Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment

The Ceramics Manufacturing Working Group

September 2010

First Edition

Recommended Citation: The Ceramics Manufacturing Working Group (2010). Best Practice Recommendations for Local Manufacturing of Ceramic Filters for Water Treatment, Ed. 1. Seattle, WA, USA.

Cover Photos (clockwise from top left): Family using the ceramic filter in Nicaragua (D. Lantagne); Potters for Peace filter (D. Lantagne); IDE Rabbit filter system, Cambodia (Potters for Peace); FilterPure ceramic filter factory in Tanzania (D. Lantagne). Used with permission.

Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment

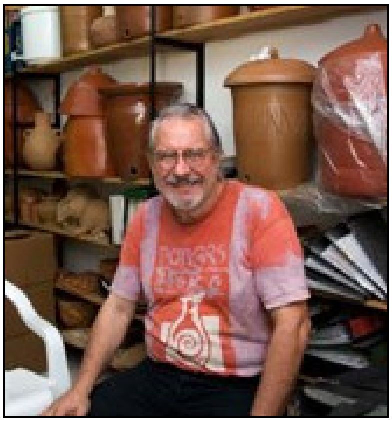
The Ceramics Manufacturing Working Group

September 2010

First Edition

This report is dedicated to the memory of:

Ron Rivera and Mickey Sampson



for their tireless efforts promoting ceramic water filtration.

CONTENTS

1 Introduction 14

2 Literature Review 16

- 2.1 Filter Efficacy 16
- 2.2 Social Acceptability 19
- 2.3 Mechanisms of Effectiveness 20
- 2.4 Summary 24

3 Overview of Filter Production 25

- 3.1 Variables in Filter Production 25
- 3.2 Survey Development and Limitations 25
- 3.3 Results 27
- 3.4 Materials 30
- 3.5 Additional Materials 31
- 3.6 Ratio and Mixing 31
- 3.7 Forming Filter Elements 33
- 3.8 Stamping, Surface Finishing and Drying 33
- 3.9 Firing 34
- 3.10 Silver 35
- 3.11 Quality Control 36
- 3.12 Health and Safety 40
- 3.13 Summary 41

4 Variables: Materials Sourcing and Processing 42

- 4.1 Water 42

4.2 Clay 43
4.3 Burn-out Material (Combustible).. 52
4.4 Laterite 53
4.5 Grog and Sand 54
4.6 Materials Checks and Documentation 54
4.7 Recommendations 55
4.8 Research Indicated 56
4.9 Chapter Details... 56
5 Variables: Filter Production 57
5.1 Process Checks and Filter Logs 57
5.2 Establishing Filter Mixture Ratio 57
5.3 Filter Mixture Preparation 59
5.4 Wedging, Pounding, Kneading, Pug Mill 61
5.5 Pressing 61
5.6 Surface Finishing, Stamping and Drying 64
5.7 Recommendations 66
5.8 Research Indicated 67
5.9 Chapter Details... 68
6 Variables: Kilns and Firing 69
6.1 Introduction.. 69
6.2 Types of Kilns... 69
6.3 Fuel Options and Storage.. 70
6.4 Mani Kiln.. 71
6.5 Controlling the Temperature... 73
6.6 Monitoring Heat-work and Temperature 74

6.7 The Firing Curve and Firing Process 77
6.8 Stacking the Kiln 78
6.9 Firing Log 82
6.10 Recommendations 84
6.11 Research Indicated 85
6.12 Chapter Details 85

7 Variables: Silver nanoparticles 86

7.1 Introduction 86
7.2 Overview of Proposed Disinfectant Mechanisms of Silver Nanoparticles (Colloidal Silver) 87
7.3 Production of Silver Nanoparticles 90
7.4 Silver in Ceramic Water Filters 91
7.5 Environmental and Health Concerns 94
7.6 Silver Guidelines 95
7.7 Recommendations 96
7.8 Research Indicated 97
7.9 Chapter Details 98

8 Variables: Quality control 99

8.1 Introduction 99
8.2 Quality Control Procedures and Frequency Intervals 100
8.3 Quality Control of Final Product 104
8.4 Research and Independent Testing 111
8.5 Recommendations 111
8.6 Research Indicated 112
8.7 Chapter Details 112

9 Variables: Packaging ... 113
9.1 Filters ... 113
9.2 Receptacle and Lid ... 113
9.3 Taps ... 114
9.4 Additional Items ... 114
9.5 Operation and Maintenance (O&M) Instructions ... 114
9.6 Packaging ... 115
9.7 Recommendations ... 116
9.8 Research Indicated ... 117
9.9 Chapter Details ... 117
10 Conclusions ... 118
10.1 Lessons Learned ... 118
10.2 Summary of Best Practice Recommendations ... 120
10.3 Summary of Research Indicated ... 122
10.4 Voluntary Nature of Standards ... 124
References ... 125
Annex A Scope of Work ... 132
Annex B Conversion Tables ... 134
Annex C Survey Results Tables ... 136
Annex D Diagnostic Tests for Raw Materials ... 141
D-1 Clay Tests ... 141
D-2 Burn-out Tests ... 147
Annex E Additional Tests ... 148
Annex F Quality Control - Filter Logs ... 150

Annex G Silver Dilution 158

Annex H Equipment Information 163

Annex I Materials Suppliers 168

Annex J Sample O&M Instructions 172

List of Figures

Figure 1-1: PFP Filter System 14
Figure 3-1: Production Variables 26
Figure 3-2: Filter Factory Locations 27
Figure 3-3: Monthly Filter Production 29
Figure 3-4: CWF Retail Prices 29
Figure 3-5: Clay Sieve Sizes 31
Figure 3-6: Burn-out Sieve Sizes 31
Figure 3-7: Clay-Rice Husk Ratio 32
Figure 3-8: Clay-Sawdust Ratio 32
Figure 3-9: Illustrations of Filter Shapes 33
Figure 3-10: Drying Times 34
Figure 3-11: Flow Rate Ranges 38
Figure 3-12: Failure Rates 39
Figure 3-13: Filters Cracked During Firing 40
Figure 4-1: Elephant's Foot Tamper 50
Figure 4-2: Hammer Mill Operation 51
Figure 4-3: Hammer Mill Screen 51
Figure 5-1: Drum Mixer 60
Figure 5-2: Pug Mill (Thirst-Aid 2009) 61
Figure 5-3: PFP Dutch Press 61
Figure 5-4: Filter Press with aluminum mold, Indo-2 62
Figure 5-5: Filter Press with cast-iron mold, Cam-1 62
Figure 5-6: Filter Press with wooden mold, Myanmar 63
Figure 5-7: Filter Press with cement mold, DR 63
Figure 5-8: Checking Mold Alignment 63
Figure 5-9: Uneven Drying 65
Figure 6-1: Heat Flow in an Up-draft kiln 70
Figure 6-2: Heat Flow in a Down-draft kiln 70
Figure 6-3: Flat Top Mani Kiln 72
Figure 6-4: Mani Kiln Cross Section 73
Figure 6-5: Cross Section of Ash Pit and Firebox 74
Figure 6-6: Cone Block 75
Figure 6-7: Digital Pyrometer 76
Figure 6-8: Thermocouple (bottom) and Protection Tube (top) 76
Figure 6-9: Firing Curve and Stages of Firing(Hamer 2004) 77
Figure 6-10: Filters Stacked for Firing, Myanmar 78
Figure 6-11: Oblong Filters Stacked for Firing 78
Figure 6-12: Flat bottomed filters stacked in kiln 78
Figure 6-13: Kiln being Fired, Cam-1 79
Figure 6-14: Cracked Filters 82

Figure 6-15: Firing/Cooling Crack 82
Figure 6-16: Firing Graph, San Mateo Ixtatán, Guatemala(Guate-2) 84
Figure 7-1: Commercial silver nanoparticle products by category 87
Figure 7-2: Proposed antibacterial mechanism of colloidal silver 88
Figure 7-3: Schematic of system used for electrochemical reduction of Ag+ to Ag^0 91
Figure 8-1: Production Flow Chart 101
Figure 8-2: Pressure Test and Evidence of Leaks 105
Figure 8-3: Calibrated T-device 107
Figure 9-1: Filter Unit with Fitting Ring 114
Figure 9-2: Packaged Filters, Myanmar 116
Figure 9-3: Packaging Filters, Nicaragua 116
Figure 9-4: Packaging Filters, Honduras 116
Figure D-0-1 Triaxial Blending Triangle 145

List of Tables

Table 1: Log Reduction Value 16
Table 2: Participating Factories 27
Table 3: Colloidal Silver Applied by Brushing 35
Table 4: Colloidal Silver Applied by Dipping 36
Table 5: Current application protocol, techniques, products and concentration of silver nanoparticles in ceramic filters 92
Table 6: Advantages and disadvantages of each silver application method 92
Table 7: *E. coli* removal in ceramic filters with and without silver application 93
Table 8: Silver release from ceramic filters 94
Table 9: Summary of Quality Control Procedures 102

ACRONYMS

3GMK	Third Generation Mani Kiln
Ag^0	Silver Oxide
CDC	US Centers for Disease Control and Prevention
CFU	Colony Forming Units
ICAITI	Instituto Centro Americano de Tecnología Industrial (Central American Industrial Technology Institute)
EPA	US Environmental Protection Agency
HWTS	Household Water Treatment and Safe Storage
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
K	Kelvin
LRV	Log Reduction Value
MF	Membrane Filtration
MOR	Modulus of Rupture
MPN	Most Probable Number
NGO	Non-governmental organization
NTU	Nephelometric Turbidity Units
NIST	National Institutes for Science and Technology
O & M	Operation and Maintenance
P/A	Presence/Absence
PA	Primary Air
PFP	Potters for Peace
PTF	Prototype Filter
RDI-C	Resource Development International – Cambodia
ROS	Reactive Oxygen Species
RPM	Revolutions per Minute
SA	Secondary Air
TC	Total Coliform
TTC	Thermotolerant Coliform (Fecal Coliform)
SEM	Scanning Electron Microscope
WHO	World Health Organization

ACKNOWLEDGEMENTS

The authors would like to thank all of the ceramic manufacturers who participated in the manufacturing survey, Pat Lennon and Jesse Schubert of PATH for their leadership and financial support in bringing this document to completion, Derek Baker of CAWST and Barbara Donachy for their review and comments on this document.

This work would not have been possible without the collaboration of the members of the Ceramics Manufacturing Working Group, which includes:

Justine Rayner	PATH/Consultant	jsrayners@yahoo.com
Daniele Lantagne, PE	US Centers for Disease Control and Prevention (CDC)	dlantagne@cdc.gov
Lisa Ballantine	FilterPure	lisaballantine@aol.com
Curt & Cathy Bradner	Thirst-Aid	
Joe Brown, PhD	University of Alabama	
Vinka Craver, PhD	University of Rhode Island	
Burt Cohen	Potters without Borders	
Terry Foecke		
Tracy Hawkins	SAFE Water Now (SWaN)	tracy.hawkins@safewaternow.org
Manny Hernandez		
Stephanie Hooker	National Institutes for Science and Technology (NIST)	
Susan Murcott	MIT	
Robert Pillers	Potters for Peace	bpillers@gmail.com
Mike Stewart	University of Colorado	

1 Introduction

An estimated 884 million people do not have access to an improved water supply (UNICEF/WHO 2008), and hundreds of millions more drink water contaminated at the source or during collection, transport and storage (Clasen and Bastable 2003). Diarrhea, one health consequence of unsafe drinking water, accounts for 1.87 million (19%) childhood deaths each year (Boschi-Pinto *et al.* 2008).

Ceramic filters have traditionally been used to treat household water in many countries, and are commonly available for purchase in both developed and developing countries. Currently, the most widely promoted household ceramic filters in the developing world are based on a design developed in 1981 by Dr. Fernando Mazariegos working with the Central American Industrial Technology Institute, ICAITI (Instituto Centro Americano de Tecnología Industrial) (AFA 1995). In the mid-1990's, the manufacturing process was re-designed by the US-based non-governmental organization (NGO) Potters for Peace (PFP). PFP has subsequently promoted filter manufacturing in over 20 countries. The ICAITI/PFP filter design is similar to a flowerpot in shape, holds about 8 liters of water and sits inside a plastic or ceramic receptacle fitted with a tap and lid (Figure 1-1). To treat water users pour water into the filter, wait for water to flow through the filter into the receptacle, and dispense water from the tap. The filters are produced in country at ceramics manufacturing facilities.

Figure 1-1: PFP Filter System

Recent research in Cambodia has confirmed that locally-made ceramic filters improve the microbiological quality of stored water and reduce the frequency of diarrheal disease in users (Brown *et al.* 2007). Based on this and other research, it has been suggested that filters may be the most effective household water treatment option (Sobsey *et al.* 2008). They have also received the highest overall score for appropriateness in the recently published booklet "Smart Disinfection Solutions" (NetherlandsWaterPartnership 2010). Although ceramic filters are a promising household water treatment and safe storage (HWTS) option, many challenges and critical research questions remain to be addressed.

A key challenge is maintaining ceramic filter manufacturing and quality control standards in decentralized production facilities. Experience from another locally-produced HWTS option, liquid sodium hypochlorite, has highlighted the importance of ongoing, stringent production and quality control standards to ensure that the sodium hypochlorite is appropriate for water treatment (POUZN 2007). Locally-manufactured ceramic filters are made by pressing a mixture of clay and a combustible material (burn-out) into the filter shape, allowing the filter to dry, firing the product to approximately 900℃ (1652℉), thus firing out the burn-out, and measuring the flow rate for quality control. In addition, silver is added as a bacteriocide. Although the manufacturing process is not complicated, there are a number of critical variables that need to be controlled to ensure the quality of the final product. Production practices vary between factories, and while some factories - such as Nicaragua, Cambodia and the Dominican Republic - have ongoing quality control and research associated with their products, many do not. As of 2007, PFP had started filter factories in 17 countries, with eight countries producing filters, and nine countries with discontinued projects (Lantagne 2006). In 2007-8, factories were built in another eight countries (PFP 2008). Currently, interest has been expressed in starting projects in 23 more locations.

Given the: 1) large demand for filter factories; 2) current lack of standardized production methods; and 3) loss of knowledge in the filter community caused by the recent passings of Ron Rivera and Mickey Sampson, it is imperative to summarize existing knowledge and quantify how production variables affect the efficacy of the filter in order to responsibly establish guidelines and scale-up filter production worldwide.

Thus, the goal of this working group panel of experts is to: "Provide guidance to assist filter factories in producing the lowest-cost, most-effective ceramic filters possible". The specific objectives are: 1) summarize the existing knowledge on ceramic filter production and effects of production variables; 2) identify lessons learned from existing filter factories; 3) make recommendations on how to produce the lowest-cost, most-effective filters; and 4) identify areas where future research is needed.

This report forms the deliverable from the working group and includes: 1) a literature review on ceramic filters (Chapter 2); 2) results from a survey of production processes at existing filter factories (Chapter 3); and 3) chapters on the filter production theory and recommendations, including materials sourcing and processing (Chapter 4), filter production (Chapter 5), kilns and firing (Chapter 6), silver (Chapter 7), quality control (Chapter 8) and packaging (Chapter 9). The conclusion (Chapter 10) includes lessons learned, recommendations for best practice and suggestions for future research. Cross-cutting themes considered throughout the report include: cost, health and safety, environmental impact, breakage, microbiological efficacy and end-user considerations.

The intentions of this report are to assist filter factories to produce high-quality ceramic filters and assist researchers in understanding what research is needed to understand and improve upon ceramic filtration production processes and technology. We encourage anyone considering carrying out research on ceramic filters to contact members of the working group and to post research proposals, summaries and reports on www.ceramicwaterfilter.org. If you have any questions, please contact the working group members listed in the acknowledgements section or refer to www.ceramicwaterfilter.org.

2 Literature Review

Before discussing the production variables associated with ceramic filtration and the work of the Ceramics Manufacturing Working Group, we would like to summarize the existing evidence-based research establishing that these ceramic water filters can be an effective and appropriate HWTS intervention in developing countries. The following sections on treatment efficacy, social acceptability and mechanisms for treatment were adapted from the literature review chapter of "Current Practices in Manufacturing of Ceramic Pot Filters for Water Treatment" (Rayner 2009).

2.1 Filter Efficacy

Diarrheal disease is caused by the ingestion of protozoan, bacterial or viral organisms. In the following sections, results from laboratory and field studies on the effectiveness of the filters at removing these organisms from drinking water, the association between diarrheal disease reduction and filter use and the filter life span are presented. Please note that throughout these sections, contaminant reduction will be reported as percent reduction or log reduction value (LRV), depending on how the data was reported by the researchers. A 0.5 LRV is equivalent to a 68% reduction, a 1-log reduction is equivalent to 90%, a 2-log 99%, a 3-log 99.9%, and so on (Table 1).

Table 1: Log Reduction Value

LRV	Reduction
0.5	68 %
1	90 %
2	99 %
3	99.9 %

2.1.1 Protozoa Removal Effectiveness

Filters have been found to be effective against protozoa, which is to be expected because of the large size of protozoan organisms and oocysts. Protozoa, such as *Giardia lamblia* and *Cryptosporidium parvum,* exist in the environment as cysts and oocysts respectively and are relatively large (>4 µm) in size. *Cryptosporidium parvum* is resistant to chlorination. A Nicaraguan filter challenged with *Cryptosporidium parvum* and *Giardia lamblia* spiked water achieved a 4-log reduction for both protozoa (Lantagne 2001a). Filters from Nicaragua, Ghana and Cambodia were tested over a 12 week period for sulfite reducing Clostridium spore (1 x 1.5 µm) removal, an indicator for protozoan oocysts and achieved 2-6 LRVs. The Nicaraguan filters performed slightly better than the Ghanaian and Cambodian filters and were found to be as effective without colloidal silver application as with (van Halem 2006).

2.1.2 Bacteria Removal Effectiveness

Results of field studies in several countries have found ceramic pot filters to be effective at improving the microbiological quality of drinking water. A study in three regions of Guatemala reported 91% of filtered water tested was free of fecal coliforms (AFA 1995). In Nicaragua, water quality analysis was performed on 24 filters in seven communities (Lantagne 2001b). Of 15 homes with *E. coli* in their source drinking water, eight (53%) tested negative for *E. coli* after filtration. In Cambodia, tests carried out after 1,000 ceramic filters were distributed showed that after up to one year in use, 99% of the filters produced water falling into a 'low-risk' range of fewer than 10 colony forming units (CFU) of *E. coli* per 100 mL (Roberts 2004). Source water quality did not seem to affect filter efficacy. Another field study in Cambodia, with 80 filter and 80 control households, found that filtered water samples from households with filters reduced *E. coli* by a mean of 98% and as much as 99.99%. Sixty-six percent of filtered water samples conformed to World Health Organization (WHO) low risk and of these, 40% conformed to WHO guidelines for safe drinking water. Whereas 62% of control households had *E.coli* levels that were high risk, 14% of households with filters were measured at high risk. Filters in this study had been in use for up to four years (Brown *et al.* 2007). In another field study in Cambodia (Brown *et al.* 2008), with 120 filter and 60 control households, found filters reduced *E. coli* by a mean of 96%, with 60% of filtered water samples meeting low risk ranges of fewer than 10 CFU of *E. coli* per 100 mL. In comparison, 85% of control households had greater than 101 CFU per 100mL in their drinking water, which is classified as high-risk. In Ghana, household surveys and water quality analyses were carried out in over 60 households in 2006 and 2007 (Johnson *et al.* 2008), over half of which were filter users. Filters in Ghana reduced *E. coli* by 99.7%. Average *E. coli* concentration was less than 10 CFU per 100 mL, falling within the 'low risk' range.

Several field studies found a higher concentration of *E. coli* in filtered water compared with unfiltered water. In Nicaragua, seven of 24 homes (29.2%) with filters had higher levels of total coliforms (TC) in filtered water than unfiltered water and some had higher levels of *E. coli* (Lantagne 2001b). In Cambodia, 5% of filtered water tested had greater *E. coli* concentrations in filtered water than stored water (Brown *et al.* 2008). In another study in Cambodia, 46 of 79 (58%) filters had a negative LRV (indicating an increase in contamination). Of the 58% with negative LRVs, 11% had negative LRVs confirmed on multiple visits (Brown *et al.* 2007). To explain these results, researchers have postulated that the receptacle and/or filter element became contaminated during cleaning. The evidence supporting this theory includes: 1) post-contamination of water at the household level is commonly documented (Wright *et al.* 2004); 2) in Cambodian households, the water quality of stored boiled water showed a similar decline in quality as filtered water; and 3) filter owners in Cambodia reported cleaning filter elements with potentially unclean cloths and the receptacle with untreated water (Brown *et al.* 2007). Limitations of this theory include that stored water: 1) might not be from the same source as filtered water; or 2) could have been stored under conditions which improved its microbiological characteristics (Brown *et al.* 2007).

2.1.3 Virus Removal

Virus removal remains a challenge for ceramic filters due to the small size of viruses and because silver has not been shown to inactivate viruses. In one study, water samples from filters with colloidal silver were less effective at removing the viral indicator MS2 bacteriophages (van Halem 2006); however, filters have not been found to be effective at removing MS2 bacteriophages in filters with or without colloidal silver (van Halem 2006).

The addition of Geothite may promote increased sorption and inactivation of viruses as an 8-log reduction in surrogate viruses was measured in batch adsorption tests of clay with Goethite fired into ceramic material (Brown and Sobsey 2009). Resource Development International – Cambodia (RDI-C) adds laterite, which is rich in goethite and other iron oxides, to their filter mixture (Hagan *et al.* 2009); however, although a 1-2 LRV (90-99%) in MS2 was measured, no significant difference was found between filters with or without laterite (Brown 2007). Likewise, in a recent study (Bloem *et al.* 2009), filters made with increased laterite (which also increased the flow rate) did not show improved viral removal efficiencies, with mean LRVs of less than 0.5 for filters tested. Filters with laterite were also heavier and more porous which might increase breakage and affect user acceptability (Bloem *et al.* 2009).

2.1.4 Diarrheal Disease Reduction

Field studies with households using locally made ceramic filters have found significant reduction in diarrheal disease. In Cambodia, users reported a 49% reduction in diarrhea in filter users versus non-filter users in one study (Brown *et al.* 2008) and a 46% reduction in another (Brown *et al.* 2007). In Guatemala, 50% fewer cases of diarrhea were reported in children under five years of age (AFA 1995) and in Ghana, filter users in traditional households were 70% less likely to have diarrhea (Johnson *et al.* 2008).

2.1.5 Filter Life Span

Implementing organizations typically recommend replacing filter elements every 1-2 years, although this has not been confirmed by research. A relationship between time in use and microbiological effectiveness was not established in Cambodia, suggesting that filters can remain effective for a minimum of 4 years and possibly longer (Brown *et al.* 2007). In another study in Cambodia, though fewer filters removed all *E. coli*, they still produced water of 'low risk' after nearly one year of use (Roberts 2004). Likewise, after five years of use, filters collected from households in Nicaragua and tested in a laboratory were successful at removing >99% of *E. coli* (Campbell 2005).

A recent study tested two filters which had been used in the field for approximately four years alongside four filters with limited laboratory use and found that although for the first batch of *E. coli* spiked water (10^6 CFU/mL) filters achieved a 3-4 LRV, the LRV decreased with each spiked batch for all filters (Bielefeldt *et al.* 2009). In addition, when filled with clean water after three batches of spiked water was put through the filter, bacteria not only re-suspended in the filtering element, but also passed through the filter into the effluent water. This suggests that in addition to re-contamination of filtered water from user maintenance, a higher bacteria count in effluent water than influent water could result from high loading of bacteria in previously filtered water. More investigation is required to determine if this would occur in field conditions. A re-application of colloidal silver improved the filter efficacy; however, removal of *E. coli* by the four-year-old field filters was not sustained, indicating that the colloidal silver did not adhere well to the ceramic after years of use.

2.1.6 Arsenic

Consumption of water containing over 10 ppb for five to twenty years may cause arsenicosis. Although arsenic has been detected in filtered water (van Halem 2006), it has been found to leach out relatively quickly and has not been found to leach from filters in concentrations that exceed the WHO guideline values of 10 ppb, indicating the leaching does not pose a health risk to filter users (Tun 2009).

2.1.7 Summary

Ceramic filters have shown to be effective in both field and laboratory settings at improving water quality. Although filtered water in the field does not always meet WHO drinking water quality guidelines of 0 *E. coli* per 100 mL sample, water quality is significantly improved, often to low risk levels. Ceramic filters have been shown to be reliably effective at removing more than 99% of protozoan and 90-100% of bacterial organisms from drinking water in households, but further research is needed to establish their effectiveness against viruses.

Re-contamination of filtered water during maintenance, including cleaning the filter element and receptacle with untreated water, multi-use cloths and dispensing treated water through a contaminated tap has been reported and is a possible explanation for why, in some cases, filtered water has higher bacteria concentrations than source water. PFP style filters have been associated with a reduction in diarrheal disease in users and filters appear to work well after several years in use; however, there might be a decline in effectiveness with time.

2.2 Social Acceptability

Regardless of any technology's ability to improve water quality, in order to achieve the goal of health improvement, it must be accepted and used. Although there are many factors which can contribute to the acceptance or abandonment of any intervention, with the ceramic filters, breakage and low flow rates are frequently reported reasons associated with disuse. In Nicaragua, the flow rate of filters in 14 of the 24 households was inadequate to provide sufficient drinking water for the family (Lantagne 2001b). The recommendation was made to scrub the filters to regenerate the flow rate (Lantagne 2001b), which has since been incorporated into general operation and maintenance (O&M) instructions. In a Cambodian field study where filters were distributed for free, 20% of households surveyed were no longer using their filter one-year post implementation. Of 35 households that reported not using their filter anymore, 71% was because the tap broke and 20% was because the filter element broke (Roberts 2004). Since replacements were not available, disuse was caused by breakage. Other reasons for discontinued use that have been reported included: preferring boiled water, too busy or unwilling to clean the filter, belief that their water does not need to be treated, or that the filter did not treat enough water (Roberts 2004). Interestingly, more than one-third of the households reported having enough water for additional uses besides drinking, despite the filter treating fewer than 10 liters of water per day.

Similarly, another Cambodian field study (Brown and Sobsey 2006) documented a 2% per month disuse rate. Sixty-five percent of disuse was due to breakage of the element, receptacle or tap. An additional 5% stopped using the filter because the filtration rate was too slow and did not meet the family's drinking water needs. Five percent stopped using the filter because it had exceeded its 1-year recommended useful life. Continued use was associated with time since implementation, with fewer filters being used with time. Continued use was associated with user financial investment in the filter, water source (whereas people using surface water were more likely to continue using the filter, people using ground water from deep wells were less likely to continue using the filters), access to sanitation and greater awareness of hygiene and sanitation practices (Brown and Sobsey 2006).

High user compliance is suggested by a field study in Cambodia where 100% of the respondents reported they used filtered water for all of their drinking water needs (Brown *et al.* 2008). In another field study in Cambodia, 95% of users reported satisfaction with the filters, that filtered water tasted good, the filter was easy to maintain, it was important to the family because of health benefits and it eliminated the need to boil water (Roberts 2004). In Ghana (Johnson *et al.* 2008), users reported that filters worked well, were easy to use and they would recommend them to others. In addition, non-users were interested in using filters. Follow-up with 1,000 households that received filters post-flooding in Ghana, 6-12 months after distribution, found 63% of the filters were still in use. Of the 13% who stopped using the filter due to breakage, 95% was due to breakage of the ceramic filtering element and 5% due to breakage of the safe storage container or a leaking tap. Twenty-four percent stopped using the filter because their access to rainwater or an improved water source resumed post-emergency (Desmyter *et al.* 2009).

2.2.1 Summary

Overall, it is clear there is high user acceptability of the filter and potential for long-term use, although breakage over time and the inability to filter sufficient water remain concerns with PFP-style ceramic filters.

2.3 Mechanisms of Effectiveness

Mechanisms that could account for the efficacy of the filter are discussed in the following sections: 1) bacterial deactivation by silver; and 2) pore size exclusion. Lastly, hydraulic properties and flow rate, the indicator that is measured locally, are discussed.

2.3.1 Silver

Filter elements are either painted with or dipped in a colloidal silver solution or colloidal silver is integrated into the filter mixture prior to pressing and firing the filters. Some factories paint a silver nitrate solution on the filters instead of colloidal silver.

Investigations into the effectiveness of different colloidal silver application methods have found that colloidal silver should be applied to both the inside and outside of the filter for increased microbiological reduction (Lantagne 2001a). Although it has been recommended that filters be dipped rather than painted with colloidal silver to ensure the full path of water flow through the filter is coated (Fahlin 2003), it has since been concluded that the quantity of colloidal silver applied is more important than the application method (Oyanedel-Craver and Smith 2008). It is unknown how deeply silver penetrates into the filter walls; however, a recent study found that after dipping, some silver segregates to the surface of the ceramic during drying (Larimer *et al.* 2010). It has been theorized that silver could reduce total pore area and adsorptive surface area (van Halem 2006), but tracer experiments post-colloidal silver application did not suggest this (Oyanedel-Craver and Smith 2008).

The amount of silver in filtered water has been measured and is below USEPA and WHO guideline values for silver (0.1mg/L), and therefore does not pose a risk to human health (Lantagne 2001b; Lantagne 2001a). In agreement with this, other studies have found that the amount of silver in the effluent water does not exceed WHO guidelines (Oyanedel-Craver and Smith 2008) and that silver contributes to the microbiological removal effectiveness (van Halem 2006; Oyanedel-Craver and Smith 2008). In addition, it has been observed that the silver inhibits biological growth from forming on the filters and in the receptacles (Oyanedel-Craver and Smith 2008; Bloem *et al.* 2009). It has been concluded that the mechanism by which silver improves filter performance is by disinfection (Oyanedel-Craver and Smith 2008). Filters produced with colloidal silver fired into the filters have also been found to be effective at removing *E. coli* and TC (Lantagne *et al.* 2009).

Some factories use silver nitrate because it is less expensive than colloidal silver. Microbiological efficacy of filters in the field with silver nitrate painted on were found to be comparable to filters with no silver applied (Brown 2007), although filters manufactured to have a high flow rate found that microbiological efficacy improved with silver nitrate application (Bloem *et al.* 2009). For more information on silver, please see Section 7.

2.3.2 Pore-size

The pores in the filter act as a physical barrier to pathogens, other organic material and turbidity in the influent water. During firing, the burn-out material added to the filter mixture fires out creating porosity in the filter. Pore size is assumed to be determined by the size and amount of burn-out material added to the filter mixture (Lantagne 2001a) but has also been linked to the clay content(Oyanedel-Craver and Smith 2008).

Pore sizes were measured in the lip of a filter from Nicaragua, where sawdust is used as a burn-out, with a Scanning Electron Microscope (SEM) were found to range from 0.6 microns to approximately three microns (Lantagne 2001a). There were also cracks and spaces measuring up to 150 microns and 500 microns respectively, which could be of concern if interconnected; however, this would also likely increase the flow rate beyond the acceptable limit. The pores were measured on the lip of the filter as it was assumed the worst-case scenario since in theory it receives the least amount of pressure during the pressing of the filters. A later study, using mercury intrusion porosimetry test, found that the pore size distribution and porosity did not vary significantly from the bottom, middle and lip sections of the filter (van Halem 2006). The total pore area, which might contribute to increased adsorptive capabilities, has been found to vary widely within a given filter (van Halem 2006).

Filters with an average pore size diameter calculated at 40 microns were successful at removing micro-organisms smaller than the pores, therefore, it was suggested that filters work by additional mechanisms to mechanical screening including sedimentation, diffusion, inertia, turbulence and adsorption (van Halem 2006). In addition, high tortuosity, which influences the distance water must travel to exit the filter walls, increases total surface area and can also encourage these processes (van Halem 2006). Although these additional mechanisms aid the effectiveness of filters at removing microbiological contamination, a correlation between pore size and bacteria removal has been found, therefore mechanical screening by size exclusion is significant. Filters with smaller pores have a higher removal rate of bacteria (Oyanedel-Craver and Smith 2008).

A correlation has been found between clay (particle size <2 μm) content, pore size and flow rate. Porosity, the volume of void space in the filter, was found to be the same when comparing model filters made from different clays, yet the median pore diameter correlated with the clay content and it was found that samples with “relatively uniform and fine-grained particle-size distributions will likely produce filters with better bacteria-removal efficiency, smaller pores, and lower dispersion than comparatively coarse-grained, heterogeneous soils” (Oyanedel-Craver and Smith 2008: 931). The predominant mineral in the clay might also influence both the hydraulic conductivity, the rate water moves through the filter and the porosity as the filter model which measured highest in these aspects also had a high kaolinite (a clay mineral) content in the clay (Oyanedel-Craver and Smith 2008).

Filters manufactured in different countries have been found to vary both in porosity and pore size. Mercury intrusion porosimetry measurements of filters from Cambodia showed a porosity of 43%, Ghana 39% and Nicaragua 37% (van Halem 2006). Pore sizes were measured at: Cambodia 25 microns, Ghana 22 microns, Nicaragua 17 microns (van Halem 2006). The application of silver also affected the pores by reducing the effective pore size (van Halem 2006). Upon comparing the tortuosity (based on the mercury intrusion porosimetry and the Kozeny constant) of filters from Cambodia, Ghana and Nicaragua it was found that the filter material from Nicaragua is more tortuous (van Halem 2006). Since tortuosity reflects the actual path the water takes through the filter, it can influence the various mechanisms at work including screening, sedimentation and adsorption. This was supported by evidence of higher removal of Clostridium spores and *E. coli* by the Nicaraguan filters (van Halem 2006). The manufacturing details for the filters used in this study were not available so it is not possible to compare the results with manufacturing methods.

2.3.3 Hydraulic Properties and Flow Rate

The amount of time it takes for water to pass through the walls of the filter will affect the filtration mechanisms and the amount of contact time with colloidal silver. Investigations into the hydraulic properties of the filters have been inconclusive (Fahlin 2003). However, using a bromide tracer breakthrough test, it was estimated that water remains in the pores of filters for 50 minutes, which, depending on the thickness of the silver layer, should provide sufficient contact time with silver to deactivate bacteria (Fahlin 2003). Whereas Fahlin (2003) described the flow through flower pot shaped filters, Miller (2010) modeled and verified flow through a parabolic-shaped (oblong) filter. Hydraulic conductivity was determined to be consistent throughout the height of the parabolic filter.

The flow rate of a filter, measured locally, is used as an indicator for: 1) cracks, holes, large pores; and 2) potential contact time with silver. It is also an important practical consideration, as filters need to treat enough water daily for a family at a rate that is convenient for an appropriate pattern of use. Considerable reduction in flow rates due to clogging have been noted in laboratory (Lantagne 2001a; Fahlin 2003; van Halem 2006) and field studies (Lantagne 2001b). Although scrubbing has been shown to temporarily increase the flow rate (Lantagne 2001b), in the laboratory, filters did not achieve their original flow rate after scrubbing and flow rates continually decreased over time to less than 0.5 L/hr, which is insufficient to meet a family's drinking water needs (van Halem 2006). Fahlin (2003) found that clogging impeded his research into the hydraulic conductivity of filters. However, in some field investigations users have reported that filters provided enough water for additional uses (Roberts 2004) and, in Cambodia, only 5% of filter disuse was attributed to reduced flow rate (Brown and Sobsey 2006).

In a study to see if flow rate could be increased without sacrificing the microbiological removal efficacy of filters, filters were made with either increased burn-out (rice husk) or increased laterite. Filters with flow rates of 8-10 L/hr were manufactured (Bloem et al. 2009). During the six-month study period, no significant difference was measured in *E. coli* removal between the filters with higher flow rates and lower flow rates. Filters with and without silver nitrate impregnation did differ significantly in their ability to remove *E. coli,* however. Filters with silver had nearly twice the mean LRV of *E. coli.* This study concluded that although future research is necessary to investigate the long-term effects, initially it appears that increasing the flow rate does not affect the microbiological efficacy of the filters.

In contrast, another study where 6 liter capacity, oblong filters were manufactured with increased flow rates by 1) increasing burn-out material and 2) altering the type of burn-out, found that beyond a flow rate of approximately 1.7 l/hr, consistent TC reduction began to drop below 99% (Klarman 2009). These filters were made at a factory that aims to leave a carbon residual within the walls of the filter, which differs from the filters used in other studies. This could have influenced the results as it appeared to affect both the flow rates and the turbidity of the effluent water, the latter was considerably higher during week one. The flow rates of several of the filters in this study actually doubled during the five week testing period (Klarman 2009).

At the RDI-C factory filter mixture ratios are adjusted to achieve acceptable flow rate ranges according to the size of the rice husks received, adding more rice husk if it is observed to be smaller (Hagan *et al.* 2009), indicating a relationship between burn-out particle size and flow rate. In a study where filters were manufactured using a larger sized mesh to sieve the sawdust, no significant difference in flow rates were measured (Klarman 2009). In addition, using different burn-out materials, even when sifted to the same size screen, can increase the flow rate but this also reduced TC removal efficiency. These findings emphasize the need to develop a new ratio when changing the burn-out type (Klarman 2009).

2.4 Summary

There are contradictory findings and continuing debate regarding the relative importance of the various mechanisms of action for the effectiveness of the filter. Colloidal silver has been found to reliably increase the effectiveness of the filter, while silver nitrate results have not been consistent. Little is known about the hydraulic properties of the filter and pore size investigations have documented significant variation by country of manufacture. Flow rate is presently relied upon as an indicator of filter quality as it is easy and inexpensive to measure locally. Studies on the association between flow rate and microbiological removal efficiency have had contradictory findings (Bloem *et al.* 2009; Klarman 2009). Therefore, more research is recommended to better understand the mechanisms of effectiveness and characterize the reasons for variation across country manufacturers.

3 Overview of Filter Production

3.1 Variables in Filter Production

The following sections are summarized from the report “Current Practices in Manufacturing of Ceramic Pot Filters for Water Treatment” (Rayner 2009), a research project carried out to identify the various filter factories worldwide and survey and document existing production practices at each facility.

To complete this research, a ‘mind-map’ (Figure 3-1) was developed which outlines the variables in ceramic water filter production, including known variations in the manufacturing process evident from the comparison of several filter production manuals. A survey was then developed based on the mind-map and implemented with production facilities worldwide.

3.2 Survey Development and Limitations

The survey consisted of quantitative and qualitative questions formulated to address each of the variables identified in the mind-map (Figure 3-1). Quantitative questions addressed typical manufacturing procedures and qualitative questions on each phase of production encouraged participants to discuss challenges and successes and comment on aspects of production not included in the questionnaire.

Contact information was gathered from representatives of PFP, Potters without Borders, FilterPure and members of the Ceramics Manufacturing Working Group. The selection criterion for survey participation was that factories must be currently producing filters on a full-time, part-time or per-order basis. All filter factories meeting the criterion were sent an invitation by e-mail (in English and Spanish) and those who expressed interest were e-mailed the questionnaire with a request to schedule an interview. Participants completed a questionnaire, a phone interview or both.

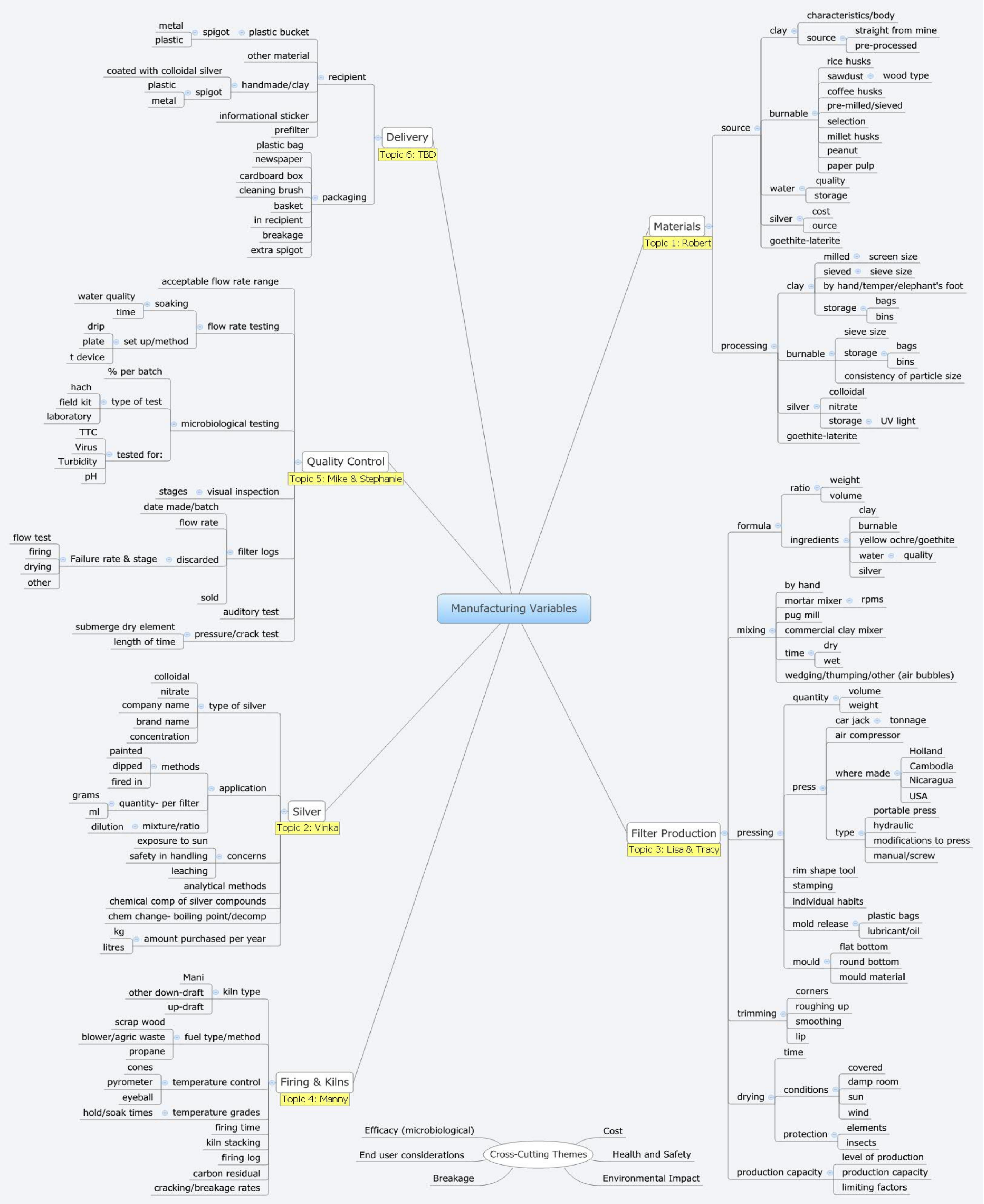


Figure 3-1: Production Variables

Before presenting the results, we would like to note that the limitations of the survey methodology included: 1) self-selection bias which may have influenced who responded to the invitation; 2) "social desirability" responding, whereby answers may have been biased to show the respondent in a desirable light (Sapsford and Jupp 1996); 3) interviewer bias is also a risk as when interviews were conducted, prompting could have introduced bias (Sapsford and Jupp 1996); 4) the questionnaire was 10 pages, which might have discouraged detailed responses; and 5) roles of participants, including level of involvement and knowledge about production, may have varied.

3.3 Results

Of 35 operational filter factories that were identified in 18 countries, 34 (97%) agreed to participate and 25 (74%) actually participated in the survey (Figure 3-2). Eight of the factories included in the 25 respondents are de-centralized Thirst-Aid Myanmar factories. The information from these factories was summarized into one data point, except for where their practices varied. In the following sections (n=) refers to the number of respondents who answered a particular question (maximum 18 respondents) when the Myanmar factories are summarized. However, when underlined (<u>n=</u>) it indicates that the Myanmar factories are counted as individual factories (maximum 25 respondents).

Figure 3-2: Filter Factory Locations

Of the 18 respondents, six (33%) completed the survey and returned it via e-mail, eight (44%) were filled out during a telephone interview and four (22%) both participated in an interview and completed the questionnaire. Filter factories are referred to according to the codes presented in Table 2, which also presents the organization that provided technical support at start-up, level of production and year filter factory was established.

Table 2: Participating Factories

Code	Country	Organization	Year Started	Production
Benin	Benin	Potters without Borders	2007	Part Time
Cam-1	Cambodia-IDE	Potters for Peace	2001	Full Time
Cam-2	Cambodia-RDI	RDI-C	2003	Full Time

Colombia	Colombia	Potters for Peace	2007	Full Time
DR	Dominican Republic	Filter Pure	2006	Part Time
Guate-1	Guatemala- Antigua	AFA Guatemala	2004	Full Time
Guate-2	Guatemala- San Mateo	Potters for Peace	2005	Part Time
Indo-1	Indonesia- Bali	Potters for Peace	2007	On Order
Indo-2	Indonesia- Bandung	RDIC & Potters for Peace	2005	Full Time
MM-1	Myanmar- Twante	Thirst-Aid	2008	Full Time
MM-2	Myanmar- Twante	Thirst-Aid	2007	Full Time
MM-3	Myanmar- Twante	Thirst-Aid	2009	Full Time
MM-4	Myanmar- Twante	Thirst-Aid	2009	Full Time
MM-5	Myanmar-Yangon	Thirst-Aid	2008	Full Time
MM-6	Myanmar- Pathein	Thirst-Aid	2008	Full Time
MM-7	Myanmar- Yangon	Thirst-Aid	2006	Full Time
MM-8	Myanmar- Sagaing	Thirst-Aid	2009	Part Time
Nica-1	Nicaragua- San Marcos	Potters for Peace	1998	Full Time
Nica-2	Nicaragua- Ciudad Sandino	Potters for Peace	unknown	Part Time
Nigeria	Nigeria	Potters for Peace	2008	Full Time
SL-1	Sri Lanka- Kelanya	Potters for Peace	2007	Full Time
SL-2	Sri Lanka- Matara	American Red Cross	2008	Full Time
Tanz-1	Tanzania- Arusha	Filter Pure	2009	Full Time
Tanz-2	Tanzania- Tabora	Potters for Peace	2007	On Order
Yemen	Yemen	Potters without Borders	2008	Full Time

Participating factories have been producing filters since 1998, 16 of which (n=24, 67%) have been established since 2007. Monthly production (Figure 3-3) ranges from 45 filters to 4480 filters per month, averaging 1500 filters per month (n=25). Nine factories (36%) produce fewer than 500 filters per month, six factories (24%) produce 500-2,000 filters per month and 10 factories (40%) produce more than 2,000 filters per month. Total production for all participating filter factories is over 37,700 filters per month.

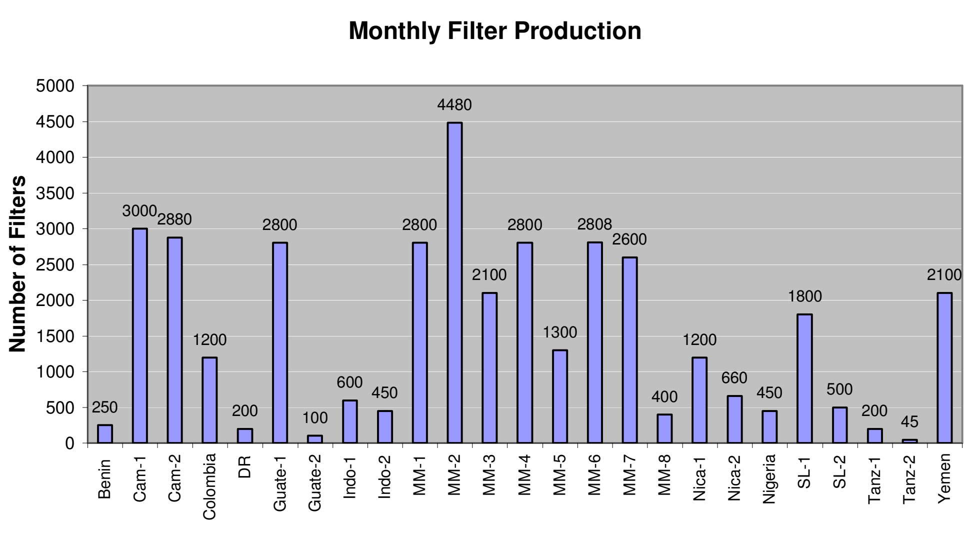


Figure 3-3: Monthly Filter Production

The average wholesale price of a complete filter unit is U$15.71 and ranges from U$7.50-35.00 (n=24). Average retail price is $16.68 (n=23), ranging from U$8.00-35.00. The replacement cost for just the ceramic filter element averages U$7.78 wholesale and ranges from U$3.00-25.00; retail, they average U$8.60 and range from U$4.00-25.00 (Figure 3-4).

