BUILDING WITH FIRE

Baked-Insitu Mud Houses of India:

Evolution and Analysis of Ray Meeker's Experiments

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"*As a potter- and pyromaniac of sorts-*
with a university background in architecture, living in a country with an acute housing shortage, I was drawn to the idea and then captivated by the process- and by the challenge- of making such a patently absurd notion work."

Ray Meeker

in his essay 'Attitude, imagination, Innovation'
in College Magazine, KRVIA, Mumbai, 1998

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Preface

Around 1976 Iranian architect Nader Khalili first had the idea of baking built mud houses by firing them from inside. It took him five years of struggle to see the first results, and then another two years to get his first ideas published.

Ray Meeker, who heard about Khalili's idea in 1983, undertook another 15 years of pioneering work to be able to bring the technology to a stage where actual liveable houses could be delivered to clients.

Meeker was extremely preoccupied by the fact that that housing as it is conventionally imagined today can at all be provided to the growing numbers of homeless people in the world, not only due to 'standard' housing being prohibitively expensive, but also because of the global shortage of resources. Houses requiring cement and steel cannot remain the standard given the rate of urbanization added to the figures of housing demand in the context of a rapidly deteriorating environment. In earlier times, housing was largely built with local natural materials and by the users themselves.

This dissertation resulted out of an underlying quest to find new, affordable and low impact ways of combining age old building materials that have stood the test of time, in order to address the issue of housing in a rapidly urbanizing world.

The title 'Building with Fire' is meant to suggest first and foremost, the literal uniqueness of a technology where fire is introduced to the building construction process, as 'cement' for bonding building elements together permanently. But 'building with fire' is also meant to suggest the passion with which the experiments have been undertaken, and the element of risk involved in the process.

1. Introduction

"Our efforts are carried out for the most part in the dark. There is yet no model for what we are attempting, no "data base" for a fired mud building technology, the information age notwithstanding. We are the pioneers."

Ray Meeker [1]

1.1 Problem statement

A unique technique of 'baked-*insitu*' mud structures has recently emerged through the pioneering work of a single person, which is radically innovative. Through extensive experimentation during 1983 - 2000, Ray Meeker, a Californian ceramist with a background in architecture settled in South India, established that large mud structures can be successfully fired in-situ, and thus strengthened for water stability without resorting to the addition of cement. This technology is still largely unknown and undocumented, and has not as yet been assessed for its performance.

A technique that might lead to a low-cost and environmentally sound solution is worth serious investigation. In this light, the research and experimentation conducted by Ray Meeker on the field if taken up for evaluation and assessment would determine the value this technique may offer.

1.2 State of the technology and available sources of information, literature review

In contrast to available literature on Baked Building Materials, both in the low-tech sector like brick manufacture in developing countries, and in the high-tech sector of sophisticated ceramic products for the building industry, there is very scanty material in regard to baking of completely built mud houses. The magazines that featured this

[1] An unpublished and undated essay 'Geltaftan: A Second Thought' written by Meeker.

theme have been more often ceramic magazines, but a few architectural, interior design and technology magazines too.

To source information on this subject a great deal on field work and interviews were necessary. The following material was available as a starting point:

- 18 surviving experiments out of 20 built in and around Pondicherry, South India between the years 1985-2000, (as yet undocumented) that are very much in use, are available as a testimony to the experiments undertaken by Meeker and continue to demonstrate the ongoing performance of houses constructed in this method. These living examples of Baked-insitu mud structures are the most important source of information supporting this thesis.

  Although these buildings have demonstrated the possibility of stabilising mud structures by fire, they also lead to serious questions that are a necessary part of the further development process.

- Meeker's pioneering experiments had been based on the vision of Nader Khalili, an Iranian Architect now based in California. Khalili has in the meantime authored two books on the subject:

  Racing Alone Harper and Row, San Francisco, 1983

  Ceramic Houses and Earth Architecture: How to Build Your Own Harper and Row, San Francisco 1986

  These books are the secondary valuable source of information. While 'Racing Alone' authored by Khalili was available to Ray Meeker before he began his own experiments, Ceramic Houses and Earth Architecture, a little more technical in nature than Racing Alone was yet unavailable.

- A few articles in various magazines, mostly ceramic magazines, and a few unpublished essays record some thoughts and struggles faced by these pioneers:

  DANISCH, Jim. *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, November 1983.

DANISCH, Jim. Ray Meeker's Fired Houses, *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, January 2001 (pg 49-52)

DE ROODEN, Jan. A Lifelong Relationship, *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, May 2000.

GREWAL, Royina. Potter Architect, *Inside Outside*, Business India Publications, Bombay, October 1993

KHALILI, Nader. Iran: Geltaftan, Mimar 8: Architecture in Development, Concept Media Ltd. Singapore, 1983

KUNDOO, Anupama. Agnijata: Economic earth construction designed by Ray Meeker: *Indian Architect and Builder*, Business Press, Bombay, November 1990

KUNDOO, Anupama. Devoted to Dance, *Inside Outside*, Business India Publications, Bombay, October 2000

MATHEWS, Neelam. Bake yourself a house, *The Hindustan Times*, New Delhi, 19 January 1996

MEEKER, Ray. *Attitude, Imagination and Innovation,* Kamla Raheja Vidyanidhi Institute of Architecture, College of Architecture, Mumbai, 1998

MEEKER, Ray. *Fired Building: the Layman's Response to an Unconventional Technology*, 27, February 1992, Unpublished essay

MEEKER, Ray. *Geltaftan: A Second Thought*, Undated, Unpublished essay

MEEKER, Ray. *Just Plain Geometry or Interior Design in Response to 'Fired Building' Technology*, Undated, Unpublished essay

MEEKER, Ray. Fired Houses: A Concept for Stabilizing Earth Structures, *Moving Technology* Volume 2 No 1, CAPART, New Delhi, February 1987

MEEKER, Ray. Fire Stabilised Mud Structures, *Moving Technology* Volume 4 No 4, CAPART, New Delhi, August 1989

MEEKER, Ray. Kiln Technology: A demonstration and a challenge, *Indian Architect and Builder*, Business Press, Bombay, November 1990

MEEKER, Ray. MUD: Towards a Fire-Stabilised Building Technology, *Architecture + Design*, Media Transasia, Delhi, March-April 1991

MENON, Sadanand. Fired-mud housing: Dirt Cheap Dwelling, *Economic Times*, 9.August.1991

PERRYMAN, Jane. Houses on Fire, *Ceramic Review* No 162, November-December 1996

- A film produced by Meeker in 1988 during the building of ‘Agnijata’ the first successful fired house built for a client is a visual account of the building process and records the challenges faced by Meeker on the site. This video produced by Ray Meeker and filmed by Auroville Video Production, Pondicherry, is available through Audio Visual Center, Oklahama State university, 121 N. Cordell hall, Stillwater, OK 74078-0398

- The practical experience of the author, having designed two architectural projects in this technique, with Meeker as consultant and guide, provided valuable background information towards understanding of the authentic and technically important concerns regarding this dissertation.

- Finally, Meeker himself had been available for extensive interviews. This has been the most invaluable part in procuring authentic background information of the struggles and challenges faced by a pioneer, along with photographic material from his own archives.

1.3 Objectives

1.3.1 To document all experiments undertaken by Ray Meeker in developing the technique of 'Baked-*insitu* Mud Structures', to trace the evolution of the technology over each subsequent experiment, and to understand the step-by-step building process involved.

1.3.2 To assess these pioneering experiments of Ray Meeker in terms of extent of firing, structural stability, fuel efficiency, environmental impact and cost performance and to identify areas of further research. To determine the areas of advantages and shortcomings of the technology and identify the circumstances in which the technology could be appropriate.

2. The Technique and Its Background

> *"The exterior of the chamber will be of masonry made with large uncut stones, in order that the outside will not seem to have been man-built. When the masonry is finished, I want to cover it [on the inside] with several layers of enamelling, from the top of the vaulted ceiling down to the floor. This done, I should like to build a big fire in it... until the enamelling has melted and coated the masonry... the inside of the chamber would seem to be made of one piece ... and would be so highly polished that the lizards and earthworms that come in there would see themselves as in a mirror."*
>
> Bernard Palissy[2]
> 16th century scholar, potter and enamellist

2.1 Definition and description of the term 'Baked-insitu' mud structure

Earth as a building material is known to have high compressive strength when dry, but in the presence of water to be extremely vulnerable. This property of earth is transformed when earth is fired to high temperatures. The thus transformed material-ceramic- is extremely versatile as a building material. Conventionally the most common structural application is the fired brick. For use as a finishing material in buildings, tiles are also a commonly used application. These bricks and tiles are made from suitable

[2] Bernard Palissy (1510-1589) was a French Potter who was known for having spent his life trying to discover the manufacture of "a white enamelled cup" that he had seen, most likely Chinese porcelain. He was so determined to find this out that he worked as he described in his autobiography "like a man who gropes in the dark". His autobiography faithfully records all these and other struggles and failures. The tragedy was that he never did succeed in discovering it, but what he did succeed in creating as a ceramic artist, was a special type of pottery that is associated with his name, decorated with modeled or applied reliefs coloured naturalistically with glazes and enamels. He also gave public lectures on natural history, and as an author he was undoubtedly more successful than as a potter. He wrote on a variety of subjects, such as agriculture, natural philosophy, and religion. He was condemned to death in the fanatical outburst of 1958 and died in one of the dungeons of the Bastille at nearly eighty years of age.

Meeker uses this quote in his essay, "Attitude, Imagination and Innovation" featured in the students magazine, of Kamla Raheja Vidysnidhi Institute of Architecture, Bombay, 1998 clay and fired in local kilns or in industries and are accordingly available in a range of sizes, surfaces and qualities.

Definition

A 'Baked-In-Situ' mud structure can be defined as a house that is primarily built using sun-dried mud bricks and mud mortar as the principal building material, which is fired on site to high temperatures suitable to the locally available brick clay (ranging from 850-1000°C as in brick manufacture)[3] until the material of the mud brick and mud mortar are transformed to ceramic. The material properties of the earth structure thus becomes like that of the burnt brick. Such a house though built using mud alone, has water-resistance properties that are far superior to a regular mud structure by its material transformation upon exposure to high temperature firing. The mud structure is stabilized thus without resorting to additives like lime or cement that are often not locally available.

The term 'baked-*insitu* mud structure' and previously used terms

Being a very new technology, the term 'baked-*insitu* mud structure' is still not an established one and has been coined as part of this dissertation. Nader Khalili, an Iranian architect who originally envisioned this technology in the late 1970s, named it 'Geltaftan'; "Gel", means "clay", and "taftan", means "firing, baking, and weaving clay" in Persian[4]. This term, effectively meaning 'fired clay' in Persian, may have served to draw attention to this technology as a new one but does not technically suggest that the firing of the structure is done after being built as a complete mud structure. As such it is not a very precise term that distinguishes this method from the conventional 'fired clay'

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[3] This figure is according to SPENCE. Robin, COOK. David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (pg 68). Meeker states that for Pondicherry clay, the required temperature is 950°C.

[4] KHALILI, Nader. Iran: Geltaftan, *Mimar 8: Architecture in Development, Concept Media Ltd. Singapore, 1983*

bricks that are previously fired in a kiln before they are brought to the building site and used in masonry. In his later publication, Khalili uses the term 'Ceramic House'[5].

Ray Meeker, who developed Khalili's vision further, names it 'Fired House'[6] or 'Fire-Stabilised Mud House'[7]. These terms do suggest that it is an already built mud house that is fired as a complete product, and also indicates that the fire stabilizes the material properties of mud.

The term 'Baked-*insitu* mud structure' is coined in this dissertation to stress the fact that the house is actually fired insitu, and that this is the most distinct particularity of the process that makes the building technology unique with extremely different implications, rather than stressing the fact that the property of earth will be transformed by fire, which in fact is an age-old discovery in building technologies.

Description

Typically the firing of an already built mud structure is carried out from inside out. This means that the inside space of the house is heated up to high temperatures till the walls of the house start changing into ceramic. For the outside surface of the walls to be also transformed, the heat must reach all the way through the wall thickness. This usually involves insulation and sometimes a combustible insulation that catches fire at a certain point and helps arrive at the final temperature needed on the external-most surface of the mud wall of the house.

