 and 4.7 investigates the VSWR and impedance attributes of the plasma beam, respectively, as produced by the water-cooled applicator. The impedance attributes of the water-cooled and non-cooled plasma beam are compared to those reported in the literature in Section 4.8. The plasma beam length as a function of microwave power and discharge gas flow rate is shown photographically in Section 4.9. To overcome materials limitations associated with the limited operating range of thermocouples, two methods of indirect temperature determination were devised and are given in Section 4.10. These methods examined the heat capacity of the plasma as well as the relative plasma temperature using heat conduction phenomena and K-type thermocouples. Lastly, a differential pressure transducer was used to measure the pressure exerted by the plasma beam for the various operating parameters. These results are reported in Section 4.11.
4.2 Background Theory of VSWR.

When microwaves are incident on a waveguide discontinuity, part or all the microwave energy is reflected and a standing wave envelope or pattern is formed [46]. Figure 76 shows the standing wave pattern for the case where the reflected and incident waves have identical amplitudes. The distance separating successive voltage standing wave maxima or minima is half of the waveguide wavelength in the slotted section, $\lambda_{sg}$.

The Electric field and hence the voltage along a waveguide is of the form

$$E = E_0 \sin \left( \frac{2\pi d}{\lambda_{sg}} \right) \quad \text{or} \quad V = V_0 \sin \left( \frac{2\pi d}{\lambda_{sg}} \right)$$

The maximum value of the standing wave envelope corresponds to the sum of the amplitudes of the incident and reflected waves, whilst the minimum corresponds to the difference between the two. By sampling the microwave power along the slotted
section, the position of the voltage maxima and minima in relation to the load distance can be determined. The VSWR is then given as

\[ VSWR = \frac{E_{\text{max}}}{E_{\text{min}}} \]

The ratio of the reflected wave to the incident wave is defined as the reflection coefficient, \( \rho \). In terms of the VSWR, the magnitude of the reflection coefficient is given by

\[ \rho = \frac{VSWR - 1}{VSWR + 1} \]

In general, the standing wave envelope is not a sine curve, the minimum being sharper than the maximum [47]. However, in the limiting case of \( \rho = 1 \) the curve does have the form of a rectified sine function. Also, as the condition \( \rho = 0 \) is approached, the curve approximates a sinusoidal variation.

4.3 VSWR Measurements on the Non-Cooled Waveguide Applicator.

This section presents data obtained using the non-cooled waveguide applicator with CW microwave radiation and argon as the discharge gas. The experimental set-up is shown schematically in Figure 77. The data used to determine the VSWR was gathered using the following procedure:

a) The plasma was initiated and the microwave power adjusted to the desired level.
b) The tuning plunger and then the tuning stubs adjusted to give a minimum reflected power.

c) The probe was inserted into the slotted section as close as possible to the load and the resultant power measured.

d) The power level at the probe and the probe position recorded. The power recorded is the resultant power from superposition of forward and reflected microwaves within the waveguide. It is not the power as set in step a), which is the total forward power.

e) The probe was then repositioned in slotted section 5 mm further away from the load (ionisation chamber).

f) The power level and the probe position was recorded again.

g) The process of repositioning and measuring the power level was repeated for the full length of slotted section, approximately 200 mm.

![Figure 77. Schematic diagram of experimental apparatus.](image)

This data, when plotted as the square root of the power as a function of slotted section reading (or standing wave scale), typically gives results as shown in Figure 78. The data labelled by VSWR=1.3 is typical of the VSWR curve for the case where the source and load are mismatched. The VSWR=1.1 curve may indicate the presence of higher order modes generated at the load. These higher modes are cut off and are therefore
evanescent. Their fields however, extend a fraction of a wavelength away from the load and add to the reactive component of the load. It is possible that the TE20 or more likely the TE30 mode may be present. The TE30 mode is more likely as it has a maximum in electric field strength centered on the broadwall of the waveguide (in a similar manner to the TE10 mode). One also expects some non-uniformity because of imperfections in the sliding probe and the generation of second, third and higher order harmonics by the plasma. These harmonics are generated since plasma can act as a non-linear medium.

![Figure 78. Standing wave pattern for the non-cooled waveguide applicator and a 2.0 and 2.4 kW plasma.](image)

The ionisation chamber used during this experiment had an O.D. and I.D. of 10 and 7 mm respectively, and was fashioned from impure boron nitride. Boron nitride has a working temperature [48] of approximately 1100 Celsius in air/oxidising atmosphere. However, the working temperature is increased to approximately 1800 Celsius in a
reducing/inert atmosphere. The thermal ruggedness of the boron nitride ionisation chambers allowed experiments to be performed in excess of the working temperature with the realisation that replacement would be necessary after a few hours due to oxidation.

Figure 79. Standing wave pattern for the non-cooled waveguide applicator both with and without a plasma.

The results in Figure 79 indicate a small change in load impedance phase with power. The fact that the “no plasma” results are a quarter wavelength shifted from the “with plasma” results indicates that the respective impedances are conjugate, i.e. the standing wave patterns for a short and open circuit are identical with VSWR=∞, but the patterns are a quarter wavelength shifted. The electric field values for the no plasma case are scaled down by a factor of ten. The approximate sinusoidal form of the two “with plasma” cases indicates that the reflected waves have a smaller amplitude than the incident waves (leading to the observed VSWR pattern).
Figure 80 is a most informative graph. The results indicate a steady change in the load impedance magnitude and phase as the sliding probe position is increased from 4 mm to 68.2 mm. The fact that the 75.2 mm results are almost a quarter wave shifted, from the 68.2 mm results, means that the impedance has changed sign, i.e. a resonance has been passed. The resonance point is the point where maximum power is being transferred to the plasma and the applicator is operating at peak efficiency. Knowledge of the resonance point is very important in applicator design since it is the ideal operating position for the applicator system. The ionisation chamber used in this experiment had an O.D. and I.D. of 8 and 5 mm respectively.

Figure 80. Standing wave pattern as a function of load-sliding short distance.
Figure 81 shows the VSWR as a function of load-sliding short distance for the waveguide applicator both with and without the plasma present and for a ionisation chamber with an O.D. and I.D. of 8 and 5 mm respectively. This graph accurately demonstrates the resonance previously mentioned as does Figure 88. In fact, there is a shift in resonance of approximately 4 mm between the "with plasma" and "no plasma" cases signifying an increase in the resonant frequency of the cavity when the plasma is present. Also note the sharpness of the resonance dip in the "no plasma" graph compared to the "with plasma" graph. This sharpness reveals that the quality factor of the cavity, Q is greater in the absence of a plasma. A broad resonance peak is of benefit when constructing an applicator since cavity dimensions are not as critical and the applicator is less sensitive to drifts in the driving frequency.

Figure 82 shows the VSWR as a function of microwave power for powers between 2.0 and 3.4 kW. The discharge gas was argon with a flow rate of 15 litres per minute and
the O.D. and I.D. of the ionisation chamber was 9.6 mm and 6.0 mm respectively. As
can be seen from the graph, the VSWR appears to have a slight dependence on
microwave power and decreases by about 5% from a power of 2.0 kW to a power of 3.4
kW. This result is significant since it means the applicator does not have to be re-tuned
if the operating power is altered. However, this dependence may be a function of the
way in which the experiment was performed since the applicator was not re-tuned for a
minimum reflected power after each increment of forward power. This issue of re-
tuning after each alteration in operating conditions is addressed during VSWR
determination experiments found later in this Chapter. In operation, it is very difficult
to tune the applicator accurately since a small change in the sliding short position can
lead to a dramatic change in the VSWR as can be seen from Figure 81.

![Figure 82. VSWR as a function of microwave power.](image)
Figure 83 shows the VSWR as a function of discharge gas flow rate for flow rates of between 5.0 and 37.5 litres per minute. Again the discharge gas was argon and the O.D. and I.D. of the ionisation chamber was 9.6 mm and 6.0 mm respectively. This graph shows a definite discontinuity in the curve occurring at a gas flow rate of 30 litres per minute. This discontinuity was due to a partial failure of the ionisation chamber because of oxidisation from operation at elevated temperatures. As can be seen from Figure 83, the VSWR increases almost linearly with gas flow rate. Again, this dependence may not represent the true effect since the applicator was not re-tuned after each increment in gas flow rate. What this Figure does show however, is that the plasma does change its behaviour with increasing gas flow rate when no other parameters are varied.

An important note should be made here. Whenever quantitative experiments are to be performed, it is imperative that the system is re-tuned after each variation in external
conditions otherwise ambiguities can occur in the experimental data that lead to erroneous conclusions. To overcome any ambiguity that may be evident in Figure 82 and Figure 83, both experiments were redone and the results given in Figure 84 and Figure 85. During the experiment, each time the power or gas flow rate was incremented, the applicator was re-tuned to give a minimum in reflected power. This ensures that variations in VSWR are a result of changes in power or gas flow rate and not a result of cavity detuning. The results given in Figure 82 and Figure 83 are still important since in practice one can still get these variations and conditions without re-tuning.

![Graph](image)

**Figure 84.** VSWR as a function of microwave power for a re-tuned cavity.

In Figure 84, the VSWR appears to increase to a plateau as the power is increased. This may be because of a levelling-off of one of the plasma parameters such as temperature or even as a result of non-linear heating with power of the ionisation tube. Figure 85 reveals the linear dependence of VSWR on discharge gas flow rate. Neglecting the
wayward points corresponding to 5 and 25 litres per minute, a linear fit to the data points yields an $R^2$ value for this curve of 0.95. The decrease of VSWR with increasing gas flow rate may be due to the cooling effect of the extra gas or the altering of the gas flow dynamics with increasing flow rate. Regardless of the mechanism, the trend in Figure 85 is unmistakable.

![Figure 85. VSWR as a function of discharge gas flow rate for a re-tuned cavity](image)

The data given in Figure 82 and Figure 84 shows well the ambiguity that can occur when the system is not re-tuned between each experiment. To reveal the true nature of the effect of power on VSWR, the following experiment was performed. The microwave power was set at a predetermined level, the sliding short at a predetermined position and the VSWR recorded. The sliding short position was incremented 0.3 mm closer to the resonance point and the VSWR recorded again. This process of increment and measure was repeated until the resonance point had been passed. The sliding short was re-zeroed and the microwave power level incremented to a new value. The process
of measuring the VSWR at various sliding short positions was repeated and the power level readjusted. This was repeated for power levels between 500 and 1300 W.

Figure 86 represents the VSWR as a function of power for two sliding short positions. These two positions are located on either side of the resonance point. Only two data sets out of the nine generated are given in Figure 86 to illustrate the trend shown. Also represented on Figure 86 are two linear regression lines corresponding to the two data sets. Clearly, on either side of the resonance point the slopes of the regressions are opposite. This point is expanded further by Figure 87.

Figure 86. VSWR as a function of power for two sliding short positions.

Figure 87 contains the regression lines from Figure 86 as well as the regression lines for another seven sliding short positions. To keep this graph as clear as possible, the experimental data points have not been plotted (the points shown are curve identifiers as used in the legend). The starting and finishing positions for the sliding short were 78.0
mm and 80.7 mm. From Figure 87, we see that the slope of the regression is positive for a sliding short position of 78.0 mm. As the sliding short is moved closer to the resonance position, not only does the slope become less positive but the VSWR is also reduced for a given power level. Once the resonance point has been passed, the slope of the regression takes on an ever larger negative value and the VSWR for a given power level increases. The change in magnitude of the VSWR leading to, and beyond the resonant point is wholly consistent with the data shown in Figure 81 and Figure 89.

This experiment was done with an argon discharge gas flow rate of 15 litres per minute and a 9.6 x 6.0 mm (O.D. x I.D.) ionisation chamber.

Figure 87. VSWR as a function of power for nine sliding short positions.
Figure 88. Voltage maxima position as a function of sliding short-load distance.

The data in Figure 88 was generated using argon as the discharge gas with a flow rate of 7.5 litres per minute and a ionisation chamber with an O.D. and I.D. of 9.6 and 6.0 mm respectively. The microwave power was set at 700 W and not altered for the duration of the experiment. The sliding short-load distance was set at 70 mm and the position of a voltage maximum on the slotted scale recorded. The sliding short was then moved a quarter turn, 0.31 mm, closer to the load and the position of the same voltage maxima recorded. This procedure was repeated until the sliding short-load distance was 85.5 mm. This span was necessary to encapsulate the resonance condition which, from Figure 88, occurred at a sliding short-load distance of approximately 79.9 mm. Note that the location of the resonance condition in Figure 88 is different from that in Figure 81. This is because of a number of factors, such as ionisation chamber dimension, discharge gas flow rate and microwave power level. Specifically, for Figure 81 the values for each were 8 x 5 mm, 20 l/min and 2.2 kW and Figure 88 the values were 9.6 x 6 mm, 7.5 l/min and 700 W.
A hitherto unmentioned benefit of the cavity applicator over the coaxial applicator is the reduced leakage of microwave radiation. Prior to striking a plasma, the coaxial applicator is essentially just an antenna radiating into free space. The situation does not change drastically after the plasma has been struck. The effect of the plasma is to reduce the radiated levels of microwave radiation as this radiation loses energy to the plasma. For the case of the cavity applicator, no microwave radiation escapes when there is no plasma since the microwaves are completely enclosed within the cavity. After the plasma has been initiated, the radiated levels of microwaves increase due to the finite conductivity of the plasma. Were the plasma to be a perfect conductor then it would act as an efficient antenna, or a waveguide to coaxial transition, and radiate microwave energy from within the cavity to free space. To determine the effect of these radiative losses on the plasma properties, the plasma exit orifice and the discharge gas inlet were fitted with chokes. The plasma was then initiated and the VSWR determined as a function of load-sliding short distance. The results, shown in Figure 89, are for a ionisation chamber with an O.D. and I.D. of 9.6 and 6.0 mm respectively. The discharge gas was argon with a flow rate of 7.5 litres per minute and the microwave power level was set at 700W. As can be readily seen from Figure 89, the external chokes had no effect on the VSWR measured. This result is important since it means that an effective microwave plasma welder can be fitted with chokes to minimise microwave leakage without impacting on the operational characteristics of the device.
In summary, Section 4.3 has shown:

- The applicator has a resonant operating condition that corresponds to maximum power transfer from the microwave field to the plasma and this resonant condition is different for differing cavity configurations.

- The applicator resonance peak broadens in the presence of a plasma which is of benefit when constructing an applicator since the cavity dimensions are not as critical and the applicator is less sensitive to drifts in the driving frequency.

- The plasma changes its behaviour in response to changing external conditions. Specifically, for a tuned system the VSWR of the plasma/applicator system decreases with increasing discharge gas flow rate. The VSWR of the plasma/applicator system as a function of microwave power shows a complex relationship that depends on the state of tuning of the applicator. That is, the VSWR increases with power on one side of the resonance point whereas it decreases with increasing power on the other side.
• External chokes have no effect on the plasma properties and hence the measured VSWR. This is an important practical result since it means that an effective microwave plasma welder can be fitted with chokes to minimise microwave leakage without impacting on the operational characteristics of the device.

