Microwave Energy for Plastic Disposal

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7th November 2021

Prepared for:
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Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Bachelor of Science degree in Electrical Engineering

Abstract

Plastic materials are used extensively throughout the world in many different industries, with an estimate of 12 billion tons to have been produced by 2050. Over recent years there has been a push to recycle these materials to reduce the amount that fills up dumps, with limited success. Researchers have continuously attempted to find new techniques to produce valuable products from used plastic materials, one of note being the use of microwave energy to power catalytic decompression of Polyethylene into Hydrogen gas and Carbon nanotube structures by *Xiangyu Jie et al [6]* . The findings of this paper sparked interest of researchers at the University of Cape Town's Chemical Engineering Department and thus they needed a device capable of providing microwave energy to reproduce and possibly improve on the work of *Xiangyu Jie et al.*

This project deals with the design of a device capable of providing the microwave energy for experiments, focusing on the electromagnetic, electronics and construction design of such a device. The crux of this device is the resonant cavity in which the plastic-catalyst mixture is inserted and the electric and magnetic fields are shaped to ensure the maximum amount of energy can be absorbed. Drawing on various literature sources and their differing design philosophies, two major designs emerged. These were then simulated and their performance evaluated, from which the best design was selected.

The selected design is then taken further into an entire physical design of the cavity, the housing of the electronics responsible for supplying the microwave energy and the user interface. The key focus of the designs being safety and ease of operation in a laboratory environment.

Plagiarism Declaration

1. I know that plagiarism is wrong. Plagiarism is to use an other's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this final year project report from the work(s) of other people, has been attributed and has been cited and referenced.
3. This final year project report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof.

Name: Jason Hillebrand
Signature:
Date: 31 October 2021

Acknowledgements

I would like to start by thanking my supervisor Dr Stephen Paine for his continued guidance and support throughout this project. The ability to call upon you at seemingly any hour and getting great feedback so rapidly heavily assisted me in the completion of this project.

I would also like to thank Associate Professor Nico Fischer from the department of Chemical Engineering for initiating this project and always being available for consultation regarding what they needed, helping me to create something that truly met the Chemical Engineering Departments requirements.

To my family, thank you for all the love and support throughout the years of this degree. Always willing to be a wall to bounce ideas off and helping me keep the ship on a steady course.

Finally I would like to thank my girlfriend Ashleigh for keeping me level headed, the constant supply of good laughs and the push to help me get through it all. I love you and thank you.

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1 Introduction

This report details the design, simulation and manufacturing of a microwave device to be used for experiments regarding to plastic decomposition with catalysts. This project was conducted in consultation with the Chemical Engineering Department and is performed as a undergraduate engineering degree final project.

1.1 Background

Plastic materials are extensively used throughout the world at a continuously rising rate. Over the last half century it is estimated that 4.9 billion tons of plastic have been produced and is expected to rise to 12 billion tons by 2050. With no efficient way of recycling these materials a majority of this waste has accumulated in landfills and natural environments. Researchers have been exploring various ways to turn this plastic waste into value-added products making the recycling of these materials financially viable.

Researchers *Xiangyu Jie et al.* published a paper showing the use of microwave initiated catalytic deconstruction of plastic polymers into hydrogen gas and predominantly multi-walled carbon nanotubes[6]. Both of these products are highly valuable due to numerous industry applications for both. This proof of concept opens the doors for recycling of plastics to become a profitable and thus self-sustaining endeavour.

The Chemical Engineering department aim to first validate this paperer's findings, and then develop further upon this idea. To do so they need a device capable of providing the microwave energy similar to that used in the original paper, from there alternative ideas and optimisations can be explored.

1.2 Objectives

This projects main objective is to design, simulate and build a device capable of providing high-power microwave energy for laboratory experiments regarding plastic decomposition. The device will be designed to maximize the amount of energy absorbed by the target material, keeping in mind the properties of this material may change and thus change the performance of the device. This device will be operated as laboratory equipment and thus it must be simple to operate, repair and replacement for components must be easily available due to the nature of experiments being conducted. The device must be safe to operate and comply with safety standards related to high-power microwave devices.

1.3 Scope and Limitations

The scope of this project is the theoretical design, simulation and production of a device capable of providing high-power microwave energy for chemical reactions. Notedly the scope of project does not include the chemistry of the purposed reaction except for factors that effect the electromagnetic factors such as the electric permittivity and the magnetic permeability of the plastic materials to be reacted upon. Thus the full scope is to:

- Select a microwave energy source.
- Selection or design of power supply and user interface for the microwave energy source.
- Design and simulate a waveguide structure to maximize the amount of energy absorbed by target material.
- Design of enclosure/s to ensure safety compliance.

The limitations for this project are:

- Keeping the cost of production low to make the project viable for the end user.
- Simplicity of operation and safety as the users will not be knowledgable of microwave energy and radiation.
- Time constraints as this project must be completed within an academic semester period.
- Additional complications due to the COVID-19 pandemic, such as supply chains being disrupted and access to campus facilities being restricted.

1.4 System Requirements

Based off the objectives above and through consultation with the Chemical Engineering Department (the end user) the following system requirements were decided upon:

System Requirement ID	Description
SR.001	High-power microwave reaction chamber that focuses microwave energy into target material
SR.002	Temperature readings of the target material must be available during operation
SR.003	The device must be easy and safe to operate for non-trained individuals
SR.004	The device must be capable performing the same experiment as *Xiangyu Jie et al. [6]*

Table 1: System Requirements

1.5 Plan of development

This report initially outlines relevant literature for the electromagnetic sections for this project, starting with a brief overview and comparisons of available technologies and techniques that have seen use in literature. The focus will then shift to issues of power supply technologies and then finally onto the safety standards and regulations for microwave energy devices.

Chapter 3 details the electromagnetic and electronic design of the device. The microwave energy source selection and how it will be powered and controlled is decided upon. Following this, two resonant cavity design philosophies are explored; their design, simulation and a comparison of their performance is completed. Any safety and regulatory concerns will also be addressed here.

In Chapter 4 the best performing design is then incorporated into a housing design, that will encompass all the power electronics and user interface, and connect the cavity to the microwave energy source. The manufacturing process is decided upon and the relevant drawings are produced. Any user safety measures will also be designed and discussed in this section.

The report will then draw to a conclusion where an analysis on the project's findings in design and how well the final design satisfies the user requirements. Finally, the report will end with recommendation for further work on the topic.

2 Literature Review

Microwave energy is used in a multitude of applications in both industry and research with governmental regulations that ensure safety and compliance of devices . This chapter will introduce the literature of various sources relating to this project. Note that the frequency range considered 'microwave' is from $0.3GHz$ to $300GHz$ with the wavelength in free-space being defined as the $\lambda = \frac{c_0}{f}$, where c_0 is the speed of light in free-space.

2.1 Cavity Magnetron

To produce high power microwave radiation there are a variety of devices available at various frequency ranges. The most popular of which being the Cavity Magnetron, a high-powered vacuum tube oscillator that makes use of an electron stream in a magnetic field to produce microwaves. This electron stream is generated by a high-voltage direct, current which may be pulsed to achieve varying power output levels, to a heated cathode. The typical construction of such a device is shown below:

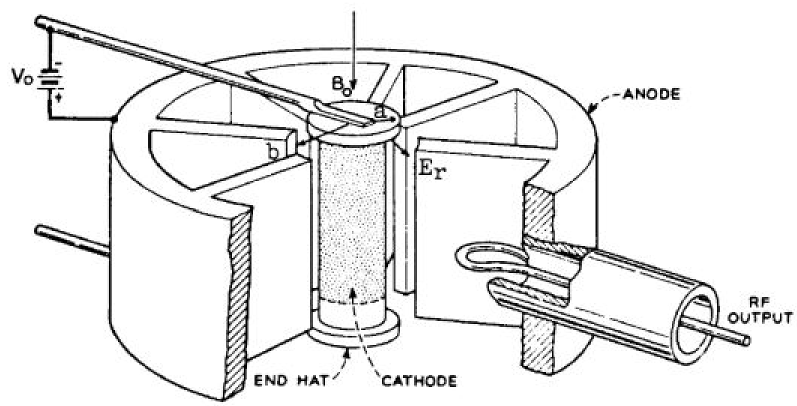


Figure 1: Cavity Magnetron structure[8]

The frequency of the RF output is governed by the resonant cavity shapes cut into the Anode. These cavities operate like multiple tuned LC circuits operating in "Π"mode, meaning that each sequential circuit is completely anti-phase of those adjacent to it, this produces a powerful alternating Electric field which is then guided out of the device via a metal loop to an antenna.