Firing a mud structure *insitu* is easier said than done. Apart from size as a challenge in successful firing of a single piece clay object, there are several areas that require special attention. A mud structure contains a huge volume of air that would need

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[5] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own*, Cal-Earth Press, California, 2000

[6] In February 1987, Meeker used this term in the first article he wrote entitled, 'Fired Houses: A Concept for Stabilizing Earth Structures' that was published in Moving Technology, Vol.2 No.1, Capart, Delhi.

[7] In August 1989, Meeker coined this term to define the technology more accurately, in the next article he wrote, 'Fire-Stabilised Mud Structures', Moving Technology, Vol.4 No.4, Capart, Delhi.

to be heated in order to cook the mud walls through and this implies a huge amount of fuel. On the other hand, when ceramic products are normally produced, they are loaded into a kiln where they are fired. In this case, a large amount of the generated heat is absorbed into the kiln walls in commonly used brick kilns, which is around 40%[8]. In Meeker's development of this technology, the house is therefore stuffed with ceramic products that are then baked in the house as if the house were a kiln. Fuel is used mainly to cook the products contained in the house-kiln. The heat that would normally be lost into the kiln structure itself during regular firing of ceramic products, is tapped, and used to heat up and stabilise the mud walls of the house kiln, that otherwise would have remained an adobe structure. The house thus gets cooked indirectly, as a consequence of having cooked ceramic objects within its space. Ideally, a brick structure can be achieved for the price of a mud structure. Apart from having had the mud structure transformed into brick structure at nearly no extra cost, a further benefit is that mud mortar joints also transform into water resistant ceramic and thus mud joints suffice- making the conventional use of cement in a brick masonry structure redundant.

A technology that is able to achieve a durable permanent house today without resorting to the use of neither steel nor cement as opposed to all current building practices was particularly attractive in the Indian context to Meeker. Except for '*katcha*'[9] houses as the 'temporary' houses in India are called, most buildings today depend on cement as a bonding material between bricks, and commonly called '*pacca*[10]'

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[8] This figure comes from the interview with Ray Meeker in August 2005.
It is also mentioned in his article 'Kiln Technology', Indian Architect and Builder, Business Press, Mumbai, November 1990 (Pg 61)

[9] *Katcha* is a commonly used word in India in several languages, (but also in official government papers in English) to suggest the houses that are not recognized as solid and permanent. This usually includes most of the user built houses in mud, thatch or materials that are not permanent but need frequent replacement or maintenance. The word itself means literally 'raw' and 'uncooked' to describe food, or 'unripe' when used for fruits. These houses, mostly made of locally available and natural raw materials, are environmentally friendly but high maintenance are unfortunately officially not recognized as permanent houses, but temporary, even though most users have spent their entire lives in them, replacing and upgrading parts according to need and affordability. The word 'katcha' also suggests the vulnerability to the natural elements in terms of durability. Interestingly this word can be taken literally in the case of an *unbaked* mud house.

[10] *Pacca* is the corresponding counter term of *Katcha* as explained above, and is commonly used to suggest houses that are built in permanent materials, by which is usually meant brick and cement. The word literally means 'cooked' or 'ripe'. Pucca houses are expected to withstand rainfall and wind and not

houses. Bricks, steel and cement are now considered the most basic and universal building materials and though bricks are available locally almost everywhere, steel and cement in rural areas are imported from neighbouring towns and transported through trucks on roads that often not in existence until building activity generates that kind of demand.

This is a unique technique to achieve strong fire-stabilized earth bonds between bricks to create a monolithic ceramic structure that is principally built with earth but overcomes in its final form, a major limitation of earth buildings; in that they are not water-resistant and although they have a high dry compressive strength, earth buildings lose this strength abruptly when wet and simply melt or get washed away if unprotected with other materials.

Khalili fired his test structures in Iran empty with kerosene. But this would be unaffordable in India, and hence Meeker's experiments there are closely associated with the production of ceramic products to be fired with in the house, to enable that the house can be stabilized affordably and energy efficiently. The house thus becomes a producer of building materials and not only a consumer of materials[11] as it is conventionally known to be. This close association of the building of a house to the manufacture of hand made ceramic products, and the interdependencies between the two, make this technique even more distinct.

Meeker has used part of the products cooked inside the house as finishing materials for the house itself. For example: tiles, window screens, toilet pans etc. The rest of the products were typically sold to recover as much of the fuel cost as possible. If the product sales cover their own production cost, including fuel, then no fuel cost would be accountable to the structure and the thus fire-stabilised structure can be the same as the cost of a sun-dried adobe structure.

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depend as much on maintenance and upkeep. Interestingly in the case of fired mud houses, the term pucca and katcha literally means cooked and uncooked mud house.

[11] Nader Khalili used this formulation of the house being a 'producer as well as consumer' of building materials in the book he authored 'Ceramic Houses and Earth Architecture: How to Build your Own', Cal-Earth Press, California, 2000 (the first edition of this book was originally published under the title 'Ceramic Houses' by Harper and Row, San Fransisco, 1986.

The three stages of structural performance

The challenge of this construction is that the design must fulfil three distinct roles during the course of its production. At the earliest stage, the building must structurally stand and perform as an unbaked earth building with all the limitations of building with earth. Secondly it must be designed to perform as a kiln, within which other ceramic products can be cooked that may or may not later be utilized to complete the house, such as fired bricks, ceramic tiles for floors, walls and waterproofing, wash basins, pipes etc. And after the process of firing the building must finally address the role that it was originally planned for, such as a residence or studio, etc.

The potential of this technique

This building technology has the potential of offering a low-cost housing solution in areas where suitable clay can be sourced. It has the further potential of being an energy-efficient solution that is socio-economically beneficial and causing a low impact on the environment.

2.2 Description and uniqueness

The principal uniqueness in this technique as opposed to the conventionally used brick masonry is the fact that the ceramic products are not manufactured elsewhere in a kiln, and then used for building at the site. Instead, the structure to be built is the kiln. The distinction of this technique therefore lies in the uniqueness of its manufacturing process, and not in its materiality.

2.2.1 Fire is taken to the product as opposed to products being taken to the fire

Traditionally clay products have been taken to the kiln and fired to obtain building materials. In this technique, fire is brought to the products instead of the products being taken to the fire[12]. This could enable high quality locally made houses in isolated areas where the availability of other supporting material may not be available, but fire is always available.

2.2.2. The house is a 'producer' rather than only a 'consumer' of building materials

Another unique feature of this technique is that instead of depending on several building materials from other towns and cities, durable rural houses can be produced with clay as the only building material, and as a consequence further building materials can be produced for others in its interior space. In order to be fuel-efficient as well as cost-efficient, the firing of a large structure can only be justified if the space inside is used to stack and fire other ceramic products that are produced and fired along with the house. In this technique therefore, there is a close association between the production of ceramic products to be fired within the house and the production of the house itself and the two are not only interdependent, but in fact, the production of the house in this technique without the production of other ceramic products is hardly viable.

The products thus generated in the process of making the house is then a resource that goes out of the site into the local area providing employment and high quality building materials, while benefiting the local economy instead of industries in the surrounding area. Ceramic products have always been closely associated with housing, and tiles, pipes, screen elements, sanitary fittings are habitually used in finishing buildings, and do not need to be sourced from the big industries in the cities.

2.2.3 Brick masonry with ceramic joints

Conventionally, buildings made in brick masonry depend on Portland Cement as a bonding material between bricks so much so that Portland Cement is being considered

[12] This is a formulation taken form Khalili's own words, "*Here, instead of taking the materials to the fire, we were bringing the fire to the material, And thus a new horizon had opened up to us*". KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 (Pg 39)

a universal building material.[13] Although bricks may be available locally in most places, there is a huge shortage of cement[14] especially in rural areas. The high costs of the centralized large plants mean that they must serve a very large geographical area, and in rural areas, the cost of cement can be as much as five times the cost at the plant[15] and where transport involves numerous handling, there is inevitable loss and deterioration.

In this technique, after firing, the mud brick and mud mortar joints are transformed into a monolithic ceramic structure. While the properties of the structure thus produced are similar to that of conventional brick masonry, a unique feature is that this is achieved without requiring cement, lime or any other bonding material. Fire is 'cement' in this technology. Such a monolithic ceramic structure that makes any other bonding material redundant is only possible through the *insitu* firing process unique to this technology. This aspect of the technique makes a high-quality hand-made house possible with only locally available materials. The environmental and socio-economical benefits of this will be investigated later in the dissertation.

2.3 Ray Meeker: background and motivation

2.3.1 Background and brief biography

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[13] "This material, used essentially in concrete, has become probably the most widely used of all for building and its importance in developing countries cannot be underestimated. Most aspects of development in the Third World countries are associated with construction and there is a clear indication that much of this construction involves the use of concrete. Thus, a continuing and expanding supply of cement is essential to provide infrastructure for development. Accordingly cement must be counted among the basic commodities and which development programmes rely, with an importance comparable to water, energy and fertilizer supply…." SPENCE. Robin, COOK. David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (pg 159).

[14] "It is currently estimated that the annual shortfall in cement production in the Indian subcontinent (India, Pakistan and Bangladesh) is between five and six million tonnes. Insufficient foreign reserves are available to overcome this deficiency and hence, as mentioned earlier, development projects are being inevitably delayed." SPENCE. Robin, COOK. David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (pg 161).

"The scarcity in the economy of the two basic ingredients- cement and steel- means that to the extent that these materials are used in domestic building they are unavailable to other vital sectors of the economy, such as the construction of roads, factories and dams." SPENCE. Robin, COOK. David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (pg 266).

[15] SPENCE. Robin, COOK. David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (pg 161).

Ray Meeker was born on July 4, 1944 in New York City, U.S.A. During the years between 1962 and 1965 he studied art on an athletic scholarship for basketball in Pepperdine College, after which he pursued four years of Architecture school in the University of Southern California, concluding in 1971 though with a Bachelor of Fine Arts in Ceramics. Meeker met his wife, Deborah Smith, in the Ceramics Department of the University of Southern California in 1969. Deborah Smith had after having graduated from Stanford in Japanese language, just returned from two years in Japan of which she apprenticed for a year with Yamamoto Toshu in Bizen, and was again on her way to Japan, this time for three months to act as an interpreter for Susan Peterson who was researching her book on Shoji Hamada.

In his website[16], Meeker explains what brought him to India and Pondicherry thus: "We had discovered in each other a vague interest in the philosophy of the East - not uncommon at the time- and would meet again in India. Pondicherry, the home of the Sri Aurobindo Ashram, was in 1970 often characterized as a quiet village on the Coromandel Coast of Southeast India, and what is now the Union Territory of Pondicherry had been a French colony. It was handed back to India in 1956, but at the turn of the 20th century it was a safe haven from the British Raj and attracted the Bengali revolutionary/mystic Sri Aurobindo Ghose. The ashram began as a closely-knit group of Sri Aurobindo and four or five disciples in 1910. Sri Aurobindo passed away in 1950, but the Ashram has become a Pondicherry institution, now with upwards of 1500 disciples. Deborah, who arrived three months before I did, was asked by one of the secretaries at the ashram if she would start a pottery workshop. "Yes," she said, "if my friend comes to build a kiln."

Together with Deborah Smith, Ray Meeker founded the Golden Bridge Pottery in Pondicherry in 1971 where they still produce a varied line of wheel-thrown stoneware pottery. The Golden Bridge Pottery (that began in a 10ft x 20ft palm leaf shed) was the first workshop to make glazed stoneware pottery by hand in South India. With an employed staff of fourteen people their work has become the standard for small-scale handmade production pottery in India. There are now more than fifteen potteries in the

[16] www.raymeeker.com

Pondicherry area, making everything from *raku* to porcelain, in one-person studios or small-scale units employing up to forty people, potters and ceramistss ranging from educated Indians and Westerners to unschooled villagers with absolutely no prior experience with clay. Deborah Smith and Ray Meeker have been teaching since twenty-seven years and there are studio potters all over India who have come to learn with them. Since 1997 they have been hosting workshops with artists/educators from abroad, including Susan Peterson, Jane Perryman, Jim Danisch, Mike Dodd, Sandy Brown and Betty Woodman.