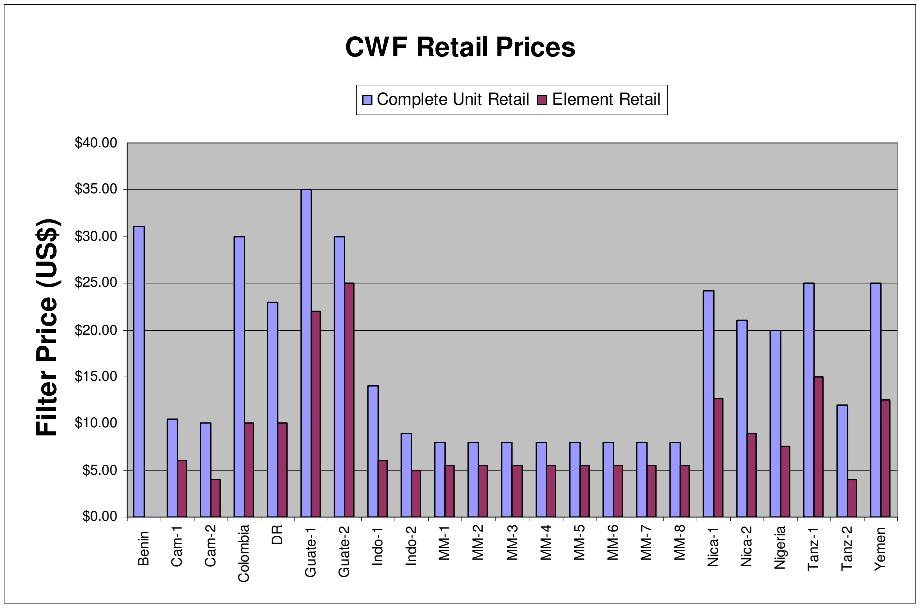


Figure 3-4: CWF Retail Prices

Fifteen factories (n=24, 62%) sell more than 50% of their filters to NGOs or international non-governmental organizations (INGOs). Six factories (25%) sell 50-100% of their filters to the public. Cam-

2 sells about 50% to the public and 50% to NGOs. One factory (MM-8) sells 90% of their filters to the government. Filters manufactured at SL-2 are sold exclusively to the Sri Lankan Red Cross.

3.3.1 Factory Set-Up

Eight factories (n=24, 33%) receive 100% of their electrical supply from the grid. Six factories (25%) rely upon a generator (Cam-2, MM-1, MM-2, MM-3, MM-4 and MM-6) and seven (30%) rely upon both the grid and a generator for their power supply. Three (13%) do not use electricity in production (Indo-2, Guate-1 and Yemen). Nine factories do not have electric mixers (n=25), two do not have hammer mills and few have air compressors.

3.3.2 Source Water

Source water is used in filter production and for flow rate testing. Factories (n=18) rely upon 24-hr piped municipal supply (8, 44%), intermittent supply (1, 6%), water being trucked in (2, 12%), alternative sources including ground or rainwater (3, 17%) or a combination of sources (4, 22%). Fourteen factories (n=18, 78%) consider their water supply reliable. Eight (n=18, 44%) have not tested their source water.

3.4 Materials

3.4.1 Clay

Clay plays an important role in filter quality. A correlation has been found between clay content, flow rate and pore size (Oyanedel-Craver and Smith 2008). Although at least five factories (n=17, 30%) mentioned having identified reliable clay sources, both the Yemen and Colombia factories mentioned the challenges and effects of inconsistent clay quality on filter production. Clay sources (n=17) are those typically used by local potters (6, 35%) and are selected based on quality (6, 35%), plasticity (5, 30%), proximity of the mine (4, 24%) and color (1, 6%).

Seventeen (94%) factories (n=18) receive their clay directly from the mine and process it themselves, while Cam-2 receives their clay pre-formed into bricks. Two factories (Benin and SL-2, 11%) prepare a clay body by blending three clays. Clay is milled and sieved to remove impurities, such as sand or organic material. Sixteen factories mill their clay (n=17, 94%) and 15 factories (n=18, 83%) sieve their clay using between 9 and 80 mesh (equivalent to 2 mm-0.18 mm openings, see B-1 Tyler Mesh Equivalent chart, Annex F) (Figure 3-5). Sieve sizes might depend upon availability of sieves in each country.

3.4.2 Burn-out Material

Factories reported using sawdust, rice husks and peanut shells as burn-out material. Ten factories use sawdust (n=18, 56%) from woods including pine, guanacaste, gravella, oak, a mixture, or depending on availability. Of the remaining factories, seven (39%) use rice husks and one (6%) uses a combination of sawdust and peanut shells as the burn-out. MM-all reported that variation in rice husk quality affects the outcome of the filters and the DR factory reported that oak sawdust leaves an oily residue on fired filters and results in a reduced flow rate.

Although 15 (n=17, 88%) factories sieve their burn-out material, only 12 (80%) indicated the mesh size (Figure 3-6). Although the 60 and 80 mesh (0.25 and 0.18 mm openings respectively) sizes reported by two participants could be mistakes, even if eliminated from the results, the remaining mesh ranges between 8-48 mesh (2.38 mm to 0.30 mm openings). At Indo-2, burn-out is sieved with two screens to separate out both the finer and larger particles. At RDI-C (Cam-2), the amount of burn-out added to the mixture is varied depending on the size of the rice husk to achieve the desired flow rate (Hagan *et al.* 2009). However, in an attempt to make faster flowing filters, sawdust screened to a larger particle size showed no significant difference in flow rate (Klarman 2009).

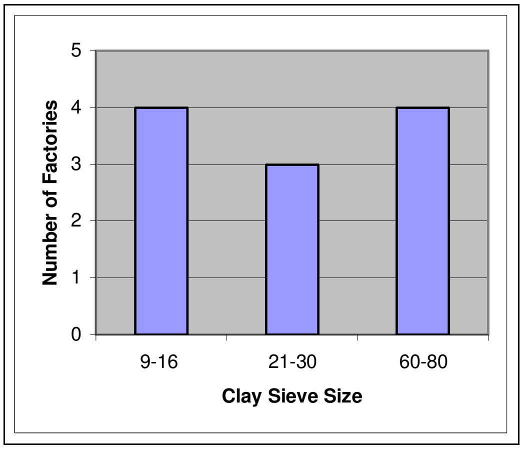


Figure 3-5: Clay Sieve Sizes

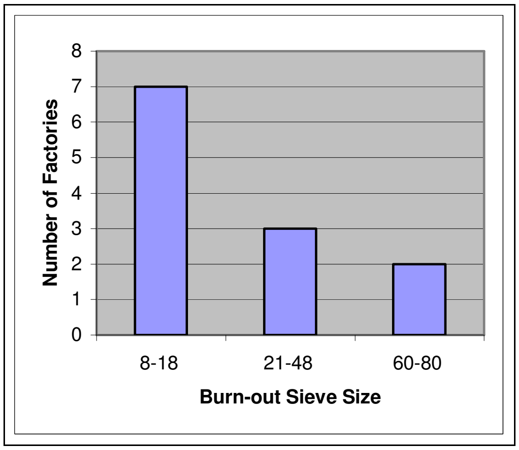


Figure 3-6: Burn-out Sieve Sizes

3.5 Additional Materials

Two factories, DR and Tanz-1 (n=18, 11%), add colloidal silver diluted in water to their dry filter mix. Cam-2 adds laterite, a mineral thought to provide additional viral binding sites. Others regularly include grog (ground up, fired clay) (Indo-2), or sand (Guate-1). Guate-2 sometimes adds grog from bricks which did not fire well, though they did not indicate why or when. SL-2 found that the addition of grog reduced shrinkage to the point the filter elements would not fit in the receptacles.

3.6 Ratio and Mixing

Mix ratios are measured by either weight or volume. Where rice husks are used (n=7), formula is measured by weight (n=6, 100%) and the percentage of rice husks added to the mixture ranges from 10 to 24% (Figure 3-7).

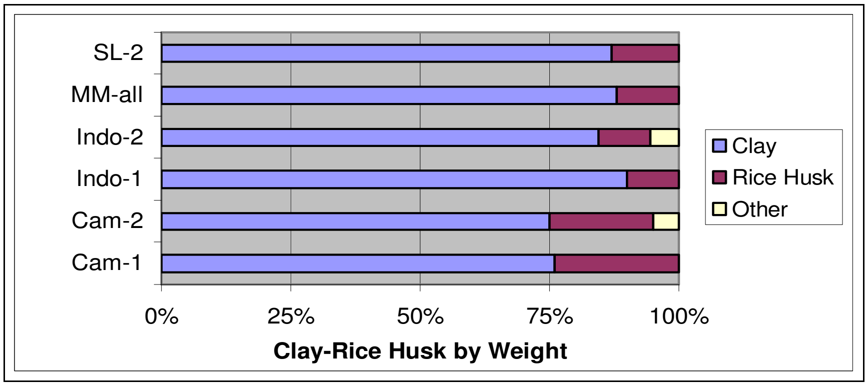


Figure 3-7: Clay-Rice Husk Ratio

Where sawdust is used (n=10), 60% of the factories measure by weight, and 40% by volume. Percentage of sawdust ranges from 5-25% by weight (Figure 3-8) or 47-50% by volume. Where both sawdust and peanut shells are used (n=1), ingredients were reported to be measured by both weight and volume, and the burn-out consists of 35% of the mixture.

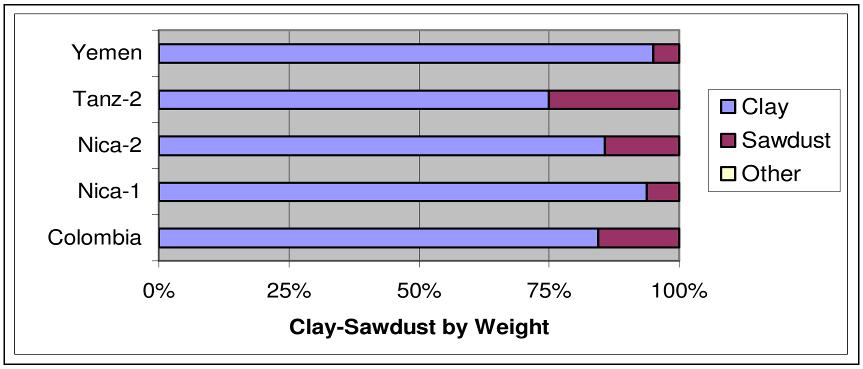


Figure 3-8: Clay-Sawdust Ratio

Once a filter mixture formula has been established, the rigidity to which the formula is adhered to often varies. Three factories (n=16, 19%) do not adjust their formula, however 6% (1) adjust it regularly and 75% (12) as needed. Five (31%) of the factories surveyed modify their formula depending on the quality of the clay. Other reasons included particle size of burn-out, weather conditions, flow rate and variation in burn-out characteristics.

Mixing times of the clay and burn-out vary between five and 20 minutes for dry mixing, with the exceptions of Indo-2, where dry ingredients are hand mixed for 60 minutes in order to achieve specified flow rates, and in Nigeria where the mixing process takes half a day. Wet mixing time ranges between 5 and 30 minutes. At Nica-2, because of the type of mixer, dry ingredients are not mixed in advance of adding water; all materials are mixed together for 45 minutes.

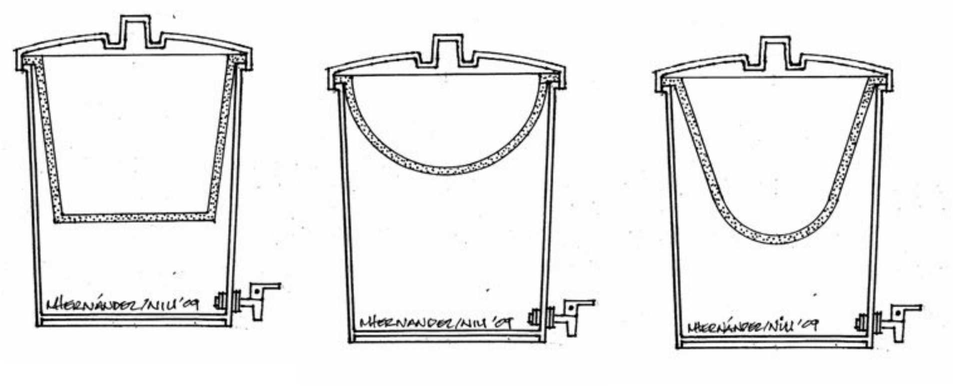
Fifteen factories (n=18, 83%) wedge, knead or thrust the mixture before pressing. Nine factories (n=15, 60%) always press filters the same day the mix is made and six factories (40%) sometimes or normally leave the mixture overnight. Ten factories (n=15, 67%) do not reprocess dried mixture, whereas five factories do (33%), two of which add silver to their filter mixture.

3.7 Forming Filter Elements

3.7.1 Presses and Molds

All factories press their filters using a mechanised press and a mold, although in Rabinal, Guatemala, filters are still made on the potter's wheel and sold through Guate-1. Press designs currently used vary between factories (Figure 5-4, Figure 5-5, Figure 5-6 and Figure 5-7).

Molds (n=25) are made out of aluminum, cast iron, cement, steel or carved from teak wood and vary in size and design. There are three filter shapes including the original flat-bottomed design, which is being produced at 15 factories (60%), eight (32%) Myanmar factories make a slightly parabolic semi-spherical filter and two (8%) FilterPure factories make an oblong, round-bottomed filter (Figure 3-9). Filter capacity ranges from 6-11 L with depths ranging from 22.5 to 29 cm. Wall thickness ranges from one to three centimeters. Filter dimensions are presented in Annex B.



Potters for Peace (7-11 liters)

Thirst-Aid (10 liters)

FilterPure (6 liters)

Figure 3-9: Illustrations of Filter Shapes

(Hernandez 2009)

All filter factories (n=17, 100%) expressed satisfaction with the method of releasing the pressed filter from the mold. Thirteen factories (n=18, 72%) use plastic bags, the Myanmar factories brush vegetable oil on plastic bags and four factories (23%) use either coconut or palm oil.

3.8 Stamping, Surface Finishing and Drying

All factories (n=18, 100%) stamp their filters with a lot number and eight (n=16, 50%) also stamp them with a logo. All but SL-1 and Tanz-2 (n=18, 89%) touch up or trim filters after pressing. However, six (SL-2, Benin, Yemen, MM-all, Guate-2 and Tanz-1) only touch up the lip of the filters and do not touch the inside or outside of the filter.

Drying time (n=18) varies depending on the weather and is a challenge for at least eight factories (44%). Some factories have modified their production pattern or increased shelving to allow for longer storage during the wet season, others have introduced quick drying methods. Drying times (n=24) average seven days in the dry season (min 3, max 21) and 13 in the wet season (min. 4, max. 45) (Figure 3-10).

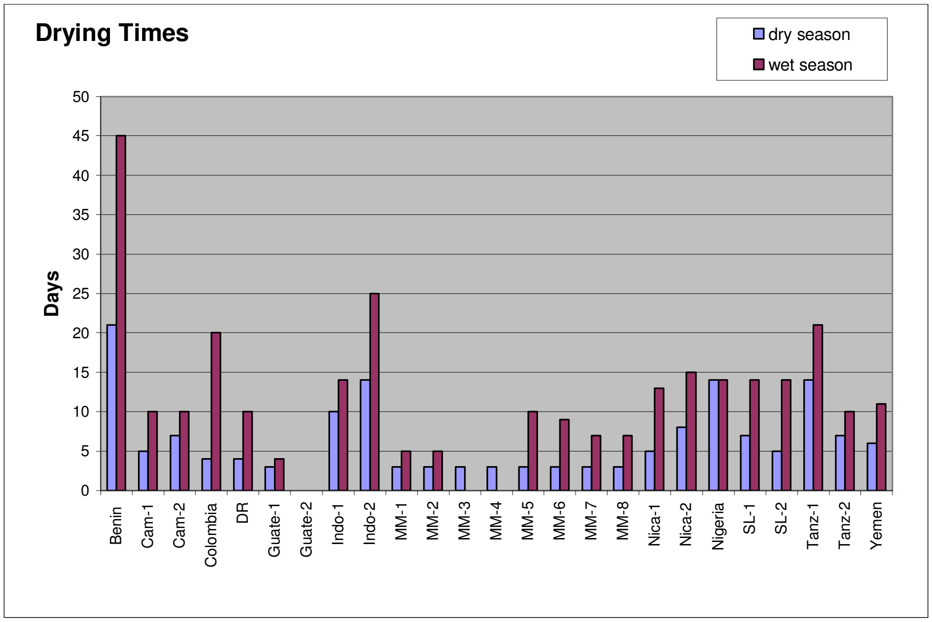


Figure 3-10: Drying Times

3.9 Firing

Five factories (28%) mentioned that production is limited by the number of kilns and the time it takes to fire and cool the kilns. Firing time ranges from 6-14 hours and cooling takes 12-24 hours. Factories (n=18) have between one and seven kilns with internal filter capacity ranging from 40 to 200 filters. Nine factories (53%) have Mani Flat Top or Mani Arch kilns (n=17), (see section 6.2 for description of kiln types). Fifteen factories (83%) fire with wood (n=18), Tanz-1 fires to 600°C with wood, then propane for the last two hours, the Yemen factory fires with propane and the Benin factory fires with oil.

Target temperature ranges from 700°C to 980°C. All factories (n=18, 100%) use either a pyrometer (9, 50%) or cones (5, 28%) to monitor temperature and four factories (22%) use both. Although six factories (33%) report estimating temperature visually they all use at least one other method (Annex B). Of the nine factories that use cones (n=9), only one (Nica-1) factory uses the three cone method (section 6.6.2). Some factories reported difficulty acquiring pyrometers or cones in country (Indo-2, SL-2).

3.10 Silver

3.10.1 Silver Type

Fifteen factories use colloidal silver (n=18, 83%), and three use silver nitrate (17%). MM-all use either colloidal silver or silver nitrate as they have recently started using silver nitrate. Tanz-2 does not use either, but rather sodium silver chloride tablets. Colloidal silver (n=15) is purchased in liquid (7, 47%) or powdered (10, 67%) form, Guate-2 and Benin use either. Silver nitrate comes in powdered form (n=3, 100%). None of the factories make their own colloidal silver.

Silver is diluted using (n=15) water purified by reverse osmosis (1, 7%), groundwater (3, 20%), filtered groundwater (1, 7%), municipal water (3, 20%), municipal water without chlorine (1, 7%), de-ionized water (2, 13%), distilled water (1, 7%) potable water (2, 13%) or untreated surface water (1, 7%). The factories that use silver nitrate, included in the above counts, use water purified by reverse osmosis (MM-all) and de-ionized water (Indo-2, Cam-2).

3.10.2 Silver Application Methods and Concentrations

A silver solution is applied (n=18) by dipping (6, 33%), painting (10, 56%) or it is fired into the filters (2, 11%). Cam-1 does not paint the rim of the filters with silver. The quantity of silver applied has been found to be more important than the application method (Oyanedel-Craver and Smith 2008). Dilution information was provided by nine of the 15 factories that use colloidal silver (n=15, 60%). The silver concentration ranges from 14-1500 ppm. Should the two extremes be excluded as possible errors, silver concentrations still range from 107 to 288 ppm. Table 3 details the dilution and concentration of *colloidal* silver when applied by brushing and

Table 4, when applied by dipping.

Table 3: Colloidal Silver Applied by Brushing

Colloidal Silver Applied by Brushing									
Country	Silver from:	Company	Form	Concentration (%)	PPM	Silver Solution (ml)	Water (ml)	Diluted Solution (PPM)	Silver in Filter (mg)
Cam-1	Spain	Argenol	Liquid	3.2	32000	1	300	107	32
SL-1	Spain	Argenol	Liquid	3.2	32000	2	300	213	64
SL-2	Spain	Argenol	Liquid	3.2	32000	2	300	213	64
Nica-1	Spain	Argenol	Powder	3.2*	32000	2	300	213	64*
MM-all	Germany	Reickerman-Spraylat	Liquid	3.2	32000	3	333	288	96

*Reports using powdered silver, Argenol Labs only sells powdered silver to the filter factories of concentrations between 70-75%; therefore, it is likely Nica-1 prepares a silver concentrate, which is further diluted according to the above specifications.

Table 4: Colloidal Silver Applied by Dipping

Colloidal Silver Applied by Dipping								
Country	Silver from:	Company	Form	Concen-tration (%)	PPM	Silver (grams)	water (ml)	Silver solution (PPM)
Benin	Spain	Argenol	Liquid/Powder	4	40000	14	40000	14*
Colombia	Spain	Argenol	Powder	75	750000	70	250000	210
Indo-1	Spain	Argenol	Powder	75	750000	20	1000**	1500
Yemen	Spain	Argenol	Powder	75	750000	14	40000	263
* If silver is purchased from Argenol Labs in powder form as reported, then it is between 70-75%. Using 75% silver would result in the diluted solution being 263 ppm. If these figures are for the 3.2% solution from Argenol Labs, then the ppm of the diluted solution is 11.								
** This might be a typographical error. Confirmation was not possible.								

Tanz-1 and DR fire a confidential amount of colloidal silver into their filters and paint colloidal silver onto fired filters. Tanz-2 dips filters in a solution made from dissolving five tablets of Katadyn Micropur Forte, a sodium silver chloride complex with 0.1% silver ions and 2.5% sodium dichloroisocyanurante in seven liters of water. The Myanmar factories, Indo-2 and Cam-2 paint a silver nitrate solution on each filter. Both Myanmar and Cam-2 make a concentrated solution, which is further diluted at the factory prior to application. At Indo-2, 0.5 grams of silver nitrate (ppm unknown) is added to 400 ml of water and painted onto each filter.

3.11 Quality Control

3.11.1 Visual and Auditory Inspections and Pressure Tests

All factories (n=17, 100%) carry out visual inspections at different stages during production and one reports using a magnifying glass. Nine factories (53%) carry out four visual inspections including before firing, before flow rate testing, before silver application and before packaging. Four factories (24%) carry out visual inspections at just two stages and three factories (18%) carry out just one visual inspection either before firing, flow rate testing or packaging. Workers look for (n=16) cracks (15, 94%), deformity (9, 56%), defects or irregularities (8, 50%) and uniformity of color (3, 19%). Note, numbers add up to more than 100% due to multiple answers.

Auditory inspections (n=15), which can detect under or over firing or the presence of cracks, are always performed at seven factories (47%). At Cam-1, auditory inspections are performed on ten filters per month.

Pressure tests (section 8.3.3) are reportedly performed (n=15) always at Benin, Cam-2, Indo-1, Nica-1 and Nica-2 and MM-all factories (40%), sometimes at the DR and Nigeria factories (13%) and never at seven factories (47%).

3.11.2 Flow Rate

All filter factories but two perform flow rate tests on 100% of their filters (n=18, 89%). DR performs flow tests on 8% of their filters and Tanz-1 on 4%. Five factories (28%) soak their filters for 24 hours prior to testing the flow rate (Benin, Indo-1, Nigeria, SL-1, SL-2). MM-all and Nica-2 soak their filters for 12 hours (11%), seven factories (39%) soak them for between two and 12 hours. Guate-1 soaks filters “until saturated” (6%) and three factories do not soak their filters prior to flow rate testing (DR, Tanz-1, Guate-2).

Factories (n=18) measure either the change in water level after an hour using a T-device (Figure 8-3) (8, 44%) or the amount of water which filters through the filter after an hour (8, 44%) or after half an hour (Tanz-1). SL-1 did not describe their flow rate testing method. Factory established acceptable flow rates range from 1.0-3.0 Liters minimum to 2.0-5.0 Liters maximum. Figure 3-11 shows the flow rate range at each factory and filter element capacity (L).

At four factories (n=14, 29%) flow rate testing water is continuously reused (Indo-1, Nica-1, Cam-2 and Colombia). At the Myanmar factories and Indo-2 the flow test water is re-used but the water used to soak the filters is discarded. Five other factories (36%) dispose of water used for soaking filters every day (Cam-1, Guate-1, Indo-2, Tanz-2, SL-2). Nigeria, Nica-2 and Indo-1 change the water between every 10 days and two months depending on the condition of the water (3, 21%). At Cam-2, there is no set protocol.

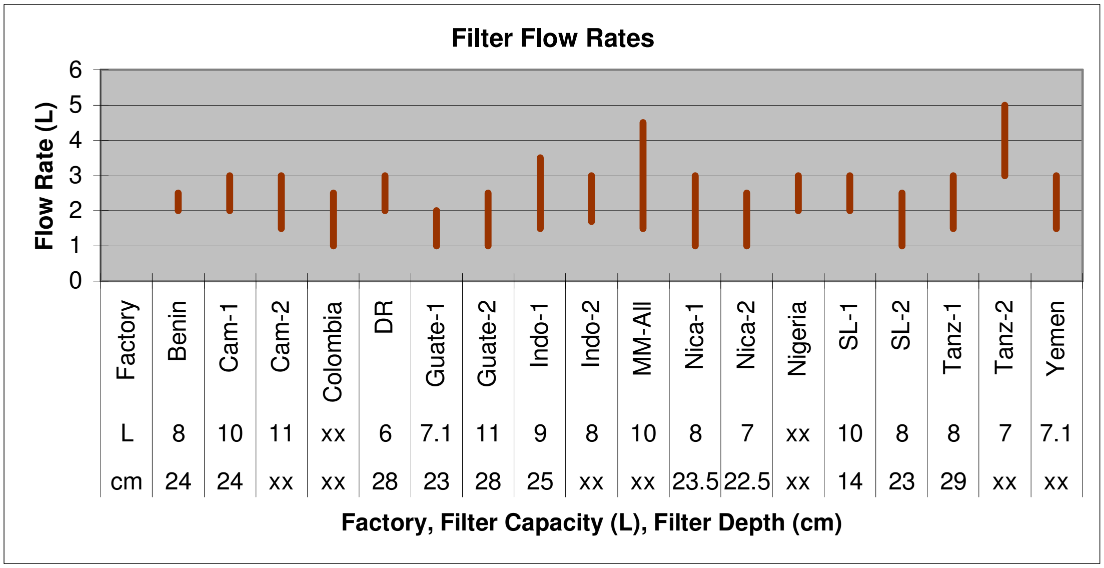


Figure 3-11: Flow Rate Ranges

3.11.3 Microbiological Testing

Thirteen factories report carrying out microbiological testing regularly (n=18, 72%) on between 0.2-15% (n=8, average 5%) of their filters. Four additional factories (22%) have carried out some tests on their filters (Nica-1, Nica-2, SL-1, Yemen). Six factories (33%) have tested their filters both in a lab and at the factory. Three factories (17%) only test their filters at the factory; eight factories (44%) only use laboratories. None of the respondents provided the data set regarding acceptable ranges for test results. Additional results from the survey on microbiological testing are presented in Annex B.

3.11.4 Failed Filters

Ten factories (n=15, 67%) reported that they do not reprocess greenware (not yet fired) filters which do not pass quality control but rather they are destroyed and used for non-filter making purposes, such as soaked and used to close the kiln door or for road fill. Six factories (n=15, 40%) reprocess greenware (DR, Nica-2, SL-2, Tanz-1, Yemen and Tanz-2). Four factories re-mill dried filter mixture prior to re-hydrating it (Nica-2, SL-2, Tanz-1 and Tanz-2).

3.11.5 Filter Logs and Failure Rates

All factories record some production data (n=18, 100%) but only 13 factories (72%) always maintain logs. Between 12-14 factories (57-88%) record the date made, filter number, lot number and flow rate. One factory also records the operator, conditions and origin of materials. Another factory collects information including filter weight, drying time, kiln temperature, visual faults and filtration rates and creates firing curves, filtration rate distributions and diagrams for analysis. More detail on information recorded on filter logs is presented in Annex B.

The average total failure rate (n=15) is 12% (range 2-27%, stdev 8%). Failure rates vary between 2% and 27% with five factories (n=15, 33%) having a failure rate of greater than 15%. Tanz-2 reported that 32% of their filters consistently crack during firing (Figure 3-12).

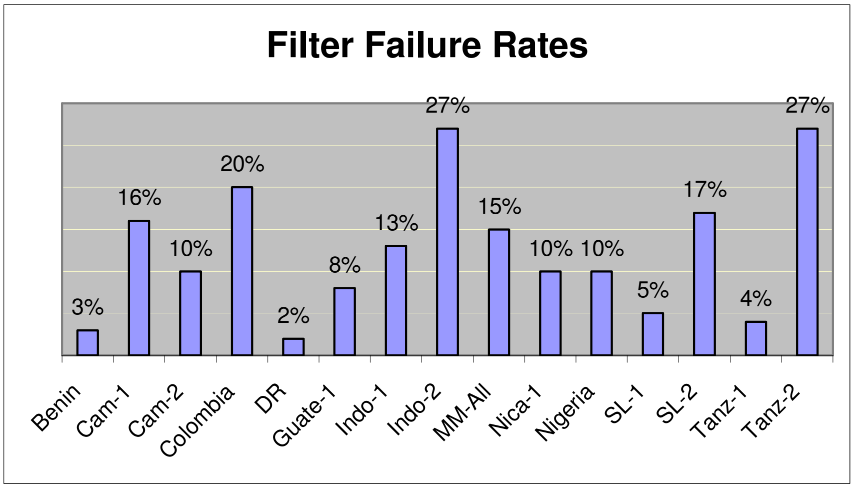


Figure 3-12: Failure Rates

Although only four factories record the reason for filter rejection, 14 factories document filter flow rates. Ten factories reported that between 0-17% of their filters do not pass flow rate tests (average 6%, stdev 5.3%) making it the number one reason for rejecting filters at 7 of these 10 factories. Of the three factories which reported other primary reasons for filters failing quality control, two (DR, Tanz-1) do not perform flow rate tests on 100% of their filters. Interestingly the third factory, Benin, which does perform flow rate testing on 100% of their filters, has the narrowest flow rate range of all the factories (2-2.5 L/hr) and reports one of the lowest failure rates. Although they usually keep a log, only the date made is recorded. These three factories also reported having the lowest total failure rates (Benin at 3%, DR at 2% and Tanz-1 at 4%). The average failure rate for these ten factories is 9%, ranging from 2-20% (stdev 6.2%) and between 0-7% of filters are damaged during firing (average 2%, stdev 2.4%), 0-1% from accidents and 0-1% during drying. Six other factories mentioned either flow rate testing, firing or both as stages when the majority of filters are rejected. Without standardized quality control procedures, rejection rates cannot be compared as stricter quality control standards could result in a higher failure rate.

Cracks that appear after firing could be from a variety of causes including drying condition or materials characteristics. Figure 3-13 shows the percentage of filters which crack per kiln-load at each of the factories. Eleven factories (n=18, 61%) reported that these rates are consistent however they are not consistent for Benin, Guate-2, Nica-1, Nica-2, SL-2 or Tanz-1.

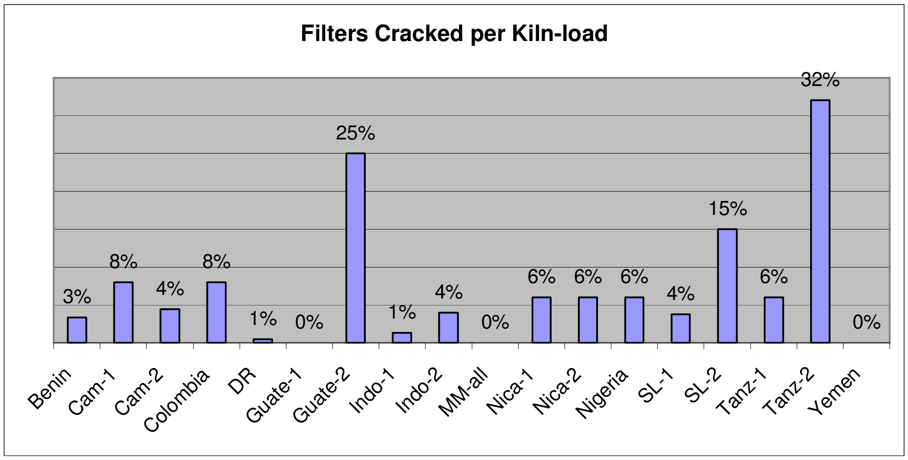


Figure 3-13: Filters Cracked During Firing

3.12 Health and Safety

3.12.1 Materials Processing

As a part of their health and safety guidelines, all factories recommend a dust mask or some sort of nose and mouth covering be worn while processing clay (n=16, 100%); however, only eight (50%) factories reported that employees wear them always. In addition, some workers wear gloves, goggles or glasses, ear protection, or closed toe shoes. At Cam-2, a fan is used to blow away clay dust. For processing burn-out material (n=15), 14 (93%) use face masks, four (27%) use goggles, two (13%) use ear protection and two (13%) wear gloves. One factory reported that no health and safety precautions are taken while processing burn-out material due to a lack of industrial health and safety guidelines. Ten (67%) reported that these precautions are always taken.

3.12.2 Mixing and Pressing

While mixing filter mixture and pressing filters (n=12), eight factories (67%) report wearing masks, three (25%) wear goggles, three (25%) wear gloves and three (25%) reported taking few or no health and safety precautions. In addition, at SL-2, helmets are worn while mixing. At Cam-1, the press has an automatic stop system and the mixer has a pulley system installed to prevent injuries. At Cam-2, shoes are required, fans blow and the press is located at a distance from other factory movements. Eight (67%) factories reported always taking these precautions. Four factories (n=14, 29%) reported minor accidents, three of which specified hand or finger injuries.

3.12.3 Firing

Six (n=14, 43%, FP75-76) factories use gloves, five (36%) use face masks, three (21%) use goggles or glasses and three (21%) do not have specified health and safely precautions while firing kilns. Seven factories (50%) reported that precautions are always observed. In Nigeria, supplements and vitamins are provided for the kiln masters and firing days are rotated to allow workers to recover between firings.

3.12.4 Silver

Of the 15 factories that work with powdered silver (n=11), all use gloves (100%), four (36%) wear face masks and four (36%) use eye protection. Seven (64%) reported always taking these health and safety measures. Of the seven factories working with liquid silver (n=5, numbers do not add up to 100% because three factories work with both liquid and powdered silver) three (60%) wear gloves, two (40%) wear face masks one (20%) wears aprons and one (20%) does not take any health and safety precautions. At one factory, the workers did not like wearing gloves and so they no longer do. Three (60%) reported that they always follow health and safety precautions when working with liquid silver.

3.13 Summary

Manufacturing practices vary both within factories and between factories. This is to be expected, as challenges during normal production will require that practices be modified to resolve inconsistencies. This technology was designed to be manufactured by artisans and therefore to be able to accommodate variation in production. While little information is available regarding the influence of many of the variables on filter characteristics, consistency of materials, materials processing, manufacturing practices, record keeping, quality control and microbiological testing by each factory should produce feedback, which will aid in producing more consistent filters.

Filters produced in different countries have been found to have different characteristics; however, as production information has not been available, very little focus has been applied to the role of production variables on filter characteristics and effectiveness. Limited research has been completed to compare specific manufacturing processes with filter quality and results of research have not translated into methods for improving filter quality. Researchers can help identify and understand the relationships between production variables which impact filter quality including the influence of clay characteristics, burn-out particle size and particle size distribution and firing schedule so that factories can focus on controlling influential variables.

In the following sections, the filter manufacturing process is discussed in detail and best practice guidelines are suggested which take into consideration information from the survey results and known information about ceramic production. Recommendations where further research can help refine best practice recommendations are presented at the end of each section.

4 Variables: Materials Sourcing and Processing

The raw materials used to prepare the ceramic filter include water, clay and a burn-out material that fires out to create porosity. At some factories sand, grog or goethite are also included in the filter mixture. Silver is covered separately in Chapter 7. A summary of recommendations and areas where further research is needed are listed at the end of the chapter.

4.1 Water

A reliable and reasonably clean source of water is required as a raw material for both filter production and flow rate testing. Acceptable water quality for silver dilution is addressed in the silver chapter, Section 7.7.

There should be enough water reliably available at the filter facility. A facility that produces 50 filters per day needs 500 L (132 US gallons) for flow rate testing and approximately 100 liters (27 US gallons) for production. Additional water is needed for factory cleaning, maintenance and to meet hygiene and sanitation needs of the employees. A rain-water harvesting system, a storage tank and/or a recirculation system can help meet water demand, and if interested, factories should consult a local contractor with experience designing such systems. Filters can be set up at the factory to provide potable drinking water for employees.

Water contaminated by some chemicals may leave toxic residues in filters that could leach into the filtered water. Heavy metals and inorganic materials might not fire out and could negatively affect filtered water. At program outset, both production and flow rate water should have a full laboratory analysis carried out which tests for heavy metals, inorganic chemicals and microbiological contaminants to fully characterize water used in the facility and address any problems up-front. Testing should be repeated annually; however, if the factory is using an intermittent or less safe source, testing should be conducted more regularly, with particular attention to locally occurring contaminants in water.

Water can be recycled for soaking and flow rate testing as long as it does not become too turbid, as turbidity will influence the flow rate results. For consistent flow rate results, water should be visibly “very clear”, or it can be measured with a turbidity tube or an on-site or laboratory turbidimeter and should be measured at <5 nephelometric turbidity units (NTU) to avoid clogging the filters.

Although we do not know the source, arsenic has been detected in the effluent water from filters from some factories (section 2.1.6). Due to the long-term health effects of arsenic consumption, all factories should test their water supply for arsenic. Arsenic testing can be carried out using field test kits (see Annex I for recommended tests). It is preferable, however, that samples be taken to a local laboratory for analysis. Samples should be properly collected in appropriate containers. Although it is important to document the occurrence of arsenic, it has not been found to leach from filters in concentrations that exceed WHO guideline values, indicating the leaching does not pose a health risk to filter users (Tun 2009).

4.2 Clay

The quality and characteristics of clay used in filter production are important, as they will influence filter strength, shrinkage and propensity towards cracking and warping, porosity, firing temperature and workability. In the following section sourcing, classifying, evaluating, preparing and processing clay is discussed.

4.2.1 Sourcing Clay

To maintain production costs as low as possible, clay should be mined close to the workshop. It is important that filter producers evaluate the clay at its source; clay taken for initial evaluation should be "sampled" from different positions in the mine or pit to indicate variability within the deposit, and producers should ensure that the clay delivered is consistent over time. An alternative clay mine with suitable clay should be identified for use in the event of a disruption or problem with the main raw clay supply to prevent interruption in filter production. Location is an important factor in choosing clay as the cost of mining and transportation can be significant; however, clay quality is evident in filter quality.

The Colombia factory reported clay not chosen carefully can result in a failure rate of over 20%.

Using unfired cracked bricks from industry can be a consistent and economical way to obtain clay, although this source will also need to be evaluated for its suitability for use in filter production. The physical requirements for brick clay (i.e. plasticity, workability, shrinkage rates) are different than for pottery clay. While the potter will look for a smooth, plastic clay, the brick maker will prefer a clay which is much coarser and contains considerable amounts of sand or other non-plastic fragments with which bricks can be formed, dried and fired without warping, cracking or shrinking too much. In some countries, pottery clays and brick clays are even called by different names and are considered different materials. Therefore, where producers rely on clay from brick makers, it is important to see the clay source, discuss the mining practices and evaluate the suitability of the material to ensure that the clay will have appropriate characteristics, be consistent and reliable. An advantage of using extruded bricks is that the material will have already been screened and processed, ensuring uniformity and increasing the plasticity of the material.

4.2.2 Classifying Clay

Clay can be classified by characteristics including origin (primary or secondary), firing temperature (refractory or fusible), maturation range (earthenware or stoneware), color (white, grey, red) and properties (plastic or short).

Generally clays are either primary, located near their mother rock, or secondary, having been transported by wind or water. Primary clays tend to be less contaminated with other materials; secondary clays are often more accessible. Clays can also be classified by the temperature at which they reach their fusion point, also referred to as vitrification. As clay vitrifies it becomes stronger but less porous, therefore the optimal firing temperature for a clay will be finding the balance between desired porosity and strength. Earthenware clays contain enough iron oxide and mineral impurities that they reach maturity at relatively low temperatures, less than 1100˚C (2010˚F, cone 02), yet they remain porous. Earthenware also typically has a narrow maturation range and therefore requires a more even and controlled firing than a clay with a broader range. Earthenware clays appear red, brown, greenish or grey in the raw state and remain slightly porous even when fired to maturity because of the organic and mineral impurities. This porosity, along with common availability, makes earthenware clays the most suitable for ceramic filter production. Earthenware is the type of clay most often used by traditional potters and is also the common raw material for building materials such as brick, floor tile and roof tile (Rhodes 1973: 22). Refractory clays, such as stoneware, porcelain and fire clay mature at temperature ranges between 1200-1800˚C (2190˚-3270˚F), have a long maturation or vitrification range and are relatively non-porous at maturity, and therefore not as suitable for making filters.

Different properties, such as plasticity, the ability of the clay particles to slide, determine how clay behaves and its workability. Plasticity is influenced by: 1) particle size; 2) purity or clay content; 3) moisture content; 4) particle uniformity; 5) plasticizers; and 6) strength of particle bond (Hamer 2004: 270).

These characteristics will influence: 1) wet and dry green strength; 2) shrinkage (and propensity toward warping or cracking in the drying or firing processes); 3) porosity; 4) fusion point; and 6) workability. A variety of materials can be blended to form a clay body which has the right plasticity to work with, a reasonable rate of shrinkage, desired porosity, that will melt at the desired temperature, hold the proper shape and not warp or deform while drying or during firing.

4.2.2.1 Particle size

Clay particles are typically plate-like, hexagonal in shape and range from 0.05-3 micrometers across, although the definition of clay based on particle size can vary across disciplines. The particle size is directly related to the plasticity, strength and shrinkage of the clay. Two chemically similar clays, if they have different particle sizes, will react differently. A clay with a smaller particle size (0.02-1.0 micron, Ball clay) will have the potential for a higher moisture content because there is a greater surface area coated with water in the plastic state. It will therefore shrink more in drying and be more likely to warp or crack. In firing, smaller particles will interact more readily with fluxes and be less resistant to the effects of temperature and time than clay with a larger particle size (0.5-20 microns, China clay) (Hamer 2004: 253).

At Cam-1 and Indo-2, clay is tested for plasticity and prototypes are fired and evaluated for cracking, breaking, firing temperature and filtration rates.

4.2.2.2 Purity

The proportion and type of impurities, or non-clay particles, will affect how the clay behaves at different stages of the process. Some impurities could make the clay unsuitable for use; others could be beneficial, up to a point. Common impurities in clay include the following:

1) **Iron:** Is often found in surface clays, but usually is not a problem unless it is coarse or nodular. It can contribute to the color and some fluxing action to lower the maturing temperature of the clay, and may possibly contribute desirable virucidal qualities to the filter (section 4.4).
2) **Sand:** High sand content correlates to low plasticity in clay and too much can cause filters to become brittle and break. It can also increase the flow rate, though we do not know how it affects the efficacy of the filters. In very plastic (fine grained) clays some sand might aid in even drying and reduce shrinkage. The addition of grog or laterite will have a similar effect.
3) **Soluble salts:** Over time, in the finished product, soluble salts migrate to the surface, causing white discoloration. The presence of a white scum on the dried clay usually indicates the presence of undesirable alkalis (Rhodes 1973: 65). This has not been found to affect filter quality, but could be of aesthetic concern if it occurs.
4) **Lime:** In firing, lime changes from calcium carbonate to calcium oxide, which can hydrate (absorb water from the atmosphere), causing it to swell and break off, a condition known as "lime popping". Clay that contains whitish lumps can be tested for lime as described in Annex 0, however; thus far lime has not been observed or reported as an issue in finished filters.
5) **Heavy metals/inorganic materials:** Examples include arsenic, fluoride and cyanide. Such contaminants in the materials used to manufacture filters raise two issues: 1) the possibility that the filter element itself could be a source of contaminants introduced into the filtered water; and 2) worker exposure to such toxins present in the materials they use daily. Raw materials and filtered water should be tested in a laboratory for possible contaminants.
6) **Organic matter:** naturally high levels of organic matter (such as leaves or twigs) in the clay can affect the strength and integrity of ceramic filters since this material can burn out during firing, leaving behind large unregulated cavities. Organic material can usually be removed during clay processing.

4.2.2.3 Moisture content

Moisture content can account for as much as 40% in weight of plastic clay and will influence workability and how the clay behaves in drying and firing. Clay contains three types of water:

1) **Water of plasticity** is the lubricant between clay particles that helps them slide and stick to one another. It accounts for between 10-30% in weight depending on the clay particle size. Smaller particles provide a greater surface area that can be surrounded by water, therefore, more water of plasticity means the clay will take longer to dry and will shrink more as there is more water to evaporate.

2) **Pore water** comprises approximately 10% in weight and is still present when clay appears dry. It evaporates as the clay is heated and should be gone by the time the clay is heated to 120˚C (250˚F).
3) **Bound or chemical water** is part of the chemical structure of clay, comprises about 14% by weight of dry clay and fires out at around 600˚C (1110˚F). When this water is removed, clay becomes a pot (Section 6.8.3).

During firing, as the water is driven off at 100˚C and 600˚C, the wares will experience added stresses, therefore attention will be required at these stages to avoid cracking (Section 6.7).

4.2.2.4 Particle uniformity

In general, fine clays of a predominantly small particle size will be more plastic with good dry green strength; but will exhibit greater rates of shrinkage due to the high water content and therefore be more prone to warping and cracking during drying. They will also be less porous. Clay with a high shrinkage rate (more than 15%) probably will not be useful, due to warping and cracking in drying and firing. Coarser clays of a predominantly larger particle size will be less plastic, will exhibit less dry green strength and make a noticeably coarser and more porous product; but will shrink less and dry more evenly with less cracking and warping. In the clay mixture, it may be desirable to incorporate different sources of clays that have a variety of particle sizes in order to create an overall particle size distribution that will maximize the strengths and minimize the weaknesses of each; that is, to create a clay composition that is of the desired plasticity, with a reasonable rate of shrinkage, good wet and dry green strength, desired texture, porosity and experience minimal warping and cracking in the drying and firing processes. In filter production, the fine burn-out material can act as the fillers in the mixture that contribute to the desirable properties associated with coarser clays including regulation of porosity, shrinkage, warping and cracking. Fine non-plastic material will decrease plasticity more than coarse materials.

4.2.2.5 Plasticizers

Local potters know the plasticity required to produce their normal production line; however, in the filter making process, the innate plasticity of the clay used is even more important because 40%-60% by volume of non-plastic, fine, burn-out material is added to the mix which drastically changes the workability of the original clay. This makes filter production a counterintuitive process for potters to take on, as the high amount of burn-out material acts as a filler altering the nature of the clay mixture and negatively impacts plasticity to such a high degree. Fortunately, plasticity tends to be common in surface clays, though the addition of plasticizers, such as bentonite, can improve the plasticity if necessary.