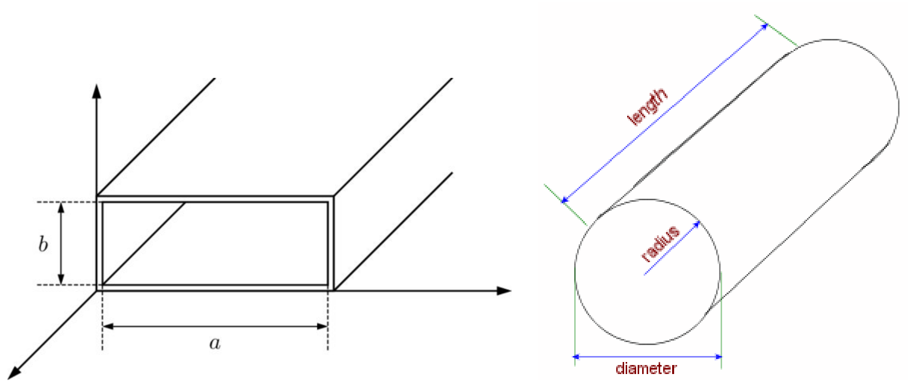
Cavity magnetrons are capable of operating from several hundred MHz to tens of GHz with output power ranges from a few hundred Watts to tens of Kilo Watts. The vast majority of cavity magnetrons available are tuned to $2.45GHz$ due to this commonly being used for food heating applications; however there are many applications that make use of full range capacity of the technology.

2.2 Waveguide Cavities for Electromagnetic Waves

Waveguides are structures used to direct and shape electromagnetic waves for a wide variety of applications. The most common, and of interest for this project, is the hollow conductive metal tube structure. The physical structure and the frequency of the wave being fed into the guide completely define the characteristics of the waveguide's effect on the wave.

Electromagnetic waves propagate through these waveguides in either Transverse-Electric (TE_{nm}) or Transverse-Magnetic (TM_{nm}) modes, these modes are formed due to the resonance of the cavity and have a impact on the energy distribution within the waveguide. The 'n' and 'm' characters denote the number of half-wave patterns across the height and length respectively of the waveguide, assuming the boundary conditions are met, the Electric and Magnetic fields are zero at the boundary of the waveguide[9]. There is a special case for these waveguides referred to as 'pill-box' where the terminals are shorted (a conducting material is attached blocking the transmission of the wave), this results in standing wave patterns to be formed in the cavity. To denote the pattern of these standing waves along the direction of propagation an additional character 'l' is added, giving rise the notation $\mathrm{TE_{nml}}$ and $\mathrm{TM_{nml}}$; however, this notation is not standard across all texts with some variations found across the literature[10, 9].

There are two shapes used for hollow conductive waveguides, these being rectangular and cylindrical. The desired mode can be calculated from the dimensions and the frequency used.



(a) Rectangular Waveguide with dimensions *'a'* and *'b'*

(b) Cylindrical Waveguide with dimensions *diameter (D)'* and *length (L)'*

Figure 2: Rectangular and Cylindrical Waveguide Dimensions

The relation between these dimensions, the cut-off frequency and mode of operation are shown in the table that follows:

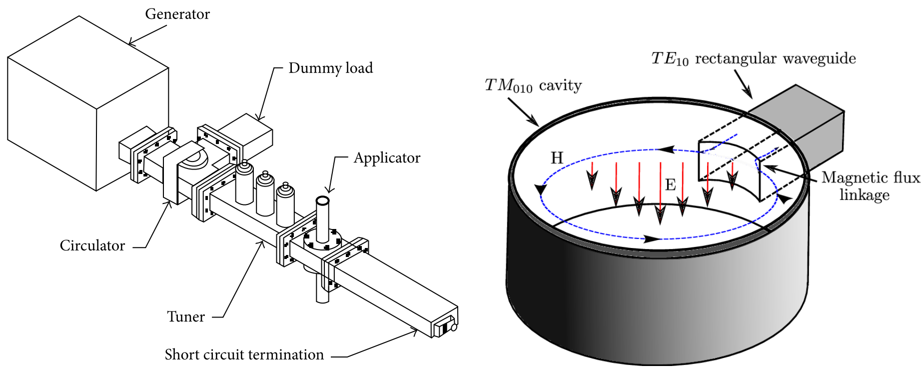
Rectangular Waveguide	Cylindrical Waveguide
$f_{nml} = \frac{c}{2}\sqrt{(\frac{m}{a})^2 + (\frac{n}{b})^2}$	$f_{nm} = c\frac{x_{nm}}{D\pi}$; $f_{nml} = \frac{c}{2}\sqrt{(\frac{x_{nm}}{\frac{D}{2}})^2 + (\frac{l\pi}{L})^2}$
Where: $m \geqslant 0$; $n \geqslant 1$; c is the speed of light.	Where: $n, l \geqslant 0$; $m \geqslant 1$; c is the speed of light and x_{nm} is the m'th non-zero root of the n'th Bessel function for TM modes or the m'th non zero root of the derivative of the n'th Bessel function for TE modes[10]

Table 2: Table of equations for Rectangular and Cylindrical waveguides

Notably the equation for the Rectangular Waveguide is the same for both the regular and pill-box structure. In comparison the equation for the cut-off frequency for a Cylindrical Waveguide differs depending on the construction of the waveguide.

2.3 Single-Mode Cavity Design For Heating Objects

Resonant Cavities offer the ability to concentrate the microwave energy into our target to increase the efficiency of the system. There are multiple approaches available to achieve this, each coming with it's own advantages and disadvantages. Two main approaches have been established which make use of strong standing waves; the first of which is a highly tuned Rectangular Waveguide (commonly tuned to operate in the $\mathrm{TE_{103}}$) where the target object is inserted at a point of maximum electric field. The other common approach used is a cylindrical cavity designed for $\mathrm{TM_{010}}$ resonance with a rectangular waveguide feeding the microwave energy through a slit in the cylinder wall[7]. These are shown in the graphic below:



(a) Tuned Rectangular TE_{103}Cavity [7] (b) Cylindrical TM_{010}Cavity with Rectangular Waveguide feed.[4]

Figure 3: Most Popular Single-Mode Cavity Designs for Heating

These designs can also be combined to create a hybrid design, such an example can be seen in [6], this brings the ability to tune the resonance whilst reducing the complexity of this tuning. Whilst the ability to tune the cavity is great for attaining maximum performance, the process is tedious and the tuning will need to change depending on the electromagnetic properties of the target. This makes constantly maintaining standing waves extremely difficult, especially if the target substances change their electromagnetic properties during a reaction. For this reason a simpler design which does not aim for a strong standing wave has been proposed in [7]. This design directly feeds a Magnetron output antenna into a shorted end of a cylindrical tube designed for TM_{01}transmission. As seen in the graphic below:

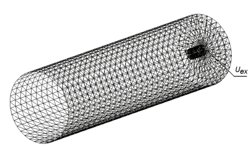


Figure 4: Alternative design with Magnetron antenna directly fed.[7]

This design reduces the complexity of use as users do not need to adjust tuning devices to guide the energy; additionally, this reduces manufacturing complexity. It does however require shielding to contain some of the microwaves that may escape through the aperture that the target material is loaded [7].

2.4 Microwave Radiation and Safety

Microwave Radiation is classified as non-ionizing, meaning that the electromagnetic wave does not posses enough energy to ionize atoms or molecules it encounters. It can however transfer its energy in the form of excitation resulting in high temperatures. This can result in tissue burns near the surface if a person is exposed to high power radiation. Depending on the country and occupation, there are varying standards for safe amounts of exposure; however, the generally accepted level is $10mW/cm^2$at microwave frequencies[2].

A Faraday Cage, an enclosure made of conducting material, is used to contain Electromagnetic radiation. The conducting material does not have to be solid and may contain many holes or even be made with a wire-mesh, as long as the largest aperture is less than a tenth of the wavelength, the radiation will be completely contained[9]. It is generally good practise to make use of Faraday Cages when using high power microwave energy to ensure the safety of those operating the machine; additionally, it acts a physical barrier preventing users from touching the high power electronics when in operation.

3 Electromagnetic Design

This section will show the design process used for this project. Drawing on the literature above as well as catering to this project's requirements stated previously, components and design philosophies will be investigated, simulated and compared to ensure the system achieves all the required features. The propagation and formation of Electromagnetic Waves is heavily influenced by the properties of the material it is in. For this section the term 'target material' will refer to a Polyethylene filled glass tube.

3.1 Microwave Source

This system requires a high-power microwave source capable of long times of operation at varying power levels to allow for experimentation similar to that conducted in [6]. To meet the requirements SR.004, the frequency of the microwave energy must match that of the original paper, thus our device must output at 2.45 GHz to meet this requirement. [6]

There are multiple devices capable of high-power microwave power at his frequency examples such as the Cavity Magnetron, Klystrons, Traveling-wave Tubes and Solid-State microwave generators. However the Cavity Magnetron has a significant advantage in terms of availability and cost as the technology is well established and easily commercially available. Recent progress has been made in power output control with the arrival of 'Inverter' Magnetrons, which make use of inverter circuitry to control the Magnetrons power output.

