

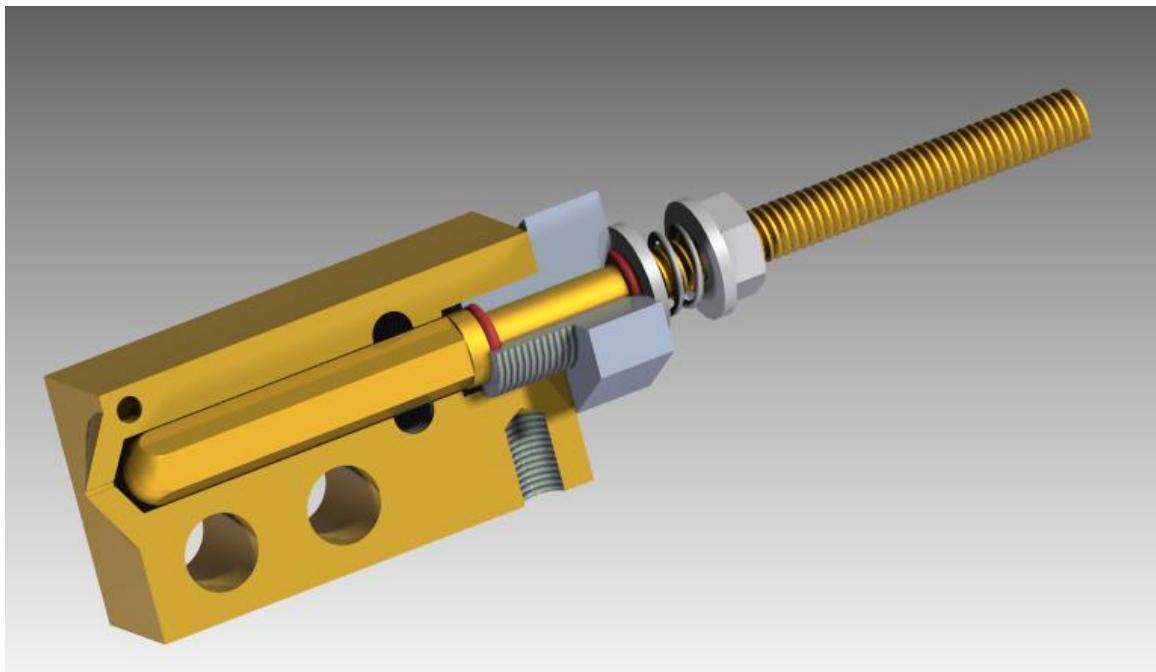


FINAL YEAR MEng PROJECT

# Reprap Colour Mixing Project

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1<sup>st</sup> May 2012



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## Abstract:

With recent technological advances the cost of 3D printing has been driven down to make the technology widely available for home users and projects such as RepRap have become much more widespread. RepRap is an open source project started by Adrian Bowyer of Bath University in 2005 which was designed around the ideal of creating a low cost home printer that could self replicate a larger proportion of its own parts and is the only current project of its type. The printing process uses a fused filament fabrication method which melts a strand of plastic which is deposited in fine layers to build up a 3D object.

The current models of printers are rather limited to using the plastics that can be bought from a supplier so a nozzle has been designed and developed in this report to enable the home user to print in any colour from only having to purchase a few colours. Eventually when this nozzle is fully developed it could be used for advanced engineering component manufacture by using hard and soft plastics.

This report concentrates on developing the mixing properties of the nozzle to a high standard of mixing of plastics and the final design incorporates an active mixing system using a hex bar to generate the necessary shear in the viscous plastic to result in homogeneous mixing.

Following this design, research should continue into its performance and development of the software and firmware should be carried out to further implement the nozzle into the RepRap design. Following the electronics being adapted to gain full independent control of each filament, a colour space map can be calibrated for use with the machine to make printing any colour possible.

## Acknowledgements:

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**Dr Andrew Dent** – for his advice and help with new and existing ideas.

## Submission Notes

This report concentrates on the specific design of the new nozzle where engineering drawings can be found in the Appendix and fine details about the specific mounting to the machine are omitted for the reason that this is very custom part of design and will vary wildly from machine to machine.

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## 1. Terminology

ABS - Acrylonitrile butadiene styrene, a thermosetting used in 3D printing

AM – Additive Manufacturing

AMF – Additive Manufacturing Format

CMYK – Cyan, Magenta, Yellow, Key (Black)

FDM – Fused Deposition Manufacturing, a rapid prototyping technique used by RepRap

FFF – Fused Filament Fabrication, an additive rapid-prototyping technology which builds 3D objects progressively by fine layers.

G-code – a standard programming language for the control of CNC machines

Infill – The process whereby the volume between the outer surfaces of a printed component is filled with structural material.

PEEK – Polyaryletheretherketone, a strong heat resistant engineering plastic.

PLA – Polylactic Acid, a thermosetting plastic used in 3D printing

PTFE - Polytetrafluoroethylene, a synthetic fluoropolymer which possess a very low coefficient of friction.

PPE – Plastic Processing Equipment, injection moulding equipment supplier.

RepRap – A Self Replicating Rapid Prototyper

RP – Rapid Prototyper

SRM – Self Replicating Machine

STL - Standard Tessellation Language, a standard file format used in 3D modelling which uses a series of triangles to represent 3D objects.

3DP – Three Dimensional Printing

## 2. Introduction

In recent years home 3D printing has grown in many ways and is now rapidly becoming available to the masses due to recent developments driving down the cost and complexity of the machines. Previously the existing systems of Rapid Prototyping despite having been around for nearly 30 years, were very expensive with large overheads and operating costs which meant the technology was only available to primarily research institutes. There are many home printer systems now available such as RepRap, Fab@home, Makerbot and Shapercube.

Generally the more common method that home 3D printers operate is known as Fused Filament Fabrication (FFF) which deposits molten material (typically plastic, but can be metal, wax, chocolate) onto a printer bed and builds up models by fine layers, which are



Figure 2-1 - Makerbot Replicator with a Dual Extruder [2].

fused to the existing layers below to create the desired geometry. This method was used previously by rapid prototyping machines (such as stratasys) but the associated costs were too great, which led to the development of the home 3D printers. The new generation of home printers can cost as little as ~£400 (RepRap Mendel can be sourced and built for this [1]) or the more expensive printers can be up to ~£2000 (Shapercube with a dual extruder which comes assembled [2]).

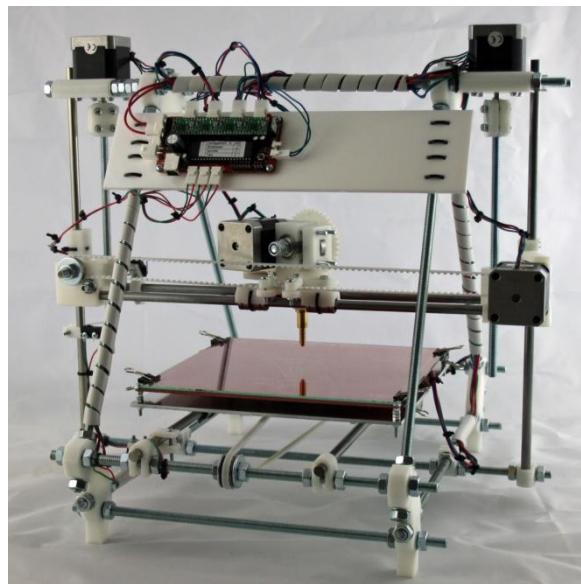


Figure 2-2 - Longboat Prusa Mendel available in kit form. [1]

RepRap is the only 3D printer that was designed with self-replicating in mind, meaning that the printer can print its own parts or even upgrade itself. This ingenious idea means that if one buys a machine today, in 10 years time it will have been able to upgrade itself to the current version meaning the machine will never become out of date. All future developments are designed with this in mind that any new features of a machine will be as easily compatible with the previous model and ideally interchangeable. Another advantage of the RepRap hypothesis of self replicating is that anyone with a printer can produce

another set of parts for a friend for a minimal cost, this has meant that over the past few years the number of RepRap machines is very difficult to estimate but is believed to be in excess of 4500 in 2010 [3], from only being one in 2005/6.

Generally the current models of 3D printer use a single filament extruder which limits the machine to printing solely in one colour, this can be change to a variety of colours available by suppliers but the selection is still limited. Some printers (such as the Makerbot replicator) are available with dual extruders which enable two separate colours to be printed (see figure 2-4).

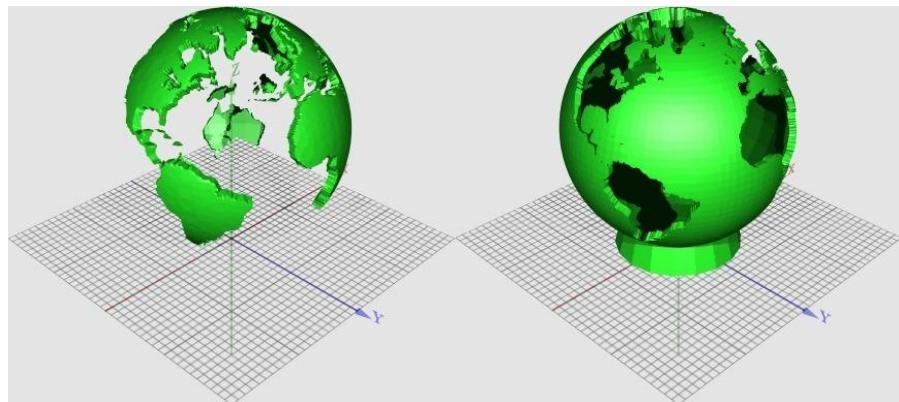


Figure 2-3 - The two separate STL files for printing the Globe in Figure 4 [4]



Figure 2-4 - Globe printed using a dual extruder machine [5].

By only being able to use one filament at a time the machine is very limited to the available plastic from the filament supplier not only in terms of colour but also material properties such as hardness. This results in a limitation to uses of the machine which can be solved by specialist manufacture of materials but this is costly and will still limit the printer to a single property/colour for a print. Changing materials can be achieved but cutting filament and fusing lengths together but this method is difficult to estimate and is still limited to filament colours provided by the supplier [6].

None of the existing printers have a system which provides a versatile means of achieving a desired colour other than using the desired colour in the filament. A new extruder head (figure 2-5) has been initially designed to test whether it is possible to mix colours during the printing process using separate feeds into a common extruder head and nozzle [7]. This will enable flexibility in the colour of the printed plastic and enable the colour to be varied throughout a print by altering the feeds rates of different colours. Printing with separate colour feeds and mixing them together should be quite similar to printing using ink in the colour composition of Cyan, Magenta, Yellow and Black (CMYK).

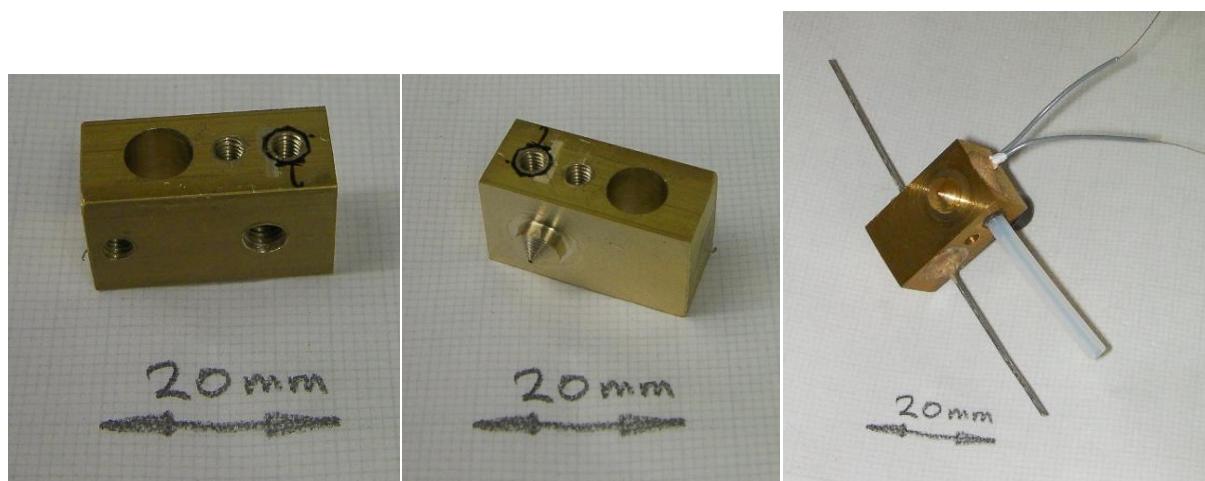


Figure 2-5 - The mixer extruder block for handling multiple materials [7].

## 2.1. The RepRap Machine Layout

For this research the machine that will be used is a Longboat Prusa Mendel RepRap (picture below), some of its main features are [1];

- LM8UU linear bearings on all three axes, replacing PLA bushings.
- Aluminium X-carriage
- Build Volume of 200 x 200 x 140 mm
- Sanguinololu Electronics
- Nema 17 Stepper Motors

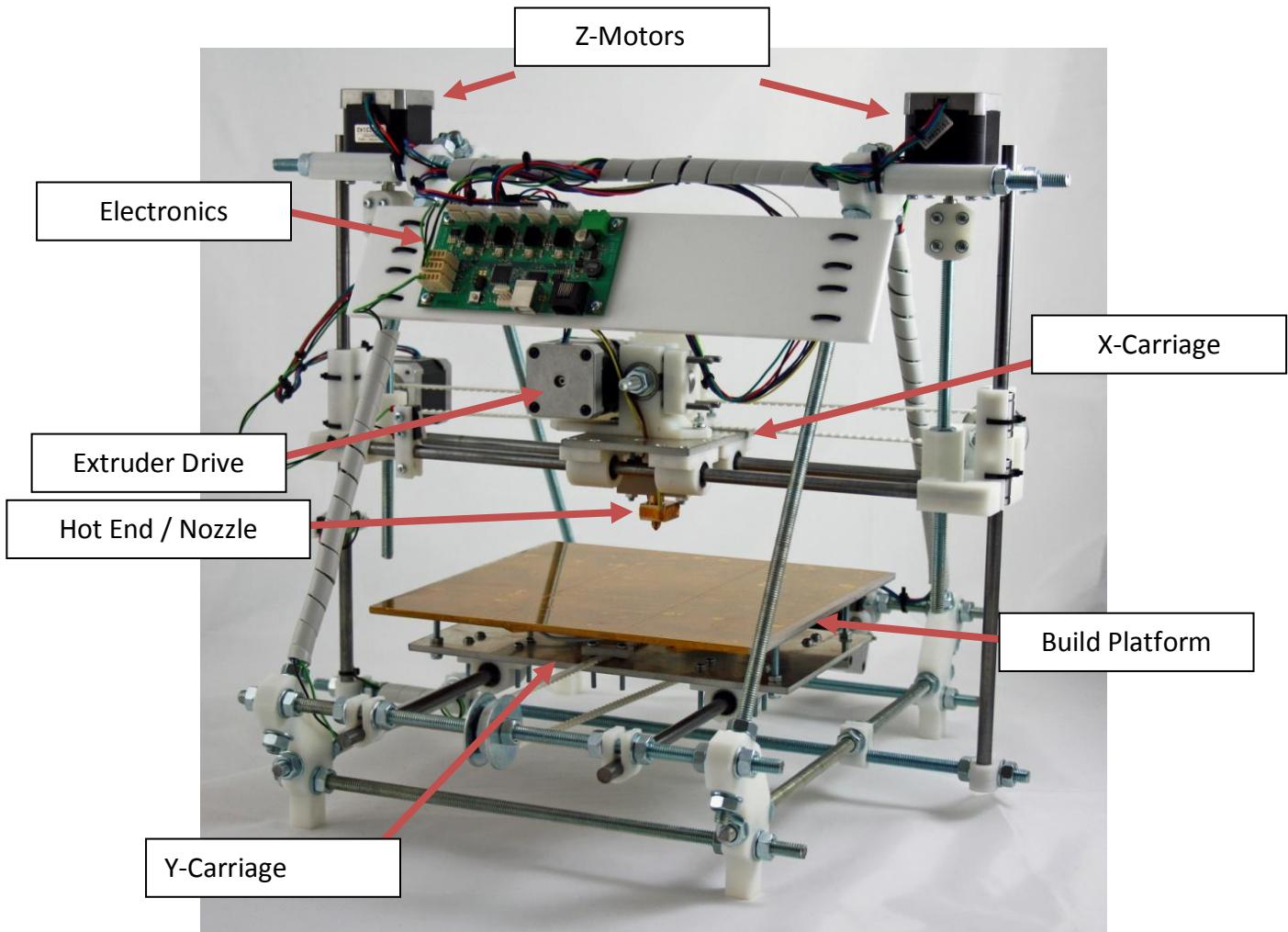


Figure 2-6 - Longboat Prusa Mendel to be modified for colour printing [1].

This machine was chosen to be used due to its simplistic and minimalistic design meaning only a few fasteners will be need to be removed to modify the machine for adaptation to fit the new nozzle and extruder designs.

### 3. Brief

To initially test and subsequently develop/re-design the mixer nozzle (figure 1-5 & 3-1) designed by Bowyer that enables the production of FFF parts in a variety of uniform colours from a few separate filament feeds. The design should be as simple as possible to manufacture as to keep to the fundamental ideas of the RepRap project;

As many of the parts used in the final design should only use (where possible) [8];

1. Any component which can be manufactured using FFF RP technology
2. Self-tapping screws/ Standard metric nuts and bolts
3. Brass Bushes
4. Lubricating Grease
5. Standard electronic chips e.g. microcontrollers
6. A low voltage power supply
7. Stepper motors
8. Simple machining methods and hand tools

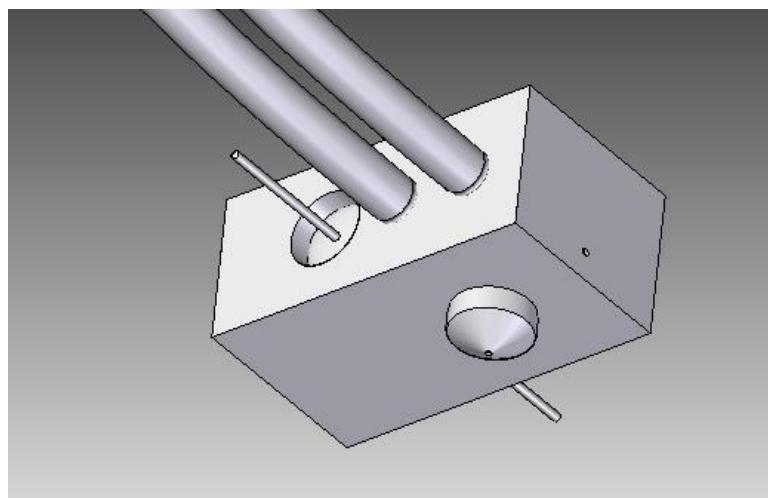


Figure 3-1 - CAD Model of the Mixer Nozzle with PTFE feed tubes and Heater resistor in place.

## 4. Literature Review

### 4.1. Single Filament Machines

As stated above the current models of 3D printer only use single filament extruder heads which results in a rather limited use of the design. The only method to change colour on most current machines is to pause a print and replace the filament or to cut the filament and fuse different filaments together. Joining the sections of filament together can be very difficult and there is little work that has been done to perfect the process as it is not widely accepted practice.

There are a few methods to join filament but require skill and practice to perfect, these methods include using a lighter or a hot-air gun to melt the ends and hold together until they cool. A better tested method for joining filament is to make an aluminium block held at 160°C with a heater channel to enable the filament to be rotated to give a smooth clean join. The block has a heater resistor and thermistor similar to that in the hot end of a RepRap meaning it can be controlled by the same board as on the machine. The process only takes a few seconds and generally doesn't cause problem in the extrusion process [6].

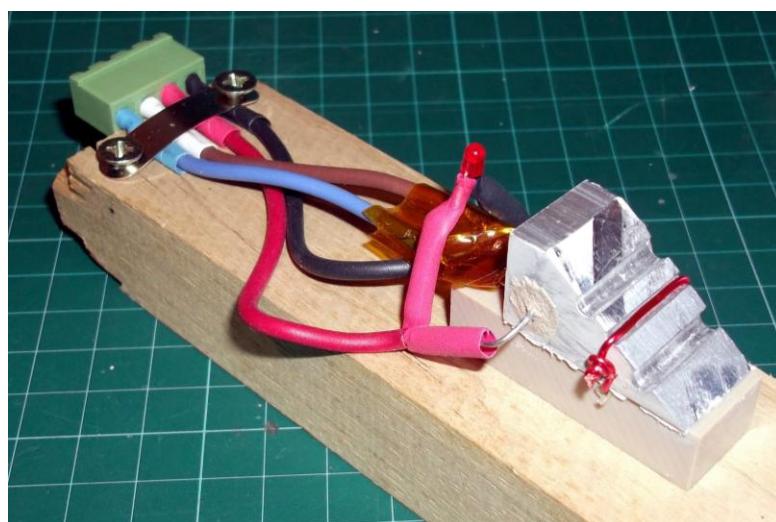


Figure 4-1 - Aluminium block with heater channel used to fuse filaments together [6]

The results of the joiner (Figure 4-1) can be seen below (Figure 4-2 & 4-3) the transition from each colour is flawless and the print quality remains meaning there is no compromise inflicted into the print by changing filament.

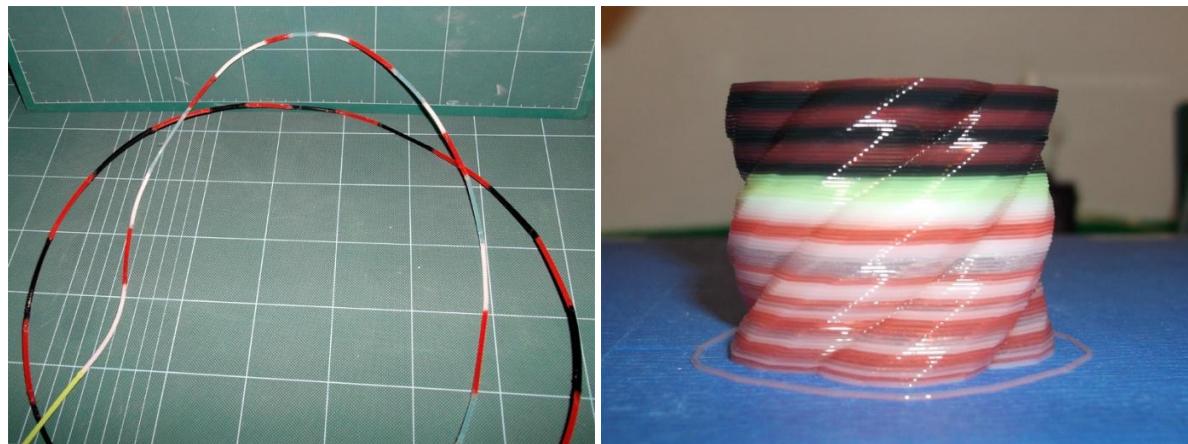


Figure 4-2 - Fused filament and associated print [6].



Figure 4-3 - Example of colour printing using filament joiner [9]

The main disadvantage to this method is the colour can only be changed by layer and each print has to be estimated, lengths cut and fused together. This is a lengthy process and has large error associated with it due to the measurement of filament. Using this method results in the shape/geometry being determined by the colour rather than designing an object and then chosen a colour for each section. This can be seen in Figure 4-3, there is a step up between each colour of the rainbow.

## 4.2. Dual Extruder Machines

As mentioned in the Introduction there are systems available that use a dual extruder system which enables the use of two filaments. The design uses two separate extruder systems side by side each with separate feeds, this arrangement uses features in the firmware and G-code to incorporate an offset to ensure the print lines up when alternating between filaments (Figure 4-4 & 4-5)



Figure 4-4 - Makerbot Replicator Extruder Carriage [10]

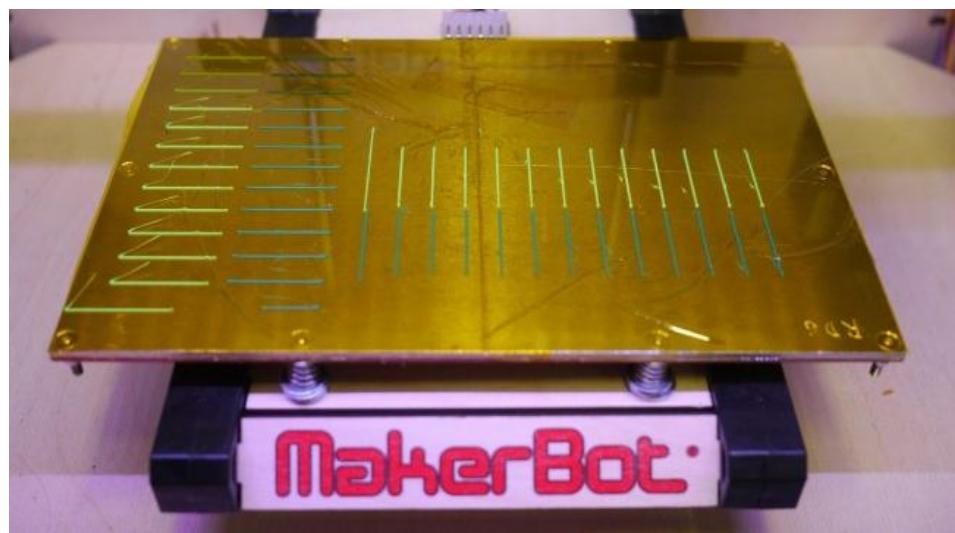


Figure 4-5 – MakerBot Calibration Print [11]

Despite having a separate nozzle, with careful calibration (figure 4-5), the accuracy of the prints is remarkable good and the printer is able to create a precise bi-colour model (figure

4-6). Fusing filaments lengths, although it can create aesthetically pleasing results, there is little control over colour changes which is solved using the dual extruder. The separate extruders have very precise control meaning the geometry printed is independent of the colour of the surface of the plastic

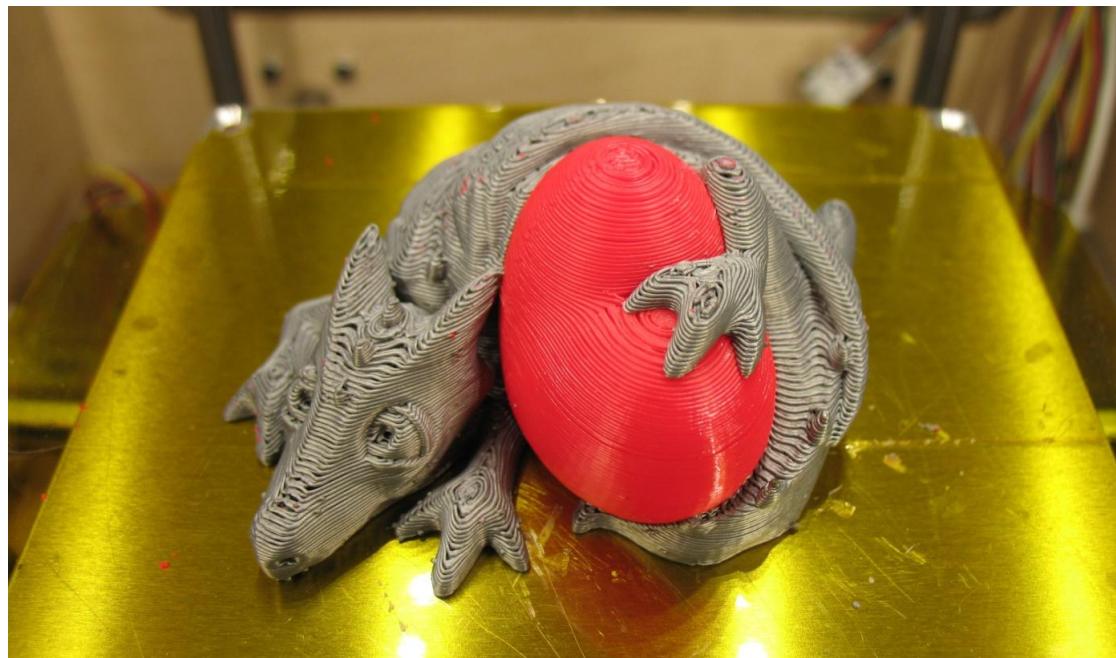


Figure 4-6 - Bi-Colour Dual Extruder Dragon Heart Print [12]

There are certain disadvantages associated with the dual extruder such as the space required to house the two extruder heads. As the X-carriage holds the entire extruder assembly, which moves in the X and Z directions, this has to be kept to a minimum in size as to not compromise the print area of the machine. It would be possible to have many separate extruders with a range of colours but the size of the X-carriage would be too large to fit on any machine. If the machine was made larger to accommodate the extra extruders this would come as a compromise on the structural rigidity of the machine and the quality of the prints would suffer.

Another problem related to the addition of extra extruders is the increase of the weight of the carriage which leads to a large accumulation of inertia, the stepper motors would have to be upgraded to drive the X-carriage to avoid miss stepping or overheating. This is an undesirable consequence especially in terms for RepRap which designed with standardised parts, cost and minimal alterations when implementing upgrades.

### Bowden Tube

A solution to having the entire extruder assembly on the X-carriage is to use a Bowden cable which moves the filament drive mechanism off from the X-carriage which is the main contributing mass to the carriage. The Bowden cable enables improved ‘controlled motion, less shaking of the machine and faster printing’ [13]. The filament drive motor is mounted on the frame of the machine and the filament is fed into the hot end nozzle via a PTFE (Teflon(tm)) tube. PTFE is used as it has a very low friction value which reduces the force required to feed the filament and it can withstand the heat of the hot end nozzle (Approx. 200°C), also it can flex and not create too much resistance to the drive of the carriage. One slight compromise of this method is that the compressive hysteresis in the filament causes slight extrusion after the motor has stop driving which is amplified by the PTFE tube, this affects the quality of the print but only minimally if the extruder motor is reversed after stopping to reduce the pressure in the hot end [14].

Using the Bowden tube enables the design of the machine to remain and also has the added benefit of being able to position the two separate nozzles closer together as the bulky stepper motors and drive mechanism previously prevented this.

Although using the Bowden tubes resolves a few problems, the main limitation of only being able to print using colours from the supplier remains, there still remains the desire to

be able to print a variety of colours from a few input filaments which can be defined by the user of the machine.

### 4.3. Material

The main two materials considered for use in this research were Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS).

#### 4.3.1. Polylactic Acid (PLA)

2-hydroxypropanoic acid is a bio-degradable polymer which is manufactured by the fermentation of glucose or maltose available from a variety of crops, it can even be produced from milk or whey using a suitable bacterium [15]. PLA has a melting point between 180-200°C and has a glass transition temperature of 60-65°C. It is dimensionally stable and widely available at a reasonable cost. One disadvantage to this material is the coefficient of friction is higher than that of ABS [16].

