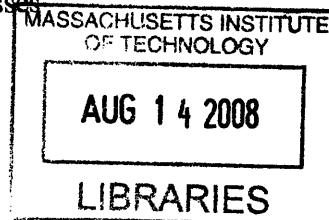Determining the Feasibility of Making Bamboo Charcoal Pencil Leads in Developing Countries
Using Graphite Pencil Lead Manufacturing Processes

by

Nadia S. Elkordy

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL
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1

Determining the Feasibility of Making Bamboo Charcoal Pencil Leads in Developing Countries
Using Graphite Pencil Lead Manufacturing Processes

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ABSTRACT

Many organizations seek to alleviate poverty in the developing world. One organization in particular strives to improve the livelihood of people in poverty through the technical development of and training in bamboo and rattan enterprises, the International Network for Bamboo and Rattan (INBAR). A team in the Spring 2008 D-Lab: Design class has been collaborating with members of INBAR located in India to develop the processes and tools necessary to make pencils from bamboo, rather than wood. The communities that launch this enterprise will need to outsource the glue and graphite leads required to complete the pencils. Waste is generated by cutting processes used to dimension the bamboo to appropriate pencil size and from the parts of the bamboo stalk that cannot be used in pencils, the nodes. If this bamboo waste is carbonized to charcoal, it can be made into pencil leads, eliminating the need for communities to purchase graphite leads from an external source. Manufacturing pencil leads from bamboo waste could raise the profit generated by the enterprise, create more jobs, and help to alleviate poverty in regions of the world where it is widespread.

This thesis presents factors affecting the feasibility of using graphite pencil lead manufacturing processes to make bamboo charcoal pencil leads using clay as a binder. The feasibility is determined by modeling industrial-scale graphite pencil lead manufacturing techniques with small-scale methods that are replicable in a developing country and then comparing the resulting charcoal lead performance to graphite lead performance qualities, including the ability of the lead to write smoothly on paper and its ability to be erased. Experimentation conducted found that vitrification of the charcoal leads is possible at kiln temperatures in excess of 1250 °C and that a sufficiently reducing environment could be simulated using a capped steel nipple. However, a higher performance lead that makes marks comparable to a graphite pencil lead can be attained by simply heat-drying or sintering the charcoal pencil leads and coating them in wax.

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1. INTRODUCTION

The first of the eight United Nations Millennium Development Goals is to "eradicate extreme poverty and hunger" [1], with the more specific target to halve the proportion of people whose income is less than one dollar a day between 1990 and 2015. In 1990, the percentage of people worldwide living on the equivalent of a dollar a day was 32% (1.25 billion people). This percentage dropped to 19% (980 million people) by 2004 [2], a milestone of global progress.

However, the progress made is not universal. Some regions have increased levels of poverty [1], and some regions see large gaps between the higher income and lower income percentages of their populations. The chart in Fig 1 illustrates the growing gap in national consumption in these regions, one small indication that the goal to eradicate poverty still needs dedicated attention.

Small enterprise in the hands of the poverty-stricken has often been cited as the most effective way to end poverty [3]. Numerous organizations and people have worked to provide the poor with the tools they need to sustain their own successful businesses. One such organization, the International Network for Bamboo and Rattan (INBAR), is committed to promoting the livelihood and economic independence of producers of bamboo and rattan products, products which could be an integral part of the lives of up to 1.5 billion people [4] who have access to bamboo or rattan.

INBAR leads bamboo and rattan technology development projects that are sustainable and generate high income. Development projects have used bamboo to create income for rural poor because the resource uses local labor and skills – but many of these projects have been simple crafts that appeal to a limited local market, rather than the higher paying markets that seek large quantities of high-quality products [4]. For this reason, INBAR seeks to develop innovative uses for bamboo and rattan, uses which can be exploited by the poor. The organization presents these technologies to poor all over the world with sufficient training to help them establish micro, small, and medium enterprises that lift them out of poverty.

One such project is making pencils. A team in the Spring 2008 D-Lab: Design class has been working with members of INBAR located in India to develop the process and tools needed to make pencil casings from bamboo, rather than wood. With further development, pencils may soon be made from bamboo extensively in rural communities across India, and later across the world.

The successful span of the technology and enterprise across the developing world will of course depend upon the prevalence of bamboo. Bamboo grows in countries all over the world, including those in Latin America, Asia, and Africa, with great versatility in its uses – it is used to make furniture, houses, clothing, and even food. It grows quickly in a variety of soils, and is often seen as an invasive species – in India, it is frequently a victim of slash-and-burn agriculture, when land must be cleared; however, its resilience allows it to grow back [4]. Developing uses for this abundant resource, such as pencils, can have a positive effect on local ecosystems as well as economies.

Left chart (Proportion of people living on less than $1 a day)

Sub-Saharan Africa
46.8
45.9
41.1

Southern Asia
41.1
33.4
29.5

Eastern Asia
33.0
17.8
9.9

Latin America & the Caribbean
10.3
9.6
8.7

South-Eastern Asia
20.8
8.9
6.8

Western Asia
1.6
2.5
3.8

Northern Africa
2.6
2.0
1.4

Transition countries of South-Eastern Europe
<0.1
1.3
0.7

CIS
0.5
5.5
0.6

Developing regions
31.6
23.4
19.2

Legend: 1990, 1999, 2004

x-axis: 0 10 20 30 40 50

Right chart (Share of the poorest fifth of the population in national consumption)

Latin America & the Caribbean
2.8
2.7

Sub-Saharan Africa
3.4
3.4

Eastern Asia
7.1
4.5

Western Asia
5.9
5.4

South-Eastern Asia
6.2
6.1

CIS
7.9
6.2

Northern Africa
6.2
6.3

Southern Asia
7.2
6.7

Transition countries of South-Eastern Europe
8.3
7.8

Developing regions
4.6
3.9

Legend: 1990, 2004

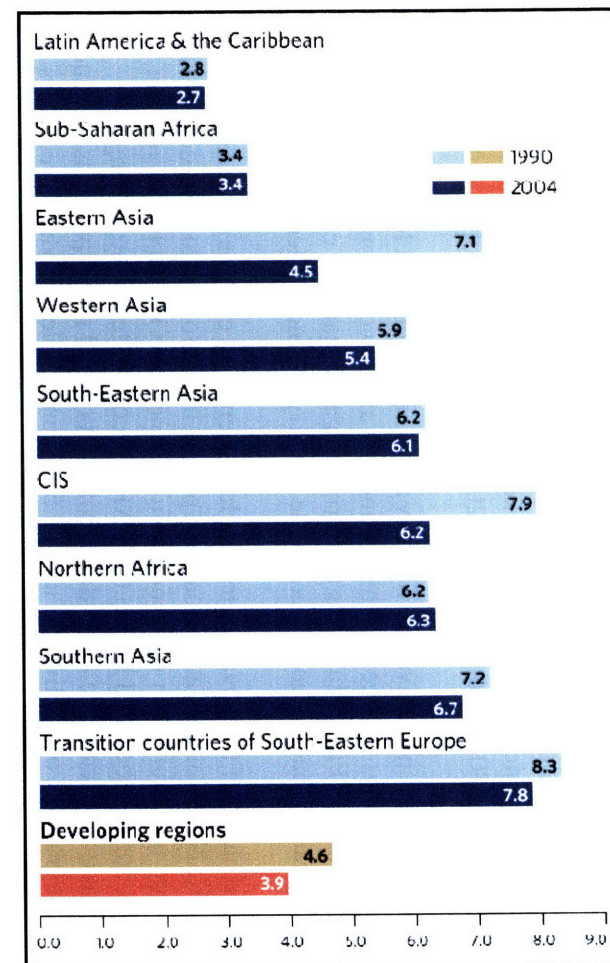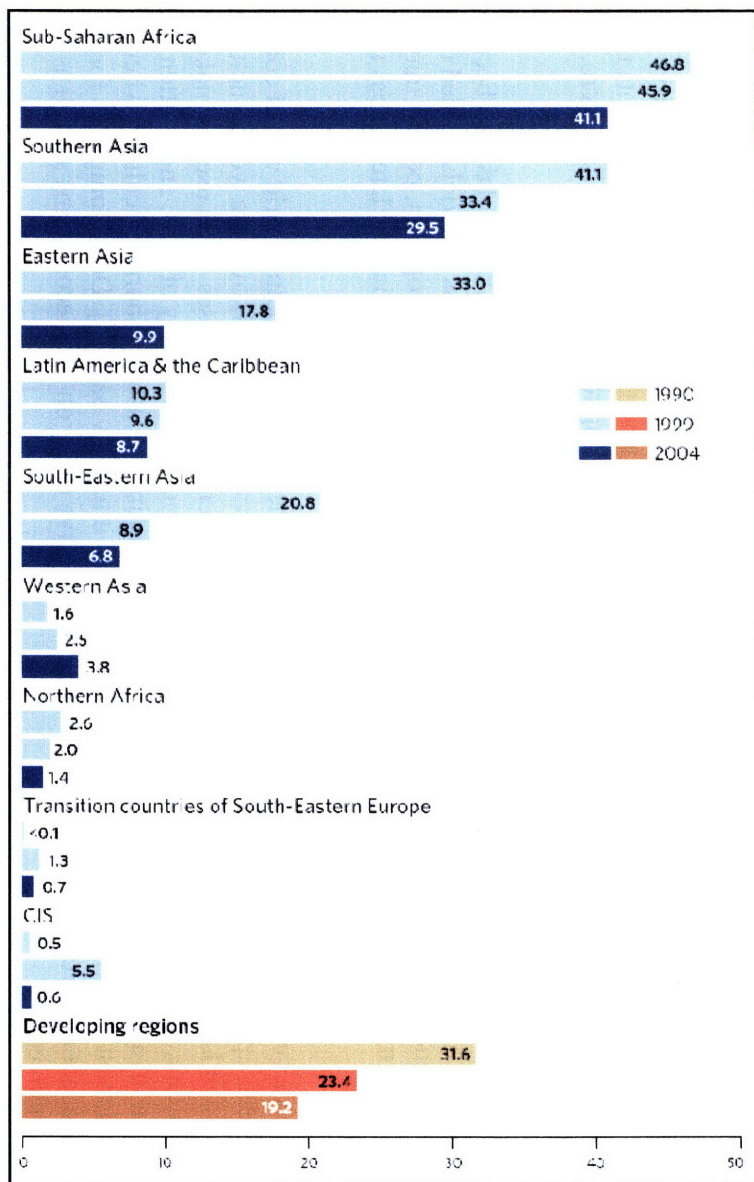x-axis: 0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0

Fig 1 Proportion of people living on less than $1 a day in 1990, 1999, 2004 (left); share of the poorest fifth of the population in national consumption in 1990 and 2004 (above)

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It will thus be greatly beneficial to make bamboo pencil making as profitable as possible. One way to do this will be to create a process such that no part of the bamboo goes unused. This thesis focuses on manufacturing pencil leads from charcoal that comes from carbonizing the waste generated in making bamboo pencils.

1.1 BACKGROUND

1.1.1 Bamboo Charcoal Lead

The bamboo pencil making toolsets currently being developed only make the outer casing, the part of a pencil normally made from wood. There are three potential methods of obtaining the lead needed to complete these pencils:

1) Buy already-made graphite leads
2) Buy graphite and manufacture the leads locally
3) Make charcoal from dried agricultural waste and manufacture the leads locally

This thesis focuses on Method 3, as it is the most widely feasible in terms of resource availability in the largest number of rural areas in developing countries. The waste commonly used in making charcoal includes coconut shells, corn cobs, corn husks, sawdust, rice husks, and other such organic material. Bamboo scrap generated from pencil production falls into this category and was used in making the charcoal worked with throughout experimentation for this thesis (See Appendix A: Making Bamboo Charcoal).

There are several markets that charcoal pencil leads can enter, the largest of which include the artists charcoal pencil market, where the marks are intended to be smudged; the traditional graphite lead pencil market, where the marks are intended to be smooth and constant for everyday use; and the novelty pencil market, intended to appeal to consumer interest trends, such as eco-friendliness.

This thesis presents the factors unique to developing countries affecting the feasibility of manufacturing charcoal pencil leads that perform at a standard comparable to that of graphite pencil leads.

1.1.2 Historical Context

In developing a writing pencil lead from charcoal, a great initial concern was finding an appropriate binder for the charcoal powder. The bound charcoal must be usable in making a rod that writes and can be placed in a wood or bamboo pencil case. There are many ways that might be explored to bind charcoal using resources readily available in the developing world, including binding with starches, such as corn starch or ground cassava, using candle wax, or using flour. One method of binding was particularly attractive for its proven functionality and quality, a method developed over a long period of trial, error, and circumstance – that used today in graphite pencil leads.

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What would eventually evolve into the graphite pencils used today began as styluses of metal, typically lead, used by the Romans. Perhaps earlier than the twelfth century, lead alloys were used to produce darker marks and write more smoothly on paper [5].
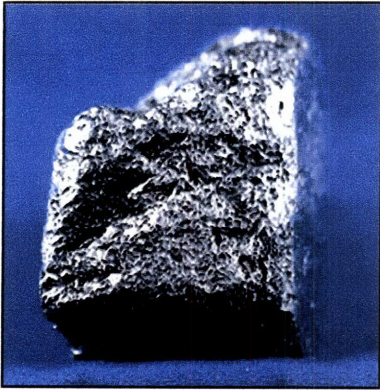

Fig 2 Lump of graphite [6]

Graphite was discovered in the Borrowdale Valley in Cumberland in northwestern England around the middle of the sixteenth century [5]. It was found to make a mark superior to that of lead, though it would be called lead for centuries after. By the seventeenth century, Borrowdale graphite, known as "black lead", was widely exported.

Rough pieces of graphite, called "wadd", were wrapped in sheepskin, and stylus- or pod-shaped pieces were wrapped in paper or string, similar to today's grease pencils. Chunks of graphite were gripped in metal or wood holders and used as writing implements until around the end of the seventeenth century, when the process for holding graphite was changed slightly. The oldest known wood-cased pencil, from the Faber-Castell collection [6], is shown in Fig 3.

Fig 3 Oldest known wood-cased pencil [6]

A precursor to graphite assembly techniques used today, lumps of wadd were cut into thin slices, dipped in glue, and placed into grooves in wood slats. The slices were then sawed off or scored and broken like a piece of glass to be flush with the top of the groove. Several more slices were done until a line of black lead filled the case (Fig 4). The grooved piece of wood and exposed graphite were planed flat, glue was spread on the surface, and a thin strip of wood was clamped on top to dry.
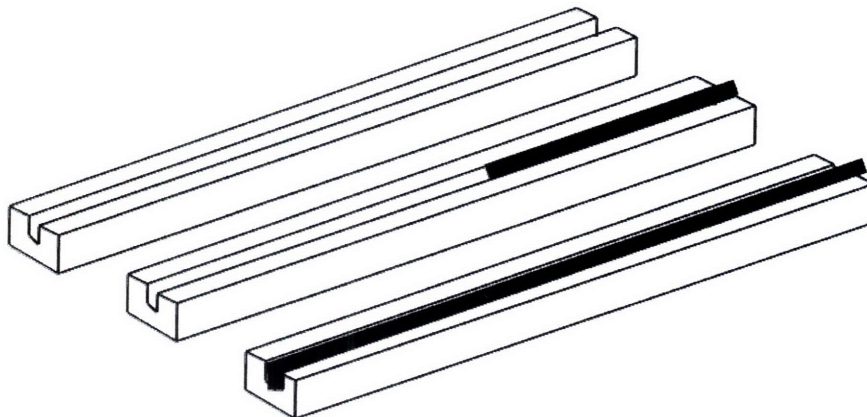

Fig 4 Slices of graphite placed into groove in wood slat until groove is filled

High quality graphite could only be found in the Borrowdale mines, and when the supply started to dwindle and export was limited, other countries that made pencils were forced to develop new methods of making pencil leads.