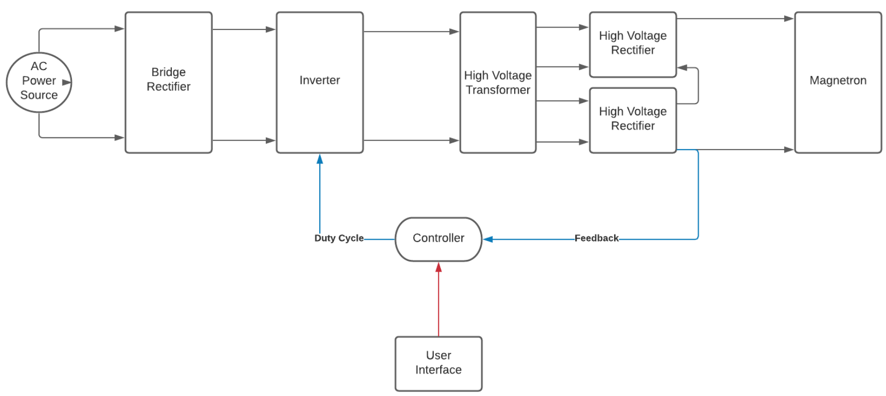
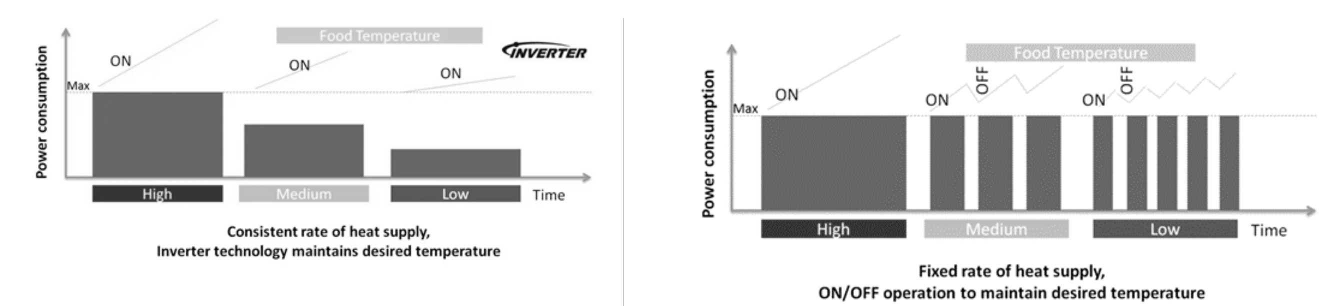


Figure 5: Inverter Magnetron block diagram

The use of the inverter before the transformer allows for the controller to regulate how much power gets sent to the Magnetron by varying the duty cycle of the inverter at very high switching frequency. This results in a very smooth variable power source capable of tracking the desired power output level set via the User Interface. A comparison of the varying power levels is shown below:



(a) Inverter Magnetron (b) Regular Magnetron

Figure 6: Inverter vs Regular Magnetron power control.[3]

The major advantage of this level of power control is it allows for users to fully control how much energy is emitted by the Magnetron. Overheating of a Magnetron will destroy it, for this reason almost all Magnetron's have an active cooling system. Overheating still occurs, typically when operated at high power for long periods; however, with the ability to reduce power level these magnetrons a capable of operation for longer whilst continuously supply electromagnetic energy.

Whilst a bespoke system could be designed for this application, this adds compexity, increases cost and additional potential points of failure. Fortunately Inverter Magnetron systems are available in consumer microwave ovens, from these devices we can take the Magnetron, power supply, controller and the user interface. For this project the LG-MS4235GIS Microwave Oven is proposed to be used to provide these components. This device is rated for a maximum microwave output power of 1200 Watts at $2.45 \pm 0.05\,GHz$.

3.2 Resonant Cavity

The resonant cavity is responsible for ensuring the target material receives the maximum amount of energy possible. There a competing ideas that have been used in different projects. From the literature we know that Tuned Rectangular TE_{103} Cavities and Cylindrical TM_{010}Cavities with a rectangular waveguide feed are popular designs, however there has been some criticism for these designs due to their high complexity in operation [7][6].

In this project the TE_{103} design will be avoided as this additional complexity of tuning with varying electromagnetic properties of the added material is almost impossible for operation during experimentation, especially considering that the users of this device will not be knowledgable in Electromagnetics and waveguides. With the focus instead being targeted on the TM_{010} cavity design similar to that used in [6] and the TM_{01} alternative design proposed in [7]. With the frequency from the microwave source being $2.45\,GHz$ this yeilds a wavelength of $\lambda = 0.0122\,m$ in free-space.

3.2.1 TM_{010} with Rectangular waveguide feed (Design 1).

This design makes use of the standing wave formation that can be achieved in "pill-box" cavities to keep the electromagnetic energy concentrated in one particular location. Depending on the geometry of the cavity, different standing wave patterns can be achieved at certain frequencies, the most dominant of these is the *fundamental* mode which will form with the greatest bandwidth. For Cylindrical waveguides this will form part of TM_{01x} mode family, where x is typically 0 but not necessarily.

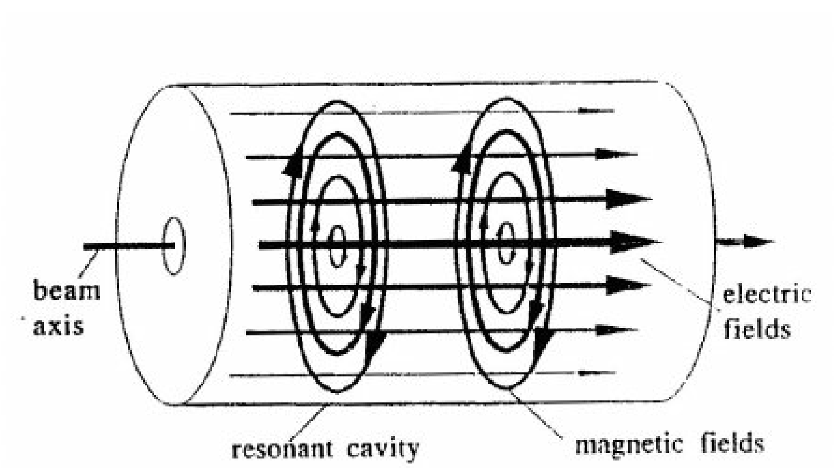


Figure 7: Field distribution in TM_{010}resonant cavities[5].

Due to the axis-symmetric nature of Circular waveguides this is used as the resonant cavity to host the reaction. This allows for more even heating of the target as the figure above shows, the centre of the cylinder is the maximum of the electric field. However, to form this resonance we cannot directly feed from the Magnetron's antenna as the polarization of its radiation could cause interference with the resonance of this cavity. Therefore the magnetrons output is shaped using another waveguide and this energy is fed into the cavity. This is achieved through a rectangular waveguide feeding from the sidewall of the cylinder[7, 9].

The literature provides us with equations for the design or industry standard components for these waveguides which will be explored below. With the Magnetron output of 2,45GHz being the frequency of interest.

Cylindrical cavity

The dimensions, frequency and mode of resonance is described as follows:

$f_{nml} = \frac{c}{2}\sqrt{(\frac{x_{nm}}{\frac{D}{2}})^2 + (\frac{l\,\pi}{L})^2}$ where c is the speed of light and x_{nm} is the m'th non-zero root of the n'th Bessel function;

for TM_{010} $x_{nml} = 2.405$:

$2.45 \times 10^9 = \frac{c}{2}\sqrt{(\frac{2.405}{\frac{D}{2}})^2 + (\frac{0\,\pi}{L})^2}$

$\therefore D = 0.29\,m$

The length of the cylinder does not of effect on the cavity's performance; however a larger cavity results in a lower field strength, reducing the potential for the target material to absorb the required energy. For this reason a cylinder length of $L = 0.2\,m$ was chosen.

Rectangular Waveguide Feed

In Figure 3.b it is shown that a cylinder is operating in TM_{010}requires a rectangular waveguide feed to take the output of the magnetron antenna and shape it into the TE_{10} mode to be fed it into the sidewall of the cylinder. There are standard rectangular waveguide dimensions used in industry to ensure compatibility of components, each of these standard sizes cover a portion of the frequency range. Such devices connected to the microwave source are known as *launcher* devices. As the operating frequency is 2.45GHz the standard that covers this best is the *WR340* standard component with its dimensions shown below.

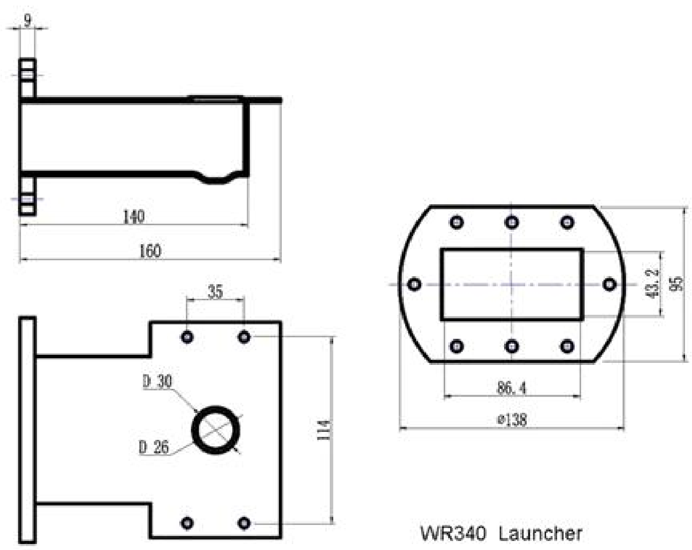


Figure 8: WR340 Rectangular Waveguide standard (mm) [1][1]

The length of this device is mostly irrelevant, however the distance from the back wall to the Magnetron antenna must be around a quarter of a wavelength for propagation to take place, in this case 30 mm will achieve this.