PLA, if left in the hot end for a period of time, can thermally decompose, in general printing this isn't an issue as the time the plastic is held at temperature is small, but if with a new extruder some drives are not used for longer periods this might become an issue.

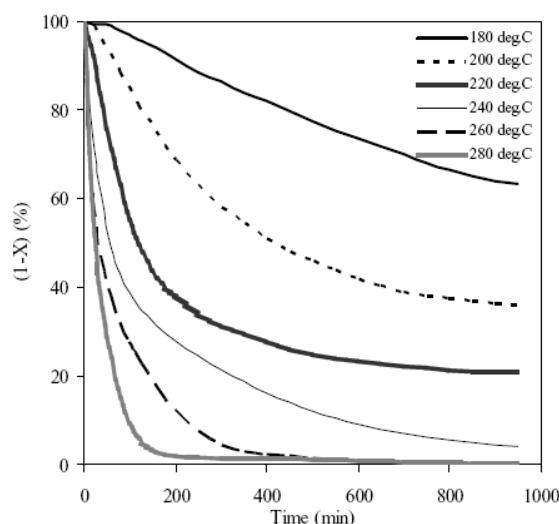


Figure 4-7 - Isothermal weight loss of PLA at various temperatures [15]

### *Colour Properties*

It has been found through experimentation that the printing quality and properties vary slightly with the colour of the PLA, each colour is summarised below [6];

Black – good printing quality and 75% opaque. Was found to be a smaller diameter but that is more down to the supplier than the material.

Blue – at higher temperatures of 196°C micro-bubbles are formed within the extruded filament, these are minimised at 187°C. Blue is a more brittle filament but produces good quality hard prints.

Red – is more viscous than other colours at the same temperature, this would probably be resolved using a slightly higher temperature.

Yellow – very good printing quality and flexible filament with enough give to not snap. The printing quality is resembles that of printing with ABS.

Green – is a combination between blue and green, has good printing quality and appearance.



**Figure 4-8 - Identical prints in a range of colours [6].**

### 4.3.2. Acrylonitrile Butadiene Styrene (ABS)

ABS is a common thermoplastic used in injection moulding and extrusion processes. Its glass transition temperature is 105°C, meaning it is more suitable for extruder and X-carriages where PLA can have issues withstanding the heat. Its production for 1kg requires 2kg of petroleum in terms of weight and energy which is much more un-environmentally friendly compared to the renewable nature of PLA.

ABS has a lower coefficient of friction than that of PLA, the lower friction means reduced extrusion force required by the motor and more control in the print resulting in better quality prints especially for smaller prints.

There are however a few disadvantages associated with ABS, one major undesirable effect is the fumes produced during extrusion which can cause eye, skin and respiratory tract irritation [17]. The fumes can be dangerous for people (or pet birds) with chemical sensitivities or breathing difficulties [18].

Another disadvantage to ABS is the higher extrusion temperature required, this isn't such an issue with current printers as the hot end is quite small and the mass of nozzle is minimal. However with a mixer nozzle design the heated mass of the nozzle will be significantly larger and reaching higher temperatures may become difficult. One final disadvantage for this material is that it requires a heated bed to print on at above 100°C to prevent warping of the part, again this is above the limit of some machines as the beds are underpowered to reach this and others have very long heat up times.

One final disadvantage to using ABS is the limitation of available colours compared to PLA, ABS tends to be available in more natural colours whereas PLA is available in a wide variety of colours.

#### 4.4. Programming & Electronics of RepRap

The current models of RepRap have very limited flexibility for future developments with multi feed drives, as up until now there have been little demand for the extra controls as methods such as fusing filament sections together required no extra programming. Generally the electronics have the ability to drive a single extruder although the RAMPS 1.4 electrics system has the accommodation for 2 extruders [19], but even with two separate extruders two completely independent CAD models need to be produced and the machine alternates between each nozzle and CAD file on each layer to build up the print.

For the development of this new nozzle, programming will have to be done manually by typing G-code (machine code) where as usually this would have been done using programs such as Slic3r which takes an STL file, slices the model to be printed into layers of defined thickness and then generates the G-code lines. Once the mechanics of the machine are designed and tested, software can be implemented to generate G-code automatically.

As well as requiring new software for the machine operation, new developments will be required to the CAD format as currently there is no scope for programming a part with different coloured sections. Generally STL (Standard Tessellation Language) file format is used which offers no representation of surface texture or colour and only represents the 3D surface geometry by a series of triangles.

There are other file formats which are in development to accommodate new features, the most likely candidate for use with different colours and materials is AMF (Additive Material Format) which allows the geometry and composition of an object to be programmed. This format, as well as offering these new features, stores a higher resolution than that of the STL format. It has been especially designed for additive manufacturing and

3D printing in mind by Cornell University, to enable seamless manufacturing regardless of printer and hardware being used [20].

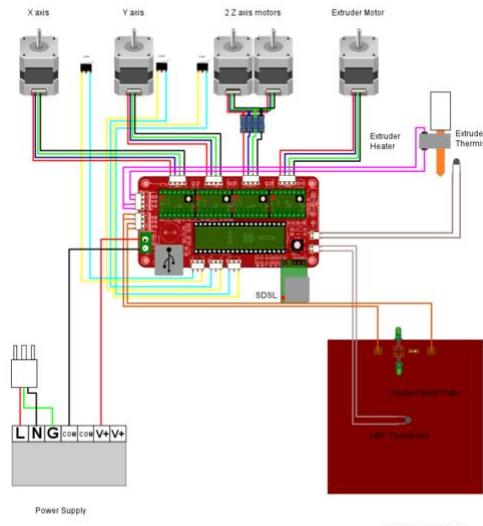
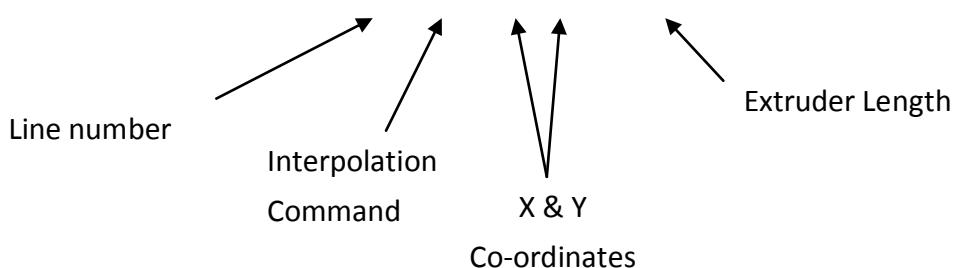


Figure 4-9 - 1.3 Sanguinololu Electronics Wiring Schematic [20]

Finally the firmware of the machine will need modification from the single extruder command (E in the G-code see Appendix for G-code commands). Initially it is thought that 6 separate filaments may be required (Cyan, Magenta, Yellow, Black, White and Clear/Water Soluble/Soft Filament) which will need 6 commands. For example A, B, C, D, J and K could be used as commands (E is already standard control as is G & H, see Appendix) for each individual filament drive but the firmware would have to check that a sum of all 6 drives equate to that expected of E as if the machine were printing with a single filament.

1 G01 X00 Y00 E2340

2 G01 X30 Y40 E2390



The standard layout of G-code for the RepRap machine, instead of E, with the new extruder head the code will have A, B, C, D, J and K to control each filament and E will remain but will control all four filaments simultaneously [22].

## 4.5. Static Mixing Nozzles

### 4.5.1. Glue Mixing Nozzles

There is a vast supply of glue mixing nozzles available which are used for mixing two part glues/epoxy resins, this saves the messy process of stirring the compound manually and also means that only the correct volume of glue is used, thus minimising waste of the expensive compounds. These types of nozzle use complicated moulded plastic inserts within a (generally clear) outer shell, from forcing the two separate glue components through this 'maze' large amounts of shear are created within the viscous liquid causing mixing to occur.

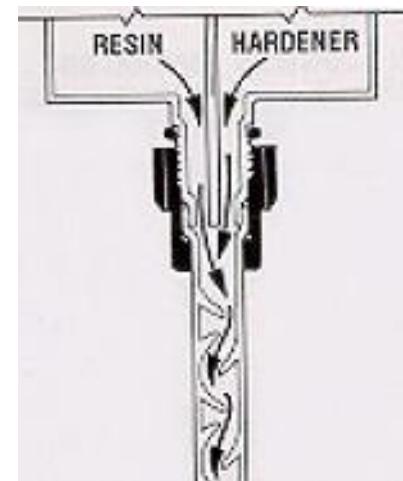


Figure 4-10 - Epoxy Resin Mixer Sketch [23].

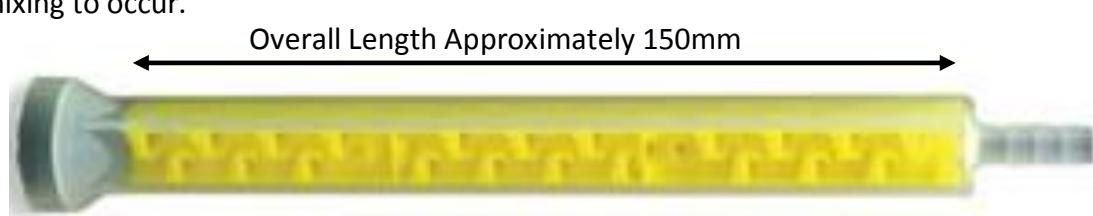


Figure 4-11 - Staggered Mixing Two Part Glue Mixing Nozzle [24]

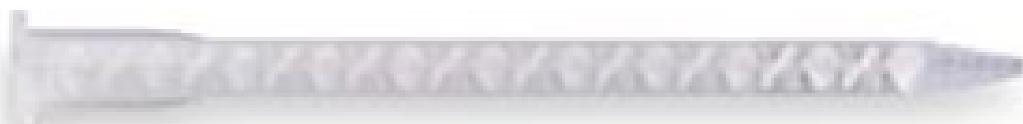


Figure 4-12 - Alternating Helical Two Part Glue Mixing Nozzle [25]

The glues used in these nozzles have a relatively high viscosity which would be similar if not higher to that of molten plastic during printing, this means that for a mixing nozzle to work well a similar amount of shear needs to be created within the mixing extruder nozzle as a two part glue mixing nozzle.

These inserts would be ideal for application in a plastic extrusion nozzle except for the fact they are manufactured from plastics which would have a similar melting point or a glass transition temperature to that of the operating temperature of the extruder nozzle. These inserts are moulded as the shapes are very complicated and near impossible to machine, therefore manufacturing them from a metal would be very difficult and costly.

#### 4.5.2. Injection Moulding Mixing Nozzles

In Injection moulding there are many static mixing nozzles available used for filtering and homogeneous mixing of a plastics during moulding. The designs of the filtering/mixing elements vary dramatically across a large range of geometries, this suggests that there is no real optimum design for general use in mixing and that some designs are favourable for different purposes in the industry.

##### PPE Linear Edge Melt Filter Nozzle [26]

The relatively simple geometry of this filter nozzle (figure 4-12) enables easy cleaning and minimises the possibility of the nozzle ahead becoming blocked. The relatively large flow area of the filter in comparison to the nozzle area induces a minimal pressure loss during use. In addition this filter can be used to homogenise and colour disperse a mix, the mixing is caused by the high shear regions between the insert and the casing.

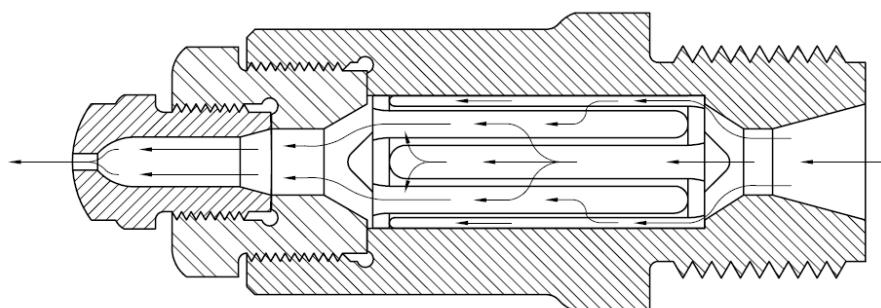


Figure 4-13 - PPE Melt Filter Design Nozzle [26]

The filter design consists of longitudinal passages around the circumference, half of which are open at one end and the other half to the opposite end. The centre of the filter insert is a slightly smaller diameter than that of the casing which allows the flow of the plastic from the entry channels to the exit (figure 4-13). The clearance between the casing and the 'land' of the filter can be reduced to increased the filter performance, which creates more shear and better mixing properties, but this would result in an increase in pressure loss across the filter.



Figure 4-14 - Linear Melt Edge Filter [26]

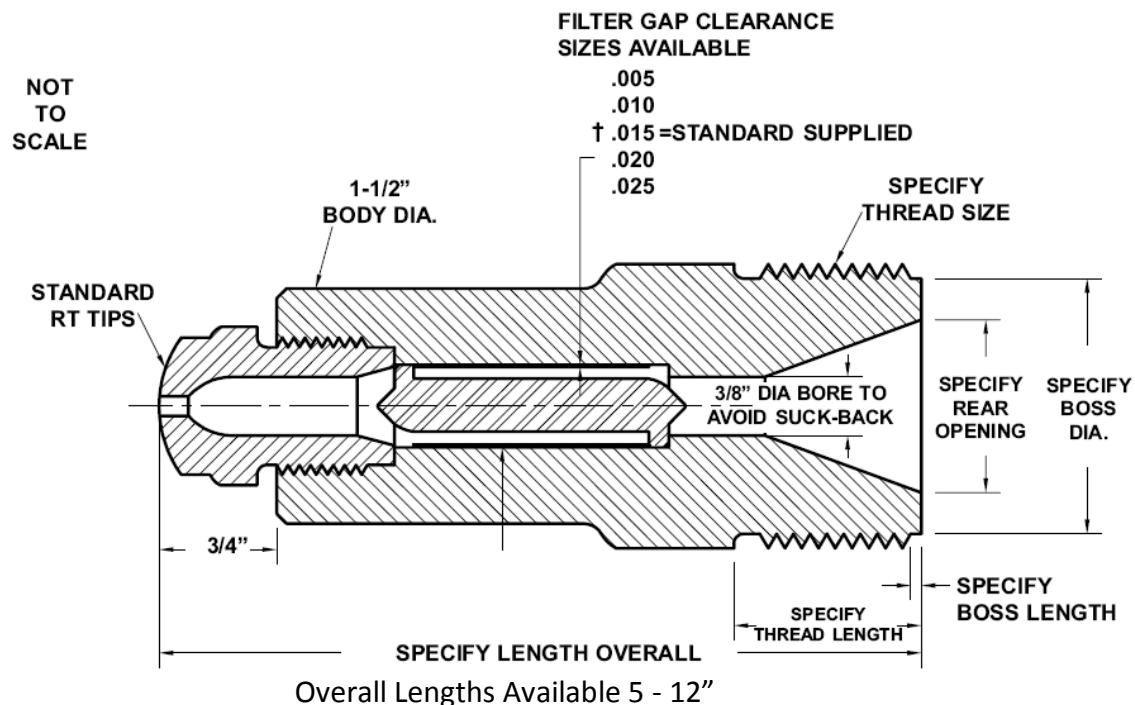


Figure 4-15 - Drawing of smallest available Filter nozzle from PPE [27]

### PPE Colour Mixing Nozzle [28]

In addition to the filter nozzle, specific colour mixing nozzles are available which are somewhat more substantial in design and manufacture. The prime purpose of these nozzles is to create maximum shear within the plastic to ensure homogenous mixing during prolonged use.

The nozzle design (figure 4-15) uses a series of coarse pitch (1.5") blades which are alternate directions (left/right hand screw) to generate the shear required for mixing. These nozzles are available with 3-18 separate blades, all the parts are fabricated from heat treated stainless steel for abrasion and corrosive resistance.

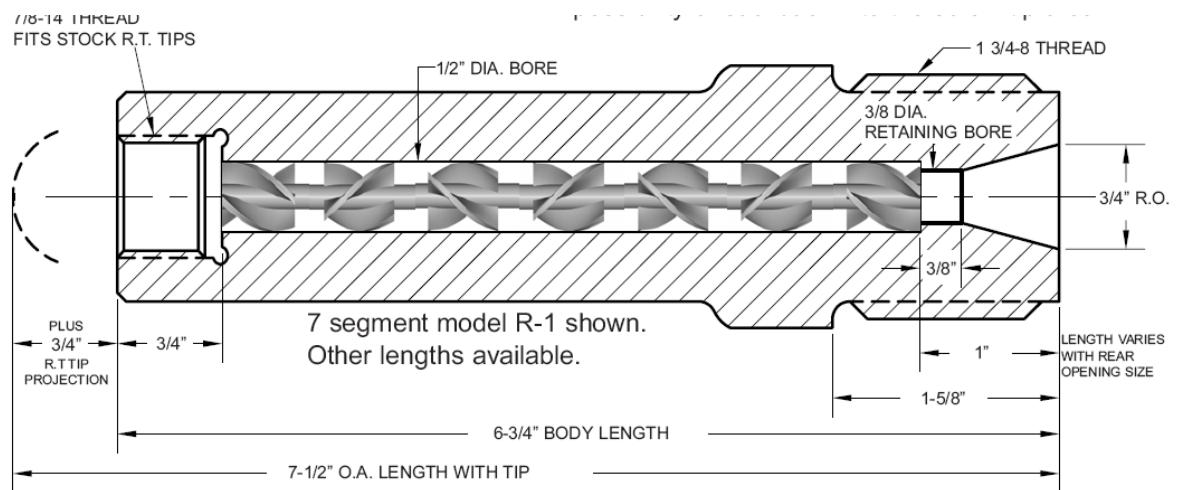


Figure 4-16 - Cross-section of colour mixing nozzle from PPE [28]

### *Other Static Mixing Nozzles*

#### Nickerson Static Mixing Nozzle [29]

Nickerson has a similar concept to PPE in having multiple short mixing elements to ensure a high level of homogenisation in the end product and are designed to be versatile with different types including recycled plastic, the designs are specifically designed to eliminate ‘spots, streaks and clouds of colorant’ [29] in the end product. This high level of homogeneous addition of colour helps to reduce the quantity of colorant used which reduces the quantity used in industry and the improvement between a standard and the colour mixing nozzle can be seen in figure 4-16.



Figure 4-17 - Comparison between a standard nozzle (left), the Nickerson Static Mixing Nozzle (centre) using the same machine settings and a mixing element (right)

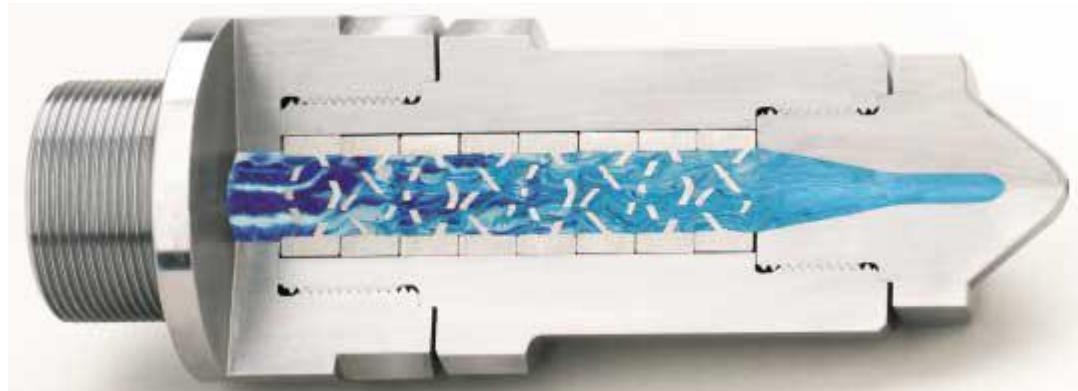


Figure 4-18 - Nickerson Static Mixing Nozzle (SNM) [29]

### StaMixCo Static Mixing Nozzle [30]

The StaMixCo mixing elements are very similar to that used by Nickerson and use a 'monolithic cast' construction to ensure the structural integrity of the element. Figure 4-19 shows the different mixing stages throughout the process and the effect of each individual element.

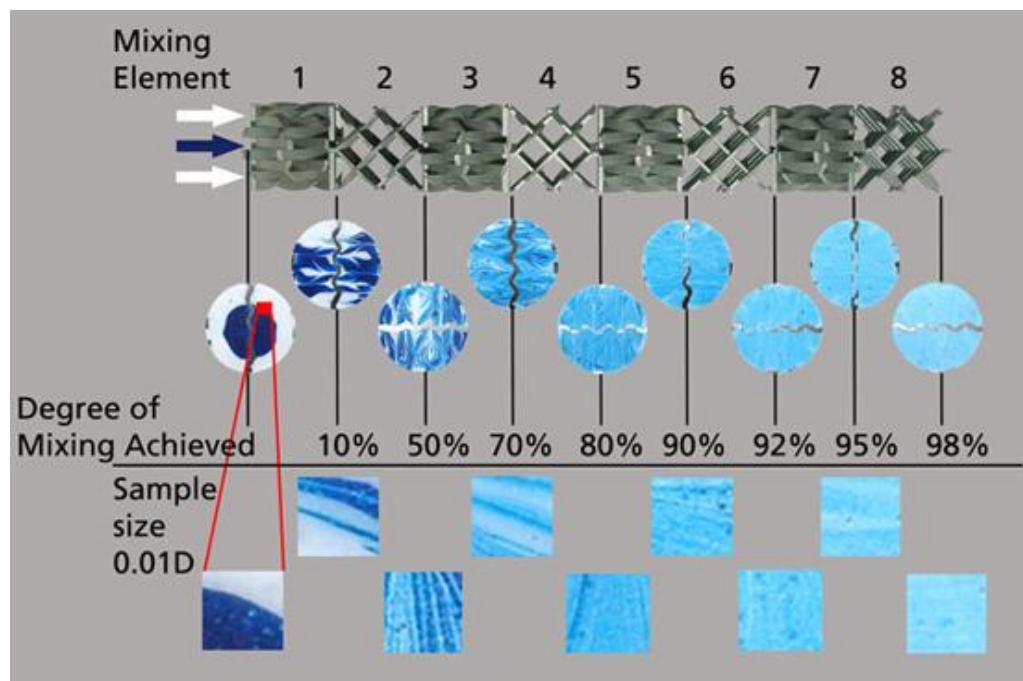


Figure 4-19 - StaMixCo Static Mixing Nozzle Performance [30]



Figure 4-20 - StaMixCo Complete Nozzle with Mixing Elements, Heater Bands and Thermocouple [30]

## 4.6. Active Mixing

### 4.6.1. Multi-material Deposition – Robocasting [31]

In 1998 Robocasting made advances in ceramic deposition which enabled multiple materials to be extruded through a single orifice. The design could handle 4 separate feeds and contained a 3mm mixing paddle which was turned when driving two feeds simultaneously to ensure a constant consistency throughout the deposited material. This enabled different ceramics to be mixed in a virtually infinite number of proportions and printed in varying gradients across a single part (figure 4-9).

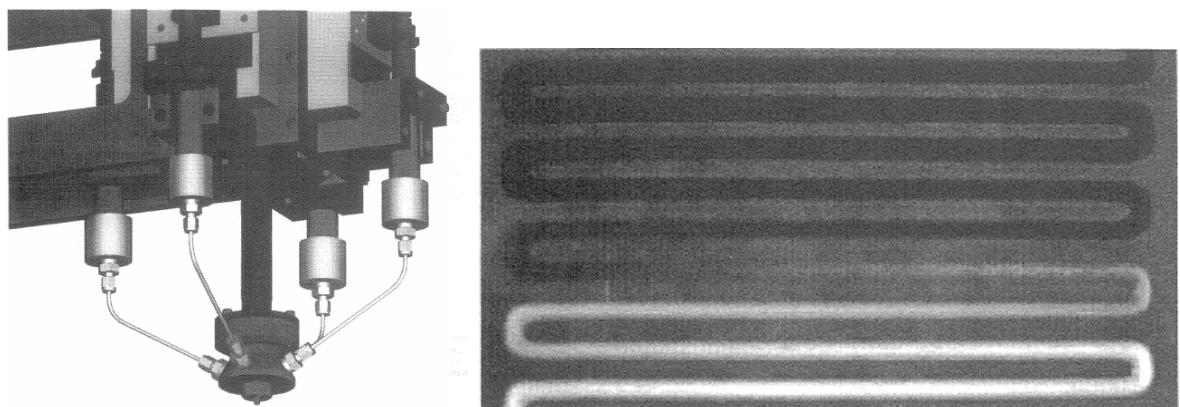


Figure 4-21 - Robocasting Multi-material Head (left) and deposited graded transition between two materials (right)

This head was designed as well for some reasons that are less relevant to today's 3D printing such as the ability to print overhangs which are possible with FFF without support material (up to 45°) as the plastic starts to set as soon as the material leaves the nozzle but ceramics remain soft until after they have been dried, burnout and sintered. For any degree of overhang to be made using ceramics, support material has to be provided or the print will simply 'slump' as the material is deposited at room temperature and doesn't increase in viscosity after having been extruded unlike FFF. An example of this sacrificial 'fugitive' support material can be seen in figure 4-22.

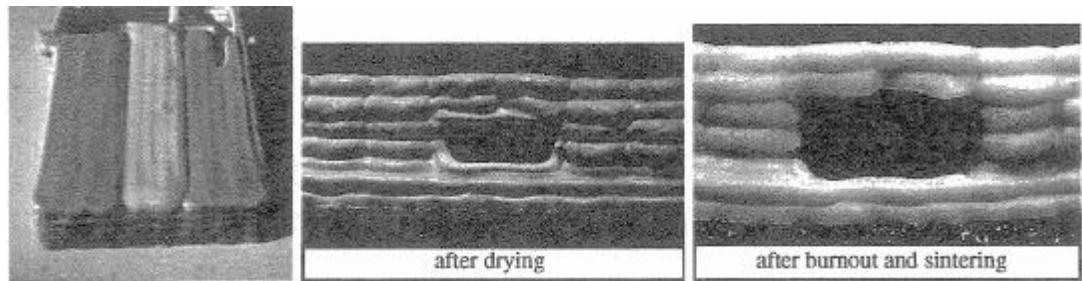


Figure 4-22 - Robocasting a kaolin slurry with a support material to demonstrate 'freeform' printing [31]

#### 4.7. Colour Space Background

Colour space is a map of all the visible colours that can be created using a method, the two main colour spaces used are RGB (Red Green Blue) and CMYK (Cyan Magenta Yellow Key (black)), which are used in displays and printing respectively. Additive colour (RGB) works on the pretence that starts with black (i.e. no light) and adds wavelengths of light to create colours which results in white light being visible when all wavelengths are emitted. Subtractive colours (CMYK), used in printing, uses the opposite principle (as the name suggests) and adding all three components results in black as all light wavelengths are absorbed. Although a representation of black can be created using three components the extra key is used as well to produce unsaturated, deeper black tones and dark colours.

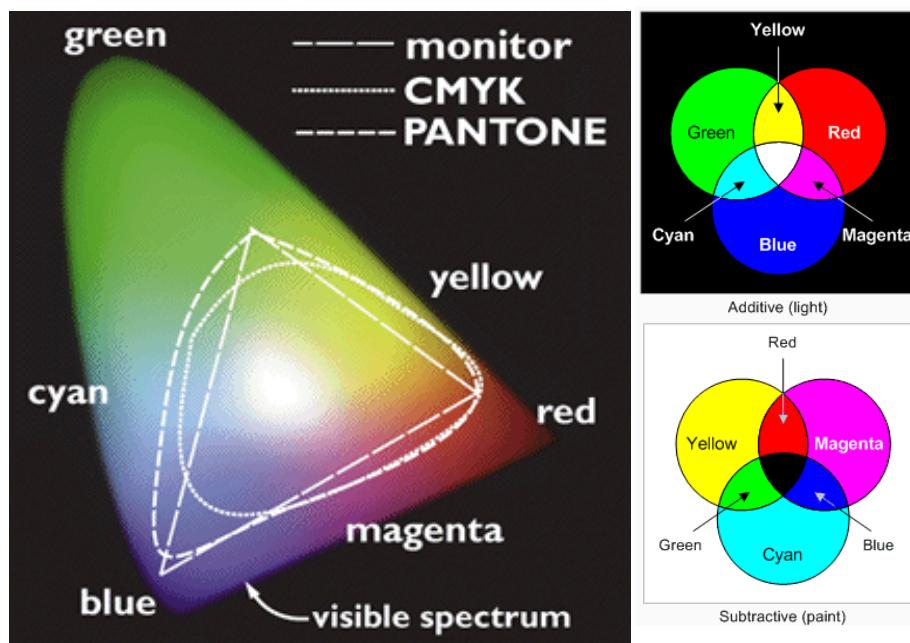


Figure 4-23 - Colour Space represented in a horseshoe shape (left) [32] and representations of RGB and CMYK (right) [33]

For this nozzle development the CMYK colour space will be used but as the FFF method does not print onto an object (i.e. paper/blank model etc), so there will need to be 5 filaments in total being Cyan, Magenta, Yellow, Black and White to obtain the full colour spectrum, white being used to create lighter shades and the absence of colour. Usually in printing white is not needed as less ink is printed onto a page to achieve a lighter shade of colour. In the programming of the nozzle with full colour capabilities white or an additional clear filament would have to be defined as a default to fill in where colours are not required.

The analysis of colours produced using the mixer nozzle will be using CMYK values (although the colours will only be compared with the original filaments used) as this will be easier to relate printing methods and when the design is fully operational the programming of colours to print with will be using CMYK based system.

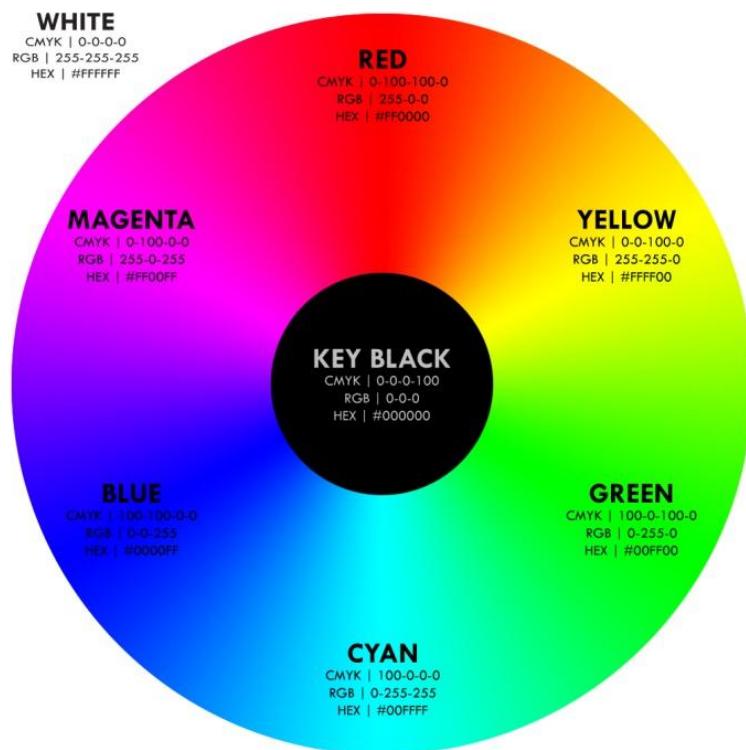


Figure 4-24 - Colour wheel showing how RGB compares with CMYK [34]

## 5. Aims and Objectives

The primary aim of this project is to enable the use of a single nozzle to print using multiple colours, this can be achieved by driving a single feed or multiple feeds simultaneously and mixing.