4.4 Electric Circuit Model of the Waveguide Applicator.

To model the electrical properties of the plasma/applicator system, it is necessary to measure the VSWR as a function of load-sliding short distance, \( L_s \). This involves not only measuring the load-sliding short distance and minimum and maximum field intensities but the positions of those minima and maxima with respect to the load.

![Electrical circuit representation used in microwave plasma diagnostics.](image)

Figure 90. Electrical circuit representation used in microwave plasma diagnostics.

Once the VSWR and the distance to the load, \( d \), are known (shown schematically in Figure 90), a Smith Chart is employed to determine the impedance of the load as seen from the point \( A-A \). Combining this with knowledge of how the plasma behaves electrically will then allow an electrical circuit analogue to be developed.
Once the data has been plotted on the Smith chart and the normalised load impedance, $Z_{\text{Load}}$, and load admittance, $Y_{\text{Load}}$, determined, all that is needed is to subtract the admittance presented by the sliding short, $Y_{\text{Stub}}$, from the load admittance to give the plasma admittance, $Y_{\text{Plasma}}$. i.e.

$$Y_{\text{Load}} = \frac{1}{Z_{\text{Load}}} = Y_{\text{Plasma}} + Y_{\text{Stub}}$$

The data used to derive the electrical circuit model of the plasma/applicator system is shown graphically in Figure 91. An alumina ionisation chamber with an O.D. and I.D. of 9.6 and 6.0 mm respectively was used for this experiment.

Figure 91. Percentage reflected power and VSWR as a function of sliding short position.

This data has been plotted on the Smith Chart shown in Figure 92 along with reference points denoting the starting and finishing points of the sliding short circuit traverse.
Recall that the sliding short circuit is at zero on the "load-sliding short distance" scale and that the distance between the load and the sliding short circuit is denoted by \( L_s \). In Table 10, \( L_s \) and VSWR were experimentally measured, \( Z_{\text{Load}} \) and \( Y_{\text{Load}} \) determined from the Smith Chart shown in Figure 92, and \( Y_{\text{Stub}}, Y_{\text{Plasma}}, \) and \( Z_{\text{Plasma}} \) calculated using

\[
Y_{\text{Stub}} = -j \cot(\beta L_s) \quad \text{and} \quad \beta = \frac{2\pi}{\lambda_g}
\]

where \( \lambda_g \) is the waveguide wavelength.
Figure 92. Smith Chart showing normalised input impedance as a function of load-sliding short distance.
<table>
<thead>
<tr>
<th>$L_s$ (mm)</th>
<th>VSWR (Meas.)</th>
<th>$Z_{Load}$ (Normalised)</th>
<th>$Y_{Load}$ (Normalised)</th>
<th>$Y_{Stub}$ -j$cot(\beta L_s)$</th>
<th>$Y_{Plasma}$ ($Y_{Load}$-$Y_{stub}$)</th>
<th>$Z_{Plasma}$ ($1/Y_{Plasma}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.0</td>
<td>4.40</td>
<td>0.295+0.540j</td>
<td>0.779-1.426j</td>
<td>2.132j</td>
<td>0.779-3.558j</td>
<td>0.059+0.268j</td>
</tr>
<tr>
<td>75.5</td>
<td>4.36</td>
<td>0.300+0.535j</td>
<td>0.797-1.422j</td>
<td>2.236j</td>
<td>0.797-3.658j</td>
<td>0.057+0.261j</td>
</tr>
<tr>
<td>76.0</td>
<td>4.07</td>
<td>0.340+0.595j</td>
<td>0.724-1.267j</td>
<td>2.348j</td>
<td>0.724-3.615j</td>
<td>0.053+0.266j</td>
</tr>
<tr>
<td>76.5</td>
<td>3.78</td>
<td>0.375+0.615j</td>
<td>0.723-1.185j</td>
<td>2.471j</td>
<td>0.723-3.656j</td>
<td>0.052+0.263j</td>
</tr>
<tr>
<td>77.0</td>
<td>3.50</td>
<td>0.430+0.670j</td>
<td>0.678-1.057j</td>
<td>2.605j</td>
<td>0.678-3.662j</td>
<td>0.049+0.264j</td>
</tr>
<tr>
<td>77.5</td>
<td>3.10</td>
<td>0.575+0.805j</td>
<td>0.588-0.823j</td>
<td>2.752j</td>
<td>0.588-3.575j</td>
<td>0.045+0.275j</td>
</tr>
<tr>
<td>78.0</td>
<td>2.83</td>
<td>0.580+0.730j</td>
<td>0.667-0.840j</td>
<td>2.915j</td>
<td>0.667-3.755j</td>
<td>0.046+0.258j</td>
</tr>
<tr>
<td>78.5</td>
<td>2.55</td>
<td>0.665+0.730j</td>
<td>0.682-0.749j</td>
<td>3.096j</td>
<td>0.682-3.845j</td>
<td>0.044+0.249j</td>
</tr>
<tr>
<td>79.0</td>
<td>2.07</td>
<td>0.910+0.715j</td>
<td>0.679-0.534j</td>
<td>3.298j</td>
<td>0.679-3.828j</td>
<td>0.045+0.253j</td>
</tr>
<tr>
<td>79.5</td>
<td>1.70</td>
<td>1.110+0.570j</td>
<td>0.712-0.366j</td>
<td>3.525j</td>
<td>0.712-3.891j</td>
<td>0.046+0.249j</td>
</tr>
<tr>
<td>80.0</td>
<td>1.28</td>
<td>1.280+0.020j</td>
<td>0.781-0.012j</td>
<td>3.784j</td>
<td>0.781-3.796j</td>
<td>0.052+0.253j</td>
</tr>
<tr>
<td>80.5</td>
<td>1.46</td>
<td>0.930-0.350j</td>
<td>0.942+0.354j</td>
<td>4.080j</td>
<td>0.942-3.726j</td>
<td>0.064+0.252j</td>
</tr>
<tr>
<td>81.0</td>
<td>2.53</td>
<td>0.498-0.450j</td>
<td>1.105+0.999j</td>
<td>4.423j</td>
<td>1.105-3.424j</td>
<td>0.085+0.265j</td>
</tr>
<tr>
<td>81.5</td>
<td>4.51</td>
<td>0.226-0.215j</td>
<td>2.323+2.210j</td>
<td>4.826j</td>
<td>2.323-2.616j</td>
<td>0.190+0.214j</td>
</tr>
<tr>
<td>82.0</td>
<td>11.66</td>
<td>0.088-0.115j</td>
<td>4.190+5.507j</td>
<td>5.305j</td>
<td>4.190+0.205j</td>
<td>0.238-0.012j</td>
</tr>
<tr>
<td>82.5</td>
<td>14.53</td>
<td>0.070-0.062j</td>
<td>8.005+7.091j</td>
<td>5.886j</td>
<td>8.005+1.204j</td>
<td>0.122-0.018j</td>
</tr>
<tr>
<td>83.0</td>
<td>16.40</td>
<td>0.060-0.007j</td>
<td>16.44+1.918j</td>
<td>6.604j</td>
<td>16.44-4.684j</td>
<td>0.056+0.016j</td>
</tr>
</tbody>
</table>


Note that the plasma admittance, as given in Table 10, contains an inductive component that, except near resonance, remains essentially unchanged with stub position and can be interpreted as the inductive component of the plasma column. Measurements of the electrical impedance of the plasma column enabled the simple electrical circuit model of
the plasma/applicator system given in Figure 93 to be developed. The purpose of the stub is to cancel the plasma inductance. \( L_s \), being longer than a quarter wavelength means the stub reactance is capacitive as indicated in Figure 93. When the stub length is 80 mm, the total load admittance is real and of value \( Y_{Load} = 0.78 \) indicating that the plasma column has a microwave resistance of approximately 28 \( \Omega \) [49]. At this point, the VSWR of the entire applicator system is 1.28 and more than 98% of the forward power is absorbed in the plasma. To complete the electrical analysis of the plasma, the impedance of the plasma at resonance is approximately \( Z_{Plasma} = 28 + 136j \Omega \).

It should be noted that the model given in Figure 93 is only valid whilst the VSWR remains below about 5. Once the VSWR becomes larger than this, the reactance of the plasma varies between small inductive and small capacitive values.

![Figure 93. Electric circuit model of the waveguide applicator.](image)

Using the method described by Alison [50], the normalised shunt susceptance of a perfectly conducting waveguide post is given by
\[ b_p \approx \frac{-2\lambda_g \sin^2\left(\frac{\pi x}{a}\right)}{a \ln\left(\frac{4a \sin\left(\frac{\pi x}{a}\right)}{\pi d} - 2 \sin^2\left(\frac{\pi x}{a}\right) - \left(\frac{\pi d}{2\lambda}\right)^2\right)} \]

where the dimensions are defined as:

![Diagram of dimensions](image)

Figure 94. Dimensions for inductive susceptance calculations.

Modelling the plasma column as a perfectly conducting wire of diameter 6 mm (equal to the inside diameter of the ionisation chamber) stretched across the waveguide and using,

1) \( \lambda_g = 0.1744 \) m
2) \( a = 0.086 \) m
3) \( b = 0.043 \) m
4) \( x = 0.043 \) m
5) \( \lambda = 0.1224 \) m
the calculated value for the inductive susceptance at resonance is -4.52. This compares quite favourably with the experimental value of -3.796, for example, the model predicts that a wire diameter of 5.07 mm, leads to a normalised susceptance at resonance identical to the experimentally determined value. This result further justifies the validity of the electrical circuit model of the plasma/applicator system given in Figure 93.

4.5 Plasma Impedance Measurements.

Following the method prescribed in Section 4.4 or the method of Ramo et al. [51], it is relatively straightforward to generate the plasma impedance as a function of the operating variables of the system. Figure 95 and Figure 96 give the real and imaginary normalised plasma impedance as a function of sliding short-load distance for the non-cooled waveguide applicator. This is a graphical representation of the data used to determine the electric circuit model of the plasma previously given in Table 10. As can be readily seen from Figure 95, the normalised real impedance of the plasma is approximately constant as resonance is approached. As resonance is passed, the impedance increases rapidly to achieve a maximum value approximately five times greater than when at resonance. We see from Figure 91 that this occurs where the VSWR starts to increase sharply. Figure 96 shows the effect on the imaginary component of the normalised impedance as the sliding short-load distance is varied. When the sliding short-load distance is 82 mm, the plasma is a purely resistive load and has a microwave resistance of approximately 140 Ω.

Figure 97 and Figure 98 give the normalised plasma impedance (real and imaginary respectively) as a function of microwave power. We see from these two graphs that the
real component of the plasma impedance decreases by approximately 30% over the microwave power range of 0.5-1.5 kW whereas the imaginary component is remarkably constant over the same range. The decrease in plasma impedance with increasing power is not unexpected since the plasma density increases with increasing power [52]. The increase in plasma density is just an increase in the number of ionised species capable of acting as electrical conductors which give a reduction in the resistance measured.

![Diagram of Normalised Plasma Impedance vs Sliding Short-Load Distance](image_url)

Figure 95. Normalised plasma impedance (real) as a function of sliding short-load distance.

Over the power range examined, the constant imaginary impedance indicates that the ability of the plasma to act as an inductive energy storage device does not change with power.
Figure 96. Normalised plasma impedance (imaginary) as a function of sliding short-load distance.

Figure 97. Normalised plasma impedance (real) as a function of microwave power.
Figure 98. Normalised plasma impedance (imaginary) as a function of microwave power.

Figure 99 and Figure 100 give the normalised plasma impedance (real and imaginary respectively) as a function of discharge gas flow rate for a 0.7 kW plasma. The results shown indicate that both the microwave resistance and the inductive reactance of the plasma increases with increasing gas flow rate. As will be shown later in this Chapter, the plasma temperature decreases with increasing flow rate thereby decreasing the number of charge carriers in the plasma which leads to an increase in microwave resistance of the plasma. The increase in the inductive reactance of the plasma in Figure 100 and the constant value in Figure 98 can be explained in terms of the gas density within the ionisation chamber. As the discharge gas flow rate is increased, the pressure and subsequently the gas density inside the ionisation tube increases. It is not unreasonable to hypothesise that the inductive reactance of the plasma is a function of gas density since a greater energy storage capacity would require a greater number of storage mediums. This cannot be the whole story however since as the temperature of
the plasma increases, with increasing power, one would expect the gas density to
decrease thereby reducing the reactance. This clearly does not happen in Figure 98 so
there may be more than one mechanism leading to the reactance of the plasma.

Figure 99. Normalised plasma impedance (real) as a function of discharge gas flow rate
for a 0.7 kW plasma.

Figure 100. Normalised plasma impedance (imaginary) as a function of discharge gas
flow rate for a 0.7 kW plasma.
4.6 VSWR Measurements on the Water–Cooled Waveguide Applicator.

Section 4.3 covered VSWR measurements on the non–cooled waveguide applicator and Section 4.4 considered the electric circuit model for the waveguide applicator derived from these measurements. This section presents VSWR data obtained for the water-cooled version of the waveguide applicator. Prior to commencing this phase of experimentation, a more stable and reliable magnetron power supply was purchased.

An estimation of experimental errors is also given where the word “estimation” is carefully chosen since it is very difficult to replicate some of the parameters that may affect the plasma properties for each experiment. For example, the rate of change of temperature of the applicator is dependent on radiative and convective losses to the surrounding atmosphere. As there was no control over the temperature, humidity or turbidity of the atmosphere, it is reasonable to assume that the data has systematic or non-estimatable errors. A source of random or non-estimatable error is the alignment of the short circuit tuning plunger. The plunger has copper beryllium fingers attached to the periphery to ensure a good electrical contact. As the direction of motion of the plunger is changed, play in the connecting shaft allows the face of the plunger to move out of square with respect to the waveguide. This misalignment could lead to noticeable errors if the plunger were located at the resonant position. For example, this may be the reason for the wayward data point in Figure 101 corresponding to 1.75 kW on the 3 litres/minute curve.
Figure 101. VSWR as a function of microwave power for 5 separate discharge gas flow rates.

Figure 101 represents the VSWR as a function of microwave power for discharge gas flow rates between 3 and 7 litres per minute. Without exception, the VSWR reduces with increasing power for a fixed gas flow rate. Error bars have been omitted from this Figure for clarity. Figure 102 shows the VSWR as a function of discharge gas flow rate for a 3 kW plasma. Two curves are represented as an indication of repeatability. Firstly, the VSWR was measured for a flow rate decreasing from 10 to 1 litres/minute and then the VSWR measured whilst increasing the gas flow rate from 1 to 10 litres/minute. These findings show that the curves are generally the same within the experimental limits and are also in agreement with the non-cooled applicator case. This result is important because it shows that within experimental limits the method of data collection has no bearing on the outcome of the experiment.
Figure 102. VSWR as a function of discharge gas flow rate for a 3 kW plasma.