The spirit and the evolution of the Golden Bridge Pottery and its activities are best described in Ray Meeker's own words[17]:

> *"Deborah intended to work as an individual studio potter, producing a very limited line of glazed stoneware. I thought that I was here only to build her a kiln and move on. We had no idea what we were beginning, but in 1972, Deborah's mother visited and prophetically proclaimed that shed - without a hint of sarcasm – 'the South-Indian Ceramic Centre!' Today, when I hear the GBP characterised as an institute it always strikes me as a misnomer. There is no doubt that the GBP has become an institution of a sort, but it is not an institute. We run a very loosely structured training program. There are no grades, certificates, diplomas or degrees. You take away what you learn and perhaps a kiln-load or two of pots. We tend to attract those who want to explore and grow, and who are committed enough to wait two years to find a place in the course.*
>
> *We are a working pottery. Students have access to highly skilled production potters at work in all parts of the process. We turn them loose into an abundant infrastructure and give enough*

[17] MEEKER, Ray. Attitude, Imagination, Innovation, Students magazine of the Kamla Raheja Vidyanidhi Institute of Architecture, Bombay, 1998, Pg 12-15

direction to get them off the ground. Kilns are big enough to get real work into, wheels are numerous, and space is open and extensive, all providing an opportunity to get deep enough into material and process to develop something of value. We push skill, rather than self-expression, through the vehicle of the "thrown" pot. If the student is an artist it will come out. Design values include function, simplicity, elegance, and an intangible thing that we call life - or presence - that is difficult to achieve with industrial processes.

The GBP is not an art school. Critiques are minimal at best. Students should become honestly self-critical and self confident, with the self-assurance to start their own workshops or go anywhere in the world for further experience. We invite different approaches by bringing in other artists for workshops. Though we do preach GBP standards, we do not expect students to remain mired in a GBP aesthetic. We believe that it is possible to find a serious way with clay art in this country and try to pass on that confidence."

Jane Perryman, in her article, 'Houses on Fire'[18], describes Ray Meeker as follows: "His reputation had preceded him as a much loved, much respected (amongst the studio and traditional pottery communities of India) six foot six inches - surfer Californian who builds and fires houses *insitu*. What an intriguing concept - it seemed to me that Ray Meeker must be fulfilling the addictive art of pyromania on a grandiose scale. I was not disappointed. Ray is one of those few charismatic people you meet in a lifetime - whose accomplishments are inspirational; who communicates his ideas quietly and modestly and who has a profound influence on those around him."

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[18] PERRYMAN, Jane, Ceramic Review No 162, (November December 1996 Pg 27-28)

Jane Perryman is known internationally for developing the ancient and traditional processes of smoke firing and transforming them into a contemporary art form. Apart from her studio work she has written several books and magazine articles on Ceramics including 'Traditional Pottery of India' A&C Black, 2000

2.3.2 Meeker's engagement with firing mud structures

In 1985 Meeker began his earliest experiments with 'Fire Stabilized Mud Building', as he called them, which he hoped would lead to both a technically sound and economically viable stabilized mud structure. Six experiments, conducted during 1985 to 1987 in his pottery campus were needed to establish the basics. By 1988, Meeker was ready to undertake actual architecture projects built in this technique for 'clients'. In 1988, he realised the first large-size fire-stabilised mud house, called 'Agnijata' for Mallika in Auroville, India and this project, his seventh test, was a major breakthrough. The 30-minute video he produced on the process of this project won a Bronze Medal at the Ceramics Millennium, Amsterdam ten years later in 1999.

From then on, after the building of Agnijata, he went on to build a series of projects adding upto 20 experiments in all, with the last project completed in 2000, during which he optimised the technique progressively. Another major break through was in 1999, when he built a shrine for the Nrityagram Dance Village, Bangalore, the eighteenth test, where he was able to substitute fire wood as a fuel by using coal dust as an additive in the brick clay, and arrive hence at a huge optimisation in fuel efficiency figures.

The fourteenth test, a project he delivered for Minota Aquatech Ltd., a subsidiary of The Indian Tobacco Corporation, Tuticorin consisting of staff housing, office, laboratory and security spaces was a notable project in terms of scale, as he had the opportunity to test the economics and technology transfer over a larger area and gain an insight into the costs in case of replicablity and for bringing this technique into the mainstream.

Deborah Smith has been in charge of the pottery production since 1985, when Meeker began his fifteen year project of developing fire-stabilized mud building. In 2000, with the fired housing period largely behind him, Meeker returned to working with clay on a more modest scale for exhibition in India.

2.3.3 Motivation for pursuing fired mud building research

Meeker has repeatedly indicated his preoccupation with the housing issues of a country like India and with the quest for 'low cost' housing solutions.

> *"A good deal has been said over the past fifty years on the need for a revival and/or upgrading of the mud building technique in order to produce a durable 'low cost' house. The call, strident in the past decade as housing demand increases, energy costs rise, and natural resource reserves seem to be on the decline, has yet to yield a totally satisfactory solution. To be sure, there has also been strong opposition to mud as a viable building material in the twentieth century. The resistance, not unjustified, stems from technical, cultural, and no doubt, political and economic prejudices. Without getting bogged down in the mud versus cement rhetoric, it should be sufficient to say that any technique which could produce a reasonably low cost solution to today's housing shortage is worth serious investigation."*
>
> Ray Meeker[19]

The Iranian architect Nadir Khalili had envisioned a method for 'stabilizing' mud structures which he outlined in his book 'Racing Alone' (Harper and Row, 1983). Khalili writes about his five year quest for a technique to improve the village house in Iran, which culminated in the firing of an existing mud house and, subsequently, the building and firing of a ten-room school building. When around 1985 Meeker read about Khalili's ideas and experiments[20] he began to seriously think of the potential of this technique in relation to the housing situation in India. He embarked on a series of experiments in his own pottery. Despite the partial failures of the first two experiments, there was enough success in them to

[19] MEEKER, Ray. MUD: Towards A fire Stabilised Building Technology, Architecture & Design, Media Transasia, Delhi, March- April 1991

[20] Ray Meeker heard about Nader Khalili for the first time when he read Jim Danish's article in Ceramic Monthly magazine, a publication of the American Ceramic Society, Ohio, November 1983

keep him going and to undertake further experiments subsequently, and solve the different issues step-by-step. In one of his first articles on Fired Houses[21], Ray Meeker expresses his background and preoccupation with Khalili's vision thus: *"To me as a potter- with a university background in architecture- and living in India- a country with both an acute housing shortage and a tradition in mud building- Khalili's experiments hold a special appeal."*

Khalili had envisioned the concept of stabilizing earth buildings by firing them *insitu* after they were constructed and had managed to test his ideas in two projects as described in Section 3.4. However his case studies were in Iran, an arid climate that posed no major threat to the collapse of unfired or poorly fired areas of the structure due to rainfall. Meeker took up the challenge to solve this concept from theory to practice particularly in a monsoon climate with extraordinary perseverance[22]. Further, Khalili didn't seem to be concerned with fuel efficiency and costs implications due to these factors, for in Iran he managed to fire the buildings empty with abundantly and cheaply available kerosene. This was the other major challenge that Meeker undertook to resolve- the feasibility of recovery of fuel cost through the products that would be fired within the house as if the house would literally serve as a kiln and then be baked, mostly as a consequence, thereby tapping the heat normally wasted into the kiln walls and achieving a building technique that could offer the stability of a brick house for the price of a mud house without even resorting to cement or other materials for mortar.

2.4 How an idea envisioned in Iran bore fruit in India

Khalili in Iran

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[21] MEEKER. Ray. Fired Houses: A concept for stabilizing earth structures. *Moving Technology* Vol.2 No.1, Capart, Delhi, February 1987 p23

[22] This idea of comparing the climatic context of the fired structures of Khalili and Meeker was originally introduced by Jim Danisch, in his article, 'Ray Meeker's Fired Houses', *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio January 2001 Pg 49-52.

Earlier in 1983 it was Jim Danisch who had written the article on Nader Khalili in the same magazine that Meeker had got to read, that ignited his interest in fired houses.

Nader Khalili, an architect of Iranian origin, had envisioned[23] this method of stabilizing mud structures by firing in*situ*. Between 1978 and 1983, Khalili had traveled in rural Iran where he, preoccupied with the idea of improving mud houses, had stumbled upon the idea of using fire to strengthen existing houses. Khalili had noticed that the old village brick kilns in the local area seemed to be in good condition structurally, as the process of firing pottery in them had hardened the inner walls and led to the kiln structure that was made in *adobe*[24] blocks to transform and become durable. In 1979 Khalili and his team including Ali Agha, a kiln specialist, succeeded in firing an existing house in a settlement of twelve houses in the village of Galeh Mofid, in the outskirts of Tehran.. By 1980 all the twelve units were rehabilitated, of which 9 were done by the villagers themselves. From 1980 - 1981 he built and fired a ten-classroom school building in Javadabad village, near Varamin, also in Iran. Political events forced Khalili to leave Iran. By 1982, Khalili began teaching earth and Ceramic Architecture and Third World Development at Southern California Institute of Architects, and began conducting workshops on *Geltaftan.* In his book, 'Ceramic Houses', he featured the experimental fired buildings of two of the workshop participants. One structure, 'The Ojai Vault' at the Ojai Foundation site in California is the work of Jim Danisch, who authored articles on Khalili in 1983 and later on Meeker in 2001; and a second structure, 'Dome on the Range' in Bushland, Texas by students.

Khalili's own experiments however were located in low-rainfall areas, where it was not critical that the walls had to be completely fired through. Problems with

[23] Khalili himself describes his vision and experiments in his book Racing Alone, Harper and Row, 1983. This has been also confirmed in the writings by Ray Meeker (MEEKER. Ray. Fired Houses: A Concept for Stabilizing Earth Structures, Moving Technology, Vol.2 No.1, Capart, Delhi, February 1987). Thereafter it has been mentioned in articles by ceramists Jim Danisch (DANISCH, Jim. Ray Meeker's Fired Houses, *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, January 2001, Page 49-52) and Jane Perryman (PERRYMAN, Jane. Houses on Fire, Ceramic Review, Ceramic Review Publishing, London, November-December 1996, Page 27-28

[24] Adobe is the term used for an earth construction technique using sun-dried earth bricks. Soil is brought to a semi-liquid consistency, and then cast or formed into blocks. The blocks are allowed to dry in the sun, during which period they gain strength and at the same time the shrinkage takes place. They can be laid up into a wall using mortar like other masonry materials, although usually a mud mortar of similar material to the block is used. In some traditions blocks are hand-shaped; more commonly, they are rectangular and cast in moulds.

The above description is taken from SPENCE. Robin, COOK. David, *Building Materials in Developing Countries*, John Wiley and Sons, Chichester, 1983 (pg 44).

financing, high labour costs and lack of technical expertise, as well as stringent building codes, prevented other experiments in the US[25]. His vision and experiments have been narrated in a book he authored entitled 'Racing Alone'[26]

Adamson and Vohra in South India

Sometime in 1982-83 Patrick Adamson, an English potter working in Auroville[27], with Angad Vohra, a former student of Ray Meeker, received through his Iranian girlfriend, Afsaneh, a manuscript of Khalili's book, 'Racing Alone' (in Pharsi) called 'Racing Alone' even before the book had been published. Patrick Adamson got interested in the idea of firing earth structures and together with Angad Vohra, actually intended trying the technique in the village of Kottakarai where they then lived and worked. They decided to go ahead, build and try to fire such a mud structure. Auroville, then only 14 years old, was still very much in its pioneering stage and a fertile ground to try experiments of any sort, particularly of building technologies and architecture as there was a great enthusiasm to address the need for finding new forms of building for a new city, seen as a replicable model in many areas.

Angad Vohra and Patrick Adamson went on to build a little vault structure next to the then community kitchen hoping to later use this test structure as toilets for the community. They managed to build the structure in bricks produced on site and even managed to build a Nubian vault. Vohra admits that they had no idea about the firing, not having yet even given the firing process a thought. Unfortunately the structure never got down to being fired, as around the time the structure was ready Vohra's mother passed away and he had to leave. Although the structure was packed with plastic sheets and tarpaulin for water protection, the monsoon rain consumed the structure. Somebody had stolen the tarpaulin. Vohra, upon his return was too busy with the consequences of

[25] According to Jim Danisch in his article, 'Ray Meeker's Fired Houses', *Ceramic Monthly*, January 2001, Pg 49-51. Eighteen years earlier, in 1983, Danisch had written about Khalili's Fired Houses, and also tried an experimental structure himself.

[26] Harper and Row, San Fransisco, 1983

[27] a new international towniship founded in Tamil Nadu, South India, 1968. It is about 10 km away from Pondicherry, a former French colony

his mother's death and as the pottery was still not so financially stable, and they didn't have the energy to build it up again.