4.2.2.6 Strength of Particle Bond

Dried clay bodies vary greatly in strength. An object made from ball clay (which is very plastic), for example, may be six or seven times stronger than one made from Georgia kaolin clay (low plasticity). The property of dry strength is directly related to particle size, the smaller the particle size, the stronger it will be in the dry state, but dry strength is also related to the strength of the particle bond. A very plastic clay with insufficient strength will not hold its shape, yet a strong clay that is not plastic enough will tear. The strength of the particle bond can be improved by bringing the particles closer together by wedging and processing filter mixture through a pug mill.

4.2.3 Evaluating Clay

A common rule of thumb (by no means limiting) to evaluate plasticity is: take the clay and roll out a coil of about the diameter of your small finger, form a one-inch ring and note if the clay cracks and if it holds its shape. If there is no initial cracking, the clay is probably plastic enough to start tests.

Sand content can be determined by settling out sand from a thin slip of clay and weighing the ratio of plastics (clay) to non-plastics (sand). Sand can be removed from source clay by dry screening. Dry screening will also remove large pieces of organic matter which may be present in the source material. The amount of sand desired will depend on the plasticity and grain size of the clay. If the filter shrinks too much and experiences drying or firing cracks, sand can be added to the point where the problem is solved, though any new formula should be confirmed with microbiological testing. Alternatively, if the clay contains too much sand, the filter will not shrink enough and/or will be too porous. If this is the case, the sand can be removed, it can be combined with a less sandy clay, or another source can be found.

Moisture content can be evaluated by measuring the Water of Plasticity (Annex D), which is the water surrounding the clay particles. The water of plasticity will vary for each clay and will range from 10% in low plastic clays to 30% in highly plastic clays. The water of plasticity will be influenced by both non-plastic materials and clay particle size, with smaller particles providing more surface area that can be surrounded by water. Clays that have a higher water of plasticity will take longer to dry and shrink more.

Shrinkage of Dried Clay (Annex D) will be affected by the amount of non-plastic material, particle size of clay and the water of plasticity. Dry clay strength can be evaluated by making a series of small tiles, and estimating the amount of force required to break them once dry. In the lab, a similar more accurate test is done with a machine that measures modulus of rupture (MOR).

Once both the pore and bound water have been fired out, shrinkage of fired clay can be measured and total shrinkage can be calculated using the formula in Annex D. Strength tests can also be carried out on test pieces fired to different temperatures. Break each piece over a white piece of paper; observing for carbon powder or a carbon line in the profile which is indicative of incomplete firing; estimate the effort required to break each one; and listen to the sound and observe the broken profile for consistency.

The firing range of a clay under consideration can be evaluated through shrinkage and porosity tests (Annex D). The porosity of a clay will influence the amount of burn-out material needed in the filter mixture. Porosity of filters have measured from 30-44% (van Halem 2006; Oyanedel-Craver and Smith 2008).

These tests should also be carried out regularly on filter mixture, as results will vary from tests carried out on clay alone. In Myanmar, for example, shrinkage rate for clay is approximately 10-14% whereas filter mixture shrinks about 5-6%. Results might also vary due to variation in raw materials.

4.2.3.1 Preparing a Clay Body

The materials that go into the formulation of a blended clay body can be thought of as plastics, fillers and fluxes. Detailed instructions for developing clay bodies are presented in Annex D.

Factors that can influence the plasticity of a clay body are its composition, wetness, aging and bacteria. Since clay for filter making is processed dry, the best way to increase plasticity is to add a more plastic clay. If bentonite, a highly plastic montmorillonite, is available locally, up to 2% by weight can be added.

In Nigeria, university students evaluate suitability in a laboratory by testing for shrinkage, ease of use, firing temperature, filtration and materials composition.

Fillers are non-plastic materials such as grog or sand that can be added to clay to add stiffness, decrease warping during drying and firing and to decrease shrinkage. Grog can be made from grinding up either fired, failed filters or bricks. Either grog or sand can be used to reduce shrinkage, thermal shock and increase flow rate (section 4.5). Burn-out material added to the filter mixture to create porosity, can be considered a specialized type of filler and it is often not necessary to add either sand or grog to the filter mixture.

Fluxes are alkaline oxides which interact with the glass-forming silica to lower the fusion or vitrification point. They are not typically needed in filter production or in earthenware clays in general due to the high iron content.

4.2.3.2 Summary

In summary, a good clay body will have the right amount of plasticity, with a reasonable rate of shrinkage, good wet and dry green strength, desired texture, porosity and experience minimal warping and cracking in the drying and firing processes. Although some clays can be used with minimal processing, others will benefit from mixing them with another clay with different characteristics or non-clay materials, experience and experimentation will aid in clay body preparation. Clay sourced from the same mine might vary in characteristics depending on the location. Clay should therefore, be continually evaluated and modifications may be necessary over time. Modifications should always be confirmed with microbiological testing of final filters.

4.2.3.3 Arsenic in Clay

The melting point of arsenic is 817˚C (1503°F) which is very close to the firing temperature at most filter factories. It is possible that arsenic is rendered ineffective after this temperature as it melts into the clay matrix, but since its melting point is so close to the maximum firing temperatures employed, it is also possible that special precautions such as longer soak times in the firing would guarantee a proper melt. Raw clay or ceramic pieces can be tested in a local laboratory or sent to Vinka Craver at the University of Rhode Island for laboratory analysis (see Annex H). Arsenic in filtered water has not been found in concentrations high enough to cause arsenicosis (see section 2.1.6).

4.2.4 Clay Processing

Health and safety measures while processing clay must be strictly enforced. Because airborne particles can travel and remain suspended for several hours, nearby workers not directly involved in clay processing may be exposed to the silica dust. Equipment location should be carefully selected and collection bags should be properly secured to hammer mills to minimize dust output. Preventative measures should be taken not only while processing these materials but also during cleaning; since dry brushing can cause settled particles to become airborne, water should always be used while cleaning.

The materials needed for clay preparation include: area protected from rain, shovel, wheelbarrow, sacks, hammer-mill, scoops and kitchen sieve. Worker safety materials needed for clay preparation include: fan, face masks, goggles, gloves and closed shoes. Note that the inhalation of airborne silica particles can cause silicosis and prevention should be taken very seriously.

About 4.5 kilos (9.9 pounds) of powered clay is required for each filter, therefore a factory producing 50 filters a day will need to prepare 225 kilos (500 pounds) of dry, powered clay daily. Extra should be prepared and stored to prevent an interruption in production in the event of machines breaking, interruption in power supply, poor weather, or other unpredictable event. Prepared clay can be stored in 25-kilo (50 pound) sacks in a dry, raised and covered location, protected from moisture.

The objectives of milling and sieving clay are to remove impurities such as sand and organic matter and so that it can be more easily wetted. Powdered clay is formed from raw clay by: 1) drying the clay in the sun; 2) pre-cleaning the clay; 3) using a manual “elephant’s foot” tamper (Figure 4-1) and/or a mechanical hammer mill to pulverize the clay; and 4) sieving the clay, generally, using a 25-30 mesh screen (equivalent to 0.7-0.6 mm openings, see Tyler mesh equivalent chart in Annex B).

Figure 4-1: Elephant's Foot Tamper
(Hagan *et al.* 2009)

Although it is possible to dry the clay (and burn-out materials) in the sun on a sheet of plastic, in practice, the nonporous nature of the plastic will continue to trap the moisture and impede complete drying which will make pulverizing difficult. It is therefore preferable that the materials be sun-dried on a cement slab.

Since clay put through the hammer mill should be a maximum of two centimeters (3/4 inch), once the clay is dry, large clumps should be broken up with a hammer or tamper such as an "elephant's foot" (heavy bamboo pole attached to a heavy metal plate) and rocks and organic material should be removed from the clay.

Before operating the hammer-mill, some equipment checks should be performed, especially ensuring that the wire mesh screens have not been broken or punctured. The hammer mill pounds the clay pieces with turning metal hammers, and when clay particles are small enough, they pass through the hammer mill screen and discharge as fine powder. A flail type hammer-mill without fixed blades is preferable as the blades are less likely to get damaged if non-millable material is introduced. Hammers on each shaft must be balanced with the others so that the mill will be in balance. When operating a hammer mill it is important that the mill be running before adding material and only a small amount of material should be fed in at a time to prevent the machine from jamming. A lid (or a square wooden bat with hole in middle) can be helpful to prevent clay from spitting out from the hammer mill. If any strange noises are heard, this may be due to the presence of rocks, wood chips, or other materials in the hammer mill chamber. In this case, the machine should be turned off, disconnected from the power source, the cover opened and screens examined for any foreign material, which should be removed and discarded. Additionally, if the screen or any other components have been damaged or punctured, they should be replaced before hammer-mill operation continues.

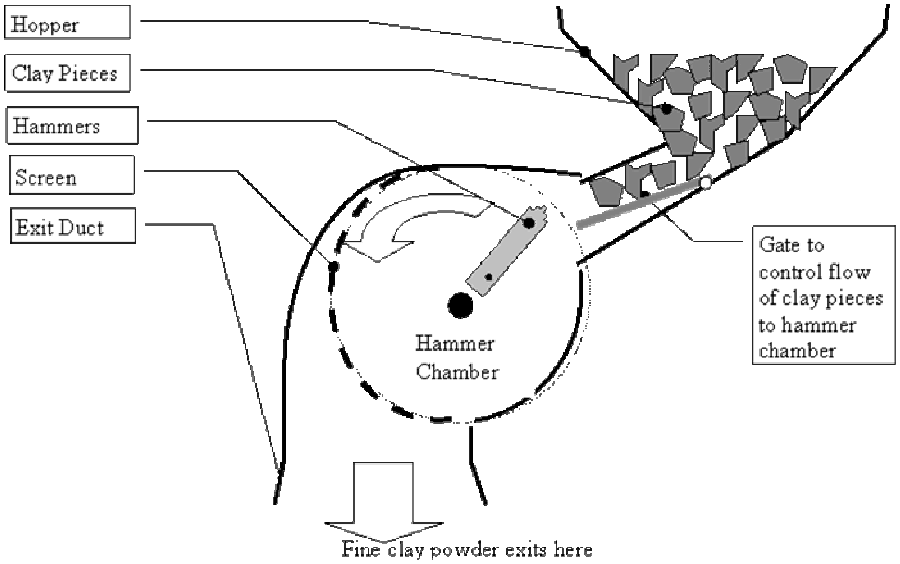


Figure 4-2: Hammer Mill Operation
(Mossman and Lam 2004)

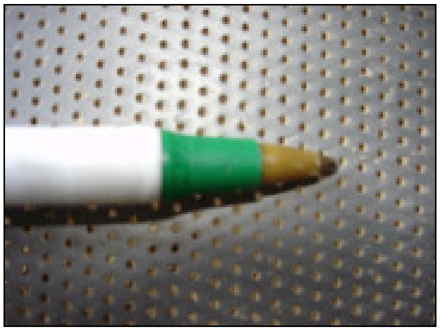


Figure 4-3: Hammer Mill Screen
(source unknown)

Since hammer mill screens are generally larger than 30 mesh (0.55 mm), after being processed through the hammer-mill clay should be sieved using a wooden frame with the appropriate mesh sieve (#25-30). Clay that does not pass through the sieve can be re-milled and sieved again. Material that still does not pass through the sieve should not be used in filter production. Sieves should be inspected daily for holes and repaired or replaced if damaged.

A huge amount of fine dust is produced during operation of the hammer-mill, posing a worker health hazard that should be taken seriously. The potential health effects of inhaling particulate matter include asthma, silicosis, lung cancer, cardiovascular issues and premature death. Silicosis is a long-term health risk associated with the inhalation of crystalline silica dust found in clay. It is an irreversible lung disease and can progress even when exposure has stopped. Inhalation of any airborne particles should be considered dangerous; silica is particularly dangerous and can remain airborne for several hours. A sack should be well secured at the outlet of the hammer-mill in such a manner as to minimize worker exposure to dust generated by the process. Although workers should be provided with protective eye goggles and facemasks and instructed to use them, in practice, they may avoid doing so, due to complaints of discomfort. It should be emphatically communicated to the workers that the importance of avoiding the long-term health risks of inhaling fine silica dust on a daily basis outweighs the short-term discomfort of wearing a facemask. Long hair should be tied back and loose clothing which could get caught in the rotating machinery should be avoided. The hammer-mill should be located in a low-traffic area of the factory so as not to pose a hazard to other workers, preferably outdoors under a roof; and where a fan can be used to blow away the dust generated. Although wet processing of clay is possible, and more considerate to worker health, processing guidelines have not yet been established.

4.3 Burn-out Material (Combustible)

The burn-out material creates the porosity in the filters by firing out during the firing process, leaving behind the small voids that trap bacteria. Factories utilize the most readily and cost-effective burn-out material available. Sawdust and rice husks are the most common materials used in local ceramic filter manufacturing, but millet husks, coffee husks, peanut husks, paper pulp and other organic materials which can be pulverized to a suitable size can be used depending upon local availability.

Indo-2 found that using sawdust as a burn-out material increased shrinkage too much yet Cam-1 expressed a preference for sawdust since the filters would be smoother and nicer looking.

Little is understood about how variation within a given burn-out material, such as sawdust from different woods, affects filter efficacy; whether chemicals, such as residues from treated lumber in the burn-out material are consumed in the firing or will contaminate the filtered water, or whether very fine particles should be included in the filter mixture as these particles might have a negative effect on the workability of clays of poor plasticity. It is generally known that different types of burn-out (sawdust vs. rice husk, for example) can impart different qualities to the filter mixture; however, more research into the specific working and firing properties, including the range of proportions useful in the mixture, of each of the different types of burn-out is very much needed.

The Dominican Republic factory found that sawdust from oak left an oily residue on the fired filters and resulted in a reduced flow rate.

Since filter consistency will be reflected in production consistency, it is recommended that factories use the same type of burn-out with similar characteristics throughout production. Evaluations should be carried out regularly with characteristics documented. When a new burn-out is used, or the burn-out varies, filter efficacy should be confirmed with microbiological testing (section 4.6).

4.3.1 Processing the burn-out material

Materials needed for processing burn-out material will depend on the characteristics of the burn-out received, but in general a protected area from rain, scoops, sieve, sacks and a grinder, blender or hammer mill with sharpened blades.

The amount of burn-out material required per filter will vary depending on the established ratio. In Nicaragua, approximately 27 kg (59 pounds) of sawdust will be used a day to produce 50 filters.

The Nigeria factory has successfully used a kitchen blender to increase yield from sawdust and as an alternative, SL-2 uses a chili grinder for milling rice husks.

The burn-out material should be inspected visually, regularly after receipt from the supplier, and during production, to ensure the material has consistent particle size distribution. There should also be no foreign material (rocks or pieces of wood) present in the burn-out.

The processing of burn-out material is important since the burn-out creates the pores and the path the water travels through the filter walls. The burn-out material should be sun-dried and sieved with a #30 mesh screen (Section 0).

If the best available burn-out is coarse or is not predominately of the desired mesh size it must be milled or ground. Some factories have two hammer-mills; however, a hammer-mill with a 5 horse-power reversible motor can be adapted for burn-out processing by sharpening the reverse side of the hammers to a sharp point at about a 60 degree angle. The blades are then tempered by heating them in the embers of the firebox. Once they reach the color of the embers, they are removed and quenched in water or oil. By reversing the direction of the motor, the sharp ends of the hammers will mill the burn-out material to a finer mesh size so the same hammer-mill can be used in one direction to mill the clay, and in the opposite direction to mill the burn-out. When operating a hammer mill it is important that the mill be running before adding material and only a small amount of material should be fed in at a time to prevent the machine from jamming. Alternatively, a chili grinder or kitchen blender may be used to grind the burn-out.

Sieving burn-out with one screen will not create a uniform burn-out particle size as there is still no control of particles smaller than the sieve used. Ideally, several sieves of varying sizes would be used (perhaps 16, 30 and 60 mesh screens), and a custom, consistent mixture would be formulated by combining appropriate amounts of representative particle size ranges. Although this could achieve a consistently high control of the particle size distribution of the burn-out material, it would also increase labor requirements. Further research is needed to determine what an ideal particle size range would be.

At Indo-2, two sieve sizes are used to eliminate both the larger and finer particles.

Health and safety precautions while processing burn-out material include wearing a face mask to protect employees from inhaling airborne particles, eye goggles to protect the eyes from dust or material spitting from the hammer mill. When using a mill or machinery, precautions such as tying long hair back and not wearing clothing that can get caught in machinery should be observed.

4.4 Laterite

Some factories add laterite, which is high in Goethite and other iron oxides, as it may potentially improve filter effectiveness against viruses; however, this has not been demonstrated (Section 2.1.3). Laterite may be added at the filter factory's discretion. If laterite is used in the filter mixture, it should be processed similarly to clay: dried, powdered, sieved to 30 mesh and added to the dry mixture before water is added. The inclusion of laterite will increase both the porosity and weight of filters and no more than a ratio of 1:6, by weight, laterite to clay, should be added or structural stability of the filters will be compromised. More research is needed on additives that will increase viral effectiveness.

4.5 Grog and Sand

In normal ceramics production, grog, previously fired ceramic material that has been ground into a powder and screened for consistent size, is often added to clay to decrease its plasticity, to improve workability and reduce cracking in drying and firing, it will also decrease shrinkage and increase porosity. Grog can be made on-site by grinding crushed, fired bricks or rejected filters in the hammer-mill and then sieving it for desired mesh size (approximately 20 mesh). The use of grog in filter production and the amount required will depend upon the characteristics of the local clay and burn-out material. In Laos they have found that up to 5% grog adds to the filtration rate, but if increased to 10% (by weight) filters were weaker (Cohen 2010). At Guate-2, where the source clay did not develop sufficient flow rates with the expected range of sawdust usage, grog was added to the mixture in volumes up to 33% of the clay portion of the mixture (two parts clay to one part grog), to make successful filters.

Sand can be used as an alternative to grog, though it must be clean. It should also be sieved and included in the dry filter mixture before adding water. Whether adding sand or grog, a reliable supply must be available for consistent production.

4.6 Materials Checks and Documentation

Material checks should be carried out during initial sourcing of raw materials, including clay, burn-out and additional materials added to the filter mix. Raw materials should be monitored continuously and evaluated at least once per year or if variation is observed and materials properties should be documented. Changes (greater than 10%) require microbiological testing of completed filters to ensure that the final product is not impacted by any change in the materials. Testing for heavy metals or inorganic chemicals in both materials and in filter effluent is recommended if source materials change. If changes to materials are reported early, testing can usually be carried out in parallel with continued production however, if variation is not identified until filters begin to fail the QC tests, then the factory could suffer greater loss, both from the amount of failed filters that will have to be rejected and destroyed, and an interruption in production while new materials are sourced and tested.

Baseline data for all materials used in filter production should be recorded. For clay, baseline data should be recorded on a clay evaluation log (Annex F) and stored for comparison with future clay analyses. Evaluations should be carried out once per year and following a change in: 1) clay source; 2) clay characteristics; or 3) filter outcome (Table 9) Results should be recorded and compared to the baseline data. When results are comparable and if filters continue passing quality control tests then production may continue. If the final product begins to fail QC tests or if results vary more than 10% from previously recorded data, factories should carry out microbiological testing as recommended when incorporating any new raw materials (section 8.3.5).

As with clay, baseline data for burn-out material should be documented and the burn-out should be evaluated yearly or when a change is noticed. It should include a general description of the burn-out supply including: type (if sawdust, type of tree and if rice husk, part of husk); supplier; processing carried out by the supplier; particle size received; particle size used in filter production; grinding or milling procedure; and sieving procedure. In addition, burn-out should be tested for moisture content and contaminants (Annex D). Employees responsible for collecting, receiving, processing and mixing materials should look for and report variation in the material including the visual appearance of the burn-out including color, texture, size, smell, presence of a coating or oils, clumping, along with any other indicator of change in the burn-out. Visual inspection should also look for unwanted materials in the supply (i.e. rocks, trash) which should be removed. Causes of inconsistencies should be identified (i.e. hole in sieves, blades needing sharpening) and corrected. The earlier this happens in the process, the less likely it will significantly affect production.

Any additives such as sand, grog or laterite should also be monitored and documented and have similar characteristics to the material used in ratio formulation, any changes should be supported by microbiological testing.

4.6.1 Material Storage

Materials approved for use and materials that have been rejected must be labeled and stored in different locations. Materials approved for use should be stored in a location that is: 1) convenient for the flow of production; 2) has sufficient space; 3) accounts for airborne contamination pathways; 4) protected from the elements; and 5) protected from contamination.

4.7 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) A reliable source of reasonably clean water is required for filter manufacturing. Both production and flow rate water should be tested for heavy metals, inorganic chemicals, arsenic and microbiological contaminants. In addition, flow rate water should be tested for turbidity. Water should be tested at project outset and yearly, or more regularly if the factory is using an intermittent or less safe source;
2) Clay should come from a consistent source and evaluated periodically or when characteristics vary;
3) Clay should be processed on site to a consistent powdered form using a #25-30 mesh sieve to remove impurities;
4) A reliable source of consistent burn-out material should be identified and sieved to #25-30 mesh;
5) Additives such as sand, grog or goethite if included in the clay mixture should be processed consistently and added according to factory ratio;
6) Materials should be evaluated during initial sourcing, yearly and when characteristics vary, or if a change in filter quality is observed. Evaluations should be documented and analyzed. Variation greater than 10% requires microbiological confirmation of filter effectiveness;

7) Materials should be stored safely and under appropriate conditions;
8) Employees should be required to follow health and safety recommendations, and those exposed to airborne particles should be required to wear face masks, remembering that very fine silica dust can remain airborne for several hours.

4.8 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) Does the presence of arsenic, fluoride, chlorine and other inorganic contaminants in water or raw materials used to manufacture the filter affect contamination in filtered water? Are they influenced by different firing temperatures?
2) What are possible additives or coatings that can make filters effective against viruses? What are simple means of identifying and processing them?
3) How do different types of clay microstructures affect fired filter strength and breakage rates? How can they be evaluated or influenced at a local level?
4) Does using unfired commercial bricks or failed, unfired filters in filter mixture affect filter performance?
5) How do different burn-out materials (sawdust vs. rice husks vs. peanut shells) affect filter performance including workability of the mixture, flow rate, appropriate clay:burn-out ratio and microbiological efficacy? Do some burn-out materials leave a residue on the filter?
6) What role does particle size of burn-out material play in pore structure and hydraulic properties? Should very fine particles of burn-out be included in the mix?

4.9 Chapter Details

The information for this chapter was collated by Robert Pillers and Burt Cohen and expanded upon and edited by Justine Rayner and Daniele Lantagne. Participants on this conference call to discuss this chapter included: Terry, Mike, Justine, Daniele, Robert, Burt, Susan, Lisa, Tracy, Vinka and Manny.

5 Variables: Filter Production

In the following section the filter production process from preparing the clay mixture through drying the filters is presented, including appropriate process checks, maintenance of production logs, establishing the filter mixture ratio, mixing, pressing, surface finishing and drying and is concluded with recommendations and areas where further research is needed.

5.1 Process Checks and Filter Logs

Indo-1 implemented Statistical Process Control (SPC) procedures whereby process parameters such as filter weight, drying time, kiln temperatures (6 positions), visual faults and filtration rates are documented. Firing curves, filtration rate distribution and diagrams are created for data analysis.

The consistency and repeatability of each of the manufacturing steps will directly affect the performance consistency of filters produced. Process checks and documentation throughout each phase of production can help maintain consistent production methods. Materials evaluations, production and firing logs should be kept to record relevant information throughout the production process that can be used for future reference, to troubleshoot variation or inconsistency noticed in finished filters, to encourage that each process is performed consistently and for researchers evaluating filters in the field or a laboratory. Examples of various logs are included in Annex F. Although these can be used as models, it is recommended that each factory modify them to suit their flow of production. Recommended data to record is suggested throughout the following sections.

5.2 Establishing Filter Mixture Ratio

The appropriate ratio of clay to burn-out is determined empirically when the filter factory is established. When initially determining the appropriate mix ratio for raw materials, factories should work with an experienced ceramic filter producer, which will help new factories start quality-controlled, reliable ceramics production. It would also be very helpful to visit a fully operational factory prior to starting production. Please visit www.ceramicwaterfilter.org for a current list of experienced filter producers who can help set up factories and factories that strive to apply best practice guidelines and accept visitors. It is also important to work with local potters familiar with the local clay who will be employed at the filter factory on an on-going basis.

The amount of burn-out added to the mixture influences the flow rate (section 2.3.3). Too much burn-out can lead to fragile filters that do not adequately treat water and not enough burn-out leads to slow filtration rates. The plasticity of the clay (Rivera 2006) and the type and size of the burn-out material (Hagan *et al.* 2009) will influence the quantity of burn-out material needed to achieve the desired flow rate. Since variation in clay, burn-out or other material characteristics can influence the ratio required to achieve the desired flow rate, in addition to routinely evaluating materials for consistency, average flow rates should be monitored throughout production. An experienced potter will be able to identify changes in materials, and can compensate by adjusting the mix proportions or the firing schedule. However, any changes in the clay:burn-out ratio should be supported by microbiological testing (section 8.3.5).

To determine the appropriate clay:burn-out ratio, batches of a minimum of ten filters are made from each clay:burn-out ratio. Depending on the local clay, initial trials should start with 50% dry powdered, sieved clay with 50% dry, sieved burn-out, *by volume.* Generally, for sawdust, a ratio between 40:60 and 60:40 clay:burn-out by volume is an appropriate range (see Section 3.6 Figure 3-7 and Figure 3-8 for existing factory ratios). Once an equal volume of clay and burn-out is measured, they should be weighed to determine the relative proportions of each and used to calculate subsequent tests, *by weight.* Although measuring materials for production by weight is more accurate than by volume since low-density burn-out material can settle, burn-out material can absorb enough moisture from the atmosphere to affect its weight, therefore factories should always dry their burn-out prior to measuring it. This can be done in a pan over a small wood fire, in a drying oven, or other method that dehydrates it. If laterite, sand or grog is added to the filter mixture, the amount of burn-out will need to be reduced, since these additives tend to increase the flow rate.

Thirty percent, by weight, is an appropriate amount of water to begin testing the mix with. The wet filter mixture should be moist but on the dry end. It should feel a little drier than a typical cement mix or a typical clay mix for wheel-throwing. It is ready when the clay can hold its shape when squeezed out through the hands or begins to compact into a snowball. If the clay is too wet, the pressed filter will ‘slump’ or fall over when removed from the press. The amount of water added to the clay mix might vary slightly depending on the climatic conditions; however, variation should be observed and documented. Masks should be worn during mixing and anytime there is risk of inhaling silica dust or other airborne particles that can have serious long-term health consequences.

After pressing, drying and firing, flow rates from test filters should be determined (section 8.3.4) and the flow rate range for each ratio test batch established. Filters made from the ratio with flow rates closest to the target flow rate should be tested for microbiological efficacy (section 8.3.5). It is critically important that filters made from the selected ratio consistently demonstrate microbiological efficacy in laboratory testing. A minimum of three batches of ten filters for the proposed ratio must be manufactured and a minimum of three filters from each batch should be tested with contaminated water in a laboratory to ensure there is a minimum 99% (2 log) reduction in microbiological indicators. This is necessary to demonstrate that the results of the first successfully fired batch can be consistently repeated in normal production. If filters with both high and low flow rates are tested it can provide information regarding the flow rate limit for actual production. Effluent water from prototype filters should also be tested for heavy metals and inorganic chemicals to ensure the selected materials and processes do not leach into filtered water. Once a materials ratio has been established and verified, production can begin.

5.3 Filter Mixture Preparation

At Indo-2, dry materials are mixed for one hour manually as they have found that when mixed for fewer than 50 minutes, flow rates become inconsistent.

Selection and processing of raw materials are discussed in Chapter 4. The equipment needed for mixing includes: a scraper, measuring container for raw materials, spring scale if measuring by weight, scoops, buckets and mortar mixer (if electricity is available). A mortar mixer, which mixes horizontally with rotating blades operating at 40-50 revolutions per minute (rpm), is recommended for this process. A cement mixer, in which the barrel rotates, is not recommended.

Each factory determines the mixture batch size according to the capacity of the mixer, daily production capacity and kiln capacity. Filters manufactured from a batch of mixture should be kept together throughout production and fired in the same kiln load. It is important that the mix ratio does not stray from the determined ratio. Since atmospheric humidity can affect the weight of burn-out material, it should be dehydrated (heated at a low temperature) to evaporate additional moisture prior to weighing it. It remains unknown whether the storage of prepared filter mixture affects filter characteristics.

In Nigeria, where ingredients are mixed manually on the ground and then pounded in a mortar and pestle, the mixing process takes half a day.

Raw materials, including powdered clay, sieved, dehydrated burn-out and in some cases additional materials such as goethite, grog, or sand, are weighed and added to the mixer. Dry materials are mixed together prior to adding water and should be mixed, at minimum, for ten minutes in a 40-50 rpm mortar mixer; if using a slower mixer, they should be mixed for additional time. In every case, the goal is that the clay and burn-out material are evenly distributed. Only after the mixture appears homogenous should the measured amount of water be gradually added to the mix. It can be sprinkled into the mix with hands or a watering can; some factories have designed automatic drip systems. Two factories add powdered colloidal silver to the filter mixture, which should be mixed with the water before adding it to the mixture to reduce airborne silver particles and promote consistent distribution. Once water has been added, ingredients should be mixed until a homogenous mixture is achieved, but at a minimum, another ten minutes.

Hand mixing is not recommended as it is difficult to obtain a homogeneous mixture; however, some factories do not have reliable or affordable access to electricity and mixing by hand is the only option. As an alternative to hand mixing that does not require electricity, a drum mixer, similar to those used in Myanmar (Figure 5-1), could be constructed and used for mixing dry materials. The addition of a colorant which could indicate thorough mixing (such as beet root juice or other coloring material) may be added to the burn-out material provided that it and fires out and does not affect the filter structure. Any addition to the filter mixture must be verified by independent testing prior to use in production.

Figure 5-1: Drum Mixer (Thirst-Aid 2009)

Materials should be inspected visually as each batch of raw materials is mixed, looking for: 1) a homogenous mix consistency; 2) unmixed material that has settled at the edges or bottom of the mixing container; 3) similar appearance to other batches; and 4) that the mixer is fully functional and not clogged.

The following information should be documented and the mixture batch should be referenced on filter logs so that details of mixture preparation for any given batch can be referred to at a future date. Details should include: operator; date; mixer used; source of materials; weight of clay; weight of burn-out; weight of additives; weight or volume of water; duration of dry mixing; duration of wet mixing; visual or other observations (including weather, variation in materials, variation in methods, or other). A sample filter mixture log can be found in Annex F.

Health and safety precautions recommended for processing clay and burn-out material (section 4.2.4) should be observed when preparing the filter mixture. Facemasks which cover the nose and mouth are particularly important to wear. Since clay dust can remain airborne for several hours, facemasks should be worn not only during mixing or by those mixing but in any area clay dust could be airborne.

5.4 Wedging, Pounding, Kneading, Pug Mill

Figure 5-2: Pug Mill (Thirst-Aid 2009)

A clean surface for wedging or kneading filter mixture and a scale to weigh the mixture, and where used, a pug mill, are needed for preparing the mixture to be pressed.

Filter mixture should be manually kneaded, wedged and/or thrust against the surface to remove air bubbles and reduce imperfections in the clay this may also aid in aligning and compacting clay particles, which can improve consistency and strength. Some factories process the mixture through a non de-airing pug mill (Figure 5-2) and in Nigeria, filter mixture is pounded in a mortar and pestle. It is recommended that filter mixture be processed through a pug mill, where available, as it should improve the plasticity and strength of the filter mixture.

The table or work surface should be a comfortable height and workers should use the weight of their whole body while wedging and not just their neck and shoulders.

5.5 Pressing

The Myanmar factories started using non de-airing pug mills at all of their factories after finding that it resulted in much stronger filters.

5.5.1 Press

A press with a mold should be used to press the filter mixture into shape. The press and mold were designed because of the difficulty in producing consistent filters manually; therefore, hand pressing or throwing filters on a pottery wheel is not recommended unless manufacturing consistency and quality is proven with microbiological testing at an independent laboratory.

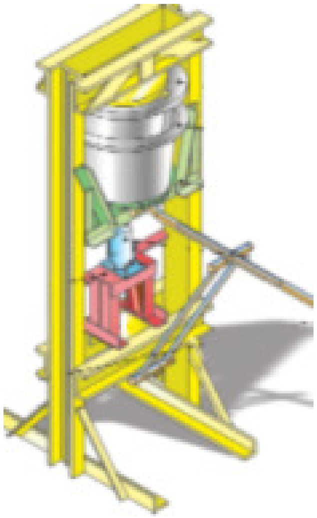


Figure 5-3: PFP Dutch Press

The use of an 8-32 ton capacity hydraulic jack decreases labor requirements and increases efficiency and consistency of product. A jack with more capacity will last longer, but the design of the press should be taken into consideration. The PFP Dutch Press is designed for a 20 ton capacity jack, although a 32 ton capacity jack will work and make pressing easier, it could cause the press to break down. Jacks used for pressing oblong filters have an 8-ton capacity and in Myanmar they use 10 ton capacity hydraulic cylinders.

Labor requirements will be reduced if the jack is above the molds (Figure 5-6) so pressure is applied downwards as opposed to “jack-upward” press designs where the jack is located beneath the molds (Figure 5-3). Using a mechanized press further reduces the labor requirements; however, the press will need a stopping device to ensure even filter thickness and to prevent the mold from getting broken. See Figure 5-4, Figure 5-5, Figure 5-6 and Figure 5-7 for pictures of different kinds of presses. The main requirements for a press are: 1) even pressure distribution; 2) consistent amount of pressure; and 3) ergonomic and safe for employees.

5.5.2 Mold

SL-2 found that coconut oil did not work as a mold release with an aluminum mold; however after switching to a cast iron mold it worked.

The mold determines the size and shape of the filtering element and can be made out of cement (FilterPure), cast-iron, aluminum, or carved from teak wood. The mold material used will also influence the type of mold release that can be used. In Myanmar, they have found that carving molds from teak wood is an inexpensive way to make molds for making prototype filters. See Annex H for instructions on making a cement mold.

Currently three filter shapes are being manufactured: flat-bottomed (7-11 liter capacity), oblong (6 liter) and semi-spherical (10 liter) (Figure 3-9). A rounded filter wall may be stronger than a straight profile and it could be less likely that the user will place the outside of a round bottomed filter on a dirty surface potentially contaminating it, or be tempted to use it as something other than a filter, such as a flower pot or a stool. In general, shorter filters will have a slower flow rate due to reduced hydraulic head. Larger filters take up more space in manufacturing and transport, but with a greater surface area they may be able to accommodate a higher flow rate.

Figure 5-4: Filter Press with aluminum mold, Indo-2 (Pelita 2009)

Figure 5-5: Filter Press with cast-iron mold, Cam-1 (IDECambodia 2009)

Figure 5-6: Filter Press with wooden mold, Myanmar (Thirst-Aid 2009)

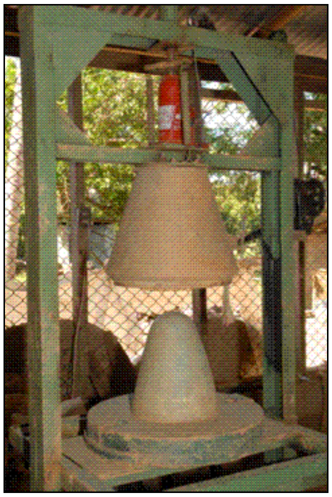


Figure 5-7: Filter Press with cement mold, DR
(FilterPure 2009)

Regardless of shape, the relationship between the filter element and receptacle is important in that enough space should be available in the receptacle below the bottom of the filter for stored water as once the water level reaches the bottom of the filter the flow rate will slow significantly. The diameter of the filter rim is usually determined by the size of locally available receptacles as filters should fit the receptacles closely to ensure proper filtration and prevent debris and insects from getting into the filtered water.

The mold can be installed on the press either male above and female below, or female above and male below. Where round-bottomed filters are produced, having the female above and male below reduces handling of the wet filter as the filters would need to be flipped upside-down when transferred from the press to the drying rack.

Molds can be checked for proper alignment by cutting a freshly pressed filter lengthwise in half or quarters with a piece of wire or fishing line. The wall and base thicknesses should be measured and compared at various heights with calipers (Figure 5-8 and Annex E).

Figure 5-8: Checking Mold Alignment

5.5.2.1 Mold Release

Plastic bags are the most common form of mold release used by filter factories. Some factories use oil such as coconut or palm oil. Since plastic bags can leave crease marks on the filter walls, using oil as a mold release reduces handling of the filters as some surface finishing requirements would be eliminated. Filter factories may choose the mold release that works best for them taking into

To reduce the need to smooth crease lines caused by plastic bags when pressing filters, Cam-1 is testing coconut, vegetable and fish oil as alternative mold releases.

consideration effectiveness, cost in terms of materials and labor, and environmental impact.

5.5.3 Pressing

Since clay particles arrange themselves perpendicularly to the pressure applied, the amount and consistency of pressure will affect filter strength. Both the moisture content of the filter mixture and the amount of mixture placed in the mold will influence the amount of pressure required to get the molds to their stopping position. It is therefore important that filter mixture be of a consistent moisture content, that the same amount of mixture, by weight, is used to press each filter and that it be placed similarly in the mold each time. The quantity of filter mixture will depend upon the shape, size and volume of the mold. Enough mixture should be used that a small amount squeezes out between the molds. The traditional PFP flowerpot-shaped filter with a fired capacity of approximately 7 liters, pressed in a manual press with a 32-ton capacity truck jack, requires approximately 7.5–8 kilos (16 pounds) of mixture. Pressure has been measured at approximately 11 ½ tons to press a flat bottomed filter (Cohen 2010).

The area of the factory used for shaping and pressing should be kept clean and free of debris. Trimmings that have fallen on the floor or excess material squeezed from the molds should not be incorporated into a filter. If the molds do not release easily after pressing, a rubber mallet can be used to separate the molds, but the filter should be discarded and a fresh amount of mixture used to press a fresh filter.

The freshly pressed filter element is very soft due to its high water content; therefore, it should be handled carefully while moving it from the press to the drying rack to prevent deformation and warping. The removal of the filter from the mold will vary depending upon filter shape and press design. With traditional PFP flat bottomed filters, before removing a filter from the press, a flat piece of wood is placed on the rim to prevent it from distorting, while the bottom is supported by a metal disk. The press operator is advised to touch only these two pieces, not the filter itself, when transferring the filter to the drying racks. Some factories place a ring tool in the filter opening while moving the filter to the drying rack to prevent distortion of the rim. Depending on the weather conditions, and if a damp room is not available, a plastic bag can be used to cover the filter so it will dry more slowly and evenly.

5.6 Surface Finishing, Stamping and Drying

Drying can take three days to three weeks, depending on weather conditions. Filters should be monitored throughout the drying process to ensure they are drying evenly. Since drying the filters slowly and evenly is particularly important, filters should be placed in an area with controllable conditions protected from wind, direct sun and rain. As water evaporates from the filter mixture, the clay particles move closer together causing the filter to shrink. The finer the clay particle size, the more water there is between the pores and the more it will shrink. Warping and cracking during drying results from the stress caused by unequal shrinkage from different rates of water loss from the surface than from the interior, or if one part of the filter dries out more

Indo-2 dries filters on rolling racks and relocates them to near the kiln so the warmth accelerates the drying process.

quickly than the other (Figure 5-9). Often cracks and warping caused by uneven drying do not show up until after the filter has been fired (section 6.8.7). Non-plastic particles, such as sand or grog, reduce the shrinkage rate and aid in even drying because they take up less water than the clay, dry out more easily and leave channels for moisture to escape to the surface (Hamer 2004). The amount and the absorbency of the burn-out material will also influence even drying and the shrinkage rate.

Figure 5-9: Uneven Drying
(Source unknown)

Ideally, filters should be allowed to dry in a damp room, which has a humid environment, covering filters with plastic bags has a similar effect. Plastic bags can be removed gradually as the filters dry. Drying filters on shelves made of slats allows for better air circulation and more even drying. If dried too slowly, however, mold can develop on the filters and unattractive marks left from the mold do not fire out.

Once the clay particles are touching, although the clay is still wet, the majority of drying shrinkage has taken place. Potters are familiar with this as the “leather-hard stage”. The piece will appear about half way between wet and dry: it can be moved and worked on with less chance of distortion, resist any major intentional distortions but will not be too dry to resist any changes made to its surface. For these reasons, the “leather-hard” stage is the optimal time for any surface finishing required as well as the application of identifying stamps.

If any surface finishing is required to ensure the rim is strong and the surface is even, it can be carried out at this time, though filters should still be handled as little as possible. Wrinkles or crease marks left from the plastic bags used to separate the filter from the mold should be smoothed over, as these may later open up into full-fledged cracks in the firing. Small voids can be filled in with wet filter mixture. Additionally, some factories roughen up the outer surface of the filter with a hacksaw blade to counteract the compression caused by the smoothing.

The final step in surface finishing is to stamp each filter with a batch, serial number and logo. A simple numbering system is to have one lot equivalent to one firing. Each filter can be labeled with a sequential number, and recorded in the production log along with the: mixture batch; date of pressing; weight of mixture put in press; date of surface finishing; and any additional observations including weather, drying conditions, visual appearance, or other important observations. A sample form is included in Annex F.

Once surface finishing is complete, the filter is again left to dry gradually; however at this point, slow drying is less critical. Potters can usually tell when clay is dry because it will get lighter in both weight and color and wet clay is much colder to the touch. Dryness can also be measured by comparing the weight of the filter to the weight of a known dry filter. Filters that are dry or nearly dry should never be patched; if any defects are observed they should not be corrected, but rather, the filter should be destroyed.

Since filter production can be limited by drying time, drying racks, kilns and firing, production should be scheduled so that the facility can meet demand throughout different weather conditions, such as the rainy season. Either more time, and shelving, is allowed for drying during the wet season, or production can be increased during the dry season. Although production capacity is not strictly a quality issue, production is affected by these limiting factors and rushed drying can become a quality control issue.

SL-2 has converted a large kiln into a drying room and warms it to 45℃ for two days using leftover charcoal from previous firings.

Throughout the drying process, filters should be inspected visually for cracks, deformation, warping, holes, large pieces of burn-out material and even wall thickness. Filters which do not pass visual inspection should be destroyed and the filter mixture should not be reused to make other filters, but rather can be used to seal the kiln door or for non-filter making purposes. Reasons for discard and observations should be recorded on the filter log.

Where electricity is available, fans can be used to ventilate the workshop, by increasing air flow, the humidity in the workshop is reduced, which will aid in drying. Fans should only be used after filters have dried to a leather hard stage and should not blow air directly on the filters. The fans should be cycled on for 3-4 minutes at a time and off for 15-20 minutes. This allows water to migrate out of the drying filters and is less likely to cause cracking than constantly operating fans (Cohen 2010).

Once filters are in the final stages of drying, they can be placed on shelves near a kiln being fired, or even in a warm kiln. Ideally, filters should be completely dry before firing. If this is not possible because of the climate “close to dry” filters can be heated in a kiln to no more than 100℃ for four hours. If the temperature remains below the boiling point of water, moisture will evaporate, not boil, out of the pores, thus drying the filters. Alternatively, the kiln can be heated to 100℃ the night before, closed up and left overnight. The walls should retain enough heat to dry the filters overnight.

In Nigeria, locally made convection ovens can dry filters in two hours; however filters are usually left to dry naturally.

Clay can be dried successfully in traditional pottery production and some factories have experimented with artificially drying filters. This is not recommended since the internal pore structure of the filter could become damaged.

5.7 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) Before establishing a factory, it is recommended that a production manager visit a fully functioning filter factory;
2) An experienced filter producer and local potters should be involved when setting up a factory and developing the mixture ratio;
3) Effluent water from prototype filters should be tested for heavy metals and inorganic chemicals before commencing production;

4) The appropriate clay:burn-out ratio should be determined at project outset, and used consistently throughout production; changes in ratio should be confirmed with microbiological testing of finished filters;
5) To confirm clay:burn-out ratio, a minimum of 9 prototype filters from 3 different batches should be tested and achieve 99% (2 log) reduction in microbiological indicators;
6) In normal production, raw materials should be measured by weight, not volume and burn-out material should be dehydrated prior to weighing it for filter mixture preparation;
7) Mixed dry materials should be inspected visually for even distribution of clay and burn-out prior to adding water;
8) Filters manufactured from the same batch of filter mixture should be kept together throughout production and fired in the same kiln-load;
9) A standard weight of filter mixture should be wedged, kneaded or thrust prior to pressing. Filter mixture should be processed through a pug mill, if available;
10) A press with a high-quality mold should be used to press the filter into shape, the filter should be handled as little as possible after pressing to prevent warping;
11) Filters should be stored in conditions that allow them to dry evenly and protected from direct sun, wind and rain. Artificial drying is not recommended;
12) Once leather-hard, each filter should be stamped with a batch, filter number and logo; a detailed production log which documents the manufacturing process for each filter should be kept;
13) Filters should be inspected visually after pressing and periodically throughout the drying process for deformation, even drying and cracks or holes. Once beyond the leather hard stage, filters should never be patched. Rejected filters should be destroyed and the mixture should not be re-used to make filters;
14) Health and safety guidelines should be strictly enforced; facemasks should be required to be worn by anyone exposed to airborne particles.

5.8 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) How does storing prepared mixed cubes before pressing affect filter performance, for example does sawdust expand and increase pore size or is plasticity increased?
2) What are the impacts, if any, on filter effectiveness if dried unfired filters are pulverized, screened and reprocessed into future batches of filter mixture? If acceptable, what is the maximum percentage of reprocessed material that can be safely introduced to the mixture batch without compromising filter effectiveness?
3) What is the acceptable range of clay:burn-out ratios for each of the various burn-out materials, taking into consideration the relationship between flow rate and microbiological effectiveness?

4) How does variation within a given burn-out material (such as different types of trees for sawdust, or different parts of the rice husks) affect flow rate, appropriate clay:burn-out ratio and microbiological efficacy?
5) Is there a visual indicator that can be added in the mix to ensure complete mixing but will not affect filter effectiveness?
6) How does the shape of the filter element (rounded vs. flower-pot shape, size variations such as diameter, depth and volume) affect its strength, hydraulic properties and biological effectiveness? What is the optimal design for filter size and shape?
7) How do the various process variables, such as hand vs. mechanical mixing, the amount of pressure applied in the press, or the use of a pug mill, affect pore structure and fired filter strength?

5.9 Chapter Details

The information for this chapter was collated by Lisa Ballantine and expanded upon and edited by Justine Rayner. Two conference calls were held to discuss topics in this chapter. Participants on the first call included: Mike, Justine, Daniele, Robert, Susan, Lisa, Tracy and Vinka. Participants on the second call included: Burt, Robert, Mike, Lisa, Tracy, Justine and Daniele.

6 Variables: Kilns and Firing

6.1 Introduction

This section has information on kilns, fuel, monitoring and controlling temperature, firing theory and concludes with recommendations for best practice and where further research is needed. Information in this section is summarised from Manny's "Firing the Manny Kiln" (Hernandez 2007) and "The Potter's Dictionary of Materials and Techniques" (Hamer 2004).

6.2 Types of Kilns

Firing is often the limiting factor in production capacity due to the eight or nine hours it takes to fire and 12-24 hours to cool a kiln, therefore, the size, shape and number of kilns should be decided with production level in mind. Size and shape are also a consideration for fuel efficiency. A cube shaped kiln will allow for the most even distribution of heat as all walls in the kiln are equidistant from the center. A factory which produces 60 filters a day will need a 1.25 x 1.25 m (1.95 m^3) interior kiln space, which has about a 1.5-2.15 meter (5x7 feet) footprint.