4.7 Plasma Impedance Measurements on the Water–Cooled Waveguide Applicator.

This section is similar to Section 4.5 in that it deals with the plasma impedance as a function of external variables such as microwave power and discharge gas flow rate. However, the data presented here is for the water-cooled waveguide applicator whereas the data presented in Section 4.5 was for the non-cooled version. This difference was made obvious because the range over which either applicator can operate is different and thus some aspects of the data generated are not directly comparable between the two designs. Wherever possible however, comparable experimental data from each applicator is presented on the one Figure.

Figure 103 and Figure 104 show the normalised plasma impedance (real and imaginary respectively) as a function of discharge gas flow rate for a 3 kW plasma. Again, two sets of experimental data were generated. The first, by decreasing the gas flow rate from
10 to 1 litres/minute and the second, by increasing it from 1 to 10 litres/minute. As with Figure 102, the results for the two curves on each of these Figures are in general agreement within experimental error. The normalised plasma impedance (real), as shown in Figure 103, increases in magnitude by between two and three times over the discharge gas flow range of 1 to 10 litres/minute whereas the normalised impedance (imaginary), as shown in Figure 104, decreases by about 20%. Another thing to note about Figure 104 is that the curve shows the same general trends as the VSWR as a function of discharge gas flow rate shown in Figure 102. The error bars were calculated by determining the maximum possible excursions for the impedance about the measured values as calculated from errors in variable determination. This method of error determination results in different values for the positive and negative error bars as seen graphically in Figure 95 and Figure 96.

![Graph](image)

Figure 103. Normalised plasma impedance (real) as a function of discharge gas flow rate for a 3 kW plasma.
Figure 104. Normalised plasma impedance (imaginary) as a function of discharge gas flow rate for a 3 kW plasma.

Figure 105. Real plasma impedance comparison for both cooled and non-cooled applicator.
Figure 105 and Figure 106 show the real and imaginary plasma impedance comparisons for both cooled and non-cooled applicator, respectively. From Figure 105 it can be seen that the trends for impedance as a function of gas flow rate are identical, i.e. the normalised real plasma impedance increases with increasing discharge gas flow rate though at differing rates for the two applicators. More importantly, the magnitude of the impedance is the same order of magnitude indicating that similar processes are occurring within each applicator.

Figure 106. Imaginary plasma impedance comparison for both cooled and non-cooled applicator.

Figure 106 is a most informative graph. Recall that the plasma admittance calculated for the non-cooled applicator led to the development of an electric circuit model of the plasma column. In addition, the reactance of the plasma column was inductive and good agreement was obtained by modelling the plasma as a perfectly conducting wire stretched across the broadwall of the waveguide. From Figure 106 we see that the
reactance has changed sign for the water-cooled applicator indicating that the plasma column now has a capacitive reactance as opposed to the inductive reactance of the non-cooled applicator. The capacitive reactance can be explained by considering the geometry of the ionisation chamber-water jacket arrangement. In many respects, this arrangement is identical to a length of coaxial cable with an inner conductor separated from an outer conductor by an annulus of non-conductor. For the case at hand, the inner conductor is the plasma, the non-conductor is the boron nitride ionisation chamber and the outer conductor is the coolant itself. As the coolant was not demineralised, electrical conduction at 2450 MHz would have been enhanced and the ionisation chamber arrangement would have acted as a cylindrical capacitor.

![Figure 107](image)

**Figure 107.** Normalised plasma impedance (real) as a function of microwave power for five discharge gas flow rates.

Figure 107 and Figure 108 show the normalised plasma impedance (real and imaginary respectively) as a function of microwave power for five discharge gas flow rates.
Again, error bars have been omitted from these graphs for clarity (the individual plots with associated error bars corresponding to these curves can be found in Figure 109 through Figure 118). For each gas flow rate, the real plasma impedance increases as a function of microwave power whereas the imaginary plasma impedance decreases. Strictly speaking, the reactance (imaginary component of the impedance) increases or becomes more negative with increasing power. If we continue with the electrical analogue, this means that the ability of the plasma to "store" energy increases with increasing power, as does the microwave resistance. Comparing Figure 107 with Figure 97, it is noted that the plasma impedance vs. microwave power dependency is significantly different even though the magnitude is similar. This is understandable when, as noted above, the geometry of the ionisation chamber is different for each applicator and as such, the electrical properties of the plasma will differ.

<table>
<thead>
<tr>
<th>Gas Flow Rate</th>
<th>Plasma Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 litres/min</td>
<td></td>
</tr>
<tr>
<td>4 litres/min</td>
<td></td>
</tr>
<tr>
<td>5 litres/min</td>
<td></td>
</tr>
<tr>
<td>6 litres/min</td>
<td></td>
</tr>
<tr>
<td>7 litres/min</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 108. Normalised plasma impedance (imaginary) as a function of microwave power for five discharge gas flow rates.](image)

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Figure 109. Normalised plasma impedance (real) as a function of microwave power for a discharge gas flow rate of three litres per minute.

Figure 110. Normalised plasma impedance (imaginary) as a function of microwave power for a discharge gas flow rate of three litres per minute.
Figure 111. Normalised plasma impedance (real) as a function of microwave power for a discharge gas flow rate of four litres per minute.

Figure 112. Normalised plasma impedance (imaginary) as a function of microwave power for a discharge gas flow rate of four litres per minute.
Figure 113. Normalised plasma impedance (real) as a function of microwave power for a discharge gas flow rate of five litres per minute.

Figure 114. Normalised plasma impedance (imaginary) as a function of microwave power for a discharge gas flow rate of five litres per minute.
Figure 115. Normalised plasma impedance (real) as a function of microwave power for a discharge gas flow rate of six litres per minute.

Figure 116. Normalised plasma impedance (imaginary) as a function of microwave power for a discharge gas flow rate of six litres per minute.
Figure 117. Normalised plasma impedance (real) as a function of microwave power for a discharge gas flow rate of seven litres per minute.

Figure 118. Normalised plasma impedance (imaginary) as a function of microwave power for a discharge gas flow rate of seven litres per minute.
4.8 Plasma Impedance Comparisons.

Cobine and Wilbur [4] measured the impedance of their microwave discharge for three gas types and at a constant input power of 3.75 kW. The gases were nitrogen, oxygen and air and the impedances are summarised in Table 2. Cobine reported that increasing the gas flow rate had no effect on the real component but did increase the reactive component. In contrast, an increase in gas flow rate led to an increase in the real and a decrease in the reactive components for the water-cooled applicator and an increase in the real and no change in the reactive components for the non-cooled applicator. In Cobine’s torch the reactive component was capacitive, as was the reactive component for the water-cooled applicator. The reactive component for the non-cooled applicator was inductive. The specific values of the impedance as determined by Cobine are not in agreement with those determined for either the non-cooled or water-cooled applicator, which is not surprising considering the vastly different plasma applicator.

Arata et al [14] determined the plasma impedance for a nitrogen plasma as a function of both discharge gas flow rate and microwave power. His results showed that the real component of the impedance increased sharply for a microwave power of 0.8 kW and thereafter the increase was gradual. The reactive component, actually capacitive, became more negative and changed proportionally with power. In contrast, the real component decreased slightly with increasing flow rate whereas the capacitive component became more positive. Neither of these situations is in agreement with the data obtained from the waveguide applicator. Also, the numerical values differ by an order of magnitude with the waveguide applicator having the smaller of the two values. This may be due to
the superior coupling achieved with the waveguide applicator, 99% as opposed to 83% with the applicator of Arata.

4.9 Plasma Beam Length.

The length of the plasma beam increases almost linearly with a discharge gas flow rate of 2 litres/min and for microwave powers up to 3.5 kW as can be seen in Figure 119 (the “beam length” in this case refers to the luminous part of the beam. Though not a quantitative measure, this description serves as a guide as to how the beam changes when viewed by the naked eye). Beyond this power, the beam length plateaus due to the transition of the plasma from a laminar to a turbulent flow pattern. This can be easily seen in Figure 125 and Figure 127. The plasma in Figure 125 has an ordered, columnar appearance whereas the appearance of the plasma in Figure 127 is "woolly". The transition occurs due to an increase in the "temperature" of the plasma with increasing microwave power. The hotter plasma expands at a greater rate and thus exits the ionisation chamber with a greater velocity. The word "temperature" is used cautiously because the plasma is not in LTE and hence the term "temperature" is meaningless. What does increase with increasing power is the heat that can be extracted from the plasma. This is due principally to an increase in the kinetic energy of the ions within the plasma, though the electron recombination temperature does increase by a few percent [14].
Discharge Gas Flow Rate = 2 litres/min

Figure 119. Plasma beam length as a function of microwave power.

Figure 120 through Figure 127 are photographs of the water-cooled applicator generating a plasma beam with a microwave power of 1.0 kW through 4.5 kW in increments of 0.5 kW. These photographs were taken using a SLR camera with ISO400 Kodak film at constant exposure (1/250 sec). No filters were used. These plasmas were generated using the non-commercial magnetron power supply which was unstable at high powers. These Figures unfortunately do not tell the complete picture as they only represent an instant in time. Because of the instability of the power supply at high powers, the plasma length oscillated by as much as 50 mm making determination of the true beam length as a function of power difficult. This oscillation in length at high powers is the reason for the increase in the size of the error bars shown.
Figure 120. Photograph of a 1.0 kW plasma beam.

Figure 121. Photograph of a 1.5 kW plasma beam.
Figure 122. Photograph of a 2.0 kW plasma beam.

Figure 123. Photograph of a 2.5 kW plasma beam.
Figure 124. Photograph of a 3.0 kW plasma beam.

Figure 125. Photograph of a 3.5 kW plasma beam.
Figure 126. Photograph of a 4.0 kW plasma beam.

Figure 127. Photograph of a 4.5 kW plasma beam.
As can be seen from Figure 124, the plasma beam has a pink core approximately 30 mm in length. The light given off by the plasma is due to electron transitions in excited atoms, as such, the pink core corresponds to a region of plasma that is in a more excited state than the body or mantle of the plasma beam. This highly excited region extends back into the ionisation chamber, or the excitation region, as would be expected. As the discharge gas flow rate increases the outer mantle of the plasma beam is "replaced" by the highly excited plasma as it is ejected from the ionisation chamber and the overall beam length is diminished. This effect can be easily seen in Figure 128 through Figure 132. Note that the photograph in Figure 130 is incorrectly labelled and should read 5.0 l/min. Though not apparent in this set of photographs, the beam is still columnar in appearance even though the brightness of the plasma beam has saturated the photographic emulsion. This saturation gives the beam a spherical appearance in the photographs.
Figure 129. A 3.0 kW plasma beam operating with a 4.0 l/min discharge gas flow rate.

Figure 130. A 3.0 kW plasma beam operating with a 5.0 l/min discharge gas flow rate.
Figure 131. A 3.0 kW plasma beam operating with a 6.0 l/min discharge gas flow rate.

Figure 132. A 3.0 kW plasma beam operating with a 9.0 l/min discharge gas flow rate.
The final plasma beam photograph, shown in Figure 133, is of a 5.25 kW plasma beam operating with a discharge gas flow rate of 3 litres per minute. As can be easily seen the beam is almost 250 mm long, is very bright and still columnar in appearance. To date, the longest beam produced with the water-cooled waveguide applicator was approximately 300 mm long. This was produced with similar operating conditions to those used in Figure 133.

Figure 133. A 5.25 kW plasma beam operating with a 3.0 l/min discharge gas flow rate.
4.10 Heat Capacity of the Plasma Beam.

The impetus for using indirect methods to determine the relative temperature was that the plasma was too hot for conventional thermometry techniques. The use of thermocouples was abandoned because it was easy to melt the platinum-platinum/rhodium from which they are constructed. Optical pyrometry of the plasma was not feasible as the plasma was essentially transparent at the wavelength used by the available equipment.

Two separate experiments were performed to qualitatively determine how the heat capacity of the plasma beam varied with ionisation chamber diameter, discharge gas flow rate and microwave power. The first used the non-cooled version of the waveguide applicator and relied on the temperature rise of a known mass of water. The second utilised the water-cooled applicator and used the temperature rise of a metal plate immersed in the plasma. Factors that could influence the temperature rise of the water, such as gas circulation patterns and turbulence, were not controlled and were assumed to be the same for both experiments. The importance of knowing the heat capacity of the beam becomes evident when materials welding and joining applications are considered. To optimise the welding process, it is necessary to know in advance the heat input into the weld pool and thus, the heat that can be extracted from the “welding torch”. The data for this section was generated collaboratively with another researcher [53] but was analysed independently to provide the results given here. The experimental arrangement used to determine the heat capacity of the plasma beam is shown in Figure 134 and the power supply used was the non-commercial unit.
Figure 134. Experimental arrangement used to determine the heat capacity of the plasma beam.

To determine the heat capacity it was necessary to monitor and record the incident microwave power, the reflected microwave power, the initial and final temperature of the water, the mass of water and the discharge gas flow rate. Two different diameter alumina ionisation chambers were used. These had an I.D. and O.D. of 4 x 6.1 mm and 5 x 7.2 mm respectively. The distance $x$ was not varied during the course of experimentation to ensure uniformity of experimental conditions. An estimate of the heat capacity of the plasma was then calculated from

$$Q = \frac{mc(T_f - T_i)}{t}$$

(W)
where:

\[ m = \text{mass of water (kg)} \]
\[ c = \text{heat capacity of water (4184 J/kg.K)} \]
\[ T_f = \text{final water temperature (K)} \]
\[ T_i = \text{initial water temperature (K)} \]
\[ t = \text{time interval (s)} \]

Figure 135. Heat transfer data for the non-cooled plasma (small ionisation chamber).

The heat transfer results are given in Figure 135 and Figure 136. Both Figures show the general trend of increasing heat capacity of the plasma beam with increasing power as would be expected. Both ionisation chambers have a similar internal diameter and as such, the results would be expected to be similar. This is born out by the results. What is not clear from the results is whether there is a trend of increasing heat transfer from the plasma beam with increasing flow rate. It is more likely that the heat transferred is not a linear function of increasing flow rate but involves a turning point, i.e. a point in
the gas flow rate beyond which the available heat from the plasma starts to decrease.

This topic is investigated further in Chapter 5.

Figure 136. Heat transfer data for the non-cooled plasma (large ionisation chamber).

The second experiment, to determine the relative heat capacity of the plasma beam, is similar to that shown schematically in Figure 134 except the test-tube is replaced by a section of 3 mm plate steel and the commercial power supply and water-cooled applicator used. The experiment involved immersing a metal plate into the plasma for a known period. A thermocouple was mounted on the rear of the plate to allow for temperature determination and the standoff distance, $x$, was computer controlled. The microwave power was set at 2.75 kW and the standoff distance of the metal plate at 6 mm where the standoff distance is the distance of the plate from the plasma exit nozzle. The results shown in Figure 137 represent the heat capacity of the plasma beam as a function of discharge gas flow rate and the results in Figure 138, a fixed microwave power and discharge gas flow rate of 3 kW and 4 litres/minute respectively.
Figure 137. Relative plasma beam temperature as a function of discharge gas flow rate.