The Germans made pencil leads from graphite dust, sulfur, and glue, with a resulting product quality described as "inferior". In the 1790s, France was at war with Britain and could not obtain the Borrowdale graphite in any quantity. The French could not even obtain the German pencils, and so commissioned an engineer and inventor by the name of Nicolas-Jacques Conté to develop a lead that did not require pure Borrowdale graphite. In 1795, he patented a method that is still used in pencils today, where finely powdered graphite is mixed with clay powder and water, molded to an appropriate shape, and fired at a high temperature. The molded leads could be inserted into a grooved piece of wood, similar to the process used with sawed slices of graphite, except that no sawing was required. The groove was twice as deep as the thickness of the rod of lead. A small slat of wood was painted with glue and used to fill the rest of the groove, securing the rod in place. Fig 5 below shows the cross-sections of wooden pencils assembled with sliced graphite leads, fired Conté graphite leads, and today's fired graphite leads.
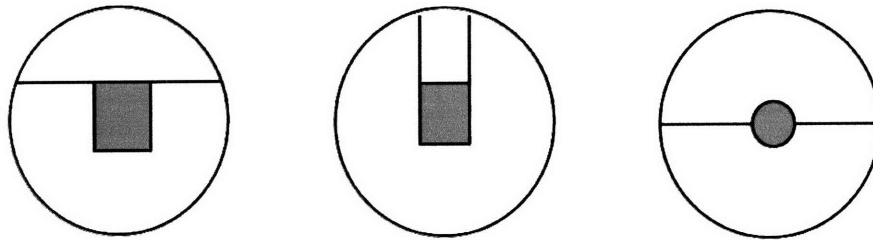
Fig 5 Evolution of wood-cased pencils; the grey center represents the cross-section of the graphite lead; the first is made using pure graphite; the middle is the initial Conté pencil using graphite mixed with clay, and the final is today's pencil also using graphite mixed with clay

1.1.3 Graphite Lead Manufacture

Today, amorphous graphite is used in pencil leads and must be mined from graphite deposits – the primary suppliers of this type of graphite are China, Korea, Mexico, Austria, Russia, Zimbabwe, and Czechoslovakia [7].

The graphite leads are produced using the same concept as the Conté leads were so many years ago. Finely ground graphite and clay are combined with water, mixed, and shaped to the desired pencil lead forms before being fired to high temperatures. The proportions of each powder determine the end hardness of the leads, which varies from very hard at 9H to very soft at 9xxB (Fig 6) . Harder graphite leads are made with a higher percentage by mass clay, and softer leads are made with a lower percentage by mass clay.

Once the leads have been fired in a furnace or kiln, they are dipped in hot oils and waxes for smooth writing quality, and they are ready to be placed in grooved wood pencil halves. Before

this stage, a large amount of effort goes into processing the graphite and clay. This effort is evident in the process descriptions offered below.

The General Pencil Co. takes chunks of graphite and clay and throws them into a large rotating drum with rocks to crush them to powder [8]. Water is added to the mixture, and it is left to rotate in the drum over a period of three days. The water is squeezed out, and the remaining sludge is left to air dry and harden for four days. Water is added again to form a paste, which is then extruded into pencil lead rods. These are dried and then fired at 980 °C.

Fig 6 Graphite pencil lead grading scale; the number and letter after the hyphen are the most commonly used. Harder leads make lighter marks, since they contain less graphite

To make Prismacolor brand pencils, the company Sanford grinds its graphite "until it floats in air" [9], grinds its clay similarly, combines the two, mixes them with water, and runs them through revolving drums for days to further refine the particles. The mixture is run through a hydraulic sieving fore-press to be refined still more before it is finally compacted and extruded by a hydraulic press providing 60 tons of pressure per square inch. The extruded rods are dried at 71 °C and fired until the clay has vitrified [9].

In a company in India, graphite particles that are 500 mesh (23-30 microns) are mixed with carbon methyl cellulose resin, clay, and water to form a solid paste that is then grinded in a triple roller machine. The ground paste is dried at a regulated temperature until the water has evaporated. The dry granules will pass through a hammering machine to be straightened and then through an extrusion machine, which brings out thin 2.2mm rods. This is cut to pencil length and put in a crucible for one hour and twenty minutes and then dipped in melted paraffin wax [10].

From these three snapshots, it can be seen that quality graphite leads require several key process steps. These steps were reproduced to some extent in experimenting with making charcoal pencil leads different from the charcoal artists' tools that already exist.

1.1.4 Charcoal Drawing Tools

Charcoal drawing tools are sold in art supply stores in many different forms, including compressed, stick, block, and white. The compressed leads in a charcoal pencil have a diameter much greater than 2 mm, they have a lower density than graphite leads, and they make wide, dark marks that smudge. Still, the charcoal lead used in charcoal pencils is similar to graphite lead in the fact that it holds its form during writing and is compressed during manufacture.
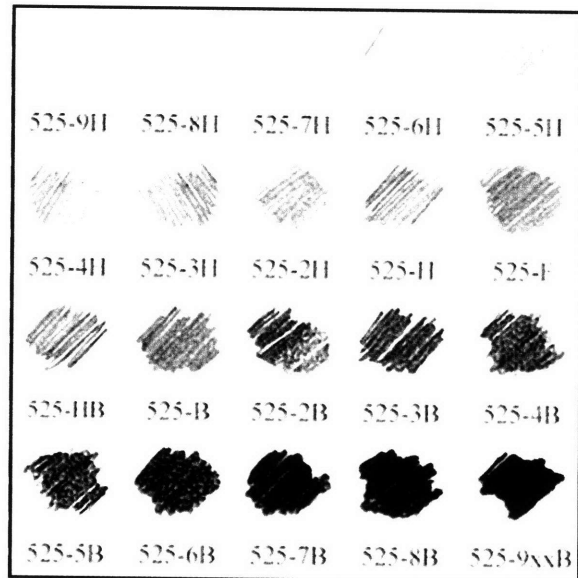
The Cumberland Pencil Company disclosed that all of their pencil leads contain clay, but that "the clay in...charcoal pencils is different from the clay in graphite pencils" [11]. The pencil leads used in graphite are fired in a kiln, and those in charcoal are simply dried at low temperatures.

Many of the larger pencil companies do not share their processes for making charcoal leads as openly and widely as they share that for making graphite leads, and the charcoal pencil leads do not write as smoothly and cleanly as graphite leads. For these reasons, the processes used and discussed in this thesis were inspired by graphite pencil lead manufacturing, most of which involves manipulation of clay.

1.1.5 Clay

Clay occurs in nature, formed from the erosion of igneous rock over time. The crystal structure of clay is $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$, called kaolinite. Most clays contain impurities they have picked up as they have washed away from their sites of formation. These clays are known as secondary, distinct from primary clays, which are found directly where they were formed.

Regardless of the exact composition of the clay body, clay particles adhere to one another and attract polar molecules, such as water. When water is added to a body of clay, the body expands and becomes "plastic", which means that it holds any shape in which it is molded. The degree of plasticity depends on the type of clay. There are three broad categories of clay: earthenware, stoneware, and porcelain. They are distinguished by the temperatures at which they mature. Clay bodies can be fired to temperatures in excess of 700 °C to mature, which means the clay particles melt together to form a glass in a process known as vitrification. The maturing temperature can reach above 2000 °C for porcelain clays. Earthenware generally matures below what is referred to as cone 6. Stoneware clays are secondary clays that mature between cones 6 and 10.

1.1.5.1 Pyrometric Cones

A pyrometric cone is a triangular pyramid 5-7cm high that is made from mixtures of kaolin, limestone, feldspar, quartz, and other minerals [12]; it serves to tell the firemaster watching a kiln when a certain temperature has been reached. The cone bends when it has reached its melting temperature, which is determined by the quantities of each mineral used in making it. Three cones are typically used during a single firing, one to signal that a temperature before the desired one has been reached, one to signal the desired temperature, and one to signal that the work pieces have been overfired. They are placed inside the kiln during each firing, just in front of the kiln's spyhole, so that the potter or firemaster can observe them.

Table 1 Partial pyrometric cone chart for firing schedule in which heating rate during last hour and a half to two hours of firing is 150 °C/hour

Cone	Temperature (°C)
06	1013
05 1/2	1025
05	1044
04	1077

Cone charts give approximate temperatures that correspond to a cone, which is denoted by a number. Clay bodies are said to mature at particular cones when they are fired at given rates of temperature increase. For example, if a clay matures at cone 06, which it should be fired to 1013 °C in order to vitrify at a temperature rate of increase of 150°C per hour. Table 1 above shows part of a chart taken from Evenheat Kiln, Inc. This part of the chart shows the cones referred to frequently throughout this thesis. A full chart is given in Appendix B.

1.1.5.2   Drying and Firing Profile for a Clay Body

Whatever the given cone for a clay body, in order to become ceramic through firing, the body must go through various stages that occur at certain temperatures. The stages are outlined below.

Table 2 Stages of firing clay

Stage (Temperature)	Description
Pre-Kiln Drying (below boiling point of water - 100 °C at sea level)	Before firing, the clay is dried at a temperature lower than the boiling point of water – if the water in the pores of the mixture turns to steam, it will crack the body, making it weaker than it otherwise would have been.
Initial Kiln Drying (above boiling point of water)	Any remaining water will evaporate during this period; if this occurs too quickly, cracking will occur.
Dehydration (450-500 °C)	The water that is chemically bonded to the clay particles is dehydrated, and the clay body is weakened; ceramic change has initiated; simply adding water to the body will not take it back to its plastic stage (this is in contrast to the earlier stages).
Organic Material Burning (300-700 °C)	Carbon burns away in oxidizing environments; if the environment is not strongly oxidizing, there is the potential for "black cores" to form, a phenomenon in which the outer surface vitrifies before the carbon in the body has had a chance to react with oxygen and burn away.
Quartz Inversion (573 °C)	The crystal structure of the clay changes; 0.45% [13] expansion occurs as a result of this change. The temperature in the kiln should change very slowly around this temperature to prevent cracking of the body
Sintering (below melting point*)	Reactions occur by which solid particles join to form larger, fewer particles and eliminate pores.
Vitrification (above 900°C*)	Particles within the body begin to melt together to form glass. There is shrinkage at this stage.
Melting*	Firing clay beyond its vitrification temperature will result in melting of the clay, which will destroy the shape in which it was molded. Pure kaolinite is fully molten at 1785 °C [13].

*Temperature depends upon clay composition

The process at each stage takes time to progress, so holding times required in certain temperature ranges will depend upon the type of clay used and the size of the body being fired. The vitrification temperature is the most important regarded in the experiments presented in this thesis, and it can be lowered with the addition of compounds known as fluxes.

1.1.5.3 Fluxes

A flux is a material which lowers the fusion temperature of the material or mixture to which it is added [13], because its melting temperature is lower than that of the material. Any clay that is not pure kaolinite has fluxing impurities in it. Most clay bodies contain impurities such as potassium, sodium, calcium, and others that melt at much lower temperatures than pure kaolinite, thus classifying them as fluxes. Whether or not an impurity acts as a flux depends on the material itself and the material to which it is added. The degree to which the vitrification temperature is lowered depends upon the melting temperature of the flux and the quantity of the flux in the clay.

Certain materials that are generally regarded as fluxes are high in alkali or alkaline earth content [13]. Of these, those that are most commonly sought out, finely ground, and deliberately added to clays as fluxes are called feldspars. Feldspars have nearly the same chemical formula as silica (SiO_2) but some silicon is replaced by potassium, sodium, calcium, or barium; these are potash feldspar, soda feldspar, lime feldspar, and celsian feldspar, respectively.

1.1.5.5 Refractory Material

While it is useful to lower the maturing temperature of clay bodies, it is also useful to have clays that mature at much higher temperatures. Refractory material is defined as material which has the ability to withstand high temperature without breaking or deforming and is required to possess the following characteristics [13]:

1) High melting point
2) Mechanical strength at high temperature
3) Resistance to chemical attack in the particular situation in which it is used

Table 3 Melting temperatures of some common refractories; data obtained from [13]

Material	Chemical Formula	Approximate Melting Temperature (°C)
Silica	SiO_2	1710
Clay (pure kaolinite)	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	1770
Alumina	Al_2O_3	2050
Graphite	C	3700

The refractories listed in the table above, particularly graphite, are referred to throughout this thesis. Graphite is well-suited for pencil lead manufacture because of its ability to withstand very high temperatures without burning away or melting.

1.1.6 High Temperature Considerations

Clays that are not mixed to a specific composition will usually need to be fired to temperatures in excess of 700 °C in order to mature. Making vitrified pencil leads from clay and charcoal will require

1) The construction of a kiln
2) A source of fuel
3) A reduction environment, so that the charcoal does not burn away

The first two are unavoidable if there is no electricity; the third can be addressed directly by taking one of the following steps:

1) Lower the firing temperature to below the ignition temperature of the charcoal
2) Use a sealed container
3) Create a reduction kiln environment

Option 1 requires an alteration of the properties of the clay body, which is possible with the addition of fluxes [13], but only to a certain degree. It also requires locating flux minerals and acquiring them, which may add an unnecessary cost to the entire production.

Option 2 requires that the container be made from a material that can withstand temperatures above the highest temperature intended for the pencil leads.

Option 3 requires that the fuel burned in the kiln is burned inefficiently, since limited oxygen entry leads to only some of the carbon released from the fuel being partially burned to produce carbon monoxide [12]. Inefficient fuel usage supports unnecessary fuel costs and thus overall production costs.

1.2 Objectives

The goal of this thesis is to answer the question: is it feasible in the developing world to produce charcoal pencil leads that perform similarly to graphite pencil leads using manufacturing processes modeled after those used for graphite?