Assembly

The assembly of these components complete the electromagnetic factors of the design, however some additional alterations will be made to make the device usable for experimentation. Most notably the material needs to be inserted and removed from the cavity, a path for gasses produced to flow through and observation/thermal measurements of the reaction will require apertures in the cylinders walls . In general, electromagnetic waves are fully contained in a conducting metal enclosure if the size of the aperture in the metal is less than a tenth of the wavelength ($\frac{\lambda}{10}$). From the wavelength discussed earlier this limits these apertures to $12\,mm$ for this device.

The two apertures added to the cylinder are firstly in the centre of the top plate for the addition and removal of material. The second is added to the curved surface to allow for observations/temperature measurements to be taken mid experiment. The final assembly can be seen below.

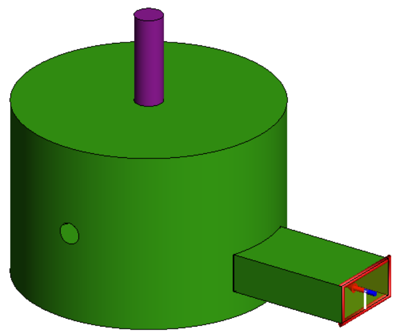
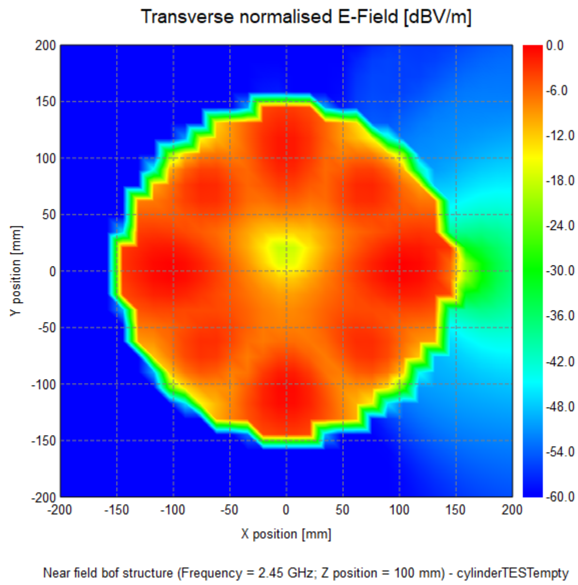


Figure 9: TM_{010} Cavity assembled Design

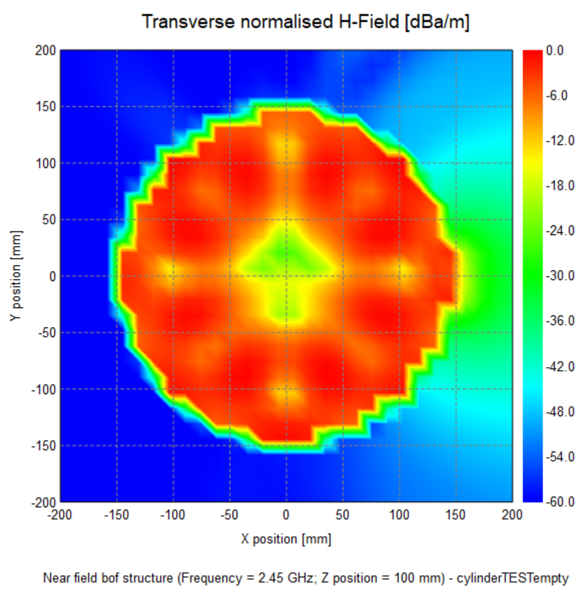
The green material denotes a highly conductive metal to shape and contain the microwave energy, the purple cylinder is the target material and the red arrow shows the microwave source and energy flow.

Simulation

The simulation of the electromagnetic performance of the design was performed with FEKO a electromagnetic simulation software package, from which the results will then be interpreted. There were two simulations conducted, the first is with no target material added (i.e. purely air filled cavity) to ensure the cavity performs as the design intended. The second simulation added the typical target material this device is expected to operate on to ensure that this does not alter the device's performance.

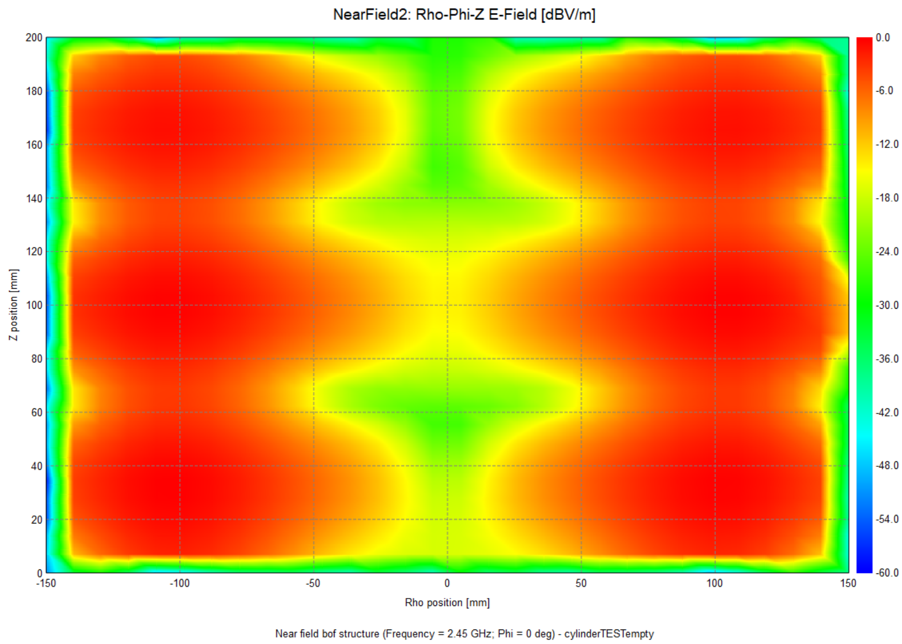


(a) Electric field simulation results Decibel scale

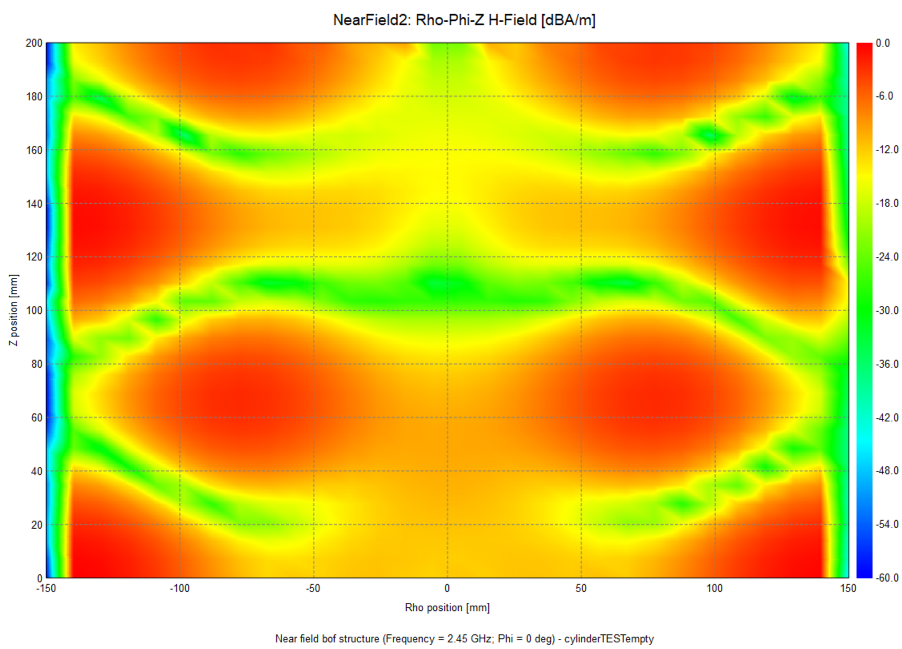


(b) Magnetic field simulation results Decibel scale

Figure 10: Empty TM_{010}cylinder Electric and Magnetic fields cross-section simulation results in Decibel scale