The data shown in Figure 138 is consistent with that shown in Figure 135 and Figure 136 inasmuch as the beam temperature is not a linear function of discharge gas flow rate. This consistency between data sets means that both the non-cooled and cooled applicators behave in a similar manner. The maximum heat extracted from a 2.75 kW beam with a 6 mm standoff distance occurred for a gas flow rate of 9 litres/minute. The results shown in Figure 138 reveal that the beam temperature, or more correctly the heat capacity of the beam, decreases with distance from the exit nozzle. This is totally as expected since as the standoff distance is increased, so too is the distance from the excitation source for the plasma. Even though Figure 137 and Figure 138 show relative beam temperature, it should strictly be the heat capacity of the beam since the temperature of the plasma is not a well defined quantity as the thermal equilibrium status is not known. These experiments provide a direct measure of the heat that can be extracted from the plasma beam, an important quantity in terms of use as a heating or welding tool.
Figure 138. Relative plasma beam temperature as a function of plate standoff distance.

4.11 Plasma Beam Pressure.

Another important characteristic of the plasma beam, in terms of applicability as a welding tool, is the pressure the beam exerts on the workpiece. A high beam pressure will essentially eject the molten metal as the beam melts the workpiece instead of allowing it to cool in situ. This results in a cutting action instead of the desired welding or fusing action. Figure 139 shows schematically the experimental arrangement used to determine the plasma beam pressure. The face of the water-cooled copper block was positioned 0.3 mm away from the exit nozzle. This dimension is represented by $x$ in Figure 139. The copper block had a fine Pitot hole, which was connected to a differential manometer from which the pressure could be read. The differential pressure was measured with respect to atmospheric pressure.
Figure 139. Experimental arrangement used to determine plasma pressure.

Figure 140 gives the relative plasma pressure as a function of discharge gas flow rate for various plasma beam powers. As can be seen, each curve is parabolic in nature and is qualitatively explained by Bernoulli's principle. A full description can be found in Fox and McDonald [54] but put simply, the density of the gas, or plasma, changes with temperature and the pressure exerted by the gas is a function of the square of the mass flow rate per unit area of the gas. Theoretically, if the pressure and mass flow rate are known, then the temperature of the gas can be calculated from the density. This works well for an idealised Pitot tube but was not applicable to the above experimental arrangement.
Figure 140. Relative plasma pressure as a function of discharge gas flow rate.

Figure 141 is the data from Figure 140 presented in a different form, namely, the relative plasma pressure as a function of microwave power. From this Figure, it is quite evident that the plasma beam pressure increases with increasing plasma beam power, which corresponds to an increasing temperature. The base pressure was 760 mm of mercury and the maximum pressure obtained was 999 mm of mercury. This corresponds to an increase of approximately 30%, which is quite significant in terms of the pressure exerted on the molten weld pool. Due to technical difficulties, data corresponding to a microwave power of 3.25 kW and discharge gas flow rates from 7 through 10 litres per minute was not obtained. This was also the case for a power of 3.5 kW and a flow rate of 10 litres per minute.

The results presented in Figure 140 and Figure 141 are important from a welding and joining applications standpoint. The pressure the plasma exerts on the molten weld pool is a critical variable of which knowledge is necessary to perform good quality welds.
Figure 141. Relative plasma pressure as a function of microwave power.

4.12 Conclusion.

This chapter has dealt with the characterisation of the plasma/applicator system through determination of the electrical and physical properties of the plasma. In Section 4.3, VSWR measurements on the non-cooled waveguide applicator revealed that there was a small change in load impedance phase with power and a steady change in the load impedance magnitude and phase with increasing sliding short-load distance. Also revealed by the VSWR measurements was the existence of a resonance condition whereby the load impedance was matched to that of the source. This occurred for a sliding short-load distance of approximately 80 mm. Analysis of the resonance condition for the cases with and without a plasma revealed that the quality factor of the cavity, Q, was greater in the absence of the plasma. The broadening of the resonance peak by the plasma is advantageous when constructing an applicator since the cavity dimensions are not as critical and the applicator is less sensitive to drifts in the driving frequency. The gradient of the VSWR linear regression line as a function of microwave
power was opposite on either side of the resonant position. Starting with the sliding short-load distance less than the resonance length, as the sliding short was moved closer to the resonance position, the slope of the regression line becomes less positive and the magnitude of the VSWR was reduced for a given power level. Once the resonance position has been passed however, the slope of the regression line took on ever larger negative values and the VSWR for a given power increased. The positioning of external chokes on the applicator to reduce microwave leakage had no effect on the recorded VSWR.

Measurements of the electrical impedance of the plasma beam enabled a simple electrical circuit model of the plasma to be developed (Section 4.4). The plasma contained an inductive component that remained essentially unchanged with short circuit stub position and this component was interpreted as the inductive component of the plasma column. Modelling the plasma column as a perfectly conducting wire stretched across the broadwall of the waveguide gave excellent agreement between the experimentally and theoretically determined value for the inductive susceptance of the plasma beam at resonance. Measurements of the electrical impedance of the plasma as a function of sliding short-load distance revealed that the real component of the impedance had a sharp maximum around resonance whilst the imaginary component of the plasma impedance fell to zero at resonance (Section 4.5). Neither the real nor the imaginary part of the plasma impedance varied much with microwave power over the range 0.5 through to 1.5 kW though both these properties did increase marginally with discharge gas flow rate.
Section 4.6 dealt with VSWR measurements on the water-cooled waveguide applicator. The VSWR decreased for microwave powers of 0.75 through 5 kW and discharge gas flow rates of 1 through 10 litres per minute. This is in agreement with the VSWR characteristics of the non-cooled applicator. In Section 4.7 it was shown that the real component of the plasma impedance increased with discharge gas flow rate as well as microwave power whilst the imaginary component decreased with increasing gas flow rate and microwave power. There was an important difference between the imaginary components for the non-cooled and cooled applicators. Specifically, the plasma beam produced by the non-cooled applicator contained an inductive component whereas the cooled applicator produced a beam with a capacitive reactance. It is suggested that this is the result of the physical arrangement of the cooling system having an electrical resemblance to a cylindrical capacitor. When compared to the literature, there was little agreement between the plasma impedance for a plasma generated by either the non-cooled or the water-cooled applicator (Section 4.8). This is due to the use of different discharge gases as well as the different physical arrangements of the applicators. Both impedances reported in the literature had a capacitive reactance as did the water-cooled applicator as previously mentioned.

Section 4.9 showed that the overall plasma beam length increased with increasing microwave power as did the central core of the beam. As the discharge gas flow rate was increased for a given power, the overall beam length decreased whilst the core length remained essentially static. The heat capacity of the beam, as discussed in Section 4.10, increased with increasing power as would be expected. However, the relative temperature of the beam as a function of discharge gas flow rate had a concave downward structure with a maxima beam temperature corresponding to a discharge gas
flow rate of 9 litres per minute. For a given microwave power and discharge gas flow rate the plasma temperature decreases with increasing standoff distance as would be expected. In Section 4.11, the pressure the plasma beam exerted on the workpiece was measured using a differential pressure transducer. Results indicated that the pressure exerted by the beam increased with increasing discharge gas flow rate and increasing microwave power.

Welding has been an accepted method for joining disparate samples for many years and techniques have been optimised through trial and error methods. Some aspects of welding are still an art since many processes are not yet well understood. As discussion of the use of a microwave induced plasma beam as a welding tool is largely absent from the literature, much work at characterising the beam’s properties as a function of external parameters is necessary. For example, the beam temperature and the pressure the plasma exerts on the molten weld pool are critical variables, prior knowledge of which is necessary to perform good quality welds.
CHAPTER 5. PLASMA TEMPERATURE DETERMINATION BY LASER SCATTERING TECHNIQUES.

5.1 Introduction.

This chapter deals with the determination of the plasma temperature through laser scattering techniques. Scattering of photons by particles small compared to the wavelength of light is known as Rayleigh scattering and is a useful diagnostic tool for measuring particle densities [55]. The intensity of the Rayleigh scattered signal is directly proportional to the number density of scattering centres, i.e. argon ions and atoms in the present case, and provides a measure of the number of scattering centres in the scattering volume. The temperature of the plasma can then be determined from the ideal gas law, \( PV = nRT \). Where \( P \), \( V \), \( n \), \( R \) and \( T \) are pressure, volume, number of atoms, universal gas constant and the temperature respectively. Boyle's Law for a perfect gas is a valid approximation for Rayleigh measurements below about 10000 K since the population of the neutral argon ground state is more than 99% of the total heavy particle population. From the ideal gas law, for a given scattering volume at fixed pressure, a rise in temperature corresponds to a decrease in the number of scattering centres contained within the scattering volume. The temperature of the heavy particles in the plasma can then be calculated from knowledge of the number density of scattering centres in argon at room temperature and pressure. This section describes the use of Rayleigh scattered Nd:YAG laser light to determine the particle density, and hence heavy particle temperature, of an argon based microwave induced plasma beam operating between 1 and 5 kW.
5.2 Temperature Determination.

The experimental arrangement is shown schematically in Figure 142 [56]. A frequency doubled, pulsed Nd:YAG laser was used as the laser source. Pulse duration and frequency were 6 ns and 20 Hz respectively. The output laser wavelength was 532 nm and the maximum pulse energy available at this wavelength was 320 mJ. The laser beam was brought to focus, at the scattering site, at 90° to the scattering-collection optics optical axis and within the focal plane of these optics. The scattered signal was collected by an ARC monochromator and measured using a Princeton Instruments Inc image intensified charge coupled detector (ICCD), model 576G/RBE. The ICCD array was 578 pixels wide and the spectral difference between adjacent pixels was 0.059 nm. Vertically, the pixel separation represents 0.022 mm at the laser focus. The entire optical apparatus, including laser and collection optics, was mounted on an XYZ table allowing the scattering site to be driven to any point within the plasma beam.

Using software control, the ICCD was configured for use in “spatial” mode. Spatial mode gives a spatially resolved image for a vertical slice through the scattering site by binning the appropriate horizontal pixels. In this mode the vertical profile of the laser beam was evident as was the plasma and any reflected laser light. The width of the slice through the scattering site was about 0.1 mm and was dictated by the width of the vertical slit at the monochromator input. The collection optics axis was centred on the plasma beam by scanning the beam across the scattering site, firstly in the x and then in the y direction, and finding the position corresponding to a maximum scattered signal. The beam centring was performed as close as possible to the nozzle where the plasma is most uniform.
After leaving the laser, the beam passes through expansion optics and a half wave plate. The half wave plate allows the intensity of beam to be adjusted whilst maintaining full power output from the laser. The laser is most stable when operated at full power. The laser output from the Brewster plate is plane polarised with the electric field vector oriented in the $z$ direction. This results in isotropic scattering in the $x$-$y$ plane and minimises, in conjunction with the polarising plate in the collection optics path, unwanted radiation from entering the detector. The diaphragms or apertures situated after the focussing lens are used to minimise stray light from entering the collection optics. Finally, the laser beam is brought to focus in the plasma before continuing to a conical beam dump. The plasma beam is parallel to the $z$ axis and the laser beam interacts with the plasma orthogonal to this axis in the $x$ direction. The Rayleigh scattered signal is viewed in the $y$ direction.
The entire experimental apparatus was enclosed in light absorbent curtaining to further reduce stray light. The level of stray light could be checked by determining the Rayleigh scattered signal for both room temperature argon and helium. The helium signal is expected to be small compared to that from argon since their Rayleigh cross sections, $\sigma_{\text{Ar}}:\sigma_{\text{He}}$, are in the ratio 66:1 [57]. Measurements of the Ar:He Rayleigh scattered signal revealed that the level of stray light was consistently found to be of order of 0.6 % of the scattered signal from room temperature argon. At this level, the stray light contribution to the scattered signal is sufficiently small that it can be ignored. However, since the Rayleigh scattered signal decreases with increasing temperature, this stray light can represent a background signal amounting to 25 % of the true signal at an argon gas temperature of 8500 K.

![Figure 143. Rayleigh scattered signal for room temperature argon.](image-url)
Figure 144. Rayleigh scattered signal for a 5 kW argon plasma beam.

The data presented in the first section of this chapter (up to Figure 162) represents measurements nominally made "on-axis" of the plasma beam. As shown later in this chapter, errors in positioning the laser beam "on-axis" can lead to errors of between 1000 and 2000 K in the measured temperatures. The data presented in Figure 143 and Figure 144 was collected for 100 accumulations, 25 seconds, and is typical of the laser scattering data collected. Figure 143 gives the intensity of the Rayleigh scattered signal as a function of CCD pixel number for a room temperature argon beam and Figure 144, for a 4 litre per minute 5 kW argon plasma beam. After integrating the area under each curve, the temperature is then derived by taking the ratio of these areas and multiplying the resultant by the room temperature, in Kelvin. For the above case, this corresponds to a temperature of approximately 6000 K.

Figure 145 gives the plasma temperature as a function of microwave power for $z = 2$ mm and a discharge gas flow rate of 5 litres per minute. The increase in the size of the
error bars with increasing plasma temperature occurs since the ratio of stray light to signal increases as the signal reduces with increasing temperature.

The increase in plasma temperature with microwave power appears to be linear in nature. Applying a linear fit to this data gives a regression line contained wholly within the $y$ axis error bars and an $R^2$ value of 0.9837. However, this would give a $y$ intercept, corresponding to zero microwave power, of approximately 1450 K. Clearly, the dependence cannot be linear in nature over the entire power range from zero microwave power up to 5 kW.

![Figure 145. Plasma temperature as a function of microwave power for $z = 2$ mm and a discharge gas flow rate of 5 litres per minute.](image)

The plasma temperature as a function of discharge gas flow rate for $z = 2$ mm and a plasma beam power of 4 kW is given in Figure 146. This data is consistent with that given in Figure 137 inasmuch as the plasma temperature is not a linear function of discharge gas flow rate but has a concave downward nature. These results also validate
the indirect methods used to determine the plasma temperature in Section 4.10. The increase and eventual decrease in plasma temperature with increasing discharge gas flow rate is a result of several factors.

As the gas flow rate is increased, the heated plasma exits the discharge region with a greater velocity and travels further during a given period. The result of this is that the temperature of the plasma, when sampled outside of the discharge cavity, appears to increase as the discharge gas flow rate is increased. This increase in plasma temperature is countered by the fact that the plasma, once outside the discharge cavity, is no longer being heated by the microwave radiation. The extra gas afforded by the increase in discharge gas flow rate also acts to cool the plasma. The combination of these two processes is eventually registered as a decrease in plasma temperature at higher gas flow rates.
Figure 147. Plasma temperature as a function of distance from nozzle for a 5 kW, 4 litre per minute plasma beam.