Updraft kilns have an opening at the top of the roof where the heat exits. A moveable damper is placed over the hole to control the heat inside the kiln (Figure 6-1). In a down draft kiln, the heat flows up inside the kiln but since there is no opening in the roof, it is forced down through the wares and exits through the flue opening in the kiln floor before flowing up and out through the chimney. Because it makes this "U" turn, the heat generated is used twice which makes this kiln design fuel efficient (Figure 6-2).

The recommended kiln for filter production is the Mani kiln, a down-draft kiln specifically designed for filter production. Other kilns may be used provided they fire evenly, with less than one cone differential in heat distribution, and produce consistent results. Heat distribution can be evaluated by Kiln Temperature Mapping, instructions are provided in Annex D.

Any kiln should be housed under a shelter with sufficient overhang to prevent it from getting damp or wet as firing a wet kiln will take longer and use more fuel.

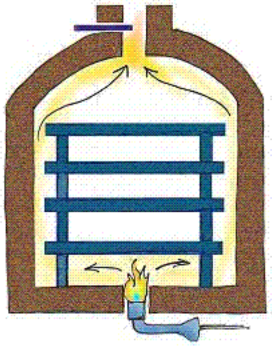


Figure 6-1: Heat Flow in an Up-draft kiln

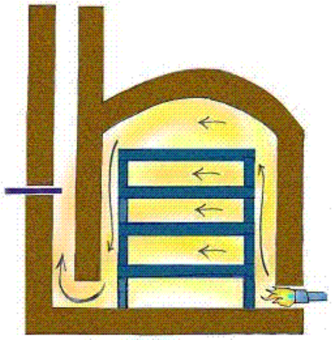


Figure 6-2: Heat Flow in a Down-draft kiln

(Peterson 2009)

Myanmar did not have success firing with rice husks; although they fired successfully with oil, it was too expensive.

The first firing of a newly constructed kiln will take longer than usual because the kiln will still be wet after construction. How the kiln reacts to factors such as outside temperature, wind and the characteristics of the fuel used can be determined and adjusted for in the first few firings. After the first few firings, from candling to target temperature, which should be about 850˚ to 900˚C (1560-1650˚F), should take eight or nine hours. If alternative fuels are used with a blower/injector system, the firing could take less time, however an eight-hour firing is recommended to ensure that all the processes are properly carried out (see section 6.7). Cooling should take between 12-24 hours. New kilns and kilns producing inconsistent results should be mapped for variation in temperature (Annex D).

6.3 Fuel Options and Storage

The three types of fuel used in filter production are firewood (treated lumber should not be used as they might produce toxic fumes or leave residue on the filters), oil and propane. Agricultural waste is an important alternative fuel source, however; although some factories have experimented with it, none currently fire with agricultural waste. Both optimal kiln size and design for maximum efficiency to reduce the amount of fuel required for firing and further experimentation firing with agricultural waste is encouraged.

If firing with wood, wood should be cut to approximately 50 cm long (20 inches) and thick wood should be separated from thin wood. Thicker pieces of wood burn slower and longer and should therefore be used in the early stages of firing. Thin pieces can be used in combination with thicker pieces towards the end of the firing to raise the temperature. In Colombia, about 600 kg of wood is used to fire 125 filters. At least one factory commented that firewood might not come from legal cutting (Rayner 2009).

At the Benin factory, kilns are fired with oil. Oil and water are dripped onto a metal stair placed at an angle in the firebox; the water helps vaporize the oil to produce a flame. With a fire lit under it, the metal plates are heated. Oil, stored in a raised oil barrel, is gravity fed, drips onto the top step of the metal plate and subsequently drips onto the lower steps. A container of water is also plumbed directly over the top metal plate. Both the oil and water have shut-off valves. Approximately 5 drops of water to one drop of oil is used.

Cam-1 successfully fired with rice husks and a blower system; however, kilns are fired with wood since it is available.

Only the Yemen factory fires with propane. When using propane, the Yemen factory recommends using several smaller canisters which helps maintain pressure.

Electricity is required to fire with agricultural by-products, such as rice husks or sawdust. Wood is used to start the firing, then, when up to temperature an alternative fuel injector system blows the agricultural waste into the firebox.

Fuel should be kept dry as the firing will take longer and use more fuel if it is wet. During storage, fuel should not be covered with plastic tarp, as it will hold in the moisture preventing it from drying. If a plastic tarp is used, it should be uncovered when the sun is out and covered overnight to protect it from rain. Alternative Fuel (AF) such as sawdust, rice husk, or other agricultural by-product, should be kept in sacks after it has been sieved and dried in the sun. The alternative fuel injector and/or blower system should be kept under cover when not in use.

Cam-2 found the cost of experimenting with alternative fuel high; injected rice husks did not burn properly, produced a lot of ash and the cost of electricity made it too expensive. Machines for making compressed fuel logs were not durable enough.

6.4 Mani Kiln

The Mani kiln is a downdraft kiln (section 6.2) designed specifically for filter production because existing smaller updraft kilns were found to be inefficient and did not have the capacity to fire a large number of filters. This larger capacity more fuel-efficient kiln was designed using the following criteria: 1) simple design; 2) inexpensive to build; 3) fuel efficient; 4) capable of using alternative fuels; and 5) can be built using local labor and materials. Mani Flat Top or Mani Arch Top kilns are currently being used by 16 factories.

Understanding the Mani kiln and its design should aid in successful firings. Although some of the following recommendations are specific to the Mani kiln, some recommendations will be transferable to any firing. Listed below are some of the features that have been designed into the kiln that the potter and/or kiln master should be aware of when firing the Mani kiln.

6.4.1 Flat top Design

Figure 6-3: Flat Top Mani Kiln
(Hernandez 2006)

The flat top design, inspired by the Minnesota Flat Top, is not actually flat, but rather a dome where the center is at least one inch higher than the sides. The domed "flat-top" only requires nine inch long (23cm) angle iron corner braces with tie rods and can be built in less than half a day. Where a kiln interior larger than 1m³ is required, an arched-top Mani kiln can be designed since structurally there is a limit to the distance that can be spanned with the domed roof. Mani arch kilns can be designed to hold up to 200 filters. To build an arched roof, an elaborate form with angle iron on all four corners and tie rods to secure the walls from being pushed outward by the weight of the arch are required.

The size of the kiln should be tailored to production capacity, considering mixture batch size, daily production capacity and factory storage capacity. Production can be smoothly coordinated if the kiln holds the number of filters that can be produced in two days, or a multiple thereof, rather than an arbitrary number of filters. This way, production runs can be fired in one firing and time is allowed for the firing and cooling of the kiln.

6.4.2 Kiln Walls

The kilns are built out of common construction grade bricks that have been fired above 1000˚C (1832˚F), which is higher than the 850-900˚C (1560-1650˚F) firing temperature of filters. Since Mani kilns are primarily used in hot climates and kiln walls absorb a lot of heat before being transferred to the wares, the Mani kiln wall is just one brick 15 cm (approx. 6 inches) thick, making it easier and faster to heat the kiln and the wares inside.

6.4.3 Grate Area

A grate was incorporated into the Mani kiln after initial firings found that an accumulation of ash and embers in the firebox did not allow sufficient air for combustion. By using metal rebar to divide the firebox horizontally, wood could be placed on the grate defining the space below as an ash pit. This allowed ash to be removed and the embers spread without disturbing the burning wood. The rebar were designed to protrude out 10-15 cm (4-6 inches) on either side of each firebox so they could be easily removed and replaced when showing signs of wear. Due to a lack of maintenance, however, the rebar often became distorted and difficult to remove. The third generation Mani kiln (3GMK) uses bricks for the grate that can be replaced easily if they break. For this reason, the floor bricks and grate bricks are the only bricks never mortared in place.

6.4.4 Fire Wall (Bag Wall)

The original Mani kilns did not have bag walls to divide the combustion space from the chamber where the filters are stacked, in the kiln. The 3GMKs have adjustable, perforated, stepped back, pyramid design bag walls, about one-third of the interior kiln height, on both fire ports in the rear corners of the kiln. This allows the flame coming into the interior kiln space to be dispersed to the bottom of the kiln as well as upward for more even heat distribution.

6.4.5 Temperature Controls

The Mani kiln has three temperature controls. The manually operated damper in the chimney should be pulled out to the full open position during the preheating stage to allow the moisture to escape, and can be pushed in or out during the firing process to control the draft and pressure within the kiln. The “loose” bricks over the firebox and flue channels, which run under the floor of the kiln chamber, can be separated slightly to allow more heat through the kiln floor, reducing the chances of cold spots. The bricks over the firebox from about the middle of the kiln to the flame port should be separated by about 0.6- 1.25 cm (1/4-1/2 inch). The bricks closer to the flue opening should not be separated, as this will cause the heat to be sucked directly into the flue opening.

The brick over the firebox and Chimney flue can also be put in an alternating rowlock (on its side) and flat position (Figure 6-4). This allows heat from the kiln to get under and into any ceramic ware that is stacked upside down.

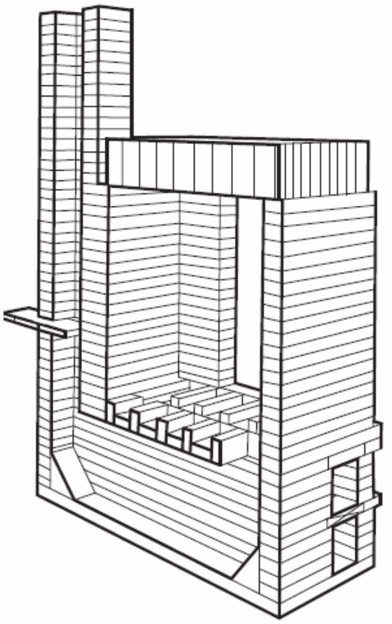


Figure 6-4: Mani Kiln Cross Section
(Hernandez 2007)

6.5 Controlling the Temperature

Fuel, such as firewood, burns in two stages. When a new piece of wood is added to the fire, the wood first gives off volatile gases which burn. In wood, the volatile gases amount to about 80% of the total mass, the remainder is in the form of fixed charcoal. The flames of the fire are these burning gases and they often do not touch the firewood. After the volatile gases have escaped, only charcoal is left which burns with gentle blue flames. The main challenge is to ensure a good strong fire with just the right amount of air needed to combine with the carbon of the fuel. The greatest rate of temperature rise will be at the stoichiometric balance (ideal air-fuel ratio), which is when there is just enough air to burn all of the fuel indicating complete combustion. The color of the flame should also provide an indication of the air-fuel ratio. If too little air is let in a reduction atmosphere will be created and some of the volatile carbon gas will go out the chimney unburned, this will be seen as black smoke which translates into wasted fuel. If too much air is allowed to enter, it will have a cooling effect and this too is a waste of fuel.

Primary air (PA) enters and passes over the embers that have collected at the bottom of the firebox just below the grate. As the PA enters through grate brick openings, it helps burn the carbon gases being released from the burning wood on top of the grate. Most of the PA is used to burn the volatile gases released from the charcoal in the ash pit, so quite often there is little air left to burn the volatile gases being released from the burning wood on the grate. The secondary air (SA) entering above the wood on the grate promotes complete combustion of these gases. By dividing the air inlets above and below the firebox with a grate, less air is needed and less cooling of the kiln takes place (Figure 6-5). The damper can also be used to control the amount of SA drawn into the kiln. By closing the damper, pressure is built up in the chamber and less secondary air is drawn in through the firebox.

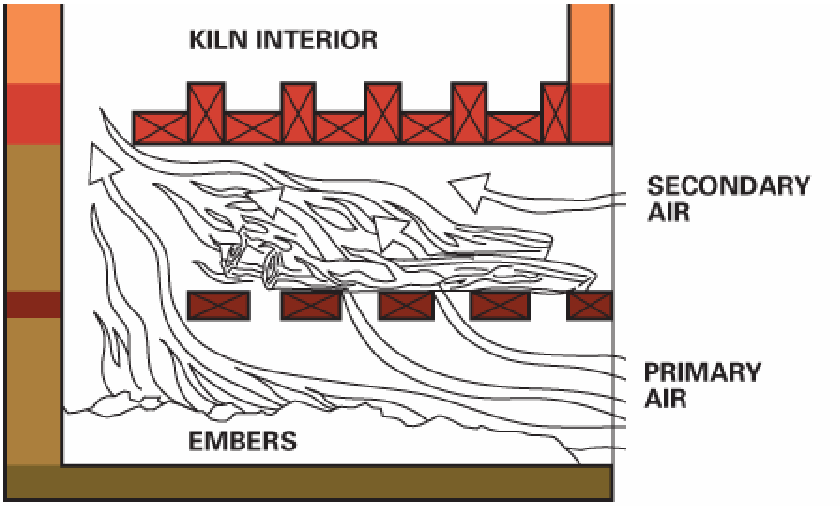


Figure 6-5: Cross Section of Ash Pit and Firebox (Hernandez 2007)

Wood should be spread out evenly on the grate so that air has easy access to it. More wood does not mean more heat. The balance between fuel and oxygen promotes complete combustion, which translates into heat. Too much wood on the grate will keep the SA from entering over the burning wood, preventing complete combustion.

For firewood, the distance between the grates should be 15-20 cm (6-8 inches) so that the wood will fall into the ash pit as soon as it is nearly burnt out. If there is not enough space between the grates it will prevent the burnt wood from falling through the grate and prevent sufficient SA from entering. If there is too much space between the grates, big pieces of wood can fall through which could block the access of PA. The ash pit should be as big, or bigger, than the area above the grate because a thick layer of embers is needed to preheat the PA. Embers should not be allowed to pile up to the point where they prevent PA from flowing over the embers, though when raking out embers, a sufficient quantity of embers must be left to preheat the PA.

The Nigeria factory commented that normal firewood does not reach peak temperatures; therefore dense wood must be used.

6.6 Monitoring Heat-work and Temperature

6.6.1 Visually

Experienced kiln masters can estimate the temperature of the wares by the color of the clay during the firing (Annex B). Although this can be reliable with an experienced potter, the use of temperature monitoring devices such as pyrometers with thermocouples and cones is recommended to support visual estimates, to provide specific information about the rate of temperature rise and heat-work, to be able to monitor the stage of firing, to document specific temperatures for preparing graphs for troubleshooting and research and to aid in improving fuel efficiency. Proper safety goggles (for example, welder goggles) should be used to protect eyes from damage caused by looking into the kiln at hot temperatures when monitoring cones or the color of the clay.

6.6.2 Cones

Cones are designed to measure ‘heat-work’, the effects of time and temperature on the wares, as opposed to the ambient temperature in a kiln.

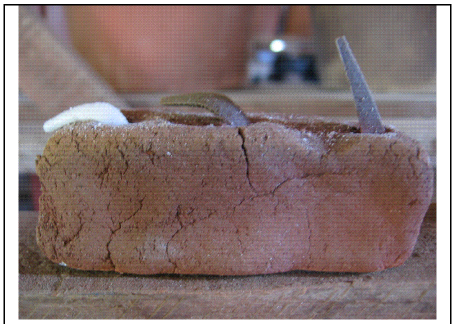


Figure 6-6: Cone Block (Rayner 2006)

Each cone is designed to ‘squat’ or collapse at a certain temperature if arrived at by a specified heat cycle (for example 150˚C (300˚F) per hour for Orton large cones or 300˚C (572˚F) per hour rise for Orton small cones). Cones made by different manufacturers may fall at different temperatures. To give consistent feedback, cones should be placed at the same angle, considered collapsed at the same position and placed in the same place in the kiln in each firing. Cones should be set at an 8˚ angle and should be considered collapsed when the tip is bent over and level with the base. Three cones of different numbers should be placed in each cone block. By using the three cone method (cones 014, 012, 010, for example) the kiln master has a warning that the desired temperature has nearly been reached when the first cone (guide cone) collapses. When the second cone (firing cone) melts the desired temperature has been reached and the third cone serves as the control (guard cone). If the guard cone melts, the desired temperature has been exceeded.

Cones can be viewed through ‘spy holes’, holes in the kiln wall which can be opened for viewing wares and cones in the kiln. Spy holes are usually located in the upper half of the kiln wall to prevent cold air from entering when viewing the cones. The air coming out of the spy hole will be very hot, therefore, caution must be used to open and when looking inside. Proper welder goggles should be worn to protect eyes from damage.

Cone blocks (sets of three) should be placed in different locations in the kiln to check for temperature variation within the kiln, especially if there is concern that the kiln is not firing evenly. After the firing, the temperature reached in different parts of the kiln can be established based on the deformation of the cones, thus hot spots and cool spots can be identified.

Cones which do not fall during a firing (including guard cones) cannot be re-used since they have already been subjected to heat-work and thus will not provide an accurate result if used again. If cones appear discolored after firing, either because they were fired too rapidly during the beginning of the firing or there was heavy reduction (not enough oxygen) early in firing, they might have taken longer to fall, giving an inaccurate reading. Brown cones (containing iron) are intended for use in fully oxidized firings therefore, they might collapse early in reduction, when there is not enough oxygen (Hamer 2004: 77-79).

6.6.3 Pyrometer

A pyrometer with thermocouple(s) (Figure 6-7 and Figure 6-8) are used to measure the ambient temperature in the kiln during the firing; therefore, the rate of temperature change during heating or cooling and hold/soak temperatures can be monitored. Although other cues, such as vapour or smoke emissions can provide an estimated temperature, using a pyrometer with thermocouples can aid in identifying: 1) temperature variation in different parts of the kiln during firing; 2) temperature fluctuation during sensitive temperatures; and 3) rate of temperature change. Monitoring these parameters can aid in fuel efficiency, allow for more consistent firings and lead to more consistent results.

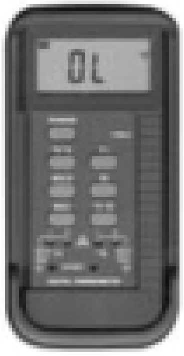


Figure 6-7: Digital Pyrometer (Source unknown)

Figure 6-8: Thermocouple (bottom) and Protection Tube (top) (Source unknown)

Thermocouples can be placed inserted at different levels to measure the temperature in different parts of the kiln. Some thermocouples are manufactured to withstand the shock of being removed during the firing; others should be left in place throughout the firing, in which case, more than one might be needed. If the pyrometer has a dual-read function, two thermocouples can be attached and the reading can be switched between the two during the firing. It is recommended that one thermocouple be inserted in the lower third of the kiln and one just above in the top third of the kiln (not on the side of the kiln where the wood is fed into the firebox). More information on selection and pyrometer and thermocouple sources are included in Annex H.

6.6.4 Draw Rings

To establish if sufficient temperature and heat-work have been achieved to fire out the carbon, a number of draw trials (rings), made of the same filter mixture and approximate thickness of the filters, can be placed in a position where they can be accessed during the firing and fired with the filters. When the desired firing temperature is reached, a ring can be carefully withdrawn through the spy hole in the kiln door. The ring should be broken and examined for the presence of carbon. If carbon remains, the firing should continue and the process repeated until there is no evidence of carbon in the draw ring removed (Cohen 2010).

6.7 The Firing Curve and Firing Process

Clay passes through several stages during the firing process before it becomes a pot, and for some stages it is important to follow the firing curve so that certain processes are successfully completed. Cracking can result from stress caused by uneven drying or from uneven heating or cooling (often called dunting). As the kiln is heated, the outside of the wares get hot before the heat diffuses to the center of the wares; the time required for this diffusion is proportional to the square of the thickness of the piece (Rado 1988). Since filters are thicker than normal pottery ware, the time required for complete diffusion will thus be proportionately longer. Heat and air circulation is important as stacked wares will take much longer to equalize in temperature than pieces placed separately (Rado 1988: 118), for example, with spacers. The internal pore structure of ceramic water filters is very important as internal, invisible cracks can affect the microbiological efficacy of the filters; therefore, extra caution needs to be taken. The following graph shows a typical firing curve for filter production and the stages of firing (Figure 6-9 adapted from (Hamer 2004: 138-143)). A typical firing should take eight or more hours to heat and 12-24 hours to cool. The following sections describe the firing process and provide some recommendations for successful firing.

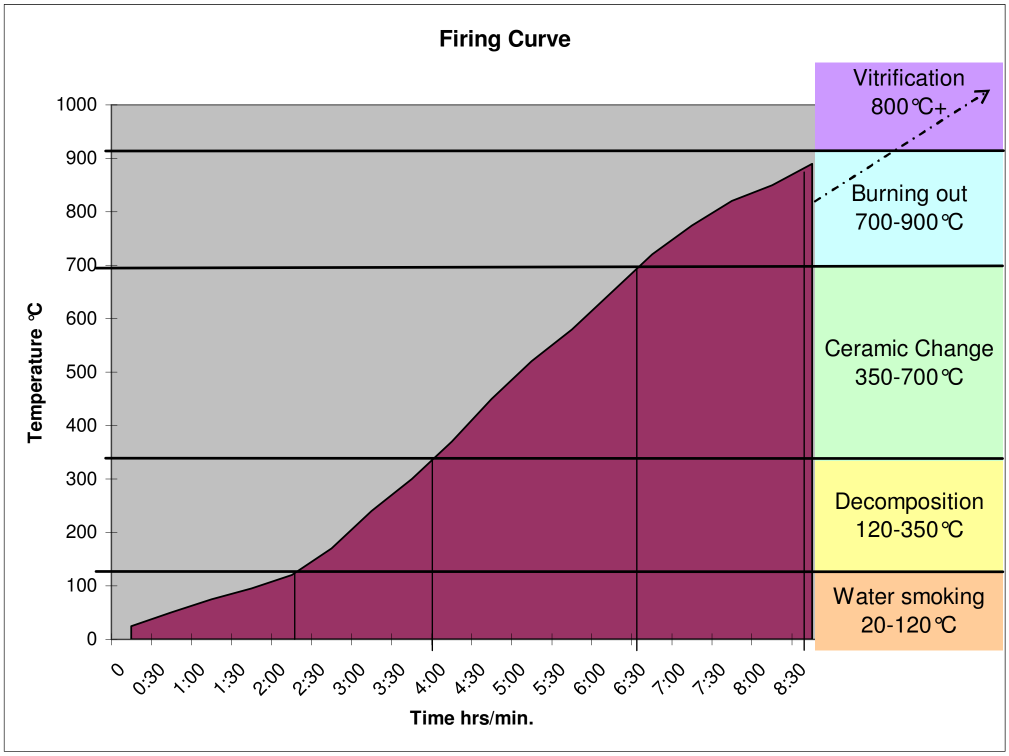


Figure 6-9: Firing Curve and Stages of Firing(Hamer 2004)

6.8 Stacking the Kiln

Before stacking the kiln, the kiln should be inspected for cracks in the walls, floor or roof of the kiln, bent firebox rods, damage to the wall at the end of the firebox, the roof loosing its dome shape or other defects. The bottom of the kiln floor should be as smooth and flat as possible; a layer of sand on the floor can reduce warping and cracking by allowing the filters to move smoothly as they shrink and contract. Filters should be as dry as possible (section 5.6) prior to stacking the kiln. Rivera (2006) suggests weighing the filters to calculate the water loss during drying.

Figure 6-10: Filters Stacked for Firing, Myanmar
(Thirst-Aid 2009)

Figure 6-11: Oblong Filters Stacked for Firing
(Hernandez 2010)

Figure 6-12: Flat bottomed filters stacked in kiln
(PotterswithoutBorders 2010)

The kiln will fire more efficiently and the heat will hold better and be distributed more evenly if loaded to capacity. Flat bottomed filters should be stacked end to end and mouth to mouth with no more than five layers of filters or else the filters on the bottom will not be able to support the weight of the others during the firing. Clay wedges should be used between layers to improve heat and air circulation (Figure 6-12). If done carefully, this can also prevent warping and carbon marks from being left on the filters. Round-bottomed, semi-spherical filters are stacked with spacers (Figure 6-10). Oblong filters are placed either horizontally in the kiln or stacked using especially designed cylindrical clay spacers with cut notches to minimize contact and resulting carbon marks (Figure 6-11).

Filter locations should be recorded on a log either while loading or unloading the kiln, the log provided in Annex F or a version modified to suit factory needs can be used.

6.8.1 Water smoking (20˚-120˚C / 68˚-248˚F)

Before starting, the damper should be in the full open position, the spy holes unplugged and the door built up to about three courses of bricks from the top. An initial fire should be started in the ash pit with a few larger pieces of firewood so that the firing begins slowly, which also helps in building up a layer of embers. This is called a candling flame. It is necessary to continue this candling flame until all the moisture has been evaporated from the kiln interior and wares stacked inside.

This first stage of firing, ‘water smoking’, is when the pore water remaining in the filter walls due to atmospheric humidity (section 5.6) evaporates. As the temperature rises the water turns to steam; if heated too quickly pressure will build and crack or break the filters. It is therefore important to raise the temperature slowly up to the boiling temperature of water (100˚C or 212˚F); although in a typical pottery firing this could take fewer than two hours when firing filters, due to their thickness, the kiln master should take 3-4 hours to get to 150˚C (300˚F). When wood or alternative fuels are used a mirror, piece of metal or a cold, glazed surface can be held next to one of the vent openings to check for steam and vapor. Use a glove or some kind of protective cloth to do this because the air coming out of the opening is hot.

The water smoking stage is complete when steam is no longer coming from the vents. When firing with natural and liquid petroleum gas, a pyrometer must be used to gauge when the water smoking stage is complete since these fuels produce vapor as they burn. Once this stage is complete, it is then safe to raise the temperature more quickly by placing the combustible further inside the firebox. At this point, a fire can be started on top of the grate and the openings, except for the damper, which is used to regulate the air entering the kiln, can be closed.

6.8.2 Decomposition (120˚-350˚C /248˚-662˚F)

At about 200˚C (392˚F), vegetable matter remaining in the clay breaks down. The burn-out material does not fire out during this phase, but rather during the ‘burning-out’ phase. The temperature between 120˚C and 350˚C can be raised quickly because although the filters will expand slightly during this phase, there is not much risk of cracking or breaking.

Figure 6-13: Kiln being Fired, Cam-1
(IDECambodia 2009)

6.8.3 Ceramic Change (350˚-700˚C / 662˚-1292˚F)

Between 350˚C and 700˚C the clay becomes ceramic. Water vapor will escape from the vents as the chemically combined water leaves the filters. At around 600˚C (1110˚F, dull red range), the clay particles are sintered together resulting in very slight shrinkage.

6.8.3.1 Quartz Inversion (573˚C / 1063˚F)

The quartz inversion, when the quartz in the clay rearranges itself, occurs around 550˚C/1022˚F to 573˚C/1063˚F. There is a risk of cracking caused by the sudden expansion during heating and contraction during cooling, therefore; temperature change should be gradual around this temperature, especially if the kiln does not fire evenly (see Figure 6-16, note the top temperature drops at this point to accomplish this).

6.8.4 Burning-out (700˚-900˚C / 1292˚-1652˚F)

This process, sometimes called oxidation, is when the carbon and sulfur present in clay are burned out. This process starts at 700˚C, reaches its peak at around 800˚C (1472˚F) and most of the carbon will have been burnt out by 900˚C. During this process, filters won't change in size. In order to ensure this process is thoroughly completed, sufficient oxygen should be present and either the rate of firing should be slowed down or the temperature should be held at around 800˚C or 870˚C for at least an hour. If this stage is hurried and all of the burn-out material doesn't combust, a black core will remain when the filter is broken open. One way of confirming that the burn-out has successfully fired out, a number of draw trials (rings) made of the same filter mixture can be fired with the filters. Rings can then be carefully withdrawn through the spy holes in the kiln door, broken and examined for the presence of carbon. If carbon remains, the firing should continue and the process repeated until the carbon has successfully been burnt out (see section 6.6.4).

Although two factories aim to leave a carbon lining in the filter wall, until further research on the effects on microbiological effectiveness, the useful life of the filter, structural integrity, desired thickness or firing protocol to achieve it controllably, we do not recommend leaving a carbon core in filter elements.

6.8.5 Vitrification (800˚C+ / 1472˚F+)

Vitrification starts at around 800˚C for most clays (when the sodium and potassium oxides within the clay start to flux the free silica). During this stage, the body contracts as the clay particles are welded together with glass, providing strength. The desired level of vitrification will be a balance between the desired strength and porosity of the final product, although a certain amount of strength is needed to withstand the shock of the quartz inversion during cooling. The vitrification temperature will vary depending on the composition of the materials in the clay body, including clay minerals, non-clay minerals (fluxes) and the burn-out material. The vitrification range for earthenware clay is much smaller than for higher-fired clays, meaning that it can quite easily be over fired.

When nearing the desired firing temperature, the peephole is opened carefully, as very hot air will come out, to monitor the cones and the color of the filters. Proper welder goggles should be worn when looking into the hot kiln to protect eyes against damage. Only the first two cones (for example, 012 and 010) should be allowed to melt. The visual clue for this temperature (887℃ or cone 012) in the kiln interior is a cherry red to red orange color (Annex B). The pyrometer should also be monitored. A draw ring, made out of filter mixture, can be carefully removed and broken to check that the carbon has been fired-out successfully (see 6.6.4). Once the desired heat-work has taken place, the firing can stop, the remaining fuel can be removed and the firebox openings are closed off to allow the kiln to cool slowly and to prevent cold drafts from entering the kiln, which can crack or warp filters near the flame port. The damper can also be closed to encourage slow cooling.

6.8.6 Cooling

During cooling, the clay contracts at a regular rate except for during the quartz inversion (550-573˚C/1022-1063˚F). The change in size, which can be up to 3% and occurs every time the quartz passes through its inversion point, can result in cracking due to stress caused by uneven contraction from variation in temperature, therefore both firing and cooling should be gradual around 550-573˚C.

Once pottery has been fired to temperatures above 1100˚C (2012˚F), the temperature change during both heating and cooling around 225˚C (437˚F) should also be gradual to prevent cracking caused by the cristobalite inversion. Since filters are typically not fired to this temperature, quartz will not convert to cristobalite and there will be little risk of crystal change each time this temperature is passed (Cuff 1996: 93).

Kilns are left to cool for 12-24 hours depending on the kiln size and weather conditions. Once the internal kiln temperature is at about 100˚C, the kiln door can be opened. Handling hot filters should be avoided to prevent burns, or heat resistant gloves should be worn. If filter locations were not recorded during the loading of the kiln, they should be recorded upon unloading the kiln. A visual inspection should be carried out and a description of cracks, deformation, discoloration or other important observation, should be noted on the filter log. This may also a good time to carry out acoustic testing (section 8.3.2) and record results.

6.8.7 Cracking

Cracks appear when stress caused by the expansion, contraction or shrinkage is greater than the clay body can absorb. Variation in filter mixture, uneven drying, firing temperature and firing cycle can all contribute towards the forming of cracks. Cracks can appear during drying, though some cracks that appear after firing can also be caused by uneven drying. The widest part of the crack is the point where the crack started and the width of the crack indicates the amount of stress. Cracks in the rim are usually caused by stresses in the raw stage, i.e. uneven drying. Frayed edges and rough faces on the two sides show the crack formed slowly and probably at the making and drying stages, even though it might have shown up after the firing (Hamer 2004).

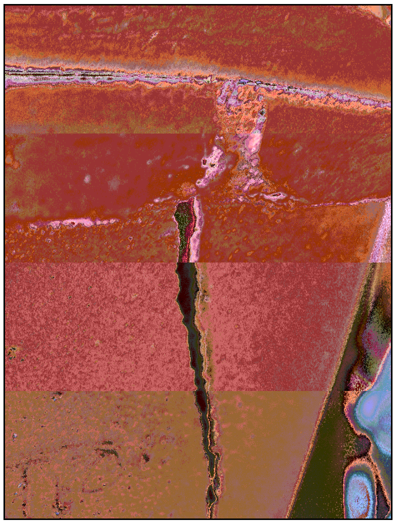


Figure 6-14: Cracked Filters

(L-R: Top: Somaliland (Wagoner 2010), Nicaragua (Rayner 2006), Nicaragua (Rayner 2006); bottom: Myanmar (Thirst-Aid 2010), Somaliland (Wagoner 2010)

Figure 6-15: Firing/Cooling Crack (Pelita 2009)

Cracks caused by stress which form during firing or cooling, sometimes referred to as dunting, can show up as hair cracks and are both concentric with the pot and vertical (Figure 6-15). They can occur when the peak temperature does not get hot enough for the clay to gain enough strength in the vitrification stage to withstand the inversion (sudden contraction) during cooling, causing it to crack. This can be prevented by: 1) firing to a slightly higher peak temperature; 2) slowing the rate of cooling (maximum 100°C per hour from 600°C or 212°F/1112°F); 3) reducing the amount of free silica in the clay (quartz, flint, sand or cristobalite); or 4) by increasing the flux in the clay body(see 4.2.3.1) which will lower the temperature needed to reach maturation (Hamer 2004). Cracks starting at the base and moving upwards or cracks which have a sharp and smooth edge are also usually caused by the firing. If one part of the filter cools before the other, the contraction can occur at different times on different parts of the filter, causing displacement in addition to the crack. These cracks can start at the rim and run downwards curving toward the cooler side. Uniform cooling and preventing drafts in kiln below 600°C (1112°F) can help prevent these cracks (Hamer 2004).

6.9 Firing Log

A firing log should be maintained for each firing. Firing curves can be made from the information recorded and can be useful to visualize and compare firings (Figure 6-16). The log should include: background information (kiln master, filter batch details, date, weather); the time the firing started; temperature measurements from each thermocouple used every 15 minutes/30 minutes throughout the firing; interpretation of visual cues at various stages (steam, smoke output, color of the filters); time to inversion point; soak time from 700-800˚C (1290-1470˚F); peak temperature reached; temperature and time when each cone fell; time firing stopped; temperature and time door opened; cone locations and results; A sample firing log and a sample filter location log for recording each filter location within the kiln are in Annex F.

Equalizing Temperature Differentials in a Wood-Fired Kiln, Robert Pillars

Mani kilns typically fire hot on top; therefore, using two thermocouples can help monitor the temperatures in both the top and bottom of the kiln (section 6.6.3). If both thermocouples are connected to a pyrometer with a dual-read feature, readings can alternate between thermocouples during the firing. By adjusting the stoking rate and the flue damper accordingly, the temperature differential can be reduced.

Upon stoking the fire, the temperature in the top of the kiln will rise quickly yet the bottom temperature will remain steady. As more oxygen enters, and as the wood burns, the top temperature will level out and the bottom temperature will begin to rise. Although the inclination is to stoke the fire when the top temperature begins to decrease, stoking will actually increase the temperature differential between the top and bottom of the kiln by causing the top to rise faster than the bottom. If patience is exercised by not stoking when the top temperature starts to decrease, with more oxygen, the bottom temperature will continue to get hotter and although the top actually gets cooler, the two will gradually begin to approach equilibrium, although they may not meet at exactly the same temperature.

The next stoke should be when the rate of climb of the bottom temperature of the kiln levels out, just before it begins to cool. The process will repeat itself and the firing graph will show a series of ups and downs in the top of the kiln, representing each stoke, while the bottom of the kiln will climb with a uniform upward curve.

In the firing graph below (Figure 6-16) the thermocouple readings from a firing in San Mateo Ixtantán, Guatemala show that after 6:15, the top temperature (black line) fluctuates, the peaks match each stoke. The middle (pink line) shows that the bottom temperature rises quite evenly. The yellow line shows the temperature differential between the top and bottom of the kiln which stays below 100℃ and gradually decreases so that at the end of the firing, when cone 010 fell, there was just a 19℃ temperature difference between the top and bottom of the kiln. The pink line follows the theoretical model in Figure 6-9 very closely!

Although this method will result in the most efficient (minimum) use of fuel as well as the most even heat distribution inside the kiln, in practice, it takes a great deal of discipline to fire this way.

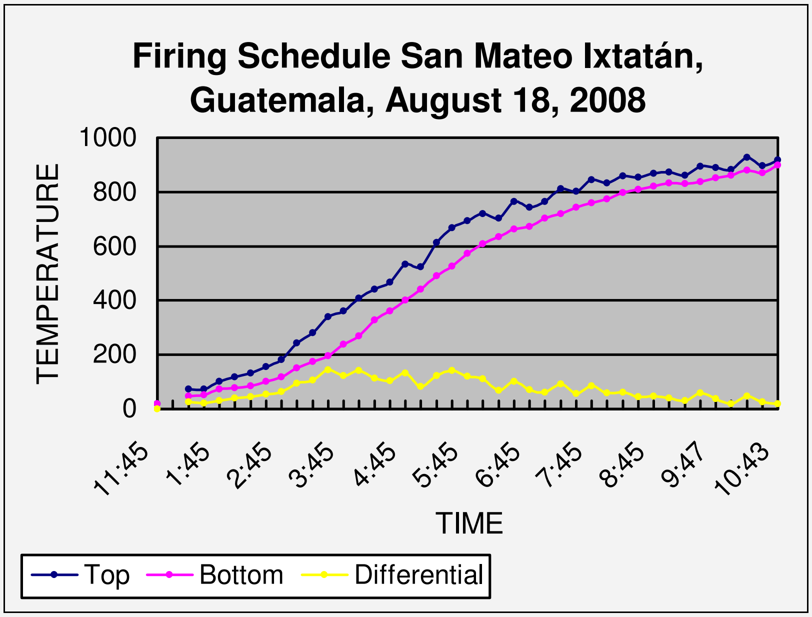


Figure 6-16: Firing Graph, San Mateo Ixtatán, Guatemala(Guate-2)

6.10 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) The number and sizes of kilns should correlate with the factory production capacity, considering mixture batch size, daily production capacity and factory storage capacity ;
2) The use of a Mani kiln is recommended; however, other fuel efficient, reliable kilns which fire evenly and consistently may be used;
3) Filters should be dry before being fired and should be stacked using clay spacers to promote heat circulation and reduce chances of warping, cracking and carbon marks.
4) The location of each filter should be recorded on a log either while stacking or unloading the kiln;
5) Alongside visual monitoring, cones (three cone method) and a pyrometer with thermocouples should be used according to guidelines in this chapter to aid in accurate temperature monitoring, documentation, troubleshooting, fuel efficiency and consistent firings;
6) Efforts should be made to acquire fuel from sustainable sources and experimentation and the use of agricultural waste or alternative fuel sources is encouraged;
7) Firing temperature and firing curve appropriate for local clay should be established and followed and a firing log should be maintained.
8) Fired filters should undergo visual and auditory inspections when unloading the kiln and observations recorded;

9) Health and safety precautions, especially the use of welder goggles when peering into the kiln, should be enforced;
10) Kiln temperature mapping should be carried out with a new kiln, annually or if firing results (filter quality) are inconsistent.

6.11 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) What are the effects of different mold releases on the firing process; do they influence the heating or leave a residue on the finished filter?
2) Does fuel contribute to arsenic leaching from filters? Does heating schedule or peak temperature affect arsenic or other inorganic materials or heavy metals in finished filters?
3) How does the firing profile affect complete combustion of different burn-out materials?
4) How does leaving a black core in filters affect filter efficacy, filter lifespan and can the thickness of the black core be monitored or controlled?
5) What are ways to improve efficiency and cost of firing with alternative fuels? Is there potential for a low-cost system for recycling energy from heat exiting the chimney?

6.12 Chapter Details

The information for this chapter was collated by Manny Hernandez and edited by Justine Rayner. Participants on this conference call to discuss this chapter included: Bill Austin, Bob, Manny, Tracy, Daniele, Mike, Justine, Robert and Vinka.

7 Variables: Silver nanoparticles

In this chapter, information about silver nanoparticles is reviewed, beginning with an introduction to silver nanoparticles (colloidal silver) and how disinfection occurs, followed by a discussion on differences between ionic silver and silver nanoparticles, how silver nanoparticles are produced and the use of silver nanoparticles in ceramic filters. The chapter is concluded with information on environmental and health concerns and a summary of recommendations and research indicated.

7.1 Introduction

Silver and its compounds have been used for disinfection since the age of the ancient Egyptians when silver vessels were used to preserve water and wine (Russell and Russell 1995). Before the emergence of antibiotics, silver compounds were widely used during World War I to prevent infections from wounds. Metallic silver was used to treat surgical prostheses and splints and served as fungicides. Soluble silver compounds were used to treat a range of diseases from mental illness to gonorrhea (Drake and Hazelwood 2005). Even today, silver sulfadiazine is the standard antibacterial treatment for serious burn wounds (Chen and Schluesener 2008). Recent advances in nanotechnology have demonstrated that nanosize particles of metallic silver have strong antimicrobial properties.

A silver nanoparticle (more commonly called colloidal silver) is a fine particle of metallic silver, which has at least one dimension lower than 100 nanometers (or 0.1 millionth of a meter). Nanosilver particles exhibit physical properties that are different from both the ion and the bulk material. Because of their strong antibacterial properties, several studies have shown the potential use of silver nanoparticles in biomedical and environmental applications, such as the treatment of wounds and burns (Furno *et al.* 2004; Maneerung *et al.* 2007) and water disinfection (LePape *et al.* 2004; Jain and Pradeep 2005).

Silver nanoparticles have large surface areas and high reactivities compared with the bulk solid; thus, they exhibit remarkable physical, chemical and biological properties, such as an increased catalytic activity because of their highly reactive facets (Morones *et al.* 2005). This has led to an increase in interest in using nanosilver as a special class of biocidal agents. Sondi (2004) showed that silver nanoparticles are an effective bactericide against *E. coli*. Other recent studies have demonstrated the antimicrobial properties of silver nanoparticles against other pathogenic microorganisms such as *Bacillus subtilis* (Ruparelia *et al.* 2008), *Staphylococcus aureus* (Dubas *et al.* 2006), *Staphylococcus epidermidis* (Panacek *et al.* 2006) and HIV-1 (Elechiguerra *et al.* 2005). Researchers have investigated the bactericidal properties of silver nanoparticles supported by a wide variety of materials, such as polyurethane foam (Jain and Pradeep 2005), a zeolite (Rivera-Garza *et al.* 2000), alumina (Heinig 1993), activated carbon (LePape *et al.* 2002; LePape *et al.* 2004), textiles (Dubas *et al.* 2006) and ceramic materials (Oyanedel-Craver and Smith 2008).

In April 2005, a partnership between the Woodrow Wilson International Center for Scholars and the Pew Charitable Trusts established The Project on Emerging Nanotechnologies. The Project is dedicated to helping ensure that as nanotechnologies advance, possible risks are minimized, public and consumer engagement remains strong and the potential benefits of these new technologies are becoming realized. The project maintains an extensive consumer product inventory with more than 800 products, produced by 420 companies, located in 21 countries. Silver nanoparticles, the active component of more than 20% of the nanoproducts currently available on the market, are the most commonly cited nanomaterial (Scholars 2008). Approximately 88% of these products have demonstrated some form of antibacterial or antimicrobial activity (Fauss 2008). Because of these antibacterial properties, the use of nanosilver products ranges from dietary supplements, to spray-on disinfectants, to anti-odor textile applications see Figure 7-1.

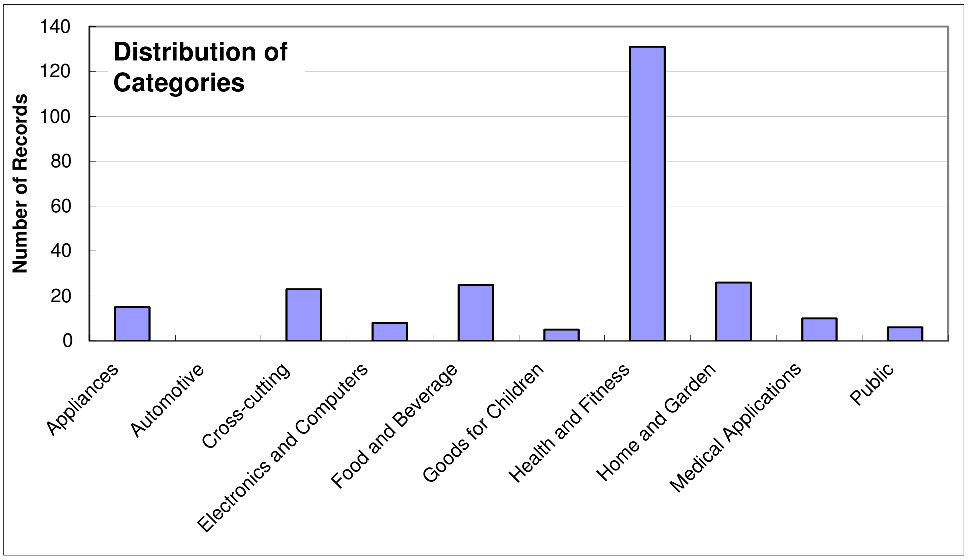


Figure 7-1: Commercial silver nanoparticle products by category

(Fauss 2008)

7.2 Overview of Proposed Disinfectant Mechanisms of Silver Nanoparticles (Colloidal Silver)

Numerous mechanisms have been commonly accepted to explain how silver nanoparticles act as a disinfectant, including: 1) interaction with the cell membrane; 2) silver ions release; and 3) generation of reactive oxygen species (ROS).

Several studies have presented data suggesting that silver nanoparticles may interact directly with the cell membrane to inactivate the cells (Cho *et al.* 2005; Panacek *et al.* 2006; Pal *et al.* 2007; Shrivastava *et al.* 2007). In addition, using images produced with a scanning tunneling electron microscope and an X-ray energy dispersive spectrometer, it has been shown that silver nanoparticles not only attach to the surface of the cell membrane (see Figure 7-2), but also trespass it (Lok *et al.* 2007).

They suggested that silver nanoparticles penetrate inside bacterium and cause damage by interacting with phosphorus- and sulfur-containing compounds.

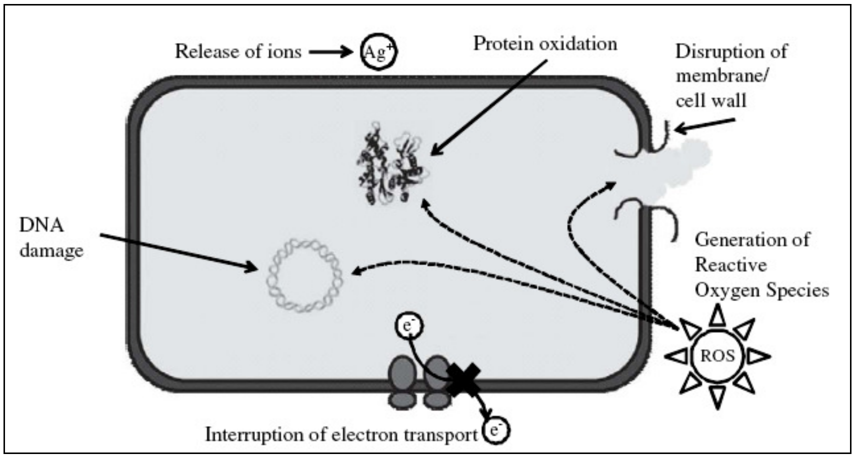


Figure 7-2: Proposed antibacterial mechanism of colloidal silver

(Li. Q. 2008)

Additional studies using different sizes of silver nanoparticles showed that smaller particles are more efficient in inactivating *E. coli* than larger particles (Lok *et al.* 2007). This mechanism implies that physical contact between nanoparticles and bacterial membranes is essential for the disinfection process.

The cell-nanoparticle interaction will depend on the net surface charge of both particles (the cell and nanoparticles). Gram-negative bacteria, such as *E. coli* and other waterborne disease causing organisms, typically have a negatively charged surface at neutral conditions because of the carboxylic groups in their outer membranes (Raffi *et al.* 2008). The surface charge of silver nanoparticles depends on the surface coating. The reported zeta potentials (indicative of surface charge) for silver nanoparticles varied from -30mV for “naked” silver nanoparticles (Merga *et al.* 2007) to +49mV for particles stabilized with cetyltrimethylammonium bromide (Soukupova *et al.* 2008). Positively charged nanoparticles more likely experience the greatest electrostatic attraction to negatively charged bacterial surfaces.