(a) Electric field simulation results Decibel scale

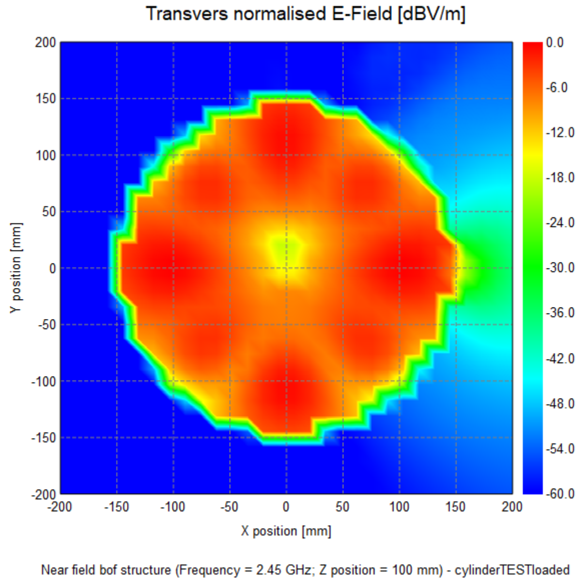


(b) Magnetic field simulation results Decibel scale

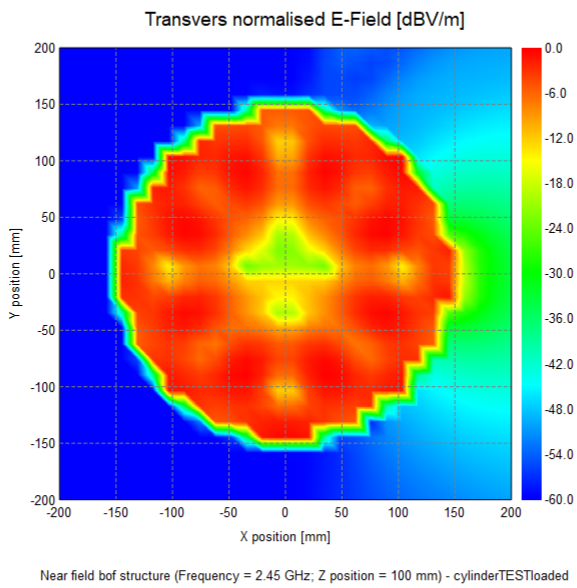
Figure 11: Empty TM_{01} Cylinder Electric and Magnetic fields Axial-section simulation results in Decibel scale

In these graphics the cavity is operating in the desired TM_{010} mode as desired by our design. Notably we can see that despite the hole in the sidewall being within the parameter settled upon there is still some microwave energy that escapes thorough this opening. Additionally, along the length of the cylinder the standing waves do not form at regular intervals.

Adding the target material of diameter 12 mm yields the following results are found:

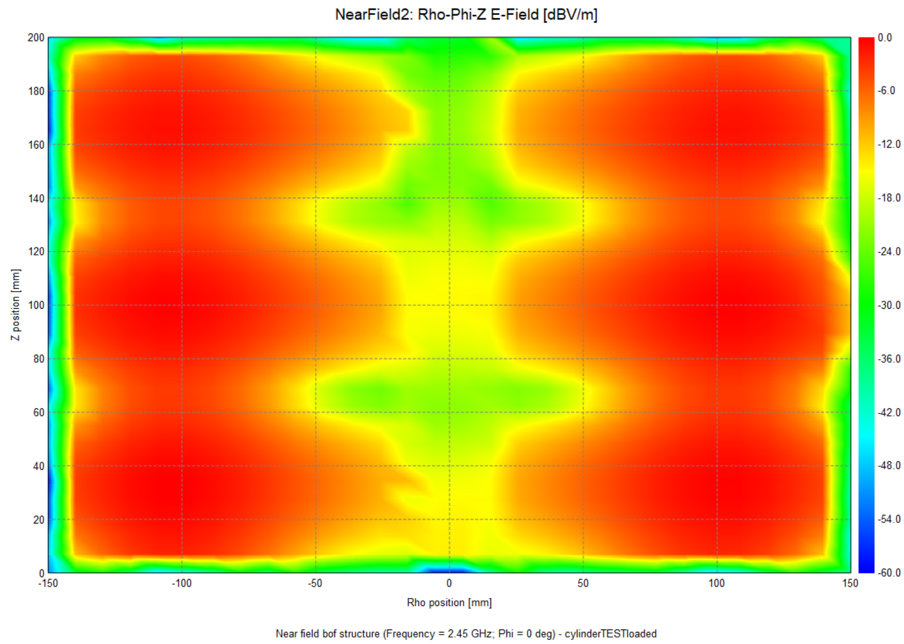


(a) Electric field simulation results in Decibel scale

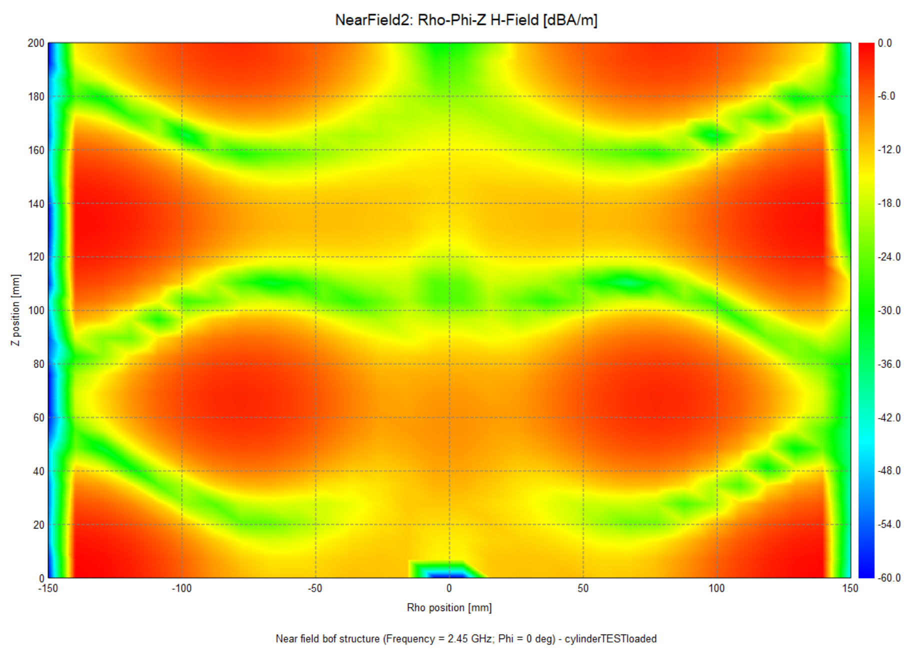


(b) Magnetic field simulation results in Decibel scale

Figure 12: Loaded cylinder Electric and Magnetic fields cross-section simulation results in Decibel scale



(a) Electric Field



(b) Magnetic Field

Figure 13: Empty TM_{01} Cylinder Electric and Magnetic fields Axial-section simulation results in Decibel scale

As the figures show, the addition of the target material has minimal effect on the distribution of the electric and magnetic fields. The most notable downside of this design is the underutilised energy that is present in the cavity but not in the target material. Additionally, the standing wave nature of these fields will result in certain pockets of the material getting all the energy whilst others will get close to none, as shown in the lengthwise fields distribution.

3.2.2 TM_{01} With direct Magnetron feed (Design 2).

This design makes use of travelling waves in a TM_{01} cylindrical waveguide to shape the electric and magnetic field such that the maximum amount of this energy is absorbed in the target material. One of the major benefits of this design is its removal of the rectangular waveguide to feed the cavity, instead the Magnetrons feed can be directly connected. This reduces the complexity of the design and removes a significant potential point of failure. This design is heavily influenced by the work of *Kybratas et al.* [7] however some design modifications are made to make SR.002 and SR.004 achievable.

Cavity Design

From the literature we get the equation for TM_{01}cylindrical waveguides to be the following:

$f_{nml} = \frac{x_{nm} \times c}{D\pi}$ where c is the speed of light and x_{nm} is the m'th non-zero root of the n'th Bessel function; for TM_{01} $x_{nml} = 2.405$:

$2.45 \times 10^9 = \frac{2.405 \times c}{D\pi}$

$\therefore D = 0.094\,m$

Whilst the length of the cavity does not impact the electromagnetics, with the Magnetron now directly coupling to the cavity a longer cavity is advantageous; firstly to protect the Magnetron Antenna from the target material being added, as well as allowing space for our wave to reach the desired mode for operation. Thus a length of $L = 0.4\ m$ was chosen.

Assembly

The single cavity will require two apertures, much like the initial design, one for the loading of material, the other for temperature measurement.The target material will be loaded on the opposite end of the cylinder to the Magnetron, with the measurement hole being located in the sidewall of the cylinder. This construction is shown in the figure below.