The plasma temperature as a function of distance from the exit nozzle for a 5 kW, 4 litre per minute plasma beam is given in Figure 147. The scattering region was aligned with the centre of the plasma beam and measurements taken at various distances along the length of the plasma beam. Care was taken to ensure the scattering region was in the centre of the plasma beam along its complete length, approximately 100 mm. As would be expected, the plasma temperature decreases with increasing distance from the excitation source. This is consistent with the findings of the heat capacity experiments performed in Section 4.10 and the findings shown in Figure 146. This is important for application to welding since they quantitatively describe the effects of two major welding variables, gas flow rate and standoff distance. There is however a difference between the data given in Figure 145 and that in Figure 147. Specifically, the temperature shown in Figure 147 is approximately 2500 K less than that in Figure 145.
for a similar discharge gas flow rate and plasma beam power. This is because the two experiments were performed with different coolant flow rates.

The effect of coolant flow rate on plasma temperature is shown graphically in Figure 148. The increase in plasma temperature with decreasing coolant flow rate is because of increased “ablation” of the inner surface of the ionisation chamber. The hotter the inner surface the greater the number of electrons ejected into the plasma by thermionic emission. These electrons are accelerated by the electric field of the microwaves and contribute to increasing the plasma temperature through collisional processes. Also, as the inner surface of the ionisation chamber is hotter with a decreased coolant flow rate, less energy is taken from the plasma through conduction. Note that the curve shown in Figure 148 appears to have a step like nature. This result is unexpected and the step in plasma temperature may be the result of a change in coupling between the microwaves and the plasma as the coolant flow rate is varied.

![Figure 148. Plasma temperature as a function of coolant gas flow rate for a 4.0 kW argon plasma beam.](image)

Figure 148. Plasma temperature as a function of coolant gas flow rate for a 4.0 kW argon plasma beam.
The applicator coolant temperature as a function of microwave power is shown in Figure 149, and as a function of coolant flow rate in Figure 150. The curves presented in these two Figures are consistent with expectations. That is, the coolant temperature increases with increasing microwave power and decreases with increasing coolant flow rate. The increase in coolant temperature with microwave power is principally due to increased conduction of heat through the ceramic ionisation chamber associated with increasing plasma temperature. Direct heating of the coolant by the microwaves is comparatively insignificant since the annulus of coolant is 0.5 mm thick.

Figure 149. Applicator coolant temperature as a function of microwave power for a coolant flow rate of 0.01875 litres per second and a discharge gas flow rate of 5 litres per minute.
Figure 150. Applicator coolant temperature as a function of coolant flow rate for a 4 kW, 3 litre per minute plasma beam.

Figure 151. Plasma beam length as a function of coolant flow rate for a 4 kW, 3 litre per minute plasma beam.
Figure 151 gives the plasma beam length as a function of coolant flow rate for a 4 kW, 3 litre per minute plasma beam. As can be readily seen from this graph, the maximum beam length occurs for a coolant flow rate of approximately 0.02 litres per second. The form of this curve is a result of a change in coupling of the microwaves to the plasma with changing coolant flow rate. The fact that the ability of the microwave power to couple with the plasma is dependent upon the flow characteristics of the coolant fluid is important since it shows that thermionic emission of electrons from the hot ionisation chamber is an important process in maintaining the plasma discharge. This is consistent with the data given in Table 7 that showed that it was not possible to spontaneously generate a plasma in a quartz ionisation chamber since this tube did not heat when placed in the microwave field.

Figure 152 and Figure 153 give the plasma temperature and plasma beam length as a function of sliding short-load distance for a 3 kW, 5 litre per minute plasma beam respectively. The plasma temperature remains fairly constant at 3000 K for the sliding short-load distance between 176 and 184 mm. At a distance of 184 mm and above the temperature is reduced to approximately 2500 K. This transition in temperature corresponds to the location of the resonance position for the water-cooled cavity. The resonance position can be easily seen in Figure 153 as this position corresponds to a maxima in plasma beam length. This result supports the hypothesis that the step like nature of the plasma temperature in Figure 148 is the result of a change in coupling of the microwaves with the plasma as the coolant flow rate is varied.
Figure 152. Plasma temperature as a function of sliding short-load distance for a 3 kW, 5 litre per minute plasma beam.

Figure 153. Plasma beam length as a function of sliding short-load distance for a 3 kW, 5 litre per minute plasma beam.
Figure 154. Plasma temperature as a function of discharge gas flow rate for various argon plasma beam powers.

Figure 154 gives the plasma temperature as a function of discharge gas flow rate for argon plasma beam of powers 2.5 through 5.0 kW in increments of 0.5 kW and for a fixed standoff distance of 2 mm. For a given flow rate there is generally an increase in temperature with increasing power whilst for a given power, the maximum temperature occurs for a flow rate of between 5 and 8 litres per minute. Since steel melts at around 1800 K, any plasma beam power above 1.5 kW would be suitable for welding steel. The plasma beam power used however would depend upon the speed and heat affected zone that was acceptable for the weld being performed.

Figure 155 through Figure 161 gives the plasma temperature as a function of discharge gas flow rate and various exit nozzle distances for an argon plasma beam of powers 1.5kW through 4.5 kW in increments of 0.5 kW. In each of these Figures, the temperature of the beam does not vary much for a given discharge gas flow rate and a standoff distance up to 5 mm away from the exit nozzle. At distances greater than 15
mm from the nozzle, the temperature is reduced sequentially with distance for a given flow rate. In Figure 155, the temperature increases from around 2250 K up to 3250 K for flow rates of 4 to 10 litres per minute and standoff distances up to about 10 mm. The trend of increasing temperature is smooth with what appears to be a gradual tapering off in temperature in the region above 3000 K. This same trend of a gradual increase with a tapering off of temperatures towards higher gas flow rates occurs for each of the Figures through to Figure 161. The results given in Figure 160 and Figure 161 show a reduced maximum temperature when compared to those given in Figure 158 and Figure 159. This is due to instrumentation failure prior to data collection. These results are included however, because they show the temperature as a function of discharge gas flow rate curves have the same form at these powers as at lower powers.

Figure 155. Plasma temperature as a function of discharge gas flow rate for a 1.5 kW argon plasma beam.
Figure 156. Plasma temperature as a function of discharge gas flow rate for a 2.0 kW argon plasma beam.

Figure 157. Plasma temperature as a function of discharge gas flow rate for a 2.5 kW argon plasma beam.
Figure 158. Plasma temperature as a function of discharge gas flow rate for a 3.0 kW argon plasma beam.

Figure 159. Plasma temperature as a function of discharge gas flow rate for a 3.5 kW argon plasma beam.
Figure 160. Plasma temperature as a function of discharge gas flow rate for a 4.0 kW argon plasma beam.

Figure 161. Plasma temperature as a function of discharge gas flow rate for a 4.5 kW argon plasma beam.
Figure 162 through to Figure 164 give the plasma temperature as a function of radial distance for various microwave powers and discharge gas flow rates and at various standoff distances. The plasma beam is about 3 mm wide at the exit nozzle and this is reflected in these Figures by the rapid reduction in temperature with radial distance as seen in the 0.5 and 1 mm standoff curves. This data suggests that errors in positioning the laser beam “on-axis” can lead to errors of between 1000 and 2000 K in measured temperatures. As the distance from the nozzle increases the surrounding air is heated by the plasma and as a result the temperature falls away more slowly with radial distance. The results given in Figure 163 and Figure 164 are for an identical plasma though the data in Figure 163 was collected by sampling a cross section of the plasma in the x direction whereas the data in Figure 164 has been sampled by scanning in the y direction.

![Figure 162. Plasma temperature as a function of radial distance for a 5 kW, 3 litre per minute plasma beam.](image-url)
Figure 163. Plasma temperature as a function of x-axis radial distance for a 3 kW, 5 litre per minute plasma beam.

Figure 164. Plasma temperature as a function of y-axis radial distance for a 3 kW, 5 litre per minute plasma beam.
The most obvious difference between these two sets of data is the maximum temperature obtained for zero radial distance for the curves with a 1 through 10 mm standoff distance. Clearly, there can be no difference as the plasma beam is identical. In actuality, the temperatures shown are the same within experimental limits though the error bars have been omitted from these graphs for reasons of clarity.

Figure 165 shows a contour map of plasma temperature as a function of y-axis radial distance and distance from the nozzle for a 3 kW, 5 litre per minute plasma beam. This graph was generated by applying a Gaussian fit to the data contained in Figure 164. The correlation coefficient was greater than 0.975 in each case and the experimental data along with the regression lines are given in Figure 166. Also shown on Figure 165 is an outline of the visual plasma beam for comparison purposes. From this graph it can deduced that the plasma is radially symmetric and decreases in temperature in a smooth fashion away from the excitation source. Furthermore, even though the width of the plasma does not vary appreciably over the length of the beam, the diameter of the hotter core of the plasma beam does, tapering to zero at the 5 mm mark.
Figure 165. Contour map of plasma temperature as a function of y-axis radial distance and distance from the nozzle for a 3 kW, 5 litre per minute plasma beam.
Figure 166. Plasma temperature as a function of y-axis radial distance and distance from the nozzle for a 3 kW, 5 litre per minute plasma beam.

Figure 167 through to Figure 171 give the plasma temperature as a function of x-axis radial distance for various standoff distances and plasma beam powers. Again, error bars have been purposefully omitted for reasons of clarity. These results show that, for a given radial distance and standoff distance, the temperature of the plasma increases with increasing microwave power. It should be noted here that, within experimental limits, the curves for 4 and 5.75 kW in Figure 168 for example are the same. Note also that the plasma temperature for each power level converges to the same value at a radial distance of 3 mm. This distance places the sampling region outside of the plasma beam and the temperature recorded is the ambient room air temperature. Since the sampling region outside of the plasma beam does not contain argon, the temperatures recorded will be in error. This is because the measurement procedure depends on the ideal gas
like behaviour of the discharge gas. To a first approximation though, these values are reasonable. The same applies for each measurement taken on the fringe of the plasma beam, i.e. essentially every figure from Figure 162 through to Figure 171. Note also that as the standoff distance, or the distance from the nozzle, increases the temperature gradient between the centre and the edge of the plasma beam decreases. This is due to the thermalisation of the plasma beam with time after it leaves the excitation region within the ionisation chamber.

![Figure 167](image)

Figure 167. Plasma temperature as a function of x-axis radial distance for z=1 and 2 mm and various plasma beam powers.
Figure 168. Plasma temperature as a function of $x$-axis radial distance for $z=5$ mm and various plasma beam powers.

Figure 169. Plasma temperature as a function of $x$-axis radial distance for $z=10$ mm and various plasma beam powers.
Figure 170. Plasma temperature as a function of x-axis radial distance for z=20 mm and various plasma beam powers.

Figure 171. Plasma temperature as a function of x-axis radial distance for z=40 mm and various plasma beam powers.
5.3 Temperature Comparisons.

Cobine and Wilbur [4] give an estimation of the gas temperature of a plasma flame as 1870-3740 K though it is not clear from the text what frequency or power was used to generate this data. The temperature was determined using buoyancy methods in which the upward deflection of a horizontally directed flame was measured and the trajectory determined. From this, an estimation of the temperature was made. The results of Cobine and Wilbur are in good agreement with those in Chapter 5 as they fall well within the gas temperature range generated by the water-cooled waveguide applicator. Though this result is interesting, since neither the discharge gas, applicator type or operating frequency are similar to those used above, it is difficult to say whether this agreement is significant.

Direct comparison of the temperatures contained within Chapter 5 with those of Arata et al [14] is difficult since the applicator of Arata is not a cavity but rather a coaxial design. The same is true of the temperatures determined by Murayama [13]. Also the discharge gas used by Arata was nitrogen, not argon. The temperatures determined by both Arata and Murayama were not directly measured but determined from methods such as electron density measurements and the Saha equation. Thus the temperatures were derived with the assumption that the plasma was in a state of LTE. Acknowledging this, it is possible however to look at the trends contained in the data and compare this to the data obtained using Rayleigh scattering techniques. Murayama obtained the gas temperature in the mantle of 200 and 400 W plasmas from measurements of the Doppler broadening of the CaIIλ3934 Angstrom line, where calcium chloride was used to seed the plasma. The values obtained were 4500±900 K and 4600±1000K respectively.
These two temperatures are within the range of temperatures determined using laser scattering techniques though an order of magnitude more power was necessary to achieve an identical temperature using the water-cooled waveguide applicator. If both applicators produced similar plasmas then this discrepancy may have been due to the probe element calcium. Calcium has a much lower ionisation potential than argon and this would have had an impact on the temperature measured since the ionised calcium would obtain energy from the oscillating electromagnetic field of the microwaves as well as from collisional processes. From the work by Arata et al, Figure 41 is qualitatively similar in form to Figure 147, that is, the temperature increases with axial distance before decreasing for a given power and discharge gas flow rate. The temperature measured by Arata is the electron temperature even though it is referred to as the plasma temperature. The distinction is made between the electron temperature as measured by Arata and Murayama and the gas temperature as measured by Murayama and that measured using laser scattering since the electron temperature is generally higher than the gas or heavy particle temperature. Strictly speaking, this is true only when the plasma is not in LTE as happens in the majority of cases. Arata justifies the assumption of LTE for nitrogen and air at atmospheric pressure from generally stated arc plasma results.

The plasma temperatures as a function of microwave power, as given in Figure 42 and Figure 145, are also qualitatively similar in form. The temperature discrepancy here is a factor of two and both curves show the same linear dependence over the power regime examined. Figure 43 and Figure 164 show the plasma temperature as a function of radial distance. In both instances, the temperature profile as a function of radial distance is qualitatively similar. Arata also examines the plasma temperature as a function of
discharge gas flow rate, Figure 44. Again, the form of this curve is qualitatively similar to that of Figure 146. It should be stated here that although the discharge gas flow rates used for this thesis were an order of magnitude smaller than those of Arata, the velocity of the discharge gas was two orders of magnitude larger. This is due to the much smaller effective cross section of the ionisation chamber as compared to the coaxial applicator of Arata.

The fact that the plasma temperature dependence curves are similar for the two different applicator types, as well as discharge gases, implies that after the plasma leaves the excitation region it has no memory of how it was formed and thus decays in an identical manner for any type of applicator. As the temperature measured by Arata was not the gas temperature, again direct comparison cannot be made unless the thermodynamic properties of the plasma are known. The literature has both cases in support of [13, 58] and against [4, 59] LTE conditions existing in a microwave generated plasma. In actuality, the LTE condition most likely varies both axially and radially along the plasma beam as the plasma has had more time to thermalise the further from the exit nozzle the temperature is measured.
5.4 Conclusion.