The zeta potential value is also used as an indicator of the stability of colloidal suspension. Higher absolute values (either positive or negative) promote a stable suspension, whereas values closer to zero imply aggregation (an increase in particle size) and possible precipitation of the particles.

The net surface charge will also be affected by the pH and ionic strength of the solution. If the cell-nanoparticle interaction mechanism is responsible for the disinfection properties of silver nanoparticles, then dissolved and particulate compounds in the water could have an important effect on the effectiveness of the disinfection process. The concentration of dissolved inorganic compounds (such as carbonates, sulfates and phosphates commonly present in natural water) determines the ionic strength and therefore the zeta potential, of both the cell membrane and the nanoparticle surfaces. Also, dissolved organic compounds (such as humic and fulvic acids) could be sorbed onto the surfaces of nanoparticles, changing their surface properties.

Of the three mechanisms proposed, the cell-nanoparticle interaction is the one most commonly invoked to explain the antibacterial properties of silver nanoparticles. However, studies using immobilized silver nanoparticles on different surfaces and matrices have also shown a considerable antibacterial effect (Rivera-Garza *et al.* 2000; LePape *et al.* 2002; LePape *et al.* 2004; Jain and Pradeep 2005; Dubas *et al.* 2006; Oyanedel-Craver and Smith 2008). Specifically, a recent study showed that the impregnation of ceramic water filters with a silver nanoparticle solution increased *E. coli* removal (Oyanedel-Craver and Smith 2008). Additionally, these studies suggest that direct cell-nanoparticle interaction could be responsible (or partially responsible) for the biocidal properties of silver nanoparticles.

Other studies have suggested that silver nanoparticle disinfection is caused by the oxidation of the silver nanoparticles and subsequent release of silver ions. It has been suggested that silver ions released from silver nanoparticles penetrate the cell membrane (LePape *et al.* 2002; Furno *et al.* 2004; Maneerung *et al.* 2007) and either react with the thiol group in vital enzymes to inactivate them (Liau *et al.* 1997) or with DNA (Feng *et al.* 2000) resulting in marked enhancement of pyrimidine dimerization by photodynamic reaction and possible prevention of DNA replication. This mechanism does not require a physical cell-nanoparticle interaction; however, it requires the oxidation of silver atoms on the surfaces of the nanoparticles and their release from the solid nucleus. It is well known that silver nanoparticles are highly sensitive to oxidation (Heinig 1993), thus the concentration of dissolved oxygen in water may control this reaction.

The surface areas of nanoparticles will also likely affect the rate of silver-ion release. Smaller particles have higher specific surface areas than larger particles, providing them with a larger area for silver oxidation. The ionic strength of the solution will also influence this process. High concentrations of dissolved ions will promote the aggregation of silver nanoparticles (reduction of the particle zeta potential), reducing the surface area available for Ag^0 oxidation and the release of silver ions. Although silver ions have been detected in solution either by direct measurement (Maneerung *et al.* 2007) or the use of scavengers (LePape *et al.* 2002), other authors suggest that the amount of silver ions released from silver nanoparticles is not high enough to deactivate pathogenic microorganisms (Lok *et al.* 2007; Petica *et al.* 2008).

The last mechanism proposed for silver efficacy was suggested by Heinig (1993) who observed when the dissolved oxygen concentration in influent water was increased from 3.2 to 8.5 mg/L, the bactericidal properties of silver-treated alumina increased. He suggested that silver had a catalytic effect that promoted the oxidation of bacteria and viruses. In studies of the interaction of oxygen and silver clusters, it was found that at temperatures between 77 and 105 Kelvin (K) (the Kelvin scale starts at a theoretical absolute zero which is 273.15˚C below the freezing temperature of water) molecular oxygen chemisorbed to the silver particles (Schmidt *et al.* 2003). At temperatures greater than 105 K, chemisorption was transformed into oxidation, invoking the dissociation of oxygen molecules and the release of highly reactive oxygen atoms (with a –2 oxidation state). This phenomenon was reported in an electron spin resonance spectroscopy study of silver nanoparticles, Danilczuk *et al.* (2006) reported Ag-generated ROS.

Few studies have been performed to support this hypothesis. It has been observed that the addition of superoxide dismutase (the enzyme that catalyses the dismutation of O_2^- to O_2 and H_2O_2)

reduces damage in *E. coli* cell membranes (LePape *et al.* 2004; Kim *et al.* 2007). These experiments did not determine the amount of superoxide produced or the presence of other ROS. Similar to the release of silver ions, the production of ROS depends on the surface area of the particle and the dissolved oxygen concentration in the water. Dissolved organic matter may compete with bacteria for oxidation and specifically, humic compounds could act as scavengers of ROS because of their large aromatic structures. ROS may be effective in the inactivation of pathogenic organisms other than bacteria and because of the high reactivity of ROS, these compounds could be more effective than chlorine in disinfecting spore- or oocyst-forming organisms such as *Cryptosporidium parvum* (Jeong *et al.* 2006).

Although it is clear that nanoparticle silver is effective at inactivating bacteria, the exact mechanism is unclear. The majority of the studies have been performed under different conditions, which makes comparison difficult. In many cases, mechanistic considerations were not the primary focus of the investigation. None of the studies previously discussed determined the optimum conditions for the application of silver nanoparticles as antimicrobial agents in water treatment. It is very likely that the disinfectant action of silver nanoparticles will depend on the properties of each microorganism and the water chemistry in which the disinfection process takes place.

7.3 Production of Silver Nanoparticles

Zero-valent (colloidal) silver can be engineered into fine particles in the nanometer size range. As mentioned above, when at least one dimension of this particles is smaller than 100 nanometers, these particles are commonly called colloidal silver or, more recently termed, silver nanoparticles.

Silver nanoparticles can be synthesized using a variety of techniques, including chemical reduction methods (Soukupova *et al.* 2008), irradiation methods (Long *et al.* 2007) and electric spark discharging methods (Tien *et al.* 2008).

7.3.1 Chemical Methods

The most common way to synthesize silver nanoparticles is the chemical reduction of a silver salt solution, such as silver nitrate, by a reducing agent, such as borohydride, citrate, ascorbate, or a reducing sugar (Soukupova *et al.* 2008). The size of the particles can be manipulated using various reducing agents in the reaction, for example, using disaccharides as a reducing agent yields a smaller particle size than using monosaccharides. The reduction of silver ions in aqueous solution generally yields silver nanoparticles with particle diameters of several nanometers. Initially, the reduction of various complexes with Ag+ ions leads to the formation of silver atoms Ag^0, which is followed by the agglomeration into clusters. These clusters eventually lead to the formation of silver Ag particles.

The synthesis of colloidal silver by chemical reduction methods is often performed in the presence of stabilizers in order to prevent unwanted agglomeration of colloids. Some stabilizers commonly used are polyvinyl alcohol, bovine albumine, citrate and starch. Solid surfaces can be used to stabilize colloidal particles. In this case, silver nanoparticles are formed and immobilized on the surfaces of different solid materials which can be added to solid matrices or can provide settling properties (solid/liquid separation). Clays such as montmorillonites, zeolites and laponites, silica spheres, hydroxyapatite, ceramic and cellulose fabrics are the more common surfaces used for this purpose.

7.3.2 Irradiation Methods

Colloidal silver solutions can be prepared without the addition of chemical reducing agents by the photo-irradiation of a silver source (such as silver salts). This process has been used since the 18th century for photographic film emersion (Long *et al.* 2007). Lasers, microwave, UV-light and white light have been reported as irradiation sources for the formation of colloidal silver. Silver nitrate and silver perchlorate have been used as silver sources for irradiation methods.

7.3.3 Electrochemical Methods

Electrochemical methods are also called "sacrificial anode methods" or "electric spark discharge". In this case, two silver wires are used as electrodes (positive and negative). The silver electrodes are placed in a high voltage setting so that silver nanoparticles are synthesized through a sparking process. This creates sufficient zeta potential for a stable silver nanoparticle aqueous suspension (Figure 7-3).

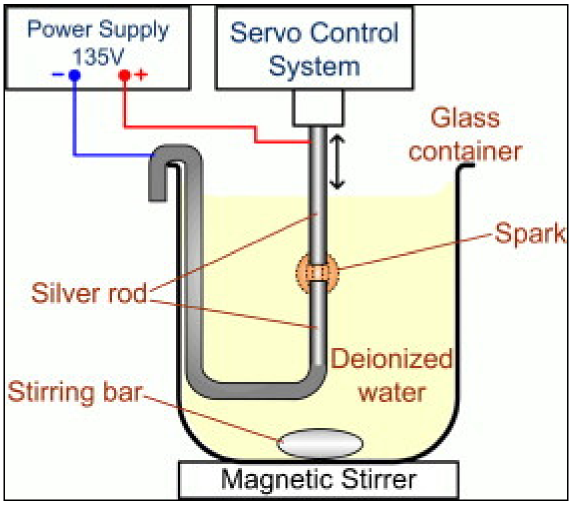


Figure 7-3: Schematic of system used for electrochemical reduction of Ag+ to Ag^0

7.4 Silver in Ceramic Water Filters

Silver is applied to the filter to achieve two objectives: 1) to take advantage of the bactericidal quality of silver in the purification of water as it is filtered; and 2) to prevent the growth of the "slime layer" of bacteria that can form on the filter wall. Organizations implementing ceramic filter programs currently apply different silver products to ceramic filters. A summary of different products and application methods by organization is presented in Table 5 and section 3.10. The most commonly used silver nanoparticle is Collargol (powder) produced by Argenol laboratories. The zero-valent silver nanoparticle content of Collargol is produced through chemical reduction of silver nitrate (Ag^+ and NO_3^-). After the reduction process a protein is added to stabilize the nanoparticle suspension. The total amount of silver in

Collargol varies from 70% to 75% in weight. Other silver compounds used in ceramic filter factories are Ultra Silver, distributed by Snow Fresh (colloidal silver used by the Ixtatán Foundation), a 3.2% liquid colloidal silver sold by Argenol Laboratories, a 3.2% liquid colloidal silver sold by Reickerman-Spraylat and silver nitrate (RDI-C, Indo-2 and ThirstAid). The main reason for switching to silver nitrate from colloidal silver is the lower price and local availability of silver nitrate. RDI-C claims that most of the silver nitrate is reduced to Ag^0 either through photo reduction or chemical reduction once applied to the ceramic filters because some inorganic groups in the ceramic matrix could act as a reducing agent (personal communication with V. Craver, 2009). Information was not provided to support these claims; however, the organization says the results will be published in a peer-reviewed publication in the near future.

According to organization protocol, the amount of silver (ionic or nanoparticles) applied to each filter ranges from 80 to 300 mg (Table 5); however, the amount of silver applied to each filter by brushing reported by factories ranges from 32-96 mg per filter (see survey results section 3.10.2). The two most common application methods are brushing and dipping. Regardless of the application method and silver product used, information is not available about the criteria used by the implementing organizations for the selection of either the silver compound or the impregnation procedure.

Table 5: Current application protocol, techniques, products and concentration of silver nanoparticles in ceramic filters

Organization	Product	Method	Concentration	Volume	Ag added	Cost/ filter
Practica	Collargol	Dipping	245 mg/L	400mL	100 mg	$0.11
PFP	Collargol	Brush	1 g/L*	300mL	300 mg	$0.33
FilterPure	Collargol	Fired in	N.I.	N.I.	N.I.	N.I.
RDI-C	Silver nitrate	Brush	232 mg/L	300mL	70 mg	$0.09
Ixtatán	Ultra silver[1]	Brush	200 mg/L	400mL	80 mg	$0.2
Thirst Aid	Silver nitrate	Brush	250 mg/L	300mL	80 mg	N.I.

1: Ixtatán foundation may change to Collargol; N.I. = no information; Contact ThristAid for info.

The three methods of application have as their main goal to provide a homogeneous distribution of silver throughout the ceramic filters and therefore to maximize the contact between the pathogens and the silver compounds. Each of the application method has advantages and disadvantages that are summarized in Table 6.

Table 6: Advantages and disadvantages of each silver application method

Method	Advantages	Disadvantages	Concerns
Dipping	• One batch can be prepared for several filters; • Fast	• Potential large volumes of waste; • Difficult to determine amount of silver absorbed by each filter	• Workers exposed to high concentration of colloidal silver; • Potential silver segregation in the surface of the filter during the drying stage

Brush	• Amount of silver added to each filter is controlled	• More labor intensive	• Potential silver segregation in the surface of the filter during the drying stage; • Frequent worker exposure to low concentration of colloidal silver
Fired-in	• It can be included during the mixing of the clay and sawdust	• Colloidal silver in the dry form may have a larger average particle size distribution than in suspension; • Potential large volume of waste as included in all filters and some will get rejected	• Colloidal silver oxidation during firing stage; • Worker exposure to airborne silver nanoparticles

Few studies have determined the efficiency of silver compounds applied to ceramic filters (Table 7). To our knowledge only one study comparing the performance of untreated ceramic filters to those impregnated with silver nitrate has been performed in the field (Brown *et al.* 2007). This study did not find differences between filters with and without silver application.

Table 7: *E. coli* removal in ceramic filters with and without silver application

Author	Type	No silver	With silver
(Brown *et al.* 2007)	Field/Silver nitrate/RDI-C	95%	95%
(Lantagne 2001a)	Lab/Microdyn/PFP	97%	>99%
(Oyanedel-Craver and Smith 2008)	Lab/Collargol/L=0.2/Lab	97%	99.99%
(van Halem 2006)	Lab/Collargol/PFP	80%-99.7%	99.999%

At laboratory scale and under controlled conditions, there seems to be some evidence that the application of silver nanoparticles could increase the removal efficiency of pathogens. Although in the field silver nitrate has not been shown to increase bacterial removal in filters, in the lab, with high bacteria concentrations, filters impregnated with silver nitrate have consistently demonstrated better performance than filters without it.

One of the main concerns about the application of silver compounds to ceramic filters is the release of silver (ionic or colloidal) from the filters over time. The loss of silver from the filters has two main disadvantages: 1) potentially undesirable health effects for filter users; and 2) reduction of disinfectant efficiency. A summary of silver concentrations in filtrate water from different ceramic filters both in field and laboratory applications is presented in Table 8. All the values reported are below the US Environmental Protection Agency (EPA) and WHO secondary standards for silver (0.1 mg/L), with the exception of RDI-C filters. It must be noted that the values of silver are not reported in the RDI-C manual and were estimated using the information provided in the report (30% silver release and 33 L of rinse before use) (Hagan *et al.* 2009). A recent study by Bielefeldt et. al. (2009) showed that the efficiency of ceramic filters decreased to 0.2 to 2.5 log reductions after loading multiple batches of highly contaminated water. They observed that the impregnation of silver has a beneficial effect in terms of bacteria removal, but it is not enough to sustain high efficiencies for a long period of time.

Table 8: Silver release from ceramic filters

Author	Study type and silver type	Max silver concentration (mg/L)	Method	Digestion	Bacteria removal
(Lantagne 2001b)	Field/Microdyn	0.015	HACH	No	--
(Kallmand 2010)	Field/Snow fresh	0.09	HACH	No	99.99%-91.37% E. coli
(Hagan et al. 2009)	Field*/Silver nitrate	0.63	N.I.	N.I.	95%
(Bielefeldt et al. 2009)	Lab/Collargol	0.00175mg/L	ICP-MS	N.A.	99.99%-10% E. coli
(van Halem 2006)	RDI-C/PFP/Ghana	0.015 mg/L	ICP-MS	N.A.	--

N.I. = no information

Regarding the procedures used to determine the silver concentration in water treated with ceramic filters, although flame atomic absorption and inductively coupled plasma mass spectrometry (ICP-MS) are both capable of determining total silver, they cannot differentiate between ionic and colloidal silver. An additional step of ultra-centrifugation may be performed before analysis so that the supernatant may be tested, allowing for determination of the ionic silver fraction. The HACH spectrophotometric method can only determine dissolved silver, however, if the sample is digested, it could be possible to determine total silver. To date, no study has determined the speciation of the silver released from the filters. This information could be very important, especially considering that the EPA could set new standards for silver depending upon the form (ionic or nanoparticle) that is present in water.

The release of silver from the filters can be affected by factors such as the chemistry of the water to be treated (ionic strength, dissolved compounds, pH and ORP) and interactions with the ceramic matrix (predominant clay, porosity, pore size and surface area).

7.5 Environmental and Health Concerns

The lower thresholds for silver ion (Ag^+) toxicity lie between 0.01 and 0.1 mg/L and the WHO has established that 0.1 mg/L of silver in drinking water can be tolerated without risk to human health (WHO 2004). The only adverse effect resulting from chronic exposure to low levels of silver ions in animals and humans is a blue-gray discoloration of the skin and internal organs, termed argyria. The WHO guideline is set to prevent argyria from a 70-year cumulative dose of 10 g (one-half of the human no observable adverse effect level). In humans, silver ions cannot cross the blood–brain barrier and are regulated by blood metallothioneins, which bind it in metal-thiolate-cluster structures for transport, storage and detoxification.

With regards to the toxicity of silver nanoparticles, a number of recent studies have observed cytotoxicity (cellular death or reduction of mitochondrial activity) in rat liver cell cultures (Hussain *et al.* 2005) and aquatic organisms (*Chlamydomonas reinhardti*) (Navaroo *et al.* 2008) at concentration of 1000 mg/L and 100 mg/L of silver nanoparticles, respectively. The first case of silver cardiomyopathy in humans due to the ingestion of colloidal silver as a food supplement was reported recently (Archer 2008). These studies highlight that silver in high concentration can be toxic.

7.6 Silver Guidelines

The recommended method for colloidal silver application is by brushing it on to the filter. Before applying the silver, the filter should have already passed other quality control inspections, including flow rate testing (section 8.3), and be completely dry to promote the absorption of silver.

Until further research has been carried out, application by dipping is not recommended because: 1) the amount of silver actually applied to the filter cannot be controlled and it is unknown how much silver is actually absorbed by the filter; 2) the concentration of the bulk dilution cannot easily be measured or controlled and might change after each filter is dipped; 3) there are environmental concerns with disposing of unused diluted silver daily; and 4) associated health and safety risks from increased exposure to silver nanoparticles are unknown. Silver nitrate disassociates at a much faster rate than colloidal silver causing concern with: 1) the amount of time silver nitrate lasts in the filter; and 2) whether the amount of silver that initially leaches into filtered water exceeds WHO guidelines. Therefore, silver nitrate it not recommended until further research has been completed and the disassociation of silver nitrate from the filter can be controlled.

A silver application area should be set up in a dark area with a roof to minimize the exposure of silver to ultraviolet light and to protect the area from rain. The floor surrounding the area for silver application should be covered with fired, broken, rejected filters or other fired ceramic material to absorb any spilled silver; if spillage occurs, the ceramic material saturated with silver should be disposed of in a sealed plastic bag. It is important to minimize the introduction of silver to the environment as it can upset the natural ecosystem. The mixing and application table should be covered with plastic. Health and safety precautions to take when handling silver include the use of gloves and a lab coat or apron when handling liquid silver in addition, a facemask and goggles should be worn when handling powdered silver.

If using powdered silver, a week's worth of 3.2% (32,0000 mg/L or ppm) silver concentrate should be prepared in advance and further diluted at the factory daily for application to filters both to minimize exposure to airborne silver particles and so the silver can be measured accurately. Calculations for preparing a concentrated solution from powdered silver and instructions for preparing liquid silver of a different concentration are provided in Annex G. Both powdered and concentrated silver should be stored in an airtight container out of direct sunlight.

The date the silver concentrate was prepared, strength of the silver, quantity silver concentrate, the quality and quantity of water added, quantity of silver solution brushed on to each filter and the date of application should be recorded on the filter log.

It is recommended that concentrated silver be diluted to the application strength immediately prior to application on each filter, however, if a known number of filters are to be treated in a given day, the appropriate amount may be diluted daily. See Annex G for calculation instructions for diluting silver daily. Concentrated silver should be diluted in a clean container using the cleanest non-chlorinated, boiled, filtered, de-ionized or bottled water to dilute the silver. The silver should suspend readily in water, that is, the silver particles should not settle to the bottom of the jar as soon as it has been mixed. If settling occurs, the silver should not be used and the supplier should be contacted.

The standard amount of colloidal silver added to the filters using a brushing application technique (established empirically at filter factories) is a starting solution of 2 mL (cc's) of 3.2% Microdyn liquid colloidal silver added to 300 mL of water. This is a concentration of 211 ppm (211 mg silver per liter of water). When all 302 mL of this concentration is applied to one pot filter, each filter will be coated with 64 mg of colloidal silver.

7.6.1 Silver Application Technique

The liquid silver mixture is applied to the inside and outside surfaces of the filter with approximately 100 mL applied to the inner surface of the filter, then 100 mL to the outer surface and then the remaining 100 mL to the inside. To guide in measuring the quantity applied, marks may be drawn on the outside of the application container at 100 mL, 200 mL and 300 mL. The following recommendations are to ensure that the entire volume of solution is applied to the filter, and that the entire surface of the filter is coated.

1) Prepare 302 mL of colloidal silver dilution by adding 2 mL of 3.2% colloidal silver to 300 mL of water;
2) Using a paint brush (approximately 3" wide), coat the inside of the filter starting on the bottom; each dip in the liquid is two strokes on the filter;
3) Brush one coat on the outside of the filter starting at the rim, including the bottom;
4) Brush the remaining 100 mL on the inside of the filter element starting at the rim.

7.6.2 Adding Colloidal Silver to the Dry Filter Mixture

Information is not available regarding the quantity of silver that should be added to the filter mixture, therefore we do not recommend including silver in the filter mixture. If silver is to be included in the filter mixture, it should be diluted in water prior to adding it to the dry filter mixture to reduce health risks associated with airborne silver particles. A facemask, gloves, goggles and apron should be worn when handling silver.

7.7 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) Ceramic filter manufacturers should apply colloidal silver to their filters, both to: 1) prevent bacterial growth in the filter (Silversty-Rodriguez 2008); and 2) potentially increase the microbiological reduction through the filter;
2) Powdered, liquid and diluted silver should be stored in a dark, airtight container to protect if from oxidation and ultra-violet light;
3) Colloidal silver should be diluted with non-chlorinated boiled, filtered, bottled or deionized water, preferably with a low calcium concentration to prevent the aggregation of silver particles;
4) Approximately 64 mg of silver colloidal silver should be applied to each filter by brushing it on;
5) Filters should pass all other quality control inspections prior to silver application to not waste silver on non-compliant filters and to reduce the amount of silver released into the environment;
6) There are potential problems with dissociation from the filter when using silver nitrate which filter manufacturers should be aware of, until further research has been carried out we do not recommend the use of silver nitrate on filters;
7) Filter manufacturers should recommend that filter owners use the first three flushes of water from the filter to wash the receptacle and tap since: 1) the first few batches contain a higher concentration of silver; 2) the receptacle and tap could have become contaminated during transport; and 3) the initial water has a bitter taste which might discourage filter acceptance;
8) Health and safety guidelines must be adhered to, in particular, the use of gloves and an apron when working with liquid silver and a face mask, protective eyewear, gloves and apron when working with powdered silver.

7.8 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) How much silver need be applied to the filter to make it effective? This requires a balancing of desired bactericidal effectiveness with concerns quantity of silver in effluent water and the safety of the workers applying the silver.
2) How much silver leaches out of a filter over time and how quickly? This has implications for potential user consumption of silver effluent, filter bactericidal effectiveness and the projected useful life of the filter unit.
3) How does the quality of the water to be filtered, such as ionic salts concentration, which are typically higher in groundwater than in surface water, affect silver leaching from the filter and filter effectiveness? In which circumstances are the different types of silver (silver nitrate vs. colloidal silver) more effective?
4) Is silver nitrate as effective as colloidal silver, in terms of both its effectiveness as a disinfectant and its ability to bond with the clay matrix? How does silver nitrate disassociate

from the filter? Is there more worker safety risk associated with the use of silver nitrate, because it can be reduced more easily than colloidal silver?

5) What are the effects of filtering chlorinated water through the filter? What is the nature of the silver/chlorine interaction? Does it compromise or improve upon the silver's bactericidal effectiveness?

7.9 Chapter Details

The information in this chapter was collated by Vinka Craver and edited by Justine Rayner and Daniele Lantagne. Participants on this conference call to discuss this chapter included Mike, Justine, Vinka, Daniele, Tracy, Lisa, Robert, Terry and Manny.

8 Variables: Quality control

In the following chapter, recommended quality control (QC) procedures for testing finished filters are presented. It begins with an introduction to quality control and a table outlining recommended QC test frequencies. Indirect quality indicator tests and microbiological testing guidelines are described. The chapter is concluded with a summary of recommendations and areas where further research is needed.

8.1 Introduction

Consistency of materials and manufacturing methods should produce consistent filters. The recommendations presented in previous chapters provide suggestions for the evaluation of materials, recommended manufacturing procedures and production documentation. Materials and manufacturing processes should be documented both to encourage employees to follow production guidelines and for future reference and research. Filters should pass visual inspections prior to each major step of the manufacturing process and once manufactured, all filters must pass a series of quality control tests outlined in this chapter (including visual, auditory, pressure and flow tests) and a percentage of filters should pass microbiological testing. Filters need to be evaluated individually but also within the context of their batch. If there is a high failure rate within a batch then the materials and manufacturing process for that batch need to be evaluated for inconsistencies and that batch should not be released for sale or distribution until the problem is identified and corrected. Likewise, if any filters that have passed all other QC tests do not pass microbiological testing, the batch and the manufacturing of that batch needs to be reviewed.

Although currently there is not an official Quality Assurance (QA) program/review board, factories are encouraged to carry out regular internal and/or external reviews after; 1) installation of any new factory; 2) immediately before the initial release of filters for consumer use; and 3) annually. Records, including a summary of the following information: QC measures in place; microbiological testing results; new material sourcing required; number of filters sent through production process; number of rejected filters and reasons for rejection; and results from independent testing (i.e., by NGOs) should be maintained at each factory. The on-going process will ensure that the QC system is controlling the filter quality to an acceptable standard and will allow for improvements and revisions based on the data over time.

While the production-floor perspective of Quality Control (QC) procedures is stereotypically that of an unnecessary hindrance, the systematic approach of ensuring all steps are completed as consistently as possible is extremely important in ensuring a quality product, reducing the chances of a high filter failure rate and associated costs caused by the absence of QC measures. Each employee plays an important role in producing high quality ceramic filters and should understand the reasons behind each quality control procedure and their suggestions can be considered for incorporation into an effective program. A chain of communication for the suggestion of improvements and reporting of any issues should be established. Identifying small issues before they become large can aid in maintaining a fluid production process. Recognition of factory workers for good efforts in quality control measures and documentation can increase the level of participation by each individual. If a bonus or awards program is implemented, caution should be used so that emphasis is placed on catching defective filters, rather than passing as many filters as possible in order to achieve the lowest rejection rate.

Each filter factory should coordinate with the local government, or other authority, to determine any applicable regulations and to ensure that those regulations are met and where possible, factories should obtain certification from the local government. Having independent laboratory test results documented will be helpful for consumers and organizations interested in purchasing the filters.

8.2 Quality Control Procedures and Frequency Intervals

All factories should: 1) consult an expert during factory set-up; 2) establish a quality control program; 3) maintain recommended documentation during prototyping and production; and 4) follow recommended testing procedures. Records and data should be kept for a minimum of 10 years. Figure 8-1 is a flow chart of a typical filter manufacturing process serving as a visual reference for the suggested steps during the production process when QC measures should take place. The Quality Control (QC) system is designed to:

1) Perform routine inspections and checks to ensure quality and consistency of materials and production process, as recommended in sections 4-7;
2) Document all materials and process activities as recommended in sections 4-7;
3) Perform various tests as indicators of product quality, as outlined in this section;
4) Confirm filter efficacy through microbiological testing, as outlined in this section;

QC procedures should be performed at the frequency intervals shown in Table 9. With regards to microbiological testing, each factory should strive to test its filters to the most stringent test method possible and at the most frequent intervals possible. It is also important to continue independent verification of filter performance. Factories that meet these guidelines are setting the worldwide standard for ceramic filter production and testing.

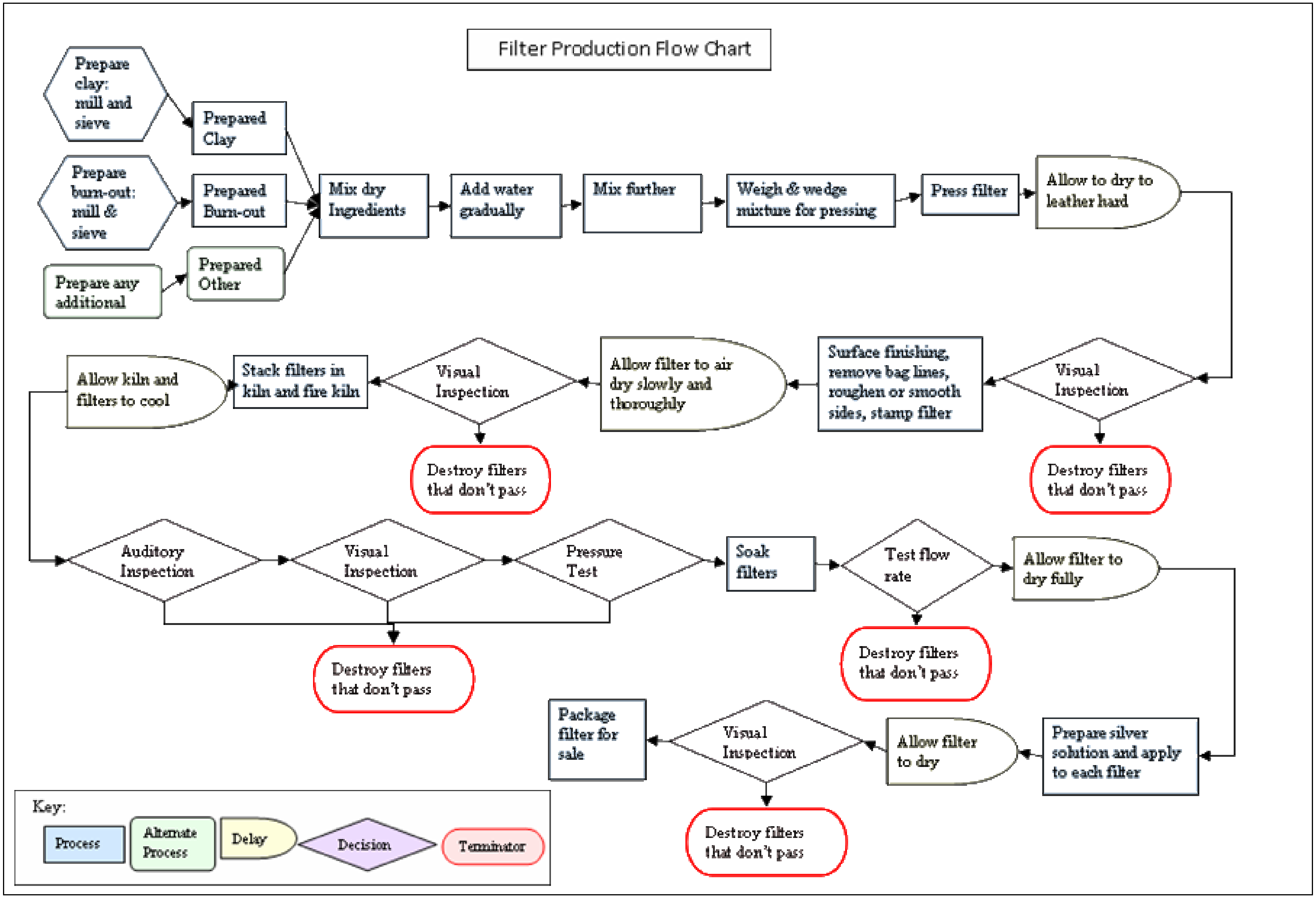


Figure 8-1: Production Flow Chart

Table 9: Summary of Quality Control Procedures

Category of QC	QC Measure	Description (page)	MINIMUM Frequency of Testing:
Materials	Source Water Quality	42	At project outset; yearly; more frequent if using intermittent or less safe water source
	Water of Plasticity	141	Sourcing; New raw material; Change in material characteristics; Annually
	Shrinkage of Dried Clay	142	
	Shrinkage of Fired Clay	142	
	Total Shrinkage of Clay	142	
	Absorption of Fired Clay	143	
	Burn-out Description	52	
	Burn-out Particle Size	52	
	Burn-out Moisture Content	147	
	Burn-out Firing Test	147	
	Tap Leak Test	149	if of concern
Process	Dry Mixing	59	per Batch
	Wet Mixing and Shaping	59-64	each Filter
	Post-Pressing Visual Inspection	64	each Filter
	Drying	64	each Filter
	Visual Inspections	104	each Filter; Stages: pre-surface finishing, pre-firing, pre-flow rate testing, pre-silver application, pre-packaging
	Kiln Temperature Mapping	148	2 runs on new kiln; or when firing is inconsistent.
	Post-Firing Visual Inspection	80	each Filter
	Acoustic Testing	80,105	each Filter
	Check Mold Alignment	148	Before Production; 0.4 % of filters
	Filter Rim Size Testing	105	each Filter

Category of QC	QC Measure	Description (page)	MINIMUM Frequency of Testing:
	Silver Solution Preparation	95 & 158	per Batch
	Silver Solution Application	95	each Filter
QC of Final Product	Independent Lab Analysis (Heavy metals, other contaminants)	110	Prototype filter effluent; Change in Raw materials; Increased frequency depending on local contaminants
	Independent Lab Analysis (microbiological)	108	3 prototype filters from 3 batches before production begins: Change in mix ratio; 0.1%
	Membrane Filtration (MF), Most Probable Number (MPN), or Semi-Quantitative Risk Level (in order of preference, in addition to laboratory testing)	109	Before Production begins; Change in mix ratio; 1% of filters, in addition to Lab Testing
	Pressure Testing	105	each Filter
	Flow Rate	106	each Filter

8.3 Quality Control of Final Product

Quality Control testing can be divided into two main categories: 1) indirect methods and 2) direct testing for microbiological removal efficiency.

While indirect tests should be carried out on 100% of the filters considered for consumer use, microbiological testing, due to the associated costs, may be carried out on only a percentage of filters sampled from different locations in the kiln, that were dried in different locations, from different shifts during the work day, and so on. Details of the recommended frequency of testing are listed in Table 9, as well as included in the description of each test that follows.

The identification of filters that do not meet the quality control standards is essential. Although this could initially increase the rejection rate, by documenting and evaluating, identifying and changing where in the process problems occurred, more consistent filters should be produced, thereby improving the consistency and quality of the filters produced. Failure rates and reasons for rejection should be recorded, the average failure rate should be monitored and production practices should be evaluated to identify the reason for change. Although manufacturing costs will be an important criterion for defining acceptable failure rates, factories should strive to achieve around a 10% rejection rate; 15-20% is an acceptable rate; however, more than a 20% rejection rate or a change in average rejection rates indicate inconsistent production practices and materials and methods should be evaluated. A less than 5% rejection rate will likely represent not strict enough quality control evaluations.

Indirect indicator tests include visual inspection, acoustic and pressure testing and flow rate testing. They are indicative of manufacturing consistency and should be performed on 100% of filters considered for sale or distribution. These indirect quality control measures should be conducted before silver application, so that silver and application time is not wasted on filters that will potentially be rejected by quality control, in addition, it is important to minimize the amount of silver discarded to minimize environmental impact.

8.3.1 Visual Inspections

At the Indo-2 factory, to emphasise and reinforce the importance of filter inspection, using a magnifying glass two people look and mark defects with chalk. Defective filters are compared and analysed to establish the cause.

Visual inspections should take place before each major step of the production process so defective filters can be removed from the production line. Formal visual inspections should be carried out before: 1) surface finishing; 2) loading the kiln; 3) flow rate testing; 4) silver application; and 5) packaging. By documenting each formal visual inspection it encourages employees to give special attention to this process, in addition, the production stage and description of the defect will aid in troubleshooting if a quality concern arises.

In greenware, filters should be examined for cracks, warping, inconsistent filter walls, large pieces of burn-out material and consistent surface finish. In fired filters, filters should be examined for: discoloration, including blackened areas indicating incomplete combustion of the burn-out; warping; cracks; holes or spaces from large pieces of burn-out material; charring; crumbling; and that the base and rim of the filter should be at the proper angle to the wall of the filter.

The filter rim of fired filters should be checked for size and warping by placing a receptacle lid on each filter element. Turn the lid slowly and check that the filter rim meets the lid evenly. If the lid does not fully cover the filter rim, grind the filter element using caution to not damage the body of the filter or grind any more material than necessary.

8.3.2 Acoustic Testing

Acoustic testing can identify incomplete firing or cracks in the filter walls. After being fired, each filter should be tapped to check for a ringing sound. A cracked or improperly fired filter will make a blunted, shorter sound (almost a thud) as opposed to the ringing sound a properly fired filter will make. A suggested test method is:

5) Balance the filter by its base on an open hand or outspread fingers;
6) Tap near the rim of the filter, as if ringing a bell;
7) If dull thud is heard, the filter should be rejected;
8) Tap the filter in at least three locations around the rim of the filter.

In Myanmar, third party inspections are performed on a random selection of 5% of all filters sold to NGOs. If any filters fail inspection, the entire shipment is held up until the issue is resolved.

Alternatively, an ear can be place just inside the filter while the filter itself is gently squeezed around the wall. If there are cracks present, a small crunching sound will be heard and that filter must be rejected.

8.3.3 Pressure Testing

Prior to saturating filters for flow rate testing, a pressure test should be carried out on all fired filters to check for cracks or large pores that allow water to pass through the filter walls quickly. This test should be performed as follows:

1) Holding the filter by the rim, submerge the filter base down in water until the water level is near the rim. Do not allow water to flow into the filter. (Figure 8-2)
2) Maintain the filter submerged for 10 seconds
3) If evidence of water entering the filter (Figure 2) is present after 10 seconds, then the filter fails this test and must be discarded.

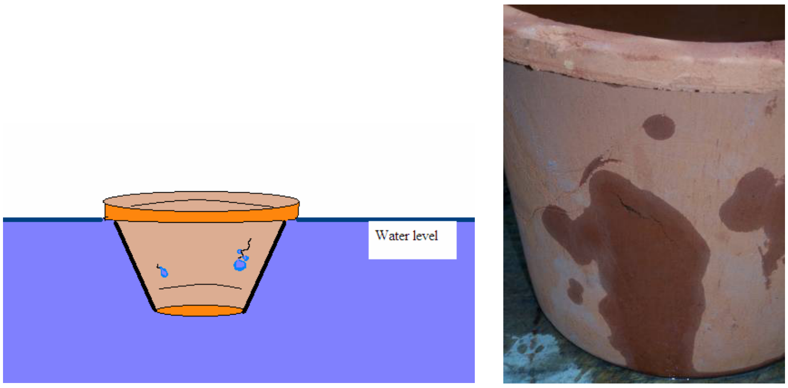


Figure 8-2: Pressure Test and Evidence of Leaks (Pillers and Diaz 2009)

Alternatively, fully submerge the filter rim down capturing air in the filter. A stream of bubbles exiting the filter is an indication of large pores or cracks and the filter should be destroyed.

8.3.4 Flow Rate

The Myanmar factories report that filters (10 L capacity) with a maximum flow rate of 4.5 liters in the first hour consistently pass microbiological tests.

Flow rate can be an indicator of cracks or large pores in the filtering element, potential contact time with silver, the ability of the filter to produce sufficient water quantity and production consistency.

Studies have been carried out to measure the effectiveness of filters with increased flow rates. One concluded that effectiveness of microbiological removal began to decrease below 99% after 1.7 L/hr (Klarman 2009); the other found there was no significant difference in microbiological efficacy between filters reaching a flow rate of up to an 8-10 L/hr and slower filters (Bloem *et al.* 2009). Filters in these two studies were produced in the Dominican Republic and Cambodia respectively, and therefore mold shape and size and production methods varied.

Flow rate has been found to diminish with use both in the laboratory (Lantagne 2001a; Fahlin 2003; van Halem 2006) and in the field (Lantagne 2001b) due to clogging of the pores. In addition, the hydraulic head influences the flow rate; therefore, the flow rate will slow as the filter empties. Although a minimum flow rate of one liter in the first hour should provide enough drinking water for a family of five if filled four to five times a day, over time, clogging might slow the filtration rate beyond acceptable limits.

Filters that do not meet a minimum flow rate of one liter per hour should be rejected and destroyed since they will likely not treat a sufficient quantity of water and could cause the consumer to stop using the filter, thereby placing their health at risk. An attempt can be made at increasing the flow rate of a filter that does not meet the minimum guidelines by re-firing it to ensure the filter reaches the appropriate peak temperature, allowing complete burn-out of the combustible material. Often this will bring a filter into compliance, but if after a second firing a filter still does not fall within the flow rate range, it should be destroyed.

Since filtration rate will vary with varying hydraulic head and surface area, assuming a minimum 2 cm base thickness and 1.5 cm wall thickness in flat-bottomed filters or 1.5 cm wall thickness in rounded bottomed filters, maximum flow rate should be calculated at 0.35 liters per liter capacity of the filter element. Therefore, maximum flow rate for 7.2-liter capacity should be 2.5 liters in the first hour and a 10-liter capacity should have a flow rate of no more than 3.5 liters. Filters that exceed the acceptable filtration rate should be destroyed.

8.3.4.1 Establishing Saturation Time

Water quality for soaking filters and flow rate testing is discussed in Section 4.1. Filters should be soaked prior to flow rate testing for reliable results (Lantagne 2001a), although the amount of time required to ensure saturation might vary per factory, Nederstigt and Lam (2005) found that after 24 hours of soaking time filtration rates became constant. If soaked for fewer than 24 hours, filters had lower flow rates (van Halem 2006: A-10).

In order to establish the amount of time it takes to saturate the filters to achieve a consistent flow rate: fully submerge a number of filters sampled from different locations in the kiln making note of the time; at equal time intervals, remove the filters from the water and test the flow rate; return the filter to the soak tank; when the filtration rate is consistent for two or three consecutive readings, that filter can be considered saturated for flow rate testing purposes. The maximum time elapsed from the sampled filters can be used as the minimum time necessary for saturating filters in production flow rate testing. Saturation time can be expected to be at least 12 hours, but as much as 24 hours. Based on variation in materials and manufacturing conditions, a different amount of saturation time will be required for each factory. This test should be carried out periodically to confirm that filters continue to be fully saturated prior to flow rate testing.

8.3.4.2 Test Flow Rate

The flow rate can be measured by either measuring the amount of effluent filtered or the drop in water level using a calibrated T-device. Instructions for making a T-piece are in Annex H, 0. Measurements should be taken after one hour. Since the drop in water volume will result in a reduced hydraulic head, the filtration rate will slow as the filter empties; therefore, readings taken after half an hour and then doubled may not provide accurate readings.

Filters should be placed in an empty bucket or receptacle supported by the rim only. Flat-bottomed filters should not be resting on their base, as this will reduce the flow rate. If the water level in the receptacle reaches the base of the filter, results will not be reliable. Therefore, if the maximum allowed flow rate is 3 liters an hour, there should be room for more than 3 liters of water in the receptacle so the water level does not reach the base of the filter within the flow rate range during the test.

Figure 8-3: Calibrated T-device (source unknown)

To test the flow rate, the filter should be completely filled with water and allowed to filter for one hour. If using a calibrated T-piece, measure the drop in water level after one hour. If measuring the effluent, carefully remove the filter so that water remaining in the filter does not spill into the receptacle. Measure the quantity of water that passed through the filter into the receptacle. Alternatively, if it is possible to see the water level through the bucket, lines can be drawn on the bucket at half-liter intervals; however the receptacle must be on a flat surface for this to be accurate.

Water used for soaking and flow rate testing may be re-used if necessary as long as the water does not become turbid (Section 4.1).

Flow rates should be recorded on the filter production log and average flow rates should be monitored throughout production. Filter elements that fall within the acceptable flow rate range are emptied and left to dry prior to silver application and packaging.

8.3.5 Microbiological Testing

In DR, no changes in production procedures are allowed without first being confirmed by microbiological testing.

Microbiological efficacy must be confirmed with independent laboratory testing on a minimum of three prototype filters from three batches prior to commencing production for distribution or sale, when the mixture ratio or other aspect of production varies, or when a QC issue arises. In order to reduce costs and minimize tests performed; testing should be carried out after filters have passed other quality control inspections and tests (section 8.3) but prior to silver application, unless fired into the filters or testing is specifically for silver in filter effluent because: 1) it is still unknown how long silver lasts in filters and 2) initial silver concentrations in the filter will be high enough to influence the testing results. In addition, microbiological testing should be performed at the frequency intervals listed in Table 9 for continued verification of production methods.

Each factory should establish a testing schedule for both in-house and laboratory testing as it will vary depending upon how the factory is set up and flow of production. This should include: method for selecting filters; frequency of testing; percentage of filters from each batch; testing methods; and indicator used.

Each factory should set up a field laboratory (in-house testing) so that a greater percentage of filters can be affordably tested in comparison with the cost of taking samples to a laboratory and so that employees are directly involved in monitoring and can see the results of the quality of the filters they produce. Experience in Myanmar has found that this involvement inspires filter producers to apply greater effort in producing quality filters.

In Myanmar, a traveling technician with a field test kit visits each of the eight factories once per month and tests 10-15 filters selected randomly. He spends the night and shows the filter manufacturers the results in the morning.

A minimum of 1% of filters destined for sale (that have passed all other quality control inspections) and at least one filter per firing batch should be tested at the in-house lab. Efforts should be made to test more filters if possible and additional testing should be carried out if there is a change in the quality of filters produced. A minimum of 0.1% should be tested at an independent laboratory.

If filters meeting all other quality control tests do not pass microbiological tests, other filters from that batch must be held from distribution until additional filters from that batch are tested. The production of those filters should be evaluated and the problem diagnosed and resolved. A greater number of filters from subsequent batches will need to be tested to increase the confidence level of consistent production. If filters consistently demonstrate microbiological effectiveness, the number of filters tested at an independent laboratory can be reduced as long as all other aspects of production remain consistent and in-house testing continues; however, routine verification by an independent laboratory should never be eliminated and should be increased again if any inconsistencies are noticed. The laboratory should be contacted in advance for requirements and guidelines for sample collection.

8.3.5.1 Indicator Organisms

Due to the difficulty of monitoring water for specific contaminants, water is tested for the presence of indicator organisms associated with fecal contamination. Commonly used indicator organisms (organisms used to measure treatment effectiveness) include: 1) total coliforms (TC); 2) thermotolerant or fecal coliforms (TTC) and 3) *E. coli*. Criteria for indicator bacteria as outlined by the WHO (2006: 142) are that they should be:

1) universally present in high numbers in human or other warm-blooded animal feces;
2) readily detectable by simple methods; and
3) should not grow in natural water.

Although the TC count is not always useful in evaluating health risk since some coliforms can grow and survive in water and are often present in the absence of fecal contamination, it can be useful as an indicator of treatment effectiveness (WHO 2006: 283). TTC are those of the TC group that are able to ferment lactose at 44-45°C. *E. coli,* often the predominant TTC organism, is rarely found in the absence of fecal contamination and is therefore a slightly more reliable indicator of water safety; however, the TTC count is an acceptable measure (WHO 2006: 284).

Although *E. coli* has been established as the most suitable indicator by the WHO, the absence of *E. coli* does not ensure water safety since some pathogens are more resistant to some disinfectants. Therefore “verification may require analysis of a range of organisms, such as intestinal enterococci, (spores of) *Clostridium perfringens* and bacteriophages” (WHO 2006: 142).

The choice of indicator bacteria will depend upon the quality of the challenge water and, whether the safety of the water or the treatment efficacy is being tested. Since TTC and TC are more likely to be present in greater numbers, they are often used in place of *E. coli* to evaluate treatment efficacy (percent reduction or LRV). Ideally, filters should be challenged with water with high concentrations of *E. coli* so that both reduction and safety can be evaluated.