A charcoal lead similar in performance to a graphite lead will
- write smoothly across paper
- remain intact against writing pressure
- remain intact during sharpening
- create marks of legible darkness that are within the pencil grading scale
- create marks that are as erasable as graphite lead marks
- create marks that do not smudge to the extent that graphite pencil marks do not smudge

Fig 7 outlines the manufacturing process for making graphite pencil leads alongside the experimental process being used for the fabrication of charcoal pencil leads.

```
CHUNKS OF GRAPHITE, CLAY          CHUNKS OF BAMBOO CHARCOAL, CLAY
            │                                   │
            ▼                                   ▼
┌───────────────────────┐          ┌───────────────────────┐
│                       │          │ GRIND CHARCOAL, CLAY  │
│                       │          └───────────────────────┘
│ GRIND GRAPHITE TO     │          ┌───────────────────────┐
│ 500 MESH              │          │ DRY CLAY ABOVE 100 °C │
│                       │          └───────────────────────┘
│                       │          ┌───────────────────────┐
└───────────────────────┘          │ SIEVE EACH POWDER TO  │
                                    │ MESH 60               │
                                    └───────────────────────┘
┌───────────────────────┐          ┌───────────────────────┐
│ MIX GRAPHITE, CLAY    │          │ MIX CHARCOAL, CLAY    │
│ TO PROPORTION         │          │ TO PROPORTION         │
└───────────────────────┘          └───────────────────────┘
┌───────────────────────┐          ┌───────────────────────┐
│ ADD WATER, MIX        │          │ ADD WATER, MIX        │
└───────────────────────┘          └───────────────────────┘
┌───────────────────────┐
│ MIX, DRY, GRIND       │
│ AGAIN, ADD WATER      │
└───────────────────────┘
┌───────────────────────┐          ┌───────────────────────┐
│ COMPRESS WITH MACHINE │          │                       │
└───────────────────────┘          │     FORM MANUALLY     │
┌───────────────────────┐          │                       │
│ EXTRUDE WITH MACHINE  │          └───────────────────────┘
└───────────────────────┘
┌───────────────────────┐          ┌───────────────────────┐
│ DRY BELOW 100° C      │          │ DRY BELOW 100° C      │
└───────────────────────┘          └───────────────────────┘
┌───────────────────────┐          ┌───────────────────────┐
│ FIRE TO VITRIFICATION │          │ FIRE TO VITRIFICATION │
│ TEMPERATURE           │          │ TEMPERATURE           │
└───────────────────────┘          └───────────────────────┘
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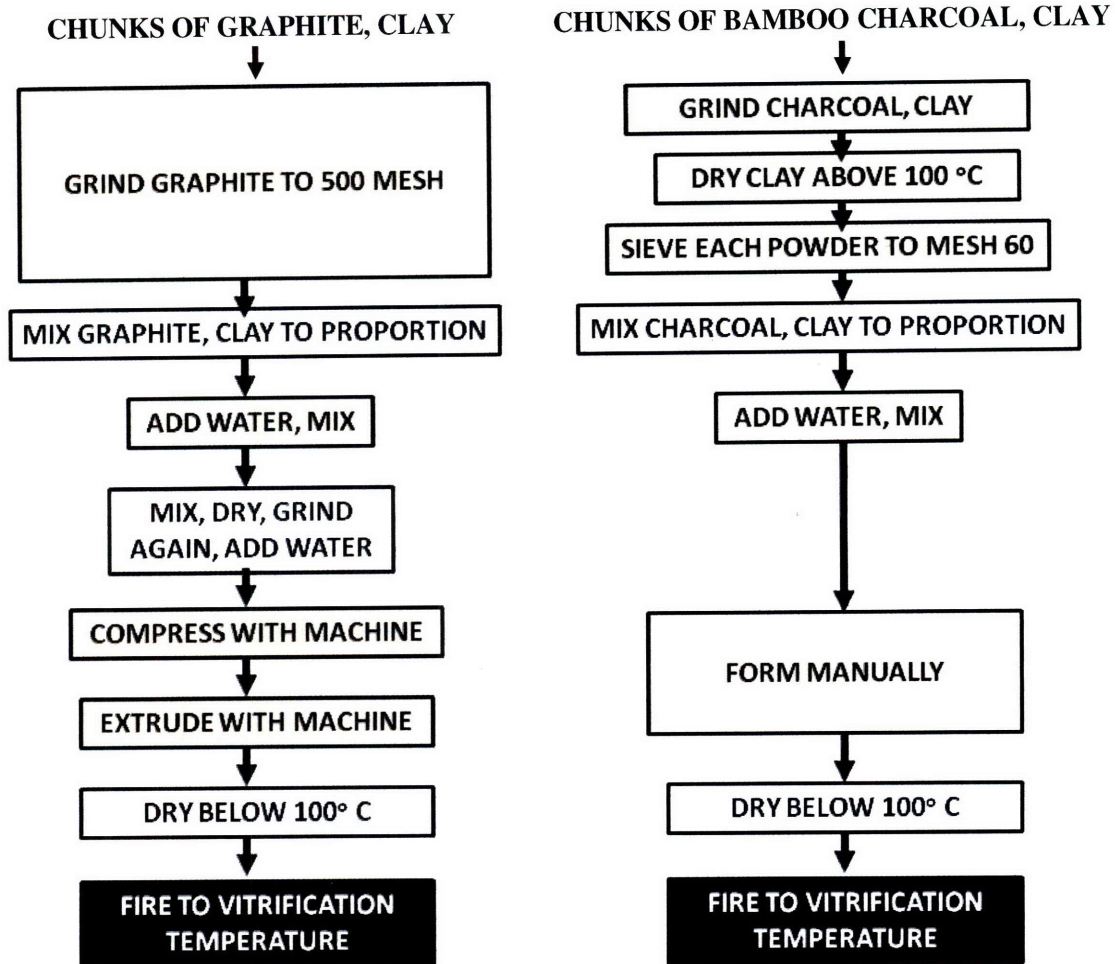
Fig 7 Industrial-scale process steps for making graphite into pencil leads (left); process steps used in these experiments for making bamboo charcoal into pencil leads (right)

There are three processes that are a large concern with respect to replication of quality in a developing country:

1) grinding charcoal to small enough particle sizes
2) forming of the charcoal leads to adequate density for robust performance
3) firing to very high temperatures

The feasibility study reported in this thesis relates entirely to item 3, firing to very high temperatures. Within this step, there are several areas to note:

1) Vitrification – Vitrification temperature is affected by the chemical content of the body being fired; the addition of charcoal to a clay whose cone has been determined will change the cone, requiring that the vitrification temperature be determined experimentally.
2) Firing Temperature – The high firing temperatures provide the opportunity for charcoal to burn away

3) Firing Atmosphere - Firing in an oxidizing kiln provides the charcoal with the oxygen needed for it to burn away at high temperatures.

4) Refractory Material - Large scale pencil lead manufacturers have access to refractory material needed to hold the leads during transport into the kiln and firing in the kiln; crucibles are typically used. In the developing world, if there is not local access[1] to refractory material, it is necessary to find another material which can be fired with the leads.

The sections that follow present the results of experimentation that addresses each of the four points described above. All experiments performed used charcoal prepared from carbonizing bamboo (Appendix A).

2. DETERMINATION OF FIRING PROTOCOL

The experiments discussed in this thesis used a type of clay premixed by the manufacturer to mature between cone 06 and cone 04 (Appendix B). The maximum temperatures reached during initial experimentation were within these cones. With the addition of charcoal to the clay, firing to the recommended cones was not sufficient to achieve vitrification, and the atmospheric conditions of the firings seemed to have an effect on vitrification. This section presents the results of firing schedules tested in reduction, oxidation, and limited-oxygen environments.

2.1 Atmosphere

2.1.1 Oxidation

It was the expectation that a fully oxidizing environment would act to burn away all the charcoal in the body, which was the case. However, when one clay body that had been mixed with charcoal and one clay body that had not were fired in the same atmosphere, they reacted differently. The body that had not been mixed with charcoal vitrified, and the one that had did not. All of the charcoal burned away, but the body only made it to the sintered ceramic stage.

The unmixed clay did vitrify at its expected cone, but the clay that had been mixed, even after the charcoal had burned away, did not. Also, the surfaces of unmixed clay bodies that were in direct contact with steel absorbed iron present in steel, used it as a flux material, and vitrified at a lower temperature than the recommended cone.

2.1.2 Limited-Oxygen

The interesting phenomenon that occurred in the limited-oxygen environment was that the charcoal at the surface of the body burned away and allowed the surface clay to vitrify before the charcoal at the core had a chance to also burn away. In cases where there was a larger proportion charcoal in the body being fired, the oxygen entering the environment was not sufficient to burn all the charcoal from the surface away, and the body simply vitrified. In cases where the

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[1] A kiln requires a refractory floor and refractory walls; if there is no refractory material located nearby, it is possible to construct kiln walls using broken pots, so the lack of refractory material does not necessarily imply that the pencil lead business cannot exist. Thus, other containment materials were explored.

composition was particularly high (above 40% charcoal), the surface layer was not sintered, but rather seemed only to have made it through the dehydration stage, as the layer was powdery and not well bonded, weaker than before the firing (Experiment 5).
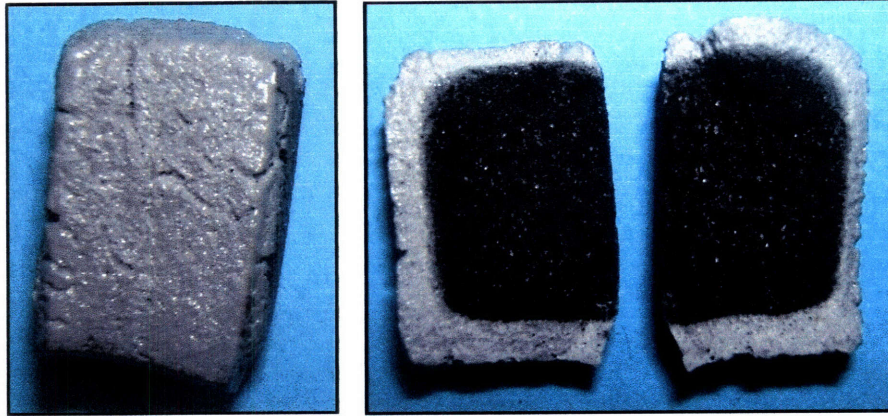

Fig 8 Body that has been vitrified in a limited oxygen environment at approximately 1220 °C (left); as shown (right), the outer surface vitrified before the carbon on the interior had burned away

2.1.3 Reduction

When the clay bodies were fired in the absence of oxygen, the charcoal no longer burned away. When the bodies inside the reduction environment were fired to vitrification (Experiment 7), bodies prepared identically that were fired on the kiln floor, i.e., outside the reduction environment, only reached the sintered stage.

It is possible that the gap created by each charcoal particle that burned away was too large a space for the clay particles to melt across and join. If this is the case, then it would mean the charcoal particles present in the clay bodies in the reduction environment acted as tiny bridges for the clay to melt across.

2.2 Schedule

The time and temperatures that characterized each firing schedule brought the clay bodies tested to different ceramic stages. The aim for this thesis was vitrification.

The schedules varied from 2.5 hours to 6 hours, with maximum temperatures ranging from 980 °C to above 1260 °C. These schedules were tested on clay bodies with different percentages by mass charcoal in the environments discussed in *Section 2.1 Atmosphere*. The rate of temperature increase was determined by the kiln setting (low, medium, or high). The electrical kiln used treated these range settings as a control for rate of increase of the temperature, rather than as a control of the final temperature. In the low and medium ranges, the rate was approximately 200°C per hour, while, in the high range, it was closer to 300°C per hour.

Each of the schedules tested is shown in Fig 13. The changes from low setting to medium and medium to high are distinguishable as a change in the slope of each graph. Temperature was recorded using a thermocouple (Appendix C).

Below Cone 06

The initial schedule used (Fig 13a) was just over two hours long and reached a temperature of 980 $^{\circ}$C (Experiment 1, Appendix D). The clay and charcoal composite fired in the reduction environment were dehydrated but unbounded. The unmixed clay that was in direct contact with a piece of steel and fired directly in the kiln's oxidation environment vitrified. The clay was made to mature at cone 06-04, higher than 980 $^{\circ}$C; the contact with steel allowed iron to act as a flux in the clay, reducing the maturing temperature.

Fig 9 Piece of cone 06-04 clay that has vitrified after having been fired to 980°C on the surface of steel; the clay is still attached to the oxidized steel as shown

In an effort to reach a higher ceramic stage, a new schedule was tested. A full hour was dedicated to the kiln's low range, a full hour to the medium, and a little over thirty minutes to the high (Fig 13b). The maximum temperature reached was 1070 $^{\circ}$C, much higher than cone 06, suggesting that vitrification would result. However, no pieces vitrified; they were only sintered.

Several more schedules were tested, and the following was observed:
- varying the time spent in each kiln temperature range affected the smoothness of the final body, because ceramic stages were approached at differing rates, which affects how cracked the end body comes out (See Table __)
- varying the max temperature affected whether or not the body came out sintered or vitrified

Cone 06-Cone 04

When the temperature was at the appropriate cone for the clay used (Figs 7b, 7c, and 7e), clay that had been mixed with charcoal, whether it was in a reduction or oxidation environment, did not vitrify. It did sinter.
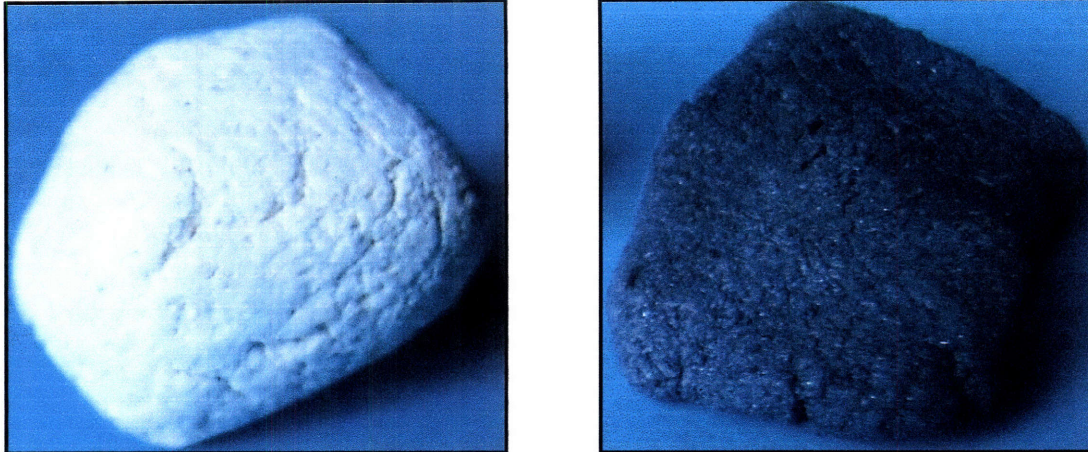
Fig 10 These two bodies were brought to 1075 °C in oxidation (left) and reduction (right) environments. Though this temperature is above the cone of the clay used, the pieces only experienced sintering.

Above Cone 04

The kiln was brought to 1150 °C (Fig 13e) when the clay bodies were in a reduction atmosphere. Though this temperature was significantly above the cone recommended for the clay, none of the bodies reached vitrification. They were only sintered when the charcoal composition of the body was below 30% by mass. At the same temperature, when the composition contained more charcoal, no sintering occurred; a charcoal-clay powder was formed, indicating that dehydration had been reached, but no other stage.

Far Above Cone 04