This chapter has dealt with the determination of the plasma temperature through laser scattering techniques and has shown that the temperature recorded is a function of microwave power, discharge gas flow rate, applicator coolant flow rate, height from the plasma exit nozzle and the state of tuning of the applicator. More specifically, the plasma temperature increased with increasing microwave power, decreased coolant flow rate and decreased height from the nozzle. For a temperature of 8500 K, the error associated with this measurement is of order 25%. This falls to less than 1 % for temperatures in the 500 K region. This is the first time that laser scattering techniques have been applied to a microwave generated plasma for the purposes of temperature determination.

The maximum temperature recorded was 7200 K and corresponded to measurements taken on a 5.75 kW argon plasma beam, 2 mm away from the plasma exit nozzle. At these temperatures, the equilibrium composition of the argon plasma consists mainly of excited neutrals with less than 0.01 % of singly ionised argon [60]. Two-dimensional temperature scans through the plasma beam have shown that a line scan of plasma temperature taken through the plasma at each standoff distance could be successfully modelled by a Gaussian distribution. This was done at various distances from the exit nozzle to produce a spectral map of the plasma showing temperature contours in 500 K steps. The temperature gradient from the centre to the edge of the plasma beam decreased with distance from the excitation source of the plasma due to thermalisation of the plasma.
The ability of the microwaves to couple to the plasma depends on the flow rate of the coolant through the applicator and manifests itself in a variation in plasma temperature and plasma beam length. A higher coolant flow rate corresponded to a lower plasma temperature for a given microwave power and a shorter plasma beam length. The terms microwave power and plasma beam power are used interchangeably since it is assumed that essentially all the microwave power goes into producing the plasma as losses to the walls are negligible as is the level of reflected power.

Variation of the sliding short-load distance, or the tuning of the applicator, had little effect on the plasma temperature on the near side of the resonance position. However, after the resonance position was passed, the temperature of the plasma beam decreased rapidly with distance. This attribute is mirrored in the effect of sliding short-load distance on the plasma impedance tabulated in Table 10. The implication here is that the plasma temperature is a function of the load presented to the microwave source, which is in turn a function of the tuning of the system.

Temperatures determined by laser scattering techniques compared well with those determined using spectroscopic techniques in terms of the trends of temperature dependence as a function of external variables. The absolute values for the temperatures however did not though they were of the same order of magnitude. This was principally due to the measurement of different species by the two techniques. Specifically, laser scattering measures the temperature of the heavy particles within the plasma (both ions and neutrals) whereas the spectroscopic methods used generated an electron temperature through measurement of the electron density. This involved the assumption of LTE conditions existing within the plasma. Technically speaking, temperatures are
determined from density measurements using laser scattering techniques also and the assumption is the plasma behaves as an ideal gas. As the discharge gas is argon, this assumption is more valid than an assumption of LTE. The use of different discharge gases and applicator configurations also contributed to the discrepancy between the temperatures measured by the two techniques. The temperatures measured using laser scattering techniques were in better agreement with the gas temperatures than the electron temperatures reported in the literature indicating the plasma may not be in LTE. The temperature measurements presented provide strong evidence that the plasma is not in LTE. For example, Figure 165 shows the extent of the "visual beam" being associated with measured gas temperatures ranging from 3000 K to below 500 K.

The characterisation given in this chapter of the plasma beam temperature with microwave power, discharge gas flow rate, coolant flow rate, state of tuning and standoff distance is important in the application of the plasma beam to welding since fine control over the temperature of the beam as well as the heat input into the sample is critical to overall weld strength and quality.
CHAPTER 6. APPLICATION OF THE PLASMA BEAM TO WELDING OF SHEET STEEL.

6.1 Introduction.

As previously mentioned the goal of this thesis was to develop a microwave generated plasma device that could produce a beam of plasma capable of welding sheet steel. To that end, this Chapter describes the culmination of research efforts to attain that goal. Also contained in this Chapter are a set of experiments that were used to develop an analytical model of the plasma beam operating conditions necessary to achieve maximum weld strength in 1 mm G550 uncoated cold rolled sheet steel [61]. The microstructure of the welded steel is examined, as is the weld strength across the fusion zone. Weld strength tests were performed to Australian Standard AS2205 (Transverse butt tensile test) and hardness test to Australian Standard AS1817 (Vickers hardness test). All samples were autogenously butt-welded and analytical modelling was performed using Response Surface Modelling (RSM). RSM was used to model the dependent variable response using mathematical models which were then used to predict new response values, determine optimal variable settings and to produce contour plots. The model generated is not so much predictive but a multiple regression best fit of the variables to the weld strength of the generated welds.

The microwave plasma beam parameters that have an impact on weld quality, as well as the ability to weld, have been quantified in Chapters 4 and 5. These are plasma beam temperature and beam pressure. The beam temperature is a function of microwave power, discharge gas flow rate, the state of tuning of the applicator, standoff distance and the ionisation chamber coolant flow rate. To optimise the quality of the weld being
performed, as much heat as possible needs to be used so as to allow increased welding speeds. Faster welding speeds mean reduced heat input per unit length into the sample which limits the size of the heat affected zone (HAZ). Beam pressure is also a function of microwave power and discharge gas flow rate. The complex inter-relationship between these variables and their impact on weld performance was the principal impetus for determining the way each variable impacted on the beam properties in previous chapters.

6.2 Results of welding trials.

In order to perform a successful weld it was necessary to first determine what combination of microwave power, discharge gas flow rate and welding speed should be used. A sample measuring 180 x 120 mm was clamped in the welding table and a combination of the aforementioned variables chosen such that the sample would melt with full penetration when passed below the plasma beam. For a microwave power of 3.1 kW, this corresponded to a gas flow rate of six litres per minute and a welding table translation speed of approximately 150 mm per minute. This technique was easy and relatively quick to perform. Firstly, the power and gas flow rate were chosen and then the sample set in motion below the plasma beam. If a cutting action ensued the table speed was increased incrementally until the desired melting action was achieved. The single sample was then replaced by the two samples to be welded.

To best simulate industrial conditions, sample preparation was kept to a minimum and all samples were cut into blanks using shears. The samples were a uniform size, had dimensions of 90 x 120 mm and were prepared from 1 mm thick, uncoated mild steel.
The samples were mounted in the welding table shown in Figure 59 and were fixed in three places. The speed of the welding table was varied through computer control and the sample standoff distance was maintained at 5 mm for the duration of the experiment. The plasma beam was kept normal to the sample surface for the duration of the welds to maximise weld penetration.

![Micrograph](https://via.placeholder.com/150)

Figure 172. Micrograph and microhardness profile for a weld produced under the following conditions: microwave power=2.8 kW, welding speed=129 mm/min, discharge gas flow rate=5.5 l/min. The measured tensile strength was 403 MPa.

The micrographs shown in Figure 172 through to Figure 177 are indicative of the current set of welding experiments. The microhardness across the welded sample is also shown for each of these Figures, except in Figure 177 where no weld was achieved. The
data points from left to centre correspond to the following regions; parent material or plate, (HAZ) and fusion or weld zone. As can be clearly seen from all the welded samples, the micro-hardness has a minimum in the region of the HAZ. The HAZ of the welds generated using a microwave induced plasma beam can be further subdivided into fine grained and coarse grained regions [62]. This fine grain structure is due to the recrystallisation of the cold rolled ferrite grains at subcritical temperatures and reaustenisation at supercritical temperatures, followed by transformation on cooling to fine ferrite grains. The coarse grained HAZ is the result of significant growth of austenite grains adjacent to the fusion boundary, followed by transformation to relatively coarse ferrite on cooling. The slight increase in the microhardness of the fusion zone is due to the formation of bainitic and/or martensitic ferrite on fast cooling of the coarse columnar austenitic grains in the weld bead. These phases are relatively hard and brittle. Welding reduces the strength and hardness in the weldment relative to the cold rolled sheet. Under load conditions, the weld would fail in either the fine grained HAZ or in the weld region itself. This is the principal impetus for reducing the size of both the weld bead and the HAZ. This reduction can be achieved by increasing both the welding speed and the plasma beam power. The shape and width of the HAZ away from the fusion zone reflects the thermal profile of the weld.
Figure 173. Micrograph and microhardness profile for a weld produced under the following conditions: microwave power=2.8 kW, welding speed=129 mm/min, discharge gas flow rate=6.0 l/min. The measured tensile strength was 363 MPa.

Figure 172 and Figure 173 demonstrate the effect of discharge gas flow rate on the measured tensile strength when all else is kept constant. The microstructure is similar for both samples though there is a slightly higher number of larger grains Figure 173. The existence of these larger grains leads to the reduction in weld strength.

Figure 174 shows good fusion but poor alignment. The misalignment is due to limitations in the clamping mechanism of the welding table. This result is important because it shows that tight fit-up tolerances are not necessary for the plasma beam
system. This is an advantage over welding systems such as laser and reduced pressure electron beam welding.

Figure 174. Micrograph and microhardness profile for a weld produced under the following conditions: microwave power=3.1 kW, welding speed=140 mm/min, discharge gas flow rate=5.0 l/min. The measured tensile strength was 399 MPa.
Figure 175. Micrograph and microhardness profile for a weld produced under the following conditions: microwave power=3.1 kW, welding speed=151 mm/min, discharge gas flow rate=6.0 l/min. The measured tensile strength was 385 MPa.

Figure 175 and Figure 176 show the effect on the microstructure of varying the welding speed for a given gas flow rate and microwave power. The microhardness and weld strength is essentially the same for both samples even though there is a marked difference in the grain structure at the fusion zone. This difference is due to the various cooling rates of the HAZ and molten metal at different welding speeds. Note also the existence of the inclusion in Figure 176. As each welded sample is sectioned and polished only once, it is not clear whether this inclusion is indicative of the entire weld bead or an isolated occurrence. In all probability it is an isolated feature. Figure 177 shows a typical micrograph of a sample that has not been successfully welded because
the welding speed was too high or the microwave power too low. This sample was welded, inasmuch as when it was removed from the welding table it did not separate into the two blanks, even though there was no clearly defined fusion zone. Welds of this nature could be easily broken by fatigue bending along the "weld bead".

![Micrograph and microhardness profile](image)

Figure 176. Micrograph and microhardness profile for a weld produced under the following conditions: microwave power=3.1 kW, welding speed=161 mm/min, discharge gas flow rate=6.0 l/min. The measured tensile strength was 399 MPa.
Figure 177. Typical micrograph of an unsuccessful weld resulting from non optimum welding conditions.

At a microwave power of 3.4 kW and welding speeds less than about 0.11 m/min, a weld was not achieved due to the cutting action of the plasma beam. At speeds greater than about 0.19 m/min, there was not enough time for the metal to reach melting point before the beam had moved on. The opposite was true for the gas flow rate. A low gas flow rate would not provide enough energy to weld whereas a high flow rate would cut instead of weld. The increase in temperature provided by an increase in gas flow rate is a double edged sword since not only does the temperature rise but so too does the pressure exerted by the plasma on the weld pool. This can be readily seen in Figure 178. The plasma pressure increases as the square of the exit velocity of the plasma with exit velocity being a function of temperature. At high enough velocities, the combined effect of gravity and beam pressure overcomes the surface tension of the molten weld pool and a cutting action is initiated. This is also true as the power is increased for a given flow rate and weld speed, i.e. for a given flow rate, the exit velocity of the plasma increases as the power is increased thereby exerting a greater pressure on the weld pool or pressure transducer.
Figure 178. Effect of Plasma gas flow rate on plasma temperature and plasma pressure.

As discussed in Section 5.2, the levelling off of temperature with increasing flow rate in Figure 178 is due to the cooling effect of the extra gas. The excited or heated gas loses energy to the cool gas and with a limited amount of excitation energy, the overall temperature of the plasma beam is reduced. Below about 9 l/min, there is enough energy to excite the increase in gas afforded by the increase in flow rate.

Figure 179. Micrograph of butt welded samples of different thickness as used in tailored blank technology.
Figure 179 shows the results of butt welding two samples of differing thickness, 0.5 mm and 1.0 mm. The microwave power used for welding these two samples was less than that for two 1 mm samples being 2.1 kW. Welding of samples of different thickness is commonly used in the automotive industry and is referred to as tailored blank technology. Tailored blank technology is designed to keep car component weight down whilst still providing the key component strength by having thicker steel only in the regions necessary. Examples of this are the hinge and lock regions of door members.

In Figure 180, the results of welding two seriously misaligned samples are shown. As previously mentioned, this misalignment is due to limitations in the clamping mechanism of the welding table. Specifically, each sample is clamped in only three places leading to sample buckling as the welding progresses. This micrograph is included because it shows quite clearly the transformation of the grain structure resulting from the welding process.

The weld strengths for the various combinations of microwave power, welding speed and gas flow rate are tabulated in Table 11. Some combinations are duplicated for
The maximum strength obtained for a single weld was 423 MPa and was achieved with a microwave power of 3.4 kW, a speed of 0.161 m/min and flow rate of 5.5 l/min. The strength of the parent material is 600-700 MPa and the reduction in strength of the plasma beam weld is in part due to softening of the weld zone and in part due to undercutting.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Microwave Power (kW)</th>
<th>Welding Speed (m/min)</th>
<th>Gas Flow Rate (litres/min)</th>
<th>Weld Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
<td>0.183</td>
<td>5.0</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>3.4</td>
<td>0.161</td>
<td>5.0</td>
<td>286</td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
<td>0.172</td>
<td>5.0</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>3.4</td>
<td>0.183</td>
<td>5.5</td>
<td>236</td>
</tr>
<tr>
<td>5</td>
<td>3.4</td>
<td>0.161</td>
<td>5.5</td>
<td>423</td>
</tr>
<tr>
<td>6</td>
<td>3.4</td>
<td>0.172</td>
<td>5.5</td>
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<tr>
<td>7</td>
<td>3.4</td>
<td>0.183</td>
<td>6.0</td>
<td>359</td>
</tr>
<tr>
<td>8</td>
<td>3.4</td>
<td>0.161</td>
<td>6.0</td>
<td>370</td>
</tr>
<tr>
<td>9</td>
<td>3.4</td>
<td>0.172</td>
<td>6.0</td>
<td>360</td>
</tr>
<tr>
<td>10</td>
<td>3.4</td>
<td>0.161</td>
<td>6.0</td>
<td>368</td>
</tr>
<tr>
<td>11</td>
<td>3.4</td>
<td>0.183</td>
<td>6.0</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 11. Weld strength tabulated as a function of operating parameters for a 3.4 kW plasma beam.
Undercutting is inherent in butt-welded samples and leads to a reduction in sample thickness along the weld line and hence a reduction in welded sample strength. The weld strengths obtained are comparable with techniques such as mash seam welding; however the welding speed is too low by almost an order of magnitude for practical industrial applications. In order to increase the welding speed the energy density at the weld pool needs to be increased by an order of magnitude. This could be achieved by decreasing the exit nozzle orifice diameter from the current 3.2 mm down to 1 mm. This is left as an exercise for future researchers.