For *E. coli*, TTC and TC, filters must, at a minimum, provide a 2-log reduction. This means, the effluent concentration of *E. coli* must be 1/100th or less than that of the influent concentration. For example, if the influent concentration is 1000 coliform forming units per 100 mL (CFU/100mL), then the effluent concentration must be 10 CFU/100mL or fewer per 100 mL. If challenge water does not have a high enough concentration to measure log reduction, the CFU/100mL in filtered water should be fewer than <10 CFU/100 mL for any of these indicators. Hydrogen sulfide producing bacteria are also a commonly used indicator, however, since currently there is no quantitative test available, it is not recommended for testing filter efficacy.

8.3.5.2 In House Testing Methods

Factories should supplement laboratory testing with in-house testing. Field test methods range in complexity, cost, the amount and quality of information provided. Efforts should be made to use the highest: 1) testing frequency and 2) highest sophistication of test method. By testing both the influent and effluent water, methods that allow for quantification of bacteria can provide information regarding disinfection capabilities. Field tests are available for *E. coli*, TTC and TC. Filtered water should have a 2 log reduction or fewer than 10 CFU/100 mL for any of these indicators.

A fact sheet on microbiological indicator testing, including a discussion of the different indicator bacteria and their usefulness, currently available and emerging field-testing options including benefits, drawbacks and cost considerations and detailed procedures for carrying out the tests can be obtained by contacting Daniele Lantagne at: dlantagne@cdc.gov. Annex I has purchasing information for some recommended field testing equipment. The following is summarized from this fact sheet.

Three recommended methods for testing microbiological indicators include: 1) Presence/absence (P/A) with Petrifilm™ for semi-quantitative risk level analysis; 2) Most probable number (MPN) with IDEXX™, which provides quantitative results using simple methods but is expensive; and 3) Membrane Filtration (MF) where the number of CFU can be counted, which requires trained laboratory staff but can be inexpensive. The three methods will require sample: 1) collection; 2) processing, including adding a specific growth media; and 3) incubation for 24-72 hours. Indicators should be selected based on the estimated quality of the water being tested, as recommended above. Please refer to the microbiological fact sheet for an extensive discussion on how to carry out each of these tests.

8.3.5.3 Guidelines for Taking Samples

Filters that meet all other QC criteria prior to silver application should be selected from the batch at random. Clean the receptacle and tap with a chlorine bleach solution and thoroughly rinse and dry. Test water should be from a contaminated source. Since different water qualities could show different results, filters should be tested using water of similar to the source water filter users will be using. Test first the influent water (positive control) and then after filtering for 1 hour, test the effluent. Care should be taken when collecting filtered water to prevent the contamination of samples. Wash hands first, then collect samples in sterilized plastic bags (for example, Whirl-Pak®) or sterilized disposable bottles. Label all samples carefully.

Because of the possibility for contamination during the testing procedure, a blank sample (using boiled or bottled water) should be included for every 10-20 samples taken. If the blank sample tests positive for bacteria, there is contamination in the procedure and the results need to be discarded. A positive control with known contamination should be tested. If the positive control does not show bacterial growth, then either the media is ineffective or the incubation temperature is incorrect and inconsistent, or the source water was not contaminated and the results need to be discarded. In addition, 10% of samples should be duplicated. If results are consistently accurate, fewer duplicates can be tested in subsequent rounds of testing.

The manufacturer's instructions for specific tests should be followed or the reader can refer to the instructions in the microbiological fact sheet.

After testing, cultures grown during incubation must be disposed of safely. Bleach should be added to each sample and left for approximately 10 to 15 minutes before pouring the sample with bleach down the drain. The test containers can be then be safely disposed of in the normal garbage.

8.3.6 Additional Testing

Filter effluent should be tested for heavy metals and inorganic chemicals that could leach into the filtered water. Initially, prototype filters should be tested for all heavy metals and inorganic chemicals. During production, filter effluent should be tested when there is a change in any materials or firing practices, with special attention paid to locally occurring contaminants.

8.3.6.1 Arsenic

Although we do not know the source, arsenic has been detected in the effluent water from filters from some factories (see section 2.1.6). Arsenic testing can be carried out using field test kits (see Annex I for recommended tests). It is preferable, however, that samples be taken to a local laboratory for analysis. Although it is important to document the occurrence of arsenic, it has not been found to leach from filters in concentrations that would pose a health risk to filter users (Tun 2009). Raw or fired clay samples can be tested at an independent laboratory or sent to Vinka Craver (Annex I).

8.3.6.2 Silver

The amount of silver in filter effluent can be measured using a HACH or other brand test kit (Annex I) and should be no more than the WHO guideline value of <0.1 mg/L.

8.4 Research and Independent Testing

Factories are encouraged to work with academic researchers, international or local NGO's, health clinics, national health organizations, or other relevant institutions to continue to prove the performance of their filters.

8.5 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) Factories are encouraged to carry out internal and/or external reviews after the installation of a new factory, before the initial release of filters for consumer use and annually;
2) Factories are encouraged to obtain certification from the local authorities;
3) Production procedures should be well documented to aid factories in troubleshooting, identify changes in material characteristics, increase efficiency, to provide manufacturing details to researchers studying filters and reduce the risk of having to stop production to resolve a quality control issue;
4) Visual inspections should be carried out before each major step of the manufacturing process, observations should be recorded on a filter log and filters which do not pass should be destroyed;
5) Indirect indicator tests including acoustic, pressure and flow rate testing should be carried out and documented for 100% of filters destined for sale or distribution;
6) Filters should be saturated prior to flow rate testing; filters which do not meet the minimum flow rate may be re-fired in attempt to increase the flow rate;

7) Flow rate can be determined either by measuring the drop in water level with a T-stick or measuring the water that passes through the filter after one hour. Filters should be suspended, not placed on their base;
8) The flow rate of each filter should be documented and average flow rates should be monitored over time;
9) Routine microbiological testing should be carried out, prior to silver application, using the highest level of accuracy and as frequently as possible. A minimum of 0.1% of the filters (minimum one from each batch) should be tested in a laboratory. A greater than 2 log reduction in Total Coliforms, Thermotolerant (Fecal) Coliforms and/or *E. coli* should be achieved.
10) Additional testing should be carried out at the factory on a minimum of 1% of filters using field kits. Results should show either a greater than 2 log reduction or fewer than 10 CFU/100 mL in Total Coliform, Termotolerant (Fecal) Coliform and/or *E. coli;*
11) Factories are encouraged to work with academic researchers, international or local NGO's, health clinics, national health organizations, or other relevant institutions to continue to prove the performance of their filters;
12) Filters which do not pass quality control tests should be destroyed so they cannot be used.

8.6 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) How accurately do current indirect testing procedures represent microbiological efficacy?
2) How strong is the relationship between flow rate, pore size and microbiological efficacy?
3) Are there other low-cost indirect performance indicator tests that could be carried out on the filters?
4) Development of improved in house testing techniques that can be used by individual factories.

8.7 Chapter Details

The information for this chapter was collated by Mike Stewart. This chapter was edited by Justine Rayner and Daniele Lantagne. Two calls were held on quality control and microbiological testing participants on these conference calls to discuss this chapter included: Robert, Susan, Tracy, Mike, Vinka, Manny, Justine, Lisa, Tracy, Mark, Daniele and Kaira.

9 Variables: Packaging

In this section, items that make up the complete filtering unit and packaging are presented with recommendations. These items include the filter element, receptacle, lid, tap, additional items and O & M instructions. Transport and end user acceptance are beyond the scope of this report.

9.1 Filters

Filters that have passed all quality control inspections (section 8.3) and have had silver applied should be thoroughly dry before packaging. It is recommended that, once dry, each filter be placed in a plastic bag to protect it from getting dirty.

9.2 Receptacle and Lid

The receptacle can be made from any material safe for water storage (including plastic, metal and ceramic but not repurposed pesticide containers). Currently factories supply plastic and/or ceramic receptacles. The size, shape and material may depend on local availability and consumer preference. Some factories have a mold made and commission a plastics manufacturer to make their receptacles, in which case, plastic should be of food grade material. If receptacles are made of clay, colloidal silver diluted according to the guidelines in section 7.6 and should be applied inside the receptacle as a layer to potentially prevent recontamination and a biological film from developing. Although some factories may receive their receptacles with the hole for the tap already made, if not, a hole for the tap can either be melted in a plastic receptacle using a heated piece of metal pipe of the same diameter as the tap, or a drill with an appropriate sized drill bit. The hole should be as low as possible so that a maximum amount of water can be dispensed, yet high enough so that the tap will clear a countertop or surface it is set on.

The flow rate will be affected as soon as the water level in the receptacle reaches the bottom of the filter, therefore, the size of the receptacle in relation to the filter size and shape and estimated pattern of use will affect how much and the rate at which water can be collected. There should be enough space below the bottom of the filter for, at a minimum, the volume of water that fits inside the filter, so as not to limit the amount of water that can be filtered overnight. Receptacles that can be stacked are convenient for transport.

Cam-2 provides a fitting ring which is placed between the receptacle and filtering element and helps to protect the filtering element against damage.

The filter should fit well in the receptacle without any gaps or spaces where source water can accidentally be introduced to the filtered water. Some factories provide a fitting ring that protects the filter rim from damage and helps accommodate for slight variation in filter size (Figure 9-1). The receptacle should have a lid with a good enough fit to prevent dirt, dust, debris and insects from contaminating the filtered water. Some factories choose lids that are slightly larger than the filter rim and receptacle and over hang.

Figure 9-1: Filter Unit with Fitting Ring
Ceramica Tamakloe, Ghana
(Source unknown)

9.3 Taps

Breakage of the filtering element or tap is a main reason for filter disuse (Brown and Sobsey 2006); therefore, choosing taps of good quality is of particular importance. Factories have had different experiences with taps. All factories who participated in the survey reported using plastic taps. Cam-1 factory found the failure rate of metal taps to be too high. Some plastic taps have a small ceramic filter inside. Taps which use a metal pin as opposed to a plastic one have been found to be more durable. Some tap suppliers are listed in Annex I.

Cam-1 found metal taps to have a higher failure rate than plastic ones.

9.4 Additional Items

Some factories include a fitting ring, scrubbing brush, or extra tap in the delivery kit. In addition, a locally available cloth normally used for pre-filtration can be provided for locations with especially turbid water.

9.5 Operation and Maintenance (O&M) Instructions

Factories should provide instructional sheets, stickers, or have O & M instructions printed into the receptacle during its manufacture. The instructions should include contact information including logo, name, telephone and website address if applicable. Examples of O&M instructions are included in Annex J.

Although the factory suggested recommended lifespan ranges from 1-5 years, unless damaged, the actual lifespan of the filter element has not been determined.

Five factories include a cleaning brush.

Recommendations for cleaning frequency should be “as needed or when flow rate slows” because increased handling can lead to both breakage of the clay filter element, which is a primary reason for disuse among users (Brown and Sobsey 2006), and can increase the chances of contamination. In Cambodia, it was noted that filters are often cleaned with multi-use cloths and that recontamination through improper handling is a possibility (Brown and Sobsey 2006). Investigations into cleaning practices after measured increases in bacteria in filtered water in Peruvian households found, that while users followed most cleaning instructions carefully including the recommended frequency of once a month when cleaning their clay filter element, they cleaned the receptacle 1-2 times per week thereby increasing the chance of breakage from removing the flay filter from the receptacle. In addition, over 50% of the households reported “cleaning” their filters with untreated water; many used multi-use rags or, cloths to wash and dry the receptacle; and the tap itself was rarely cleaned. Thirty percent did not wash their hands before washing the filter (Dundon 2009). It is therefore important that users clearly understand not only how and when to clean the receptacle, tap and filtering element, but also the reasoning behind the process.

Scrubbing with a brush is an effective way to remove particles in the surface pores, although internal pores may still remain blocked (van Halem *et al.* 2009). Some factories recommend waiting until the filter is dry before refilling it to ensure any microbiological contamination is inactivated, although this is unproven by evidence and of unknown effectiveness.

Although local context will influence the style and format, the following should be included in the O&M instructions:

1) Wash hands before cleaning filter;
2) Upon receipt of a new filter unit, users wash the receptacle and tap with the first three batches of filtered water because the first few flushes will have higher concentrations of silver and a bitter taste;
3) Filtering element and receptacle, lid and tap should be cleaned when the flow rate slows;
4) Do not touch the outside of the ceramic filter element during cleaning;
5) Upon removing the filter element from the receptacle, it should be placed rim down on the inside surface of the lid;
6) Only the inside of the filter element should be cleaned and it should be scrubbed with a clean brush and rinsed with potable, boiled or filtered non-chlorinated water.
7) Soap, bleach, chlorine, or other cleaning agents should not be used on the ceramic filter element itself;
8) The receptacle, tap and lid should be cleaned when the filter element is cleaned, and not more frequently unless needed, with a clean sponge or cloth, soap or bleach, and rinsed with potable (boiled, filtered or chlorinated) water. Clay receptacles coated with silver should not be cleaned with bleach or chlorinated water.

FilterPure provides different cleaning instructions since they fire silver into the filters. They recommend using 1-2 tablespoons of bleach to wash both the receptacle and element, and every 3 months they recommend boiling the element for 5 minutes.

Thirst-Aid Myanmar factories ship an extra 5% to accommodate for breakage but have found that fewer than 2% break during transport.

9.6 Packaging

Packaging will vary depending on locally available materials and whether filters are being packaged individually or for a bulk sale or distribution.

All ceramic filtering elements should be packaged in a plastic bag to prevent contamination. If taps are detached from the receptacle for ease of stacking for transport, they should be packaged in a plastic bag and attached by someone properly trained to do so at the destination unless clear instructions are provided.

For individual sale, ceramic filter elements are often packaged individually in a cardboard box the same size of the filtering element. The chance of the filter breaking will be reduced if it does not move within the box. Although some factories acquire used boxes, Nica-1 and one factory in Myanmar has their name and logo printed on the box. Elements can also be packaged directly in the receptacle.

Some factories package filter elements in locally made baskets. One of the Myanmar factories recently switched to cardboard boxes and although they are easier to stack and NGO's think they look nicer, they are not as practical as they get soggy when wet and are not re-used by recipients as the baskets are.

A variety of packaging materials are used at different factories. Although the DR factory reported that popcorn did not prevent breakage, factories report success with newspaper, bubble wrap, styro-foam, cardboard separators or wild grass. Waste material from local industries such as straw, rubber scraps or shredded paper from a notebook factory can also be used as long as it is not a potential source of contamination. Good packaging materials should hold the filter in place inside the container, if it can move around; it will be more likely to break. Five or six filters can be packaged together, or stacked and packaged in crates or cardboard boxes for bulk sale/distribution.

Figure 9-2: Packaged Filters, Myanmar
(Thirst-Aid 2009)

Figure 9-3: Packaging Filters, Nicaragua
(Rayner 2006)

Figure 9-4: Packaging Filters, Honduras
(Hernandez 2009)

9.7 Recommendations

Based on the knowledge summarized in the previous sections, the following recommendations are made to filter manufacturers by the Working Group:

1) Plastic receptacles should be of food grade material and clay receptacles should be coated with silver;
1) Receptacles should be large enough to hold at least as much water as the filter itself before the water level reaches the bottom of the receptacle;
2) Lids should fit well enough that insects, dust and debris cannot get in the filter or filtered water;
3) Tap should be of high quality;

4) O & M instructions should be provided with the filter and cleaning instructions should include the items listed in this section;
5) Recommendations for cleaning frequency should be as infrequently as possible, or when flow rate slows;
6) The receptacle, tap and lid should be cleaned when the filtering element is cleaned, and not more frequently unless needed;
7) Packaging should be developed to minimize breakage.

9.8 Research Indicated

The following areas require further research in order to refine recommendations for best practice in ceramic water filter production:

1) Establish evidence-based guidelines for filter lifespan;
2) Improve cleaning methods and ways of unclogging pores deep within the filter structure.

9.9 Chapter Details

The information for this chapter was collated by Justine Rayner and edited by Daniele Lantagne.

10 Conclusions

These ceramic water filters were designed to be manufactured by artisans and therefore to be able to accommodate variation in manufacturing. That these filters are being produced in 35 factories in 18 countries means there is inevitable variation in materials and methods of production. Variation in production exists not only between factories in different countries, but within each factory. Factories adjust their production practices according to their experience, continuously trying to improve upon their production process and end product.

Although the tolerance for variation exists, there are aspects of production that should be more strictly adhered to in order to consistently manufacture a product of sufficient quality for a public health intervention and that will improve the microbiological quality of water and reduce diarrheal disease. In part, the objective of this project has been to identify and explore the production variables which require more attention to detail and those which have a greater range for variation. We hope this report will help filter factories improve the quality of filters being produced by promoting manufacturing consistency within factories and by encouraging the documentation of daily production practices. Overall, the objective of this project is to provide consensus-based guidelines for local manufacturing of a product that meets minimum standards for health and safety.

We have worked towards this objective by: 1) forming the Ceramics Manufacturing Working Group; 2) holding conference calls to discuss topics in production; 3) identifying operating filter factories; 4) surveying and documenting existing practice in manufacturing; 5) summarizing knowledge on how filters work; 6) making best practice recommendations; and 7) identifying areas where further research is needed.

One of the challenges of standardizing the production process is bridging the art of working with clay, a highly intuitive process, with the manufacturing a reliably effective health tool. The relationships between and effects of variables are many and are not always clear, posing challenge when attempting to establish best practice guidelines. In addition, each factory is limited to the locally available materials, equipment and resources.

Despite these limitations, we have worked as a group to define best practice in ceramic filter manufacturing and have summarized the information gained from the discussions and research into: 1) lessons learned; 2) recommended research; and 3) manufacturing recommendations.

10.1 Lessons Learned

The results of the literature review and filter factory survey suggest six key lessons learned: 1) little is known about how the many variables in filter production influence filter characteristics and quality; 2) production practices are not consistent and are not well documented; 3) guidelines for diluting silver are needed; 4) microbiological testing needs to be carried out regularly at established frequencies; 5) flow rate testing procedures need to be standardized; 6) health and safety precautions need to be enforced; and 6) factories could benefit from sharing experiences. Each of these lessons are discussed below.

10.1.1 Little is known about how the many variables in filter production influence filter characteristics and quality.

There are few studies characterizing the effects and relationships of the many variables in filter production (Figure 3-1). The goal is to create a filtering element that improves the microbiological quality of water. Mechanisms that aid in improving water quality are affected by characteristics such as pore size, pore size distribution, porosity and hydraulic conductivity, which can be affected by many different areas in the manufacturing process including material characteristics, and how they interact with each other, materials processing, mixing, pressing and drying and the firing profile. Additional research is needed in many areas in order to refine recommendations for best practice.

10.1.2 Production practices are not consistent and are not well documented.

There is variation in filter production both within and between factories. Filters produced in different factories have been found to have different characteristics. Although some variation in daily production might be inevitable, the documentation and analysis of production practices cannot only encourage consistent practice but also aid in increasing production efficiency and troubleshooting. In addition, investigations into filter characteristics and effectiveness could benefit from having production details available.

10.1.3 Guidelines for diluting silver are needed.

During the survey, respondents found it difficult to answer questions regarding the amount and concentration of silver applied to filters. Based on the information reported, silver application is not consistent. Although further research is still needed regarding the effects of different types of silver, application methods and concentration on the efficacy of the filters, clear information about silver concentrations and corresponding dilution formulae need to be made available to the factories.

10.1.4 Microbiological testing needs to be carried out regularly at established frequencies.

Factories provided little information regarding what tests are carried out and acceptable water quality parameters. Microbiological testing of filters is not consistent between factories. Eight factories reported testing 0.2-15% of their filters regularly. Guidelines for the percentage of filters which should be tested, frequency of testing and what should be tested for have not been available. Although the availability of a local, certified laboratory may vary depending on the factory location, with training, in-house testing should be implemented to compliment laboratory and third party testing.

10.1.5 Flow rate testing procedures need to be standardized.

Flow rate testing is used as a primary indicator of filter efficacy; however, factories do not follow a standard procedure. Lantagne (2001a) noted that it is important to soak filters until they are saturated prior to flow rate testing to obtain consistent results. Nederstigt and Lam found that the flow rate of filters became consistent after a 24 hour soaking period (van Halem 2006). Only five filter factories soak their filters for 24 hours prior to flow rate testing and three factories do not soak their filters prior to testing flow rates. Although the soaking time required to achieve saturation may vary from factory to factory, it is important that filters be saturated prior to flow rate testing to ensure consistent flow rate measurements. Filter characteristics such as capacity and wall thickness should be considered when establishing acceptable flow rates.

10.1.6 Health and safety precautions need to be enforced.

Health and safety risks can include both injury and long-term health risks. Four factories reported minor injuries to hands and fingers. Although no factories reported back injuries, the use of proper lifting techniques and ergonomic work conditions are important to minimize such risks. Although all factories reported using dust masks or some sort of nose and mouth covering while processing raw materials, these precautions are not strictly adhered to or enforced as only eight factories reported always using facemasks while processing raw materials or mixing. In order to reduce occupational health risks, appropriate preventative measures need to be outlined and enforced for various aspects of production, but particularly when working with or near airborne dust particles.

10.1.7 Factories could benefit from sharing experiences.

During the survey, factories were asked about current and previous challenges, solutions and what they have tried in the past but that did not work. The length of the survey likely influenced the amount of detail some participants provided. Although what works at one factory might not work at another, many participants expressed interest in sharing their experiences and curiosity about the experiences of others.

10.2 Summary of Best Practice Recommendations

Based on the knowledge summarized in this report, following is a summary of recommendations to filter manufacturers by the Working Group. A reliable source for raw materials should be identified and materials should be of consistent quality and evaluated during initial sourcing, yearly and when characteristics vary, or if a change in filter quality is observed. Evaluations should be documented and compared and variation in materials characteristics greater than 10% should be followed-up with microbiological confirmation of filter effectiveness. All materials should be stored safely and under appropriate conditions and employees should be required to follow health and safety recommendations for every stage of the production process, with particular emphasis on preventing the inhalation of silica dust by wearing a facemask.

Both production and flow rate water should be tested for heavy metals, inorganic chemicals, arsenic and microbiological contaminants. In addition, flow rate water should be tested or visually monitored for turbidity. Water should be tested more regularly if the factory is using an intermittent or less safe source. Clay should be processed on site to a consistent powdered form using a #25-30 mesh sieve to remove impurities. Burn-out material should be of a consistent type and quality and should sieved with a #25-30 mesh. Any additional materials included in the filter mixture should be consistently processed according to specifications.

Visiting an operational factory prior to implementing a factory is recommended. An experienced filter producer and local potters should be consulted when setting up a factory and developing the filter mixture ratio which should be used consistently throughout production. Prototype filters should be tested for heavy metals and inorganic chemicals in filter effluent and achieve a minimum 99% (2 log) removal of microbiological indicators. If any change is made to the clay:burn-out mixture, filter efficacy should be confirmed with microbiological testing. In preparing filter mixture, raw materials should be measured by weight; burn-out material should be dehydrated prior to weighing it. Dry materials should be mixed thoroughly and inspected visually for even distribution of clay and burn-out prior to adding water to the mixture. A press with a mold should be used to press the filter into shape. A standard weight of filter mixture appropriate to the specific mold and amount of pressure applied by the press should be wedged, kneaded or thrust prior to it being pressed into a filter shape. If available, the mixture should be processed through a pug mill. The freshly pressed filter should be handled as little as possible after pressing. Filters manufactured from the same batch of filter mixture should be kept together throughout production and fired in the same kiln load. Filters should be stored in conditions which allow them to dry evenly and protected from direct sun, wind and rain. Once leather-hard, each filter should be stamped with a batch, filter number and logo. A detailed production log documenting the manufacturing process for each filter should be kept. Filters should be inspected visually after pressing and periodically throughout the drying process for deformation, even drying and cracks or holes. Damaged filters should never be patched. Rejected filters should be destroyed and the mixture should not be re-used to make filters.

Mani kilns are recommended for use in production; however, other fuel efficient, reliable kilns which fire evenly and consistently may be used. The number and sizes of kilns should take into consideration level of production. Filters should be dry before being fired and should be stacked in the kiln using clay spacers to promote heat circulation and reduce chances of warping, cracking and carbon marks being left on the filters. The location of each filter should be recorded on a log either while stacking or unloading the kiln. Alongside visual monitoring, cones (three cone method), draw rings and a pyrometer with thermocouples should be used to aid in accurate temperature monitoring, documentation, troubleshooting, fuel efficiency and consistency of firings. The firing temperature and firing curve appropriate for local clay should be established and followed and a firing log should be maintained. Fired filters should undergo a visual inspection when unloading the kiln or prior to flow rate testing and observations should be recorded. Efforts should be made to acquire fuel from sustainable sources and experimentation and the use of agricultural waste or alternative fuel sources is encouraged.

Ceramic filter manufacturers should apply silver nanoparticles (colloidal silver) to their filters, both to: 1) prevent bacterial growth in the filter (Silversty-Rodriguez 2008); and 2) potentially increase the microbiological reduction through the filter. Powdered, liquid and diluted silver should be stored in a dark, airtight container to protect if from oxidation and ultra-violet light. Approximately 64 mg of colloidal silver should be applied to each filter by brushing it on. Colloidal silver should be diluted with non-chlorinated, boiled, bottled or deionized water; preferably with a low calcium concentration. A week supply of concentrated silver may be prepared in advance, but should be diluted daily for application at the factory. Unused silver should be disposed of according to local regulations. Filters should pass all other quality control inspections prior to silver application to not waste silver on non-compliant filters and to reduce the amount of silver released into the environment. Filter manufacturers should be aware that there are potential problems with dissociation from the filter when using silver nitrate, therefore, currently the use of silver nitrate is not recommended. Factories should recommend that users use the first three flushes of water from the filter to clean the receptacle and tap as the first few batches will have higher concentrations of silver, the receptacle and tap could have become contaminated in transit and the first few batches of water will have a bitter taste. Health and safety guidelines must be adhered to, in particular, the use of gloves and an apron when working with liquid silver and a face mask, protective eyewear, gloves and apron when working with powdered silver.

Factories are encouraged to carry out internal and external reviews after the installation of a new factory, before the initial release of filters for consumer use and annually. Factories are encouraged to obtain certification from the local authorities. Production procedures should be well documented to aid factories in troubleshooting, identify changes in material characteristics, increase efficiency, to provide manufacturing details to researchers studying filters and reduce the risk of having to stop production to resolve a quality control issue. Visual inspections should be carried out before each major step of the manufacturing process and indirect indicator tests including acoustic, pressure and flow rate testing should be carried out and documented for 100% of filters destined for sale or distribution. Prior to flow rate testing filters should be saturated and during the test filters should be suspended, rather than placed on their base. Flow rate can be determined by measuring either the drop in water level with a T-stick or the volume of water that passes through the filter after one hour. An attempt may be made to increase the flow rate of filters that do not meet the minimum flow rate by re-firing them. The flow rate of each filter should be documented and average flow rates should be monitored.

Microbiological testing should be carried prior to silver application, using the highest-level accuracy and as frequently as possible. A minimum of 0.1% of the filters should be tested in a laboratory and achieve a greater than 2 log (99%) reduction in Total Coliforms, Thermotolerant (Fecal) Coliforms and/or *E. coli*. A minimum of 1% of filters (at least one per batch) should be tested using field kits and should achieve a greater than 2 log reduction or have fewer than 10 CFU/100 mL in Total Coliform, Thermotolerant (Fecal) Coliform and/or *E. coli in* effluent water. Factories are encouraged to work with academic researchers, international or local NGO's, health clinics, national health organizations, or other relevant institutions to continue to prove the performance of their filters. Filters which do not pass quality control tests should be destroyed so they cannot ever be confused with an effective filter.

Receptacles should be large enough to hold at least as much water as the filter itself before the water level reaches the bottom of the receptacle. Plastic receptacles should be of food grade material and clay receptacles should be coated with silver. Taps should be of high quality and lids should fit well enough that insects, dust and debris cannot get in the filter or filtered water. O & M instructions should be provided with the filter and cleaning instructions should include the items listed in the delivery section of this report. Recommendations for cleaning frequency should be when needed or when the flow rate slows and the receptacle, tap and lid should be cleaned when the filter element is cleaned, and not more frequently unless needed. Packaging should be developed to minimize breakage.

10.3 Summary of Research Indicated

Further research is needed to understand the effect on filtered water of arsenic, fluoride, chlorine and other inorganic contaminants in the water or raw materials used to manufacture the filter on filtered water and the possibility of altering firing practices to reduce any negative impact found.

Investigations into possible additives or coatings which could make filters effective against viruses and simple means of identifying and processing them locally are needed. Research is needed into the effects of different types of clay microstructures on fired filter strength and breakage rates and how this can be evaluated or influenced on a local level. The effects on filter performance of using unfired commercial bricks or failed, unfired filters in filter mixture needs evaluation.

How different burn-out materials (such as sawdust, rice husks and peanut shells) influence filter performance, including the workability of the mixture, flow rate, appropriate clay:burn-out ratio and microbiological efficacy needs further investigation, including if some burn-out materials leave a residue in the filter. Little is understood about the role the burn-out material particle size plays in pore structure and hydraulic properties and whether very fine particles of burn-out should be included in the filter mixture. It is unknown whether storing prepared mixture before pressing affects filter performance, for example whether over a short period of time, the sawdust expansion from moisture absorption increases pore size and therefore filtration rates, or if and how storage affects the plasticity of the mixture. Also untested, is whether dried unfired filters can be pulverized, screened and reprocessed into future batches of filter mixture without compromising quality, and if so, the practical limit of recycled material that can be included. An acceptable range of clay:burn-out ratios for each of the various burn-out materials, optimizing flow rate and microbiological effectiveness, need to be defined. Likewise, how do variations within a given type of burn-out material (such as different types of trees for sawdust, or different parts of the rice husks) affect flow rate, appropriate clay:burn-out ratio and microbiological efficacy? The identification of a visual indicator that can be added in the mixture without affecting filter effectiveness would aid in determining when dry mixing is complete.

Investigations into the advantages and disadvantages of each of the three filter shapes being used and how other filter characteristics such as diameter, depth, volume and wall thickness and their affect on filter strength, hydraulic properties and biological effectiveness are required to see if there is an optimal design for filter size and shape. In addition, certain process variables that can affect pore structure and fired filter strength, such as the use of a pug mill in processing the mixture, or the amount of pressure applied in the pressing process, need to be identified. Research is needed to confirm that the use of different oils as a mold release does not affect the firing or leave a residue on the finished filter.

It is currently unclear whether heating schedules and peak temperatures can neutralize arsenic, heavy metals, or other inorganic materials naturally present in some local clay sources by melting them into the fired clay matrix. Also unknown is whether impurities present in a fuel source can be transferred to the filters, for example, contributing to arsenic leaching from fired filters. It would be useful to identify optimum firing profiles that accomplish complete combustion of each type of burn-out material. The effects on efficacy and the lifespan of the filter of leaving a black core within filter walls and whether the thickness of the black core can be monitored or controlled needs to be researched. Ways of improving the efficiency and reducing the cost of firing with alternative fuels, and whether there is potential for a low-cost system for recycling energy from heat exiting the chimney, could be investigated.

The amount of silver needed, balancing the desired bactericidal effectiveness with the quantity of silver that leaches into effluent water and the safety of the workers applying the silver, needs to be determined. Since the amount and rate of silver leaching out of a filter over time has implications for potential user consumption of silver, filter bactericidal effectiveness and the projected useful life of the filter unit, it is important that the expected silver leaching rate be quantified. How do the quality and characteristics of source water, such as ionic salt concentration which is typically higher in groundwater than in surface water, affect silver effectiveness and leaching rates? Research is needed to determine whether silver nitrate is an acceptable substitute for colloidal silver and under which circumstances the uses of these different types of silver are appropriate. The effectiveness of silver nitrate as a disinfectant, its ability to bond with the clay matrix, how it disassociates from the filter and worker health risks associated with its use need to be determined. The nature of the silver-chlorine interaction needs to be investigated: it is unknown whether chlorine compromises or improves upon the silver's bactericidal effectiveness; also unknown are the effects of filtering chlorinated water or washing filters with bleach.

The strength of the relationship between flow rate, pore size and microbiological efficacy needs to be evaluated to determine whether current indirect testing procedures accurately correlate with microbiological efficacy. Additional low-cost indirect performance indicator tests which could be carried out on the filters need to be developed along with improved in-house testing techniques that can be used by individual factories. Standard water quality parameters for influent water used in disinfection testing also need to be defined.

Research into the variables that influence filter lifespan can help develop evidence-based guidelines for manufacturer lifespan recommendations. Investigations are also needed into developing improved cleaning methods capable of unclogging pores deep within the filter structure.

10.4 Voluntary Nature of Standards

Throughout the conference calls, there were many discussions regarding whether these recommendations should be enforced or voluntary, and the logistics associated with establishing a quality assurance program, and the possibility for quality certification. Although several individuals and organizations hope to see this develop in the future, currently no board exists to inspect, oversee or certify production at the different facilities. We expect that filter factories interested in producing quality filters that improve the microbiological quality of water will use the theory and guidelines presented to voluntarily implement improvements where appropriate.

In conclusion, we encourage factories and organizations to report that they are adhering to the recommendations in these guidelines fully, in part or have adapted them for the purposes of their own facility. In addition, we invite any interested parties to participate in revisions of these guidelines over time. At this point, no one in the group plans to act as an enforcer, regulator or certifier of these guidelines. We see this document, much like the Sphere Standards for Emergency Response, to be a document sharing the best information we have at this time to define best practice in ceramic filter manufacturing. We look forward to revising this document over time as new information and research is made available.

References

AFA (1995) *Contra la morbilidad infantil: Filtros artesanales y educación.* Instituto de Investigaciones Económicas y sociales (IDIES): Guatemala.

Archer, S.L. (2008) Dilated cardiomyopthy and left bundle branch block associated with ingestion of colloidal gold and silver is reversed by British antiLewisite and vitamin E: the potential toxisity of metals used as health supplements. *Canadian Journal of Cardiology* 24(5): 397-399.

Asopafin (2009). Colombia**:** Photograph provided by Asopafin, Colombia in response to questionnaire.

Bielefeldt, A.R., Kowalski, K. and Summers, R.S. (2009) (In Press) Bacterial treatment effectiveness of point-of-use ceramic water filters. *Water Research (2009)* doi: 10,1016/j.w.watres.2009.04.047.

Bloem, S.C., van Halem, D., Sampson, M.L., Huoy, L.S. and Heijman, B. (2009) *Silver Impregnated Ceramic Pot Filter: Flow Rate versus the Removal Efficiency of Pathogens*. International Ceramic Pot Filter Workshop. Atlanta, GA, USA.

Boschi-Pinto, C., Velebit, L. and Shibuya, K. (2008) Estimating child mortality due to diarrhoea in developing countries. *Bull World Health Organ* 86(9): 710-717.

Brown, J. (2007) *Effectiveness of ceramic filtration for drinking water treatment in Cambodia*. Unpublished Thesis, University of North Carolina.

Brown, J. and Sobsey, M. (2006) *Independent Appraisal of Ceramic Water Filtration Interventions in Cambodia.* Submitted to UNICEF:

Brown, J., Sobsey, M. and Proum, S. (2007) *Use of Ceramic Water Filters in Cambodia.* Water and Sanitation Program/UNICEF: Cambodia.

Brown, J. and Sobsey, M.D. (2009) Ceramic media amended with metal oxide for the capture of viruses in drinking water. *Environmental Technology* 30(4): 379-391.

Brown, J., Sobsey, M.D. and Loomis, D. (2008) Local drinking water filters reduce diarrheal disease in Cambodia: a randomized, controlled trial of the ceramic water purifier. *Am J Trop Med Hyg* 79(3): 394-400.

Campbell, E. (2005) *Study on Life Span of Ceramic Filter Colloidal Silver Pot Shaped (CSP) Model.* Managua, Nicaragua.

CeramicArtsDaily (2010) *2010 Workshop Handbook*, Ceramic Publications Company.

Chen, X. and Schluesener, H.J. (2008) Nanosilver: A nanoproduct in medical application. *Toxicology Letters* 176: 1-12.

Cho, K., Park, J., Osaka, T. and Park, S. (2005) The study of antimicrobial activity and preservative effects of nanosilver ingredient. *Electrochimica Acta*: 956-960.

Clasen, T. and Bastable, A. (2003) Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use. *J Water Health* 1(3): 109-15.

Cohen, B. (2010) Personal Communication

Cuff, Y.H. (1996) *Ceramic Technology for Potters and Sculptors*. A & C Black (Publishers) Limited: London.

Danilczuk, M., Lund, A., Saldo, J., Yamada, H. and Michalik, J. (2006) Conduction electron spin resonance of small silver particles. *Spectrochimaca Acta Part A* 63: 189-191.

Desmyter, D., Adagwine, A.P., Ibrahim, S., Jaeckson, M.K. and Murcott, S.E. (2009) *Monitoring and Evaluation of 1,000 Households receiving Ceramic Pot (Kosim) Filters after an Emergency Flood Mass Distribution in Northern Ghana*. WEF09. Atlanta.

Drake, P.L. and Hazelwood, K.J. (2005) Exposure-Related Health Effects of Silver and Silver Compounds: A Review. *Annals of Occupational Hygiene* 49: 575-585.

Dubas, S., Kumlangdudsana, P. and Potiyaraj, P. (2006) Layer-by-layer deposition of antimicrobial silver nanoparticles on textile fibers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 289: 105.

Dundon, S.M. (2009) *Use and Effectiveness of Potters for Peace Ceramic Water Filter in a Peri-Urban Slum in Lima, Peru*. HWTS09. RCSI, Dublin, Ireland.

Elechiguerra, J.L., Burt, J.L., Morone, J.R., Camacho-Bragado, A., Gao, X., Lara, H.H. and Yacaman, M.J. (2005) Interaction of silver nanoparticles with HIV-1. *Journal of Nanobiotechnology* 3(6): 1-10.

Fahlin, C.J. (2003) *Hydraulic Properties Investigation of the Potters For Peace Colloidal Silver Impregnated, Ceramic Filter*. Unpublished Thesis, University of Colorado at Boulder, Boulder, CO, USA.

Fauss, E. (2008) *Silver Nanotechnology Commercial Inventory Analysis*. Unpublished Work. Woodrow Wilson International Center for Scholars.

Feng, Q.L., Wu, J., Chen, G.Q., Cui, F.Z., Kim, T.N. and Kim, J.O. (2000) A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. *Journal of Biomedical Materials Research* 54: 662-668.

FilterPure (2009). Dominican Republic**:** Photograph provided by FilterPure in response to questionnaire.

Furno, F., Morley, K.S., Wong, B., Sharp, B.L., Arnold, P.L., Howdle, S.M., Bayston, R., Brown, P.D., Winship, P.D. and Reid, H.J. (2004) Silver nanoparticle and polymeric medical devices: a new approach to prevention infection? *Journal of Antimicrobial Chemotherapy* 54(1019-1024).

Hagan, J.M., Harley, N., Pointing, D., Sampson, M., Smith, K. and Soam, V. (2009) *Resource Development International - Cambodia Ceramic Water Filter Handbook-, Version 1.1.* Phnom Penh, Cambodia.

Hamer, F.a.J. (2004) *The Potter's Dictionary of Materials and Techniques*. A&C Black Publishers Ltd: London.

Heinig, C.F. (1993) O_3 or O_2 and Ag: A new catalyst technology for aqueous phase sanitation. *Ozone Science & Engineering* 15: 533-546.

Hernandez, M. (2006) *Kiln Building*. ETHOS Conference Presentation. Kirkland, WA, USA.

Hernandez, M. (2007) *Firing the Mani Kiln*. Unpublished

Hernandez, M. (2009). Professor of Art. Northern Illinois University**:** Illustrations and photgraphs provided by Manny Hernandez.

Hernandez, M. (2010)**:** Photographs provided by Manny Hernandez.

Hussain, S., Hess, K., Gearhard, J., Geiss, K. and Schlager, J. (2005) In vitro toxicity of nanoparticles in BRL 3A rat liver cells. *Toxicology in Vitro* 19: 975.

IDECambodia (2009)**:** Photographs provided by IDE Cambodia in response to the questionnaire.

Jain, P. and Pradeep, T. (2005) Potential of silver nanoparticle-coated polyurethane foam as an antibacterial water filter. *Biotechnology and Bioengineering* 90(1): 59-63.

Jeong, J., Kim, J.Y. and Yoon, J. (2006) The role of reactive oxygen species in the electrochemical inactivation of microorganisms. *Environmental Science and Technology* 40: 6117-6122.

Johnson, S.M., Peletz, R.L. and Murcott, S. (2008) *Results from household ceramic filter evaluation in northern Ghana*. Access to Sanitation and Safe Water: Global Partnerships and Local Actions. 33rd WEDC International Conference, Accra, Ghana.

Kallmand, E., Oyanedel-Craver, V., and Smith J. (2010) Ceramic Filters Impregnated with Silver Nanoparticles for Point-of-Use Water Treatment in Rural Guatemala. *Journal of Environmental Engineering (accepted)*.

Kim, J.S., Kuk, E., Yu, K.N., Kim, J.-H., Park, S.J., Lee, H.J., Kim, S.H., Park, Y.K., Park, Y.H., Hwang, C.-Y., Kim, Y.-K., Lee, Y.-S., Jeong, D.H. and Cho, M.-H. (2007) Antimicrobial effects of silver nanoparticles. *Nanomedicine: Nanotechnology, Biology, and Medicine* 3: 95-101.

Klarman, M. (2009) *Investigation of Ceramic Pot Filter Design Variables*. Unpublished Thesis, Emory University, Rollins School of Public Health, USA.

Lantagne, D. (2006) *Potters for Peace: Filter Production Facility Best Practices.* Potters for Peace: Managua, Nicaragua.

Lantagne, D., Klarman, M., Mayer, A., Preston, K., Napotnik, J. and Jellison, K. (2009) Effect of production variables on microbiological removal in locally-produced ceramic filters for household water treatment. *International Journal of Environmental Health Research*.

Lantagne, D.S. (2001a) *Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 1: Intrinsic Effectiveness.* Alethia Environmental: Allston, MA, USA.

Lantagne, D.S. (2001b) *Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter Report 2: Field Investigations.* Alethia Environmental: Allston, MA, USA.

Larimer, C., Ostrowski, N., Speakman, J. and Nettleship, I. (2010) The segregation of silver nanoparticles in low-cost ceramic water filters. *Materials Characterization* 61: 408-412.

LePape, H., Solano-Serena, F., Contini, P., Devillers, C., Maftah, A. and Leprat, P. (2002) Evaluation of the anti-microbial properties of an activated carbon fibre supporting silver using a dynamic method. *Carbon* 40: 2947-2954.

LePape, H., Solano-Serena, F., Contini, P., Devillers, C., Maftah, A. and Leprat, P. (2004) Involvement of reactive oxygen species in the bactericidal activity of activated carbon fibre supporting silver: Bactericidal activity of ACF(Ag) mediated by ROS. *Journal of Inorganic Biochemistry* 98: 1054-1060.

Li. Q., M.S., Lyon. D.Y., Brunet. L., Liga. M.v., Li. D., and Alvarez. P. J.J. (2008) Antimicrobial nanomaterials for water disinfection and microbial control: Potential applications and Implications. *Water Research* 42: 4591-4602.

Liau, S.Y., Read, D.C., Pugh, W.J., Furr, J.R. and Russell, A.D. (1997) Interaction of silver nitrate with readily identifiable groups: relationship to the antibacterial action of silver ions. *Letters in Applied Microbiology* 25: 279-283.

Lok, C.-N., Ho, C.-M., Chen, R., He, Q.-Y., Yu, W.-Y., Sun, H., Tam, P.K.-H., Chiu, J.-F. and Che, C.-M. (2007) Silver nanoparticles: partial oxidation and antibacterial activities. *Journal of Biological Inorganic Chemistry* 12: 527-534.

Long, D., Wu, G. and Chen, S. (2007) Preparation of olichitosan stabilized silver nanoparticles by gamma irradiation. *Radiation Physics and Chemistry* 76: 1126-1131.

Maneerung, T., Tokura, S. and Rujiravanit, R. (2007) Impregnation of silver nanoparticles into bacterial cellulose for antimicrobial wound dressing. *Carbohydrate Polymers* 72(1): 43-51.

Merga, G., Wilson, R., Lynn, G., Milosavljevic, N.H. and Meisel, D. (2007) Redox catalysis on "naked" silver nanoparticles. *Journal of Physical Chemistry C* 111: 12220-12226.

Miller, T.R. (2010) *Optimizing Performance of Ceramic Pot Filters in Northern Ghana and Modeling Flow through Paraboloid-Shaped Filters*. Unpublished Thesis, Massachusetts Institute of Technology

Morones, J.R., Elechiguerra, J.L., Camacho, A., Holt, K., Kouri, J.B., Ramirez, J.T. and Yacaman, M.J. (2005) The bactericidal effect of silver nanoparticles. *Nanotechnology* 16: 2346-2353.

Mossman, A. and Lam, S. (2004) *Ceramic Water Purifier Factory Equipment Manual*. Unpublished

Navaroo, E., Peiccapietra, F., Wagner, B., Marconi, F., Kaegi, R., Odzak, N., Sigg, L. and Behra, R. (2008) Toxicity of silver nanoparticles to *Chlamydomonasreinhardtii*. *Environmental Science and Technology* 42(33): 8959-8964.

NetherlandsWaterPartnership (2010) *Smart Disinfection Solutions*. KIT Publishers: Amsterdam.

Oyanedel-Craver, V.A. and Smith, J.A. (2008) Sustainable colloidal-silver-impregnated ceramic filter for point-of-use water treatment. *Environmental science & technology* 42(3): 927-933.

Pal, S., Tak, Y.K. and Song, J.M. (2007) Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? A study of the gram-negative bacterium Escherichia coli. *Applied and Environmental Microbiology*: 1712-1720.

Panacek, A., Kvitek, L., Prucek, R., Kolar, M., Vecerova, R., Pizurova, N., Sharma, V.K., Nevecna, T.j. and Zboril, R. (2006) Silver colloid nanoparticles: synthesis, characterization, and their antibacterial activity. *Journal of Physical Chemistry* 110: 16248-16253.

Pelita (2009). Indonesia (Indo-2)**:** Photograph provided by Pelita Indonesia in response to questionnaire.

Peterson, B.E. (2009) *Kiln Types by Construction.*About.com:Pottery. http://pottery.about.com/od/potterykilns/tp/typkilncons.htm. (Accessed 2009).

Petica, A., Gavriliu, S., Lungu, M., Buruntea, N. and Panzaru, C. (2008) Colloidal silver solutions with antimicrobial properties. *Materials Science and Engineering B* in press.

PFP (2008) *PFP Home Page*. http://www.pottersforpeace.org. (Accessed 2008 Jan 20).

Pillers, B. and Diaz, R.T. (2009) *Factory Overview; Addressing Recontamination*. International Ceramic Pot Filter Workshop, WEF Disinfection. Atlanta, GA, USA.

PotterswithoutBorders (2010) Potters without Borders. www.potterswithoutborders.com. (Accessed September, 2010).

POUZN (2007) *Best Practices in Social Marketing Safe Water Solution for Household Water Treatment: Lessons Learned from Population Services International Field Programs.* The Social Marketing Plus for Diarrheal Disease Control: Point-of-Use Water Disinfection and Zinc Treatment (POUZN) Project: Bethesda, MD.

Rado, P. (1988) *An Introduction to the Technology of Pottery*. Pergamon Press, The Institute of Ceramics: Oxford.