Meeker's introduction to the idea

Around this time Ray Meeker, a Californian potter, who had settled in Pondicherry[28] and together with his wife founded the Golden Bridge Pottery, got to read about Nader Khalili's work in an article in 'Ceramic Monthly' written by Jim Danish, published in November 1983 and started to get interested. Meeker had a background in architecture studies in the US before he started studying Ceramics, and he was in the unique position of knowledge about both the necessary areas of expertise needed. He wrote, "Being a potter- with a university background in architecture- and living in India- a country with both an acute housing shortage and a tradition in mud building- Khalili's experiments held a special appeal"[29] Meeker was also the ceramics teacher of Angad Vohra, and he had earlier on been informed of these ideas and the intention of Vohra and Adamson to start an experiment. At that time, Meeker admits, he had thought it was an extremely absurd idea, and didn't quite take the whole thing serious.

Meeker wrote to Danisch enquiring about the process[30]. Danisch at that time was in Nepal, advising traditional potters on glazed earthenware techniques, and three months passed before Meeker received a reply with Nader Khalili's address in California. Jim Danisch confirms this much later in January 2001 in his article for Ceramic Monthly, 'Ray Meeker's Fired Houses' that he wrote after having visited the work of Meeker in India: "In November 1983, Ceramics Monthly published my article about Nader Khalili's vision for fired houses, which I wrote after constructing the first small test vault in the U.S. A few months later, I received a letter from Meeker (an American potter living in Pondicherry, South India, where he and Deborah Smith

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[28] Pondicherry is a small town in the South-East coast of India, a former pocket of French colony in the midst of British India

[29] MEEKER, Ray. Fired Houses: A Concept for Stabilizing Earth Structures, Moving Technology Volume 2 No 1, CAPART, New Delhi, February 1987

[30] DANISCH, Jim. Ray Meeker's Fired Houses, *Ceramic Monthly*, January 2001, a publication of the American Ceramic Society, Ohio, November 1983 (Pg 49-52)

established Golden Bridge Pottery in 1971) inquiring about the process. But by then I was in Nepal, advising traditional potters on glazed earthenware techniques. So on his next trip back to the U.S., Meeker attended a two-day workshop with Khalili."[31]

Khalili sent Meeker a schedule for his three day workshops. By then Meeker had already decided to try out one such structure and he attended Khalili's workshop in Colorado[32] to see what he could learn about it. "I am afraid I didn't learn very much at the workshop because you made little bricks and built tiny kilns", said Ray Meeker[33]. Khalili's workshops were about building small models with small mud bricks and then firing them. This was in no way a preparation for building and firing a house-sized structure. So Meeker, who was by then determined to solve the challenge of firing a large structure, had to work out his own path.

Meeker's Experiments

Jan de Rooden, a Dutch ceramic artist who was already hosted by Golden Bridge Pottery along with his ceramist wife, Shawney in 1981, had in the meantime written to Meeker about his wish to return to Golden Bridge Pottery. Meeker knew that it was easy to accommodate his wife, as she also worked with salt glazes as they did at the Golden Bridge Pottery, into an 'artists-in-residence' situation, but felt it was more challenging to keep occupied Jan de Rooden who was the type who was bursting with energy, for 3 or 4 months. "So this is it!" Ray thought, "Now is the time to do a fired building". [34]

Jan de Rooden had thought that this was a wonderful idea and had applied to the Dutch Government for a travel grant to come to India which he then got. Meeker admits that he actually got a little nervous that the grant had come through and that he would

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[31] DANISCH, Jim. Ray Meeker's Fired Houses, Ceramic Monthly, January 2001, a publication of the American Ceramic Society, Ohio, November 1983 (Pg 49-52)

[32] PERRYMAN, Jane. Houses on Fire, Ceramic Review No 162, Ceramic Review Publishing, London, November December 1996, Pg 27-28

[33] From the interview with Meeker with the author in 22nd August 2005

[34] From the interview with Meeker with the author on 22nd August 2005

now actually have to go ahead and do start the project, so on his way back form the US (after Khalili's workshop) he stopped over at Amsterdam and suggested to Jan de Rooden, "why don't you go to Egypt or something and meet Hassan Fathy or something and learn about Nubian Vaults etc"[35]. Jan de Rooden then applied for a further grant which he also was granted. As per the plan, he did then meet Hassan Fathy and then arrived in Pondicherry.

With Jan de Rooden, Ray Meeker started a vault structure at Golden Bridge Pottery, (Case Study 1, Golden Bridge Pottery Vault 1) in 1985. Although the firing of this structure was fairly successful, the 18 inch thick wall wasn't cooked through and so they destroyed the structure before the monsoon set in[36]. Meeker subsequently went on to build 19 structures of different scales and firing techniques accommodating different products within, always progressively working out different aspects of this complicated task. His hope was that this effort would lead to a technically sound as well as an economically viable stabilized mud structure. In his unpublished essay, 'Geltaftan: A Second Thought', he expressed his own motivation thus: "As a potter- and pyromaniac of sorts- with a university background in architecture, living in a country with an acute housing shortage, I was drawn to the idea and then captivated by the process- and by the challenge- of making such a patently absurd notion work."

In the first three years Meeker built and fired six test structures in his own pottery site. These earliest six structures were fairly small and simple consisting of single-vaulted rooms varying in carpet area from 6 to 18 square meters. They were conceived with basic experience in building mud brick vaults to become familiar with the behaviour of large mud brick structures during firing. Further, it was necessary to determine whether a 15cm thick vault could be thoroughly fire-stabilised, with how much fuel, and what kind of post-firing treatment would be effective. According to the assessment of Jim Danisch, who himself had known Khalili and himself worked on a fired building

[35] From the interview with Meeker with the author on 26th August 2005

[36] DANISCH, Jim. Ray Meeker's Fired Houses, Ceramic Monthly, a publication of the American Ceramic Society, Ohio, January 2001, Pg 49-52. Here Danisch refers to an autobiographical article by Jan de Rooden in Ceramic Monthly issue of May 2000 called ' A Lifelong Relationship'

experiment[37], South India proved to be an ideal place to work out large-scale construction involving bricks, as they are plentiful and labour is cheap. The challenge though would be the heavy annual rainfall.

By the seventh test structure Meeker had successfully fired a large house, a five meter diameter dome surrounded by four vaults, the surface area totalling 65 square meters. “The goal was to develop a cost-effective, energy-efficient solution to the problem of housing for low income groups using as far as possible the materials closest to hand: brick clay and a local fuel source”, Meeker spelt out his quest thus[38]. Hereafter he continued to further refine the technique and increase its efficiency. The last two case studies were projects where Ray Meeker had restricted his role to being a ‘firing consultant’ while he left the designing to an architect. The last project was completed in 2000.

Summary of persons and chronology of events that led to the further development of firing large mud structures:

Chronology of Events that led to the further development of firing large mud structures				
Period	**Person**	**Nationality**	**Living in**	**Role in Fired Mud Houses**
1976-1981	Nader Khalili	Iranian	California	vsionary and author of 'Racing Alone'
1982-1983	Afsaneh	Iranian	Auroville	brought unpublished manuscript of 'Racing Alone' to Auroville from Iran
1983	Patrick Adamson	English	Auroville	Potter and then boyfriend of Afsaneh had recieved manuscript and with partner Vohra initiated test structure
1983	Angad Vohra	Indian	Auroville	partner of Adamson and student of Meeker initaited test structure with Adamson
1985	Ray Meeker	Californian	Pondicherry	Potter with architecture background took up the challenge, visited Khalili though didn’t find it useful
1985	Jan de Rooden	Dutch	Amsterdam	Invited by Meeker to Pondicherry to collaborate on test structures, after visiting Egypt to gather mud building experience

[37] Jim Danisch built a small 2.1 m x 2.1 m x 2.4 m structure at the Ojai Foundation site in California, after a workshop with Khalili. This structure is mentioned in Khalili’s book “Ceramic Houses” as the first fired structure produced in the US.

[38] MEEKER, Ray. *Fired Building: The Layman's Response to an Unconventional Technology*, 2 February 1992, Unpublished essay.

2.5 Ray Meeker's assessment of Khalili's idea and his own preoccupation with the technique

Meeker summarized his analysis and impressions of Khalili`s work in an article he wrote in an essay titled "Geltaftan: A Second Thought"[39] as such:

> *"The discussion that follows should not be read as negativity or pointing to failure, but rather as the beginning of real discourse with a focus on what in my experience are the difficulties standing in the way of a viable fired building technology.*
>
> *<u>Assumptions Challenged</u>*
>
> *There are four basic assumptions upon which the "Geltaftan" technique is based.*
>
> *1. That mud or rather clay is an abundant resource.*
>
> *2. That anyone can learn to build and fire his/her own house.*
>
> *3. That it is cheap (no cost?).*
>
> *4. That it is ecologically appropriate because scarce building resources are efficiently used.*
>
> *It is perhaps possible to say yes to numbers 1, 2, and 3, and perhaps, though at the moment testing shows this to be doubtful, even to number 4. Nevertheless it is necessary to examine carefully each of these assumptions to determine to what degree they are accurate and how important each assumption is to the viability of the Geltaftan process in the context of truly "low cost housing".*

This text reveals his own attitude to the technology after due reflection. It indicates that in spite of the appeal that Khalili's idea had held, Meeker himself had adopted an attitude towards his experiments that were less dreamy, more grounded in realities and his approach was rather critical right from the beginning. Rather than

[39] An unpublished essay with date unknown

glossing over any of the areas that were not worked out or practically and comparatively more efficient than other prevailing practices, Meeker kept raising doubts and questions as they arose in his mind, publicly as can be noted in each and every article that he wrote over the years that followed, always making comments about his own reservations and pointing out the areas yet unclear, rather than writing about this technique in a glorifying way.

One can see in these writings, that apart from wanting to be able to successfully build and stabilize clay structures with fire, his preoccupation with also determining if and to what extent this technique could serve as a viable solution for a high quality but low-cost house while also creating a low environmental impact. In this search, he was interested in actually verifying the details rather than be satisfied if the technique only proved to be advantageous in theoretical ideal circumstances.

Over the later years, upon having already established that structurally stable buildings could be achieved, Meeker focused more and more on achieving cost efficiency and fuel efficiency. The environmental impact was of utmost importance to Meeker, and at one point, before he began successfully using coal dust as a fuel (Case study 18, Nrityagram Temple, 1998) he was rather sceptic about doing further fired buildings and had declared that he was most probably not going to do anymore of them[40] given the amount of firewood that would get consumed on the site. When asked why he wasn't satisfied with the fuel efficiency figures, when in fact his experiments were already able to eliminate cement and steel particularly in roofs, and deliver a strong mud house without consuming more energy than the regular brick houses, he was very firm in replying that that wasn't enough reason to justify fired building as a viable technique, and that for him it would only make sense if it would provide a much bigger environmental advantage. Fuel efficiency therefore became his chief preoccupation in the years to come and the success of his last three experiments involving a coal dust-

[40] 'In Attitude, Imagination & Innovation', he wrote: "I spent 13 years firing houses. I have stopped fro several reasons, but in the main because I viewed the process as an experiment in the pursuit of an eco-friendly technology, and in fact it proved to be too energy intensive for sustainable development. But living in the thrall of the process- on technical as well as aesthetic levels- I continued to fire houses long after I realized that it was not going to work as I had hoped." This was before he succeeded to reduce consumption with using coal dust.

infused brick clay mixture renewed his interest in exploring further a work that he had thought had reached a dead end.