6.3 Modelling of Welding Parameters.

Using the experimental results from Section 6.2, it was possible to analytically fit the plasma beam operating conditions necessary to achieve maximum weld strength in 1 mm G550 uncoated cold rolled mild steel. Analytical regression analysis was performed using a computer software package based on Response Surface Modelling (RSM), with the dependent and independent variables used listed in Table 12. Preliminary welding trials showed that for each power setting there was a unique welding speed range that would result in acceptable welds. At the extremes of this range, the results of the fit can be biased since there may not be enough heat for fusion or too much resulting in a cutting action. This bias occurs since the software cannot differentiate between too much power or too little power when a low or zero weld strength is recorded. To overcome this problem, weld speeds were selected for the various power settings that gave acceptable welds. This resulted in variable combinations for the eleven welding experiments previously tabulated in Table 11. By maintaining a constant microwave power of 3.4 kW and a constant butt pressure of 535
kPa, the number of dependent variables could be reduced from four down to two. This was valid since preliminary welding trials showed that varying the operating pressure range between 220 and 850 kPa had no significant influence on the weld strength at various power levels. The resultant dependent and independent variable ranges are listed in Table 12.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave Power</td>
<td>3.4 kW</td>
</tr>
<tr>
<td>Welding Speed</td>
<td>0.161 to 0.183 m/min</td>
</tr>
<tr>
<td>Gas Flow Rate</td>
<td>5 to 6 litres/min</td>
</tr>
<tr>
<td>Butt Pressure</td>
<td>535 kPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Strength</td>
<td>0 to 600 MPa</td>
</tr>
</tbody>
</table>

Table 12. Dependent and Independent variables used for optimising welding parameters.

Figure 181, Figure 182 and Figure 183 represent the analytical fit for welding speed and discharge gas flow rate data obtained from eleven weld experiments given in Table 11. Figure 181 gives the weld strength as a function of discharge gas flow rate, Figure 182 the weld strength as a function of welding speed and Figure 183 a contour plot of weld strength as a function of discharge gas flow rate and welding speed. Also shown on these Figures is the weld strength data to which the analytical fit was performed. At
first glance the fit to the data given in Figure 181 seems poor and if it were not a multiple regression then this would be the case. However, a multiple regression was performed and as such there are compromises between the fit for each dependent variable in order to obtain the best overall fit to the data.

Figure 181. Weld strength as a function of discharge gas flow rate for a microwave power of 3.4 kW and a welding speed of 172 millimetres per minute.

From Figure 183 it can be seen that maximum weld strength of 400+ MPa was achieved for a microwave power of 3.4 kW, for a flow rate of between 5.3 and 5.9 l/min, and a welding speed of less than 0.166 m/min. This is not unexpected since a lower welding speed was found to be necessary to generate a sound weld for the range of microwave powers examined.
Figure 182. Weld strength as a function of welding speed for a microwave power of 3.4 kW and a discharge gas flow rate of 5.5 litres per minute.

Figure 183. Contour plot of weld strength as a function of discharge gas flow rate and welding speed.
6.4 Comparison with Conventional Welding Techniques

To determine where the plasma beam sits with respect to commercially available autogenous welding systems it is necessary to present an overview of the capabilities of each of the competing systems in terms of the types of materials that can be welded. An excellent comparison between the microwave induced plasma beam system and commercially available welding systems can be found in Reference 63. These systems are:

- Gas Tungsten Arc Welding (GTAW or more conventionally TIG)
- Plasma Arc Welding
- Laser Welding
- Electron Beam Welding (Reduced Pressure Systems)

Gas Tungsten Arc Welding (GTAW) welding systems can be used to autogenously weld most metals. The metals commonly welded are steels (carbon, alloy, and stainless), copper based alloys, beryllium, nickel based alloys, refractory and reactive metal alloys, and cast irons. GTAW is especially suited to welding aluminium alloys and magnesium alloys since the arc can be used to clean and remove the refractory surface oxides electronically. Plasma arc welding systems are capable of welding low carbon steels and stainless steels, nickel based superalloys, titanium and zirconium based alloys, refractory metals, and aluminium based and copper based alloys. Laser welding systems are capable of welding low carbon and stainless steels, nickel based superalloys, titanium and zirconium based alloys, refractory metals, and aluminium based and copper based alloys. There are difficulties for lasers to weld aluminium based and copper based
alloys due to their high light reflectivity and high thermal conductivity. Electron beam welding systems are capable of welding in both vacuum and reduced pressure environments. Electron beam welding systems are capable of welding low carbon and stainless steels, nickel based superalloys, titanium and zirconium based alloys, refractory metals, and aluminium based and copper based alloys. Electron beam welding systems have difficulty welding high vapour pressure metals such as cadmium and zinc. The microwave induced plasma beam welder is similar to plasma arc welding system in operation and should be able to weld all metals that plasma arc welding systems are capable of. One of the great strengths of this plasma beam welder over many conventional welding systems is the ability to weld non-conducting workpieces. This opens the arena of welding refractory/metal composite as well as ceramic/ceramic components. Of the welding systems listed above, laser and electron beam welding are capable of welding non-conducting workpieces though the capital costs of such systems are orders of magnitude greater than the microwave plasma beam welder. The welding of non-conducting workpieces is not pursued as it outside the scope of this thesis.

Each of the welding systems examined have both advantages and disadvantages in terms of capabilities, operation etc. These are examined below:

For GTAW the advantages are: High quality welds can be produced for low capital cost. The system can weld most metals and can weld dissimilar metals together with or without filler. Because the arc operates in an inert environment, it is considered the best currently available method to weld reactive or refractory metals.
For GTAW the disadvantages are: GTAW is less economical than some other processes for welds greater than 10 mm in thickness due to lower metal deposition rates. The maximum useful speed is limited by undercut and weld bead humping. This can be overcome by using multiple electrodes, known as multi-cathode TIG, although this is costly as a separate power source is required for each electrode.

For plasma arc welding the advantages are: Plasma arc welding, though similar to GTAW, produces a collimated plasma arc with a greater energy density than GTAW. The collimated plasma arc has a better standoff distance tolerance and can weld with less likelihood of tungsten contamination. Thicker welds can be accomplished in a single pass using the keyhole mode.

For plasma arc welding the disadvantages are: The great number of welding set-up variables requires a greater level of operator skill. The plasma torch nozzle requires regular maintenance for consistent weld quality and sample fit-up or joint alignment needs to be better than for GTAW welding.

For laser welding the advantages are: The heat affected zone and detrimental metallurgical effects are minimised because the heat input is highly localised due to the very small beam dimensions, diameter < 0.15 mm. High welding speeds means the distortion of the workpiece is minimal. The system is ideal for close fit-up autogenous welding because of the reduced need for joint preparation and filler wire. The optical systems of the laser allow the beam to reach difficult areas not accessible to other systems as well as allowing closely spaced welds.
For laser welding the disadvantages are: The requirement of accurate positioning and control of the weld joint with respect to the laser beam. The maximum practical weld joint thickness in steel is 19 mm. Additionally, aluminium and copper alloys are difficult to weld due to their high thermal conductivity and light reflectivity. For thin section welds, the high cooling rates at the weld can cause metallurgical problems.

For reduced pressure electron beam welding the advantages are: The electron beam welding system has high efficiency since the electrical energy is converted directly into beam energy. The beam is capable of single pass welding of thick joints. For instance in air, it is capable of welding steel 25 mm thick at 56 kW with a 16 mm working distance and a speed of 1.9m/min. Due to the narrow beam, the heat affected zone is minimal whilst providing reduced distortion and deep penetration. Electron beam welding systems can easily weld aluminium and copper alloys as well as refractory metals due to the low total thermal energy input.

For reduced pressure electron beam welding the disadvantages are: The working distance between weld joint and beam source must be kept to less than 38 mm due to beam dispersion at atmospheric pressure. This close working distance limits the geometry of the weld that can be made and there is also the difficulty of tracking the weld seam whilst welding. High depth to width ratio welds require precision machining with tight fit-up tolerances and accurate alignment. To prevent deflection of the electron beam during welding, the workpiece needs to be demagnetised prior to welding. Radiation shielding is also necessary since x-rays are generated by the interaction of the electron beam with the weld sample. Rapid solidification of the weld
metal can cause cracking of the weld in some metals and configurations. The large physical size of the electron beam generator limits welding agility.

For microwave induced plasma beam welding the advantages are: The plasma jet welding system is able to do the same types of welds as the plasma arc welding system. It has a better standoff distance and weld penetration than plasma arc due to the highly collimated beam with no possibility of tungsten contamination. The plasma beam is inherently safer than the plasma arc since no currents flow from the beam to the sample and less radiation is produced (UV, visible, and x-ray) in all but the 2.45 GHz microwave band. The profile of the plasma beam can be elongated to produce pre and post weld treatment with minor modifications to the ionisation chamber assembly. Also, powder or reactive gases can be easily added to the plasma discharge gas stream. The ability to weld non-conducting materials, when coupled to the ability to dial a beam temperature from ambient up to 7000 K, enables the plasma beam system to weld plastics, ceramics and metals.

For microwave induced plasma beam welding the disadvantages are: There are more and different process weld variables than GTAW or plasma arc welding. The system, in its current incarnation, cannot be used manually as with the GTAW and plasma arc methods. The low cost non-flexible microwave waveguide limits welding agility and necessitates the requirement of automated sample jigs as in laser and electron beam welding.
6.5 Conclusion.

The prototype microwave induced plasma beam device developed for materials welding applications has proven successful in welding 1 mm sheet steel. The operating parameters necessary to achieve a maxima in weld strength for a microwave power of 3.4 kW are; plasma gas flow rate - 5.5 l/min; welding speed - 0.161 m/min. Regression analysis on the experimental data has shown that an acceptable weld can be produced at 3.4 kW when operating within the welding envelope which includes a flow rate of between 5.3 and 5.9 l/min and a welding speed of less than 0.166 m/min but greater than 0.161 m/min. Operating within these confines will produce a weld with two-thirds the strength of the parent material which is consistent with mash seam welding techniques. Mash seam techniques can weld an order of magnitude faster than the present microwave induced plasma beam system meaning that use of this technology in an industrial application is limited. To weld an order of magnitude faster the energy density at the weld pool would need to be an order of magnitude greater. This increase in energy density could be achieved by reducing the internal diameter of the ionisation chamber from 3.2 mm to 1 mm. This corresponds to a change in cross-sectional area of the beam by a factor of approximately 10. The ability to increase the microwave energy, and corresponding beam energy, from 3.4 kW to 6 kW should more than make up for any energy losses involved with the smaller diameter ionisation chamber. Pre and post weld treatment of the weld bead can be accomplished by beam shaping techniques involving minor modifications to the ionisation chamber. The ability to weld non-conducting materials, when coupled to the ability to dial a beam temperature from ambient up to 7000 K, enables the plasma beam system to weld plastics, ceramics and metals. A summary and comparison of the various welding techniques available is given in Section 6.4 to emphasise the characteristics of microwave plasma welding.
CHAPTER 7. CONCLUSION.

As discussed in Chapter 1, applications for microwave induced plasmas are diverse; research ranges from use as a heat source to applications in the area of space propulsion. By far the most interest for microwave induced plasma applications comes from the spectroscopy community. Microwaves are capable of generating high power, inert, stable and luminous plasmas at atmospheric pressure. The use of a large diameter ionisation chamber (or cooling of the tube) leads to reduced atomic and molecular emission since ablation of the tube walls does not occur from contact with the plasma thereby increasing sensitivity and reducing detection limits.

Though microwave plasma applicators have been in development since the late 1940’s, applicators with small diameter plasma ionisation chambers and operating at high powers have not been described in the literature. Application of microwave generated plasmas to welding of sheet steel is also not covered in the literature. This is because a microwave induced plasma applicator capable of welding sheet steel requires: i) a well collimated beam with a diameter as small as possible, ii) a plasma beam with sufficient power to rapidly melt steel, iii) a discharge gas flow rate low enough to ensure molten metal is not ejected from the weld pool, iv) and the ability to shape the cross section of the plasma beam. A small diameter, well-collimated beam can be most easily produced by use of a ionisation chamber that has a small inside diameter. This translates to using a cavity applicator, as there is no provision for a ionisation chamber in a coaxial design.
Chapter 2 discussed experimental design and development of equipment and procedures necessary for production of a suitable plasma. It was shown that a cylindrical resonant cavity applicator suitable for materials welding applications was not feasible. The use of rapid prototyping, a network analyser and high power tests showed that the maximum efficiency attainable for the investigated cylindrical cavity design was only 60%. Rapid prototyping of the cavity involved sculpting the desired cavity from Polystyrene foam and then wrapping it in conducting aluminium tape. When examined using the network analyser, these prototypes behaved as machined aluminium cavities but take a fraction of the time to construct. Being made from foam however, meant that operation was limited to low power tests only. The low power limitation meant that it was not possible to use the network analyser to model the cavity whilst generating a plasma. To overcome this, a method was developed whereby a small diameter brass tube was used to simulate the plasma for the low power tests. The dimensions of the brass tube were selected such that it gave the same VSWR and load phase impedance when examined on the network analyser. Rapid prototyping of the cavity as well as simulation of the plasma by a brass insert allowed the electrical properties of the cavity to be determined at low powers.

High power tests were performed on a 100 mm long cavity fashioned from aluminium. The internal diameter of the cavity started at 60 mm and was increased in 2 mm steps until it reached 92 mm. For each of these increments a high power test was performed. Results of these measurements showed that it was possible to generate a plasma for each cavity I.D. when using argon as the discharge gas though these plasmas were not generated spontaneously. The electric field strength of the microwaves in the cavity was insufficient to cause dielectric breakdown in argon and thus a secondary mechanism was
necessary to initiate the plasma. In the case of pulsed power and an impure boron nitride ionisation chamber, this mechanism was thermionic emission of electrons from the heated tube. For the case of CW microwave power and either quartz or pure boron nitride as the ionisation chamber, it was necessary to insert a length of tungsten wire into the ionisation chamber to initiate the plasma.

It was also not possible to generate a plasma in a rectangular cavity with dimensions 45 x 45 x 43 mm because the dimensions are below cutoff, and thus insufficient microwave energy penetrates into the cavity to sustain a plasma.

In Chapter 3 the task of designing, building and testing a microwave plasma applicator suitable for welding applications was successfully completed using a waveguide applicator. The applicator is efficient, stable, operates at high powers and produces a highly collimated pencil like plasma beam. Routine operating efficiencies are greater than 98% without the use of a coupling aperture and extended operation at microwave power levels of 6 kW is possible. Before the development of this device, power levels for comparable applicators were limited to sustained operation below about 1 kW (a non-cooled version of the waveguide applicator operated with comparable efficiencies and stability as the water-cooled version but was limited to sustained operation below 1.5 kW). The design detailed here is unique in that it uses a small diameter water-cooled ionisation chamber to produce the high power collimated beam. A systematic investigation of these operating parameters is all but absent from the literature, and this is the first time that a high power plasma generated in a small diameter ionisation chamber has been demonstrated. Previous attempts by researchers at producing high power plasmas in small diameter ionisation chambers have resulted in failure due to
materials limitations. In effect, the ionisation chambers have melted due to thermal runaway. A provisional patent has been taken out on this applicator design.