The main objectives of the project, which will initially be tested using black and white filaments on two feeds to the new extruder head design, are;

- To investigate the mixing properties of the extruder head when two colours are fed simultaneously into the head. For example if blue and yellow are fed into the head either; green will be fed out of the nozzle, or if the viscosity of the plastic within the heating head is sufficient this may prevent mixing and result in a 'stripy' outcome. If the latter is the case then further investigation maybe required into encouraging the mixing of the plastics.
- To investigate the performance of the mixing head to print using single colours and alternating between different feed sources.
- To investigate the proportions of input feed rates to get a desired outcome of colour.
- Investigate the method for printing colour gradients across a component.

## 5.1. Possible Additional Work

If time prevails further investigation that may be explored might include;

- Investigate the possibility of using varying property plastics in the mixing nozzle to get desired material properties.
- Investigate the possibility of using water soluble plastics (such as PVA) together with standard used plastic (PLA) to make more complicated geometries by printing as a solid piece before dissolving the water soluble plastic to leave the standard plastic.

## 6. Mixer Extruder-Head Development

### 6.1. Design Methodology

Considerable research has gone into RepRap and other 3DP extruder designs which have been tested thoroughly by the online community, therefore as the performance of other extruder drives are well known, the incorporation of as many existing designs/parts as possible is necessary to maximise the reliability of the drive mechanism to ensure the main variable is the new mixing nozzle. Also if existing parts and designs are used, then upgrading existing machines will require minimal effort.

#### 6.1.1. Extruder Design

There are many different types of extruder available for RepRap machines but it was decided at the onset of this research to use the Bowden tube extruder (section 4.2 & Appendix C), the main reason for this was down to the separate mounting on the machine. As the intention is to use 4/6 extruders for the final design the available space on any X-carriage would not be sufficient to hold these, as well as the additional weight would cause problems with the drive causing miss stepping and compromising on print quality. Having the motors mounted on the frame of the machine would mean the weight of the X-carriage is reduced and the accessibility of the nozzle is increased for maintenance. Finally the extruder heated mass should be kept to a minimum to reduce warm up times and refrain from upgrading to a more powerful heater resistor thus keeping the energy consumption of the machine down.

#### 6.1.2. Material Selection

Using the information from section 4.3 it was decided to use PLA for this particular research project as it is more common in the laboratory at the moment due to ease of

supply, lower printing temperatures and pleasant smell from the extrusion process. In addition PLA has a lower viscosity than ABS so should be more easily and readily mixed. PLA is available in different chain lengths (hard and soft) which if mixing was possible would mean the user could define the hardness of the printed part. Also PLA is more widely available in a variety of colours compared to ABS so close matching plastics to CMYK can be found for printing a full colour spectrum. Finally the renewable source of this material makes this plastic much more appealing and its biodegradability makes it environmentally friendly.

For initial experiments it was decided to use black and white filaments only to give the biggest possible contrast in colour so it would be easily observed whether mixing of the two plastics had taken place.

### 6.1.3. Design for Manufacture

A large part of the RepRap fundamentals is Design for Manufacture, as many of the parts as possible that cannot be RP by the machine itself and are not standard parts should be able to be manufactured by as few tools as feasible. If possible everything should be able to be manufactured using a lathe (basic operations if possible), a pillar drill and standard hand tools. Other considerations that should be made while designing parts is that they should be: simple; easy to repair/replace; economical; reliable; strong and accurate.

## 6.2. Method

### 6.2.1. Mixing Performance Testing Method

This section describes the general method for testing the mixing properties of a nozzle, each design requires variations in the testing procedure which are outlined in more detail in the relevant nozzle section.

For testing of the nozzle, first step is to analyse the performance of the head while being fed manually. The nozzle should be rigged up to the electronics of the machine (thermistor and heater resistor) and ensure that the correct thermistor look up table is selected in the firmware of the machine (Appendix H), for these experiments the firmware used will be Sprinter. The filament drive motors for these initial trials should be wired in series with one another, this is done for two main reasons; the first being to ensure the motors are driven at the same rate which results in a ratio of filament 1:1; the second being to keep the load down on the machine electronics as the motors are driven by current (if the motors are wired in parallel the total current required is approximately doubled). The sequence for wiring is as follows ;

```
1B -- black -- motor1 -- green -- black -- motor2 -- green -- 1A  
2A -- red   -- motor 1 -- blue  -- red   -- motor2 -- blue  -- 2B
```

Connect up two PTFE feed tubes (simply threaded into the nozzle block) and blank off any other remaining feed holes using grub screws with PTFE tape around the threads. Then blank off the mixing chamber hole on top of the block using the appropriate thread (leaving approximately 5mm protruding) and PTFE tape to ensure no leaking. Finally attach the PEEK insulating block onto the protruding thread from the mixing chamber blank thread and clamp the PEEK in a vice to hold the nozzle for heating up to temperature. Carefully feed the filaments down the PTFE tubes taking note of how much force is required for this, the force should be easily done by hand if tools such as pliers are required then this will most probably result in the drive motors stalling.

Following this initial trial and assuming the force required to feed the filament into the nozzle is not excessive, the nozzle can be mounted via the PEEK insulator onto the X-carriage

of the machine then the Bowden tubes can be connected up to the drive mechanism (Appendix C), after this is done the nozzle is ready to be used for printing. To keep the programming to a minimal amount at this time the two separate stepper drive motors were wired up in series (hence driven at the same speed) meaning only a ratio of 1:1 is possible, this means that the machine retains all its other functions (X, Y, and Z axis) and printing using this nozzle requires minimal change to the software. The slic3r settings used for this initial print can be seen in Appendix B-3.

Initially the temperature of the nozzle used for extrusion should be set to 200°C which is common for printing with PLA, if the mixing is not entirely sufficient trials can take place at up to 220°C to reduce the viscosity of the plastic which should aid mixing, unfortunately this is nearly the limit of the plastic and further increase of temperature may cause thermal decomposition of the plastic which could induce a colour change so the ending result will be difficult to judge.

Following this method, inserts may be made to cause extra turbulence within the mixing chamber, these shall be made to a comfortable fit (i.e. clear of the retaining thread and easily fitted by hand into the mixing chamber, but a good enough fit that the plastic will not easily flow around the insert). Then the same method as above should be repeated.

### *Standard Apparatus*

1. RepRap Electronics
2. RepRap Machine
3. Bowden Extruder Drives x 2
4. PTFE tubes with approximately 6 – 8mm of either end threaded (M4/M3)
5. Pronterface (User Interface to control RepRap Electronics)
6. PTFE tape
7. Vice or Clamp
8. Lengths of Black and White Filament

## 6.3. Initial Experimentation

### 6.3.1. Colour Mixing Trial

#### *Summary*

This short experiment was carried out to prove that the mixing of coloured PLA filament is possible and produces expected effects (similar to mixing paint colours) and was designed to roughly evaluate the relative pigment strengths to one another, so that when using a mixer nozzle, the extruded filament colour should be easily predictable. This will help identify whether both extruders are working properly during future experiments.

#### *Introduction*

Due to the limited literature found about the pigments used to colour PLA filament initial trials were carried out to verify that the PLA plastics would mix and colours would behave as expected (e.g. blue and yellow mix to produce green) and discover how much effort is required to mix a small sample. Finally this trial would determine the relative strength of pigments used in the PLA.

#### *Apparatus and Material*

1. Hotplate
2. Glass Beaker
3. Insulated Stirrer
4. Glove
5. Variety of Plastic Filament [35]

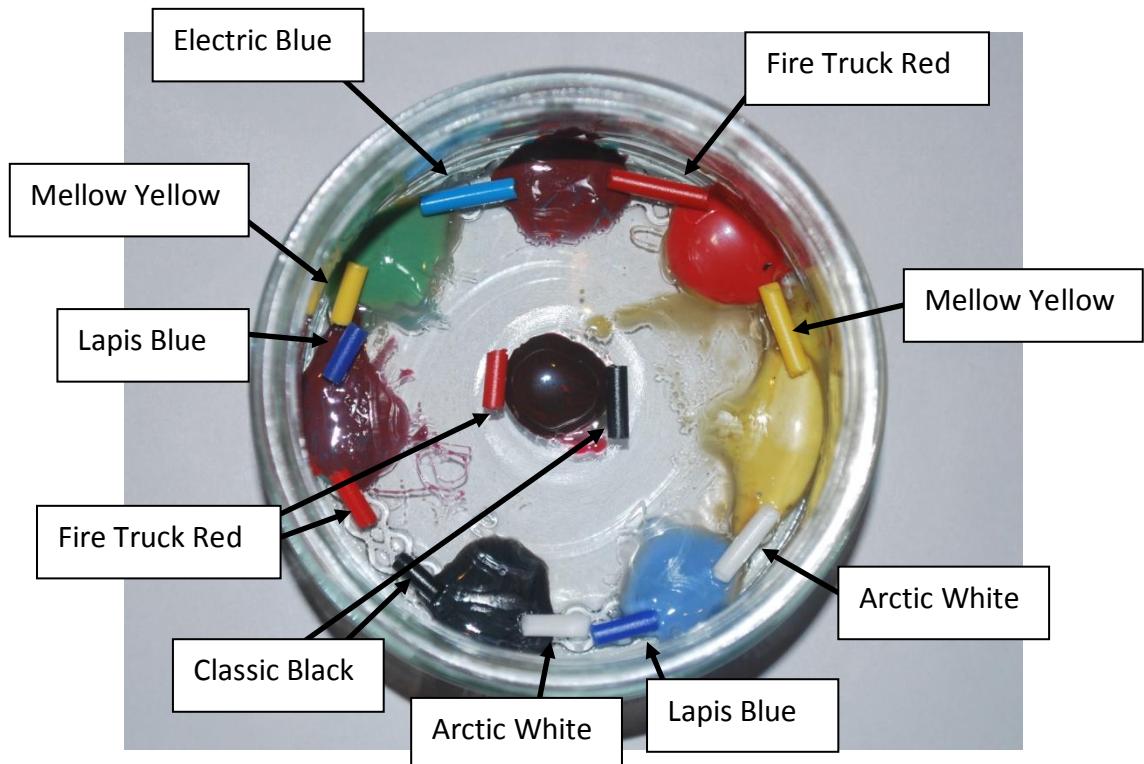
#### *Method*

1. Pre-heat the hotplate and glass beaker to just above the melting point of PLA ~150°C.
2. Pre-cut some equal lengths of two colours of PLA approximately 10mm should be ample.
3. Place two pieces (1 of each colour) of filament into the dish and allow to melt before carefully stirring until a uniform colour is observed.

4. If the one colour dominates the mix then add another piece of the opposite colour and mix.
5. Repeat step 4 until the resulting colour is a rather distinct colour between the two initial colours.

### *Results and Discussion*

The experiment was repeated 8 times using Faberdashery filament colours of Classic Black, Arctic White, Fire Truck Red, Electric Blue, Lapis Blue and Mellow Yellow [35]. These colours were chosen as they were to closest available comparison to CMYK and white from the company. The results can be seen in the figure 6.1 for a 1:1 mix ration below.



**Figure 6-1 - Mixing results from ratio of 1:1.**

Further mixing and varying the mix ratios was not as successful as intended due to the plastic melting to a lower viscosity causing adjacent colours to run and blend, despite the

experiment not working to a brilliant standard the results were still clear and figure 6-2 shows further mixing with respecting mix ratios. The samples were not fully mixed due to the viscosity of the plastic, further mixing pulled extra plastic from the side hence it was deemed acceptable to leave the 'swirls' in the sample.

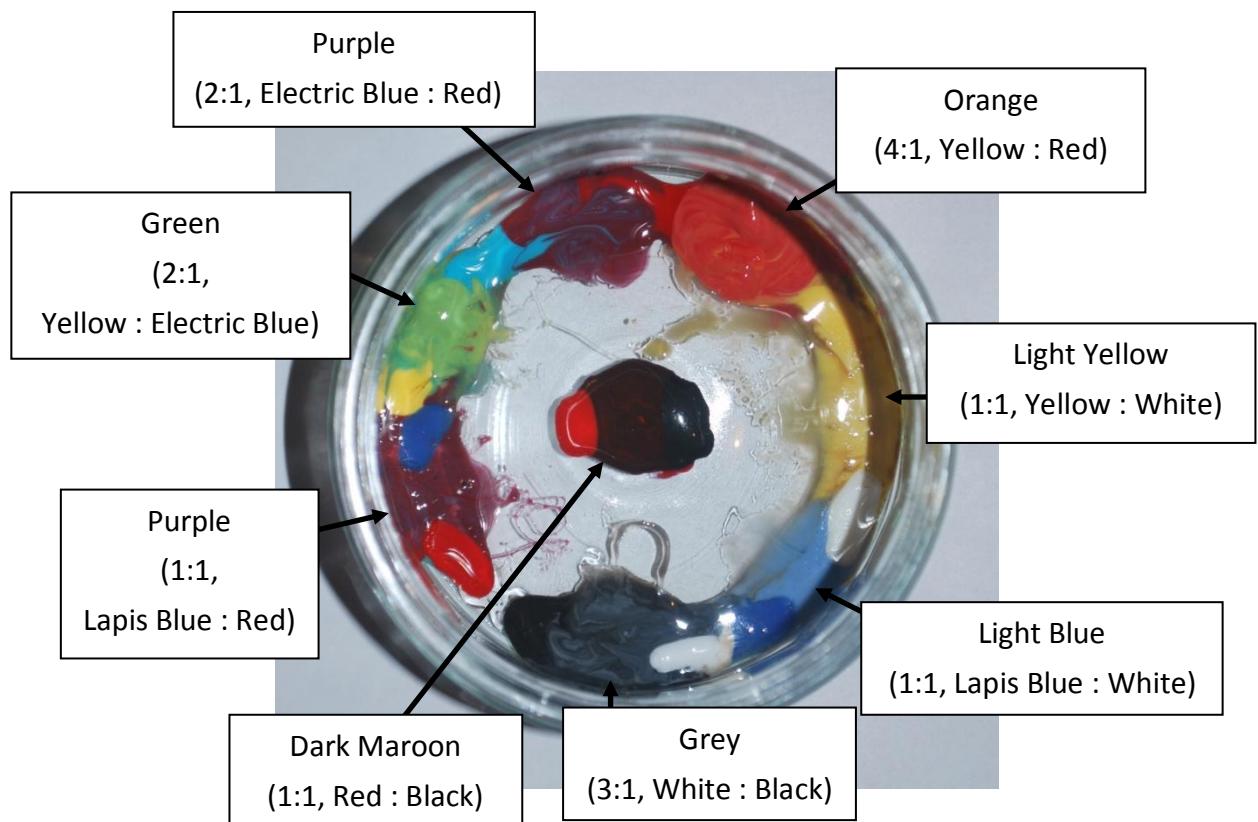


Figure 6-2 - Mixing Results with different ratios of colour.

The mixing performed exactly as expected and produced uniformly mixed samples (initially) with a short stirring time and some brightly coloured end products. This short experiment proved that the two different filaments can be mixed to produce another colour at a much lower temperature than that within the nozzle at printing temperature, thus more viscous for this experiment, therefore the mixing within a nozzle should be feasible.

The relative strengths of the pigments were found to be as follows;

Strength	Filament Colour
Strongest ↓	Classic Black
	Fire Truck Red
	Electric Blue
	Lapis Blue
	Mellow Yellow
	Arctic White
Weakest	

Table 1- Relative colour pigment strengths in order (strongest at the top).

### Conclusion

Progression with the mixing nozzle can now take place as this experiment has shown that the plastics can be uniformly mixed. The relative strength of the plastic pigments have been determined approximately so the colours to be expected from future experiments is known which will help evaluate the level of mixing occurring within the nozzle. It is also now clear that mixing black and white filament in a ratio 1:1 will result in a colour not very dissimilar to that of solely black, this will make it easy to determine the level of mixing happening within the nozzle as only a small amount of mixing will result in the white filament turning grey.

### 6.3.2. Initial Testing of the Nozzle MkI designed by Bowyer

#### *Introduction*

It is necessary to assess the performance of the mixing nozzle without any static mixing inserts as suggested in section 4.5. This will help identify how much extra mixing is required to achieve the desired effect of the nozzle, the performance of the nozzle is completely unknown and it is possible that no extra design is necessary although this outcome is very unlikely.

This experiment can result in three separate outcomes; first being unlikely, and could be a great impediment on the future of this idea if it is to be the case, is the force required to drive the filaments into the nozzle is excessive which would cause the stepper motors to stall if they were connected; the second possible outcome is that the two filaments (black and white) will mix uniformly to produce a dark grey extruded material; finally the third and most likely outcome is that the two filaments (black and white) will not mix and extrude out of the nozzle to produce a stripy ('toothpaste') effect, half black and half white. The final outcome may not be as undesirable as first thought as the nozzle diameter is only 0.5mm and to the human eye the two separate strands may appear a uniform colour, but further investigation will still be required to improve mixing quality of the nozzle.

#### *Additional Apparatus*

1. Mixing Nozzle MkI (Figure 2-5 & Appendix D-1) with heater resistor and 100k bead thermistor fire cemented in place.
2. 3mm OD (2mm ID) PTFE Tubes
3. Length of M4 threaded rod approx 12mm length and M4 nut
4. PEEK insulators (M4 internal thread)
5. M3 Grub Screws

### ***Method***

Set up as in section 6.1.4, this can be seen in figure 6-3 with white filament being fed from the left and black from the right. The mixing chamber blank is wrapped in PTFE to create a good seal and is locked using an M4 nut to ensure the blank remains firm in place.

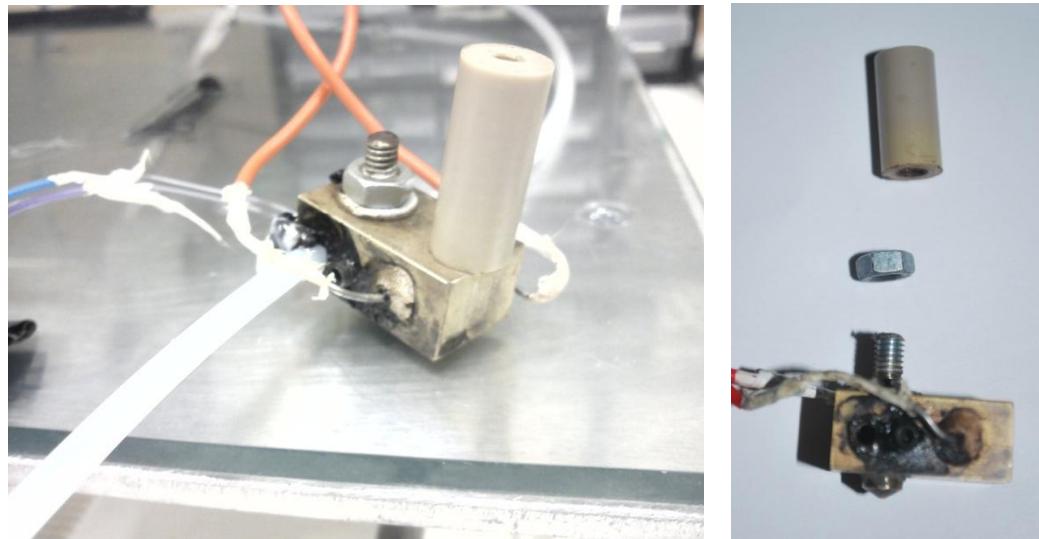


Figure 6-3 - Initial set-up of mixer nozzle (left), nozzle mixing chamber plug, locking nut and PEEK insulator set-up (right).

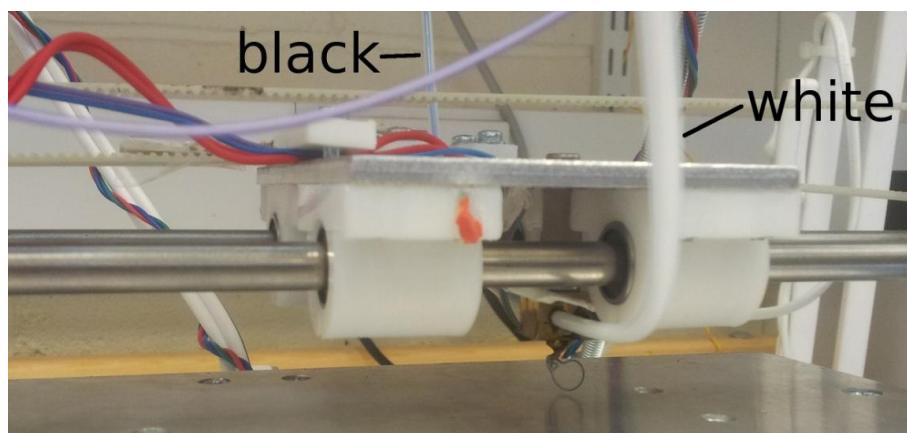


Figure 6-4 - Mixer nozzle mounted for printing.

### ***Results and Discussion***

The two separate filaments were easily observed in the extruded filament with a clear distinction between the black and white filaments on either side. The extrusion forces were

not significantly increased compared to normal extrusion therefore it was possible to rig the nozzle up to the machine for a test print.

The first test print can be observed in figure 6-5 and produced some interesting results, as stated above the filaments failed to mix and came out as two separate colours, in the print this is apparent as two sides are almost completely black and two sides are white, on the top and bottom of the print each pass of the printer can be seen with a streak of black and white side by side.



Figure 6-5 - First mixer nozzle print with very different appearance from opposite sides



Figure 6-6 - Underside of first print, the extra shear caused between the nozzle and the print surface caused extra shear thus better mixing qualities

The underside of the this first print was similar to the side and top, but with closer inspection there was small evidence of mixing, this was believed to be caused by the extra shear between the build surface and the nozzle tip, the distinction between the black and white filaments were slightly blurred with a slight grey region between the two.

### ***Conclusion***

From this initial trial is it clear that a significant amount of extra mixing is required to reach the target of uniform colours. The extrusion forces were as per normal for a standard nozzle and the printability with this new nozzle appeared unaffected from standard use, any untidy edges seen in the figures could be cleaned up by more careful calibration of the extruder steps and other settings within the Slic3r configuration file (Appendix B-3).

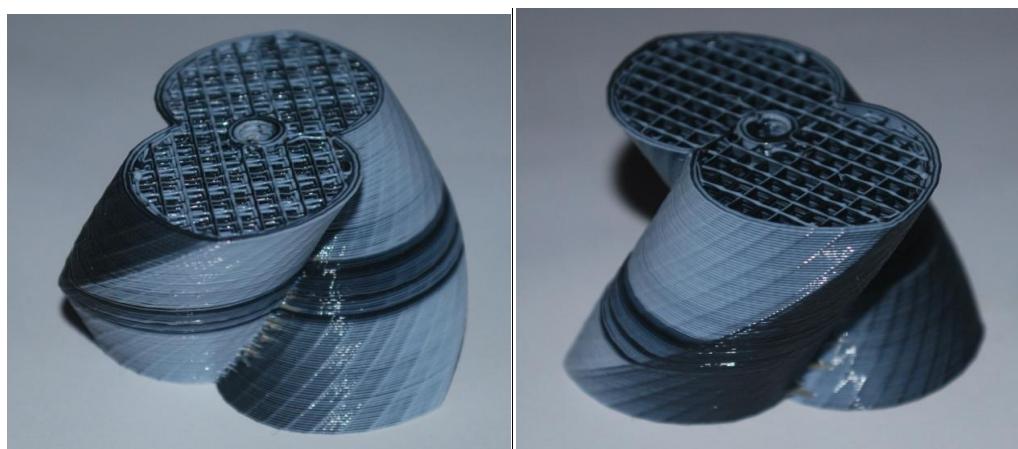


Figure 6-7 - Mk1 Nozzle print

Out of interest another print was tested and the result can be seen in figure 6-7 one side was mostly black and the other was mostly white. It can also be observed how the colour fades between the two. Another observation during the print was the failure of the white filament feed which led towards the black streak in the centre of the print, initially this was thought to be caused by the filament slipping on the hobbed bolt caused by the pressure within the nozzle. After further inspection it was discovered that the clamping force on the idle bearing was far too great for the filament which caused the filament to become deformed and flattened which consequently the filament to become lodged in the PTFE tube causing the hobbed bolt to slip on the filament, this could become a problem later if large extrusion forces are required.

## 6.4. Static Mixer Nozzle Development

### 6.4.1. MkII Nozzle Design

#### *Introduction*

Following the previous trial with the MkI mixer nozzle a similar nozzle was machined but with a larger diameter mixing chamber, this enabled a brass insert to be placed within the mixing chamber to cause extra turbulence. It may have been possible to fabricate an insert for the MkI nozzle but the diameter of the chamber was very limited which would have required precision engineering and fine tolerances, so for ease of manufacture and experimental purposes this new nozzle was made so that inserts can be easily manufactured to perfect the design then trials can be made to scale the insert down to reduce the size of the final nozzle.



Figure 6-8 - MkII Brass mixing Nozzle with Mixing Chamber Brass Mixing Insert in Place

#### *Apparatus*

1. Mixing Nozzle MkII (Figure 6-8 & Appendix D-2) with heater resistor and 100k axial thermistor in place.
2. 3mm OD (2mm ID) PTFE Tubes/4mm OD (2mm ID) PTFE Tubes
3. Length of M6 threaded rod 12mm/ Mixing Insert with M6 thread and locking nut.
4. PEEK insulators (M6 internal thread)
5. M3/M4 Grub Screws

### ***Method***

This nozzle was first tested using the identical set up as with MkI to verify that the results are similar with no insert (figure 6-9) which produced a virtually identical print as before (figure 6-12), then repeated with four different brass inserts (figure 6-10 & Appendix E).



Figure 6-9 - Nozzle MkII set-up with blank (left) and mixing insert (right).

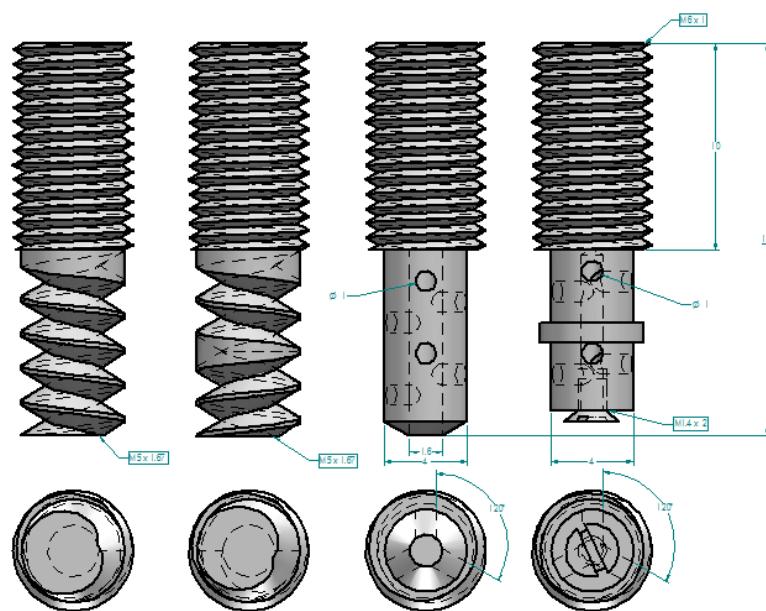


Figure 6-10 - Brass Inserts Tested; No.1 LH Thread Pitch-1.67mm Cut Depth-1mm (Far Left): No.2 LH Thread with Reversal to Right Hand Thread Pitch-1.67mm, Thread Depth-1.25mm (Left): No.3 Hollow Insert with 6 Holes ( $\varnothing 1\text{mm}$ ) equally spaced at  $120^\circ$  (Right): No.4 Hollow Insert with ridge and end blanked off (Far Right).

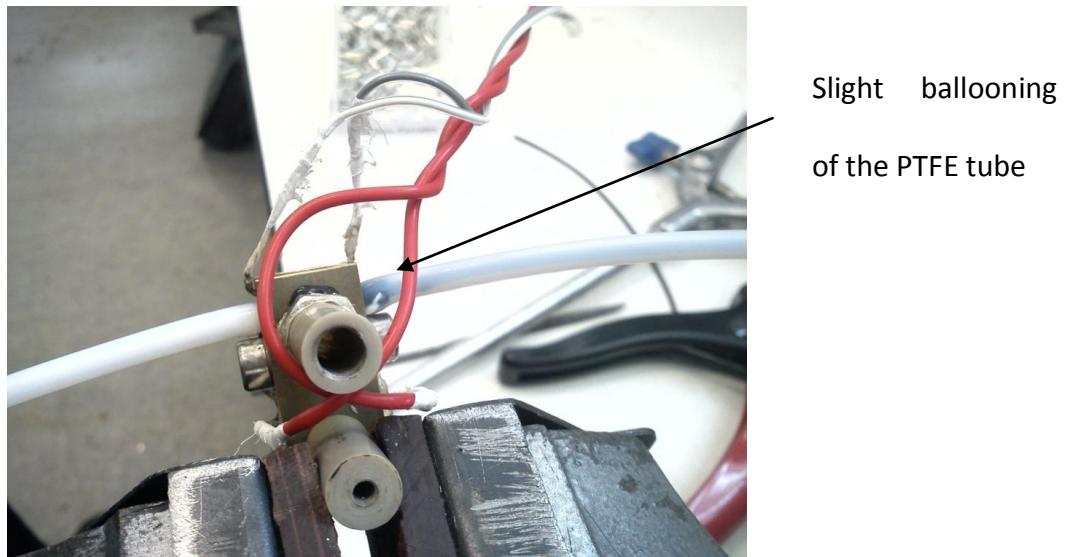


Figure 6-11 - MkII Nozzle set up in vice for testing with mixing insert in place.