In a limited-oxygen atmosphere, raising the temperature to 1220°C (Fig 13d, significantly above cone 04, caused bodies with fractions lower than 40% charcoal by weight to vitrify. Vitrification only occurred where charcoal had burned out of the body and, as mentioned in the limited-oxygen discussion, once the surface had vitrified, the charcoal on the inside did not burn away (Fig 6).

Vitrification of the charcoal core did not occur; this is expected to have been the case because the temperature was not high enough for a long enough period, rather than because the charcoal could not burn away.
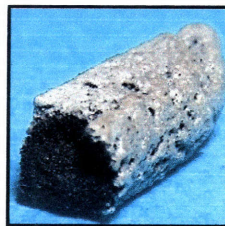

Fig 11 The body vitrified at the surface, leaving a black core of charcoal; the illustration shows the fired body broken in half, so that the cross-section is revealed

Vitrification Achieved in Reduction Environment

In the final experiment, fired in a reduction environment, the temperature is expected[2] to have reached above 1260 °C (Fig 13f). The clay bodies with some percentage composition charcoal fired in the reduction environment vitrified (Fig 12), but the clay bodies with the same percentages composition charcoal fired directly in the kiln environment did not. Of the bodies fired in the reduction environment, the body that contained 30% charcoal did not vitrify, as shown in Fig 12. The body with 20% charcoal by mass vitrified up to a line where the body is only sintered. The body with 10% vitrified completely.

VITRIFICATION STOPPED
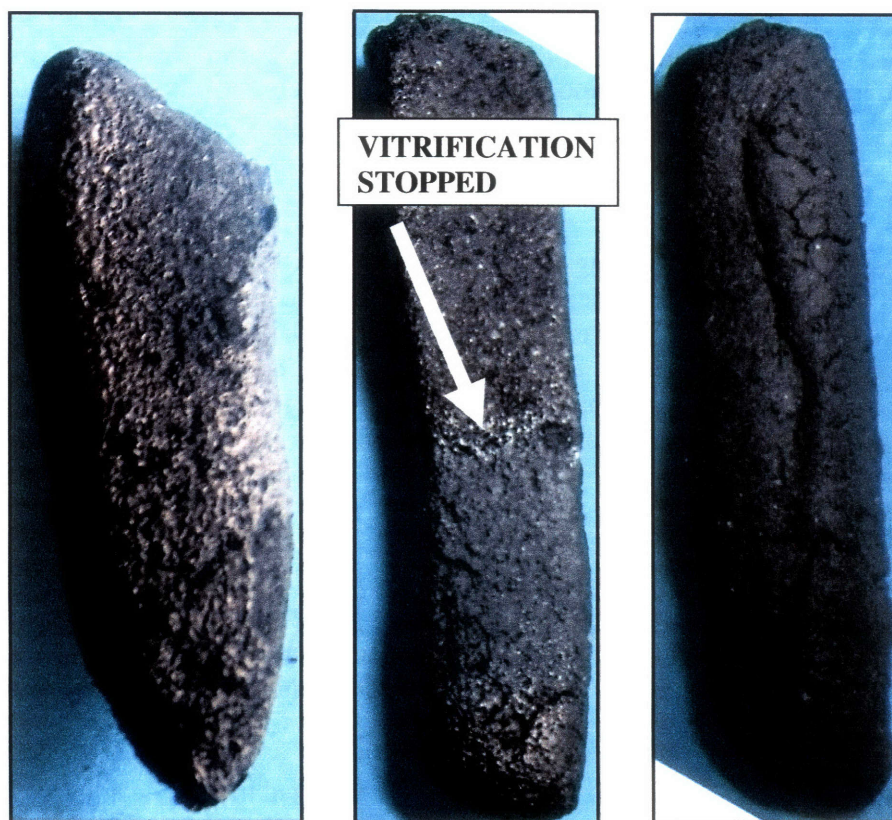
Fig 12 The three bodies above were fired to above 1260 °C in a reduction environment. They contain different percentages by mass charcoal (left to right – 10%, 20%, 30%) and experienced vitrification to differing degrees. The first vitrified completely on the surface – chipping shown is due to sharpening; on the second, a vitrification wave front can be seen; the third only sintered.

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[2] The thermocouple was removed from the kiln after forty-five minutes in high range; in an earlier experiment, an identical thermocouple had exceeded its range when the kiln had been in high range for longer than an hour and a half. The projection shown in Fig 13e comes from data obtained from that thermocouple, and the kiln temperature is expected to have reached even higher.

Table 4 Ceramic stages reached by varying compositions of clay that matures unmixed at cone 06-04 (1013-1077 °C) but that matures at different temperatures when mixed with charcoal; data is arranged in order of increasing max temperature

| Experiment Number (Appendix D)	Environment	Percent Composition by Mass Charcoal	Max Temperature	Ceramic Stage
1	reduction	50	980	dehydrated, unbound
1	oxidation, iron	0	980	vitrified
2	oxidation	10 and higher	1070	sintered
3	oxidation	30	1075	sintered
3	reduction	30	1075	sintered
6	reduction	30 and lower	1150	sintered
6	oxidation	30 and lower	1150	sintered
5	limited-oxygen	35 and lower	1220	partially vitrified, partially sintered
5	limited-oxygen	40	1220	sintered
5	limited-oxygen	45 and higher	1220	dehydrated
5	oxidation, iron	0	1220	vitrified
7	oxidation	30 and lower	1260	sintered
7	reduction	20 and lower	1260	vitrified
7	reduction	30	1260	sintered

Fig 13a Steel tin, reduction atmosphere
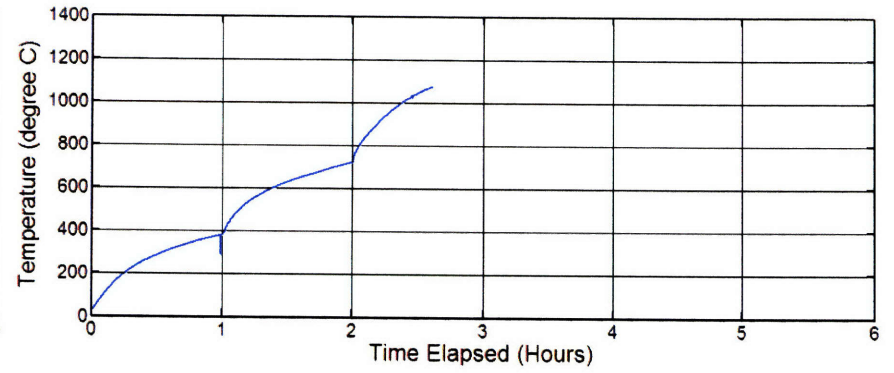
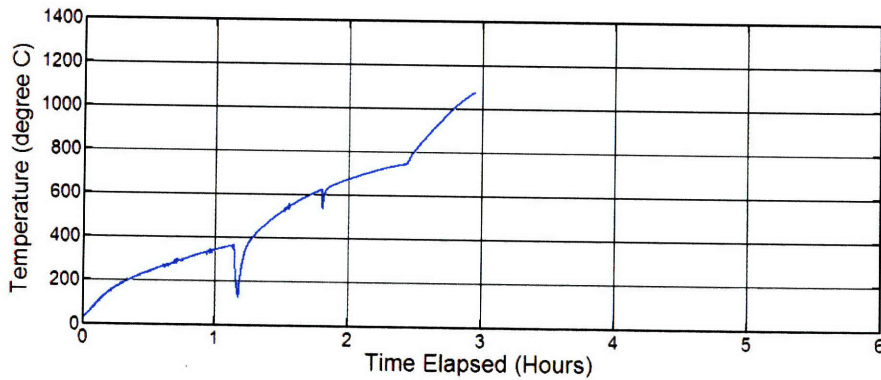**Fig 13b Tool steel foil, oxidation atmosphere**

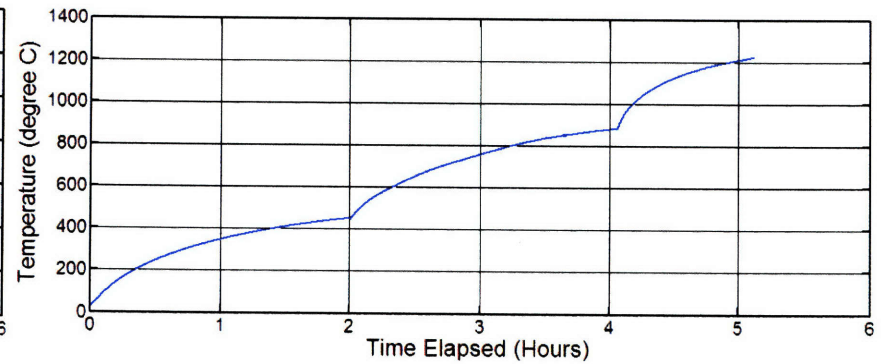

Fig 13c Capped black steel nipple, reduction atmosphere

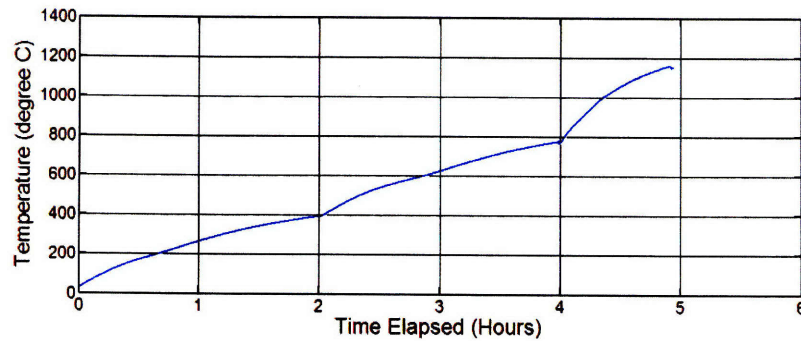**Fig 13d Steel tin with hole, limited-oxygen environment**

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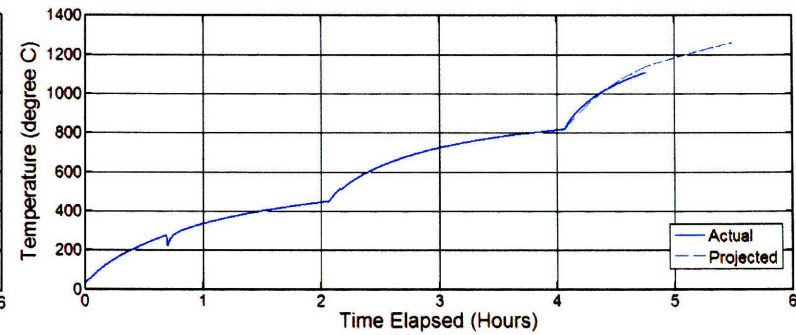**Fig 13e Capped stainless steel nipple, reduction atmosphere**   **Fig 13f Capped stainless steel nipple, reduction atmosphere**

3. INVESTIGATION OF CONTAINMENT VESSELS

Containment and protection from oxygen were a large concern during these experiments, because a major goal was to maintain the charcoal composition of the fired bodies, so that firing schedule effects and writing performance could be accurately measured.

Refractory materials are used in kilns because of their ability to withstand high temperatures and maintain low chemical reactivity. In developing countries, mild steel scrap is readily available, and because of its ability to withstand high temperatures and its ability to be formed and constructed into different objects, it was tested in many of these experiments to determine its behavior and interaction with the bodies being fired.

The expectation was that airtight containers of particular dimensions could be made from steel at low cost. However, materials other than mild steel were tested to provide a wider range of containment vessel designs to compare. These tests are presented below.

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3.1 Slotted Steel Bars

The first plan of containment was intended to also hold the shape of a clay pencil lead. The design is illustrated in Fig 14. It consists of two faced steel bars with slots milled across the lengths of their faces. The slots are intended to be the size of the unfired pencil lead body to allow for an appropriate amount of shrinkage.
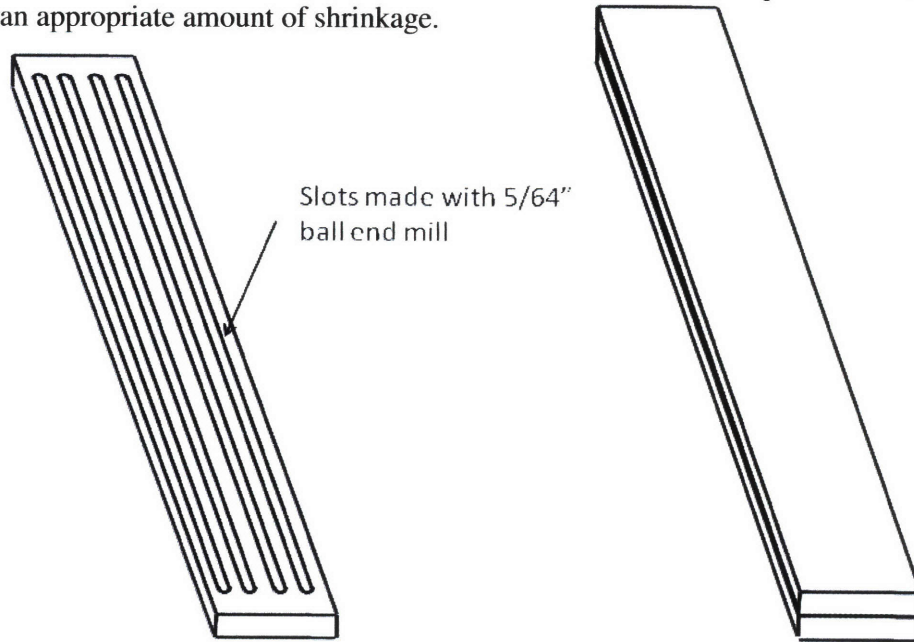

Slots made with 5/64" ball end mill

Fig 14 Schematic drawing of containment vessel in which unfired pencil leads fit directly into small grooves in a steel bar. An identical steel bar with grooves is placed over the unfired leads, forming a mold and potential seal.

Fig 15 Mild steel bar with pencil lead groove milled along its length

For proof-of-concept testing, just a single groove was made on each of two faced pieces of mild steel stock. When the two pieces put together were held up to the light, the gap between them

was evident, so rather than firing directly in the kiln, they were placed in a stainless steel tin (a reconstituted Milo powdered drink tin with the paint burned off with a blow-torch; approximately 0.001 m^3 in volume).

The grooves were made 155mm in length and 1mm deep with a 5/64" (just under 2mm) ball end mill. It was intended that the flat faces would be brought together and could be airtight. The original design (Fig 8) includes multiple slots, so that more than one pencil lead might be fired at the same time.

Fig 16 Steel tin container

A 1:1 clay to charcoal mixture was packed into the grooves, and spillover was scraped off and leveled so that the bars would fit together flat. The molds were then sandwiched together, placed in the tin, and adjusted so that the grooves were aligned. The tin was capped, set in the kiln, and subjected to the firing schedule shown in Fig 13a, bringing the mold to 980 ^{o}C.

Upon removal from the kiln, the weight of the steel bar molds against the thin and newly brittle wall of the tin punctured the wall of the tin. The outside of the tin was covered in plates of oxidized metal that could easily be broken off. The tin itself shattered in places at a firm grip, and could not be reused.

The material that had been packed into the steel bars had been untouched by oxygen and had not undergone any visible ceramic change. The two mold halves had contained identically filled grooves before firing, and, after firing, they contained the very same identically filled grooves. No sintering or vitrification had taken place in either groove.

In order to test if the level of oxygen-restricting offered by just the molds was enough to protect the charcoal in their grooves, a second firing was held with a schedule similar to that shown in Fig 13d, bringing the molds up to 1200^{o}C. A small amount of charcoal and clay was added to the grooves, the two bars were sandwiched together, and they were placed and aligned on the kiln floor. Upon cooling, the bars were pried apart against the oxidation that had stuck them together. There was no charcoal remaining in the grooves, indicating that the air exclusion had not been sufficient to create a reduction environment.

Fig 17 Steel mold bars after exposure to high temperatures in oxidizing kiln environment

3.2 Tool Steel Foil

A material called Ticronic tool steel foil wrap, made from type 321 annealed stainless steel, was tested next (Experiment 2, Appendix D). It is typically used to protect tool steels from oxidation during heat treatment (personal communication, Pierce Hayward, 8 May 2008). The foil looks just like aluminum foil and feels a bit heavier. It is intended to be folded securely around the material it is protecting from oxygen (Fig 18)
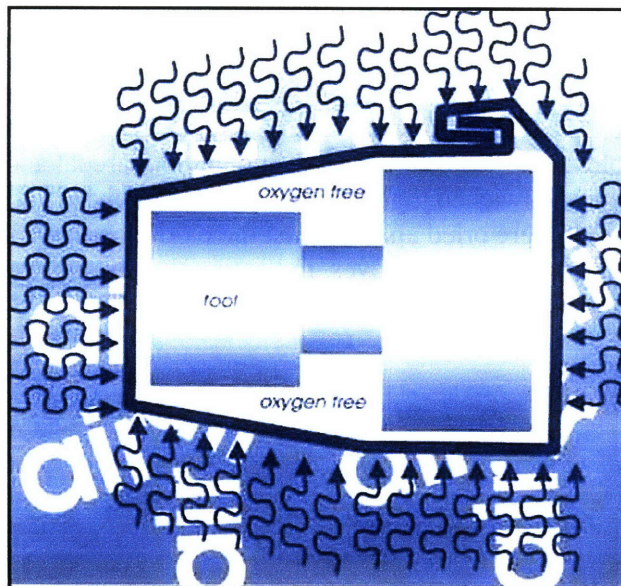

Fig 18 Tool steel foil surrounding the piece to be protected from oxygen is folded over (image taken from company ToolandSupplies.com)

The foil was wrapped around eight pellets of clay containing different percentages charcoal by mass. These pellets were resting on a small stainless steel mesh platform.

Type 321 annealed stainless steel has a melting temperature of about 1400 $^{\circ}$C [14], but the product specifications guarantee performance up to 2000 $^{\circ}$F (1093 $^{\circ}$C). When subject to the firing profile shown in Fig 13b, with a maximum temperature of 1070 $^{\circ}$C, the foil disintegrated in areas. It had been opaque and ended up transparent, as well as somewhat dissolved. The stainless steel base was unaffected.

Fig19 Ticronic tool steel foil dissolved after kiln reached 1070 $^{\circ}$C

It is possible that the temperature measured by the thermocouple was lower than the temperature of the gases released from the clay bodies during firing. These gases in direct contact with the tool steel foil may have caused the temperature to rise above its limit.

3.3 Black Steel Nipple and End Caps

A nipple consists of a short length of pipe threaded on both ends (Fig 21). This enclosure is one that has been used in case-hardening when carburizing steel in a reduction environment (personal communication, Pierce Hayward 8 May 2008). Charcoal is often used as the carbon source for the carburization process - the carbon from the charcoal is absorbed by the steel tool sealed into the enclosure with the charcoal.

Two experiments (Experiments 3 and 4, Appendix D) were performed that reported on the oxygen-limiting and high-temperature firing capacity of the steel nipple.

The first three bodies shown in Fig 20a were put directly into the kiln, while the fourth was placed in the steel nipple, which was then capped. The caps were screwed on and left loose, so that any pressure generated during firing could be released without creating a potentially dangerous situation. After about an hour and a half (the kiln was at a little under 400 $^{\circ}$C), the first

two pellets pictured were removed. The remaining two, one in the enclosed nipple, one in the kiln atmosphere, were removed at the very end of firing to about 1075 °C, Fig 13c.
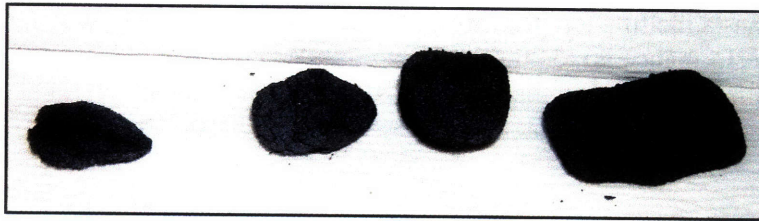

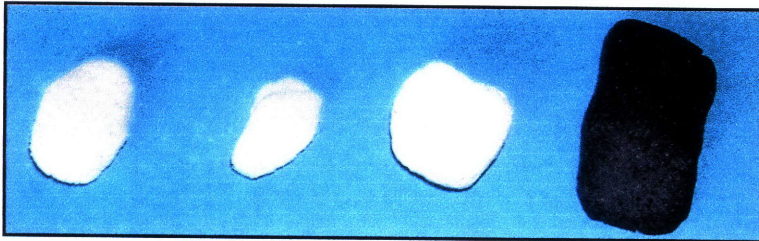**Fig 20a All four pellets shown contain the ratio 7:3 clay to charcoal**

Fig 20b The first two pellets on the left were removed from the kiln after an hour and a half; the final two were left until the end of firing and cooling; the last pellet was enclosed in the steel nipple

As shown in Fig 20b, the pellet fired in the steel nipple was protected from oxygen, and that left outside was not. The steel nipple came out oxidized (Fig 21) but otherwise unaffected. The caps came off the threading with ease, indicating that the threads had not melted together.