In Chapter 4, parameters vital to welding are discussed and the plasma investigated accordingly. Welding has been an accepted method for joining disparate samples for many years and techniques have been optimised through trial and error methods. Aspects of welding are not well understood and as the use of a microwave induced plasma beam as a welding tool is absent from the literature, much work at characterising the beam’s properties as a function of external parameters is necessary. For example, the beam temperature and the pressure the plasma exerts on the molten weld pool are critical variables, prior knowledge of which is necessary to perform good quality welds.

The plasma/applicator system was characterised through determination of the electrical and physical properties of the plasma. VSWR measurements on the non-cooled waveguide applicator revealed that there was a small change in load impedance phase with power and a steady change in the load impedance magnitude and phase with increasing sliding short-load distance. Also revealed by the VSWR measurements was the existence of a resonance condition whereby the load impedance was matched to that of the source. This occurred for a sliding short-load distance of approximately 80 mm. Analysis of the resonance condition for the cases with and without a plasma revealed that the quality factor of the cavity, Q, was greater in the absence of the plasma. The broadening of the resonance peak by the plasma is advantageous when constructing an applicator since the cavity dimensions are not as critical and the applicator is less sensitive to drifts in the driving frequency. The gradient of the VSWR linear regression line as a function of microwave power was opposite on either side of the resonant
position. Starting with the sliding short-load distance less than the resonance length, as the sliding short was moved closer to the resonance position, the slope of the regression line becomes less positive and the magnitude of the VSWR was reduced for a given power level. Once the resonance position had been passed however, the slope of the regression line took on ever larger negative values and the VSWR for a given power increased. The positioning of external chokes on the applicator to reduce microwave leakage had no effect on the recorded VSWR. This is an important practical result since it means that an effective microwave plasma welder can be fitted with chokes to minimise microwave leakage without impacting on the operational characteristics of the device.

Measurements of the electrical impedance of the plasma beam enabled a simple electrical circuit model of the plasma to be developed. The plasma contained an inductive component that remained essentially unchanged with short circuit stub position and this component was interpreted as the inductive component of the plasma column. Modelling the plasma column as a perfectly conducting wire stretched across the broadwall of the waveguide gave excellent agreement between the experimentally and theoretically determined value for the inductive susceptance of the plasma beam at resonance. Measurements of the electrical impedance of the plasma as a function of sliding short-load distance revealed that the real component of the impedance had a sharp maximum around resonance whilst the imaginary component of the plasma impedance fell to zero at resonance. Neither the real nor the imaginary part of the plasma impedance varied much with microwave power over the range 0.5 through to 1.5 kW though both these properties did increase marginally with discharge gas flow rate.
VSWR measurements on the water-cooled waveguide applicator revealed that the VSWR decreased for microwave powers of 0.75 through 5 kW and discharge gas flow rates of 1 through 10 litres per minute. This is in agreement with the VSWR characteristics of the non-cooled applicator. It was also found that the real component of the plasma impedance increased with discharge gas flow rate as well as microwave power whilst the imaginary component decreased with increasing gas flow rate and microwave power. There was an important difference between the imaginary components for the non-cooled and cooled applicators. Specifically, the plasma beam produced by the non-cooled applicator contained an inductive component whereas the cooled applicator produced a beam with a capacitive reactance. It is suggested that this is the result of the physical arrangement of the cooling system having an electrical resemblance to a cylindrical capacitor. When compared to the literature, there was little agreement between the plasma impedance for a plasma generated by either the non-cooled or the water-cooled applicator. This is due to the use of different discharge gases as well as the different physical arrangements of the applicators. Both impedances reported in the literature had a capacitive reactance as did the water-cooled applicator as previously mentioned.

The overall plasma beam length increased with increasing microwave power as did the central core of the beam. As the discharge gas flow rate was increased for a given power, the overall beam length decreased whilst the core length remained essentially static. The heat capacity of the beam increased with increasing power as would be expected. However, the relative temperature of the beam as a function of discharge gas flow rate had a concave downward structure with a maximum beam temperature corresponding to a discharge gas flow rate of 9 litres per minute. For a given
microwave power and discharge gas flow rate, the plasma temperature decreases with increasing standoff distance as would be expected. The pressure the plasma beam exerted on the workpiece was measured using a differential pressure transducer. Results indicated that the pressure exerted by the beam increased with increasing discharge gas flow rate and increasing microwave power. This characterisation is of interest because this pressure affects the weld quality and if too great leads to cutting rather than welding. It is shown that an adequate range of pressures for welding is available.

In Chapter 5 it is shown that characterisation of the plasma beam temperature with microwave power, discharge gas flow rate, coolant flow rate, state of tuning and standoff distance is important in the application of the plasma beam to welding since fine control over the temperature of the beam as well as the heat input into the sample is critical to overall weld strength and quality.

Quantitative determination of the plasma temperature, performed using laser scattering techniques, has shown that the temperature recorded is a function of microwave power, discharge gas flow rate, applicator coolant flow rate, height from the plasma exit nozzle and the state of tuning of the applicator. More specifically, the plasma temperature increased with increasing microwave power, decreased coolant flow rate and decreased height from the nozzle. As far as can be determined from the literature, this is the first time that laser scattering techniques have been applied to a microwave generated plasma for the purposes of temperature determination. The maximum temperature recorded was 7200 K and corresponded to measurements taken on a 5.75 kW argon plasma beam, 2 mm away from the plasma exit nozzle. Two-dimensional temperature scans through the plasma beam have shown that a line scan of plasma temperature taken through the
plasma at each standoff distance could be successfully modelled by a Gaussian
distribution. This was done at various distances from the exit nozzle to produce a
spectral map of the plasma showing temperature contours in 500 K steps. The
temperature gradient from the centre to the edge of the plasma beam decreased with
distance from the excitation source of the plasma due to thermalisation of the plasma.

The ability of the microwaves to couple to the plasma depends on the flow rate of the
coolant through the applicator and manifests itself in a variation in plasma temperature
and plasma beam length. A higher coolant flow rate corresponded to a lower plasma
temperature for a given microwave power and a shorter plasma beam length. The terms
microwave power and plasma beam power are used interchangeably since it is assumed
that essentially all the microwave power goes into producing the plasma as losses to the
walls are negligible as is the level of reflected power.

Variation of the sliding short-load distance, or the tuning of the applicator, had little
effect on the plasma temperature on the near side of the resonance position. However,
after the resonance position was passed, the temperature of the plasma beam decreased
rapidly with distance. This attribute is mirrored in the effect of sliding short-load
distance on the plasma impedance. The implication here is that the plasma temperature
is a function of the load presented to the microwave source, which is in turn a function
of the tuning of the system. Relative temperatures determined using indirect techniques
were in agreement with those determined using Rayleigh scattering in terms of the
dependence of the temperature on the operating variables.
Temperatures determined by laser scattering techniques compared well with those determined using spectroscopic techniques in terms of temperature dependence as a function of external variables. The absolute values for the temperatures however did not though they were of the same order of magnitude. This was principally due to the measurement of different species by the two techniques. Specifically, laser scattering measures the temperature of the heavy particles within the plasma (both ions and neutrals) whereas the spectroscopic methods used generated an electron temperature through measurement of the electron density. This involved the assumption of local thermodynamic equilibrium (LTE) conditions existing within the plasma. Strictly speaking, temperatures are determined from density measurements using laser scattering techniques also though the assumption was that the plasma behaves as an ideal gas. As the discharge gas was argon, this assumption was more valid than an assumption of LTE. The use of different discharge gases and applicator configurations also contributed to the discrepancy between the temperatures measured by the two techniques. Gas temperature measurements were in better agreement than the electron temperatures reported in the literature indicating the plasma may not be in LTE. It is clear from this work that both the range and distribution of temperatures available from the microwave plasma are in principle sufficient for welding applications.

In Chapter 6, the suitability of microwave plasmas for welding is demonstrated by the prototype microwave induced plasma beam device, developed for materials welding applications, proving successful in welding 1 mm sheet steel. The operating parameters necessary to achieve a maxima in weld strength for a microwave power of 3.4 kW are; plasma gas flow rate - 5.5 l/min; welding speed - 0.161 m/min. Regression analysis on the experimental data has shown that an acceptable weld can be produced at 3.4 kW
when operating within the welding envelope which includes a flow rate of between 5.3 and 5.9 l/min and a welding speed of less than 0.166 m/min but greater than 0.161 m/min. Operating within these confines will produce a weld with two-thirds the strength of the parent material which is consistent with mash seam welding techniques. The ability to weld non-conducting materials, when coupled to the ability to ‘dial a beam temperature’ from ambient up to 7000 K, enables the plasma beam system to weld plastics, ceramics and metals. Strengths and weaknesses of various welding techniques, including microwave welding, are given in Section 6.4. The most likely applications for microwave plasma welding are applications where fine control over sample heat input is required or where heat energy needs to be “beamed” to inaccessible locations. The non-transferred nature of the microwave plasma beam also means that application to advanced ceramics welding is now possible.
CHAPTER 8. SUGGESTIONS FOR FURTHER WORK.

8.1 Introduction.

Now that the problems of creating and maintaining a high power, stable atmospheric pressure plasma beam have been overcome, the obvious question is "Where to from here?" Further work on the microwave plasma can be broadly divided into two parts. The first is further development and characterisation of the plasma beam and the second, applications of the beam.

8.2 The Use of Different Discharge Gases.

Characterisation of the beam has not been performed for different discharge gas combinations and or mixtures. The addition of hydrogen to the discharge aids in wetting whereas oxygen increases available heat through exothermic processes. Different discharge gases will change the operating parameters of the plasma beam which will have an impact on welding performance.

8.3 Increasing the Energy Density at the Weld Pool.

To bolster industrial acceptance of the microwave plasma beam as a viable welder, welding speeds need to be increased. Mash seam techniques can weld an order of magnitude faster than the present microwave induced plasma beam system meaning that use of this technology in an industrial application is limited. To weld an order of magnitude faster the energy density at the weld pool would need to be an order of magnitude greater. This increase in energy density could be achieved by reducing the internal diameter of the ionisation chamber from 3.2 mm to 1 mm. This corresponds to
a change in cross-sectional area of the beam by a factor of approximately ten, thereby leading to an increase in the energy density at the weld pool by a factor of ten. The ability to increase the microwave energy, and corresponding beam energy, from 3.4 kW to 6 kW should more than make up for any energy losses involved with the smaller diameter ionisation chamber.

8.4 Beam Shaping Techniques.

Pre and post weld treatment of the weld bead can be accomplished by beam shaping techniques involving minor modifications to the ionisation chamber. Essentially the internal cross-section of the ionisation chamber is machined into an oval instead of a circular cross-section. In doing so, the leading edge of the beam acts to preheat the sample, the core of the beam then creates the weld pool and the trailing edge of the beam performs the post weld heat treatment.

8.5 Application to Welding Steel.

To date, efforts at welding have concentrated on welding uncoated mild sheet steel. The applicability of welding coated sheet steel needs to be assessed as there is considerable interest from industry for such a process. The ability to weld through zinc and zinc/aluminium alloy coatings will save both time and money since post weld processing is eliminated (whilst cutting zinc coated steel with the plasma beam system, it was noted that the molten zinc coating flowed back to the cut edge re-solidifying to form a protective layer).
8.6 Application to Welding Ceramics.

The non-transferred nature of the microwave plasma beam means it is ideally suited to the welding of ceramics. The industrial ceramic Alumina, Al₂O₃, was easily melted with the plasma beam and rudimentary welding of 9 x 6 mm (O.D. x I.D.) alumina tube was performed. The plasma beam was also used as a form of drill to create a 1.5 mm diameter hole through the wall of the tubing. A highly energetic plasma beam has distinct advantages over conventional microwave plasma joining and brazing techniques since the beam can be directed at the interface between the two samples to be joined thereby raising only this region to the temperatures necessary for fusion to occur. Development in this area is a natural progression from welding of conducting samples.

8.7 Application to Welding of Plastics.

Again, the non-transferred nature of the plasma beam means it can be used for welding plastics. The non-cooled applicator was used to weld 0.4 mm polyethylene sheet by detuning the system. At a later stage, the water-cooled applicator was used to weld thick walled (30 mm) polyethylene pipe. This experiment was not exhaustive and was performed only as a demonstration of “proof of principle”. The ability to “dial a temperature” and have that temperature distributed along a beam makes the microwave plasma beam unique in this ability. By comparison, an oxy-fuel flame burns at essentially a non-variable temperature far in excess of the fusion temperature of all plastics.
8.8 Application to Chemical Vapour Deposition of Diamond Films.

Chemical vapour deposition, CVD, of diamond and diamond-like films at atmospheric pressure using a high power microwave beam as both the discharge and carrier gas is largely absent from the literature. The welding vessel was constructed to facilitate flexibility of use since it can also be used for controlled atmosphere experiments such as CVD. All that is necessary is the addition of a gas manifold system, a water-cooled sample stage and appropriate oxygen level detectors.

8.9 Application to Plasma Spraying.

The hollow cylindrical design of the ionisation chamber places it in an ideal position to be used for plasma spraying applications. There is no central electrode to interfere with the flow of the discharge gas and metallic, reactive alloy, plastic and other non-conducting powders can be fed into the discharge gas flow upstream from the discharge region. The molten material is then carried forth to the substrate by the flow of the plasma. As a variation on plasma spraying on substrates, it is totally feasible to direct the plasma stream upwards and have microspheres form from precipitates of the molten powder allowed to cool as they fall earthward. This would obviously need to be performed within a clean collection vessel. As an example of a possible application, sub-micrometre titanium spheres could be used instead of grease as a lubricant in harsh industrial environments.
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Figure 1. General Assembly view of the three stub tuner.
APPENDIX B.

Engineering Drawings of the Plasma Beam Applicator and Components

Figure 185. Water-cooled waveguide applicator engineering detail.
Standard Waveguide Flange

Vacuum/Pressure vessel lid constructed from 10 mm aluminium plate. Solid plate machined and welded to uprights to form a waveguide chamber.

Hole drilled from underside and tapped. NB Hole not to pierce upper surface. Diagonally opposite hole similar.

Figure 186. Vacuum/Pressure vessel lid engineering detail. Plan view.
Figure 187. Vacuum/Pressure vessel lid engineering detail. Front view.
Figure 188. Vacuum/Pressure vessel lid engineering detail. Side view.
Figure 189. Vacuum/Pressure vessel engineering detail.
Figure 190. Welding table engineering detail. Front view.
Figure 191. Welding table engineering detail. Top view.
Figure 192. Welding table and mounting unit engineering detail. Side view. To fit inside vacuum/pressure vessel.
Figure 193. Welding table in mounting unit and positioned in vacuum/pressure vessel.

Top View.
Figure 194. Welding table in mounting unit and positioned in vacuum/pressure vessel.

Front View.