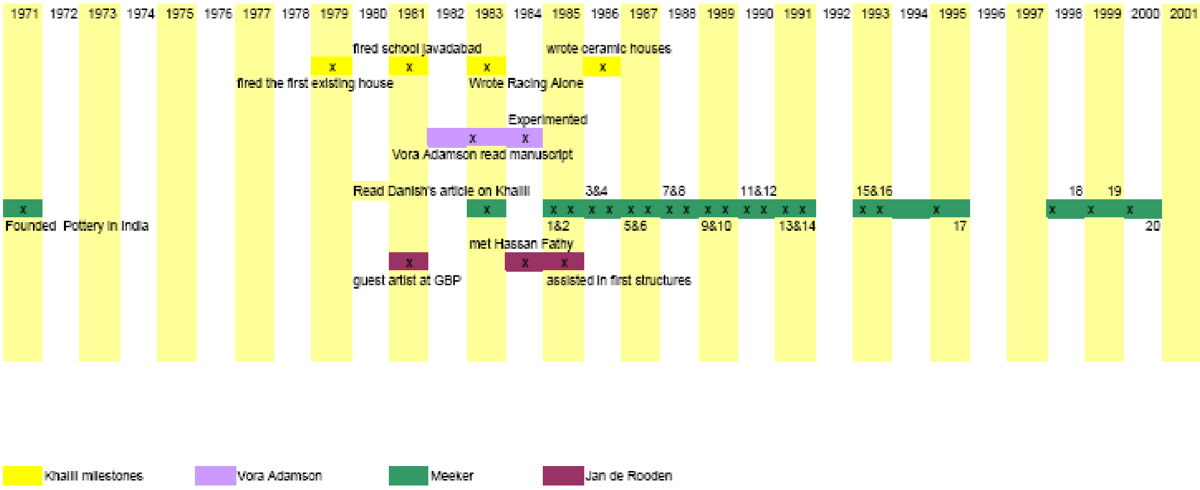

Table 1: Milestones in the history of the evolution of fired mud structures

2.5 Nader Khalili's acknowledgement of Ray Meeker

In his book 'Ceramic House'[41], Khalili mentions in the 'Chronology' section that in 1983, two of his workshop participants built what he called 'prototype geltaftan system structures' in India and Mexico. It can be assumed that he was referring to Meeker although Meeker actually built the prototype in 1985.

In 'acknowledgements' Nader Khalili mentions that he would like to show his gratitude for 'the spirit of the friendship and support shown for his work and words to Ray Meeker and his wife, Deborah Smith and James Danisch among others'.

Khalili was clearly aware that Meeker had been exploring fired building further.

[41] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (see page xii)

3. Vision and experiments of Nader Khalili

> *"I had already decided to try a fired structure and so I wrote to Nader, who sent me a schedule for his three day workshops. When I had met him in California, and even later, Khalili hadn't fired anything in the U.S. He had also never stacked products in the structure even in Iran. His book 'Racing Alone' didn't contain anything technical anyhow. Mostly he is just revving up his motorbike and driving into the sunset…I went to that workshop to see what I could learn about it. But we made little bricks and tiny kilns. I am afraid I didn't learn very much at the workshop…"*
>
> Ray Meeker[42]

3.1 Brief biography of Nader Khalili

Nader Khalili is an architect of Iranian origin, and the one who originally envisioned the idea of firing mud houses after they were built. In his own book and writings he refers to this technique as 'Geltaftan', a Persian word for baked clay.

Khalili studied philosophy and architecture in Iran, Turkey and the US and since 1970 is a licensed architect in the State of California. Since 1975 he has been involved in Earth Architecture and Third World Development. He is a UN Consultant for Earth Architecture and his project "Housing for the Homeless: Research and Education" of 1987 received a special recognition from the UN International Year of Shelter for the Homeless and US Department of Housing and Urban Development (HUD). Since 1982, Khalili directs the Architectural Research Program at the SCI-Arc, California, and is the director and founder of the Geltaftan Foundation and California Institute of Earth Art since 1986[43].

[42] In his interview with the author on 22nd August 2005

[43] From Khalili's current website http:www.calearth.org/Khalili.htm

3.2 Milestones in pioneering the ‘geltaftan’ technology

From 1979 to 1980, Khalili and his team undertook the rehabilitation of 12 houses in the village of Ghaleh Mofid in Iran, in which existing mud structures were fired in situ for stabilizing them. 9 of these are done by villagers themselves following the first three examples and lessons learnt. One of these was fired using native ceramic glaze.

From 1980 to 1981, Khalili was engaged in the construction of a new school in Javadabad village, near Varamin, in Iran. Here he managed to produce a new mud structure and fire it in place, and managed that 95% of the total budget was spent on local material and labour.

In 1982, Khalili began teaching earth and ceramic architecture and Third World Development at Southern California Institute of Architecture.

By 1983, he had published his vision and ideas on ‘Geltaftan’ or Firing of Mud Structures in a book he authored called ‘Racing Alone’ published by Harper and Row. Khalili continued his interest in promoting this technique by offering workshops in which people like Ray Meeker, and a Mexican (name unknown) had participated, and who had gone back and built prototype fired structures in India and Mexico. In the US Jim Danisch had also built a small prototype vault at the Ojai Foundation site in California. In 1986, Khalili had authored a second book ‘Ceramic Houses: How to build your own’, published by Harper and Row, San Francisco.

3.3 Vision of Nader Khalili

> *"My dreams were of a simple house, built with human hands out of the simple materials of this world:*
>
> *the elements: Earth, Water, Air and Fire.*
>
> *To build a house out of earth, then fire and bake it in place fuse it like a giant hollow rock.*

The house becoming a kiln, or the kiln becoming a home.

Then to glaze this house with fire to the beauty of a ceramic glazed vessel."

Nader Khalili[44]

The origin of the idea of using fire to stabilize earth buildings insitu

After his education in America, Nader Khalili had returned to his homeland, Iran, in 1978, with a dream of building resistance into village houses to survive the earthquakes, which are very frequent in Iran affecting mostly the poor. In quest of his dream when he travelled across the deserts of Iran, where he came across brick kilns which led him to develop the idea of ceramic houses which he called 'Geltaftan'. Khalili had noticed that the old village potter's kilns in the local area seemed to be in good condition structurally, as the process of firing pottery in them had hardened the inner walls and led to the kiln structure that was made in *adobe* blocks to transform and become durable. Khalili had noted that many kilns all over the world in China, Japan, Korea, Nigeria and the West including Native American kiln and bread-ovens were built with clay and based on the same principle. The process of building a kiln, being very simple, Khalili began to see that it could become a house.

In 1979 Khalili and his team including Ali Agha, a kiln specialist, succeeded in firing an existing house in a settlement of twelve houses in the village of Galeh Mofid, in the outskirts of Tehran.. By 1980 all the twelve units were rehabilitated, of which 9 were done by the villagers themselves.

The term 'Geltaftan'

[44] KHALILI, Nader, Ceramic Houses and Earth Architecture: How to Build Your Own Cal-Earth Press, California 2000

Khalili coined this word 'geltaftan' a composite word from Persian, *gel* in common use meaning clay, and *taftan* meaning firing, baking and weaving[45]. 'Taftan' also being the name of a volcano in South East Iran, fitted perfectly with his idea of the molten earth turning into a rock.

Building using only the four elements and not 'building materials'

> *"Once fire is introduced to adobe and clay, it changes the characteristics of the earth mixture so radically that its most vulnerable point- disintegration in water- will change to its strongest point- permanent resistance to water. And that is the difference between a piece of sun-dried adobe (three elements) and a fired adobe (4 elements)."*
>
> Nader Khalili[46]

In his book 'Ceramic Houses' Khalili writes that it all started first as an inspiration and then became a dream, to create human shelter out of the four universal elements, with the hope that this may open new doors for the poor of the world to acquire safe and beautiful shelters with the only material available to them- earth, water, air and fire. He recalls the volcanoes and their effect on earth as another inspiration thus: "The vision inspired by volcanoes, and the message they have been giving us as they belch out molten earth and make cave spaces and sculpted forms: The use of the element of fire to bring into equilibrium the destruction created by the element of water as in earth structures."[47] And he writes about the inter-relations and inter-dependencies of the four elements: "Water, like the other universal elements

[45] KHALILI, Nader. *Iran: Geltaftan*. In MIMAR 8: Architecture in Development, Concept Media Ltd, Singapore: 1983.

[46] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 (Pg 149-150)

[47] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 (Pg 41)

earth, air, and fire, is both constructive and destructive. When in equilibrium with the other elements, water can create balance. The water that destroys strong structures of earth could also help to create landscapes integrated into the building, or help to cool interior spaces. The concept of 4 elements is simple, yet crucial. For example to a ceramic bowl, which includes three elements (earth, air and fire) water is a welcome addition. Each element enhances the other, none destroys each other. In a word what we may lack in our earth architecture may be the fourth element, fire. Fire can bring about equilibrium with the earth, water and air. And that thought led me to search for an answer."[48]

The pioneering aspect of this technology

"Even though firing of kilns- some as large as small houses- has been done in many parts of the world, firing and glazing of buildings for human habitation is a new dimension in earth architecture"

Nader Khalili[49]

His idea was that adobe blocks would be moulded using earth on the site and sun dried. The bricks would then be piled like a tower, and plastered with straw and mud. A storage tank would supply oil in the pit under the tower. Fire would be set and the bricks would be burned. This technique had been used in for thousands of years, but it was Nader Khalili's imagination which led him to the usage of the kiln structure as a house. Nader Khalili mentions the possibility of baking his clay form into a single piece of ceramic ware.

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[48] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 (Pg 21-22)

[49] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg x)

Once the fire would be brought to the building, instead of building materials taken to the fire, a completely new set of possibilities would be created. One such possibility would be that the building could become a producer of material instead of only a consumer. While firing a room the space could be used as a kiln to bake bricks, tiles, pottery, or even the household pots and dishes. Each time a house was fired the sale of the products could pay for the house.

While working on the first rehabilitation project, it occurred to Khalili that the house itself was becoming a kiln and that if this kiln could be filled with sun-dried blocks, tiles, water jars and flower pots, they could be baked along with the house. The products could be used for courtyards and walls, or sold.

Khalili's vision led to developments that were a breakthrough in the stabilization of earth structures. It took him five years to reach the first results as buildings. It is to be noted that the innovation is not in the area of construction of the building but in the area of stabilization of constructed earth structure.

Khalili's Motivation

The dream of making 'no-cost housing instead' of 'low-cost housing' with earth architecture could become a reality.[50] The economic justification of Khalili's work was a determining factor in the construction technique, but not the main philosophy driving his work. His main philosophy was to use local materials and indigenous techniques, and to provide jobs and self-sufficiency while creating beautiful architecture that respected the traditional forms and spirit.[51]

The Opportunity to Test 'Geltaftan'

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[50] KHALILI, Nader, Ceramic Houses and Earth Architecture: How to Build Your Own Cal-Earth Press, California 2000 Pg 21-26

[51] KHALILI, Nader, Ceramic Houses and Earth Architecture: How to Build Your Own Cal-Earth Press, California 2000 Pg 36-37

The great earthquake of 16 September 1978 in Iran, measuring 7.7 on the Richter scale, resulted in a death toll of around 26,000. The town of Tabas, 965 km from Tehran which was at the epicentre was worst affected and completely flattened while 40 villages within a 48 km radius suffered significant damages.

Among all that survived were domed clay and traditional brick buildings. In his article, Iran: Geltaftan[52], Khalili wrote that he had managed to hitch a ride on an official helicopter carrying a team to inspect the damage. He heard the chief official architect promising 'a modern prefab town' and that, 'that the government should not build any type of building that does not follow the seismic code'. Khalili reacted with great concern to these government strategies, "The myth of earthquake-proof structures created by the specialists and government advisors should be uncovered. Sixty-five thousand villages of Iran should wait for three thousand years if they are hoping to be rebuilt with these technocrats' recipes." His response was: "I agree with them, but only: if there are enough engineers to design them, if the engineers would be ready to leave the city comforts and go to supervise, if there are roads to these villages, if there are enough supplies of imported concrete and steel, if the steel and cement are not used as symbols of wealth, if these materials could withstand the scorching heat and the freezing cold and make life bearable, if they would be accepted by the villagers."

This post earthquake situation gave Khalili a chance to think of building with Gelaftan. The arrival of the great revolution and change in the ruling authorities also provided him the opportunity to experiment with his technology of stabilizing the remaining earth structures and saving the poor from being rendered homeless.

Nader Khalili with the help of Ali Agha, the kiln operator and a ceramist Nasser Agha implemented this technique first by rehabilitating an old village, Ghaleh Mofid. Khalili built clay models of houses schools etc for imaginary but ideal situations

[52] KHALILI, Nader. Mimar 8, Architecture in Development, Concept Media Ltd. Singapore: 1983

and fused them with fire. Clay forms with sawed flower pot windows and sculpted interior shelves and spaces resulted from the experiments[53].