### *Results and Discussion*

The initial testing on insert No. 1 (Figure 6-10) showed up a few problems with the set-up, due to the reduced cross sectional within the mixing chamber, the pressure required to drive the filament through the nozzle was greatly increased to the point that the 3mm OD PTFE tube was forced out of the block due to the flexibility of the tube and minimal thread depth. Before the tube was forced out of the block the end couple of millimetres of the PTFE tube nearest the nozzle had a slight ballooning effect, this is down to the PTFE losing some rigidity at higher temperatures. This ballooning and ‘blowing out’ from the nozzle was solved by increasing the outer diameter of the PTFE tube to 4mm and retaining the inner diameter at 2mm. By using the larger diameter PTFE tube the volume of material is increased approximately 2.4 times meaning the strength is more than doubled, this increase in strength was enough to withstand the pressure in the nozzle.

After modifying the nozzle the experiment was re-attempted which saw little difference from the original Mk1 nozzle, the two separate filaments could easily be depicted from the extruded material. It was also noted that the force required to drive the filament was greatly

increased from the original nozzle although didn't appear to be excessive. The nozzle was then attached to the machine to test the print quality so a comparison can be made with MkI.

After connecting the nozzle to the RepRap extrusions were attempted but due to the large forces required to drive the filament the stepper motors stalled, therefore the power was increased to the motors which subsequently caused the hobbed bolts to slip on the filament. From these results it was deemed an unusable design so the experiment was attempted with a second insert which incorporated a left hand thread which reversed into a right hand thread, this reversal in thread direction was to try to induce extra shear into the molten plastic to induce some further mixing. In addition to the thread reversal the thread was made using a deeper cut of 1.25mm in an attempt to reduce the pressure within the nozzle.

Using the second insert the hand feeding of filament into the nozzle force was not significantly reduced and the mixing performance was unchanged, the same results were yielded with the nozzle mounted on the machine with the stepper motors being unable to drive the filament so no print was produced. This resulted in the design of the third insert which tried an alternative method for mixing.

The third insert consisted of a hollow tube with a chamfered end which initially this was left high from the bottom of the mixing chamber (approx 1mm gap), the hollow tube had 6 x Ø1mm holes which the plastic would be forced through before heading down towards the nozzle end. It was thought that forcing the filaments through a number of small diameter holes would increase shear within the plastic inducing shear. The results can be seen in

Figure 6-12, from sample No. 3 there was no real visible change in the mixing quality of the nozzle and the prints were practically identical.

After print No. 3 was produced it was tested to see if increasing the temperature caused any additional mixing due to the reduction in viscosity which produced sample No. 4, this was in vain and no difference was noticed. This was thought because even though the viscosity of the fluid is reduced the Reynolds number is still very low due to the minimal velocity of the fluid as Reynolds number is a function of both these variables.

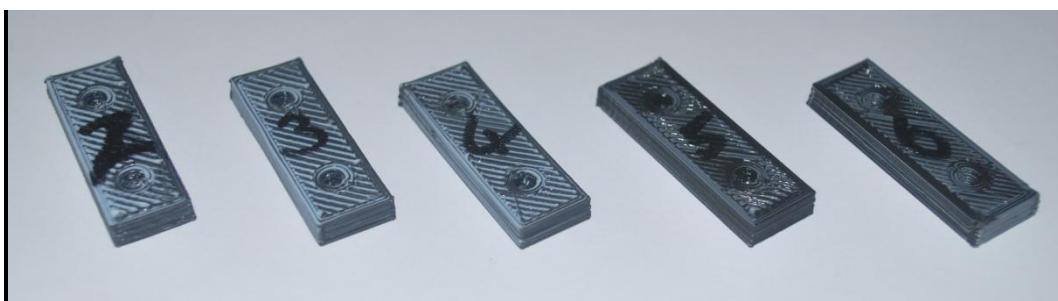


Figure 6-12 - Test prints from MkII nozzle; (From left to right) 2. Control Print with no insert, 3. Insert No.3 used at 200°C, 4. Insert No.3 used at 220°C, 5. Insert No. 3 used after tightening at 200°C, Insert No.4 used at 200°C.

The third insert was tested again after ensuring a seal with the bottom of the mixing chamber was made, this would reduce the flow area towards the nozzle thus increasing the pressure but the compromise could have paid off with the extra shear created by increasing the velocity through the small diameter holes. This created a noticeably different print (No. 5 in figure 6-12), there was no clearly visible white filament remaining in the print, where there had been white filament in previous prints now appeared a light grey, although the black filament remained unchanged from previous test prints, it was hoped that the final insert would create more mixing due to the plastic being forced through small diameter holes twice before the nozzle, as the plastic is forced into, down and then out of the insert.

The results from No. 4 insert can be seen in figure 6-12 sample No.6 which was almost identical mixing quality to that from sample No.5, two further test prints were carried out which consisted of a 15mm diameter cylinder with a dome top (figure 6-13).

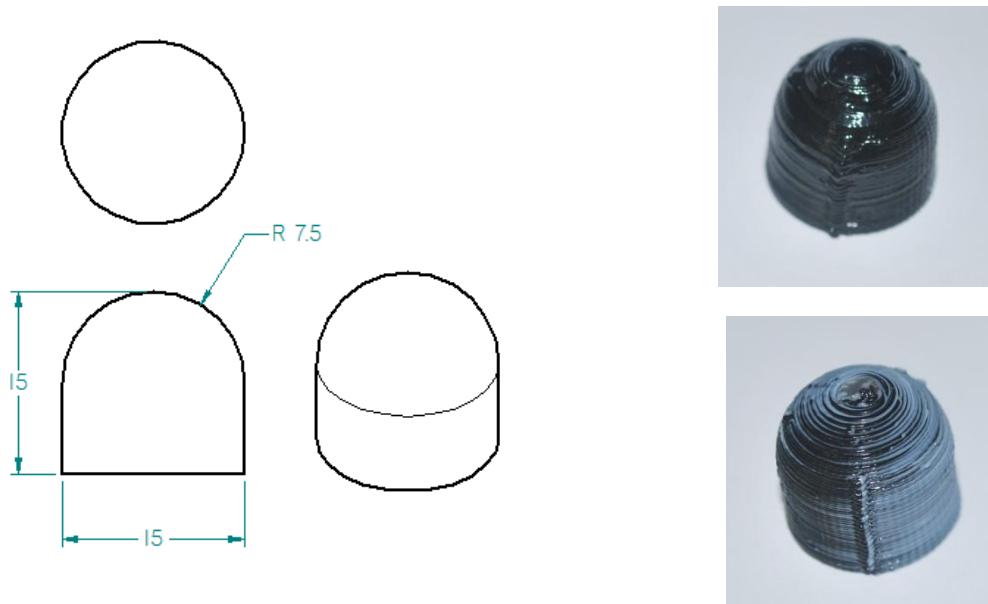


Figure 6-13 - Test Dome Print Drawing (Left), 2/3 Black Dome Print (Top Right), 2/3 Grey Dome Print (Bottom Right).

The results were apparent from a quick observation, two prints were carried out with exactly the same Machine settings but with the black and white filaments swapped over between, thus changing the relative orientation of the insert. It was clear that one colour dominated one side of each print which was reversed when the filaments were swapped.

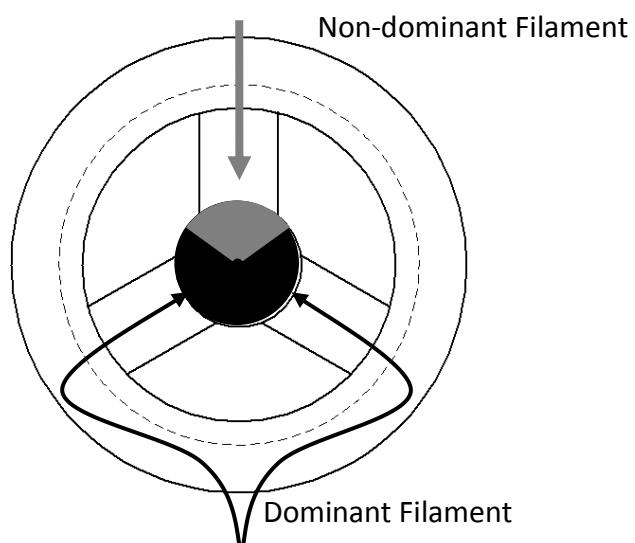


Figure 6-14 - Schematic showing plastic flow through Insert No. 3 & 4.

Figure 6-14 shows the filament flow through the insert which causes approximately 2/3 of the print being dominated by one colour and 1/3 by the other. This effect would occur no matter the number of holes or the orientation, the more holes in the insert would cause the print to become identical to that with no insert.

### ***Conclusion***

It was clear from experimenting with the MkII nozzle that the screw threads inserts were not a practical solution with the depth of cuts used as the cross-sectional area that the plastic can flow through was too small, this resulted in a too high extrusion force which the stepper motors could not produce in this current set-up resulting in the inability to print.

The last two inserts resulted in promising prints which clearly showed mixing potential with the white filament not being visible in the end print as appeared grey. Although there were still two distinct regions and there is much left to be desired in terms of mixing properties. These two inserts showed that it is essential to induce a swirl in the mixing chamber or these results will be repeated with one colour being biased on one side, also it is necessary to in future nozzles to ensure that the insert orientation does not affect the printing qualities.

#### ***6.4.2. MkIII Nozzle Design***

##### ***Introduction***

Following the MkII nozzle results it was clear that a longer mixing length is needed to start working towards homogeneous mixing and with this in mind the MkIII nozzle (figure 6-15 and Appendix D-2) was designed with a horizontal mixing chamber with a length of 1  $\frac{1}{4}$ " and a vertical chamber the equivalent size to that within the MkII nozzle. This resulted in an available mixing length of nearly 1  $\frac{1}{2}$ " in total. This longer mixing length will enable a coarser

pitch thread to be used on the inserts which should result in lower extrusion forces compared to the MkII design and screw thread inserts.

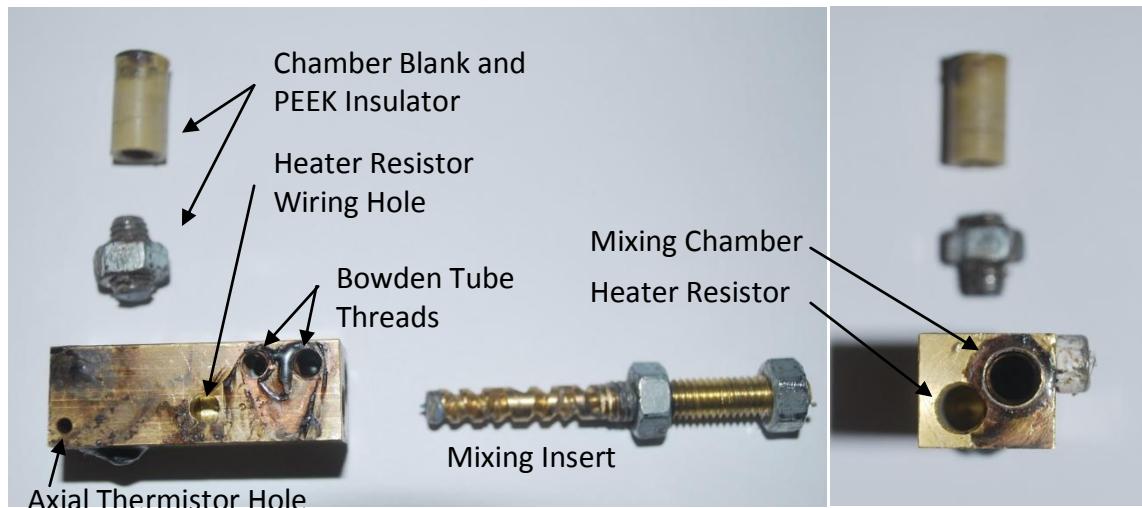


Figure 6-15 - MkIII nozzle with exploded parts, side view showing a long mixing insert (left) and end view showing the arrangement of the heater resistor and mixing insert (right)

### Apparatus

1. Mixing Nozzle MkIII (Figure 6-15 & Appendix D-3) with heater resistor and 100k axial thermistor in place.
2. 4mm OD (2mm ID) PTFE Tubes
3. Length of M6 threaded rod 12mm and locking nut.
4. Long Mixing Insert (overall length approx 1 ½")
5. PEEK insulators (M6 internal thread)
6. M4 Grub Screw

### Method

The MkIII nozzle was tested in an identical method to the MkII by first printing a control print with just an empty mixing chamber, which as expected produced a print practically identical to the previous prints figure 6-17. Following this, the brass inserts seen in figure 6-16 were all tested with the nozzle held in a vice.

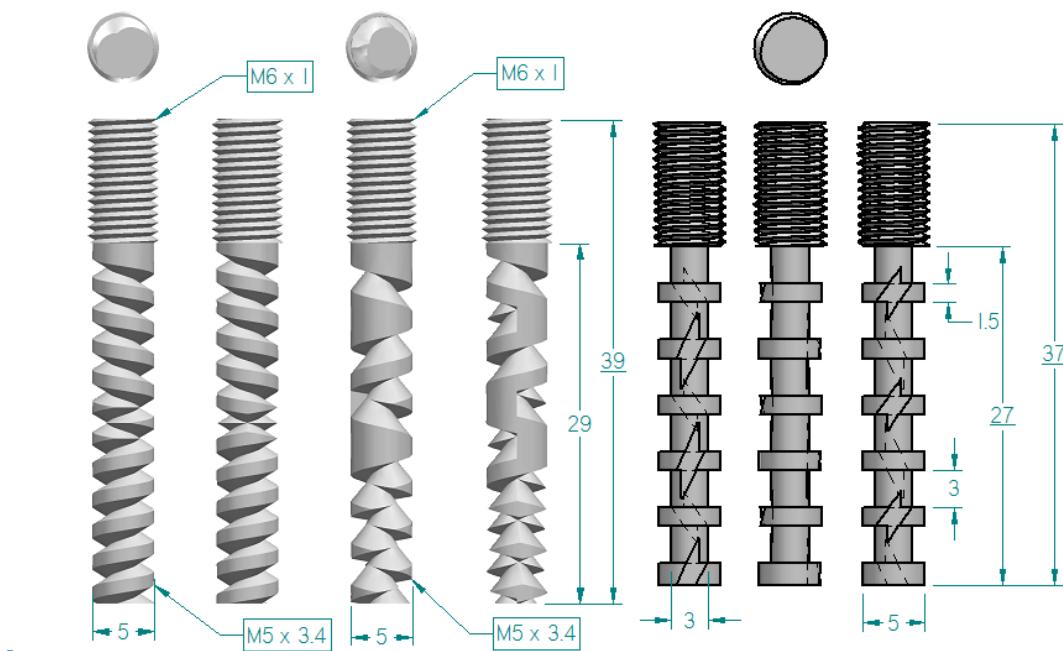


Figure 6-16 – Brass Long Inserts, No.5 Single Reversal Insert Pitch-3.4mm Depth of Cut-1.5mm Tool-60° thread cutting tool (left), No.6 Multiple Reversal with a Pineapple (Left and Right Hand Thread cut together) Pitch-3.4mm Depth of Cut-1.5mm Tool-60° thread cutting tool at an angle of 20° to perpendicular (centre), No.7 Straight insert with multiple baffles and filed slots (right).

### Results and Discussion

Manufacturing the inserts illustrated in figure 6-16 proved to be very difficult and a cutting tool had to be ground to shape in order to achieve the coarse pitch of 3.4mm, the problem encountered was due to the tool side relief angle (figure 6-18) was smaller than the cutting angle on the material, this caused undue pressure on the material being cut causing many failures during machining (figure 6-17).



Figure 6-17 - Two examples of the brass failing during thread cutting due to lack of relief angle on the tool.

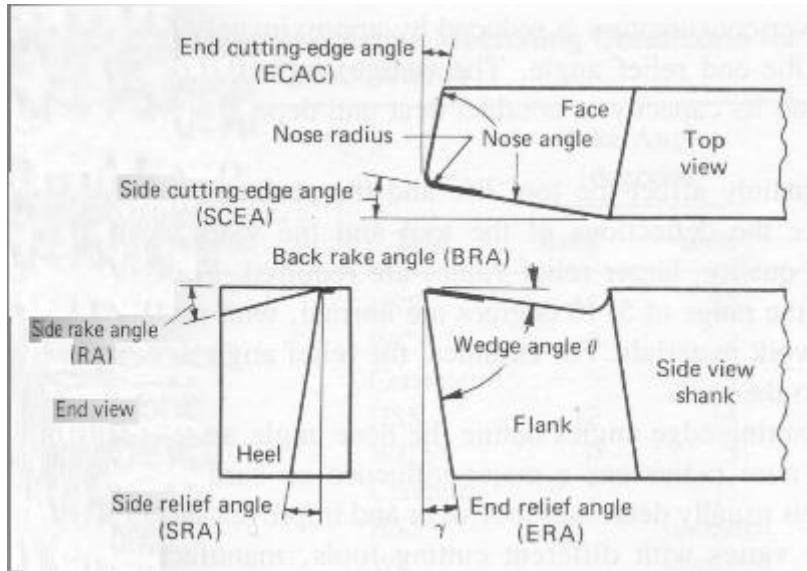


Figure 6-18 - Lathe Tooling Geometry [36]

All of the specialist custom threads for these inserts were cut by turning the lathe by hand to reduce the forces on the piece, the relatively deep cuts mean the remaining effective core is very small (approximately 2mm diameter) and any undue forces caused failure of the piece. It was tried using aluminium instead of brass to fabricate the insert but aluminium proved far too soft to cut deep threads on as the aluminium simply bent over the tool.

No.5 insert was tested by hand first which immediately flagged up a problem with the configuration of the design, having the mixing chamber to one side left the PTFE tubes on the respecting side with very little retaining thread in the block and as soon as the pressure was applied with the hand feeding this caused the PTFE tube to be forced out, rendering the feed tubes holes on one side of the nozzle to be unusable. The feed tubes were blanked off and experimentation was continued using the feed tubes on the opposite side which had ample thread holding the tubes in place. The original hypothesis for using the layout of the mixing chamber with the heater resistor on the same axis and staggered, as can be seen in

the drawing (figure 6-19), was to reduce the thermal mass of the nozzle keeping the overall depth of the nozzle to a minimum.

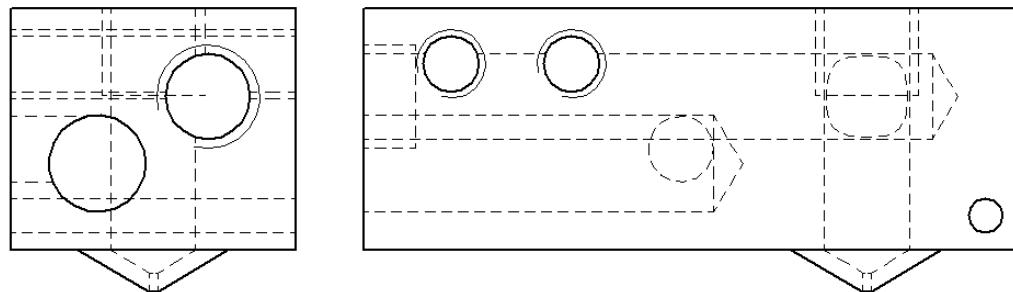


Figure 6-19 - MkIII nozzle drawing showing the internal arrangement

With both PTFE tubes mounted on the same side the testing using hand feeding was continued with insert No. 5 (figure 6-20), the force required to drive the filament into the nozzle was excessive and required the use of pliers to easily get the plastic flowing through the nozzle tip. If too much force was applied to the filaments, by means of using pliers to create much higher pressures, problems became apparent with the PTFE tubes as the ballooning effect that was seen in early experiments became much more of a problem and the tubes ruptured under these pressures (figure 6-21). It was apparent that the stepper motors would be unable to create the pressure required to extrude the filament and when this was tried the hobbed bolt simply stripped the plastic filament and failed to extrude resulting in no print being produced.

From this No. 6 insert was made using the same cutting tool but at an angle to remove more material creating a bigger cross section for the plastic to flow through thus reducing the pressure required to feed the plastic through the nozzle. This was proved when hand feeding which required significantly lower forces to drive the filament although still relatively high compared to the MkII nozzle. The mixing performance of the nozzle was unchanged

from before and still two distinct black and white streaks were produced in the extruded plastic.



Figure 6-20 - MkIII Nozzle set up in a vice for manual testing.

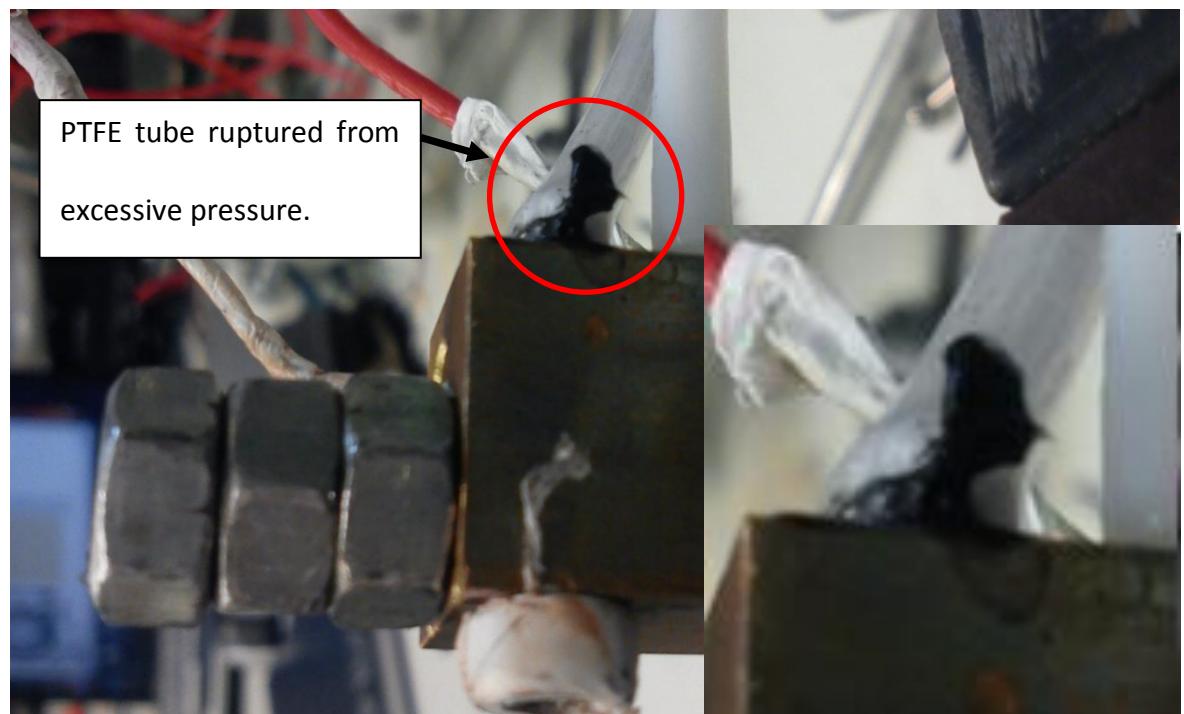


Figure 6-21 - MkIV Nozzle with ruptured PTFE feed tube, Insert: close up picture of ballooning PTFE tube.

When attempting to print the stepper motors struggled; drive of the filament was intermittent and could not consistently drive the filament to produce a print, the temperature was increased to 220°C to see if the reduced viscosity associated with the increase in temperature aided the stepper motors but this created no noticeable difference. Another attempt was made to print but at a much slower extrusion speed in the hope that slower extrusion speed would allow time for the plastic to flow slower through the nozzle but this caused no difference in the printing performance of the machine.

No. 7 insert concept was first thought up by Bowyer and was much simpler to manufacture compared to previous designs of the screw thread concept, this new insert consisted of a solid shaft with various baffles along the length with slots cut to allow the plastic to flow to the next segment. With this insert in place hand testing proceeded and resulted in much lower extrusion force compared to that of the previous inserts, although the mixing quality was almost indifferent to that compared to the first print with no insert.

### ***Conclusion***

The MkIII nozzle was unsuccessful in attempting to cause a substantial amount of mixing, it was unclear exactly how much was caused by inserts No. 6 & 7 due to the very high back pressures meant that only very little amounts of plastic could be extruded there did appear to be regions of grey in some of the extruded plastic but this was thought to be due to thermal decomposition of the PLA as it only occurred when the nozzle was left at temperature before attempting extrusion.

It was clear from early testing that the design of this nozzle was flawed as even if the mixing inserts did work, the second filament would have been fed into the mixing chamber  $\frac{1}{4}$ " further down the mixing chamber than the first. This would result in subsequent

filaments being fed into the chamber a  $\frac{1}{4}$ " further down, so if four filaments were intended for use with this nozzle the final filament would have been almost feed into the very last section of the mixing insert meaning that very little mixing could take place. Therefore it was chosen to manufacture a larger design of nozzle where both filaments, or even up to four filaments, could be fed into the very beginning of the mixing insert.

#### 6.4.3. MkIV Nozzle Design

##### *Introduction*

The MkIV mixing nozzle was similar design to that of the MkIII except that the depth was increased which enabled the heater resistor to be position perpendicular directly below the mixing chamber which permitted the position of the mixing chamber central in the block, giving equal thread depths for the PTFE feed tubes to achieve substantial purchase on the nozzle. Consequently the thermal mass of the MkIV nozzle was substantially increased from that of the MkIII, which in itself had a substantially long heat up time, this meant that the nozzle would be benefitted with fibre glass insulation to minimise the heat loss due to convection around the nozzle. In addition this nozzle was designed for the vertical mixing chamber section to be expanded to M8 or M10 to enable the fitting of a gauze insert causing finer mixing at a later stage.

With these modifications the nozzle would be tested as with previous designs and the same inserts as with the MkIII nozzle to test whether mixing using these inserts is possible when using their entire length. If mixing is achieved uniformly with these inserts then a new filament drive system would have to be designed to create the forces required for extrusion.

### *Apparatus*

1. Mixing Nozzle MkIV (Figure 6-20 & Appendix D-4) with heater resistor and 100k axial thermistor in place.
2. 4mm OD (2mm ID) PTFE Tubes
3. Length of M6 threaded rod 12mm and locking nut.
4. Long Mixing Inserts (overall length approx 1 ½")
5. PEEK insulators (M6 internal thread)
6. Woven Fibreglass Thermal Insulation [37]

### *Method*

The testing procedure was identical for the MkIV nozzle as with the MkIII nozzle except for the nozzle was wrapped in PTFE insulating tape on all sides to reduce the heat loss from the brass surface and the sides of the nozzle were wrapped once with woven fibreglass insulation to further reduce heat loss. This was found to be necessary as the nozzle was tested without insulation which proved the heater resistor could not dissipate enough heat into the block to raise the temperature and maintain 200°C.

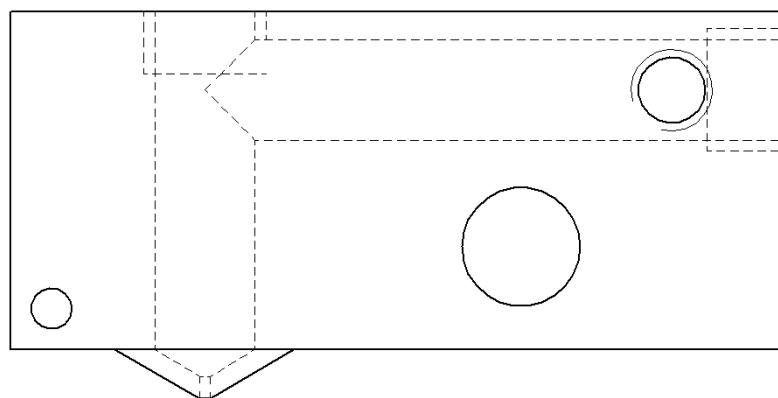


Figure 6-22 - MkIV Nozzle sketch showing the layout

### *Results and Discussion*

It became apparent early on that the thermal mass of this nozzle caused excessively long heat up times and took longer than the heated bed on a machine to warm up. Even with the

thermal insulation the heater resistor was on permanently to maintain a temperature between 195 – 200°C when not extruding, this would become problematic during printing as the constant flow of plastic would take a certain amount of heat from the nozzle, which would cause the temperature of the nozzle to drop to a less than optimum temperature.

All of the inserts from the MkIII nozzle were trialled with the MkIV nozzle and despite both filaments being fed being forced down the entire length of the mixing inserts, the mixing quality was still far from satisfactory and the two separate filaments formed a two colour extruded plastic, which can be seen in figure 6-23.

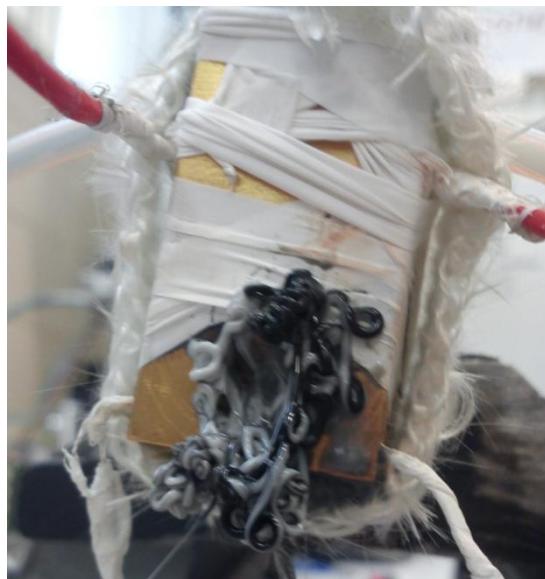


Figure 6-23 - Manual Feed results for the MkIV nozzle, white and black are clearly unmixed.

Following this failure one final idea to use stainless steel gauze tightly coiled within the mixing chamber was attempted which can be seen in figure 6-24. The theory behind the use of gauze was that the amount of shear generated from passing through the small holes would be much greater than that from the previously used threads, although the viscous friction in theory should be increased due to the large surface area of contact between the fluid and insert. The additional viscous friction was cancelled out by the very low velocity of the fluid so this proved not to be a problem and the forces required to drive the filaments

was much reduced from that required with the screw thread inserts which would be easily created by the existing extruder arrangement.