Raffi, M., Hussain, F., Bhatti, T.M., Akhter, J.I., Hameed, A. and Hasan, M.M. (2008) Antibacterial characterization of silver nanoparticles against E. C oli ATCC-15224. *Journal of Material Science and Technology* 24(2): 192-196.

Rayner, J. (2006) *Potters for Peace Ceramic Filter Production Manual*. Unpublished

Rayner, J. (2009) *Current Practices in Manufacturing of Ceramic Pot Filters for Water Treatment*. Unpublished Thesis, Loughborough University

Rhodes, D. (1973) *Clay and Glazes for the Potter*. Krause Publications: Iola Wisconsin.

Rivera-Garza, M., Olguin, M.T., Garcia-Sosa, I., Alcantara, D. and Rodriquez-Fuentes, G. (2000) Silver supported on natural Mexican zeolite as an antibacterial material. *Microporous and Mesoporous Materials* 39: 431-444.

Rivera, R. (2006) *Production of Ceramic/Colloidal Silver (CCS) Water Filters*. Unpublished

Roberts, M. (2004) *Field Test of a Silver-Impregnated Ceramic Water Filter*. People-Centred Approaches to Water and Environmental Sanitation. 30th WEDC International Conference, Vientiane, Lao PDR.

Ruparelia, J.P., Chatterjee, A.K., Duttagupta, S.P. and Mukherji, S. (2008) Strain specificity in antimicrobial activity of silver and copper nanoparticles *Acta Biomaterialia* 4: 707-716.

Russell, A.D. and Russell, N.J. (1995) *Biocides: Activity, Action and Resistance*. Fifty Years of Antimicrobials: Past Perspectives and Future Trends. P. A. Hunter, G. K. Darby and N. J. Russell. Cambridge, Cambridge University Press.

Sapsford, R. and Jupp, V. (1996) *Data collection and analysis*. Sage.

Schmidt, M., Masson, A. and Brechignac, C. (2003) Oxygen and silver clusters: Transition from chemisorption to oxidation. *Physical Review Letters* 91(24): 3401-3405.

Scholars, W.W.I.C.f. (2008) *The project on emerging nanotechnologies*.

Shrivastava, S., Bera, T., Roy, A., Singh, G., Ramachandrarao, P. and Dash, D. (2007) Characterization of enhanced antibacterial effects of novel silver nanoparticles. *Nanotechnology* 18: 1-9.

Silversty-Rodriguez, N.B., K.R., Slack, D.C., Uhlmann, D.R., and Gerba, C.P. (2008) Silver as a residual disinfectant to prevent biofilm formation in water distribution systems. *Applied and Environmental Microbiology* 74(5): 1639-1641.

Sobsey, M., Stauber, C.E., Casanova, L.M., Brown, J. and Elliott, M.A. (2008) Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environ Sci Technol* 42(12): 4261-7.

Sondi, I. and Salopek-Sondi, B. (2004) Silver nanoparticles as antimicrobial agent: A study on E. coli as a model for gram-negative bacteria. *Journal of Colloid and Interface Science* 275: 177-182.

Soukupova, J., Kvıtek, L., Panacek, A., Nevecna, T. and Zboril, R. (2008) Comprehensive study on surfactant role on silver nanoparticles (NPs) prepared via modified Tollens process *Materials Chemistry and Physics* 111: 77-81.

Thirst-Aid (2009)**:** Photograph provided by Thirst-Aid in response to questionnaire.

Thirst-Aid (2010) *Photograph provided by Curt Bradner*.

Tien, D.-C., Tseng, K.-H., Liao, C.-Y. and Tsung, T.-T. (2008) Identification and quantification of ionic silver fromc olloidal silver prepared by

electric spark discharge system and its antimicrobial potency study. *Journalof Alloy sand Compounds* in press.

Tun, W.W. (2009) *A Study of Arsenic Leaching from Colloidal Silver Ceramic Water Filters Manufactured in Myanmar.* UNICEF, Myanmar:

UNICEF/WHO (2008) *Progress on drinking water and sanitation: special focus on sanitation.* UNICEF/WHO: Geneva, Switzerland.

van Halem, D. (2006) *Ceramic silver impregnated pot filters for household drinking water treatment in developing countries*. Unpublished Thesis, Delft University of Technology, Delft.

van Halem, D., van der Laan, H., Heijman, S.G.J., van Dijk, J.C. and Amy, G.L. (2009) Assessing the sustainability of the silver-impregnated ceramic pot filter for low-cost household drinking water treatment. *Physics and Chemistry of the Earth* 34(1-2): 36-42.

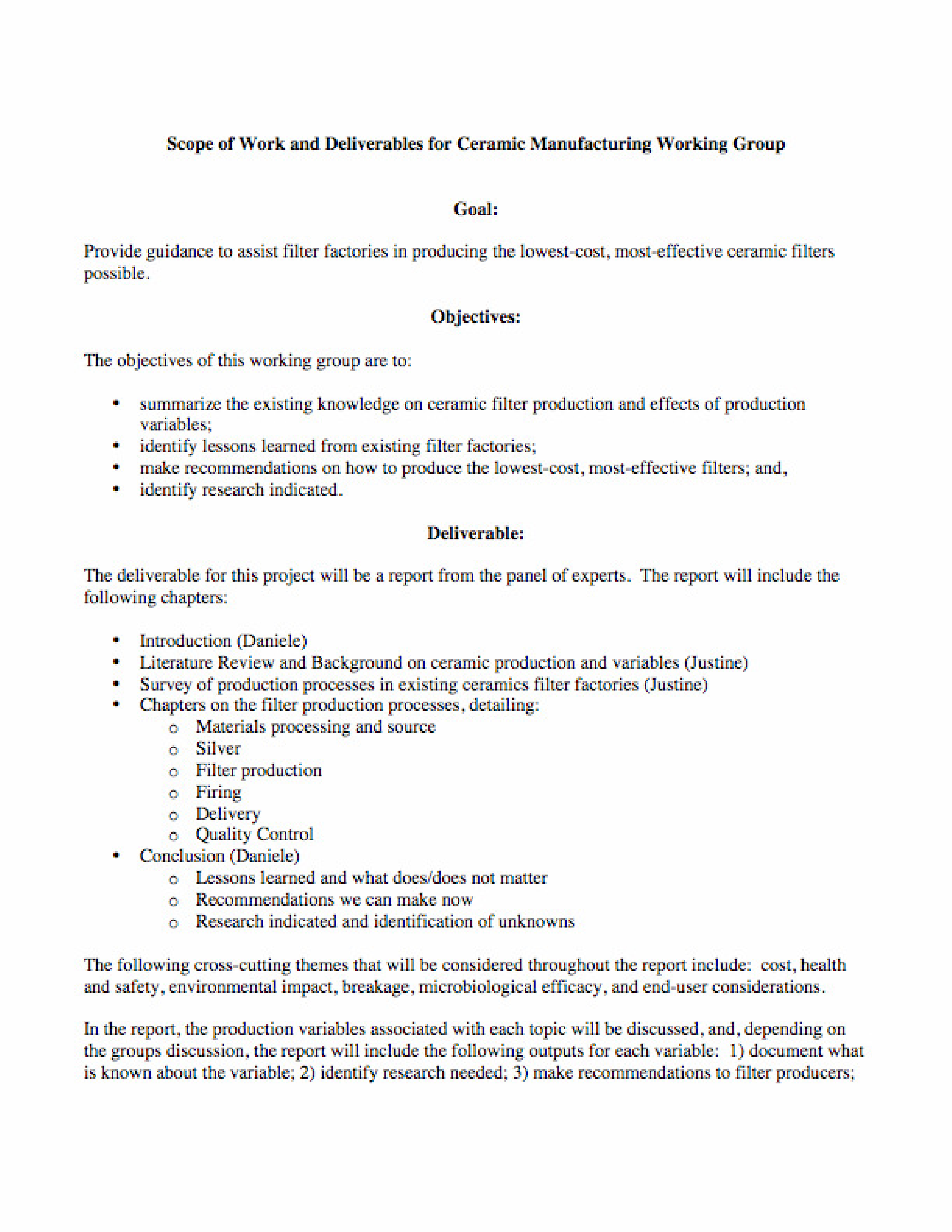
Wagoner, K. (2010) *Photograph provided by Kaira Wagoner*.

WHO (2004) *Guidelines for drinking-water quality, 3rd Edition; Volume 1: Recommendations.* Geneva, Switzerland.

WHO (2006) *Guidelines for drinking-water quality: first addendum to third edition.* World Health Organization:

Wright, J., Gundry, S. and Conroy, R. (2004) Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. *Trop Med Int Health* 9(1): 106-17.

Annex A Scope of Work



Scope of Work and Deliverables for Ceramic Manufacturing Working Group

Goal:

Provide guidance to assist filter factories in producing the lowest-cost, most-effective ceramic filters possible.

Objectives:

The objectives of this working group are to:

- summarize the existing knowledge on ceramic filter production and effects of production variables;
- identify lessons learned from existing filter factories;
- make recommendations on how to produce the lowest-cost, most-effective filters; and,
- identify research indicated.

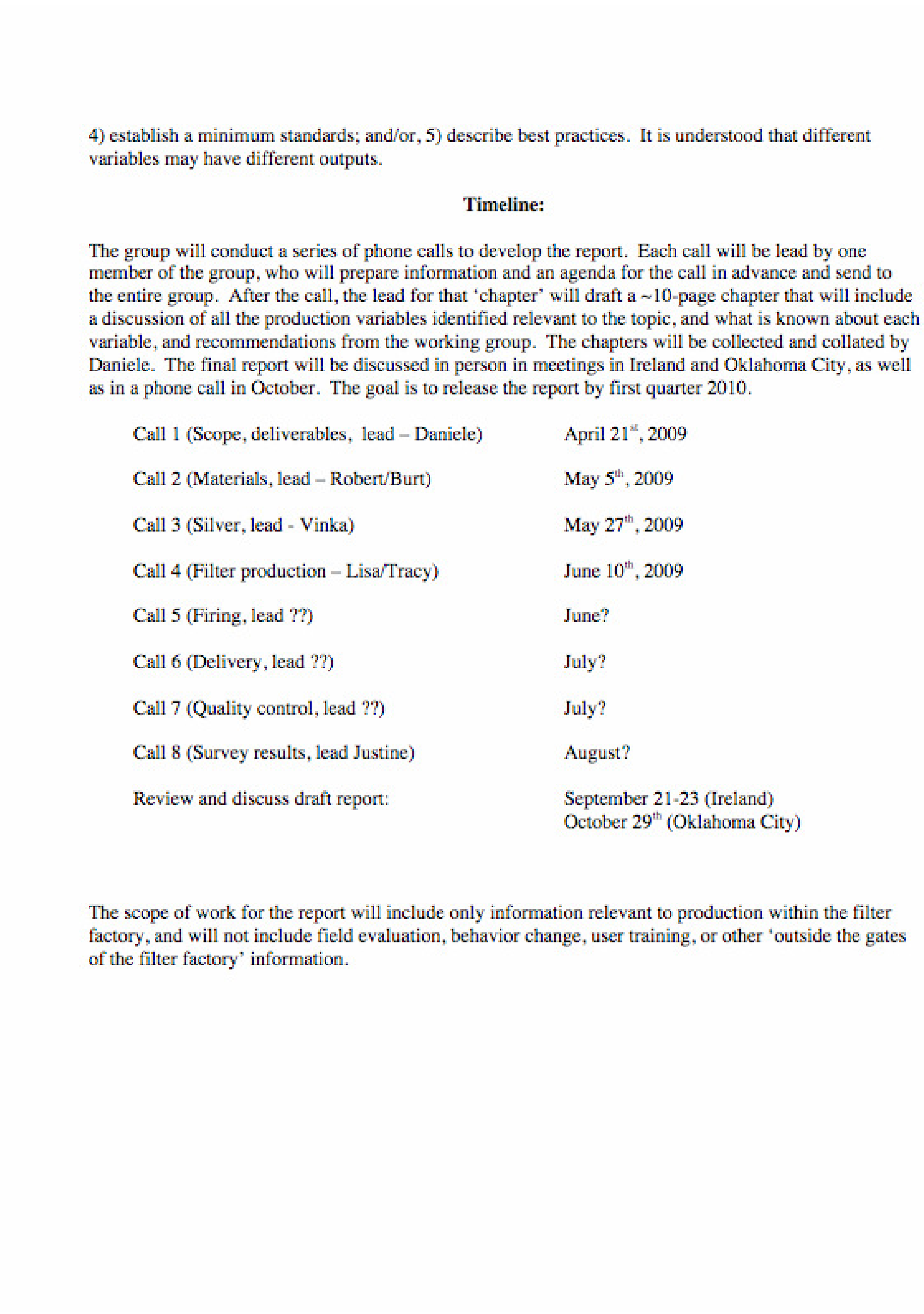
Deliverable:

The deliverable for this project will be a report from the panel of experts. The report will include the following chapters:

- Introduction (Daniele)
- Literature Review and Background on ceramic production and variables (Justine)
- Survey of production processes in existing ceramics filter factories (Justine)
- Chapters on the filter production processes, detailing:
  - Materials processing and source
  - Silver
  - Filter production
  - Firing
  - Delivery
  - Quality Control
- Conclusion (Daniele)
  - Lessons learned and what does/does not matter
  - Recommendations we can make now
  - Research indicated and identification of unknowns

The following cross-cutting themes that will be considered throughout the report include: cost, health and safety, environmental impact, breakage, microbiological efficacy, and end-user considerations.

In the report, the production variables associated with each topic will be discussed, and, depending on the groups discussion, the report will include the following outputs for each variable: 1) document what is known about the variable; 2) identify research needed; 3) make recommendations to filter producers;



4) establish a minimum standards; and/or, 5) describe best practices. It is understood that different variables may have different outputs.

Timeline:

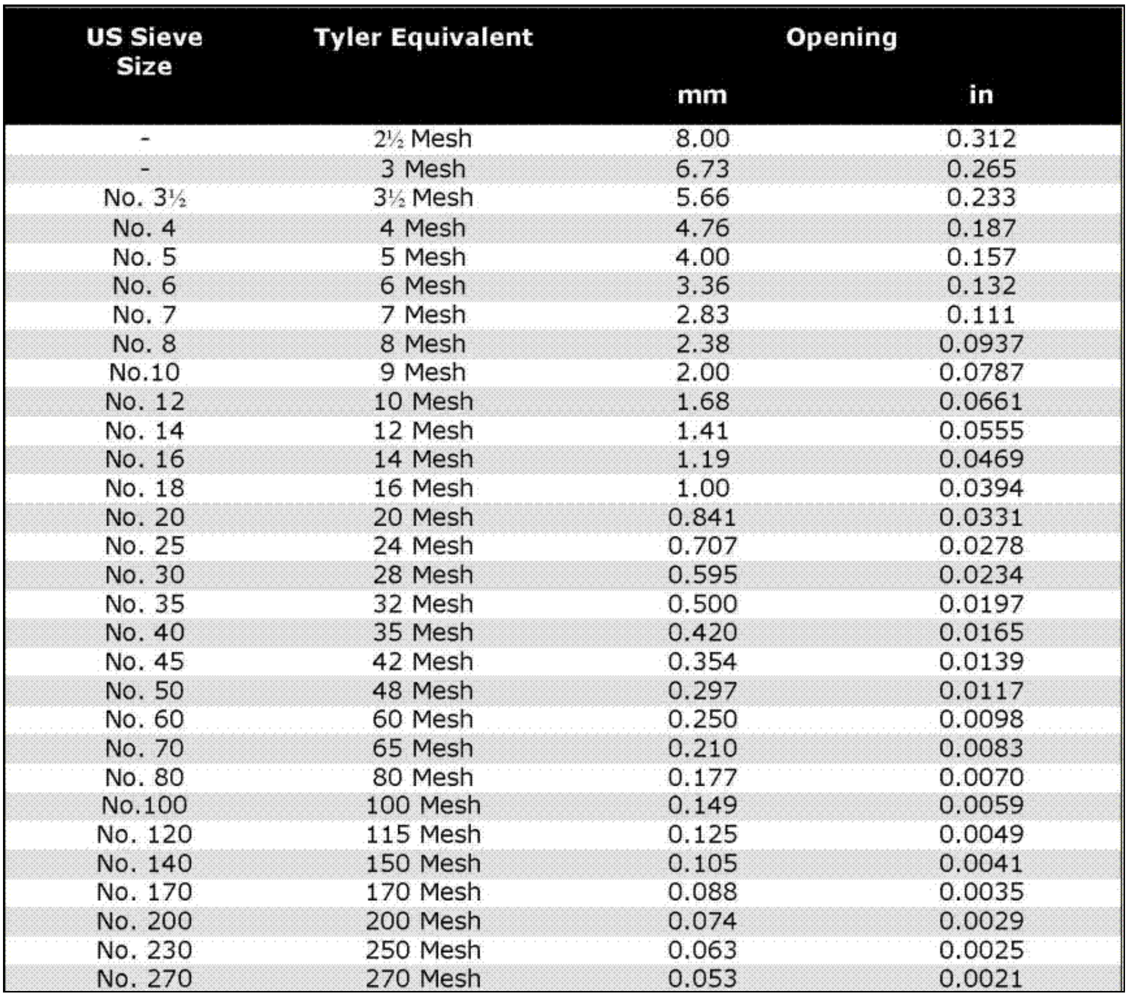
The group will conduct a series of phone calls to develop the report. Each call will be lead by one member of the group, who will prepare information and an agenda for the call in advance and send to the entire group. After the call, the lead for that 'chapter' will draft a ~10-page chapter that will include a discussion of all the production variables identified relevant to the topic, and what is known about each variable, and recommendations from the working group. The chapters will be collected and collated by Daniele. The final report will be discussed in person in meetings in Ireland and Oklahoma City, as well as in a phone call in October. The goal is to release the report by first quarter 2010.

Call 1 (Scope, deliverables, lead – Daniele)	April 21st, 2009
Call 2 (Materials, lead – Robert/Burt)	May 5th, 2009
Call 3 (Silver, lead - Vinka)	May 27th, 2009
Call 4 (Filter production – Lisa/Tracy)	June 10th, 2009
Call 5 (Firing, lead ??)	June?
Call 6 (Delivery, lead ??)	July?
Call 7 (Quality control, lead ??)	July?
Call 8 (Survey results, lead Justine)	August?
Review and discuss draft report:	September 21-23 (Ireland) October 29th (Oklahoma City)

The scope of work for the report will include only information relevant to production within the filter factory, and will not include field evaluation, behavior change, user training, or other 'outside the gates of the filter factory' information.

Annex B Conversion Tables

B-1 Tyler Mesh Equivalent



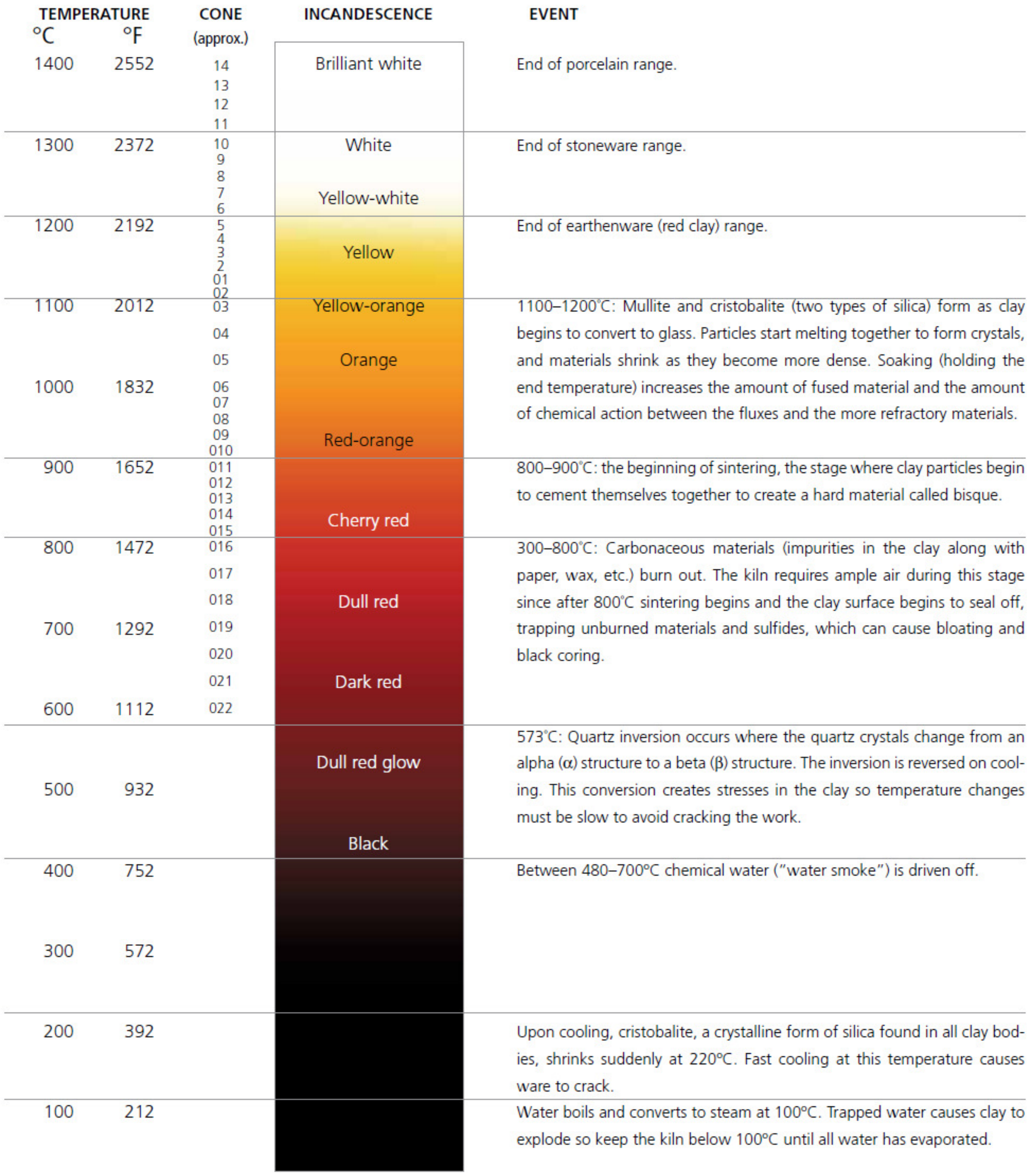
US Sieve Size	Tyler Equivalent	Opening	
		mm	in
-	2½ Mesh	8.00	0.312
-	3 Mesh	6.73	0.265
No. 3½	3½ Mesh	5.66	0.233
No. 4	4 Mesh	4.76	0.187
No. 5	5 Mesh	4.00	0.157
No. 6	6 Mesh	3.36	0.132
No. 7	7 Mesh	2.83	0.111
No. 8	8 Mesh	2.38	0.0937
No.10	9 Mesh	2.00	0.0787
No. 12	10 Mesh	1.68	0.0661
No. 14	12 Mesh	1.41	0.0555
No. 16	14 Mesh	1.19	0.0469
No. 18	16 Mesh	1.00	0.0394
No. 20	20 Mesh	0.841	0.0331
No. 25	24 Mesh	0.707	0.0278
No. 30	28 Mesh	0.595	0.0234
No. 35	32 Mesh	0.500	0.0197
No. 40	35 Mesh	0.420	0.0165
No. 45	42 Mesh	0.354	0.0139
No. 50	48 Mesh	0.297	0.0117
No. 60	60 Mesh	0.250	0.0098
No. 70	65 Mesh	0.210	0.0083
No. 80	80 Mesh	0.177	0.0070
No.100	100 Mesh	0.149	0.0059
No. 120	115 Mesh	0.125	0.0049
No. 140	150 Mesh	0.105	0.0041
No. 170	170 Mesh	0.088	0.0035
No. 200	200 Mesh	0.074	0.0029
No. 230	250 Mesh	0.063	0.0025
No. 270	270 Mesh	0.053	0.0021

Source: Primary author: AZoM.com, http://www.azom.com/details.asp?ArticleID=1417

B-2 Firing Chart

Kiln Firing Chart

Firing converts ceramic work from weak greenware into a strong, durable permanent form. As the temperature in a kiln rises, many changes take place at different temperatures and understanding what happens during the firing can help you avoid problems with a variety of clay and glaze faults related to firing.



TEMPERATURE °C	°F	CONE (approx.)	INCANDESCENCE	EVENT
1400	2552	14 13 12 11	Brilliant white	End of porcelain range.
1300	2372	10 9 8 7 6	White Yellow-white	End of stoneware range.
1200	2192	5 4 3 2 01 02	Yellow	End of earthenware (red clay) range.
1100	2012	03 04 05	Yellow-orange Orange	1100–1200°C: Mullite and cristobalite (two types of silica) form as clay begins to convert to glass. Particles start melting together to form crystals, and materials shrink as they become more dense. Soaking (holding the end temperature) increases the amount of fused material and the amount of chemical action between the fluxes and the more refractory materials.
1000	1832	06 07 08 09 010	Red-orange	
900	1652	011 012 013 014 015	Cherry red	800–900°C: the beginning of sintering, the stage where clay particles begin to cement themselves together to create a hard material called bisque.
800	1472	016 017 018	Dull red	300–800°C: Carbonaceous materials (impurities in the clay along with paper, wax, etc.) burn out. The kiln requires ample air during this stage since after 800°C sintering begins and the clay surface begins to seal off, trapping unburned materials and sulfides, which can cause bloating and black coring.
700	1292	019 020 021	Dark red	
600	1112	022		
			Dull red glow	573°C: Quartz inversion occurs where the quartz crystals change from an alpha (α) structure to a beta (β) structure. The inversion is reversed on cooling. This conversion creates stresses in the clay so temperature changes must be slow to avoid cracking the work.
500	932		Black	
400	752			Between 480–700°C chemical water ("water smoke") is driven off.
300	572			
200	392			Upon cooling, cristobalite, a crystalline form of silica found in all clay bodies, shrinks suddenly at 220°C. Fast cooling at this temperature causes ware to crack.
100	212			Water boils and converts to steam at 100°C. Trapped water causes clay to explode so keep the kiln below 100°C until all water has evaporated.

(CeramicArtsDaily 2010)

Annex C Survey Results Tables

C-1 Mold and Filter Details

Country	Made in:	Material:	Filter Height (cm)	Filter Diam. (cm)	Walls Thick (cm)	Capacity (liters)	Quantity in press (kg)
Benin	blank	Aluminum	24	32	0.1*	8	8
Cam-1	Cambodia	Cast-iron	24	33.5	1.7	10	9
Cam-2	Cambodia	Aluminum	blank	blank	blank	11	8
Colombia	blank	Aluminum	blank	blank	blank	blank	8
DR	Dominican Republic	Cement	28	28	1.6	6	5.4
Guate-1	Guatemala	Aluminum	23	32	blank	7	don't know
Guate-2	blank	Aluminum	28**	30.5**	2	11**	blank
Indo-1	Nicaragua	Aluminum	25	32	1.5	9	8.4
Indo-2	Indonesia	Aluminum	blank	blank	1.8	8	5.7
MM-All	Myanmar	Cast iron, Carved teak, Steel or Aluminum	blank	blank	1.4	10	7
Nica-1	Managua	Aluminum	23.5	32	1	8	7.3
Nica-2	Nicaragua	Aluminum	22.5	31	blank	7	5
Nigeria	Nicaragua	Aluminum	blank	blank	blank	blank	blank
SL-1	Cambodia	Cast Iron	14*	blank	3	10	10.5
SL-2	Cambodia	Cast Iron	23	32	2.5	8	10
Tanz-1	Tanzania	Cement	29	33	2.1	8	8
Tanz-2	Nicaragua	Aluminum	blank	blank	0.5*	7	3*
Yemen	Nicaragua	Aluminum	blank	blank	blank	7	9
*this information does not appear to be accurate							
**calculated from answers provided in inches and US gallons.							

C-2 Firing Practices

Country	Fuel	Pyro-meter	Cones	Visual	Number of Cones	Cone numbers	Target Temp ℃	Frequency Achieved	Fire Time (hrs)
Cam-2	Wood	x	x		2	012,014	866	Always	10 - 12
MM-all	Wood	x	x	x	2	09,010	900	Almost Always	6 - 7
Nigeria	Wood	x	x		3	06	900	Almost Always	10 - 12
Tanz-1	Wood & Propane	x	x	x	3	012	880-900	Always	8
Cam-1	Wood		x		1	014	830	Always	12
Guate-1	Wood		x	x	varies	012	private	blank	private
Guate-2	Wood		x		2	014,012	847	Almost Always	11
Nica-1	Wood		x		3	010,012, 014	886	Always	8
Nica-2	Wood		x	x	1	012	830	Almost Always	8
Benin	Oil	x			n/a	n/a	900	Almost Always	12
Colombia	Wood	x			n/a	n/a	900	Usually	6
DR	Wood	x		x	n/a	n/a	980	Always	12
Indo-1	Wood	x			n/a	n/a	900	Always	8.5
Indo-2	Wood	x		x	n/a	n/a	832	Always	10 - 14
SL-1	Wood	x			n/a	n/a	800	Almost Always	15
SL-2	Wood	x			n/a	n/a	800	Almost Always	10 - 11
Tanz-2	Wood	x			n/a	n/a	700-920	Usually	6 - 8
Yemen	Propane	x			n/a	n/a	880	Always	11

C-3 Production Logs

Country	Date made	Filter #	Lot #	Flow rate	Discard date	Discard reason	Date sold	Buyer Info.	Other
Cam-1	x	x	x	x					monthly account of number of filters sold
Guate-1	x	x	x	x			x	x	operator, conditions, materials/where from
Guate-2							x		
Indo-1	x	x	x	x	x	x	x	x	filter weight, drying time, kiln temp, visual faults
Indo-2	x	x	x	x	x	x	x	x	payments
MM-All	x	x	x	x			x	x	
Nica-1	x	x	x	x					dates cs applied, packaged, time and date of firing
Nigeria	x	x	x	x	x			x	
SL-1	x	x		x	x			x	
SL-2	x	x	x	x	x	x*			formula for batch
Tanz-1			x	x		x			number of filters fired, micro bio test results
Tanz-2	x	x	x	x		x	x	x	
Yemen	x	x	x	x					
Benin	x								
Colombia		x	x	x					
DR	x	x		x*			x		Bacteria testing results

*information is sometimes recorded

C-4 Filter Testing

Country	Regular Testing	Quantity (%)	Fact-ory	Lab	Turb-idity	pH	TC	TTC	Fluo-ride	Silver	Arsenic	Comments
Guate-1	yes	blank	x	x	F/L	F/L	F/L	F/L	F/L	F/L	F/L	Based on quality control manuals.
Indo-1	yes	15%	x			F	F	F				
Indo-2	yes	2%		x		L	L	L	L	L	L	Two filters per week chosen randomly. Monthly: effluent water from 5-10 filters in the field is tested.
Benin	yes	blank		x	L	L	L		L	L	L	blank
DR	yes	8%		x		L	L					Effluent water is also tested from two filters in use every two months.
Cam-1	yes	0.2%	x	x			L			F		Microbiological tests carried out in lab. Field kit is used to confirm silver application.
MM-All	yes	1%		x			L					
Tanz-1	yes	4%	x	x			F/L					4% from each firing tested at factory, 4% from every other firing tested in lab.
Cam-2	yes	blank		x								Water quality index and primary chemical contaminants are tested for on a random sample monthly.

Guate-2	yes	blank		x								
Nigeria	yes	10%	x	x								Hach tests in factory. Two or three samples (in nine months) tested in lab for *E. coli* and chemical analysis.
SL-2	yes	2%	x	x								Presence/Absence Hydrogen Sulfide kit in factory and some samples to lab.
Tanz-2	yes	blank		x								
Nica-1	no	blank		x			L	L				Also tests for streptococcus & *E. coli.*
SL-1	no	blank	x	x			F/L	F/L		F/L	F/L	
Yemen	no	blank	x				F					Hach tests from time to time. Clients conduct complete tests.
Colombia	no	blank										Others have tested the filters.
Nica-2	no	blank	x									

* Key: F= in factory testing, L= laboratory testing

Annex D Diagnostic Tests for Raw Materials

The following sections describe simple tests for evaluating clay and burn-out material for quality and consistency. As raw materials are likely to change over time, by carrying out these tests and documenting results, characteristics can be compared to provide an indication of the suitability and/or the need for modification or rejection of the material, or when microbiological testing is needed to confirm the change in material has not negatively affected the quality of the filters produced. In addition, tests for checking the mold alignment and for leaky taps are described.

D-1 Clay Tests

The following tests are described below and are recommended to determine the usefulness of a clay: 1) presence of lime; 2) water of plasticity; 6) shrinkage (dry, firing & total shrinkage); and 7) determining firing temperature (using total shrinkage and percent porosity) (Rhodes, Clay and Glazes for the Potter). In addition, clay body blending methods are described.

In testing clay to determine whether it can be used, it is not usually necessary to make a chemical analysis. While such an analysis may be essential in determining and controlling the composition of commercial clay, the physical nature of the clay and its reaction to firing are much more important to the ceramist. Chemical analysis rarely gives any surprising data which could not have been guessed at by an experienced person who has actually worked with the material.

Test for the Presence of Lime

Although lime has not been observed to cause a problem in filters, if a clay contains whitish lumps and/or the area is known to contain limestone, finished filters should be checked for “lime popping” and clay can be tested for calcium. To detect the presence of calcium in a clay source, a sample of the clay can be put into a beaker containing a 50% solution of hydrochloric acid (HCl); if lime is present, it will bubble furiously (Rhodes 1973: 65). If the lime poses a problem in finished filters, screening clay with a #40 mesh should be sufficient to remove lime large enough to cause a problem. If this does not work, another clay source might need to be identified.

Test for the Water of Plasticity

This test determines the amount of water which is required to make a clay plastic and workable. The more water a clay requires to become plastic, the finer its grain structure is apt to be, and therefore the more it will shrink during drying (Rhodes 1973). Carrying out this test periodically will identify changes in clay characteristics which might affect filter mixture ratio and the flow rate of the filter as the amount of water required to achieve a plastic mixture is one determinant of the pore structure.

1) Thoroughly dry the clay sample, pulverize it and sieve it through a 30-mesh screen;
2) Weigh out 500 grams of clay (one pound) onto a glass or other smooth, non-porous surface;

3) Fill a 500 mL (cc/gr) graduated cylinder with water and add the water to the clay a little at a time, mixing well after each addition;
4) Knead the clay, adding more water from the cylinder if necessary, until it is a smooth mass of about the right consistency for modeling;
5) Note how much water was added to the clay;
6) Calculate the amount of water of plasticity using the following formula:

$$\text{Percent water of plasticity} = \frac{\text{Weight of water}}{\text{Weight of dry clay}} \times 100$$

Shrinkage

The amount of shrinkage is an important characteristic of any clay and will be somewhat determined by the amount of non-plastic material, particle size and water content. A clay with a high shrinkage rate (more than 15% total shrinkage) probably will not be useful, due to warping and cracking in drying and firing. Knowing the total shrinkage rate for filter mixture of the proposed ratio will be useful for designing molds of the proper dimensions, so the filtering element will fit precisely inside the available receptacle. Shrinkage tests should be carried out both on source clay and filter mixture regularly to confirm consistency of raw materials. The same water to clay ratio (by weight) should be used for comparable results.

Dry Shrinkage

In this test, the dry linear shrinkage, or how much the clay shrinks during the drying process, is determined.

1) From a well-kneaded mass of clay using a specific water to clay ratio (for example, the amount of water used in the water of plasticity test above) make 5-10 bars that are 14 cm long, 4 cm wide and about 1 cm thick;
2) On the face of each bar make a sharp scratch exactly 10 cm long;
3) Allow the bars to dry slowly and evenly, turning every couple of hours to prevent warping;
4) Determine dry shrinkage using the following calculation:

$$\text{Percent linear shrinkage} = \frac{\text{Plastic length - dry length}}{\text{Plastic length}} \times 100$$

Firing Shrinkage

Firing shrinkage is usually determined on samples which are fired to several different temperatures (for instance, 800˚C, 850˚C and 900˚C, following the standard firing curve and soak times). This gives an idea of the progressive tightening of the clay with advancing temperature:

1) Fire the dried bars made in the previous test;
2) Measure the length of the scratch on the fired bar;
3) Calculate the firing shrinkage using the following formula:

$$\text{Firing shrinkage} = \frac{\text{Dry length - Fired length}}{\text{Dry length}} \times 100$$

Total Shrinkage

Total shrinkage may be calculated using the following formula:

$$\text{Total shrinkage} = \frac{\text{Plastic length - fired length}}{\text{Plastic length}} \times 100$$

Percent Absorption (Porosity)

The firing temperature of a clay can be assessed by evaluating total shrinkage (see above) and absorption test results. During the ceramic change (600˚C), the chemical water fires out leaving spaces where the chemically bound water was, making the ceramic very porous. As firing continues, these spaces fill up and the ceramic shrinks. As a clay body vitrifies, it becomes less porous. Therefore, the degree of water absorption, or percentage porosity, is also a measure of the maturity of a fired clay body. Earthenware clay, by definition, will have a greater than 5% porosity when fired to maturity. Porosity of filters has been measured to range from 30-44% (van Halem 2006; Oyanedel-Craver and Smith 2008).

1) Make bars of the clay about 5 cm x 5 cm x 10 cm. At least three bars should be made for each temperature at which the clay will be fired and tested;
2) Fire the bars following the proposed firing curve;
3) Carefully weigh the fired pieces while still warm from the kiln to the nearest centigram;
4) Boil the fired pieces in water for five minutes;
5) Dry the surface of the bars with a damp sponge and weigh each one again;
6) Calculate the absorption, using the following formula:

$$\text{Percent absorption} = \frac{\text{Saturatated weight - dry weight}}{\text{Dry weight}} \times 100$$

Clay Blending Methods

Methods of line and triaxial blending are essential in determining material ratios when preparing a clay body with two or more ingredients. For example, if two materials are to be used (a local clay and a burn-out material), a simple line blend working within the narrow range of 60% of one material to 40% of the other can establish the initial composition. In some cases, one local clay may not be suitable, but will work fine when combined with another local clay. In this case, where three materials are to be tested, for example, a blend of two local clays and one burn-out material (or, alternatively, one local clay and a combination of two types of burn-out material), a triaxial blend in the range of 40 – 60% total clay composition, with varying amounts of the burn-out material(s), can be employed. In most cases, experimentation will start with an initial body composition of 50% clay and 50% (by volume) burn-out material, with testing proceeding within the relatively narrow range of 40-60% by volume of these materials. Details of these methods follow.

Line Blending

The simplest type of methodical blend is the line blend. This kind of blend establishes a series of variations or mixes between two materials. Since we know that the acceptable range of materials in a filter mixture varies from 40% to 60% by volume of clay to burn-out material, we can begin the initial testing process by preparing the following ratios:

40% Clay	45% Clay	50% Clay	55% Clay	60% Clay
60% Burnout	55% Burnout	50% Burnout	45% Burnout	40% Burnout

If, in the initial round of testing, the most successful candidates were the mixtures containing 50% and 55% clay, for example, a second series of tests could be performed within this range as follows:

50% Clay	51% Clay	52% Clay	53% Clay	54% Clay	55% Clay
50% Burnout	49% Burnout	48% Burnout	47% Burnout	46% Burnout	45% Burnout

In this manner, the most effective ratio of the two ingredients can be efficiently arrived at with a minimum of testing.

Another type of line blend may be illustrated as follows:

1	2	3	4	5	6
	1-2	1-3	1-4	1-5	1-6
		2-3	2-4	2-5	2-6
			3-4	3-5	3-6
				4-5	4-6
					5-6

The top numbers, One to Six, may be any set of variables. In the next row down, 1-2 is a half-and-half mixture of Number One and Number Two; 1-3 is a half-and-half mixture of One and Three; and so on. What this type of blend exhausts all the mathematically possible 50-50 combinations between the original variations in the top row.

Tri-axial blending

When three materials are to be blended, such as when clay from two sources need to be blended with a burn-out material, the triaxial blending method is used to test various combinations of the three materials.

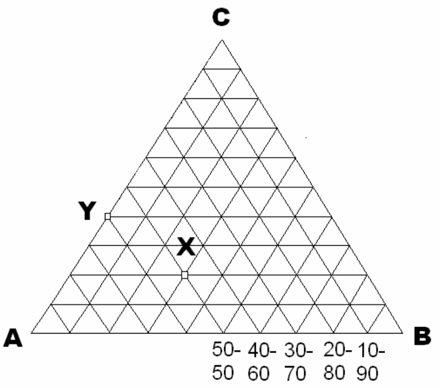
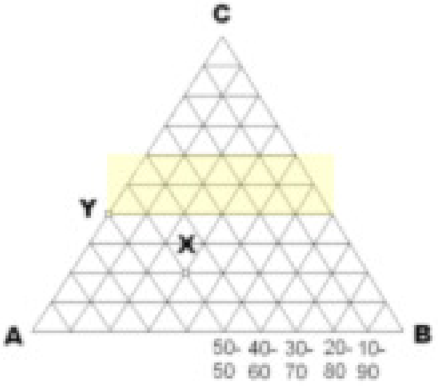


Figure D-0-1 Triaxial Blending Triangle

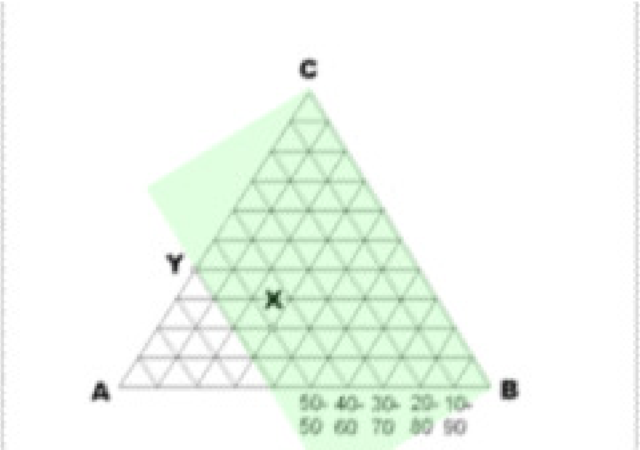
In the above diagram, A and B could represent clays from two different sources, and C could be the burn-out material. Since the points on the outside lines of the triangle only contain two of the three materials, they are, in effect, the same as straight line blends. The points between A and B represent a line blend of the two clays; the points between B and C represent a blend of Clay B with Burnout C; and the points between A and C represent a blend of Clay A with Burnout C. The mid-way point in each line represents half of one ingredient and half of the other. Since the triangle is divided into ten parts, each point at the intersection of the lines represents a 10% change in the amount of each material. So, each point on the outside lines of the triangle will have more or less of the end ingredients, depending on its distance from that ingredient's corner. Point Y, for example, represents a mixture of 60 percent of Clay A and 40 percent of Burnout C. This would be within the normal range for filter mixture testing.

The points inside the triangle represent various mixture ratios of all three ingredients. The composition of a point on the inside similarly depends on its distance away from the points at the corner. Point X, for example, will contain 50 percent of Clay A, since it is five spaces removed from A. It will contain 30 percent of Clay B, since it is seven spaces removed from B, and 20 percent of Burnout C, since it is eight spaces removed from C, which would be outside the normal range for filter mixture testing, since the burnout material is less than 40%. The composition of any other point in the diagram can likewise be determined by counting the number of spaces it is from each corner. The total of the three ingredients must always add up to 100%.

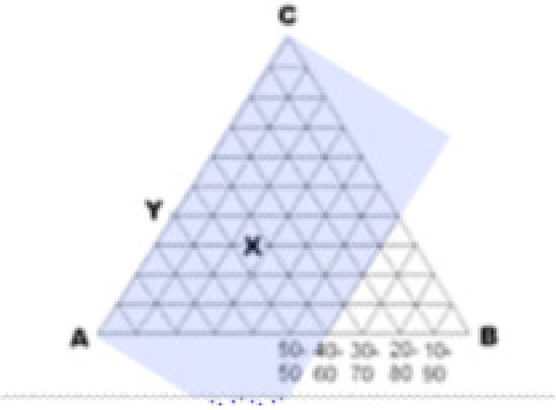
In filter mixture testing, we do not need to use the entire triangle. Since we normally test burnout ratios between the ranges of 40 to 60%, we can simplify our testing by eliminating those portions of the triangle outside of those ranges, to create a new diagram that only includes the area to be tested. To begin, we highlight the portion of the diagram that represents Burnout C within the ranges of 40% - 60%:



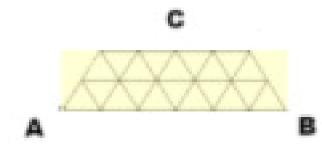
The horizontal line at Point Y represents 40% of Burnout C, the line above it 50% of Burnout C, and the top highlighted line 60% of Burnout C. Next, we apply to same process to Clay A, highlighting that section of the triangle within the range desired:



And then do the same for Clay B:



By selecting the area where the colors overlap, we determine the proportions of each material to be tested:



We have now reduced the number of tests necessary from 66 to 18. The proportions of each of the three ingredients at each point on the diagram are calculated as follows:

A 40 B 0 C 60	A 30 B 10 C 60	A 20 B 20 C 60	A 10 B 30 C 60	A 0 B 40 C 60		
A 50 B 0 C 50	A 40 B 10 C 50	A 30 B 20 C 50	A 20 B 30 C 50	A 10 B 40 C 50	A 0 B 50 C 50	
A 60 B 0 C 40	A 50 B 10 C 40	A 40 B 20 C 40	A 30 B 30 C 40	A 20 B 40 C 40	A 10 B 50 C 40	A 0 B 60 C 40

Once again, these 18 options can be used for initial testing. If one of them it not the obvious best choice, the three options that give the best results can be chosen for new corners of the triangle, and by testing the ratios in between these corners, similar to the explanation given in the line blend section, we can target the precise ratio of materials to be used in production.

D-2 Burn-out Tests

Measuring Moisture Content

Some factories have found the ambient humidity can affect the weight of burn-out enough to affect the accuracy of the filter mixture ratio. When changes are noticed in burn-out this test can be carried out. Heat a measured amount (by weight) of burn-out material to approximately 100˚C and hold the temperature for a few hours. Compare the weight of the fully dried mass to initial mass. If the weight of the burn-out is not consistent, regularly drying it prior to preparing filter mixture should be considered.

Test for Purity of Burn-out

Place one spoonful (approximately 5 grams), of burn-out in a ceramic dish and fire it under a standard firing profile. If there is material remaining in the dish after the firing is complete, the burn-out material may be contaminated and another source should be found.

Annex E Additional Tests

E-1 Mold Alignment – Filter Cross-Section

When a new mold is installed in a press the alignment is checked by cutting a freshly pressed filter in half lengthwise with a wire tool to measure and identify any deviation in wall thickness, including the thickness of the bottom of the filter (Figure 5-8). Fired filters meeting other quality control guidelines should also be cross-sectioned to check for mold alignment and to check for complete firing both while making prototype filters and regularly throughout production. If high discard rates are noted, cross sections can be completed on discarded filters to help identify problems. While manufacturing prototype filters, it is recommended that 20% of the fired filters be cross-sectioned. Although this is a destructive test, once the factory is producing filters for sale, 0.4% of all filters should be checked (Table 9).

Use a handsaw or other appropriate tool to cut the filter lengthwise into at least 2 pieces. Inspect and record the following:

Check mold alignment by:

1) Measuring the thickness to the nearest millimeter with calipers and recording the thickness of the filter wall;
2) Measuring and recording the thickness of the opposing filter wall at the same height on the filter;
3) Do this at several heights in the filter wall and the thickness of the bottom of the filter;
4) Compare the thicknesses of the walls and base; if it varies more than 10%, the molds need to be checked for alignment.

Check for complete firing by:

1) Visually inspecting the inside of the filter walls for consistent color throughout, a small amount of color variation is to be expected;
2) Look for evidence of incomplete burn out of combustible material;
3) Record observations and compare with the firing-log from the specific firing. At this time, leaving a black core in the filter walls is not recommended.