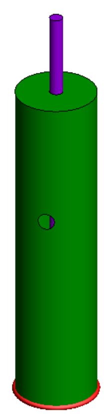
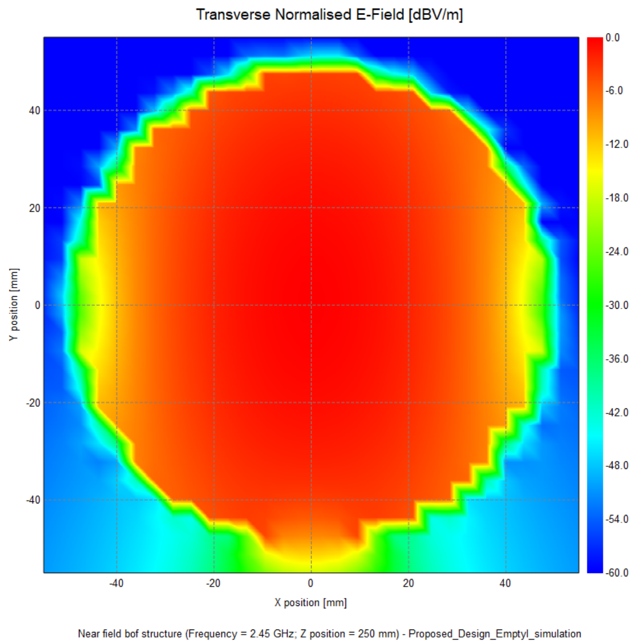


Figure 14: TM_{01} Cavity structure

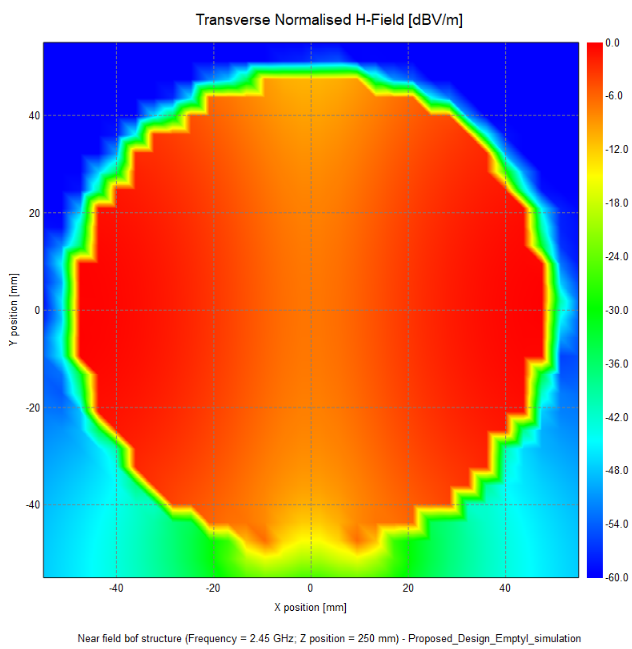
The green material denotes a highly conductive metal to shape and contain the microwave energy, the purple cylinder is the target material and the red circle shows where the Magnetron will be connected.

Simulation

The simulation of the cavities performance was performed in FEKO, allowing analyses of this cavity's performs when its empty and when it is loaded. Firstly, affirming if it operates as designed and then comparing the design efficiency. The results shown below:

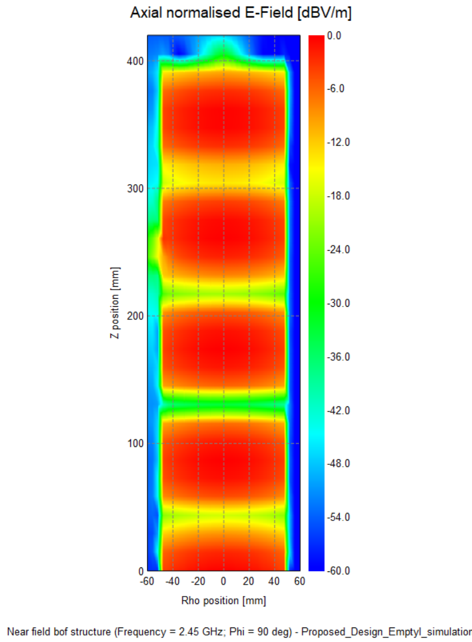


(a) Electric Field in Decibel scale

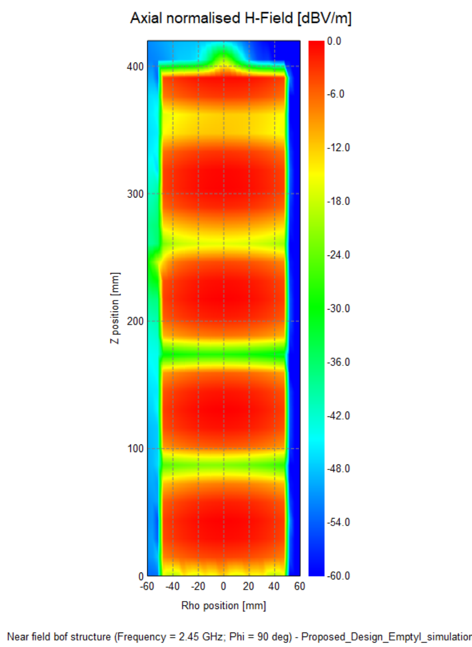


(b) Magnetic Field in Decibel scale

Figure 15: Empty TM_{01}Cylinder Electric and Magnetic fields cross-section simulation results in Decibel scale



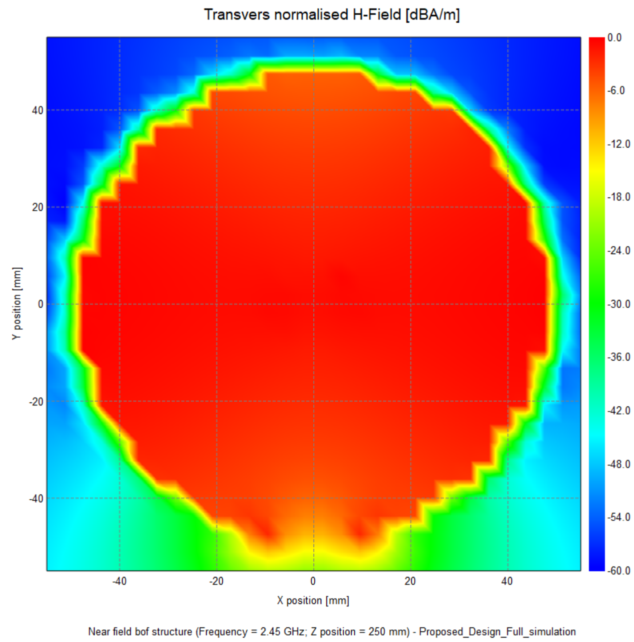
(a) Electric Field



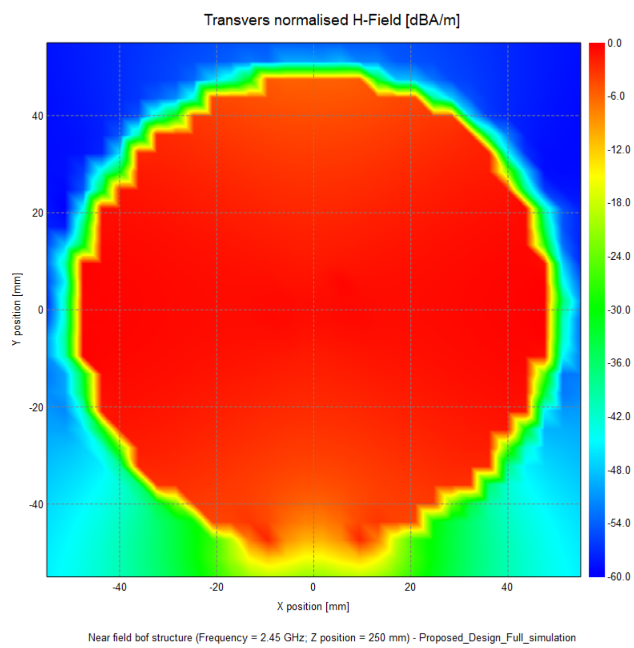
(b) Magnetic Field

Figure 16: Empty TM_{01} Cylinder Electric and Magnetic fields Axial-section simulation results in Decibel scale

These figures show that the microwave energy is distributed as expected for the TM_{01} mode of operation. Now adding the target material we get the following results.

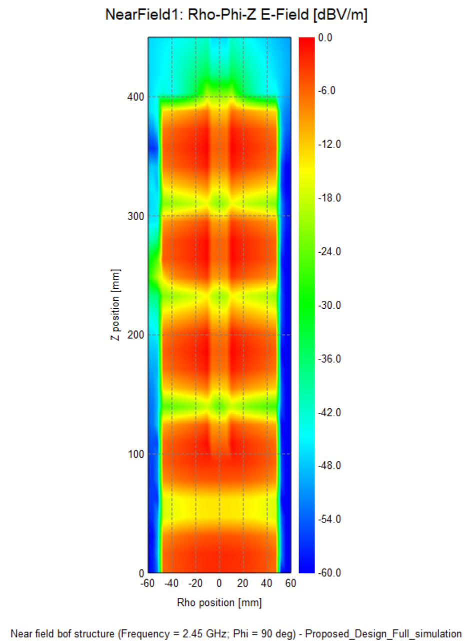


(a) Electric Field in Decibel scale

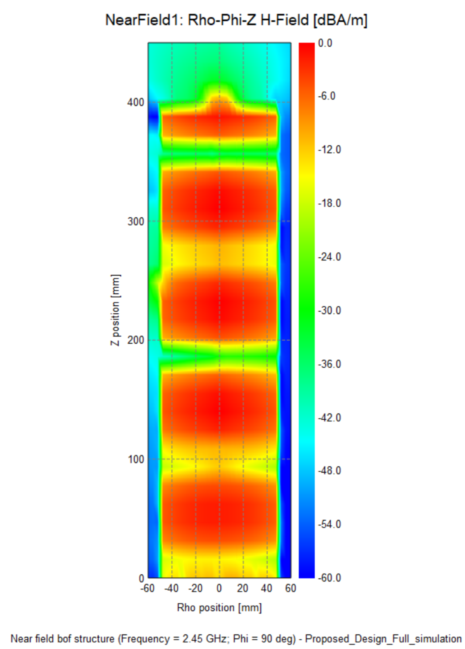


(b) Magnetic Field

Figure 17: Loaded TM_{01}Cylinder Electric and Magnetic fields cross-section simulation results