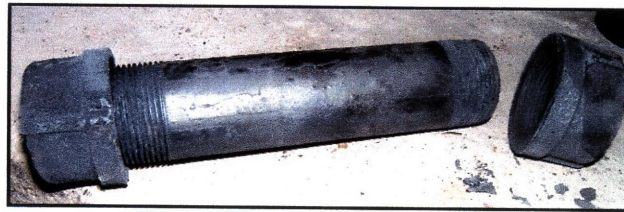

Fig 21 Black steel nipple oxidized after being subject to high temperatures in an oxidation environment

The nipple was tested again to verify that it would work at higher temperatures. The firing schedule is shown in Fig 22.
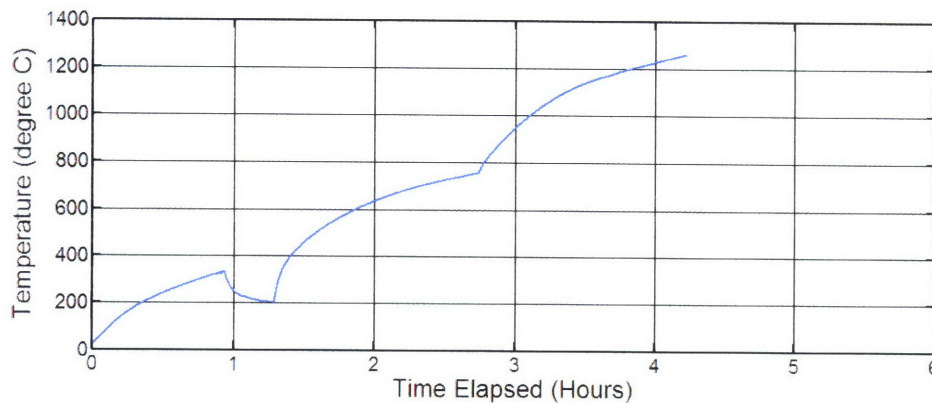

Fig 22 Firing schedule that melted malleable black steel caps

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The malleable black steel could not withstand the higher temperature, and it melted (Fig 23).

Fig 23 The temperature reached approximately 1250 °C before the kiln was switched off. The black malleable steel end caps melted onto the kiln floor and the nipple.

3.4 Steel Tin

After this event, the steel tin was tested again, on this occasion with no heavy steel bars leaning against the thin walls. The clay bodies prepared in a series of. The firing schedule now rested at low and medium settings for two hours each and at high for just an hour. The tin used in this experiment had been used to make bamboo charcoal (Appendix A) and thus had an approximately 5mm hole in the bottom. The hole was with a loosely-fitting bolt and then covered with a piece of clay. During firing, the hole came open, and oxygen was allowed into the system.

The result was a partially reducing environment, in which only charcoal from the surface of the clay bodies burned away. This occurred only in bodies that had less than 30% charcoal by mass. Bodies with higher percentages composition charcoal were still completely black bodies.

The tin itself survived the firing. However, its walls were completely oxidized and very brittle, breaking at a squeezing grip.

3.5 Sheet Steel

Although no vessel was made using mild steel sheet, a thin (0.79mm) piece was bent to 90°, placed in the kiln, and exposed to a firing schedule similar to that shown in Fig 1e, bringing it above 1260°C. The sheet came out oxidized, but undeformed. It was not particularly brittle, as the walls of the tin container had been.

3.6 Stainless Steel Nipple, Stainless Steel End Caps

This vessel performed the best. Because of its thickness, it could survive many firings and oxidation rounds, but because of its chromium coating, it did not undergo noticeable oxidation.

The threaded caps were screwed on loosely as had been done with the black steel nipple, and the effect was a reduction environment. Stainless steel has a melting temperature of about 1510 °C, so reaching just above 1260° C, as was done in Experiment 7 (See Fig 13f for the firing schedule, Appendix D for description of the experiment), was not a worry.
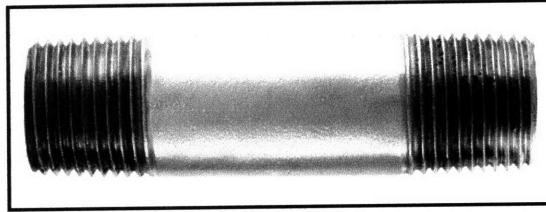

Fig 24 Stainless steel nipple

4. ANALYZING CHARCOAL LEADS

Each clay body formed during experimentation that held its shape was tested for performance as a pencil lead. Presented below are the four categories of bodies analyzed: heat-dried, sintered, vitrified, and wax-coated.

Heat-dried
These were prepared during Experiment 6 (Appendix D) to three different proportions clay to charcoal: 7:3, 8:2, 9:1. They were then dried just below 100°C for 7 hours.

Sintered
These came from three different experiments that resulted in sintered bodies, Experiments 3, 5, and 6.

Vitrified
These came from two different experiments that resulted in vitrified bodies, Experiments 5 and 7.

Wax-coated
Pencil lead companies coat their leads in waxes and oils for smoothness of writing; in order to evaluate the performance of charcoal leads produced in these experiments under such conditions, paraffin wax and beeswax were used to coat the heat-dried and sintered bodies from Experiments 3 and 6. The coating process used is described in Appendix D.

Table 5 Qualitative description of the marks produced by vitrified, heat-dried, and sintered bodies in the clay to charcoal ratio most able to write per category; in cells where a comparative (less, more) is used, the comparison is being made to the first mention within the same category, e.g., "slightly less smooth writing" indicates that the paraffin wax-coated heat-dried body wrote less smoothly than the uncoated heat-dried body

ceramic stage	Environment (clay to charcoal ratio used)	finish	characteristic of mark			
			smooth writing	legible darkness	erasable	non-smudging
Vitrified	Reduced-oxygen (7:3)	uncoated	Somewhat crumbly	Yes	Yes	No
	Reduction (8:2)	uncoated	No	No mark	n/a	n/a
heat-dried	Oxidation (7:3)	uncoated	Yes	Yes	Yes	No
		paraffin wax	Slightly less	Yes	Less	Yes
		beeswax	Slightly less	Yes	Still Less	Yes
sintered	Reduction (7:3)	uncoated	Somewhat	Yes	Yes	Almost
		paraffin wax	More	Yes	Less	Yes
		beeswax	More	Yes	Still Less	Yes

4.1 Vitrified

The vitrified surface of the leads produced in a limited-oxygen environment did not produce any mark, as the charcoal had all burned away. However, these leads could be sharpened (ratio had been 7:3 clay to charcoal) to reveal a charcoal tip as shown in Fig 14, which made a mark also shown in Fig 14. The mark could be smudged at the touch of a finger, and a lighter mark remained underneath which was legible and could be erased. The tip held up under light writing pressure and sharpening, but broke easily under heavy pressure.
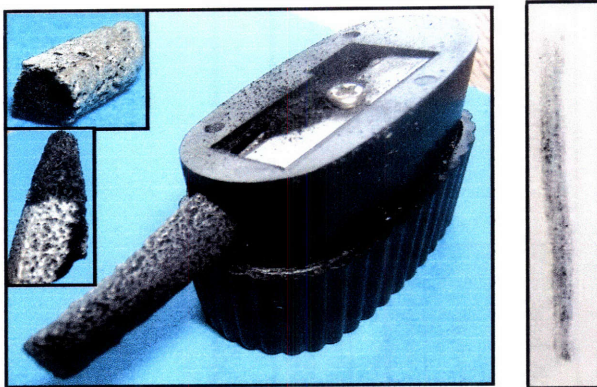

Fig 25 Clay bodies fired in a limited-oxygen environment vitrified on the surface before the internal charcoal had a chance to burn away (top left); the vitrified body could be sharpened easily (center) to produce a charcoal tip (bottom left), which left the mark shown at right on a piece of white paper
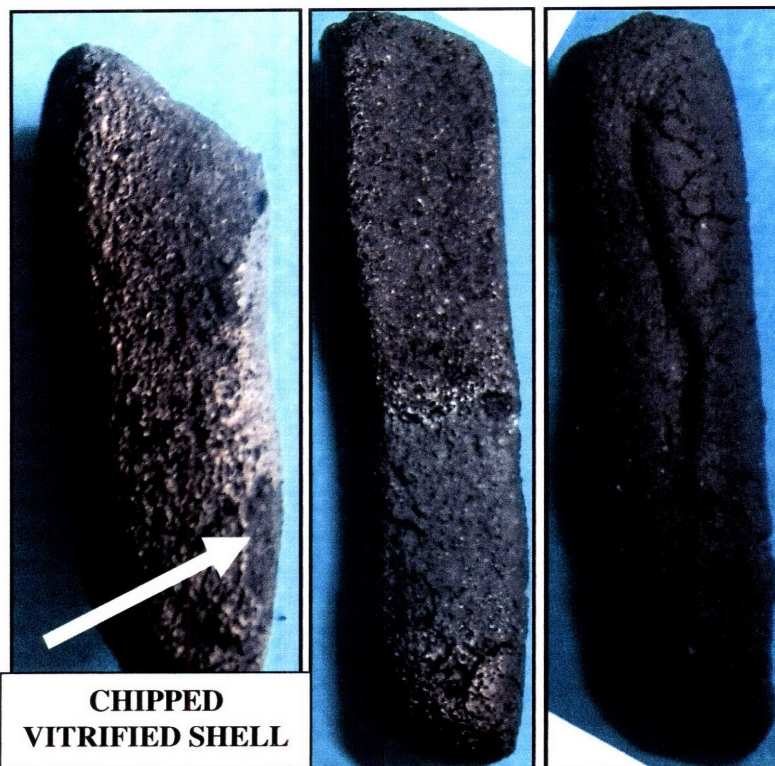

CHIPPED VITRIFIED SHELL

Fig 26 The vitrified bodies produced in the reduction environment were too hard for the pencil sharpener used in these tests, but as shown at left, a tiny section of the surface could be chipped away. None of the bodies made a mark on paper, whether it was their vitrified regions or their sintered regions being tested.

4.2 Sintered

The sintered pellet fired in a complete reduction environment (Experiment 3) made marks as shown in Fig 15a; the second paragraph shows that the writing has faded at the touch of a finger. A different location on the same pellet made more consistent marks and wrote more smoothly (Fig 15 b). The middle statement was rubbed with a finger and smudged in response. A mark made using graphite pencil lead and one made using a sintered pellet are shown side-by-side; erased with the same eraser across the center and erased with a poorly-performing eraser across the bottom tip of each mark.
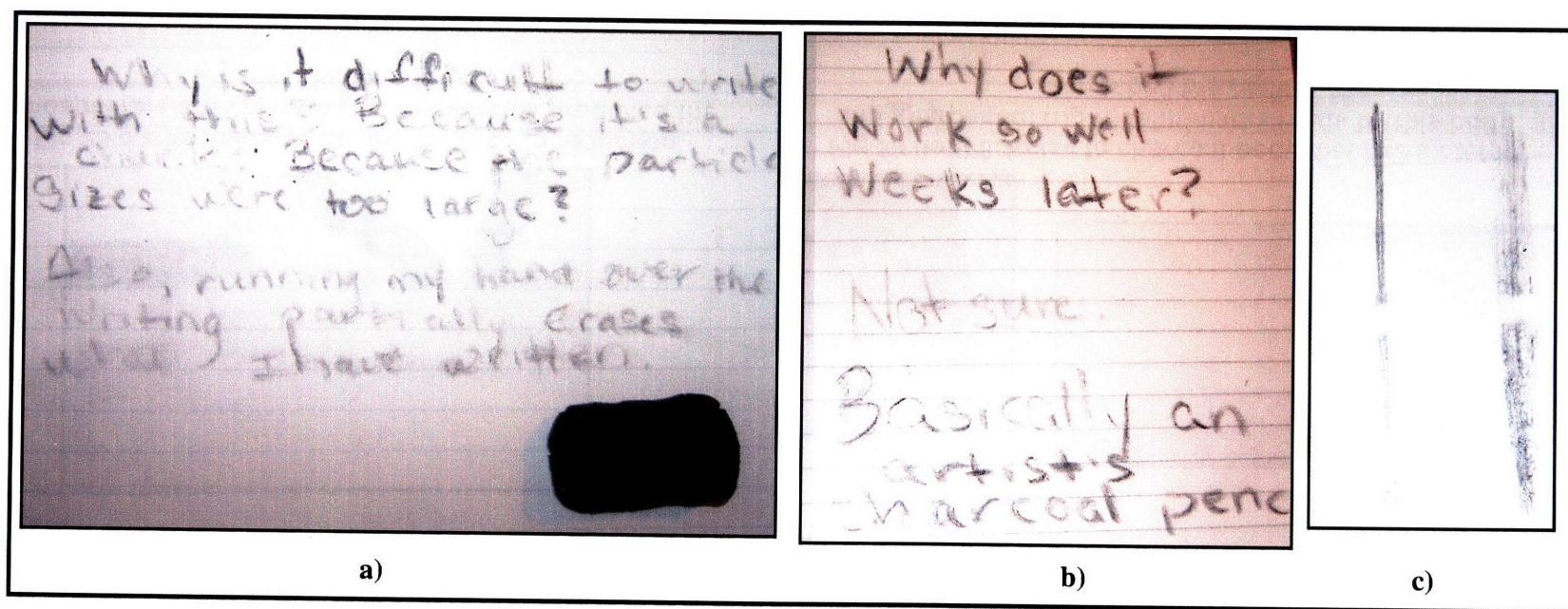

a)   b)   c)

Fig 27 a) Writing done using the sintered pellet fired in a complete reduction environment, smudged; b) marks made using a different part of the same pellet; c) mark made using a graphite pencil lead (left) and the sintered pellet (right) – each mark has been erased across the center using the same eraser and also across the bottom using a poorly-performing eraser.

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Fig 29 shows a sintered piece produced from the 7.5:2.5 clay to charcoal proportion that has been sharpened to a tip. It held up well to sharpening and high writing pressure, but it barely made a mark (Fig 29), and it had a scratchy feel against the paper.

The three proportions sintered in the stainless steel nipple all made marks, shown in Fig 28, but only the mark made by the 7:3 clay to charcoal piece was comparable to that made by a pencil. All of the marks could be erased, but they all also smudged slightly when touched with a finger (shown at the bottom tip of each mark made).
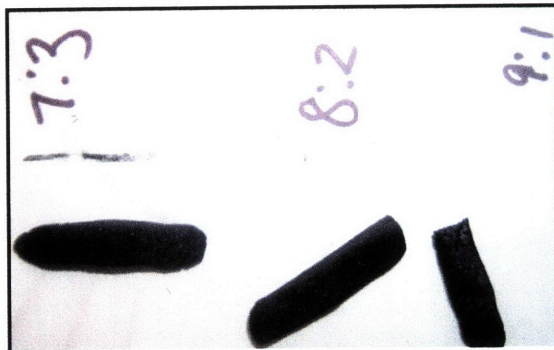

Fig 28 marks made by bodies sintered in reduction atmosphere; (left) 7:3 ratio clay to charcoal produced the most legible mark
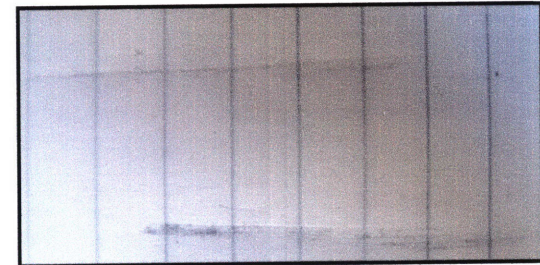

Fig 29 (left) 3:1 clay to charcoal body that has sintered and sharpened; (right) faint marks made by this body scratched the paper

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4.3 Heat Dried

The heat-dried charcoal held together very well, made marks on paper, did not break under writing pressure, could be sharpened, could be erased. All three clay to charcoal ratios made passable marks. The only stark quality issue was that the marks could be smudged. Fig 30 shows the smudging effect at the right tip of each of the first three marks. The figure compares the top three marks made with the heat dried bodies to the bottom mark made with the body sintered in the black steel nipple. The heat dried marks erase more completely using the same eraser, but they also smudge more.
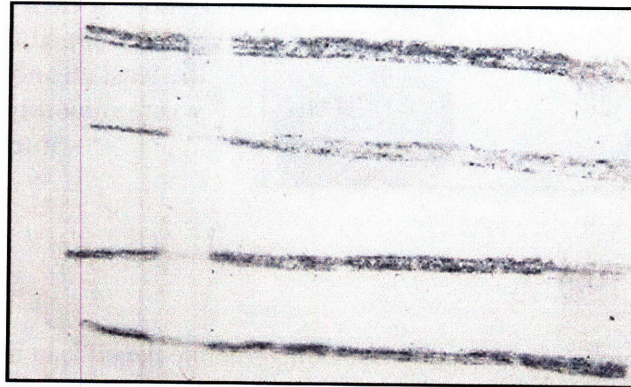

Fig 30 The top three marks were made with the heat dried bodies, in ratios of 7:3, 8:2, and 9:1 (clay to charcoal); the bottom mark was made with the sintered pellet shown in Fig 16. All four marks were rubbed at the right tip to test for smudging, and each was erased using the same eraser to test for erasability.

4.4 Wax-Coated

When each of the the sintered and heat-dried bodies were coated in paraffin wax and beeswax (see Experiment 6, Appendix D for details), the marks made did not smudge nearly as much as they had before the coatings had been applied. Some marks did not smudge at all. The paraffin wax performed slightly better, in that marks made by bodies coated in paraffin wax erased more completely and smudged less than those made by bodies coated in beeswax.
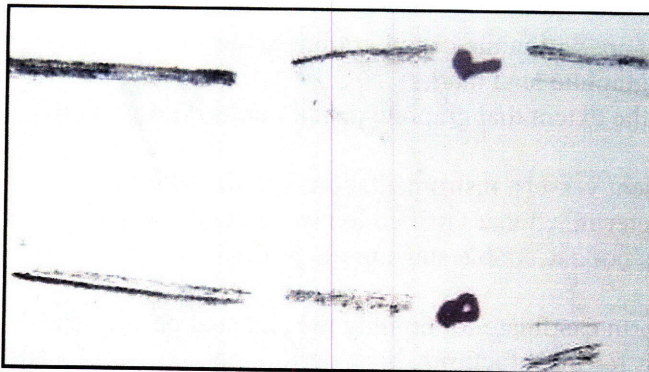

Fig 31 Left to right: marks made before dipping the sintered bodies in wax, just after removing them from wax, and after 30 minutes dry time. Top row: marks made by the sintered body dipped in paraffin wax. Bottom row: marks made by the body dipped in beeswax. A finger was run over each mark; smudges are shown in the image. The faded marks in the third column are marks that were erased
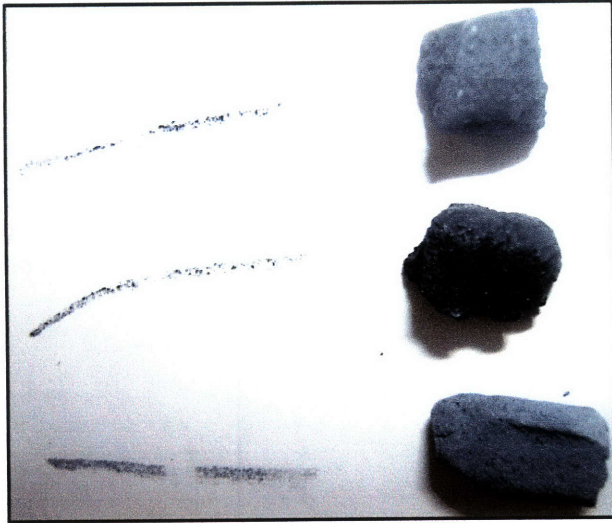
Fig 32 Each of the bodies pictured has only been heat-dried. The bottom piece is untreated, while the top one has been coated in paraffin wax, and the middle one has been coated in beeswax. Each has been subjected to smudging at the right tip of the mark, and the same eraser was used in the middle of each mark. The middle mark smudged the least and erased the least cleanly. All three bodies wrote smoothly, particularly the uncoated.

5. DISCUSSION

This thesis aimed to determine the feasibility of using graphite pencil lead manufacturing processes to make charcoal pencil leads that make marks comparable in performance to those made by graphite leads. In particular, the stage the author found to be the most important in pencil lead performance, the binding of the charcoal powder, was explored. Though technologies exist for production of charcoal leads found in artist's charcoal pencils, these technologies do not match those used in graphite pencil lead manufacturing in performance of the end product.

The feasibility was determined by imitating industrial manufacturing techniques using small-scale methods that could be replicated in a developing country.

The metric used for evaluation of the performance of the end product requires that the charcoal lead
- write smoothly across paper
- remain intact against writing pressure
- remain intact during sharpening
- create marks of legible darkness that are within the pencil grading scale
- create marks that are as erasable as graphite lead marks
- create marks that do not smudge to the extent that graphite pencil marks do not smudge