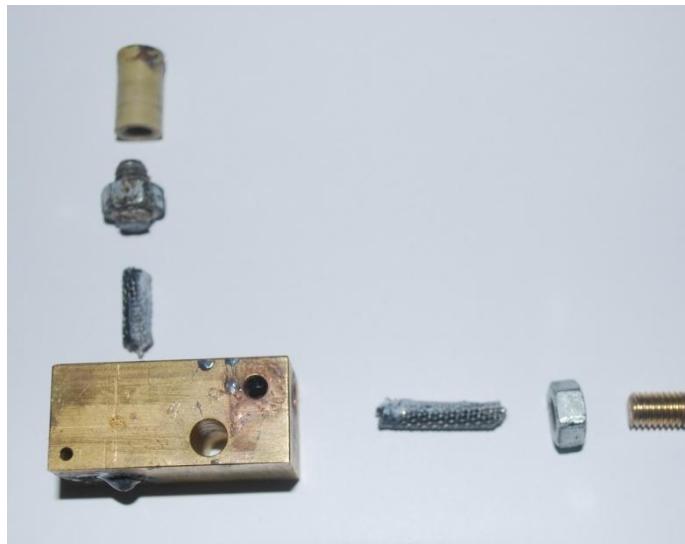


Figure 6-24 - MkIV Nozzle set-up with coiled stainless steel gauze inserts

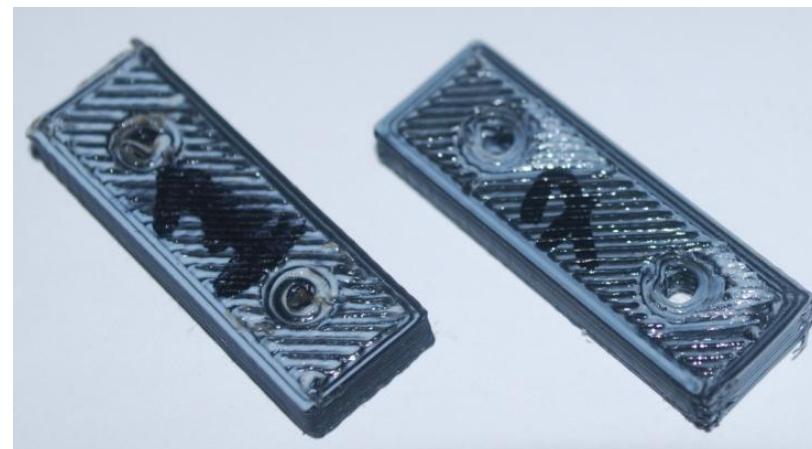


Figure 6-25 - MkIV nozzle print with the stainless steel gauze inserts compared with the original print from the MkI nozzle (left) and the gauze insert from after the print (right)

The results from using the gauze were unchanged from the previous inserts which can be seen in figure 6-25, two distinct colours can be seen in the print and from the removed gauze after the print was finished it can be seen how each colour flowed down either side of the gauze remaining completely separate from each other.

### ***Conclusion***

It was clear from these results that there was little improvement in performance of the nozzle from utilising the entire mixer insert length and that to achieve successful mixing another approach should be taken.

#### **6.4.4. Conclusions from Static Mixer Nozzle Development**

Testing showed that using the concepts from plastic injection moulding, using static mixer inserts, were flawed for this application into 3DP. None of the tested methods gave results that were promising to reach homogeneous mixing, the length of mixer required to achieve this is far greater than can be applied to the machine and the associated thermal mass would be excessive, resulting in multiple heater resistors. The other associated problems with a longer mixing nozzle are the pressures required to extrude the plastic increase drastically far beyond that which can be produced by existing nozzle design, as well as the PTFE tubing failing which would mean a direct extruder would have to be mounted on the nozzle if the forces were to be achieved, even then the stepper motors would be likely to stall.

From these trials the static mixer nozzle seemed impractical as none of the results were remotely close to that desired, if there were better results then further development of extruders and Bowden tubes may have been worthwhile to increase the feeding forces, but the margins required were too great. Therefore it was decided to trial using an active mixing system to generate the shear required for mixing the plastic within the nozzle, this would solve any problems associated with high nozzle pressures as the shear energy would come from an external source so the major components of the machine could remain.

## 6.5. Active Mixer Nozzle Development

### 6.5.1. MkI Active Mixer Nozzle Design

#### *Introduction*

Active mixing creates many more problems and requires careful design, the main issue surrounding this method would be sealing the mixing chamber to prevent leaks, this is difficult due to the high operating temperature of the nozzle so the seal would have to be able to withstand 200°C continuous use (as prints can take several hours to complete). One advantage which could aid this sealing is the internal pressure within the nozzle is relatively high so the design could incorporate this pressure to keep any seal on its seat. The most obvious O-ring material to use was Silicone which is rated to operate at 200°C.

Initially a 12V geared down DC motor was selected to drive the mixer (as the RepRap operates at 12V) so the torque available for a mixer was not immense so precautions should be taken to reduce the drag from the mixer. The designs used for mixers were initially just be a cylinder turning within a hole approximately 0.5mm diameter larger than the cylinder, which would create plenty of mixing shear within the fluid, although this might cause to much friction for the motor, or another option was to use a hexagonal bar within a hole 0.4mm diameter larger than that across the points of the bar, this would create higher shear regions than the cylinder but less resistance to the motor. The direction of drive of the mixing shaft was clockwise ensure the mixing camber sealing bolt could not be loosened by friction on the shaft.

The design was based around the MkIV static mixing nozzle with a horizontal long mixing chamber and a short vertical mixing chamber before the nozzle, the active mixer would be located in the horizontal chamber and the vertical chamber was left in the design so that

stainless steel gauze insert could be used if the final mix was not entirely homogeneous the layout can is illustrated in figure 6-26.

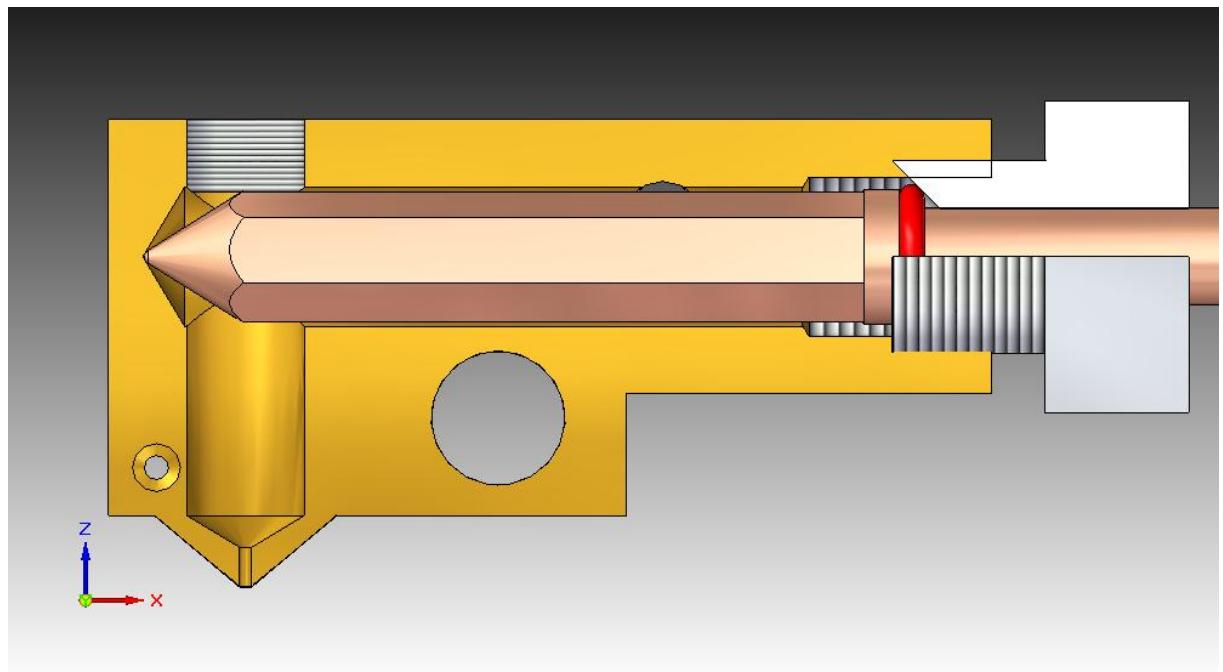


Figure 6-26 - Cross Section View of Active Mixing Nozzle MkI

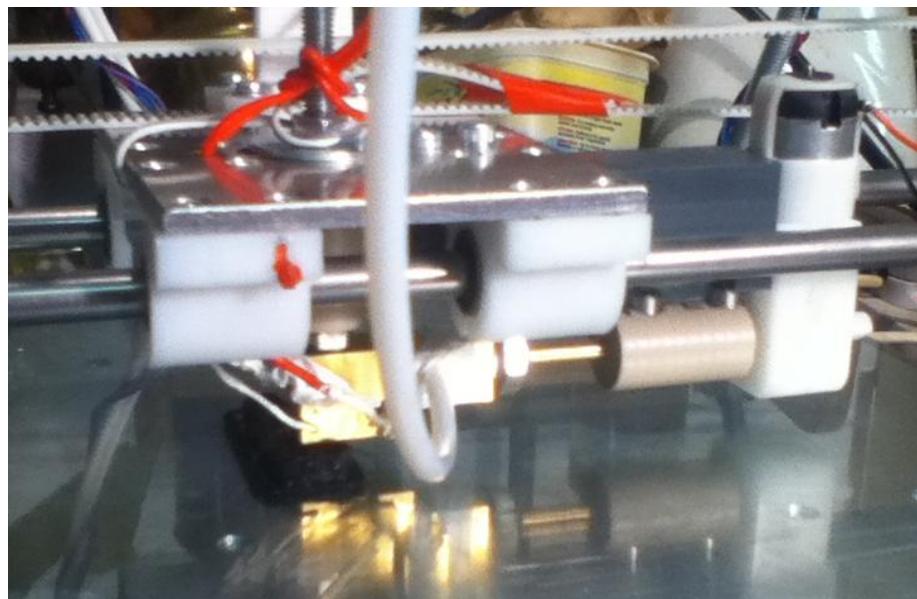


Figure 6-27 - Active Mixing Nozzle MkI in situ on the RepRap completing the first print

### *Apparatus*

1. Assembled Active Mixing Nozzle MkI (Figure 6-26/27 & Appendix D-5) with heater resistor, 100k axial thermistor, Hex Mixer, Brass Washer, Silicone O-ring, PEEK Insulator, 12V DC geared motor and support all in place as in figure 6-27.
2. 4mm OD (2mm ID) PTFE Tubes
3. Length of M6 threaded rod 12mm and locking nut.
4. PEEK insulator (M6 internal thread)
5. Woven Fibreglass Thermal Insulation [37]/ PTFE Thread Tape

### *Method*

From previous experiments it was clear that the pressure required to drive the filament through this nozzle would be easily within the limits of the current extruder set-up, also the 12V motor was fixed to the X-carriage of the machine, so the nozzle was initially tested in situ driven electronically to observe the results, first with the cylinder mixing insert then repeat with the hex insert.

First the nozzle was heated up to 200°C before turning on the electric motor and then the motors were told to extrude 25mm of filament at a time until the plastic was fed out of the nozzle.

Following the initial trial, test prints can be carried out to see the dynamic performance of the mixing nozzle. The nozzle must be preheated up to at least 185 degrees before the mixing motor is turned on and the motor should be turned off when the nozzle is not in use (i.e. not printing /extruding).

### *Results and Discussion*

While using the cylindrical mixing insert the 12V DC motor stalled constantly and the motor emerged to be underpowered to drive the mixing insert as the viscous friction of the molten plastic appeared to be too much for the motor so the test was repeated with the hex

mixing insert which gave promising results. Black and white filaments were fed simultaneously and a consistent dark grey/black plastic was extruded from the nozzle, the filament drive motors had no problem driving the filament and neither did the mixing motor, which ran consistently whether or not filament was being driven. Following this result the test print was carried out, which although was a poor quality print, showed very good mixing qualities which appeared to the naked eye to be a homogeneous mix. The printer settings were calibrated to produce a better quality print which can be seen compared to the first print and the original control print from Bowyers mixer nozzle n figure 6-28. There was a slight leaking issue from around the mixing shaft which accumulated to a single bead over a 15 minute print (figure 6-29) which will require a redesign of the O-ring arrangement with the possible addition of a second O-ring.

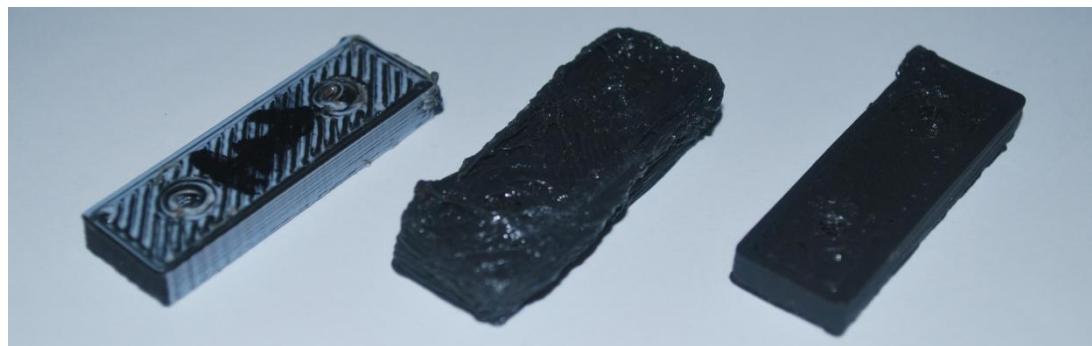


Figure 6-28 - Comparison of Prints; (left) original print from the MkI Static Mixer Nozzle, (centre) First print from Active Nozzle MkI, (right) calibrated second print using the Active Mixing Nozzle



Figure 6-29 - First mixing print from the active nozzle



Figure 6-30 - Various colours mixes producing very identical quality prints with good mixing quality Appendix K

### **Conclusion**

The active mixing nozzle performed well and produced well mixed prints as can be seen from figure 6-30. It became apparent that the vertical part of the mixing chamber was unnecessary as the quality of mixing was sufficient from the hex mixer, but there was a slight leaking issue from the seal which should be addressed in the next design. This design was primarily built to test the concept of using an active mixer and was less than ideal for practical use, there were two main issues which were; the motor and mixer being mounted horizontally meant that the X-travel of the machine was compromised and secondly the motor and insulator shaft was very low relative to the nozzle tip which would foul on a print with a large area.

### 6.5.2. MkII Active Mixer Nozzle Design

#### *Introduction*

Following the results from the MkI Active Mixing Nozzle the design was reiterated with various improvements; the extra section of mixing chamber was eliminated to reduce the volume of plastic within the nozzle to minimise the plastic that has to be extruded to change colour; the mixer was mounted vertically to restore the print area of the machine back to its original size and reduce the chance of the motor and other parts fouling on the print due to the limited clearance between the nozzle tip; the M8 mixing chamber seal bolt had an improved seat for the O-ring to illuminate the leaking from the previous design. This design incorporated two heater resistors to reduce the warm up time and enable higher temperatures to be reached for printing. The MkII design can be seen in Appendix D-6 and the set-up can be seen in figure 6-31, the second outer O-ring in this design was not designed to act as a seal as the spring was very weak, this seal was put in place for the M4 washer to seat on and reduce wear, the spring was designed so that it could be removed and the M4 nuts tightened on the outer O-ring to create a seal to stop any leaking if it becomes an issue.

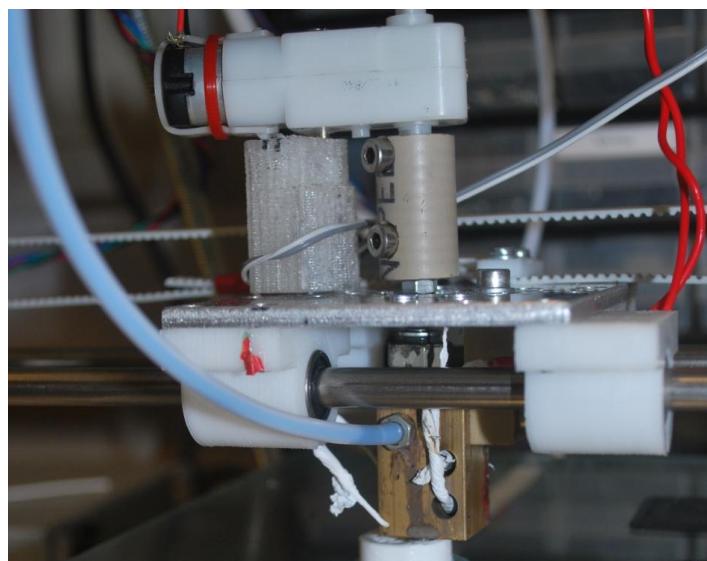


Figure 6-31 - MkII Active Nozzle Set-up

### *Apparatus*

1. Assembled Active Mixing Nozzle MkII (figure 6-31 & Appendix D-6) with heater resistor x 2, 100k axial thermistor, Hex Mixer, Brass Washer, M4 Washer x 2, M4 Nut x 2, Silicone O-ring x 2, PEEK Insulator, 12V DC geared motor and support all in place as in figure 6-27.
2. 4mm OD (2mm ID) PTFE Tubes
3. Length of M6 threaded rod 12mm and locking nut.
4. PEEK insulator (M6 internal thread)

### *Method*

This nozzle was tested using the same method as the MkI nozzle before testing proceeded with printing performance testing (section 6.2.2)

### *Results and Discussion from Mixing Performance Testing*

The mixing qualities of this nozzle were uncompromised from the previous design and produced a practically identical print (figure 6-32). Following this result a larger print was carried out (figure 6-33) to further test the performance of the nozzle, and the possible print quality of the new design, which was unchanged from using a standard calibrated machine.



Figure 6-32 - MkI (left) and MkII (right) Active Nozzle prints with a 1:1 (black : white) ratio

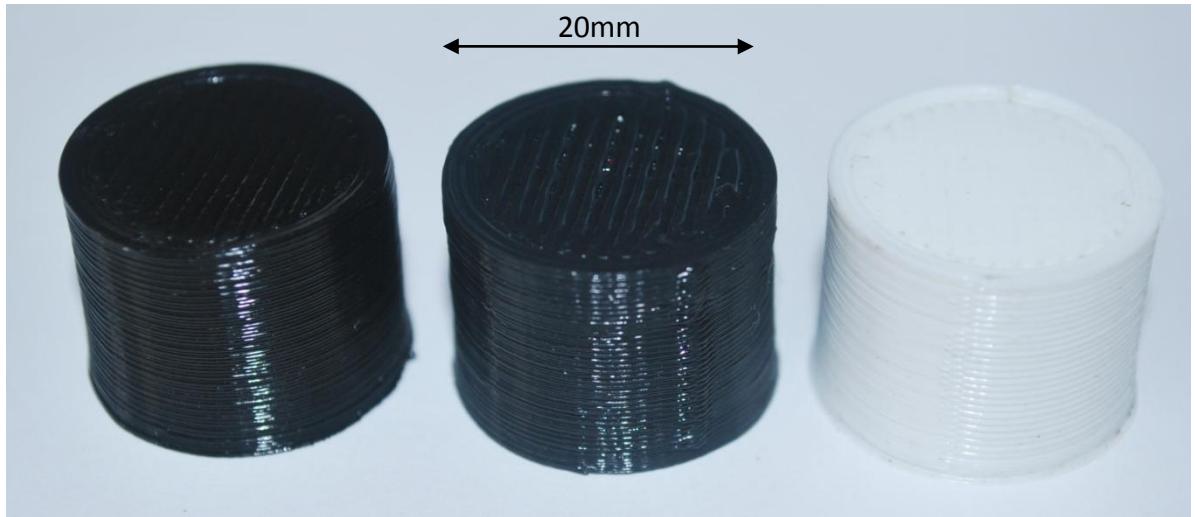


Figure 6-33 - Comparison print between a standard machine prints using black and white filaments (left, right) and the MkII Active Mixing Nozzle Print using the same black and white filament (centre)

Next an hour long print to endurance test the nozzle to highlight any possible problems was carried out which proved the new design to be durable for this length of time and no performance problems surfaced. The nozzle was disassembled following these prints to assess the sealing performance of the silicone O-ring, with the new arrangement one silicone O-ring was sufficient to stop leaking and there was no noticeable plastic up the shaft, rendering the second seal redundant.

### *Conclusion*

Following the results from the initial tests the performance of the nozzle was at an acceptable standard to proceed with Printing Performance Testing as in section 6.2.2. Any apparent leaking issues from the MkI Active Mixing Nozzle design have been solved with the new M8 mixing chamber seal bolt design. The reduced diameter of the mixing chamber by 0.1mm seemed to create no additional backpressure and gave the same performance as the MkI design if not increased mixing due to the regions of higher shear.

## 7. Printing Performance Testing

Following the extruder development the printing performance of the nozzle needed to be assessed more accurately to determine how the nozzle would perform under varying printing conditions, mainly the altering the ratio of plastics fed into the nozzle.

### 7.1. Method of Testing

#### 7.1.1. Single Colour Printing Method

- With the printer set-up as before, disconnect one filament drive motor leaving just one drive motor connected and change the extrusion multiplier in the Slic3r settings to 1 from 0.5. White filament was left connected as small traces of black would be easily visible.
- Preheat the nozzle up to 200°C and extrude filament with the mixer motor switched on until the single colour is cleanly extruded from the nozzle tip.
- Upload a simple print into Pronterface (A cylinder diameter 20mm and height 15mm was used).
- Send print and carefully monitor the machine to observe any problems that emerge.
- Analyse the print for defects/differences from a standard machine set up print.
- Scan prints and analyse colours using Photoshop.

#### 7.1.2. Mix Ratio Analysis Method

##### *Firmware Alteration*

For this method both filament drive motors should be connected but to different motor outputs on the electronics board, one to E (extruder) and the other to Z (Y-axis). The

firmware should be altered to accommodate this output to drive the extruder, changes required for the **Sprinter** Firmware under the configuration tab are as follows (alterations required will depend on the firmware used);

- Change steps per mm of the Z-axis to equal the steps per mm of the E drive, in this case 1050.
- Invert Z-direction to false (will depend on the orientation of the motors and wiring)
- Increase Z max length to a large number such as 5000.

### *Testing Method*

- Pre-heat the nozzle up to 200°C and turn the mixing motor on.
- By moving the Z-axis by hand, adjust the nozzle height to a couple of mm.
- By typing a single line of G-code into Pronterface set the positioning system to relative (G92 command).
- Purge the nozzle with a filament ratio using the same method (e.g. for a ratio of 1:1 send G1 Z50 E50).
- Clean the glass print surface, and then perform the same extrusion ratio onto the glass plate.
- Allow sample to cool and remove from print surface.
- Repeat the purge with a different filament ratio, followed by an extrusion onto the glass plate.
- Repeat with as many ratios of filament as required.
- Scan samples and analyse colour using Photoshop.

## 7.2. Results and Discussion

### 7.2.1. Single Colour Prints

Initially the printing with one colour proved to be of good quality and showed minimal problems, figure 7-1 shows the resulting prints with white and black being driven independently for either print, these prints are compared to the quality from a standard set up RepRap. The apparent poor quality finish of the prints from the mixer nozzle is due to federate settings and can be solved by further calibration. This type of printing was enabled by the PLA filament in the non-driven tube melting to a certain extent and effectively blocking the tube opposing the internal pressure of the nozzle.



Figure 7-1 - Black only print with mixer nozzle (far left), black print from standard machine (left), white only print from mixer nozzle (right), white print from standard machine (far left)

Towards the end of the prints a problem arose with the PTFE feed tubes in the nearest 5mm to the hot end, with the prolonged heat and pressure from the mixing chamber the feed tube ballooned as the PTFE at 200°C even though it does not melt, the strength is greatly reduced allowing this stretching (figure 7-2). This effect can be solved with further development and insulation of the PTFE tube. A quick solution used for further experiments was to use a PEEK sleeve approximately 10mm long with an internal diameter of 4mm which provided extra hoop strength of the tube and stopped any rupturing of the PTFE tube. A more permanent solution would be to incorporate the design used on the RepRapPro Huxley

hot end [35] on which a stainless steel sleeve with a large heat sink and cooling fan are used, this has the effect of minimising the transition region of the temperature.

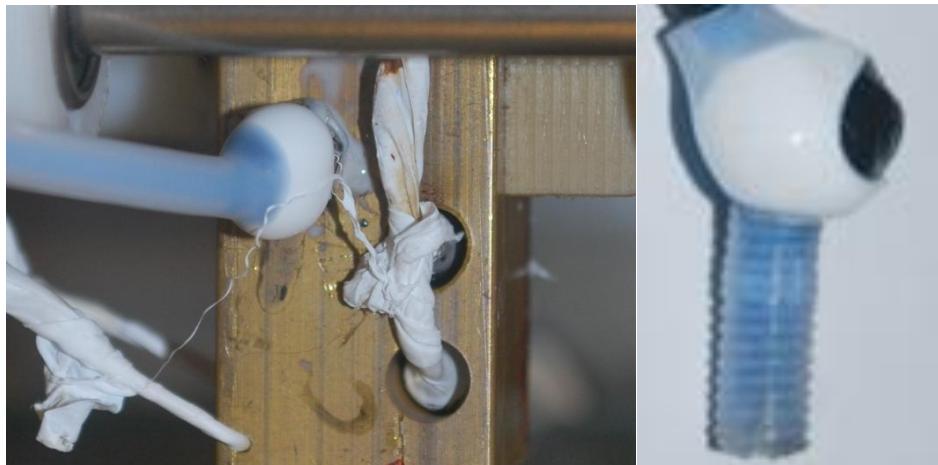


Figure 7-2- 'Inflated' PTFE feed tube (left) which was shortly followed by the rupture (right)



Figure 7-3 - RepRapPro Huxley Hot-End Assembly [38]

A scan was taken of the prints and compared using Photoshop software, the results can be seen in figure 7-3, and the colours were measured using average CMYK values over a 100 pixel diameter circle.

The purpose of measuring these colour values was to determine if any colour remained in the nozzle after purging thus contaminating the print, the values from the measurement show very little trace of other colour, the two white and the two black prints show colours all within 3% of each other which suggests there was no contamination from the non driven filament.



**Figure 7-4 - Control White Print - C:1 M:1 Y:2 K:0 (far left), Mixer Nozzle White Print- C:1 M:4 Y:5 K:0 (left), Mixer Nozzle 1:1 White:Black Print- C:79 M:71 Y:60 K:76 (centre), Mixer Nozzle Black Print- C:76 M:68 Y:65 K:85 (right), Mixer Nozzle Black Print- C:76 M:69 Y:66 K:86 (far right)**

The difference of 3% could easily be down to measurement variation from the scanning or within the software, another cause of this error could be due to scanned surface not being perfectly flat, and this can be most clearly seen on the mixer nozzle black print which has light areas where the plastic was not in contact with the scanning glass. These regions are quite small so the effect on the average colour measurement should not be affected greatly.

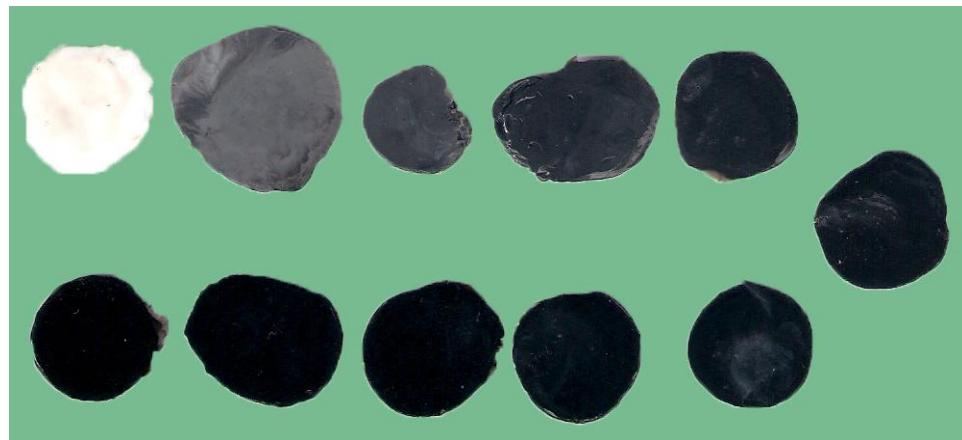
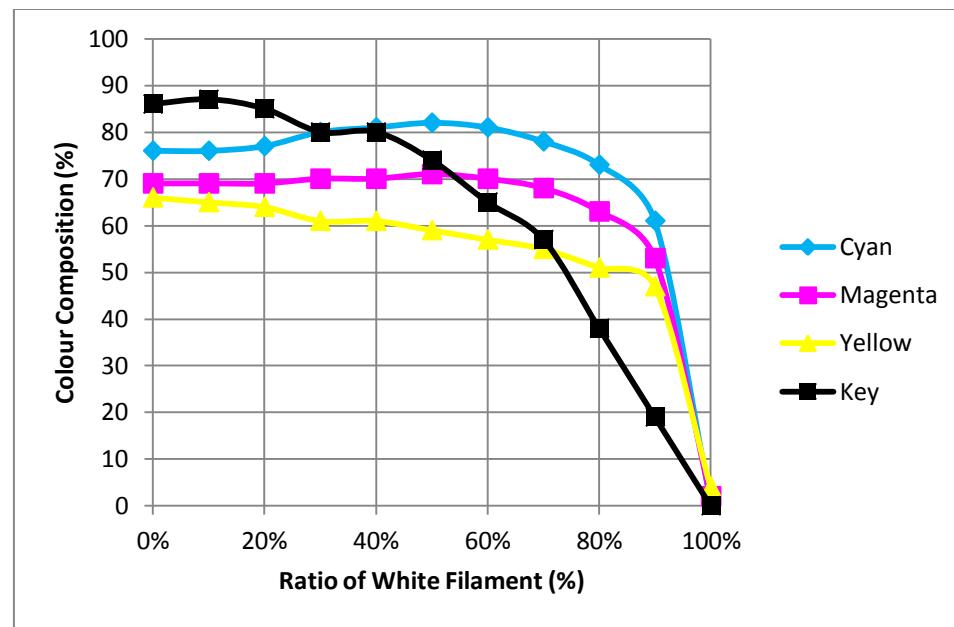
### 7.2.2. Varying Mix Ratios of Filament

11 samples (figure 7-5) were produced varying from 100% white to 100% black, the samples were analysed and the results are plotted below (table 2). The graph shows how much stronger the black pigment is compared to the white as the colour composition of the samples is within 10% from pure black up to a ratio of 50% and it's not until above 70% where the difference is clearly noticeable in the colour of the samples.

The largest change in colour was at a ratio with more than 90% white, this would make accurately predicting a colour composition of extruded plastic very difficult to calibrate as the black filament needs to be very finely controlled and able to be driven at very slow rates. The accurate driving of the filament is made harder by the Bowden tube as the hysteresis in

the tube can build up and release causing fluctuations in the drive of the filament, due to the sensitivity of the resulting colour being dependant on black these small fluctuations could cause difficulty achieving a uniform colour. This could possibly be improved by mounting the black filament drive on the X-carriage which would eliminate the hysteresis and give more accurate control, the other filament drives could remain using Bowden tubes as their control doesn't have as much as effect as the black. Another solution to give the user more control over the colour would be to use a black filament with a weaker/less pigment which would mean each colour (black and white) would have a similar effect on the final colour.