E-2 Kiln Temperature Mapping

Prepare five cone packs of three cones each (for example, cone 013 as a guide cone, 012 as the fire cone and 011 as the guard cone). Place each cone pack in a different location in the kiln, including: one cone pack in each of the four corners, one on each end of the bag wall, one by each of the spyholes (located halfway up the wall opposite the door and one halfway up the door) and one in the middle of the kiln about halfway up. The kiln should be stacked with filters so the firing will be representative of a normal firing and the kiln should be fired according to a standard firing profile. After cooling the kiln, label each cone pack as it is removed from the kiln and mark the location where it was in the kiln on a drawing of the interior of the kiln. Note the difference in cone behavior to learn where the cool spots versus hot spots are in the kiln. Adjustments, which could include lowering, raising or adding openings near the floor of the bag wall, can be made to the kiln before the next firing. Bricks should only be separated near the flame port as if the bricks close to the flue exit are separated, heat will be sucked in from the firebox.

E-3 Tap Leak Test

Taps have been found to leak at the screw tap or at the inlet seal. One person should be able to test approximately 250-300 taps in 4-5 hours. RDI-C tests their taps using the following method:

1) Attach compressed air to an open end of the tap;
2) Apply approximately 1 kg/cm2 (100 kPa) of air pressure;
3) Submerge the tap in water;
4) Bubbles rising from the tap indicate a leak.

Annex F Quality Control - Filter Logs

F-1 Clay Evaluation Log

Clay Evaluation Log

Factory:
Employee:
Clay Source:
Location:

Date:
Code: C-
Level in mine:

Reason for carrying out tests:
Description of Raw Clay: Color:
Texture:
Other:
Observations :
Processing: Sieve mesh #:
Amount discarded: kg per: kg

Water of Plasticity %
Starting Mass: gr
Water Added: ml

Dry Shrinkage %
Plastic length cm
Dry length cm

	Temperature fired:	℃	℃	℃
Fired Shrinkage	Fired length	cm	cm	cm
	Fired shrinkage	%	%	%
Total Shrinkage		%	%	%
Water Absorption	Fired weight	gr	gr	gr
	Saturated weight	gr	gr	gr
	Percent absorption	%	%	%

F-2 Burn-out Evaluation Log

Burn-out Evaluation Log

Factory:
Employee:
Supplier:
Date Received:
Type:

Date:
Code: B-

Reason for evaluation:

Description:
Part of husk:
Color:
Texture:
Other:

Processing by supplier:
Particle size received:
In-house processing:
Mill/grinder: Type:
Sieve Mesh #1 Estimated particle size for production:
Mesh #2
Quantity discarded kg per kg

Moisture content: %
Contaminants test result:
Observations:

F-3 Filter Mixture Log

Filter Mixture Log

Factory:
Employee:
Clay Code:
Burn-out Code:

Date:
Code: M-

Estimated number of Filters:
Ratio (this batch):
Clay: kg
Burn-out: kg
Water: kg/liters

Established Ratio:
Clay: kg
Burn-out: kg
Water: kg/liters

Additional Materials:
Description:
Quantity: kg
Reason for variation in ratio:

Dry mix machine/method:
Dry mix time: min
Wet mix machine/method:
Wet mix time: min

Additional Processing:
Kneading/Wedging:
Pug mill:

Mixture Evaluation:
Plastic length cm
Dry length cm
Dry Shrinkage %

Temperature fired: ℃

Fired Shrinkage:
Fired length cm
Fired shrinkage %

Total Shrinkage: %

Water Absorption:
Fired weight gr
Saturated weight gr
Percent absorption %

F-4 Filter Weight and Filtration Rate Log

FILTER FACTORY NAME

DP 1

Daily Production YEAR

#of Filters Pressed DATE

BATCH XX

Fire Date

Code: S/N per factory 12 ltr water **MIX ratioXX**

No: filter	**Weight check**				Filtration after firing	No: filter	**Weight check**				Filtration after firing
	Press	Before firing	Out kiln	Wet			Press	Before firing	Out kiln	Wet	
1						26					
2						27					
3						28					
4						29					
5						30					
6						31					
7						32					
8						33					
9						34					
10						35					
11						36					
12						37					
13						38					
14						39					
15						40					
16						41					
17						42					
18						43					
19						44					
20						45					
21						46					
22						47					
23						48					
24						49					
25						50					

#of Filters low filtration after firing

F-5 Production Control log

		LOT #			KILN:			FIRING TIME:		
	DATE		DATE				DATE	DATE	DATE	
					FILTRATION RATE					
FILTER #	PRESS	DRY	FIRE	<1 LR/H	1-2.5 LR/H	>2.5 LR/H	REFIRE	SILVER	PACK	OBSERVATION
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										
26										
27										
28										
29										
30										
31										
32										
33										
34										
35										
36										
37										
38										
29										
40										
41										
42										
43										
44										
45										
46										
47										
48										
49										
50										
TOTAL										

F-6 Production Control Log

Filter Production workshop

Production Control

		Fired		Filtration rate		Comments and final destination, NGO and user			Fired		Filtration rate		Comments and destination
Item	Pressed Code	Date	Damaged in firing	Lt/hr	Not Accepted		Item	Pressed Code	Date	Damaged in firing	Lt/hr	Not accepted	
1		/ /					31		/ /				
2		/ /					32		/ /				
3		/ /					33		/ /				
4		/ /					34		/ /				
5		/ /					35		/ /				
6		/ /					36		/ /				
7		/ /					37		/ /				
8		/ /					38		/ /				
9		/ /					39		/ /				
10		/ /					40		/ /				
11		/ /					41		/ /				
12		/ /					42		/ /				
13		/ /					43		/ /				
14		/ /					44		/ /				
15		/ /					45		/ /				
16		/ /					46		/ /				
17		/ /					47		/ /				
18		/ /					48		/ /				
19		/ /					49		/ /				
20		/ /					50		/ /				
21		/ /					51		/ /				
22		/ /					52		/ /				
23		/ /					53		/ /				
24		/ /					54		/ /				
25		/ /					55		/ /				
26		/ /					56		/ /				
27		/ /					57		/ /				
28		/ /					58		/ /				
29		/ /					59		/ /				
30		/ /					60		/ /				
Total							**Total**						

F-7 Firing Log

Process Control Report No.:

Factory:

Item	Broken			Rejected		Filtration Lt/hr			Observations
	Trim	**Dry**	**Fire**	**Dim.**	**Other**	**Low**	**Pass**	**High**	
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									
41									
42									
43									
44									
45									
46									
47									
48									
49									
50									
51									
52									
53									

Actvity:			**Date:**		
Pressed					
Trimmed					
Fired					
Flow rate test					
Firing Log					
Time	Firing Time	T1	T2	T3	T4
	00:00				
	00:15				
	00:30				
	00:45				
	01:00				
	01:15				
	01:30				
	01:45				
	02:00				
	02:15				
	02:30				
	02:45				
	03:00				
	03:15				
	03:30				
	03:45				
	04:00				
	04:15				
	04:30				
	04:45				
	05:00				
	05:15				
	05:30				
	05:45				
	06:00				
	06:15				
	06:30				
	06:45				
	07:00				
	07:15				
	07:30				
	07:45				
	08:00				
	08:15				
	08:30				
	08:45				
	09:00				
Peak Temperature Reach					
Cone Fall Times (Do not let the control cone fall!)					
	014	012	010	08	06
Temp					
Time					
Materials Used					
Clay					
Burnable					
Water					
Mould release					
Fuel					
Number of Rejected Filters:					

F-8 Filter Placement Log in Kiln

FILTER FACTORY NAME **PF2**

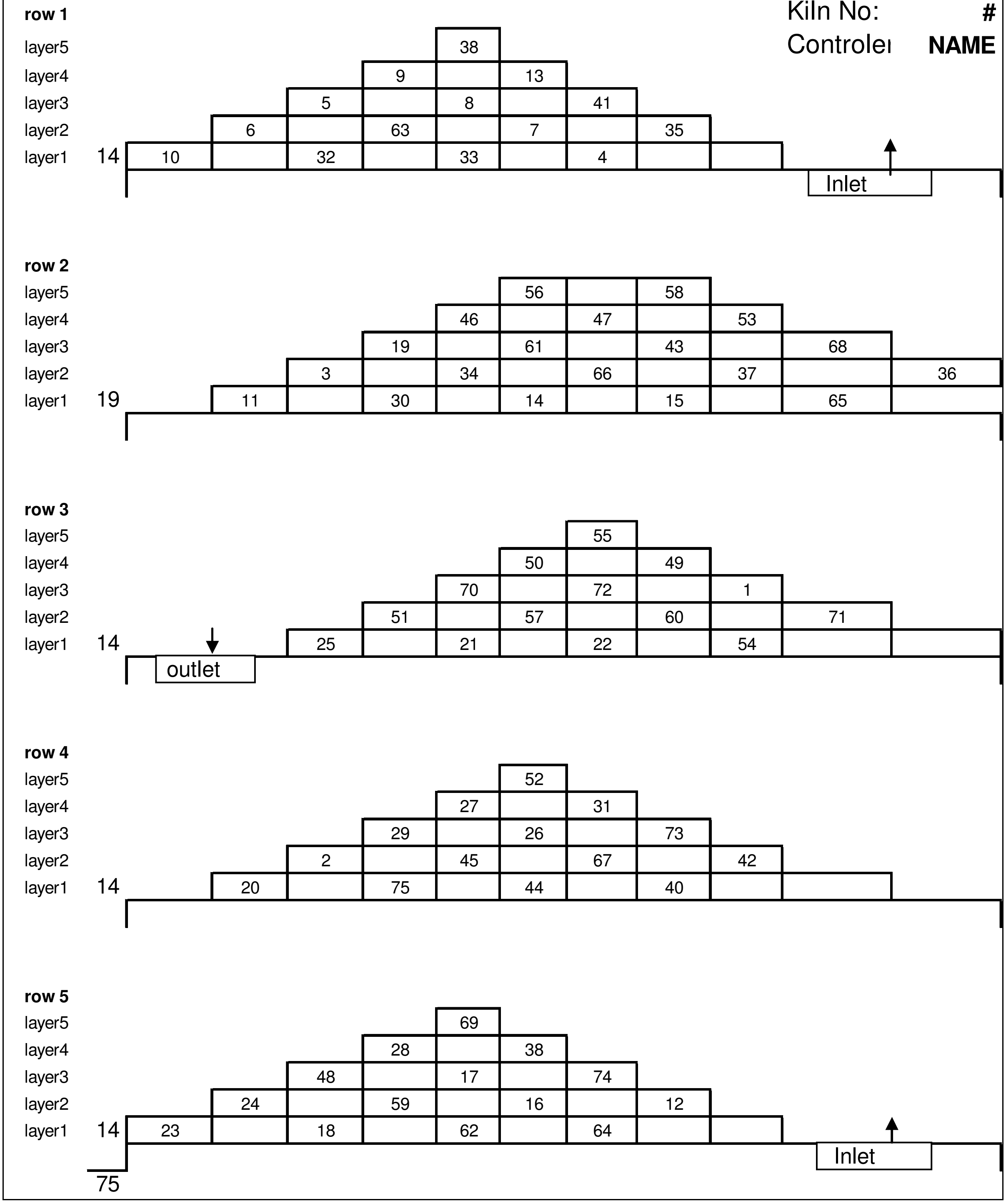
Filter postion in Kiln ## filters

EXAMPLE SHEET

BATCH **##**

Kiln No: #

Controlei **NAME**



Annex G Silver Dilution

A concentrated colloidal silver solution may be prepared on a weekly basis for further dilution in the factory. The application solution should be diluted on the day it is to be applied and should not be stored for later use. Only the amount that will be used in that day should be prepared to avoid having to discard silver as it can be harmful to the environment. Any unused diluted silver should be disposed of according to local regulations. Appropriate health and safety guidelines should be strictly followed. When working with powdered silver, gloves, protective eyewear, an apron and a mask should be worn. When working with liquid silver solution, gloves and an apron should always be worn. Contact with skin should be avoided since little is known about whether silver nanoparticles (colloidal silver) can be absorbed through the skin.

A specific area for silver dilution and application should be established in a dark area with a roof to minimize the exposure of silver to ultraviolet light and to protect the area from rain. The floor surrounding the area for silver dilution and application should be covered with fired, broken, rejected filters or other fired ceramic material to absorb any spilled silver; if spillage occurs, the ceramic material saturated with silver should be disposed of in a sealed plastic bag. It is important to minimize the introduction of silver to the environment as it can upset the natural ecosystem. The mixing and application table should be covered with plastic.

Silver should be diluted using the cleanest non-chlorinated water possible: boiled, filtered, de-ionized or bottled water to dilute the silver.

The following sections provide guidelines for diluting powdered and liquid colloidal silver for application to fired ceramic water filters by brushing. The calculations provided can be used to calculate the amount of colloidal silver (in mg) actually applied to each fired ceramic pot filter.

The first section provides guidelines for preparing a 3.2% concentrated solution from powdered colloidal silver, which should then be diluted further prior to application, as per the instructions in the second section. The second section provides instructions for diluting a 3.2% concentrated solution to the 0.021% strength required for application to each filter. Additional instructions are provided for preparing the appropriate dilution if liquid silver of a different concentration than 3.2% is purchased.

The standard amount of colloidal silver applied to each filter is 64 mg achieved by brushing 302 mL of 211 ppm (211 mg of silver per liter of water, 0.021%) solution.

The following conversions might be helpful in understanding the quantities discussed:

Conversions: 0.001 gram/L = 1 mg/L = 1 PPM = 0.0001%;

Concentrated solution: 32 gram/L = 32,000 mg/L = 32,000 PPM = 3.2%; and

Application solution: 0.211 gram/L = 211 mg/L = 211 PPM = 0.021%.

G-1 Preparing a 3.2% concentrated solution from powdered silver

Dry silver powder is rarely 100% silver. Collargol, from Laboratorios Argenol in Spain, ranges from 70-75% silver. To calculate the dilution factor needed to create a 3.2% liquid concentrated solution, first find out from the label, or directly form the manufacturer, the silver content of the powder to be used. The goal is to add 16 grams of silver to 500 mL of water.

Calculate the quantity of powder to add using the following formula:

$$\frac{16}{\text{Silver concentration (decimal)}} = \text{Amount of powder to add (grams)}$$

For example, with 70 % silver, 23 grams of 70% (0.70 in decimal) silver powder should be added to 500 mL of water, found by dividing 16 by 0.70:

$$\frac{16}{0.70} = 23\,\text{(grams)}$$

The table below shows some other possible silver concentrations, and the calculated amount of powder that must be added to introduce 16 grams of silver to 500 mL of water.

Silver content of powder	Grams of powder to add to 500 mL
30	53
40	40
50	32
60	27
70	23
75	21
80	20
90	18

Thus, for a powder containing 50% silver, add 32 grams of the powder to 500 mL of water to obtain a 3.2 % (or 32,0000 mg/L) concentrated solution.

In order to make 1 liter, double the amount of powder and double the amount of water, so for 50% silver add 64 grams (32 x 2) of 50% silver powder to one liter (500 mL x 2) of water.

For multiple liters of concentrate solution, multiply the quantity of powder to add to each liter by the number of liters desired. For example, 5 liters of water would require 320 grams (64 x 5) of 50% silver.

G-2 Preparing application strength solution (0.021%) from a 3.2% concentrated solution

This section has calculations to create the application solution by diluting the 3.2 % (32,000 mg/L or ppm) concentrated solution to an application solution with 0.021% silver (or 211 mg/L or ppm).

It is recommended that silver be diluted per filter, immediately prior to application. Instructions are in section 7.6. However, should factories chose to dilute it on a daily basis, care should be taken to dilute only the amount that will be applied that day as application solution should not be stored for use the next day and disposal of silver should be avoided as it can be harmful the local ecosystem. Unused silver should be disposed of according to local regulations.

First, determine how many filters will be coated by this batch of application solution. The mix for each filter requires 2 mL of the 3.2 % concentrated solution to be added to 300 mL of filtered water. In order to mix a large enough Application Solution to coat the batch, use the following equations:

$$(\text{number of filters}) \times 2 = \text{amount of concentrate (mL)}$$

$$+$$

$$(\text{number of filters}) \times 0.30 = \text{amount of water (L)}$$

Mix the calculated amount of concentrated silver solution with the calculated amount of dilution water above to prepare a batch of application solution to coat the number of filters specified.

The example calculation below was calculated for a batch of 50 filters, but this number can be adjusted according to the number of filters that will be coated that day. For example, for a batch of 50 filters, add 100 mL of 3.2 % concentrate solution to 15 L of filtered water:

$$(50\ \text{filters} \times 2\text{mL}) = 100\ \text{mL of concentrate}$$

$$+$$

$$(50\ \text{filters} \times 0.30) = 15\ \text{L of water}$$

302 mL of this solution should be measured out in a separate container and applied to each filter to ensure each filter receives 302 mL of solution according to guidelines in section 7.6.

G-3 Preparing a 0.02% application solution from a colloidal silver solution other than 3.2%

If the starting colloidal silver solution has a concentration greater than 3.2%, use water to dilute the solution to 3.2%, then follow the procedures above (section 0). Use the following equation to calculate the quantity of water required to dilute 100 mL of colloidal silver solution:

$$\left[\frac{\%\text{strength colloidal silver solution}}{3.2}\right] - 1 = \text{water (mL)}$$

Add the amount of water calculated above to 100mL of the colloidal silver solution to dilute it to the concentrated strength of 3.2%.

So, for a colloidal silver solution at 5% silver, add 155 mL of filtered water to 100 mL of the 5% solution to obtain 255 mL of 3.2 % solution:

$$\left[\frac{5}{3.2}\right] - 1 = 1.55\text{mL water} + 100\text{mL (of the5\% solution)} = 255\text{ mL (3.2\% solution)}$$

If the starting colloidal silver solution is lower than 3.2 % (and greater than 0.021 %, or 211 ppm), then create the application solution directly, using the same calculations suggested above (section 0) for the batch preparation, but scaled. After determining the number of filters to be coated in the batch, use the following equations:

$$0.30\text{x (number of filters)} = \text{water (L)}$$

+

$$2\text{x (number of filters) x} \left[\frac{3.2}{\%\text{ concentrate solution}}\right] = \text{concentrate solution (mL)}$$

So, to prepare an application strength solution from 1% silver content, 320 mL of the 1% colloidal silver solution would be added to 15 L of water and is enough to coat 50 filters, each with 302 mL of the newly created application solution:

$$0.30\text{x } 50 = 15\text{ (L)}$$

+

$$(2\text{x } 50)\text{ x} \left[\frac{3.2}{1}\right] = 320\text{ (mL)}$$

G-4 Silver Nitrate Dilution

At present, we do not recommend using silver nitrate on ceramic water filters until further research has been carried out as it appears to disassociate from the filter at a much faster rate than colloidal silver causing concern with: 1) the amount of time silver nitrate would last in the filter; and 2) whether the amount of silver that initially leaches into filtered water exceeds WHO guidelines. Effort must be made to obtain colloidal silver for application to ceramic water filters.

The following instructions were copied from the RDI-C manual (Hagan *et al.* 2009) for diluting silver nitrate:

1) Add 100g $AgNO_3$ crystals (99.8% purity) to 500 ml of deionized water, mix well;
2) Add another 1000 ml of deionized water and mix for 1 minute;
3) Store the silver solution concentrate in a light proof plastic container;
4) To dilute silver concentrate for use, dilute 100 ml of the silver concentrate with 18 liters of distilled water and mix.

This makes enough for approximately 60 filter elements. Keep containers closed to prevent oxidization. Approximately 47 mg of silver nitrate (200 ml) is applied to the inside and approximately 23 mg (100 ml) is applied to the outside of the filter by brushing.

Annex H Equipment Information

Whenever possible equipment should be purchased or manufactured locally both to support the local community & economy but also, so if something breaks down, it can be repaired locally.

H-1 How to make a T-Piece

Adapted from the RDIC Ceramic Water Filter Handbook (Hagan *et al.* 2009):

A calibrated T-piece can be used to measure the drop in water level for flow rate testing. Factories which choose to use this method should make their own to ensure it measures the drop in water level accurately in the filters they produce.

1) 1. Take two pieces of plastic pipe about 45 cm long;
2) 2. Cut one piece of pipe 2 cm longer than the rim width of the ceramic filter (this will be the horizontal pipe);
3) 3. Cut out a horizontal section (about 5cm long) from half the width of the pipe at both ends so the pipe sits flat on the rim of the filter element;
4) 4. Drill a hole horizontally through the other pipe (the vertical pipe), about 3 cm from the end, that will allow the horizontal pipe to insert tightly;
5) 5. Insert the horizontal pipe through the hole in the vertical pipe until it forms a T shape;
6) 6. Drill a small hole in the bottom of a fired filter element;
7) 7. Saturate the filter;
8) 8. Set up the filter, with the t-piece inside (horizontal pipe resting flat across the top – vertical pipe inserted inside the filter element) and a measuring container below;
9) 9. Fill the filter with water;
10) 10. When 0.5 L is collected in the measuring container below, block the hole and make a notch on the vertical pipe to indicate the water level after that volume of flow;
11) 11. Repeat at 1L, 1.5L, 2L, 2.5L, 3L, etc.;
12) 12. Double-check the measurements by setting up another saturated filter (without a hole in the bottom) with the t-piece and adding measured amounts of water to the filter: start by filling the filter element to the lowest level marked;
13) 13. Add water according to the increments measured (i.e., 0.5 liters);
14) 14. Check that the water level matches the markings for each addition of water;
15) 15. Drill a small hole at each notch on the t-piece and label the drop in water volume at that point with waterproof paint;

Note:

The hole drilled during step 6 must be small enough to have a steady but slow flow rate; after the t-piece is made, the filter with a hole in the bottom should be destroyed; water levels other than those suggested above can be marked onto the t-tester if required; variation in filter shape and volume will affect the accuracy of the t-tester.

H-2 Mixer

Manny Hernandez manufactured a mixer for the Haiti project by modifying a car differential for the transmission as it was found to be cheaper than buying a reduction motor or a transmission. The formula he used was:

$$\frac{\text{Velocity of motor}}{\text{Diameter of pulley on motor (3" dia)}} = \frac{\text{Diameter of Pulley (mounted on Drive Shaft - 16" dia)}}{\text{Velocity of shaft (modified wheel shaft) 5 to 1 ratio}}$$

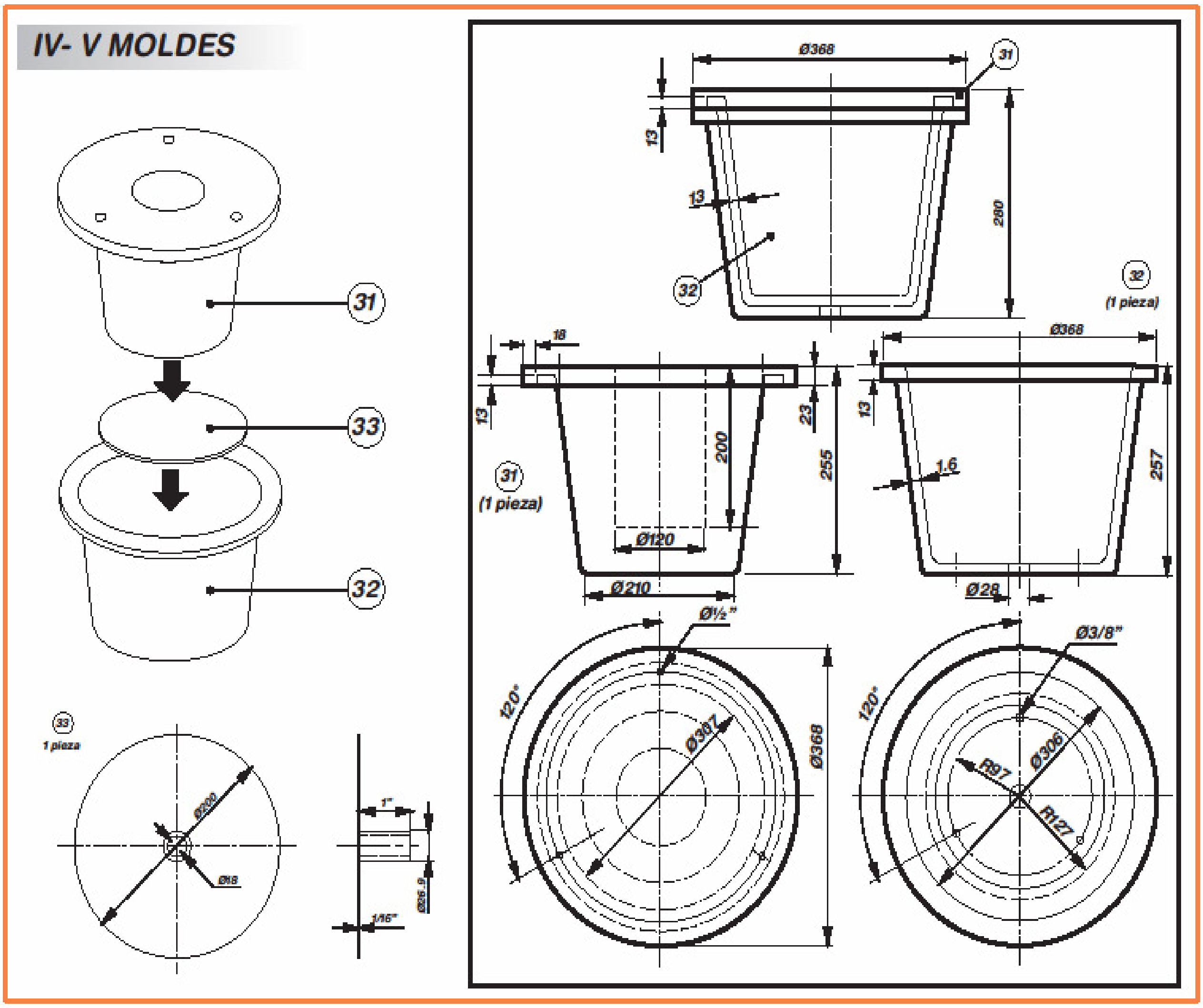
He used a 7.5 HP motor with a 3” pulley. The modified differential on the drive shaft side had a 15” pulley which was turned by the motor. A 3” diameter sprocket was mounted on the wheel shaft side of the differential. The sprocket on the mixer shaft was 16” diameter. The sprockets and the chain were heavy duty at #80.

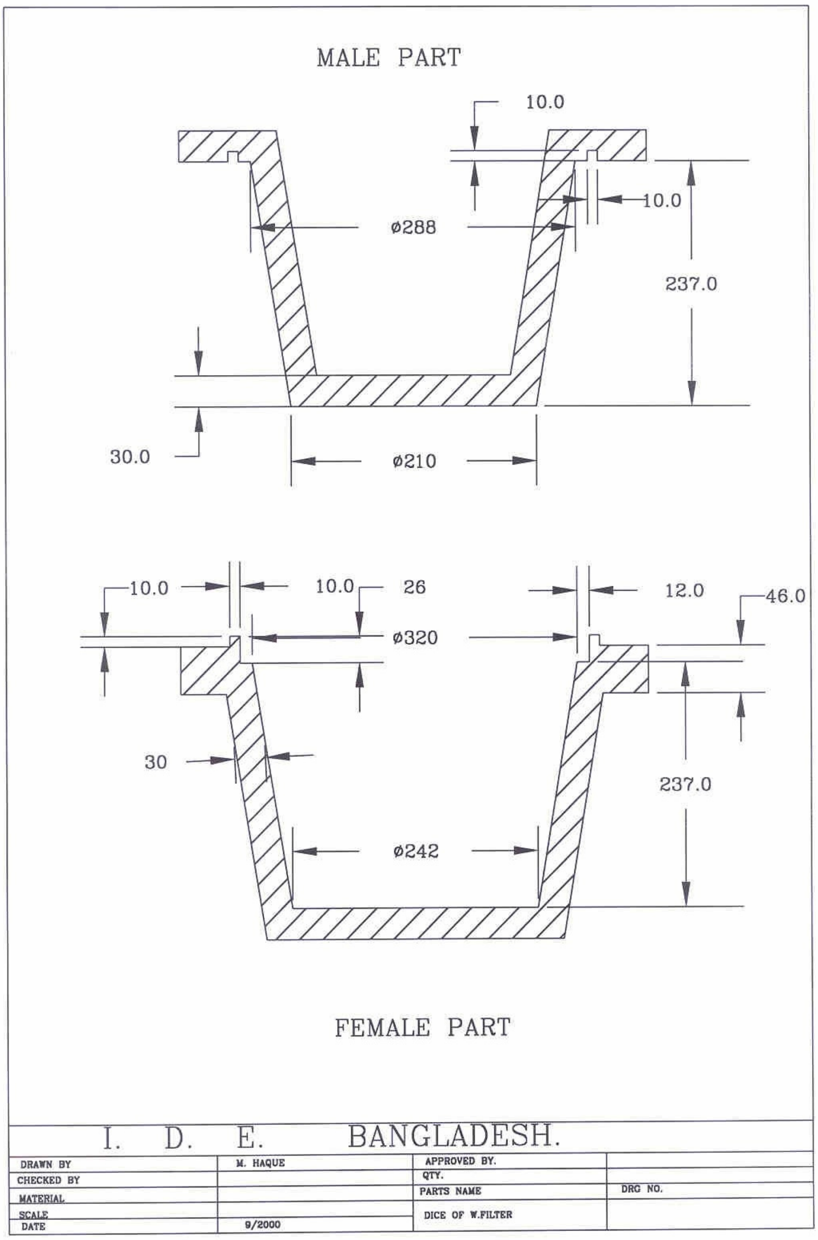
Mixer in Haiti
(Hernandez 2010)

10.4.1 H-3 Press

Plans for the construction of a press using a hydraulic truck jack can be reviewed and downloaded from http://www.pottersforpeace.org/.

H-4 Molds


IV- V MOLDES
31
33
32
33
1 pieza
Ø200
Ø18
1"
Ø26.9
1/16"
Ø368
31
13
13
32
280
32
(1 pieza)
18
13
23
200
255
31
(1 pieza)
Ø120
Ø210
Ø368
13
1.6
257
Ø28
Ø½"
Ø3/8"
120°
Ø307
Ø368
120°
R97
Ø306
R127



H-5 How to Make a Cement Mold

To make a mold using cement, Manny Hernandez first makes a prototype filter (PTF). The finished size of the filter needs to be known, which will depend upon the size of the receptacle available. The shrinkage rates of the clay and filter mixture need to be calculated and added to the dimensions of the prototype filter design, so the final filter will fit in the receptacle. The PTF has to go through 2 shrink stages and 2 firings before arriving at the size of the finished filter. A prototype filter is made, usually by throwing it on a pottery wheel. When the PTF is first formed to the specified dimensions, it is air-dried. After it has dried sufficiently it is fired in the kiln usually with other items to be fired so as not to waste firewood. After it is fired, the PTF will be used as the core to make the cement molds.

The PTF is used to make a cross-section drawing of the mold and a metal cage to fit around it. The metal cage is used for reinforcement when the cement is poured over it. This is done by clamping the rim of the PTF to a vertical surface. A piece of paper such as craft paper is placed on the horizontal surface below the PTF. Using a carpenter square, project the outline of the PTF on the paper by making dots about 1 to 1 ½ inches apart. After completing the outside profile, connect the dots.

The next step is to measure about 3/4 of an inch and about 1 to 1 ½ inches apart as before, to the inside of the outside profile, then, connect the dots. This will give you the inside profile of the filter and this same line will be the outside profile of the male mold. Keep in mind that the mounting of the cement molds on the hydraulic filter press is opposite to the PFP press (Figure 5-7, Figure 5-3). In this press, the female filter is fixed at the top of the press with the opening facing down and the male mold is mounted on a frame table that slides out to clear the female mold, so the male mold faces up. It is also mounted to a plywood base that can be adjusted in any direction to make sure it is centered with the female mold.

A cage is made to fit loosely around the rim of the PTF. The cage for the female mold is attached to a metal ring that is about 1/8 by 1 ½ inch wide flat stock. This ring will act as a cutter to separate the excess clay from the pressed filter. The cage also has 4 bolts welded to the top ring for mounting to the horizontal "H" member that the female mold is attached to. The "H" member moves up and down within the vertical sides of the hydraulic press. A hand winch is attached to the side of the press frame and is used to raise and lower the female mold.

Two cone shapes, which were calculated on the cross-sectional drawing, are cut out of a piece of metal which is about as flexible and thick as aluminum flashing. One metal cone fits outside of the metal cage and the other fits around the metal ring and against the outer cone. The cone shaped metal form used to retain the cement from the outside is secured firmly with wire to hold it down, otherwise the pressure of the cement will raise the metal cone and all the cement will spill out (lesson learned). The two cones are used to retain the cement when it is poured to make the female mold. The PTF (core) retains the cement for the inside of the mold. Both the inside of the cone shaped metal forms and the PTF must be covered with Vaseline so that they can be easily separated.

A core is also set at the top of the mold and sets directly on the crowned top of the PTF which will create a hole at the top of the mold. After the cement has hardened and the core is pulled out, the hole is allows access to force the PTF filter out of the female mold. This is usually accomplished with a wooden dowel and a hammer.

Before the PTF is removed, the male mold is poured. This is done by inverting the female mold (open end up) and pouring the cement inside the PTF. The male mold is set up by attaching a board across and in the middle of the open end of the PTF. The board has two bolts set into it which will be used to attach the male mold to the moveable table mount. After the male mold is attached to the female mold, it is leveled with a bubble level or a spirit level. After the Vaseline is applied to the inside of the PTF the cement can be poured into the inside cavity the PTF. This will form the male mold. When the male portion of the set of molds is dry, the male mold can be removed from the inside of the PTF. After the male mold has been removed, the PTF can be removed from the female mold with the dowel and hammer. Both of the sheet metal cones can then be removed from the outside of the female mold. Any defects, such as air pockets, in either mold can be filled with plaster of Paris; then sanded.

Annex I Materials Suppliers

Whenever possible, materials should be sourced in country.

I-1 Cones

Orton Cones can be purchased at: www.ortonceramic.com. Seger is another well known brand name for pyrometric cones. Small, large or self supporting cones may be used; however different sized cones and cones from different manufacturers are designed to deform at different temperatures; therefore, check manufacturer specifications prior to purchase.

I-2 Pyrometers

Pyrometers provide a measurement of the temperature inside the kiln. A thermocouple is a device inserted through the kiln wall which heats up inside the kiln; this information is transmitted by wire to the pyrometer which reads the temperature of the tip of the thermocouple. A pyrometer with two inputs is recommended, as it will be used with two thermocouples to measure temperatures at relatively higher and lower locations in the kiln, indicating temperature differentials between hot and cold spots. A single-input model will only measure the temperature from one thermocouple in one location, and thus cannot be used to bring a kiln to an even temperature distribution.

Fluke Double-input, model #52-2 NIST:

http://www.grainger.com/Grainger/FLUKE-Hand-Held-Thermometer-4YV89

Fluke Single input, model #FLUKE 51 II (not recommended unless on a tight budget, it is $120 cheaper):

http://www.grainger.com/Grainger/FLUKE-Hand-Held-Thermometer-4YV88

EXTECH Double input, model #421502 (Probably the most cost effective for a factory without computer access, $90 cheaper than the Fluke single-input):

http://www.grainger.com/Grainger/EXTECH-Hand-Held-Thermometer-4PC60

Other more expensive models can be purchased at www.grainger.com; however, models listed above are adequate.

Digital data loggers are a better deal. For about the same price as the Fluke single-input pyrometer, the Extech 3-input data logger has memory storage that can be programmed to log in temperature data at set time intervals. After the firing, the data can be transferred to a computer, and the firing curves will be automatically generated. Used at Filtrón in Nicaragua.

This one from EXTECH, model # HD200 is recommended:

EXTECH HD200
Data logger

http://www.grainger.com/Grainger/EXTECH-Thermometer-IR-Thermometer-4TXH8

Fluke, model # FLUKE 52 II, is more expensive, and has less memory storage:

http://www.grainger.com/Grainger/FLUKE-Hand-Held-Thermometer-4YV90

Type K thermocouples:

Tempco, model # MTA00804:
http://www.grainger.com/Grainger/TEMPCO-General-Purpose-Thermocouple-5ZY12

Tempco MTA00804
Thermocouple

Tempco, model # MTA01187:
http://www.grainger.com/Grainger/TEMPCO-Thermocouple-Probe-3AEY4

I-3 Silver Products

Collargol

Laboratorios Argenol sells Collargol powdered colloidal silver as per specifications below. The current price is US$ 806 for one kilogram. They also sell colloidal silver in liquid form with a 3.2% concentration. Their website address is: http://www.laboratorios-argenol.com/quiensomosi.htm

PRODUCT DATA SHEET	
PRODUCT	COLLOIDAL SILVER
PHARMACOPEA	French IX Edition
DETERMINATIONS	SPECIFICATIONS
CHARACTERISTICS	Grey to black-blue brilliant flakes or granulated powder. Almost odorless.
SOLUBILITY	Insoluble in alcohol and ether. Slowly soluble in water.
IDENTIFICATION	Corresponds
ASSAYS	
S Solution	Complete
Sol. Appearance	Corresponds
Alkalinity	>= 1,5 ml NaOH 0,1 N
Silver Salt	No opalescence

SILVER CONTENT	70 - 75 %

SYNONIMS	Collargol, Argentum Colloidale
USAGE	Strong antiseptic
STORAGE	In well closed containers, protected from Light
PHARMACOPEAS	French IX, Belgian, Swiss, Spanish, DAB-6, Russian

Ultra silver

The 40,000ppm (mg/L) solution of colloidal silver is not available for purchasing online. Snow Fresh produces this solution for industrial purposes (Personal communication with the manufacturer at 1-888-396-1893). The price is $100/quarter.

They claim the average particle size is 34-35 nm (no documentation was provided). The process used to prepare the solution is using the electrochemical reduction of silver. After they produce the electrolysis they add a protein to stabilize the colloidal silver suspension.

I-4 Taps

One recommended plastic tap manufacturer in the United States is Tomlinson Industries, available at gstrunak@tomlinsonind.com.

RDI-C uses taps from a supplier in China: Ruxlin Manufacturing Model F20E1, this model is ceramic inside

IDE purchases metal taps manufactured in Vietnam from Mr. Ly To Ha, House #493, St. Gla Phu, Quarter 3, District 6, Ho Chi Minh City, Vietnam. Telephone: 0938-168608

I-5 Water Quality Analysis

Microbiological Testing

For microbiological tests, brands and suppliers, please refer to the Microbiological Fact Sheet or contact: Daniele Lantagne at: dlantagne@cdc.gov.

Silver Testing

Silver tests can be purchased from: http://www.hach.com/.

Arsenic Testing

Recommended field tests for arsenic in water:

1) HACH Arsenic Test Kit, Product # 2800000 available from: http://www.hach.com/

2) Arsenic Quick Test, model # 481396-2 by Industrial Test Systems available at: http://filter.filtersfast.com/search?w=Arsenic+Test+Kit&submit1=Search)

3) Samples of raw or fired clay can be sent to Vinka Craver for testing at the following address: Vinka O. Craver, Assistant Professor, Department of Civil and Environmental Engineering, University of Rhode Island, Bliss Hall 213, Kingston, RI 02881. Phone (401) 874 2784; Fax (401) 874 2786

Annex J Sample O&M Instructions

1 Lavarse muy bien las manos.

2 Lavar la tapa y el balde con agua clorada (o hervida) y jabón.

3 lavar el filtro con un cepillo y enjuagar con agua desinfectada.

ojo: ¡nunca lave el filtro con cloro ni jabón!

4 Colocar el filtro encima del balde.

5 Llenar el balde pasando el agua por un paño limpio. (retirarlo al terminar).

6 Poner la tapa. (mantener siempre lleno y tapado).

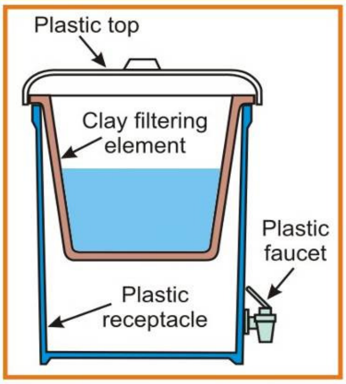
7 lavar manos y trastos con jabón y agua limpia antes de servir el agua.

Fabricado por:
ASOPAFIN
Vereda el Hatillo - Parcela # 32
Telefax (7) 5698004
E-mail: asopafin@hotmail.com
www.asopafin.es.tl
Ocaña N. de S

Fecha de entrega:

J-1 Cleaning Instructions, Colombia
(Asopafin 2009)

HOW TO USE YOUR FILTRON



1. Washing the RECEPTACLE

Wash your hands with soap .
Attach the spigot (faucet) to the plastic receptacle.
Fill the receptacle one quarter full with water and add two tablespoons of chlorine bleach.
Leave this for thirty minutes to disinfect the plastic receptacle.
Use this water to wash the entire inside of the plastic receptacle and the lid with a brush or cloth.
Drain the water out through the spigot to disinfect.
If you do not have bleach, wash the receptacle and lid with soap and water as described above.
You can use either filtered or boiled water to rinse.

2) Place the plastic receptacle in a location that is stable and out of the way of activity.

Using both hands on the edge of the clay filter, place it on the mouth of the receptacle.

3) To get rid of the clay taste of the new filter, fill it with water and drain through the spigot. Repeat until all taste is gone.

4) If your water is turbid, strain it through a clean piece of fine cloth. Tie the cloth in place around the outside of the plastic receptacle.

5) **Keep your filter filled and covered at all times.**

The filter will flow more rapidly (one to two liters per hour) if it is kept full.

Remember: Before serving water wash your hands and cups with soap.

HOW TO CLEAN YOUR FILTRON

Cleaning your CLAY FILTER

1) When the flow rate decreases, it is a signal that the pores of the clay filter are clogged.

To wash:

- **Do not lift the clay filter when it is full of water**. Wait until the clay filter is empty and there is filtered water in the plastic receptacle.
- Wash your hands with soap.
- Remove the clay filter from the plastic receptacle and put it on a plate that has been washed with filtered water.

- Pour a few inches of filtered water back into the filter.
- Scrub the filter with a stiff laundry brush on the inside and outside to remove any debris or particles.
- Do not worry if some of the clay comes off. It means you are scrubbing well.
- Rinse with filtered water until the water is clear.

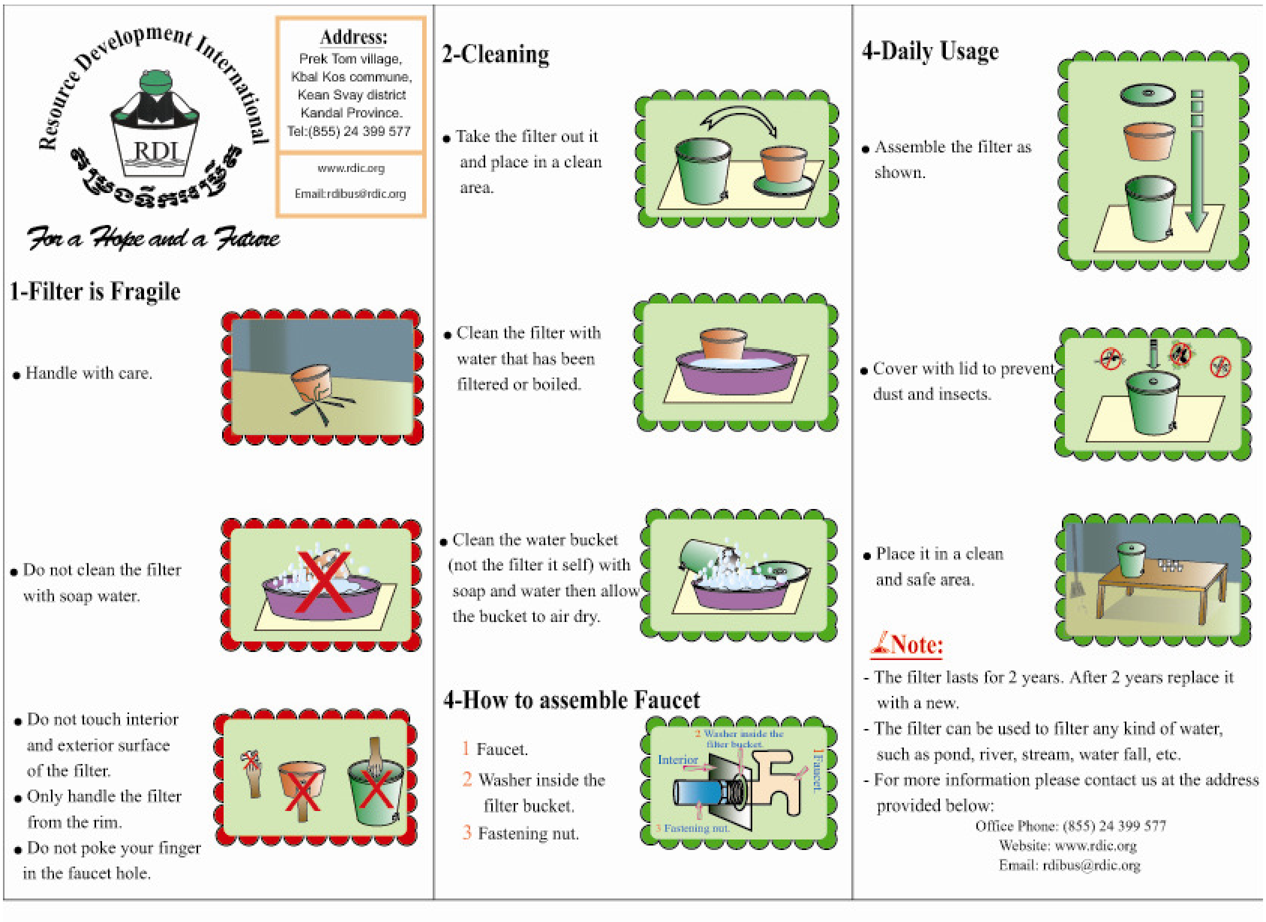
Attention! Never use chlorinated water or soap to wash the clay filter.

3) **Washing the PLASTIC RECEPTACLE**

Wash the plastic receptacle each month with chlorinated water or with soap as explained in part 1. Once you have finished washing, return the clay filter to the plastic receptacle to begin use.

Attention: The Filtron filter generally functions well for a year and a half or more. If you have problems, contact the organization that distributed your filter for advice on what to do.

J-2 Operation and Maintenance Instructions, Nicaragua



Address:
Prek Tom village,
Kbal Kos commune,
Kean Svay district
Kandal Province.
Tel:(855) 24 399 577

www.rdic.org
Email:rdibus@rdic.org

1-Filter is Fragile

- Handle with care.
- Do not clean the filter with soap water.
- Do not touch interior and exterior surface of the filter.
- Only handle the filter from the rim.
- Do not poke your finger in the faucet hole.

2-Cleaning

- Take the filter out it and place in a clean area.
- Clean the filter with water that has been filtered or boiled.
- Clean the water bucket (not the filter it self) with soap and water then allow the bucket to air dry.

4-How to assemble Faucet

1 Faucet.
2 Washer inside the filter bucket.
3 Fastening nut.

4-Daily Usage

- Assemble the filter as shown.
- Cover with lid to prevent dust and insects.
- Place it in a clean and safe area.

Note:

- The filter lasts for 2 years. After 2 years replace it with a new.
- The filter can be used to filter any kind of water, such as pond, river, stream, water fall, etc.
- For more information please contact us at the address provided below:

Office Phone: (855) 24 399 577
Website: www.rdic.org
Email: rdibus@rdic.org

J-3 Operation and Maintenance Instructions, RDI-C
(Hagan *et al.* 2009)