These metrics were met using the containment vessels, instrumentation, and firing protocol described in the previous sections. It was determined that vitrification was not only *not* a required stage in the process, but that it was not a desirable stage in the process.

However, because clay is a proven-to-perform candidate for binding the charcoal powder and sintering is still a viable stage in the process for manufacturing high-performance charcoal leads, the potential need for high temperatures implies the potential need for some form of kiln and containment vessel, similar to those discussed in this thesis. The real test for feasibility, then, is

whether or not the resources used to enact these experiments could be reproduced in a developing country using locally available materials.

5.1 Bamboo

Assuming the chosen ratio of clay to bamboo charcoal is 7:3, each bamboo charcoal lead has about 1g of charcoal in it. A bamboo burn of 300g of bamboo that is 15% efficient will produce 45g of charcoal, enough to make 45 pencil leads.

Bamboo slat producers (it takes two bamboo slats to make one pencil) cannot use the curved-grain nodes in their business. If there are 6 nodes that come from a 40mm inner diameter stalk of bamboo, and between each node is 400mm of usable bamboo that can produce casings for 10 full pencils, 50 bamboo pencil casings will be created, requiring 50 pencil leads. If 6 nodes amount to 300g, and the remaining cutting waste, including bark and shavings, amount to at least 33g of matter, the waste generated per pencil creates the charcoal necessary for every lead.

The small bamboo charcoal burn done for this experiment had a 30% efficiency (see Appendix A), so the above estimates are conservative; any excess charcoal produced can be used to make additional charcoal leads or can even be used as heating fuel for a kiln.

5.2 Kilns

Kiln construction can be simple and cheap. The majority of the cost will go into labor, but this cost can be cut out for the pencil lead enterprise owner if he builds his own kiln. Depending on the firing temperature required, the kiln can be constructed using just broken ceramic pots and soil (bonfire kiln) and operate on fuel that is straw, cow dung, or grass [12]. The temperature of the kiln in this particular example goes up to 900 °C. Other, higher temperature kilns use firebrick in their construction, which can be made using clays that mature at a higher temperature than the temperature to which the pencil leads will be fired. It is possible to add flux minerals to the clay used in pencil leads so that they vitrify at lower temperatures, and then the very same clay with no flux minerals can be used as refractory lining in the kiln. However, as vitrification detracts from the writing quality[3] obtained by simply firing to the sintering temperature determined for the clay, the pencil leads will most likely not be fired to vitrification, and the same clay used to fire them may be used in construction of the kiln.

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[3] This statement is based on experimental results discussed in this thesis; further research is required to verify that this is the case. See Future Work: Graphite testing

5.3 Fuel

Table 6 Energy consumption for three particular kilns[4]

Type of kiln	3-chambered wood	unknown	electric
Type of fuel	firewood	rice husk	electricity
Space (m^3) in kiln	10.5	1	3.67E-03
Number of leads that can fit in kiln	20023	1900	1400
Typical temperature ($^\circ$C)	1100	1100	1260
Typical time (hours) to temperature	8-10	8	6
Energy (J) required	6.97E+07	9.75E+06	3.24E+07
Quantity fuel needed (of type listed above)	4900 kg	650kg	9kWh
Number of pencil leads needed per year	262800	262800	262800
Number of required firings per year	13	139	188
Energy (J) required per year	9.06E+08	1.36E+09	6.09E+09
Quantity fuel needed per year	63700kg	90350kg	1692kWh

The energy required to fire a kiln depends on the type of kiln, its efficiency, the desired temperature, and the duration of the firing. Three specific energy consumption cases are given in Table 5 above. The electric kiln information is based on the kiln that was used in the experiments discussed in this thesis; it gives a high estimate based on the max power rating given in the kiln specifications. The information about the rice husk kiln and the three-chamber kiln comes from an appropriate technology book [12] about how to build kilns using locally available raw materials in developing countries. Fuel energy ratings for various fuels are given in Appendix E.

There are many types of kiln and many fuel options for kilns, including wood, charcoal, sawdust, waste oil, natural gas, coal, rice husks, other agricultural wastes, and more (Appendix E). It is expected that a community in a developing country would select the type of fuel in greatest abundance locally, or use more than one type of fuel.

For such a small firing piece as a pencil lead, it may not make sense to prepare and load 20,023 of them into a kiln all at once, even if it does occur only thirteen times a year. Such a large number of small bodies requires a large number of containers and large storage space to hold the containers while they are waiting to be loaded into the kiln. It will also be a very large and tightly packed stack in the kiln, probably hindering even heat transfer.

Multiple small kilns may be more feasible. The 3-chambered wood kiln is one to which multiple chambers can be added with only a small increase in the amount of fuel required [12].

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[4] Energy data for this table obtained from [12], energy data for rice husks obtained from fuel energy rating given in the Handbook of Charcoal Making; number of pencil leads needed per year based on estimate from Spring 2008 D-Lab: Design team where 720 pencils are produced daily – assuming 365 days of work, there will be need for 262,800 pencil leads per year; number of leads that can fit in kiln is based on an estimate of a firing container that takes up a little more space than the stainless steel nipple used, which can hold approximately 200 unfired leads

Depending on the size of the kiln, the small-scale pencil lead manufacturer can choose how frequently firings are required to meet the pencil lead demand. The number of times a year a kiln of a given size will need to be fired to make leads for 720 pencils a day (estimate from Spring 2008 D-Lab: Design Bamboo Pencil Team) is included in the table, and it assumes that 200 pencil leads will be held in containers that themselves take up a volume equal to 5.24×10^{-4} m^3 (approximately that occupied by the stainless steel nipple used in the final experiments discussed in this thesis).

5.4 Material

Steel nipples and end caps are most commonly made of stainless steel, black steel, malleable black steel, brass, and other materials that are not as commonly available in developing countries as is mild steel. The more likely metal option would be mild sheet steel fashioned into an airtight box using locally available techniques, such as bending, cutting, and welding.

Because the charcoal leads will be fired at lower than the clay vitrification temperature, the firing medium may be made of clay and used over again. As it was determined that a significant amount of oxidation takes place when an untreated metal is used, using clay would be a better option. The clay needed for the pencil leads themselves can be found in areas such as creeks and riverbeds to begin with, though if this supply is not great enough, a more permanent deposit can be sought.

Clay might be found anywhere there is soil, rock, or a body of water. The feasibility of manufacture as it depends on material will depend upon the location of the enterprise and of the surrounding environment.

6. RECOMMENDATIONS FOR FUTURE WORK

This thesis is only the very beginning of research and development of the manufacturing processes required to make pencil lead production from charcoal a feasible business in developing countries. There are many directions that may be taken in several areas of the process, including in selection of the binder material and the forming method, and still more directions within each category once they have been determined.

More work will be spent on the current path during the summer of 2008. The non-exhaustive recommendations given in this section will be the basis for much of the work, though new ideas may be pursued as well.

Binder
Clay has many winning characteristics as a binder, but it may be that a different binder will work better under non-industrial manufacturing conditions. One binder in particular that will be tested is cassava, which works well in making briquettes from charcoal powder.

Natural Clay

Only one type of clay was used throughout experimentation, and it was free from impurities, having been purchased from a manufacturer. If these techniques are to be applied in regions where the type of clay will not be a choice, then the processes developed for pencil lead production must be easily adaptable to any clay found in nature. With this in mind, clay should be gathered from several different locations and characterized for any differences required in pencil lead manufacture.

Grinding

Large-scale pencil lead manufacturers take extreme care to acquire graphite particles that are very small, so small-scale pencil lead manufacturers will need to do the same. It is assumed that there is some method of grinding used for food production in the rural villages that would be making charcoal pencil leads. Future studies should determine the various grinding methods available to a sample size of villages, compile a list of the most common, test them on charcoal to see the fineness of particles achievable with each, determine if the results are satisfactory, and then take one of two paths. If the particle size achievable with current technologies is satisfactory, then a method for capturing and preserving the majority of the particles that float on air should be developed to ensure the smallest particles are being used. If it is not, a method must be devised to make the particles fine enough

Extruding

Extrusion may be the most effective manner of producing cylindrical rods 2mm in diameter that have enough strength to be handled before firing. In designing a die, attention must be paid to the diameter of the holes, the size of which is dependent upon the shrinkage rate of the pencil lead clay and charcoal composite. In a few preliminary tests using the mockup pictured in Fig 33. the diameter of the charcoal leads that were extruded was smaller than the diameter of the holes that were drilled, though the leads had not had any time during which to shrink. It is probable that some small burs remained in the holes.
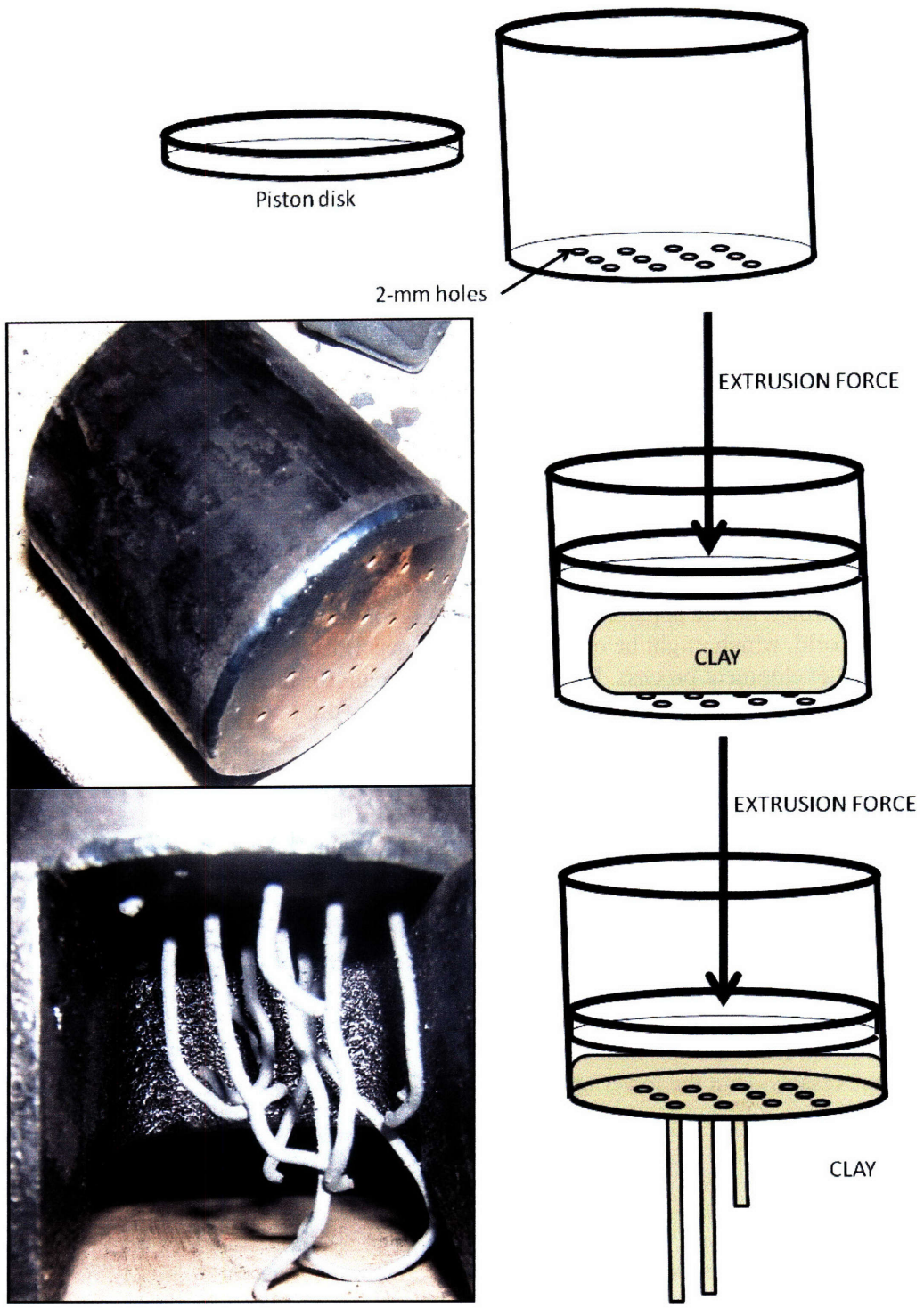
Fig 33 Mockup of extruder in which 2mm holes were drilled into sheet steel, which was then welded to a piece of steel pipe. A small round of steel was used as a piston under the force of an arbor press

Aside from the nontrivial development of the optimal extrusion die, a mechanism for applying sufficient force for extrusion of clay at a certain degree of plasticity must be developed.

Coating Choice
Pencil lead companies coat their leads in waxes and oils for smoothness of writing; it will thus be an aid in attaining similar quality writing to find a variety of waxes and oils that work in this capacity, which are also safe to work with, and find which are common in developing countries, or if there are similar substances that can be used as substitutes.