(a) Electric Field



(b) Magnetic Field

Figure 18: Loaded TM_{01}Cylinder Electric and Magnetic fields Axial-section simulation results

These simulation results show that whilst the addition of the target material does effect the Electromagnetic energy in the tube, this change is minimal and even acts to concentrate the energy which is advantageous. The increase ratio of the tube being occupied by the material means this cavity will additionally be more efficient as more of the energy is contained in the target material. An interesting result from this simulation is the leakage of microwave energy when the target material protrudes from the cavity. This result was initially unexpected as the aperture in the conductive material is less than a tenth of the wavelength, however this raises the requirement for electromagnetic radiation shielding around the device to ensure it meets safety requirements.

3.2.3 Design Selection

Both designs discussed performed as intended in simulation forming the correct field patterns. For the selection of one of these designs the criteria revolve around efficiency of the cavity, ease to manufacture and safety during operation. The comparison for $TM_{010}$with Rectangular Waveguide feed (Design 1) and TM_{01} with direct feed (Design 2) over these criteria will be explored below.

Cavity efficiency Both designs achieved the intended field distributions within the cavity. The larger radius of the cavity in Design 1 results in a broader distribution and thus a less intense filed strength in the center of the cylinder, this reduces the cavity's efficiency as the size of the target material is limited by aperture limitations discussed earlier. Thus the smaller diameter of the cylinder in Design 2 increases the theoretical efficiency of the cavity.

Safety in Operation There are two areas of safety concern for this system, microwave energy leakage and the high power electronics supplying power to the Magnetron. Whilst both designs show little to no leakage when empty it is seen that by adding material to the cavity can impact how much is contained by the apertures. For this reason a Faraday Cage made with a wire-mesh is required to ensure that all the microwave energy is safely contained. The Magnetron's power supply circuity needs to be contained by a grounded housing with no wires exposed to users. The Magnetron's location in Design 1 makes achieving this far more complex as it has to connect to the Rectangular Waveguide from above, making running the power cables to the Magnetron safely very complex. In contrast, Design 2 has the Magnetron connect underneath the tube, allowing for us to keep all the high power electronic in a single housing, thus ensuring that nothing is exposed to the user.

Manufacturing Complexity Reducing the manufacturing complexity keeps the cost of the system down whilst also ensuring it operates as designed with fewer points of failure. Design 1 is obviously more complex for manufacturing with the two waveguides and the connection of the Rectangular Waveguide onto the curved surface of the Cylinder. In comparison Design 2 has a singular cylinder with no sidewall joints and the Magnetron connecting to the flat end-plate is a far simpler design to manufacture.

Considering the above points, Design 2 has significant advantages to that of Design 1 in both efficiency and manufacturing. Both designs have safety concerns, however Design 2's can be rectified with a relatively cheap and highly effective countermeasure. For this reason Design 2 is taken forward in this project.

4 Physical Construction

This phase of the system design will explore the design for the manufacturing process and assembly of the metallic structure of the Cylinder and the housing container for the Magnetron and power electronics. The key points is keeping costs low and assembly simple. The SOLIDWORKS CAD software was used for this design process. As this equipment will be used in Laboratory experiments the ability to clear out the Cylindrical Cavity where material may spill and the ability to get to components that may get damaged heavily influenced the design.

4.1 Material and Process Selection

The choice of material and processing of the material deeply impact the design and assembly considerations for the components. As discussed earlier, Aluminuim is the metal of choice for this project due to it having good properties for microwave energy containment whilst still being relatively cheap. As there is no heavy load-bearing to be done by the structure Sheet-metal can be used. This makes manufacturing simple as it can be cut and bent to form the desired shapes and reduces unnecessary waste. However, to make us of this the CAD design needs to properly allow for this material to be used. The sheet metal does not take any loading, but must be sturdy and resilient to deformation as this can significantly impact the performance of the Cavity. For this reason Gauge 11 ($2.3\,mm$ thick) Aluminuim sheet metal was chosen. The metal is bent to shape and the seams formed are welded for both a good physical and electrical connection.

4.2 Cylindrical Cavity CAD

To make this component detachable and accessible for cleaning, a flange was added to the cylinder shape designed in the Electromagnetic Design section. The CAD drawing below shows the sheet-metal dimensions and construction.

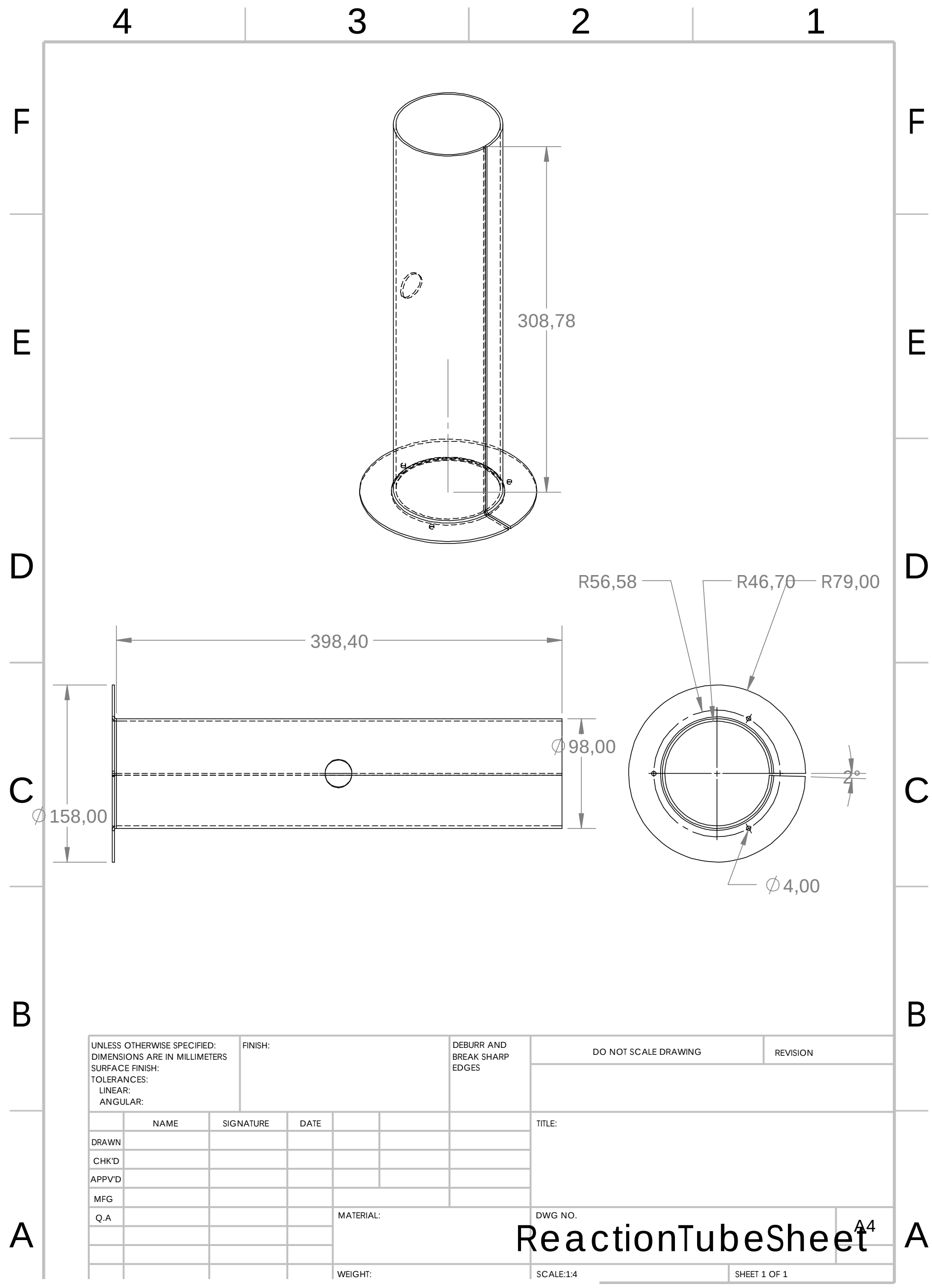


Figure 19: Cylinder Sheet-metal Design

The gap formed along the cylinder's length is welded and covered with Aluminium Tape to ensure that this manufacturing compromise does not effect the Electromagnetic performance of the design. The wide flange is added to provide stability and good electric conductivity.