**Table 2 - Colour Composition of different proportions of black and white filament**



**Figure 7-5- Varying Colour Ratios samples, the slight light patches were due to thin parts of the sample or the sample not being in full contact with the scanning surface which had negligible effect on the average colour reading of the sample**

## 8. Project Conclusions

Initial trials showed that the PLA plastic would mix to produce the expected colours (similar to paints) and the relative strengths of the pigments in each filament were approximately determined to be in the following order (strongest first); black, red, electric blue, yellow then white. These colours were selected as they are the closest representation to CMYK widely available.

This project showed that the use of a static mixing nozzle was impractical for this home 3D printer application due to the very high pressures required to drive the filament which led to the drive mechanism stalling and slipping on the filament. Also the tests ran showed no promising mixing results that deemed this method of inducing mixing impracticable to pursue with development.

This led to the design of an active mixing system which consisted of a hexagonal bar rotating within a cylinder 0.3mm larger diameter than that across the points on the bar, this was driven by a 12V DC motor at a gear ratio of 200:1 and a turning speed of approximately 80rpm (max.). The results appeared to be homogeneously mixed with no visible streaks in any of the prints produced, the nozzle was tested briefly with various combinations of two filaments to produce a wider variety of colours.

Following these results a more practical configuration of the nozzle was fabricated to simplify the design and eliminate initial minimal leaking problems, the new nozzle performed faultlessly even over a longer print until the driven speed of the filaments were altered to give different feed ratios. The slowing of one filament led to a build up of heat and pressure in the end of the Bowden tubes which led to rupturing, this was temporarily solved using a PEEK sleeve but will require further development to resolve the issue.

While investigating the effect of varying the ratio of filament inputs it was made clear how much stronger the black filament than white, the ratio of white to black had to be 30/40% before any noticeable difference in the colour can be seen to the eye and to make a significant lightening to the black at least 80% white needs to be used. This would make calibration very difficult as the colour printed is very dependent on the black filament and any varying in the drive could cause large fluctuations in the colour printed, therefore the black filament driver could be mounted closer (on the X-carriage) to increase the control of the filament, or a weaker black filament could be developed which would give more control of the colour as a greater change of ratio would be required to alter the colour.

Unfortunately time did not allow for detailed testing of colour proportion mixing and alternating filament feeds to determine the purge volume of the nozzle and printability which would lead into the investigation of the possibility of printing colour gradients. The next stages of the development are outlined in the following section.

## 9. Further Work

The design of the nozzle leaves much to be desired with further development, firstly the length of the mixer should be shortened in steps and subsequently tested at each length, this will help determine the minimum length of mixing insert that can be used to produce satisfactory mixing results. Following the optimisation of the length of the insert the original nozzle can be shortened to the equivalent length of the insert, with the internal design of the nozzle modified any excess material of the nozzle can be milled off. This modification will reduce the thermal mass and the volume of plastic of the nozzle to a minimum which will increase the thermal control and printability of the nozzle.

As mentioned before the ballooning effect of the PTFE feed tubes needs to be addressed possibly by using a stainless steel barrel connected to a heat sink being actively cooled by a fan. This will require some careful design and manufacture to incorporate all the feed tubes into one heat sink to result in the need for just a single fan, also the flow of air around the nozzle will require special consideration to minimise the cooling of the nozzle which already has compromised heating performance due to the large thermal mass.

With the previous modification in place the printability of the nozzle can be tested, meaning the transition volume of plastic required to be extruded to alter between two mix ratios. This can be tested by printing the Colour Transition Ladder G-code and using the method found in Appendix J. The nozzle should be initially purged with black then the print should be started and only white filament being driven. The colour of the extruded filament should then be analysed to test at what stage of the print the colour has reached a consistent composition. This will enable the determination of how much plastic needs to be purged during a print to create a sharp colour transition.

Firmware and electrical modifications require the most development to accommodate the new nozzle as they both need to incorporate the ability to independently control a minimum of 5 separate filament drives (Black, White, Cyan, Magenta and Yellow) this may be increased to also utilise colourless, water soluble or soft composition plastics. The electronics and software development were far beyond the scope of this project but once these modifications are in place it will enable the more comprehensive testing and calibration of the nozzle drives. The control of the ratios of the filament drives would be controlled using a widespread map across the full available colour space that could be produced by the printer, this map would relate to CMYK percentage values as normal ink printing does.

Another feature that will be required of the firmware, will be a method to purge the nozzle with the correct printing colour before applying the colour to the print, there are a couple of theories to achieve this; the first is to print a block in tandem with the print which will be used to purge material on, this method will be somewhat wasteful with having to print this block for every print, also the size of this block will have to be increased for multiple colour changes on the same layer. Another more economical solution would be to use the infill of a part to purge the plastic to the correct colour, and possible the inner boundary as the outer boundary will define the appearance of the object. This method will create much less waste although will not be as practical if parts of an object are desired to be clear as the infill will appear messy in terms of colour. Nor will this method be practical when determining the hardness of an object by using hard and soft plastics or by printing support material using water soluble material so a ‘purge print’ will have to be done alongside prints with these features.

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## 11. Appendices

### Appendix A – Useful G-Code Commands for Manual Control of RepRap

Control	Example
<b>G0: Rapid move</b>	G0 X12
<b>G1: Controlled move</b>	G1 X90.6 Y13.8 E22.4
<b>G28: Move to Origin</b>	
<b>G4: Dwell</b>	G4 P200
<b>G20: Set Units to Inches</b>	G20
<b>G21: Set Units to Millimeters</b>	G21
<b>G90: Set to Absolute Positioning</b>	G90
<b>G91: Set to Relative Positioning</b>	G91
<b>G92: Set Position</b>	G92 X10 E90
<b>X: X Position</b>	X100
<b>Y: Y Position</b>	Y100
<b>Z: Z Position</b>	Z10
<b>E: Extruder Position</b>	E32
<b>F: Feedrate</b>	F150
<b>M0: Stop</b>	M0
<b>M17: Enable/Power all stepper motors</b>	M17
<b>M18: Disable all stepper motors</b>	M18
<b>M104: Set Extruder Temperature (Fast)</b>	M104 S190
<b>M105: Get Extruder Temperature</b>	M105
<b>M106: Fan On</b>	M106 S127
<b>M107: Fan Off</b>	M107
<b>M109: Set Extruder Temperature</b>	M109 S190
<b>M112: Emergency Stop</b>	M112
<b>M114: Get Current Position</b>	M114
<b>M115: Get Firmware Version and Capabilities</b>	M115
<b>M116: Wait</b>	M116
<b>M117: Get Zero Position</b>	M117
<b>M140: Bed Temperature (Fast)</b>	M140 S55
<b>M143: Maximum hot-end temperature</b>	M143 S275
<b>M160: Number of mixed material</b>	M160 S4

## Appendix B - Printing Programs

### Appendix B-1 Pronterface , User Interface for Printer

Pronterface was chosen for use with this project for its simplicity to use and good user interface properties. This program allows the user to monitor the temperature of the nozzle constantly, which is important in this project as a dropping temperature could cause difficulties and damage due to the rise in viscosity of the plastic.

Another useful feature of this program is its link to the G-code generating software, Slic3r, an STL can be selected through this printer interface and the file will be run through the slicing software to create the G-code automatically which saves time.

Finally one very useful feature is the ability to send G-code manually, the user can type in a single line of G-code and send it to the machine, this was a very useful feature when varying the ratios of colour to use.

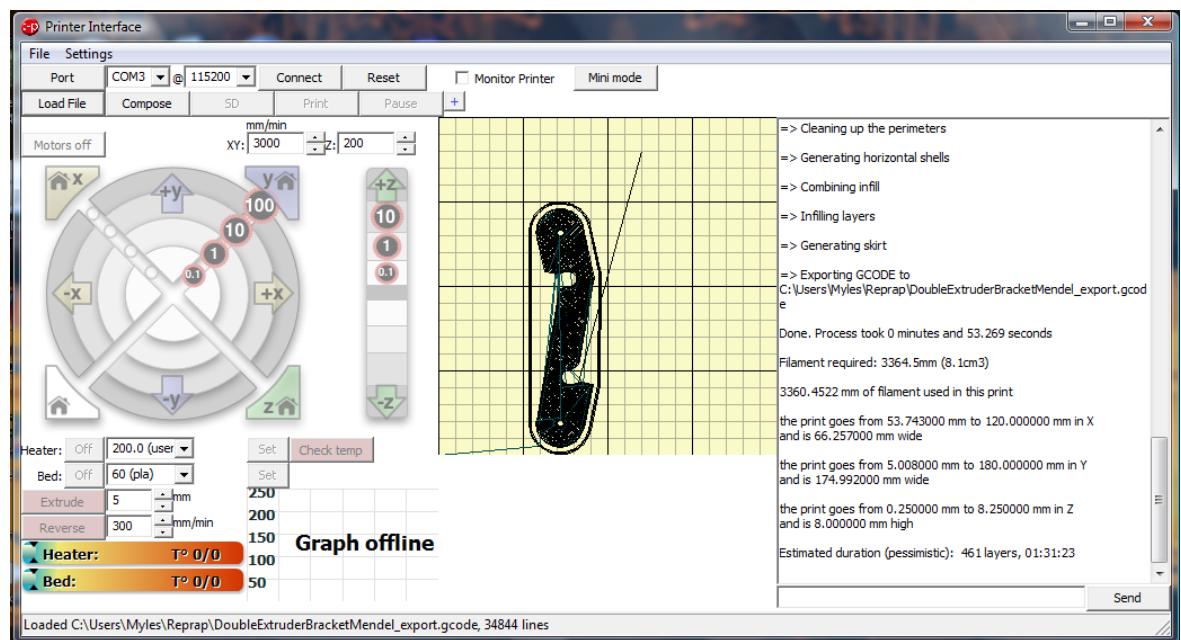
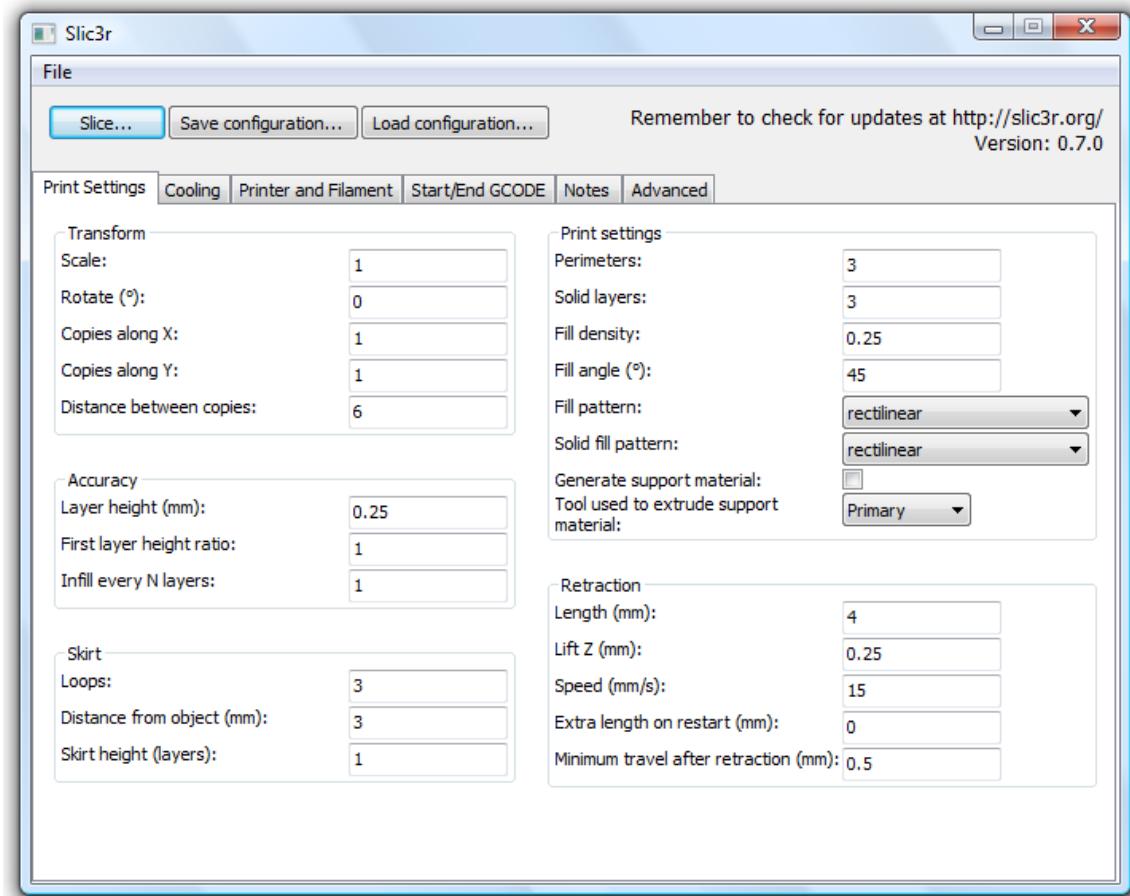
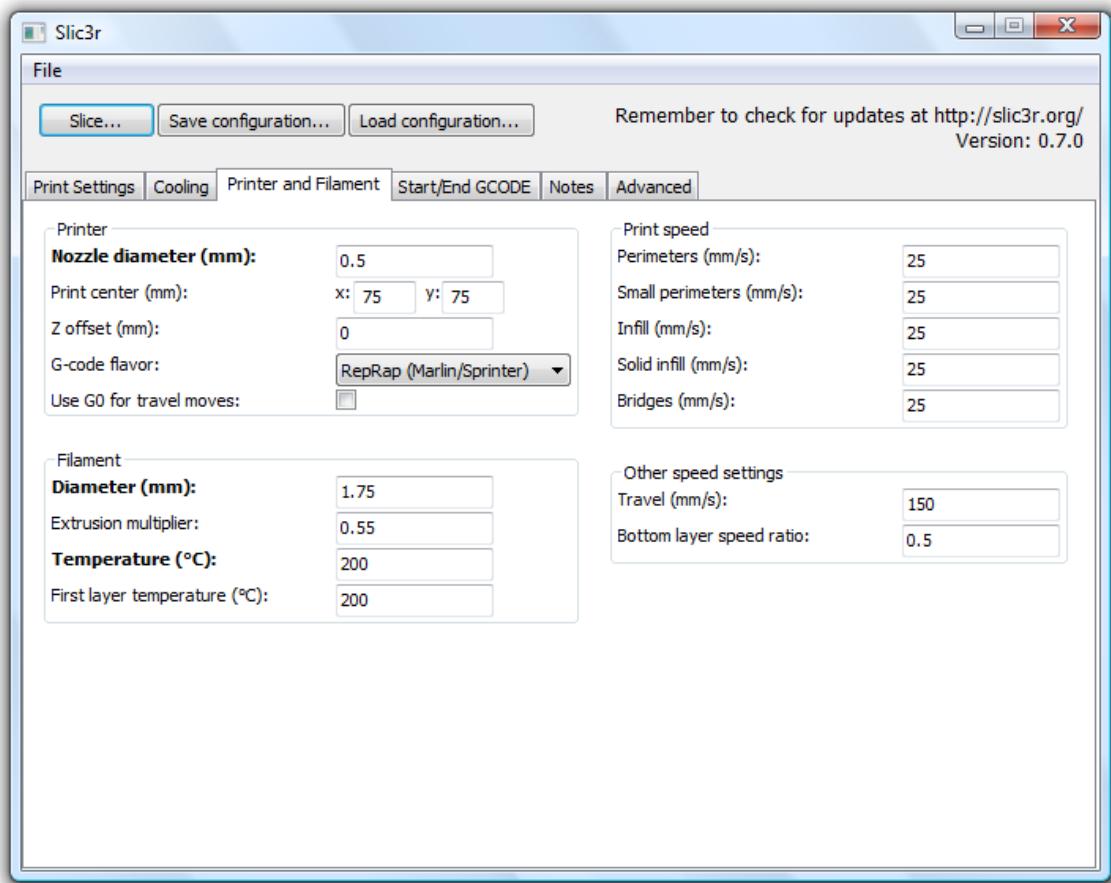


Figure 11-1 - Screenshot of the Printer User Interface Screen

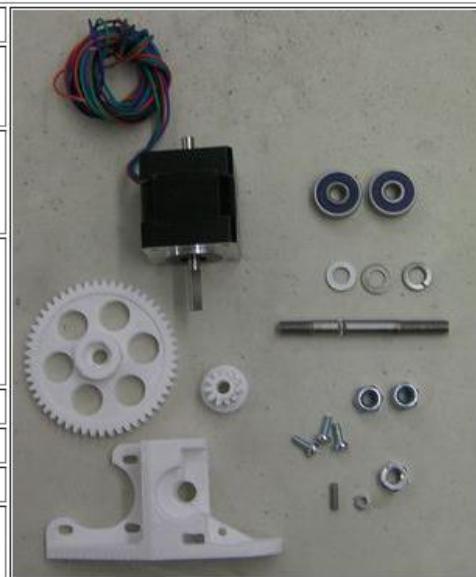
## Appendix B-2 Slic3r Configuration File Settings for Two Colour Printing



## Appendix C – Bowden Extruder Parts from RepRap Wiki

The instructions for assembly of this design can be found at [http://reprap.org/wiki/RepRapPro\\_Huxley\\_extruder\\_drive\\_assembly](http://reprap.org/wiki/RepRapPro_Huxley_extruder_drive_assembly)

RP parts	Quantity
	1
	1
	1
Hardware	Quantity
M6 hobbed stud	1
M6 full nut	1
M6 nyloc nut	2
M6 split washer	1
M6 plain washer	2
626 Bearing	2
NEMA 14 stepper motor	1
M3x10mm socket set screw (Grub)	1
M3 nut	1
M3x8mm screws	3
M3x25mm countersunk screw	1 (Mendel only - not Huxley)



RP parts	Quantity
	1
Hardware	Quantity
M3x30mm screw	1
626 bearing	1
M3x45 screws	2
M6x20mm socket set screw	1
M3 washers	6
M3 full nuts	2
M3 nylock nut	1
Springs	2



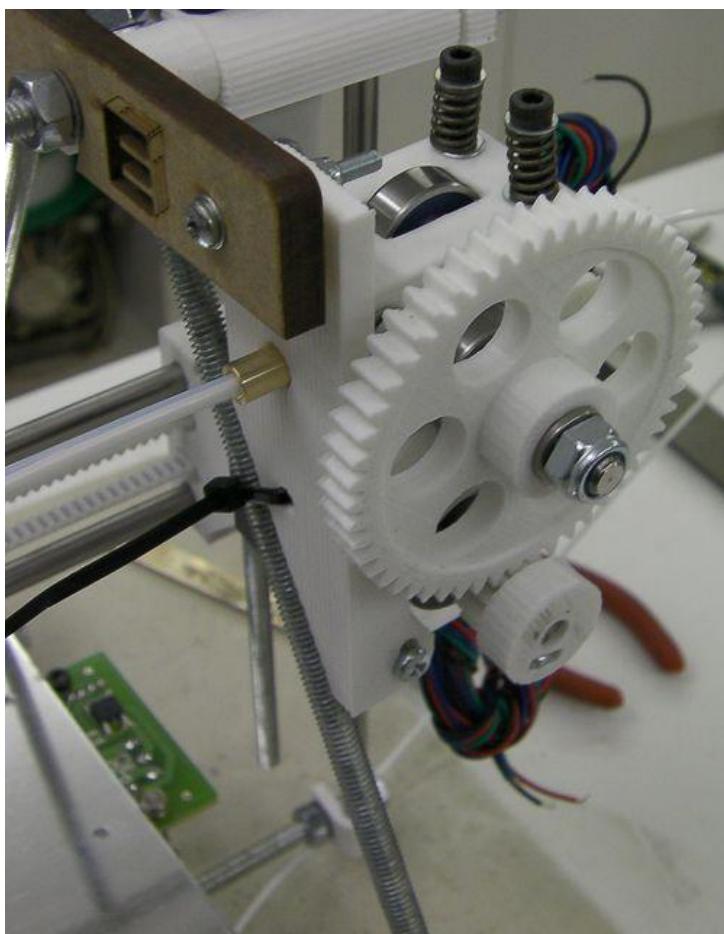
ReprapPro

RP parts	Quantity
	1
Hardware	Quantity
slotted brass retainer	1
PTFE tube	1



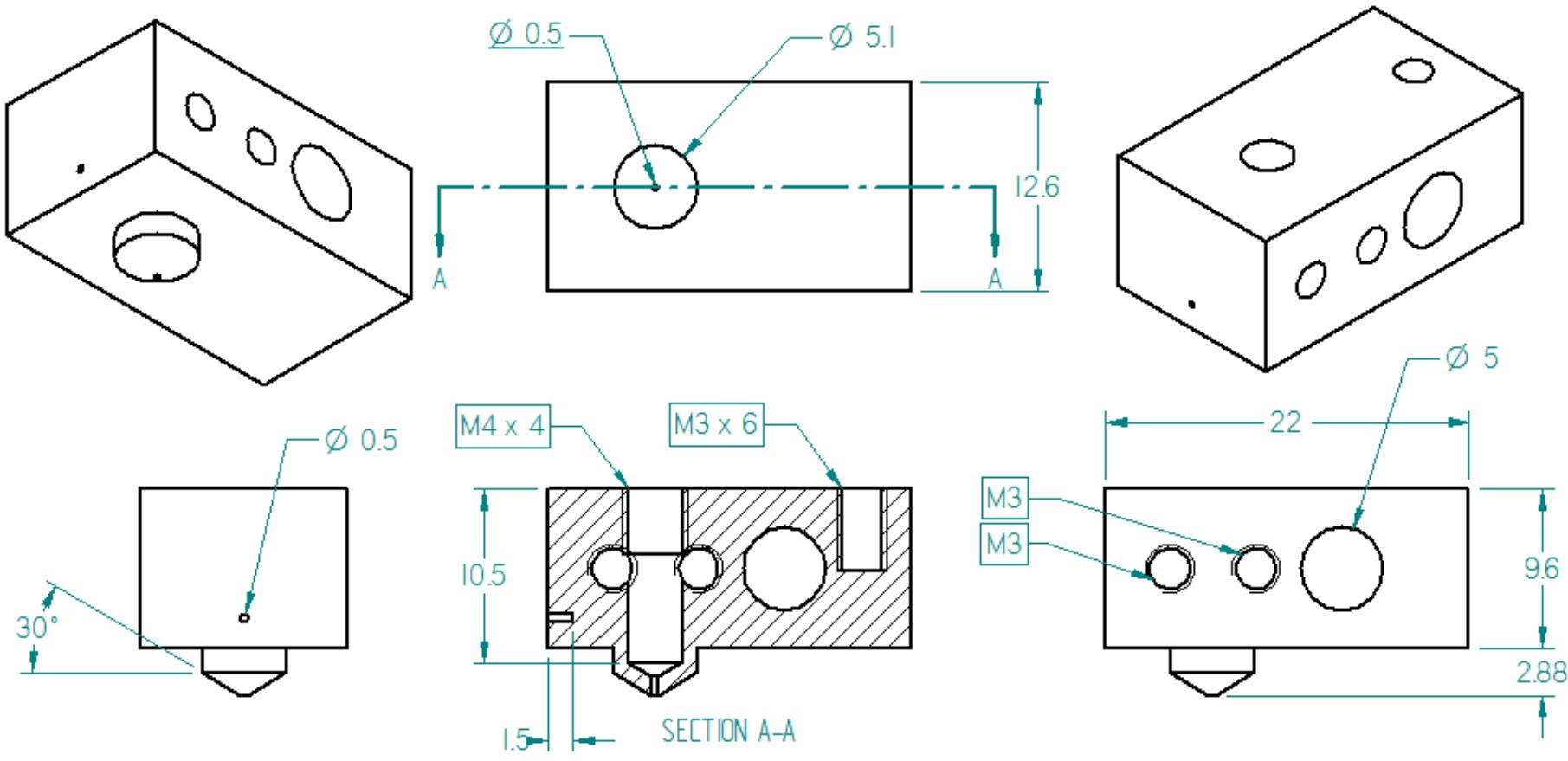
Don't confuse the 300mm PTFE tube (shown) with the shorter translucent heatshrink also supplied with the kit.

The assembled extruder can be seen below;



## Appendix D – Nozzle Drawings

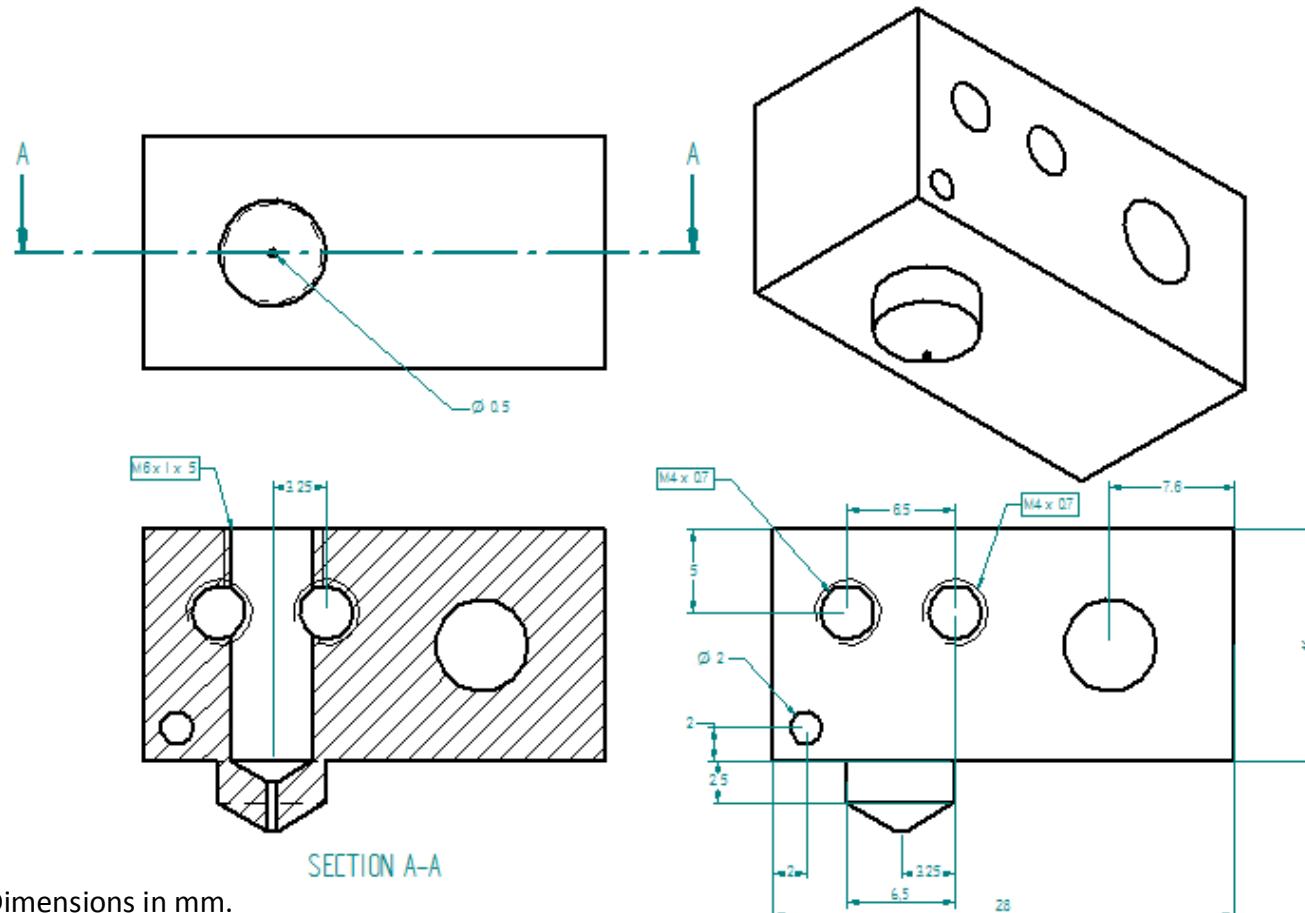
### Appendix D-1 MkI Mixer Nozzle designed by Adrian Bowyer



All Dimensions in mm.

Drawing Not to Scale

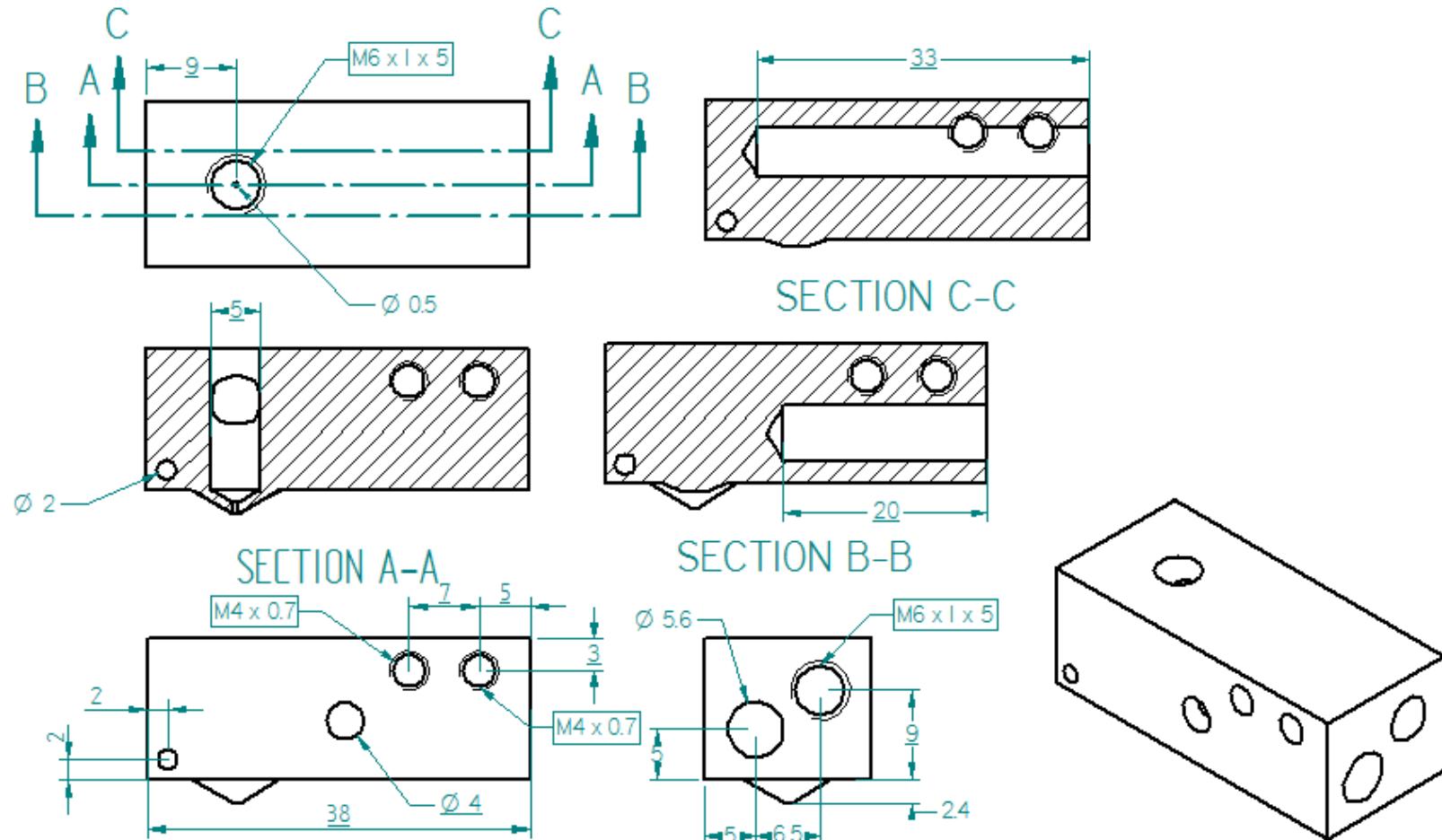
Figure 11-2 – MkI Mixer Nozzle designed by Adrian Bowyer

**Appendix D-2 MkII Mixing Nozzle**

All Dimensions in mm.