Compression
The density of the leads made in these experiments was visibly less than that of commercially manufactured graphite leads. The companies researched and contacted reported compressing using large machinery before extruding under extreme forces. A manner of replicating the effects of compression and extruding should be investigated. It could be that small-scale production will not require such high forces.

Fieldwork
Even before any prototypes are complete, visits to several different potential users to learn about their abilities, their resources, their interest, and their preferences could help to determine solutions that would not be apparent otherwise. It is recommended that different regions of the developing world, which might be open to running a pencil lead business, be visited at different stages of the development process. People should be sought for their input and advice to learn what resources and labor are available to them, what they would be willing to do personally, etc.

7. CONCLUSION

Though it is feasible to produce vitrified charcoal pencil leads as part of a manufacturing process carried out in the developing world, the performance of the vitrified leads was not comparable to that of a graphite lead. Better quality writing was attained with oven-dried leads, which have the benefit of not requiring a kiln or any special containment vessel to protect the charcoal from burning away if the temperature is kept lower than about 300 °C.

Sintered charcoal leads also performed well. Sintering does require the use of a kiln and containment vessels – but the lower temperature required allows use of a simple kiln, such as the bonfire kiln.

The use of any type of metal with a melting temperature above that of the firing temperature will typically create a situation in which there is oxidation eating away at the box – only if the metal is treated, like stainless steel, will this not be a worry. Though oxidation does not interfere with the quality of the pencil leads being fired within the containment vessel, it does limit the lifetime of the vessel and create more production costs.

Kiln construction is flexible in its resource requirements, which can be as simple as broken ceramic pots and soil. The size and efficiency of the kiln can be modified to meet the needs of production. The number of times a year it will need to be fired will depend upon its size, which should in turn depend upon the frequency and size of the demand for pencil leads.

There are many different types of fuels available in developing countries that can be used to fire a kiln, such as agricultural waste, waste oil, natural gas produced from a biodigestor, straw, rice husks, dung, sawdust, charcoal produced from organic material, and others.

With further research and development, charcoal pencil lead manufacture can be a profitable business for communities in the developing world.

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Appendix A – Making Bamboo Charcoal

Method I
The kiln was placed at low setting for about an hour. Dry bamboo pieces were placed in small tin with a 5mm hole in the base. The lid was snapped into place, and the tin was placed in the kiln. It immediately began to smoke as loosely bound water and volatile chemicals were burned off. Opening the kiln door during this period resulted in the smoke lighting on fire the first time this method was run, so caution is advised.

After 20 minutes of smoking, the kiln was turned off, and the tiny hole was plugged with a bolt to keep oxygen from entering and burning away the remaining carbon. During this period of the carbonization process, the chemical reactions occurring in the tin are exothermic, supplying enough energy to keep the reactions going until the remaining chemicals are burned away and solid carbon (charcoal) is left behind.

The yield for the initial 273g sample of bamboo was 31% charcoal by mass.

Fig 34
The paint was burned off the tin can with a blow-torch in a well-ventilated area to avoid putting paint vapors into the close atmosphere of the kiln at such high temperatures.


Fig 35 Bamboo charcoal made in a kiln.

Method II – 55-Gallon Oil Drum

1. ADDING DRY ORGANIC MATERIAL TO OIL DRUM

A clean, 55-gallon steel oil drum was used. The drum had four small holes in the bottom for air to enter at the start of the burn, when the drum was to be set on bricks; there was a large hole on top to let the smoke escape and the flames shoot up before a metal lid was to be used to seal the top.
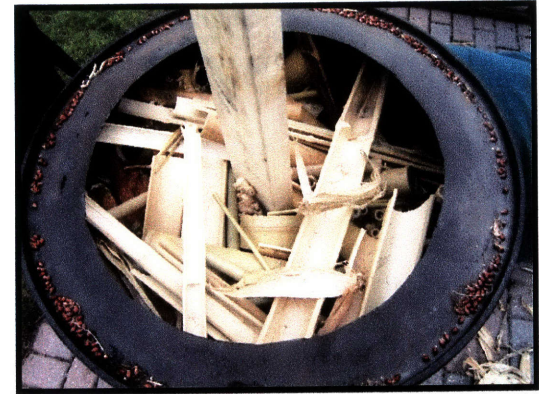
A layer of corn husks was added to the bottom of the drum, since they catch fire/burn readily, and it was certain how fast the bamboo would catch fire; note the 2x4 piece of wood in the drum; it was there to mold a path to the very bottom of the drum even after it was to be full.

This was a mixed corncob- and bamboo-charcoal. It was expected that the corncobs would catch before the bamboo, too, so a layer of them was added directly after the husks.

Then, pieces of bamboo were added. The 2x4 was still in the drum. Dry corn husks, fast-burning matter, were added to the holes in the bottom of the drum.

2. Lighting the Fire

The corn husks that had been stuffed into the holes at the bottom of the drum were lit just after the 2x4 was removed carefully from the full oil drum. It would have also worked to light the end of a long stick and insert the stick into the hole left behind by the 2x4, but lighting from the bottom worked fine.

The drum gave off a lot of smoke as first water and then volatile gases evaporated. The dryer the starting material, the faster the entire process will go.

After a very short while (less than 5 minutes), the smoke was lit on fire by holding a flaming corn husk in the smoke.

3. Sealing the Oil Drum
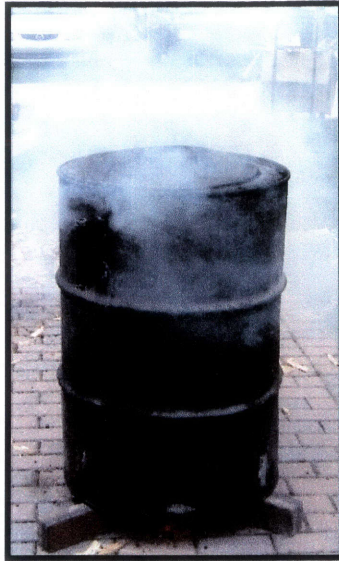
The smoke burned more cleanly for a few minutes, after which the metal lid was thrown on to cut off the inflow of oxygen.

Because the burning material had been so dry, the stages between lighting the material inside and lighting the smoke were very close together in time.

The holes on the bottom also had to be sealed. One person tilted the drum over with a stick while another kicked away a single brick; this was repeated for each brick.

Sand was added to seal the holes where the metal lid met the drum. Bricks were added to weigh down the metal and help with the seal. The corn cob shown in the picture acted as a plug in a hole in the top of the lid.

This type of burn has been performed numerous times using corn cobs, and, typically, the drum is left sealed for two hours to ensure complete carbonization and to ensure that the charcoal does not burn away with the addition of oxygen in a hot environment.

In this case, the drum was left to sit for nearly 3 hours before being opened.

4. Results of the Burn

Fig 36 Bamboo that has been carbonized in an oil drum

YIELD

21.8 kg of starting material (15.9kg bamboo, 5.7 kg corn cobs and husks) gave a 16% yield of charcoal (12% yield bamboo, 19% yield corn cobs and husks – there was some sand in the corn cobs and husks mix, and some bamboo pieces as well, so the numbers are only approximate)

It is expected that the lower yield using Method II as compared to Method I resulted because the fire was allowed to burn longer than what was needed given the dryness of the starting material.

Appendix B - Pyrometric Cone Chart

These temperatures may be used for bodies fired at a rate of 150°C for the last hour and a half to two hours of the firing schedule

Cone	Temperature (°C)
022	590
021	617
020	638
019	695
018	734
017	763
016	796
015	818
014	838
013	861
012	882
011	894
010	915
09	930
08	956
07	987
06	1013
05 1/2	1025
05	1044
04	1077
03	1104
02	1122
01	1138

Cone	Temperature (°C)
1	1154
2	1164
3	1170
4	1183
5	1207
5 1/2	1225
6	1243
7	1257
8	1271
9	1280
10	1305

Appendix C - - Equipment and Instrumentation

The following equipment was used during experimentation.

1. Victoria Grain Mill

2. Thermocouple and Logger Set
Product Name and Number
Onset HOBO U12 J, K, S, T Thermocouple
Logger - U12-014
Range (Logger and K Type Thermocouple)
0° to 1250°C (32° to 2282°F)
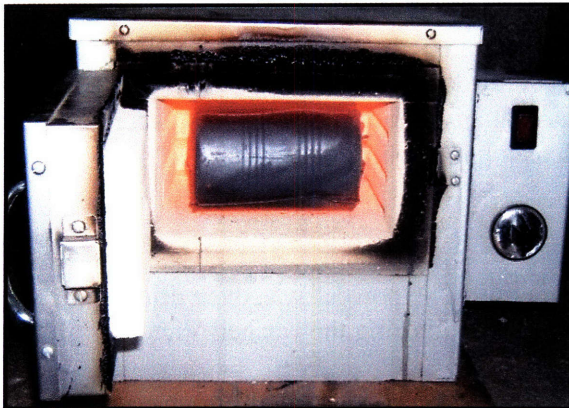**Resolution (Logger and K Type Thermocouple)**
0.32° to 625°C (0.58° at 1157°F)
Accuracy (Logger only when used with K Type Thermocouple)
±4.0°C (±7.2°F)

3. Electric Kiln

Ratings
115 V
1.5 - 1.75 kW
14 A

4. Drying Oven

Ratings
110 V
660 W
6 A

Appendix D – Experiments

In preparation for each of the experiments run, clay and charcoal used were finely ground. The varied parameters of each run were: firing schedule, max temperature attained, atmosphere (oxidation, reduction, limited-oxygen), percent composition charcoal, and firing container.

1. Charcoal-packed mild steel bar molds in steel tin

Lumps of air-dried clay were ground using a Victoria mill. The powder was not sieved or oven-dried. Bamboo charcoal was ground using the washed Victoria mill. A 50:50 mass ratio of clay to charcoal was prepared, water was added, and the mixture was packed into the groove of each steel bar mold discussed in *Section 3.1 Slotted Steel Bars*. The two bars were placed in a drying oven at 80 °C for 2 hours and then removed and sandwiched together so that the grooves were lined up to form a cylinder of packed clay and charcoal.
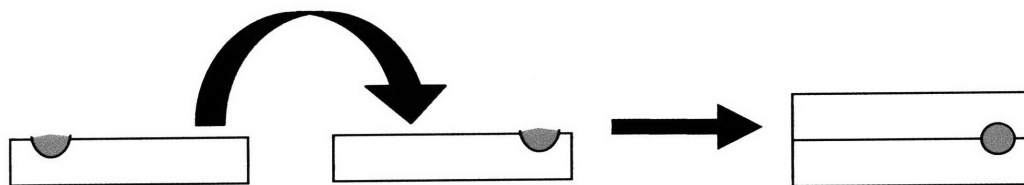

Fig 37 Cross-sectional view of steel bar molds sandwiched together and aligned so that the grooves meet to form a cylinder of the material packed inside

The aligned bars were carefully placed in a small tin like that shown in Fig __, which had had the paint burned off. The lid was fitted securely in place. The firing schedule is shown in Fig 13a.

After about 3 hours of cooling time, the tin was taken out of the kiln. In the process of being moved from the kiln, the thin wall was punctured where the corner of the steel bars had rested on it. The wall had thin plates of oxidation coating the outside and was brittle to the touch.

The steel bars were removed from the tin and easily separated. The charcoal that had been packed into the grooves remained in the grooves. A screwdriver was used to chip the half rods out. Short, fragile lengths came out. It didn't appear that any ceramic change had taken place, and little or no oxygen had made it to the charcoal, as it had not burned away.

2. Ticronic tool steel foil

Lumps of air dried clay were ground using a Victoria mill. The powder was oven dried at just above 100°C for about 3 hours. Bamboo charcoal was ground using the washed Victoria mill.

Eight clay bodies were prepared in the following mass ratios clay to charcoal (grams clay to grams charcoal, each ratio made using red clay and white clay): 9.0:1.0, 8.0:2.0, 7.0:3.0, 6.0:4.0. The dry mixtures were combined with water and molded by hand. They were set on a stainless steel mesh platform and wrapped in Ticronic tool steel foil, made from 321 annealed stainless steel. The setup was fired according to the schedule shown in Fig 13b.

Type 321 annealed stainless steel has a melting temperature of about 1400 °C, but the product specifications guarantee performance up to 2000 °F (1093 °C). The foil started out opaque and emerged from firing transparent as well as somewhat dissolved. The stainless steel base was unaffected.