3.4 Khalili Experiments

The major problem was "how to build a room and put it in a kiln, or build a house and then construct a kiln around it". Khalili started searching for firing systems and kilns around the world but found the answer right where he was. That there would be no kiln, it was simple. 10,000 or more sun-dried adobe blocks were piled up in a circular form like a tower and a fire was started in the tunnel under it. One centimeter of thick mud-straw plaster covering the outside perimeter worked as the kiln. The absence of vertical mortar in the adobe walls allowed the fire to penetrate to the outer plaster.[54]

3.4.1 Rehabilitation of Existing Housing in Ghaleh Mofid

His first experiment was set in a village called Ghaleh Mofid. 12 of 37 structures of an old housing were still standing, the others totally or partially ruined in the recent earthquake. This project was partially funded by the new government and a private organization and the rest of the cost was borne by the working team. Two of the houses were fired by Khalili's team and the rest by the villagers themselves. His clients, the twelve surviving families of the village had no money to offer but "enough time, prayers and moral support to get the Geltaftan team going high with a spirit".

Typically, a house of 30 sqm each was contained within a single vault roof with a low partition in the middle to divide the room into two. Electricity and plumbing facilities were absent in the houses and so there were no such lines to deal with. Khalili was assisted in this venture by Ali Aga (Kiln operator), two architectural students Mehmood and Ezzat, Seddhi (an engineer) and Ostad Ghodrat (mason).

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[53] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg 21-25)

[54] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg 21-25)

First, the doors and windows were removed and a temporary adobe partition was constructed and after the damage done to the structure was repaired by a local mason, a few vent holes and a fire pit were cut out, as was habitually done in kilns.

Fuel and firing

The fuel used was kerosene. The Firing technique and equipment consisted of the basic kerosene gravity-flow system used and tested by native potters and kiln operators. Two sawed pipes welded together with an air sandwich within built by a local blacksmith under Ali Aga served as a burner. The burner was fed kerosene oil from two barrels that were placed on the adjacent rooftop with enough head pressure to start a fire and gave a continuous fire so long as the barrels were full. The barrels were connected to the burner with pipes and a valve was used to control the flow of the oil and thus the fire and heat produced. There were no pumps, no electricity, and no complicated control system.

The first house was fired from underneath the structure, where a pit was dug, for twenty four hours. Fire started slowly, and for ten to fourteen hours, steam escaped from the structure through flues, even though the structure was quite old about 17 percent moisture still remained in the earth. This system was subsequently improved in the next experiments. Instead of digging tunnels under the structure and placing the burners in the tunnels, blow torches were placed outside the house near the openings and tilted at a 45 degree angle which throws the fire inside the hollow structure.

Results

After the firing was completed, the structure was cooled for two days before opening it. Khalili reports that the structure was cooked and that the ‘miracle had worked’ although there is no description or investigation about whether the walls and vaults actually cooked through its entire thickness[55]. There is also no mention of expansion of walls and the impact of this expansion on structural elements.[56]

Khalili notes that one of the unexpected and interesting advantages of this method was realized during the process of firing. Just about an hour after the fire began, insects and rodents that the house was infested with began to leave the structure. Khalili considered this method to therefore be also an environmentally friendly pest control mechanism, which normally would require polluting and unhealthy chemicals.

The "climax" of their work was to glaze a house from the inside in a second firing using native glaze agents as well as milled coke bottles. The glaze solution, a water-base mixture was applied using the farmer's insecticide sprayers operated by bicycle pumps. They even did a single-firing experiment although most experiments involved double firing.

Collaborators

For the rehabilitation project, 'Geltaftan Group' as they were called consisted of Khalili himself, Ali Aga, kiln operator and ceramist, Mahmood and Ezzat, two architectural students, Sedehi, as engineer. Others who also participated were Nasser Aga, who made huge bread ovens the size of small rooms, Ostad Ghodrat, mason, Nahid, his sister, a social worker, and other villagers.

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[55] In Meeker's experiments there have been several areas where the structure wasn't fired through and through and Meeker had been monitoring this meticulously. From the inside what may appear to be brick, may be sometimes even less than a third of the thickness as observed in Meeker's experiments. Also the extent of firing through of walls, the wall thicknesses that are much larger than vault and domes thicknesses, are an open question. Khalili does mention this in a general way, "After 2 days of cooling, the house was opened, and was found to be transformed into a solid brick shell inside to a less burnt adobe on the outside."

[56] In Meeker's early tests the end walls had separated by outward bending of the external walls due to uneven temperatures on the inside and outside.

Cost

52 USD of kerosene were used to fire each 30 sqm house, and this was paid by the government grant which also took care of the plastering costs. The firing equipment was developed and provided by Khalili’s team.

Fact File

Location: Ghaleh Mofid, a village in Iran
Client: The residents of an existing settlement that survived the earthquake
Year of Construction: 1978
Area: 12 houses of 30 sqm each
Form of roof: Single vaults
Fuel and firing: Kerosene
Products: none
Duration of Firing: 24 hours and a further second firing of 12 hours for glazing

3.4.2 School at Javadabad

Nader Khalili's second experiment was an elementary school in the village of Javadabad, a project of the development department of the provincial government of Tehran.

The school building with an area of 500 sqm was a ten class room structure with courtyards, administration area and a domed arcade. The toilets were in the courtyards as per the tradition. One classroom was fired as a test sample and the rest were fired later. The design was developed with the mason’s help as he was the one with the most experience in earth building. The plan of the 10 classroom school was like a T with long arms containing classrooms while the stem being the administration with courtyards on either side. A continuous domed open arcade connected all the classrooms and administration. Vaults covered the classrooms while the principal area was also domed.

A single mason made all the mud vaults for the classroom without any instruments or help. Construction time was approximately four months, and the firing of the entire school took ten days.

Although the site earth was found to be appropriate, even better earth-clay was sourced from outside the village from abandoned sites of local bricks. 60,000 adobe blocks were made with a single mould. Nothing had to be mixed into the clay and the transportation was minimal. All the 60,000 bricks were hand made by the mason himself with only one mould.

Costs

Ostad Asghar, the mason, volunteered to build at a third the cost he was charging to build conventional buildings. Khalili retained the general contracting responsibilities and the firing. There were cost overruns of 25% however, that Khalili concludes was on the account of relocation after foundations were executed, political events, as well as the mason’s own underestimation of adobe buildings that he hadn’t built in a while. The client didn’t raise the budget however. In spite of these cost overruns, the final project cost a third of the conventional buildings. Khalili analyses that this is due to the project involving a single trade, only masons as opposed to also carpenters, steel and concrete workers, and also due to having used only local material and labour, (This project was finished in a year while a nearby school had to wait 4 years for the imported material that the project was planned with). Khalili’s team worked for free but with the condition of total acceptance of the project by the client. After a year of occupation and correction of faults there was some cash left to deposit into the Geltaftan foundation.

Fuel and Firing

As in the previous experiment, oil was pumped to the roof by a hand pump in this case. Khalili describes this as an appropriate technology that prevented wastage and danger.

Experiments were made for various conduits to be kept for utilities, from wiring in the joints to placing wood strips that burnt in the firing to leave channels. Each room and few products inside used 54 USD of fuel, half of which was needed to transport bricks to the site. Cost of imported fired brick and imported cement would be even more.

After one classroom was tested, several rooms were fired simultaneously. It took 4 months to build and10 days to fire over many weeks as the oil was rationed. It could have been fired in 24 to 48 hours with more experience and facilities. Traditional mud straw plaster covered the roof which helped bake it to a certain extent.

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Ali Agha, the kiln operator who had assisted in the pilot project of rehabilitation of 12 houses in Ghaleh Mofid fired the first class room, but the construction team had to do the rest, as due to the danger due to the war Ali Agha couldn't continue. Thus the team gained experience in firing. In spite of the blackout order issued due to the ongoing war, the project was executed and the fire was kept going.

Khalili notes in his book 'Ceramic Houses', that while more experience was available after this second experiment, and the first building that was built to be fired, that the result was still not ideal. Unfortunately, he does not quite specify what was not exactly ideal and analyze the results of the firing.

Products

The kiln was used to fire "a small amount of"[57] adobe bricks and sculptures inside.

Finishing

Gypsum plaster was used in the interior with a few exposed areas.

[57] In his second book Ceramic Houses, Khalili makes only this vague mention on having had some products in the structure. Meeker and Danisch insist that Khalili fired his structures empty. In his first book he does not mention any products contained in his structures either.

Fact File

Location: Javadabad, Iran

Year of Construction: 1980-81

Area: 500 sqm

Products: A small amount of adobe bricks and a few sculptures

Costs: In spite of 25% cost overruns, it cost a third of the cost of a conventional building, due to the involvement of a single trade and material.

3.5 Lessons learnt

One of the main experiences was that the manufacture of mud bricks would have to be scheduled to fit the season, and this would need a much greater pre-planning. Regarding the firing process it was learnt that cracks that may develop due to expansion and contraction and would need to be repaired Small ones can be repaired and lived with while structural ones will need reinforcing. The other experience was that fired surfaces are to always be sprayed with water before plastering or glazing to avoid that the gravel sized lime pieces in the clay mixture absorbs water later and blisters.

It was concluded that many more experiments in building and firing were to be done to standardize construction, firing details and specifications; and many more tests needed to be conducted before the technique would be perfected.

4. Adamson and Vohra's Attempt

"Patrick who was then working with Angad, had received a manuscript of Khalili's yet unpublished book and got interested and actually built a mud structure intending to fire it. I talked with Patrick and Angad about it. I actually had thought it was an extremely absurd idea…."

Ray Meeker[58]

4.1 Background Patrick Adamson

Patrick Adamson is an English potter, who lived for several years in Auroville, and now lives in London. While in Auroville, he had heard through his Iranian girlfriend about Khalili's experiments in baking mud houses and was urged to try one such structure out. He was at that time living and working in Kottakarai with an Indian potter Angad Vohra. Together they began the first experiment in Auroville.

4.2 Background Angad Vohra

Angad Vohra, has been a potter since 1976. In 1994, he started Mantra Pottery in Auroville, India, where he produces high fired stoneware using a wood fired natural draft kiln. The pots are made on kick wheels and the clay is prepared by hand. Everything is done by hand and they use as few tools as possible. Vohra explains that as in India there are no ceramic supply shops, they have had to search for all their materials and to build all their equipment themselves, from wheels to banding wheels, kilns, moulds and finally now a ball mill, their first real machine. The kilns are fired with locally grown firewood. Fortunately good quality refractories are now available in India and they can have fairly efficient kilns. The pottery is dedicated to making high quality pots and tiles while generating employment and providing good working conditions. The dozen or so employees come from the nearby villages.

[58] From an interview with the author on 22nd August 2005

Vohra learnt pottery by apprenticing for over 3 years at Golden Bridge Pottery, in Pondicherry, founded and run by Ray and Deborah Meeker. Vohra acknowledges that as a mark of their success, there are at least 7 units producing glazed ware and a couple more focussing on terracotta and more than 12 kilns functioning in the Pondicherry and Auroville area today. “It was strange to learn a craft from Americans who were very inspired by the Japanese way. I am Indian and I have had to search within my roots for an expression that I feel comfortable with” reflects Angad Vohra.

Vohra says that he has been greatly inspired by the fine examples of terracotta ware excavated from the Megalithic Burials that were found in the Auroville area.

4.3 The experiment in Kottakarai, Auroville

Fig. 4.1 Adamson and Vora’s first attempt, Auroville, 1984, Source: Angad Vohra

Sometime in 1982-83 Patrick Adamson, the English potter working in Auroville, had heard about Khalili’s idea through the yet unpublished manuscript of Khalili’s book, ‘Racing Alone’ that he got to see via his girlfriend of Iranian origin but from Germany, Afsaneh, who had moved to India and was living in Auroville. Patrick Adamson together with Angad Vohra, an Indian potter, former student and apprentice of Meeker, got interested in the idea of firing earth structures themselves and decided to actually make a prototype in the area next to the village of Kottakarai where they then lived and worked together.

Without having solved all aspects of firing a house, they had simply begun enthusiastically intending to solve the problems that came up as they went along. The structure was planned to be adjacent to their community kitchen[59] and to be used as a toilet in that connection. If the test would prove to be successful, Angad Vohra would build his own house in the same technique.