Drawing Not to Scale

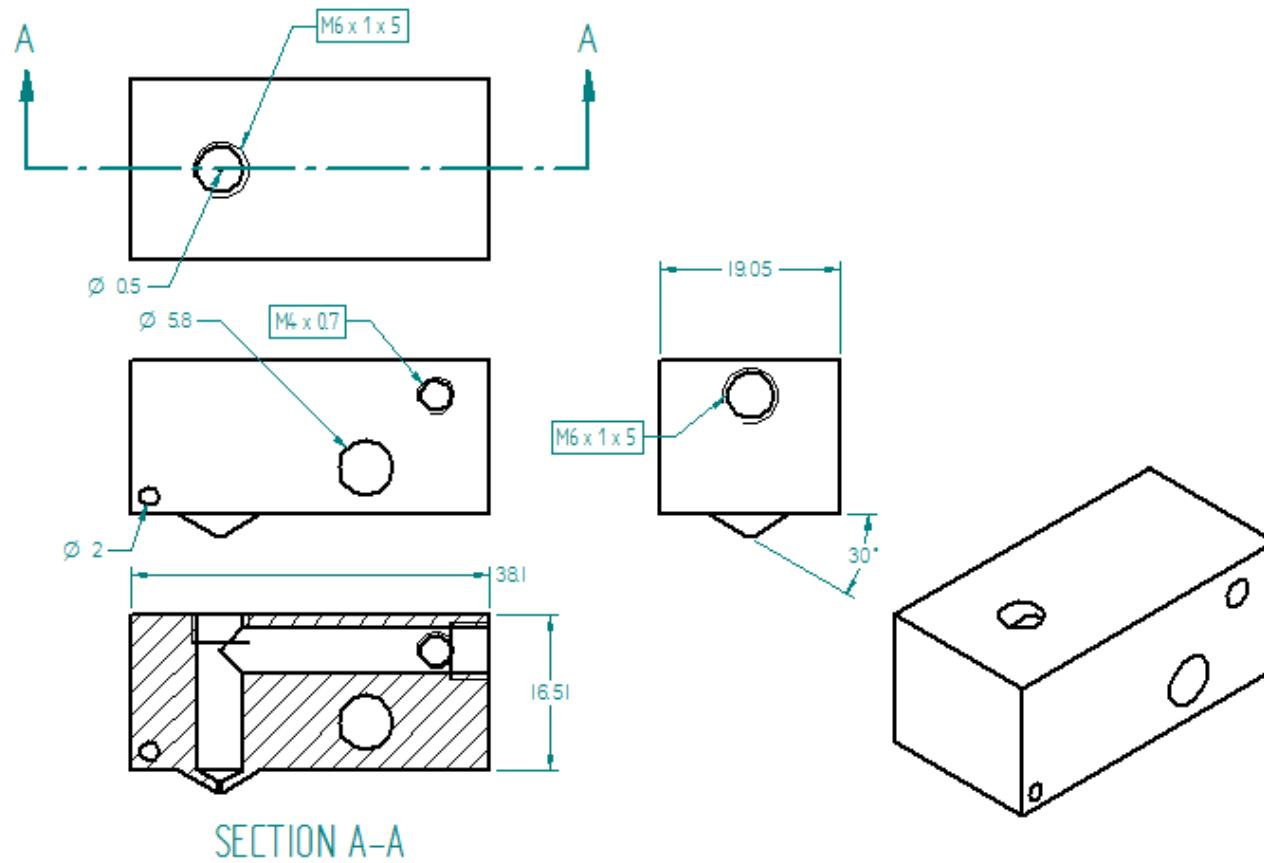
Figure 11-3 – MkII Brass Nozzle Drawing



All Dimensions in mm.

Drawing Not to Scale

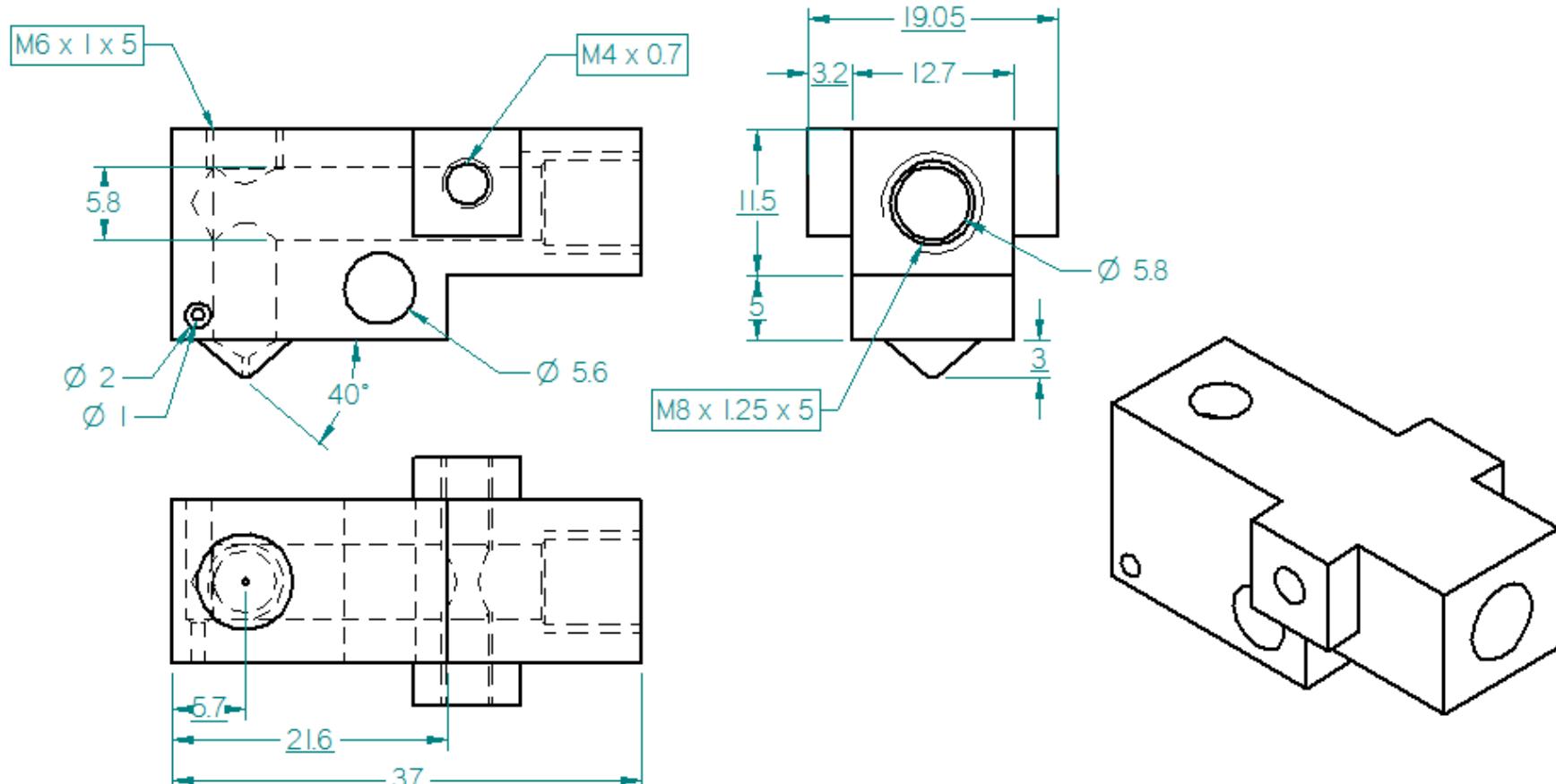
Figure 11-4 - MkIII Brass Nozzle Drawing



All Dimensions in mm.

Drawing Not to Scale

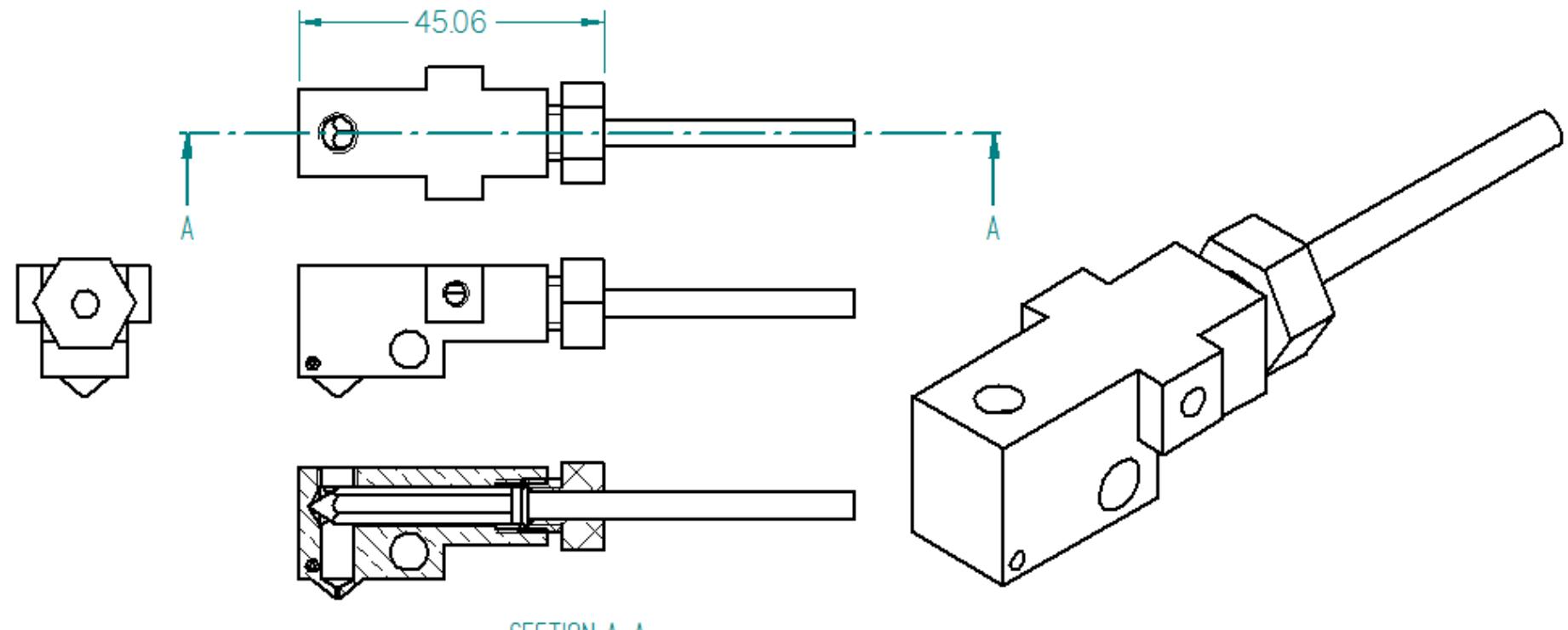
Figure 11-5 - MkIV Brass Nozzle Drawing

**Appendix D-5 MkI Active Mixing Nozzle**

All Dimensions in mm.

Drawing Not to Scale

Figure 11-6 - MkI Brass Active Mixing Nozzle Drawing.



All Dimensions in mm.

Drawing Not to Scale

Figure 11-7 -Assembly Drawing for MkI Active Mixing nozzle.

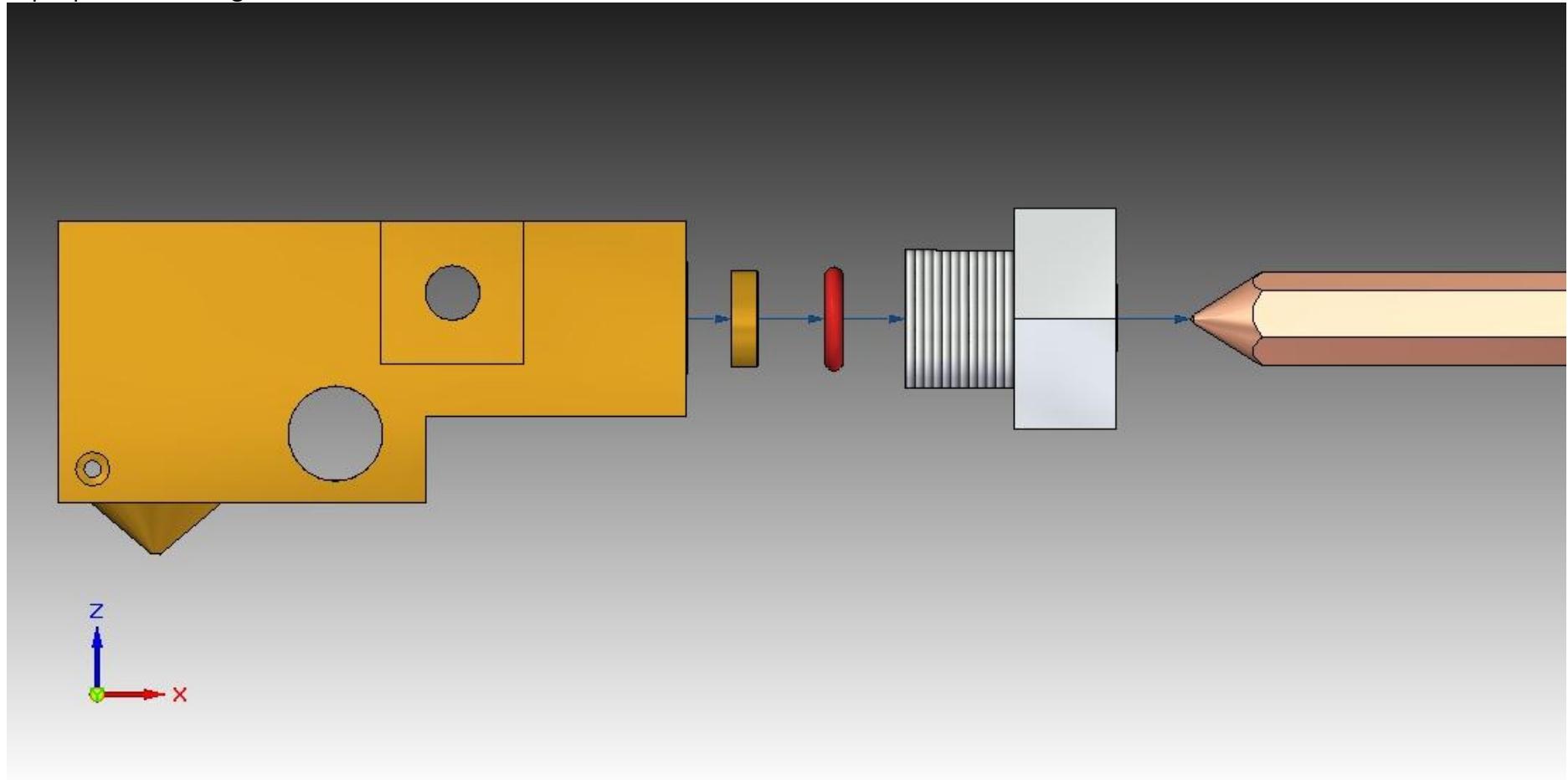


Figure 11-8 - Exploded view of MkI Active Mixing Nozzle

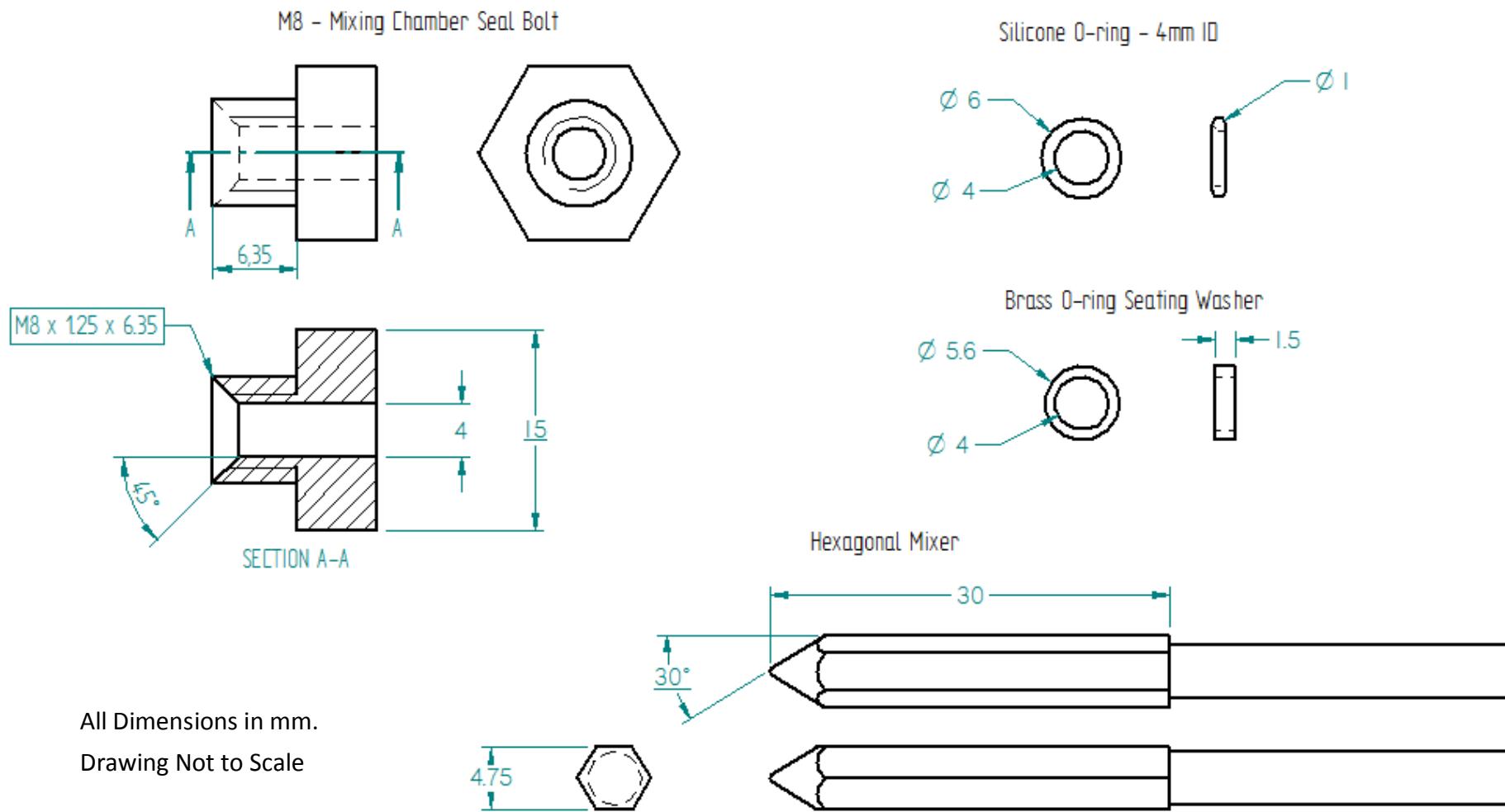


Figure 11-9 - Active Mixer Mk1 Part Drawings.

**Appendix D-6 MkII Active Mixing Nozzle**

All Dimensions in mm.

Drawing Not to Scale

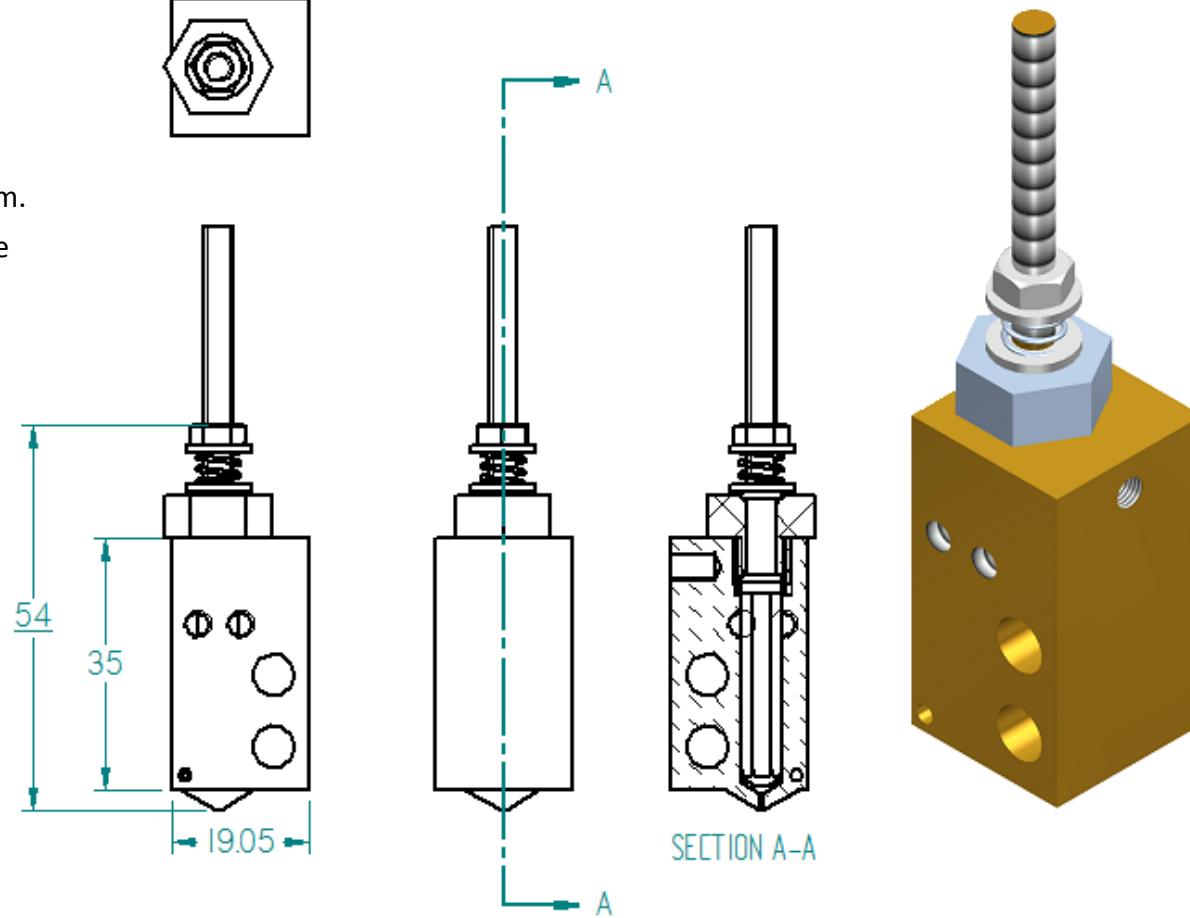


Figure 11-10 - Assembly Drawing of the MkII Active Mixing Nozzle

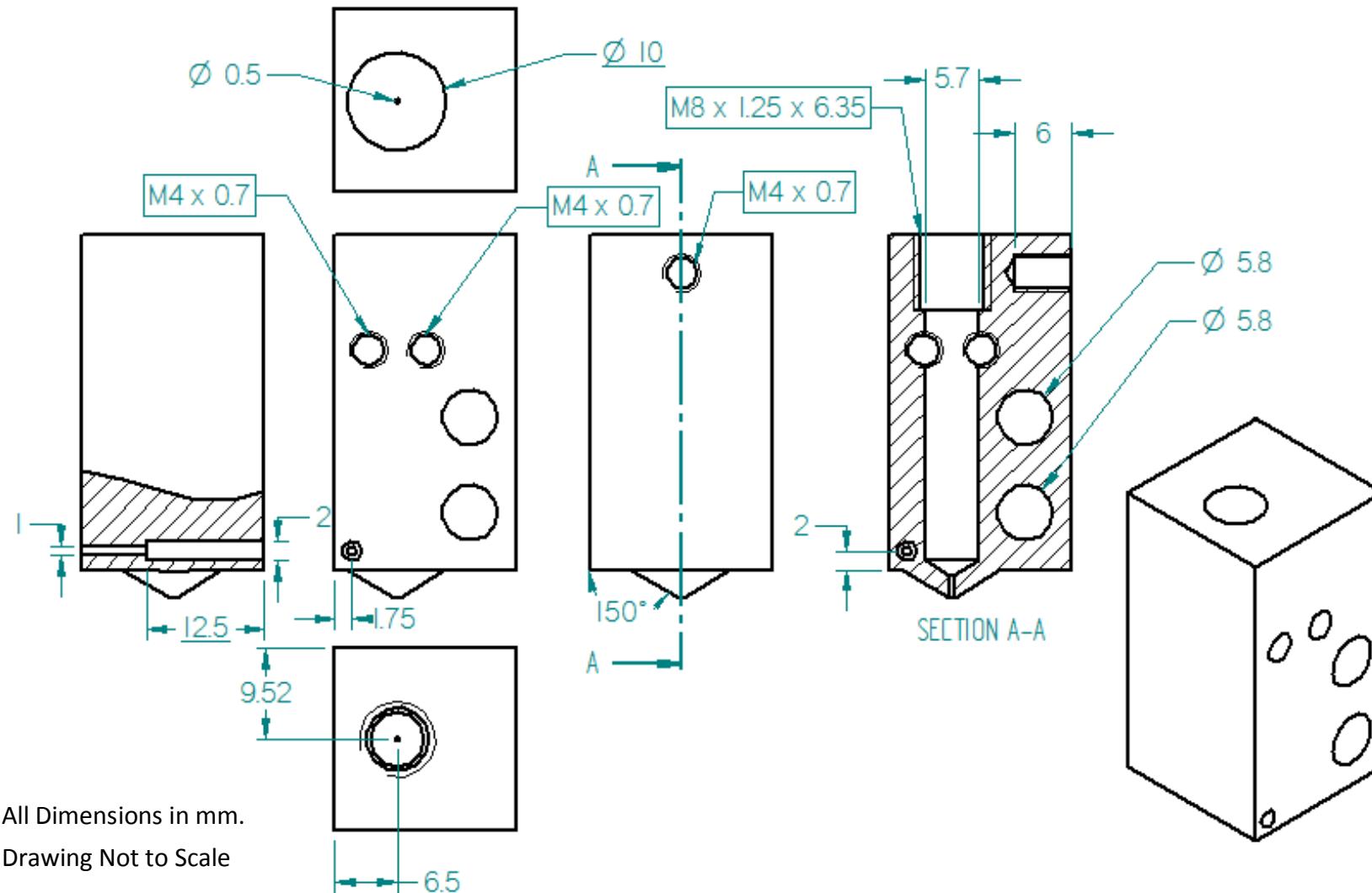


Figure 11-11 - Active Nozzle MkII Nozzle Drawing.

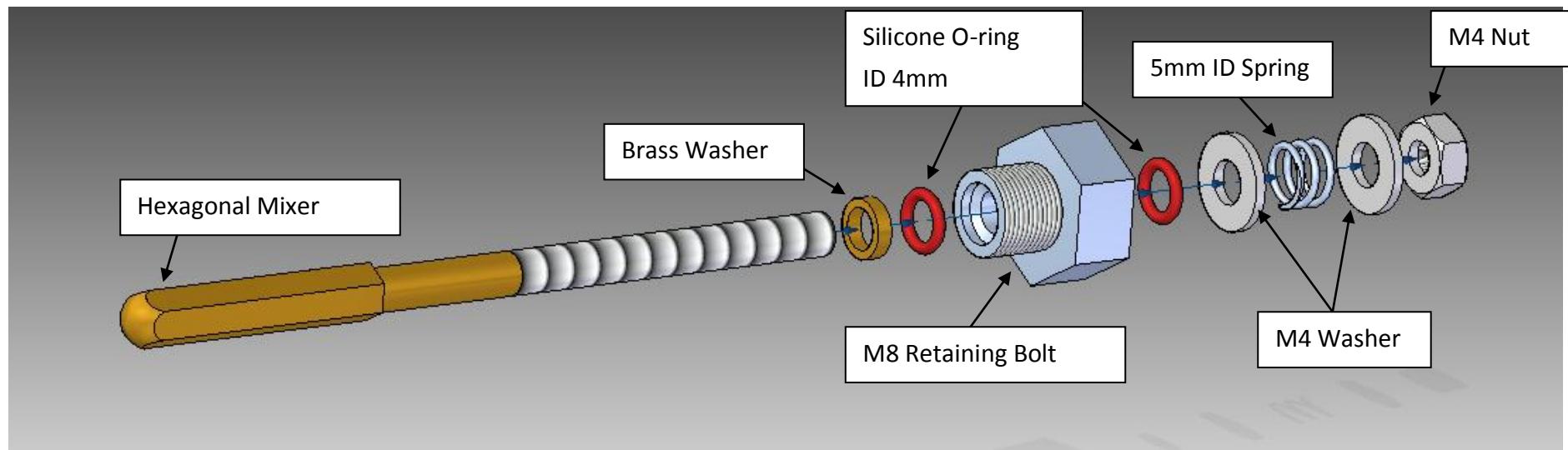


Figure 11-12 - Exploded view of the Active Mixing Nozzle MkII Components (Excluding Main Block).