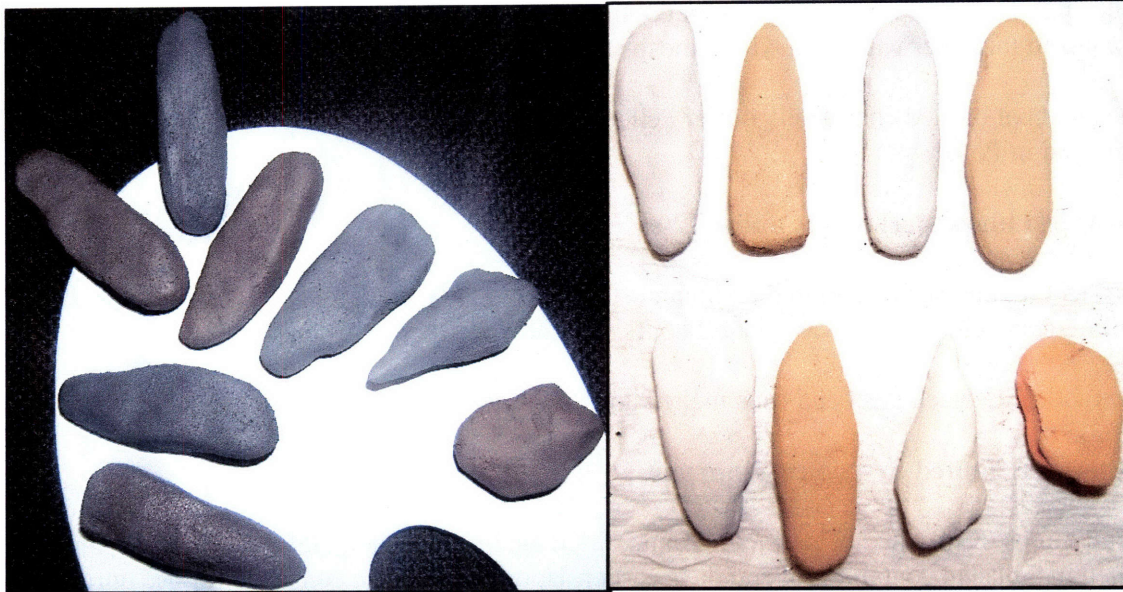

Fig 38 Clay and charcoal bodies before firing - red clay was used in four of the bodies (left); the bodies after firing in oxidation atmosphere (right)

Once the foil had disintegrated, the charcoal burned out of the clay, leaving just ceramic bodies, which did not vitrify, though the temperature in the kiln had reached just above Cone 04 (the firing range for the type of clay used was Cone 06-Cone 04). The bodies had sintered.

3. Black steel nipple, malleable black steel end caps

Using clay and charcoal ground from Experiment 2, a clay to charcoal mixture was prepared in a ratio of 7:3, some water was added to allow molding of the mixture, and four pellets were shaped. These were left to dry at 130 °C for approximately 9 hours. Three pellets (Pellets #1-#3) were placed on a piece of steel pipe on the kiln floor and the final pellet (Pellet #4) was sealed in a black steel nipple. The caps were screwed on only partway, so that pressure gases could be released safely.

Table 7 Qualitative observations of pellets after firing

Pellet	Comments
1, 2	Grayish, soft body, off-white streak on paper
3	White, hard, porous body, no streak
4	Black, hard body, erasable charcoal streak on white paper, smudges at touch

Pellets #3 and #4 were subjected to the schedule shown in Fig 13c and allowed to cool to about 23 °C, while Pellets #1 and #2 were removed when the kiln had reached 360 °C, just after dehydration had begun (Table 3) and before it was expected that too much ceramic change had taken place.

Pellets #3 and #4 experienced different cooling rates, because one was left enclosed in the steel nipple and the other was in the kiln atmosphere.

The charcoal burned completely out of Pellet #3 and mostly out of Pellets #1 and #2; charcoal remained in Pellet #4.

4. Capped black steel nipple above 1200 °C

The steel nipple was placed in the kiln and subjected to the firing schedule shown in Fig 22. The cooling period in the kiln was about 2 hours, not shown in the graph.

The malleable black steel end caps melted and the black steel nipple did not.

5. Steel tin, limited oxygen environment

Small lumps of clay had been dried, ground, dried again as powder, sieved to mesh 60, and sealed in a plastic container several days earlier. Upon opening the container for use during this experiment, particles were clumped together, indicating that the clay had absorbed some moisture. It was dried for approximately 1 hour at 90 °C, enough time to remove only some of the moisture.

Charcoal was ground using a Victoria mill and then sieved to two particle ranges: mesh 60 and below and mesh 60 – mesh 30.

The ratios of clay to charcoal made using mesh 60 and smaller particles are shown in Table 8. The first four preparations were done using the clay that still had tiny clumps; the remaining preparations were made with clay that had been sieved to mesh 60. The clay was shaped into pellets and sticks of cross-section approximately equal to 5mm x 5mm.

The mesh 60-mesh 30 charcoal was used in a 7:3 ratio with mesh 60-mesh 30 clay; results are shown in Table 9.

All of the bodies were dried for 6 hours at approximately 90 °C and then packed into the small tin described in Appendix A, the smaller bodies separated from the rest by a small sheet of steel. The kiln had an approximately 5mm hole in which a screw was loosely inserted and covered by a patch of clay.

Fig 39 Pellet and stick forms from raw clay and charcoal bodies

The tin was capped securely, placed in the kiln, and exposed to the firing schedule shown in Fig 13d with a maximum temperature of 1220 °C. The resulting bodies are shown in Fig 40 below.

Fig 40 Bodies after having been fired in limited-oxygen environment

OBSERVATIONS

Table 8 Qualitative observations of bodies fired in limited-oxygen environment

Gram Ratio (Clay:Charcoal)	Mesh 60 (pellet)	Mesh 60 (stick)
9.0:1.0	No black on surface, tiny pores, no writing	Vitrified outside, charcoal inside, No sharpening
8.5:1.5	Mostly black, clay-colored tip, very tiny pores, no writing	Vitrified outside, charcoal inside, No sharpening
8.0:2.0	Half the surface is black, remainder is clay colored, no writing	Vitrified outside, charcoal inside, No sharpening
7.5:2.5	Entire surface is black, very light writing, scratches paper	Sharpens with some difficulty, Vitrified outside, charcoal inside, writing doesn't rub away, but scratches paper, made erasable mark on paper, very light
7.0:3.0	Partially black, partially loose charcoal, large pores, charcoal in pores, charcoal writing	Sharpened with ease, broke easily, Vitrified outside, charcoal inside, charcoal writing (powder-like)
6.5:3.5	Half black, partialyl metallic, remainder clay colored, charcoal writing	Very soft loose charcoal powder, held its form, not in sharpening
6.0:4.0	Completely black and covered in loose charcoal powder	Very soft loose charcoal powder, held its form, not in sharpening
5.5:4.5	Same, crumbles	Very soft loose charcoal powder, crumbled
5.0:5.0	Same, completely crumbled	Very soft loose charcoal powder, did not hold form

Table 9 Qualitative observations of clay to charcoal bodies with gram ratio 7.0:3.0 fired in a limited-oxygen environment

Mesh 60-Mesh 30 (pellet)	Mesh 60-Mesh 30 (stick)
Large craters, no writing, half charcoal colored, half clay-colored	Same as pellet

No distinctions were observed between the bodies formed with mesh 60 clay versus mesh 60-mesh 30 clay.

The patch of clay securing the small bolt in the tin loosened during firing, so air was admitted into the can. Qualitative observations for each body are recorded in the tables above. Upon breaking the sticks, it was observed that vitrification had occurred on the outer surface before the carbon on the inner surface had had the chance to burn away. Vitrification did not seem to have occurred on the inner surfaces.

Because oxygen entry into the can was restricted, there was not sufficient oxygen to react with all of the carbon in the charcoal - the carbon located toward the surface of the pellets and sticks

burned away, but before the carbon located toward the center had a chance to burn away, too, vitrification of the surface layer formed a barrier restricting oxygen entry into the pores. This was evident in every ratio that had lost charcoal from the outer surface.

5. Mild steel bar molds – oxidation environment

Experiment 1 was repeated with a half-filled pair of molds and a 7:3 ratio of clay to charcoal. The clay powder had been sieved to mesh 60, and so had the charcoal powder. The two mold halves were aligned by hand on the kiln floor, with no external weight added to hold them together, and then the kiln was turned on. After a similar firing schedule to that used in Experiment 4, the molds were allowed to cool, and then they were separated to reveal that the charcoal had burned away.

6. Capped stainless steel nipple

Drying Clay Powder
Clay powder was dried in an oven at over 100 °C for 4 hours.

Uniform Particle Size For Mixing
The clay was sieved to mesh 60
The charcoal used was mesh 60

Mixing
The clay and charcoal were mixed together in the following dry mass ratios, for a total mass of 10.0g:

(clay:charcoal)
9.0:1.0
8.0:2.0
7.0:3.0

Water was added until the mixture had a plastic consistency (about 4g, 5g, and 6g water for the 9.0:1.0, 8.0:2.0, and 7.0:3.0 ratios, respectively)

Molding
6 bodies were prepared from each proportion

Drying
The 18 bodies were left to dry 7 hours at 90-100 °C

Upon removal from the oven, the particles were very well bound and the bodies were hard. The bodies of each ratio made marks smoothly; some dust was created surrounding the marks. The marks could be smudged and erased with a pencil eraser, and the body could be sharpened.

Firing

3 bodies from each ratio were fired in a stainless steel nipple using the firing schedule shown in Fig 13e.

The remaining 3 bodies from each ratio were fired directly in the kiln atmosphere, to use for comparison.

Cooling

After the 5-hour firing, the bodies were left in the kiln to cool for 3 hours.

Soaking in Wax

Upon removal, it was noted that none of the bodies fired in the kiln atmosphere or fired in the steel nipple had not vitrified, but had sintered. One from each ratio was dropped into a bath of paraffin wax at 64°C; one from each ratio was dropped into a bath of beeswax at 64°C. They were left to soak for 5 hours.

A bath of paraffin wax and a bath of beeswax were prepared at roughly 110 °C. One piece of the sintered writing body from Experiment 3 was dropped into the paraffin wax bath, and another was dropped into the beeswax bath. They were left to soak in the waxes for three hours at the heightened temperature.

After three hours, the pieces were removed from the waxes, shaken off immediately to prevent caking of the wax, and used to make a mark on paper. They were then left to dry for about a half hour, and then another mark was made. The results are presented in images and in the table below.

Table 10 Qualitative observations of wax-soaked charcoal pellets

Ratio (Clay:Charcoal)	Paraffin Wax	Beeswax
9.0:1.0	No mark, scratches paper	No mark, scratches paper
8.0:2.0	Faint mark, scratches paper	Very faint mark, scratches paper
7.0:3.0	Clear mark, no smudge, erases, sharpens, rough on paper	Faint mark, scratches paper

7. Vitrification

The charcoal bodies from Experiment 6 that were not placed in wax were placed in the steel nipple to be put in the kiln. The bodies that had been fired directly in the kiln atmosphere were placed directly in the kiln atmosphere again. All were fired using the schedule shown in Fig 13f.

Fuel Material	Energy Rating (KJ/kg)
bituminous coal	31,300
bituminous coke	26,700
charcoal, lump	30,000
charcoal, briquettes	27,000
hardwood, green	10,500
hardwood, dry	15,500
pine bark	20,000
sawdust, fresh	9,600
sawdust, dry	14,600
coconut shells	14,650
bovine manure	15,900
bagasse, wet	8,350
bagasse, dry	15,900
coffee husks	6,550
rice hulls	15,000
rice straw	14,800
paper-mill sludge	12,100
sewage sludge	4,700
kerosene	44,300
diesel oil	40,100

Fuel Material	Energy Rating	Units
Bamboo Charcoal	2.60E+07	J/kg
Pyrolisis gases, bamboo	4.52E+06	J/nm^3

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[5] Data in table at left taken from The Handbook of Charcoal Making by W. Emrich; data in table at righr taken from INBAR [4]

Appendix F - Kilns

A kiln facilitates heat transfer to one region within its walls via insulation and purposefully constructed geometries. Fuel is burned in a firebox, constructed depending upon the type of fuel used. It is possible to have more than one firebox.

The walls and floor of a kiln must be able to withstand the highest temperature to which a kiln will be subjected, which means that it must be made of clay with a much higher maturing temperature than that of the objects fired in it. Refractory material, such as kaolin, fireclay, or silica sand, is typically used in construction of the interior surfaces.

Kilns are constructed all over the world, including in developing countries. Many kiln designs discussed in [12] describe specific kiln constructions in regions such as Bangladesh, India, Tanzania, Nepal, Bujora, and China.

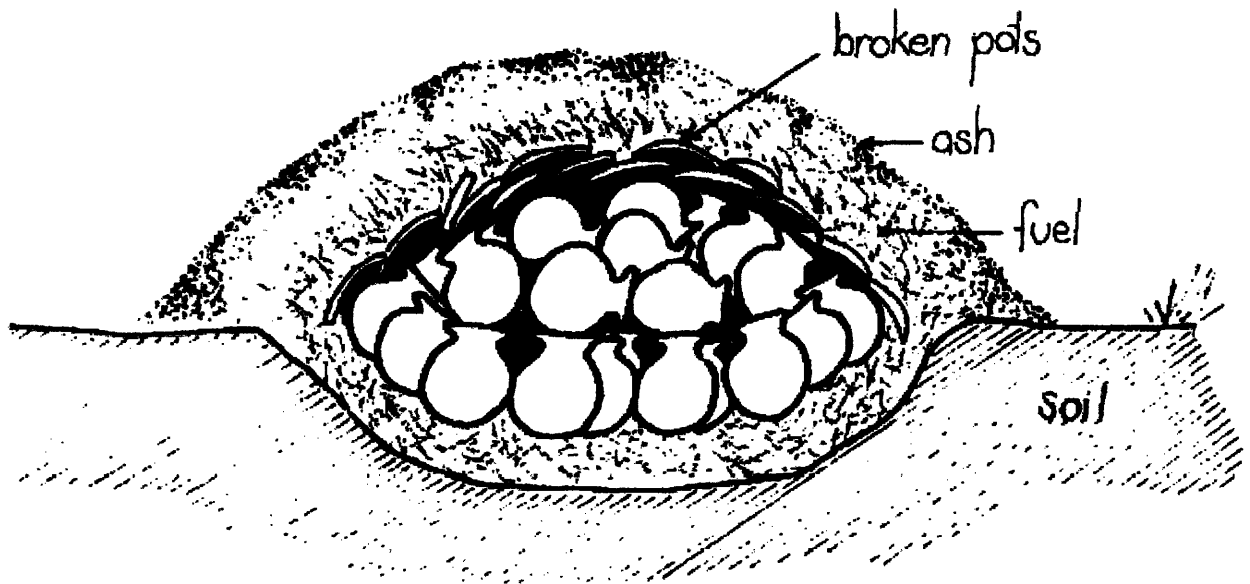Materials for kiln construction are as basic as broken pots and soil, used to make the bonfire kiln.

Fig 40 Bonfire kiln can be brought to 900 °C; image taken from [12]

More complex kiln construction involves the use of firebricks constructed using fireclay.