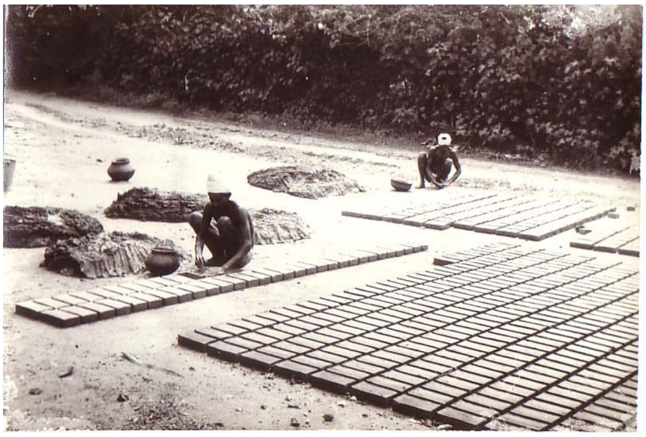


Fig. 4.2 Brick making, Kottakarai, Auroville, 1984, Source: Angad Vohra

Fig. 4.3 Angad Vohra, closing the two approaching ends of the Nubian Vault, 1984, Source: Angad Vohra


Fig. 4.4 Tunnels left for loading fuel in preparation of stacking of product bricks in the kiln, 1984

Fig. 4.5 Angad Vohra, practicing the Nubian vault on the ground supported on the store room wall, 1984

Source: Angad Vohra

Vohra and Adamson went on to build a little vault structure next to the then community kitchen hoping to later use it as common toilets for the community. They managed to build the structure with mud bricks produced on site and even managed to

[59] This kitchen has now transformed into 'Decauram', a handicraft unit in Auroville. The foundations of the structure should still exist.

build a Nubian vault. Clay was sourced from the Irumbai temple tank which is very close to the site. The clay was not great but good enough they felt for doing bricks. Later, however they did procure clay from further away. They made 2 catenary vaults. The structure used to get wrapped up regularly with tarpaulin and plastic.

Vohra admits that they had no idea about the firing, and that they had not yet even given the firing process a thought[60]. But unlike Khalili's experiments, they had thought of filling the space with product bricks. "Khalili had fired his structures empty. In Iran not only did they have enough oil, but also in the desert climate it didn't quite matter if it got fired properly or not." said Vohra.

Unfortunately the structure never got down to being fired, as around the time the structure was ready Vohra's mother passed away and he had to leave suddenly. And during this time, although the structure was meticulously wrapped with waterproof material - plastic sheets and tarpaulin - for protection from rain, the structure fell apart in rain damage. The tarpaulin was stolen, water came up in capillary action, and the monsoon rain consumed the structure. Upon his return, Vohra got busy with the consequences of his mother's death and as the pottery was still not so financially stable; they didn't have the energy to build it up again. The project was sadly abandoned.

Fact file:

Location: Kottakarai, Auroville, Tamil Nadu, India
Condition: Does not exist anymore
Client: None
Year of Construction: 1984
Dimensions: unknown
Area: unknown
Form of roof: Two simple catenary vaults
Fuel and firing: There was no thought given to the whole firing aspect as yet.

[60] From Angad Vohra's interview 25. August, 2005

Products: They made bricks as products that they were intending to fire inside the structure.

Special steps taken towards the technology: Learning the building of a Nubian vault in adobe blocks made on site. They made larger square bricks for the vaults, for the larger the area of the brick, the better the adhesion. They also made rectangular smaller standard bricks for wall construction.

Important results: The enthusiasm of young potters who felt that they could easily build houses of adobe and stabilize them, had its role in grounding the idea of Khalili in South India, and in spite of the collapse due to rain damage even before firing, the experiment did generate interest and through discussions probably influenced Ray Meeker to take up from where they left, although he had originally dismissed the idea as absurd and not at all appealing. Later though upon reading an article by Jim Danisch[61] he became genuinely interested.

[61] DANISCH, Jim, *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, November 1983

5. Ray Meeker's Experiments

"On the threshold of the 21st century, architects and engineers and contractors must not fail to respond to this emerging trend with bold new experiments in form and material, drawing on traditional as well as advanced technology. It is a wonderful opportunity to set new directions which will supplement and diversify the form of the built environment."

Ray Meeker[62]

5.1 Golden Bridge Pottery Vault 1, Pondicherry

Fig. 5.1 GBP Vault 1, firing stage, 1985, Source: Ray Meeker

Fig. 5.2 GBP Vault 1, finished structure, 1985, Source: Ray Meeker

This structure was begun when Jan De Rooden, a Dutch Ceramic artist, in response to Meeker's invitation managed to acquire a travel grant to participate in the project. Ray Meeker had known that in order to undertake this experiment, a sound knowledge of building in mud as the only building material, was of crucial importance. So Meeker had urged him to also try to go to Egypt and meet Hassan Fathy[63], visit earth

[62] MEEKER, Ray, *Fired Building: The Layman's Response to an Unconventional Technology*, 2 February 1992, unpublished essay

[63] Hassan Fathy (1900-1989), an Egyptian architect was the first to revive the use of mud brick and ancient vaulting techniques and to adapt them to present-day building requirements, and to show how

buildings and inform himself of the Nubian Vault technique[64] and other methods of simplifying and economizing the building mud structures, which he did.

Although there had been a few experiments undertaken in Earth Construction in Auroville, Meeker's structure was the first one needing to be built entirely in earth, including roofs. This meant limiting the roofs to compression structures such as vaults and domes. There was no experience of building vaults and domes in adobe in the area as yet. This meant that there was no skilled labour available for this work and the skill would have to be acquired during the job. It was therefore important that Jan de Rooden come prepared and informed.

The aim of this structure was to find out if a mud structure could be fired. And the construction of the mud structure itself therefore was kept as simple as possible. No drawings were produced for this simple structure as they were found to be unnecessary.

5.1.1 The raw mud structure

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suitable they still are in response to climate, local materials and existing building skills. His book 'Architecture for the Poor' describes in detail the way he introduced the Nubian vault technique for construction of the village of New Gourna in the 1940s. Although he had already started building with mud bricks, as the war began, steel and timber supplies were cut off, and it occurred to him that if he had mud bricks and nothing else, he was no worse off than his forefathers.

[64] Typically the building of a vault would need a strong wooden centering, running through the entire length and supported on wooden props, which has to be removed when the vault is made. Fathy had known that in ancient times in Egypt vaults were constructed without centering and after several failures, he discovered that in Nubia this ancient technique had survived. In Nubia, he discovered a village whose architecture had been preserved for centuries uncontaminated by foreign influences. Later he found masons from Aswan who still knew how it was done.

A Nubian vault rests on side walls but during construction is supported on an end wall that is somewhat higher, against which the vault leans while being built. Masons roughly outline a catenary arch with handfuls of mud. Then the first brick course stands on its end on the side wall. The second course is laid after a wedge shaped packing that allows the next course to lean slightly towards the end wall instead of standing up straight. The third course inclines even more acutely, and so on till the two curved lines of brick meet at the top. The inclination holds the bricks in place, till the vault is completely spanned.

This is the simplest and cheapest way of building vaults with mud bricks as it avoids the use of centering, and is not affected adversely by the 37% shrinkage that occurs when the mud mortar dries.

The resulting structure was a very small 2m span and 3 m long building (Fig 5.1 and Fig 5.2) primarily based on the Nubian Vault method of building (Fig 5.3 and 5.4). This meant that the structure had to have end walls along which the catenary vault could lean and the vault brick courses could support themselves by leaning and only with the help of the mortar used for adhesion of brick layers. The end walls are therefore the typical buttressed gable walls[65] that one sees with Nubian vaults. The Nubian Vault had the additional advantage that unlike other vaults that may need shuttering, vaults built in uncooked and un-stabilised mud bricks continue to shrink and lead to the sinking of their shape. The walls were 45 cm thick and 1.65 meters high, and the Nubian vault rose to another 1.35 meters over the wall height.

Fig. 5.1 Nubian Vault leaning on end walls, 1985, Source: Ray Meeker

Fig. 5.2 Nubian Vault, first leaning courses, 1985, Source: Ray Meeker

5.1.2 Products

Unlike Khalili who had always fired his structures empty, right from the beginning Meeker was determined that this technology only made sense if the house would first be a kiln and that the space would be stacked with products which when fired, would lead to the firing of the house as consequence. This was the only way that the fuel could be a justified consumption, as energy efficiency was always a concern for Meeker. For this structure 4500 bricks were produced as the principal product and

[65] In Nubian Vaults the gable walls are needed for the brick courses of the vault to lean during construction and so the end walls are typically raised higher than the height of the vault and buttressed to support the leaning load, even though after construction the buttresses are only needed in the side walls where the vault would exert a thrust.

another 1000 small tiles were produced and stacked in the structure to be laid over the vault after its firing as a waterproofing and finishing layer.

5.1.3 Preparation for firing, and the firing

The structure was stacked with products and the doors were closed with loose bricks. The kiln was planned as an up-draught kiln[66]. Then a ten cm insulation layer, a mixture of clay sand and ash was applied all over the structure. Using fire wood as fuel a temperature of 960° C was reached. The firing continued for 40 hours.

5.1.4 Important firing results

Product

The bricks stacked within turned out to be of remarkable fired quality, far superior to most bricks made in the area.

Firing of the Structure

The inside of the vault was well cooked but was not sufficiently stable on the exterior. The 45 cm thick walls, though well burnt on the inside remained absolutely untouched on the exterior. About two-third the length of the wall was fired, with the top parts being fired but the bottom not, and the inside fired but the outside not at all. The roof cooked about two-thirds through.

Meeker felt that there was no way a 45 cm external wall was going to get fired all the way through unless it was a fired from both sides. So in subsequent structures, some fired brick would have to be used on the outside while still using mud mortar.

Occurrences those were significant in developing the technology as a whole

End wall separation

[66] See Section 9.4 on 'Types of kilns'

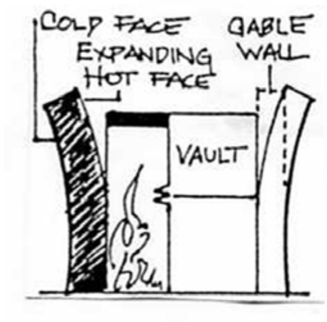

Fig. 5.5 End wall separation after firing, 1985, Source: Ray Meeker's own sketch

The end walls of the structure, which were used for leaning the Nubian vault during construction separated form the vault on firing. This was the most notable result. Interestingly, this separation did not in any visible way affect the vault. (Fig. 5.5) This separation occurred because as the interior of the structure reaches temperature of 850 to 1000°C, the inner surface of the walls undergo significant expansion, while the outside of the end wall remains cool and doesn't. These walls start bending outwards leaning out of plumb and separating altogether from the vault. Upon cooling, though the gable walls move back they do not quite move back to their original plumb position. In itself this is not a major problem structurally, as the vault after construction rests on the side walls and not the end walls which only serve as support to lean the mud brick courses on the vault structure while it is being built. The gap that remains, reduced after cooling down of the structure, can be filled when plastering.

Uneven expansion of inner and outer surfaces of the side walls

Just as in the end walls, the side walls too are exposed to uneven temperatures on the inside and outside as they receive heat only from the inside. This phenomenon results in the inner surface expanding more than the outer surface during firing and therefore the leaning outward of structural walls. However, unlike in the end walls which lean out so much that they separate altogether from the vault, the side walls are seen to lean out to a far lesser extent. This is due to the fact that the walls are prevented from outward movement by the weight of the vault that sits on these walls. After cooling, these walls almost return to their original position. In the case of the side walls this expansion phenomenon is not worrying as there is no separation of the walls and roof.

Rain Damage due to insufficient firing

Fig. 5.6, GBP Vault1, after rain damage, 1985, Source: Ray Meeker

After the firing, some finishing tiles were laid and the structure was left to face the rain. The wall failed from the top as well as from the bottom. As the walls were insufficiently fired towards the exterior, the top of the wall that was exposed, where no vault rested, was mostly unfired mud brick and vulnerable. From the bottom the wall soaked water due to capillary action. It was very valuable to have gained the experience of the actual process of rain damage. It was interesting to observe that the under-fired structure didn't collapse, the unfired portion just fell off and split away. (Fig. 5.6)

5.1.5 Finishing

In spite of the structure being inadequately fired, the structure was plastered and painted on the outside and the product tiles fired inside were used to finish the vault on the outside as a final layer. The structure was to be then observed in its reaction to the rainfall in the area.

5.1.6 Fact file

Location: Golden Bridge Pottery, Pondicherry

Condition: Does not exist anymore as was taken down after partial success and partial failure of the test.