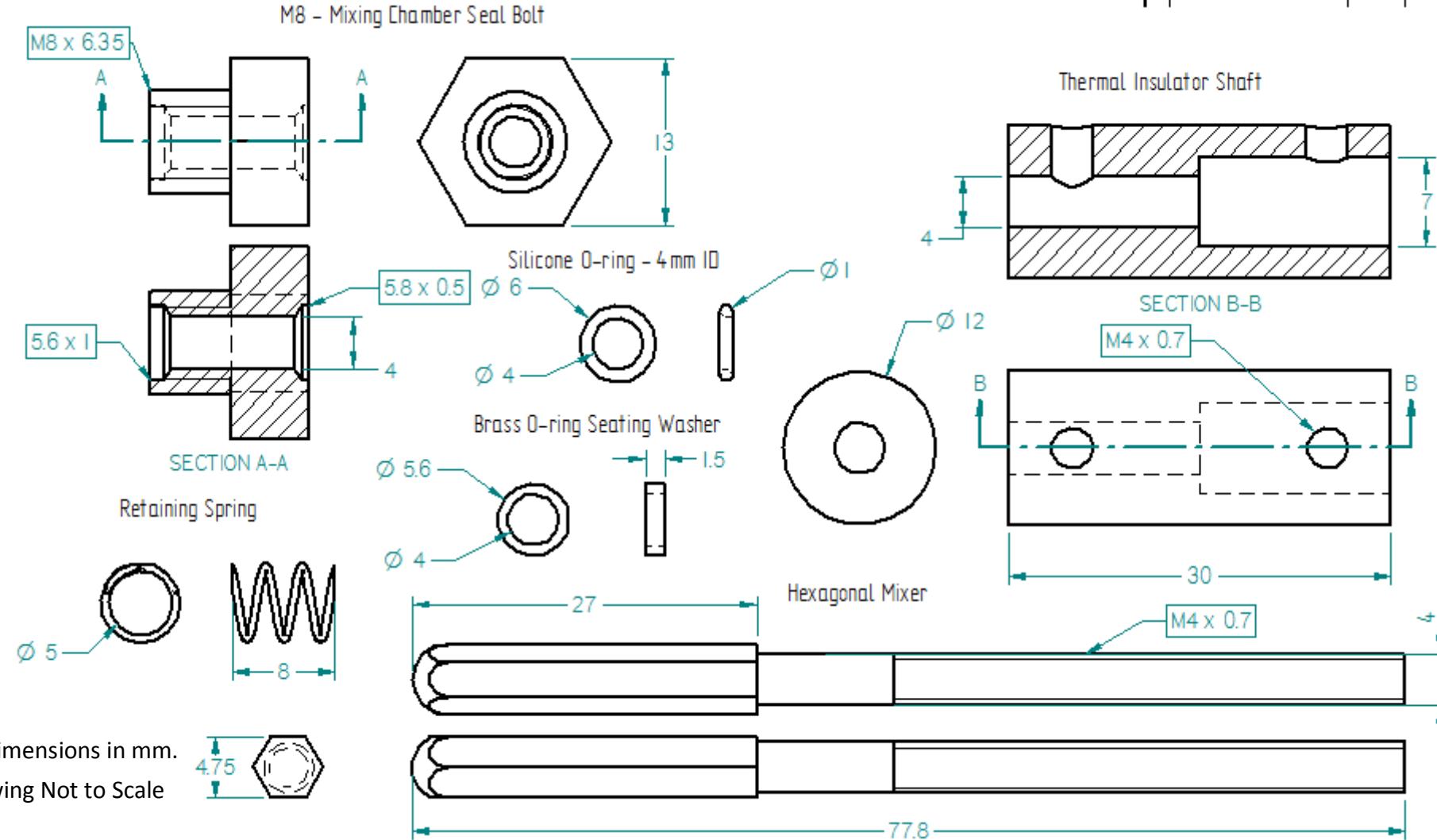


Figure 11-13 – Active Mixer MkII Part Drawings.

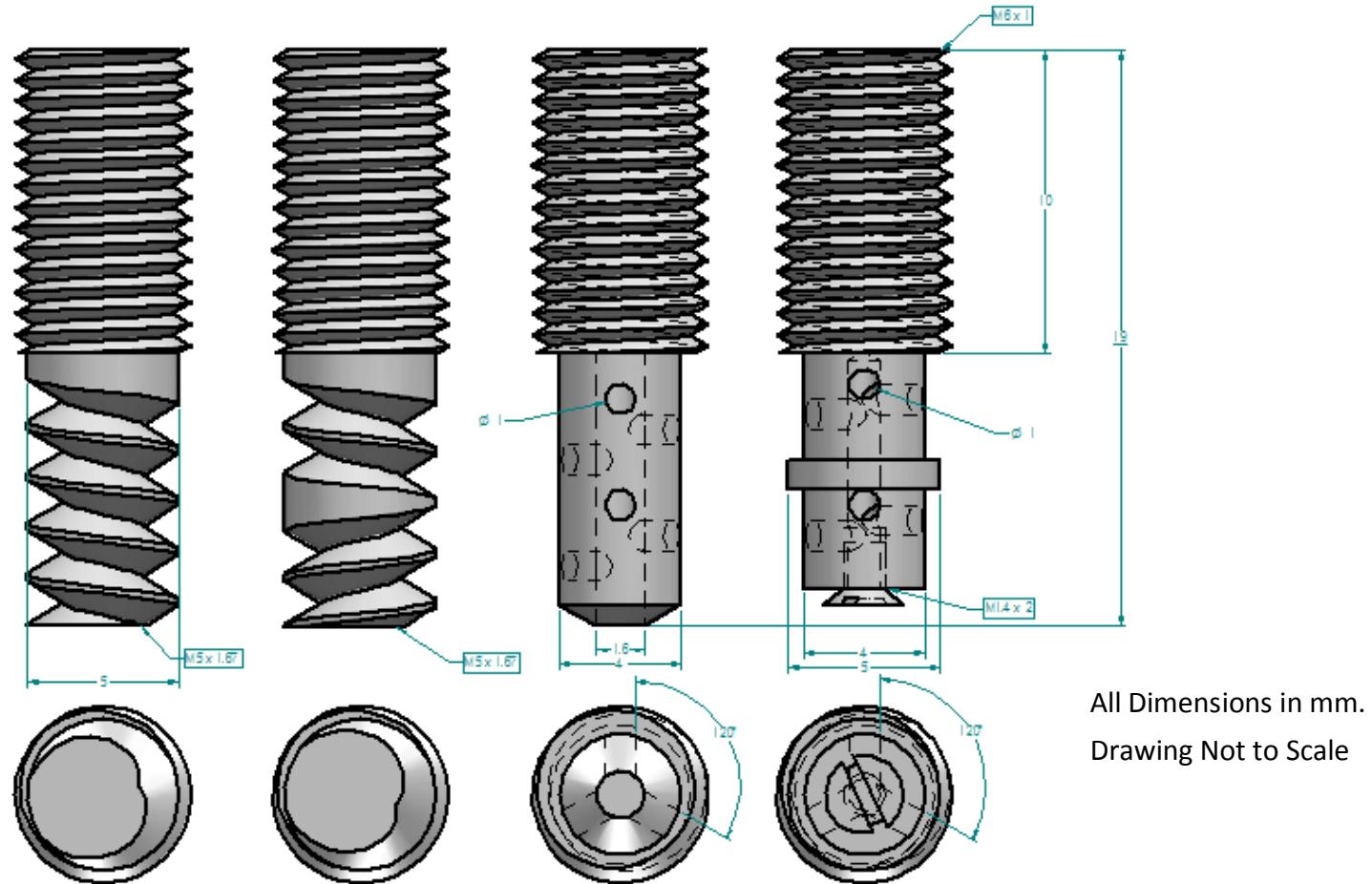


Figure 11-14 - Inserts No. 1-4 Drawings.

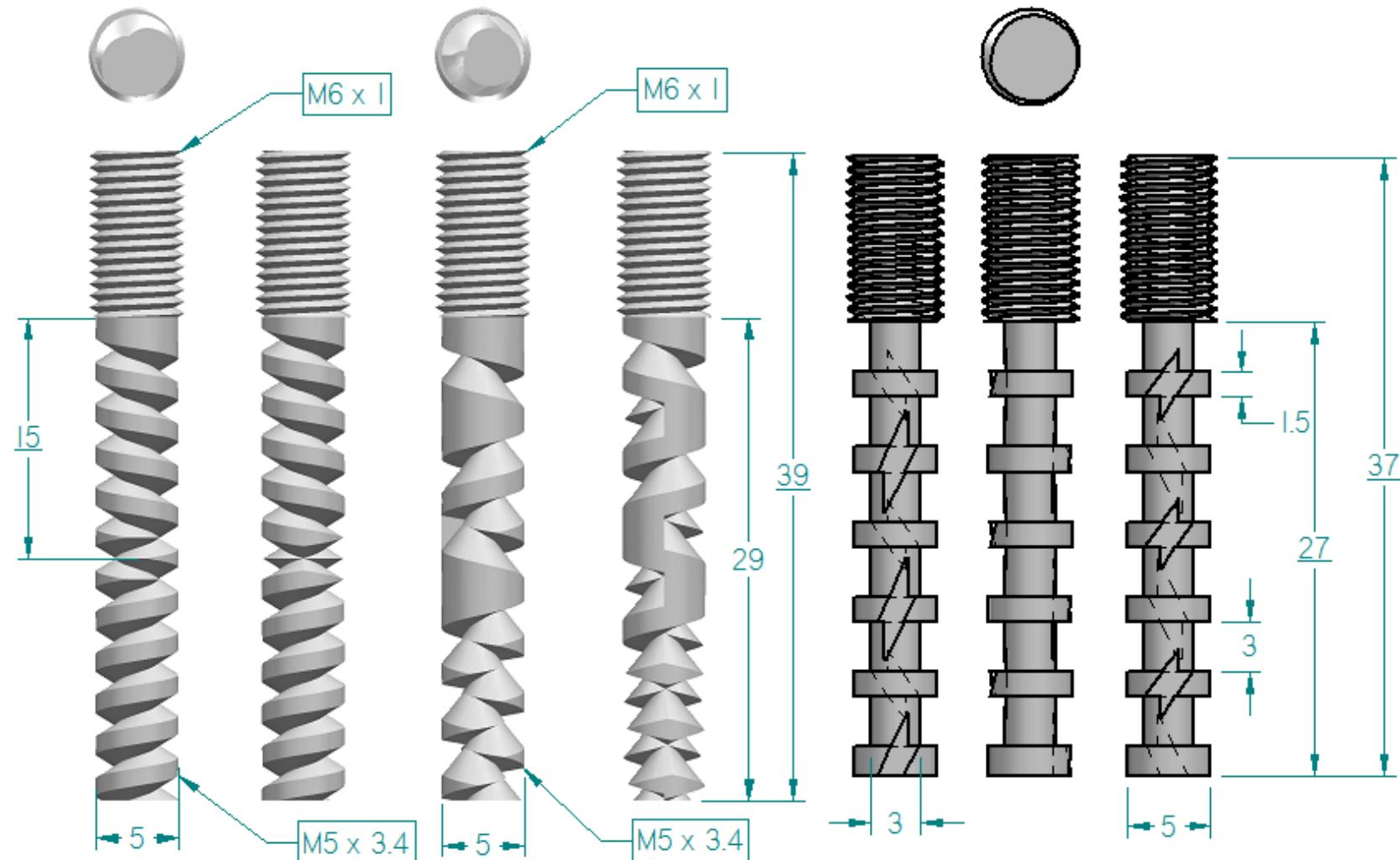


Figure 11-15 - Inserts No. 5-7 Drawings

All Dimensions in mm.

Drawing Not to Scale

## Appendix F – Materials

Item	Dimensions/Part No.	Supplier	Part
Brass Square Rod	5/8" x 1 1/8"	-	MkII Nozzle
Brass Square Rod	5/8" x 1 5/8"	-	MkIII Nozzle
Brass Square Rod	3/4" x 1 1/2"	-	MkIV Nozzle
Brass Square Rod	3/4" x 1 1/2"	-	MkI – Active Mixing Nozzle
Brass Square Rod	3/4" x 1 1/2"	-	MkII – Active Mixing Nozzle
Brass Rod	1/4" x 12"	-	Nozzle Inserts
Brass Hex Rod	3/16" AF x 6"	-	Active Nozzle Inserts
Silicone O-ring	4 x 1 (ID x diameter)	AltecWEB.com	Active Nozzle Seal
PEEK Rod	16mm x 100mm	-	Nozzle Insulator
PTFE Tape	-	-	Electrical Insulator/Heat Insulator
Woven Fibreglass	2mm x 15mm x 500mm	Thingfarm.com	Hot-end Insulation
PTFE Tube	3mm OD, 2mm ID, Length 400mm	-	Bowden Tubes
PTFE Tube	4mm OD, 2mm ID, Length 450mm	-	Bowden Tubes
Thermistor	RS Stock No. 198-961	RS	Nozzle Thermistor
Heater Resistor	RS Stock No. 485 1672	RS	Nozzle Heater
PLA Filament	1.75mm Diameter, Classic Black	Faberdashery	Printing Material
PLA Filament	1.75mm Diameter, Arctic White	Faberdashery	Printing Material

## Appendix G – Silicone O-Ring Data Sheet

**ERIKS** SEALING ELEMENTS

**VMQ-Silicone compound 714177 - Technical Data Sheet**

**1. Introduction**  
Silicone compound 714177 is a general purpose silicone with excellent physical and temperature resistance up to 220°C. Standard compound for O-Rings.

**2. Product Description**

Chemical Composition :	Silicone Rubber having both Methyl and Vinyl groups on the Polymer Chains	
Physical form :	O-Rings / Mouldings	
Colour :	Red	
Odour :	None	
Storage stability *	10 years	

\* : Following ISO 2380 conditions

**3. Physical Properties**

Test Method	Norm	Test Values
Hardness	ISO 48 Method M	70 ± 5 IRHD
Tensile Strength at break	ISO 87	min 7 MPa
Elongation at break	ISO 87	min 300%
Specific Weight	ISO 2781	1,25
Compression Set 25% compression - 22h/150°C on slab	ISO 815	
on O-Ring (3,33 mm)	ISO 815	max 20%
Heat Ageing 70h/100°C		max 40%
Hardness Change	ISO 188	max +12%

**4. Temperature Resistance**

- -60° to +220°C
- TR-10: -60°C

**5. Chemical Resistance**

Air	: excellent
Alcohol	: satisfactory
Hydrocarbons	: unsatisfactory
Fats	: good
Vegetable oils	: good
Silicone oils	: unsatisfactory
Ethers/esters	: unsatisfactory
Acids	: good
Steam	: poor at high temperatures; OK up to 130°C

**6. Advantages**

- Very good compression set
- Stock item for ca. 2000 dimensions

**7. Other Information**

- Other colours on demand.
- Platinum cured USP class VI on demand.

This information is, to the best of our knowledge, accurate and reliable to the date indicated. The above mentioned data have been obtained by tests we consider as reliable. We don't assure that the same results can be obtained in other laboratories, using different conditions by the preparation and evaluation of the samples.

12.01.2010





## Appendix H - Thermistor Data For Firmware

```
// Thermistor lookup table for RS thermistor 198-961
// Made with createTemperatureLookup.py
(http://svn.reprap.org/trunk/reprap/firmware/Arduino/utilities/createTemperatureLookup.py)
// ./createTemperatureLookup.py --r0=100000 --t0=25 --r1=0 --r2=4700 --
beta=3960 --max-adc=1023
// r0: 100000
// t0: 25
// r1: 0
// r2: 4700
// beta: 3960
// max adc: 1023
#define NUMTEMPS 20
short temptable[NUMTEMPS][2] = {
    {1, 929},
    {54, 266},
    {107, 217},
    {160, 190},
    {213, 172},
    {266, 158},
    {319, 146},
    {372, 136},
    {425, 127},
    {478, 119},
    {531, 111},
    {584, 103},
    {637, 96},
    {690, 88},
    {743, 80},
    {796, 71},
    {849, 62},
    {902, 50},
    {955, 34},
    {1008, 2}
};
```

## Appendix I – Heater Resistor Data Sheet

**Wire wound power resistor, 6R8 2.6W**



**View larger image**  
This image is representative of the product range

RS Stock No.	485-1672
Manufacturer	Vishay
Manufacturers Part No.	RWM04106R80JR15E1
RoHS Status	<input checked="" type="checkbox"/> RoHS RoHS Certificate of Compliance
<b>qty</b>	<b>Price Each (In a Pack of 5)</b>
5	49.68 Rs
50	44.91 Rs
250	39.82 Rs
500	35.50 Rs
1000	32.10 Rs
<b>Add to Cart</b>	
<a href="#">- Log In</a>	

**55 in stock in the UK.**  
This stock information was correct at 30/04/2012 12:44 PM. This information is updated daily so availability may vary at time of order placement.

Please note that the price displayed excludes Central Sales Tax, VAT, etc. These will be added when invoiced. Please note the tax rate for this product is 5.00%

**Technical data sheets**  
 Click here to access technical data sheets in PDF format online.

**Attributes**

Attribute Type	Attribute Value
Resistance Value	6.8Ω
Power Rating	3 W
Tolerance	5%
Temperature Coefficient	±75ppm/°C
Case Style	Conformal
Termination Style	Axial
Technology	WireWound
Mounting	Through Hole
Product Diameter	5.5mm
Product Length	12mm

**Overview**  
RWM 4x10 Series 2.6W, Axial

- Enamelled wirewound power resistors
- Axial leads
- Fireproof

Power rating at 70°C	2.6W
Power at 25°C	3W
Resistance tolerance	±5%
Temperature coefficient	+75ppm/°C typical
Limiting element voltage	120V
Temperature cycling	-55°C → +200°C
Body Length	12 mm
Body Diameter	5.5 mm
Lead Length	25 mm min.
Lead Diameter	0.8 mm

**Range Overview**  
**Vitreous Enamel, Axial - 2.5W to 14W**  
A range of high power resistors in small body sizes suitable for use in harsh environments. Their high stability and reliability make them particularly suitable for use in protection circuits. The resistance wire element is wound onto a high purity ceramic substrate and employs an all welded cap and lead method of construction giving considerable strength and resistance to damage. The vitreous enamel protective coating is resistant to all normal PCB cleaning solvents. Application note. Terminations should not be bent closer than 1.5mm from the body. Recommended minimum bend radius is 1mm. For full rated power dissipation terminations should not be soldered closer than 4mm from the body. When cold, vitreous enamel has excellent insulation resistance; however the specific resistance decreases with increasing temperature. Therefore if the resistor is operating at or near maximum temperature it cannot be classed as insulating and should not be in contact with any conducting materials.

## Appendix J – Colour Transition Print G-Code

### Colour Transition Analysis Method

- With the machine set-up identical from the single colour printing method, purge the pre-heated nozzle full of white filament.
- Switch over the filament drive motors from driving white to black.
- Without further purging before printing, run the colour transition print which was programmed manually.
- Carefully remove the PLA from the glass print surface.
- Scan the print and analyse colour transition using Photoshop.

### Colour Transition Print G-code

```

; layer_height = 0.5                                G1 Z0.7500 F9000.000
; perimeters = 3                                     G1 X50 Y50
; solid_layers = 3                                    G1 F900.000 E5.00000
; fill_density = 0.25                                 G1 X50 Y50 F750.000 E5
; nozzle_diameter = 0.5                               G92 E0 ; reset extrusion distance
; filament_diameter = 1.75                            G1 X95 Y50 E9.5
; extrusion_multiplier = 0.6                          G1 X95 Y55 E10
; perimeter_speed = 25                               G1 X50 Y55 E14.5
; infill_speed = 25                                   G1 X50 Y60 E15
; travel_speed = 150                                 G1 X95 Y60 E19.5
; extrusion_width_ratio = 0                           G1 X95 Y65 E20
; scale = 1                                         G1 X50 Y65 E24.5
; single wall width = 0.53mm                         G1 X50 Y70 E25
                                                               G1 X95 Y70 E29.5
                                                               G1 X95 Y75 E30
                                                               G1 X50 Y75 E34.5

M104 S200 ; set temperature
G28 ; home all axes
M109 S200 ; wait for temperature to be             G1 X50 Y80 E35
reached
G90 ; use absolute coordinates                      G1 X95 Y80 E39.5
G21 ; set units to millimeters                     G1 X95 Y85 E40
G92 E0 ; reset extrusion distance                 G1 X50 Y85 E44.5
M82 ; use absolute distances for extrusion        G1 X50 Y90 E45
                                                               G1 X95 Y90 E49.5

```

G1 X95 Y95 E50	G1 X105 Y105 E140
G1 X50 Y95 E54.5	G1 X105 Y100 E140.5
G1 X50 Y100 E55	G1 X150 Y100 E145
G1 X95 Y100 E59.5	G1 X150 Y95 E145.5
G1 X95 Y105 E60	G1 X105 Y95 E150
G1 X50 Y105 E64.5	G1 X105 Y90 E150.5
G1 X50 Y110 E65	G1 X150 Y90 E155
G1 X95 Y110 E69.5	G1 X150 Y85 E155.5
G1 X95 Y115 E70	G1 X105 Y85 E160
G1 X50 Y115 E74.5	G1 X105 Y80 E160.5
G1 X50 Y120 E75	G1 X150 Y80 E165
G1 X95 Y120 E79.5	G1 X150 Y75 E165.5
G1 X95 Y125 E80	G1 X105 Y75 E170
G1 X50 Y125 E84.5	G1 X105 Y70 E170.5
G1 X50 Y130 E85	G1 X150 Y70 E175
G1 X95 Y130 E89.5	G1 X150 Y65 E175.5
G1 X95 Y135 E90	G1 X105 Y65 E180
G1 X50 Y135 E94.5	G1 X105 Y60 E180.5
G1 X50 Y140 E95	G1 X150 Y60 E185
G1 X100 Y140 E100	G1 X150 Y55 E185.5
G1 X150 Y140 E105	G1 X105 Y55 E190
G1 X150 Y135 E105.5	G1 X105 Y50 E190.5
G1 X105 Y135 E110	G1 X150 Y50 E195
G1 X105 Y130 E110.5	G1 X150 Y45 E195.5
G1 X150 Y130 E115	G1 X105 Y45 E200
G1 X150 Y125 E115.5	G92 E0
G1 X105 Y125 E120	G90; Ensure absolute postioning
G1 X105 Y120 E120.5	G92 E3; Set position of extrusion for
G1 X150 Y120 E125	retraction
G1 X150 Y115 E125.5	G0 X100 Y160 Z10 E0; Fast move extruder
G1 X105 Y115 E130	out of the way
G1 X105 Y110 E130.5	M84 ; disable motors ; filament used = 135mm
G1 X150 Y110 E135	
G1 X150 Y105 E135.5	

## Appendix K - Different Filament Feed Colour Preliminary Analysis

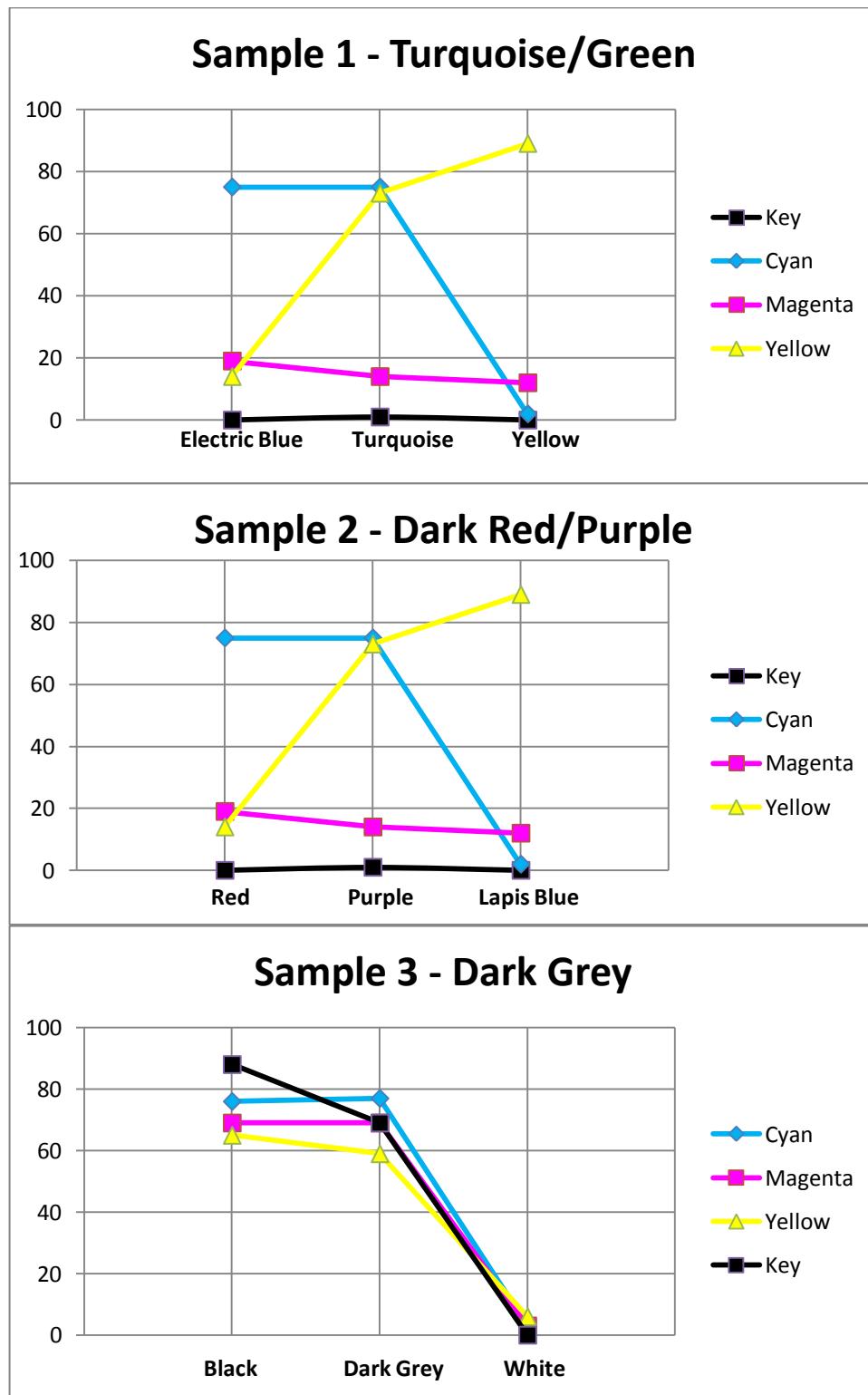
The figure below shows a variety of prints made the selection of colours tested in section 6.3.1, the samples are as follows;

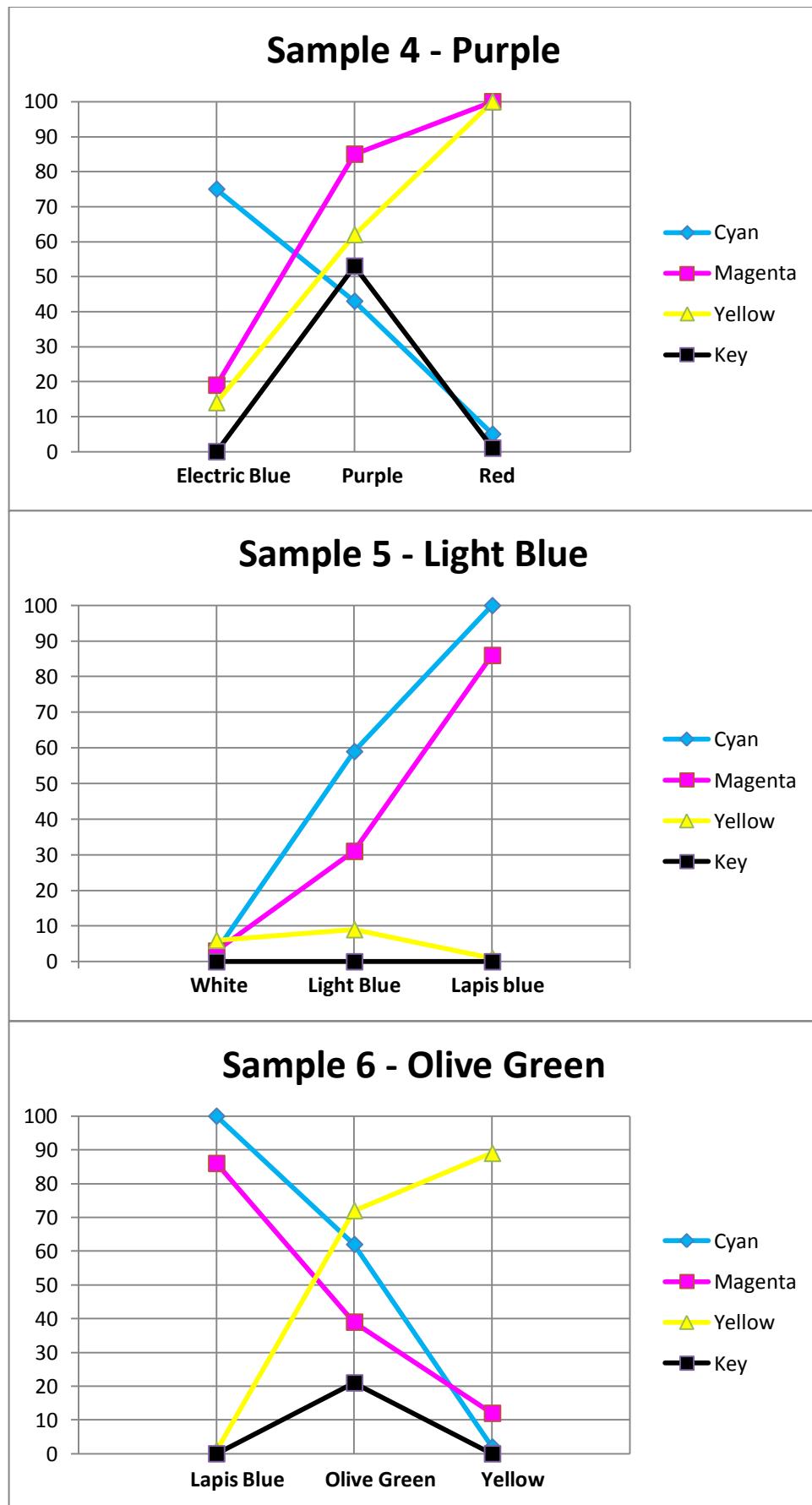
1. Electric Blue and Mellow Yellow → Turquoise
2. Lapis Blue and Arctic White → Dark Red
3. Classic Black and Arctic white → Dark Grey
4. Fire Truck Red and Electric Blue → Purple
5. Lapis Blue and Arctic White → Light Blue
6. Electric Blue and Mellow Yellow → Olive Green
7. Classic black
8. Fire Truck Red
9. Lapis Blue
10. Electric Blue
11. Mellow Yellow
12. Arctic White



Figure 11-16 - Printed Samples and samples of plastics used

These samples were made simply out of interest to see the results, the average CMYK values were measured and plotted against the colour composition of the two individual filaments which can be seen below. More analyse of different samples is required to get conclusive results but the graphs give a rough representation of how the colours behave.





11-17 - CMYK (%) Composition of samples

## Appendix L – Project Synopsis

3D printing is becoming much more widespread but is still limited by the materials available from the supplier. This project aims to develop a new nozzle for RepRap to enable the mixing of multiple colours of thermosetting plastic to give an infinite number of colours available to the home user with only having to purchase a few distinct colours. This design could vary the mechanical properties of a print by using hard and soft plastics.