4.3 Housing CAD

The key function of this component is to connect the resonant cavity and the Magnetron whilst housing all the electronics for the operation of the Magnetron. The general shape of this housing was based off the LG-MS4235GIS microwave oven's dimensions with additional space to allow for some adjustments that may be needed.

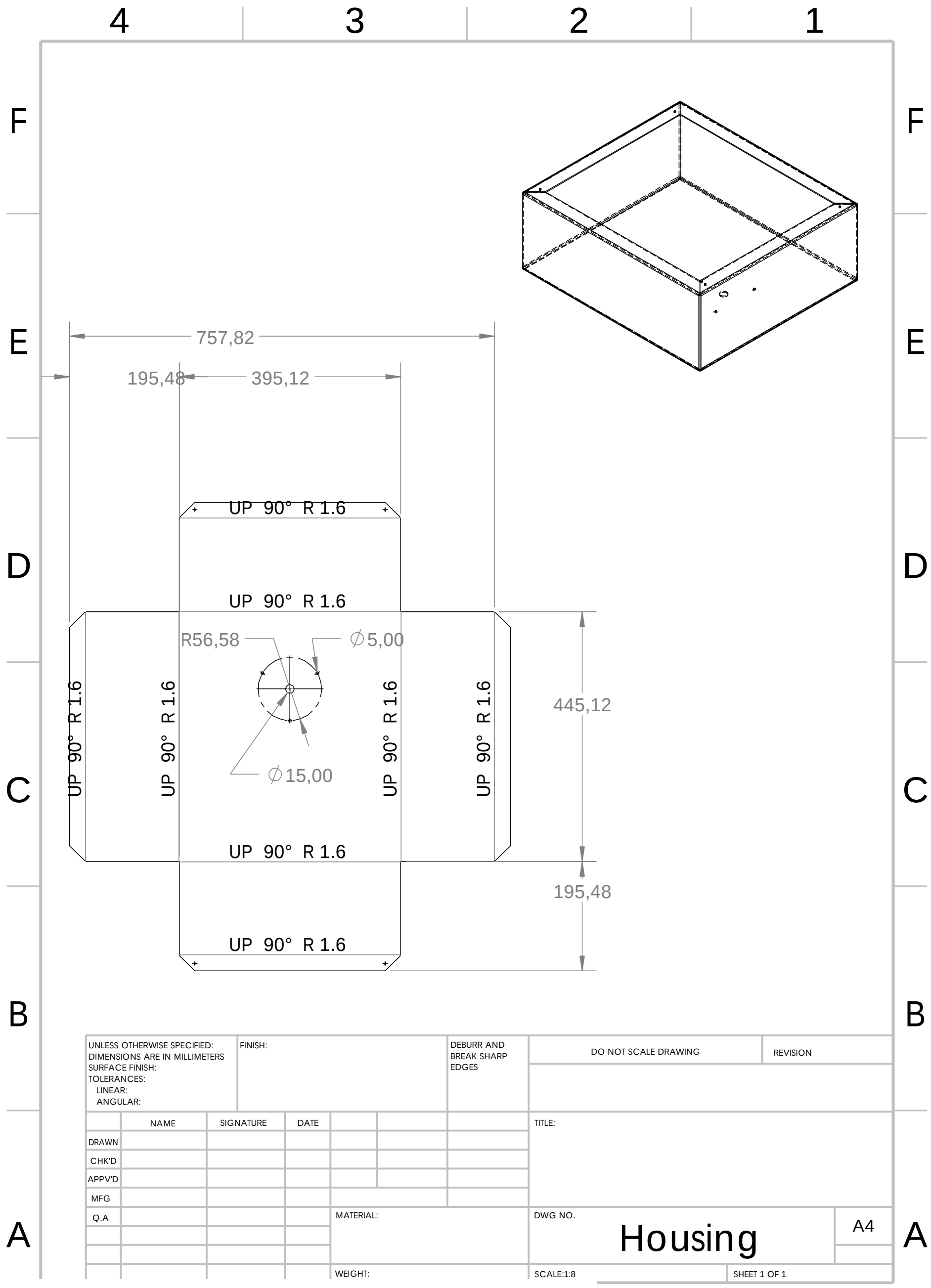


Figure 20: Housing Sheet-metal Design

The Magnetrons antenna is to be inserted through the centred hole with the coaxial holes for screwing the tube onto the housing ensuring that the cylinder is centred around this point. The planned usage of the space within this cavity is shown below in Figure 21.

4.4 Complete Assembly

The bottom plate of this housing is detachable to allow for repairs and component replacement whilst still ensuring that the device is safe for operation. The complete assembly of these components is shown below in Figure 21.

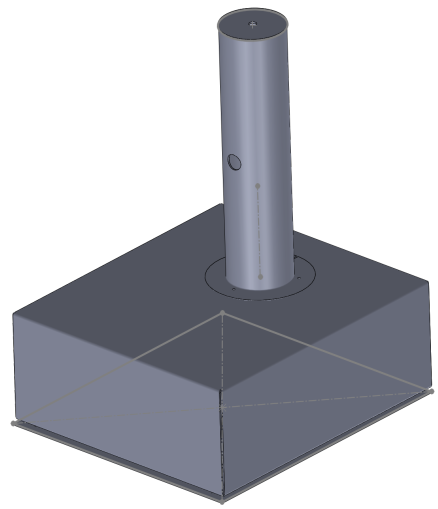


Figure 21: Sheet-metal Assembly

Notably there are no ventilation holes or an opening for the User Interface cut into the material in this design. This is because the arrangement of the internal components has been planned using schematics publicly available for the LG-MS4235GIS microwave Oven, there is no guarantee that these are accurate, thus these cuts are to be completed once all components are available.

4.5 Faraday Cage

The Faraday cage offers protection from any microwave radiation that may be emitted by the device. There is no limitation to the size or shape of this construction as long as it is fully electrically connected. The Chemical Engineering Department stated that they already possessed a wire mesh Faraday Cage that met the maximum aperture requirements discussed earlier and would be able to contain this device.

5 Conclusion

The aim of this project was to design a device that maximizes the microwave energy available for catalytic decomposition of plastic materials. This required an overview of the literature regarding microwave energy and Waveguide designs in order to gain an understanding of what this would entail. With this device being intended to be used initially to validate, and then improve upon the results found in *Xiangyu Jie et al [6]*.

From the literature two potentially viable designs emerged with differing design philosophies, especially regarding the use of standing waves to target the energy. These were then both fully developed and their results compared. From here it was decided that the TM_{01}(Design 2) that makes use of travelling waves performed better in simulation, especially in terms of energy concentration, and was taken further in the project. Notably this differs from the design used in *Xiangyu Jie et al [6]*, whilst still being capable of performing similar experiments. The design also reduced the complexity for the waveguide feed making the device easier and safer for use.

The physical construction of this design is made from 2.3 mm Aluminium sheet metal cut and bent to form the cylinder as well as a housing to host the high power electronics as well as the user interface. Aluminium is a common material used for electromagnetic Waveguides due to its good conductance. A thinner gauge could have been used; however, this device will be used as laboratory equipment and for this reason sturdiness is required.

The result of this project is a fully-simulated and ready-for-construction device approved by the end users (the University of Cape Town's Chemical Engineering department). Unfortunately, due to the time constraints the device could not be built and was not included in the projects scope. With all this considered, the project is considered a success.

6 Recommendations

The unfortunate consequence of the short time frame for this project is it limits the possible scope of the project, in this case the actual construction and validation of simulation results were not possible. In this section further work on this project is proposed considering if it were to have been made.

Firstly the construction of the Aluminium housing as designed should be performed after which the electronic components decided upon can be installed. All welded joints should be covered with Aluminium tape to ensure all the microwave energy is properly contained.

For the validation of the simulation results there are multiple possible tests that can be performed to asses the performance in practice. One of these is to place a wet sheet of paper within the cavity and turn the microwave on. This will result in extreme regional heating where the field strengths are at their highest, this burns the paper allowing for estimates of the field distribution. This simple test gives a deep insight into the performance of the device before it is used in experimentation, especially if thermal paper is used, giving a more detailed graphic for these field distributions.

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Appendix A

All files relevant to this project including simulation files, CAD drawings and Files, figures and other media used in this project can be found in full scale in the GitHub repository at the following address: https://github.com/JaceHille/EEE4022S_Project.git.

Appendix B

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

ETHICS APPLICATION FORM

Please Note:
Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior* to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: http://www.ebe.uct.ac.za/ebe/research/ethics1

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Jason Hillebrand
Department		Electrical Engineering
Preferred email address of applicant:		HLLJAS007@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	BSc. Electrical Engineering
	Credit Value of Research: e.g., 60/120/180/360 etc.	40
	Name of Supervisor (if supervised):	Stephen Paine
If this is a researchcontract, indicate the source of funding/sponsorship		
Project Title		Microwave Energy for Plastic Disposal

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Jason Hillebrand		16/08//2021
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	Stephen Paine		16/08/2021

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).			