Client: None

Year of Construction: 1985

Dimensions: 3meters x 2 meters

Carpet Area: 6 sqm

Form of roof: catenary vault of 2meter span with a rise of 1.35 meters

Type of walls: 1.65meters high, 45 cm thick mud walls

Fuel: Casuarina fire wood

Products: 4500 bricks and 1000 small tiles

Insulation: A mixture of clay, ash and sand in a 10cm layer

Temperature reached: 960°C

Duration of Firing: 40 hours

Kiln description: Up-draught kiln

Special steps taken towards the technology: Learning to build a Nubian vault without centering and testing the behaviour of a large mud structure in firing, when fired from the inside alone.

5.1.7 Conclusion

In spite of the problems that arose, there was enough success in this experiment to show that the prospect of being able to fire a house was promising. This encouraged Meeker to go on with a second experiment. It was also clear that there was no way that a 45 cm thick external wall could get fired when the heat was coming from only the inside of the structure as the wall was simply too thick. The end wall separation was a phenomenon that had to be addressed.

5.2 Golden Bridge Pottery Vault 2

Fig. 5.7 GBP Vault 2, 1985, Source: Ray Meeker

In the same year in 1985, after having had the experience of Vault 1, Meeker proceeded to undertake a further experiment in his own pottery site. Jan de Rooden was there too, but only at the initial stages of the structure. The aim was to try and build an even bigger structure than the one before and to try to improve on the firing result.

5.2.1 The raw mud structure

A single vaulted room was built with the experience of the previous structure but this time much bigger than necessary with a 3 meter span and a 4m interior height, with the idea of being able to add a loft after firing (Fig. 5.7). In one of the side walls, 3 openings were introduced as arches to see the future potential for interconnecting vaults in a series through open passages.

Composite exterior walls

Meeker had been convinced from the previous experiment that such a thick external wall of 45 cms had no chance of being fired through if it gained heat from only one side, the inside. Although a number of methods for stabilizing mud walls externally through appropriate plasters do exist, Meeker opted for a composite brick wall in this test, introducing fired bricks on the exterior surface and using mud bricks on the inside surface (Fig 5.8). This did raise the cost of the structure to some extent but Meeker felt that this raise in the cost was justified by the increased life span and reduced maintenance that the structure would have thereby required.

Fig. 5.8 Composite wall with fired bricks externally and sun-dried bricks internally, 1985, Source: Ray Meeker

Deviating from the catenary shape

Jan de Rooden had visited Golden Bridge pottery again to see the progress on the fired houses, and had been present during the initial stage of this second structure. De Rooden had proposed a deviation from the typical catenary shape, in order to have something more beautiful. Although Meeker himself didn’t have a problem with the shape being catenary he had given in to accommodate De Rooden’s idea and a vault was built in a shape that was outside the catenary curve.

As the structure was really close to the railway line, Meeker recalled, “each time a train passed, we had about a Richter 3”. The structure faced with the vibrations, began to develop a crack horizontally through the length of the vault structure. Meeker contacted Dr. Chamanlal Gupta[67], solar scientist who lives in Pondicherry to get someone to look at this structure and advice. That day, Dr Gupta was with a foundry engineer at his house who happened to be visiting him. So they went over to the Golden Bridge pottery site and examined the structure, and the engineer looked at the crack and thought that nothing really would happen. But as it still developed, Meeker decided to

[67] Dr. Chamanlal Gupta, is a nationally known expert on renewable energy, who lives in Pondicherry.

take it down, and just before that he went in to photograph it. But even while he was photographing, the vault collapsed right above him. The mason who was standing just beside him, pulled him out in time, but the camera, and of course the pictures, were lost.

This vault then got rebuilt in a perfect catenary shape this time, planned to be in total compression.

5.2.2 Products

For this structure there was a lot more space available and 18,000 bricks were produced to be fired inside.

5.2.3 Preparation for firing, and the firing

The structure was stacked with products and the doors were closed with loose bricks. The kiln was planned as an up-draught kiln[68]. As in the Vault Structure 1, a 10 cm thick insulation layer, a mixture of clay sand and ash was applied all over the structure. Using fire wood as fuel a temperature of 960° C was reached. The firing continued for 48 hours, a little longer than the previous structure.

5.2.4 Finishing

In spite of the structure being inadequately fired, the structure was plastered and painted on the outside and the product tiles fired inside were used to finish the vault on the outside as a final layer. The structure was to be then observed in its reaction to the rainfall in the area.

5.2.5 Important firing results

Product

[68] See Section 9.4 on Kiln Types

Just as in Structure 1, the bricks stacked within were of remarkable fired quality superior to most bricks made in the area.

Firing of the Structure

The vault was not sufficiently stable on the exterior. The exterior of the vault had improved in terms of fired quality, as compared to test structure 1, but still showed large areas of unstable brick.

The walls, though well burnt on the inside, again remained absolutely untouched by fire on the exterior just as in the previous structure. But this time as composite walls were introduced, the external face of the masonry contained fired bricks; and despite the additional cost incurred there, the structural wall would be durable.

The gable walls predictably responded exactly in the same manner as they had in Structure 1. The gable walls, a typical component of Nubian vaults seemed to be quite bothersome as they meant a lot of extra mass for nothing. It was felt that they should be subsequently eliminated altogether.

The large arched openings showed what seemed to be minor cracks but subsequently, with a very heavy monsoon, they proved to be disastrous.

Occurrences those were significant in developing the technology as a whole

The importance of maintaining the catenary curve

A deviation of the catenary shape was attempted in vault construction and after the dangerous crack that was appearing in the structure along the entire vault length, the vault finally collapsed even before it was taken down as planned. Hereafter the lesson was learnt that the catenary shape must be strictly followed for vault construction.

The success of the composite wall for external wall construction

The walls were built using fired brick on the external face of the brick masonry using raw mud bricks on the inside.

End wall separation

As already experienced in Structure 1 exactly the same behaviour occurred as predicted and the gable wall leaned out of plumb during firing and separated from the vault altogether; and upon cooling, although it moved back to some extent, didn't return all the way to the original position.

This led to a valuable conclusion that the end wall has to be reconsidered in the subsequent structure and another way of supporting the vault during construction had to be attempted in order to consider the removal of the end wall altogether.

Uneven expansion of inner and outer surfaces of the side walls

Just as in the previous test, the side walls too, are exposed to uneven temperatures on the inside and outside and results in the inner surface expanding more than the outer surface during firing and therefore the leaning outward of structural walls and after cooling, almost return to their original position.

As observed in the previous test this is not worrying as there is no separation of the walls and roof.

5.2.5 Fact file

Aim: to find out if a larger house, both in terms of height and in terms of carpet area, could be fired.

Location: Golden Bridge Pottery, Pondicherry

Condition: Does not exist anymore as was taken down after partial success and partial failure of the test.

Client: None

Year of Construction: 1985

Dimensions: 5meters x 3 meters

Carpet Area: 15 sqm

Form of roof: single vault of 3 meter span with a rise of 2 meters

Type of walls: 2 meters high, 45 cm thick mud walls

Fuel: Firewood

Products: 18,000 bricks

Insulation: A mixture of clay, ash and sand in a 10cm layer

Temperature reached: 960°C

Duration of Firing: 48 hours

Kiln description: Up-draught kiln

Special steps taken towards the technology: Building a bigger structure and learning the importance of the catenary shape in a vault construction. A composite wall of external fired bricks and internal mud bricks was introduced, to give the structure a longer life, through protection against water externally in areas that were too thick to be fired through.

5.2.6 Conclusion

Three lessons were learnt in this experiment. First, that it was important not to deviate from the catenary shape. The second, was the composite wall consisting of fired bricks to the outside and mud bricks to the inside as a solution to the fact that external walls that were 45 cm thick were not likely to get fired towards the outside from the heat that came from the inside of the structure as the walls were simply too thick. The third was the conclusion that the typical gable end walls that brought more extra mass than it actually solved, were bound to separate from the vault due to uneven expansion on the inner and outer wall of the structure, and so they should be hereafter eliminated.

5.3 Golden Bridge Pottery Vault 3

 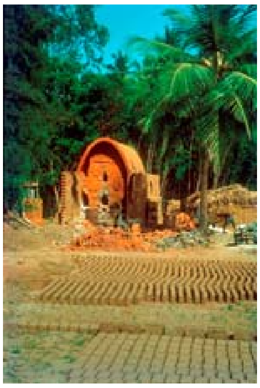

Fig. 5.9 GBP Vault 3, during firing, 1986, Source: Ray Meeker

Fig. 5.10 GBP Vault 3, after firing, 1986, Source: Ray Meeker

After the previous vault had almost collapsed on his head, although it was mainly due to the deviation from the catenary shape, Meeker wanted to be more modest with this structure and built a smaller span of 2.25 meters.

5.3.1 The raw mud structure

As in GBP Vault 2, 45 cms thick walls were repeated in composite brick masonry, with fired bricks on the outside and raw mud bricks on the inside using mud mortar. The vault (Fig 5.9 and Fig. 5.10) was built strictly according to the catenary shape, after the lesson learnt with the collapse of Structure 2. Due to the elimination of the end gable walls the vaults had to be constructed on shuttering and a moveable centering of 1 m length was used for this purpose and slid along the length as the vault construction proceeded (Fig 5.11).

Fig. 5.11 GBP Vault 3, sliding centering instead of Nubian vault technique, 1986, Source: Ray Meeker

As the structure was made of raw sun-dried earth bricks, it continued to shrink in position, and it becomes difficult to remove the shuttering or slide it along[69].

The end walls that were added after firing, being built in fired brick, their foundations could be much less massive and this was also an advantage.

No drawings were produced for this structure.

Elimination of the end wall and its consequence

In order to address the problem of the gable walls falling out of plumb upon expansion of inner surface during firing, a significant change was proposed and tested in GBP Vault 3. The gable walls were eliminated altogether, and were only added later in fired brick after the completion of the firing process.

There were advantages and disadvantages to the elimination of the typical end walls. It meant that Nubian Vault construction, that is a shuttering-free vault building technique could no longer be used, as the end walls on which the vault would be supported until built, was removed altogether. As a result a shuttering had to be introduced for vault construction. Vault 3 was constructed over a moveable section of centering, 1 m in length. This was definitely a disadvantage as compared to the simplicity of the Nubian method, but this disadvantage was weighed against the other advantages expected, the principal one being the prevention of end wall separation.

While this meant extra expense and the added complication of using centering, in fact it proved to be an excellent way to maintain the catenary curve so necessary for the stability of the structure.

[69] This is typical in mud brick roof construction as a shrinkage of 37% is incurred. This is why the revival of the Nubian Vault by Hassan Fathy was so significant as it eliminated the need for shuttering and therefore many related problems due to shrinkage.

Centering is a simpler matter when working with stable materials like brick and cement, but when working with materials like mud bricks and mud mortar, the materials shrink significantly and so it becomes difficult to get the shuttering out, or to slide it. There are ways to around this to avoid that the vault must not be allowed to shrinks over the shuttering- like no mortar on the inside and pebbles in the joints on the outside- but this still remains an area that needs careful attention.

5.3.2 The products

To fill the space of this structure 13,000 bricks were produced to be fired inside.

5.3.3 Preparation for firing, and the firing

The structure was stacked with products as in GBP Vault 2 and 3 and the doors were closed with loose bricks. The kiln was planned as an updraft kiln[70].

In an effort to improve the extent of firing as the structures were not being fired through, Jan de Rooden who had visited again during this time, had suggested using burnt bricks as insulation. Burnt bricks are more porous and therefore more insulating than mud bricks. Meeker accepted to try this suggestion even though this was not what he would have done himself. In subsequent structures, Meeker didn’t repeat this idea further.

For the firing stage, the open ends of the structure that resulted due to the elimination of end gable walls were temporarily filled with unfired brick for enclosing the space to serve as a kiln.

Using fire wood as fuel a temperature of 960° C was reached. The firing continued for 78 hours, much longer than the previous structure.

5.3.4 Finishing

[70] See Section 9.4 on Kiln Types

After the structure was completely fired and cooled, and products removed, end walls were added in fired bricks and exterior walls and vaults were waterproofed and finished with a mixture of cement, sand, lime and clay.

Although the vault was stable and wouldn't have washed away, having the characteristics of fired brick, the vault remained quite porous and did require treatment in order to make it water resistant.

5.3.5 Important firing results

Product

Just as in Structure 1 and 2, the bricks stacked within were of remarkable fired quality superior to most bricks made in the area.

Bricks that temporarily closed the openings in the end wall

After firing, 1500 of these temporary "door" bricks were found to be well fired on one end and were incorporated as headers in the exterior of the walls of Structure 4.

Firing of the Structure

Although the fuel consumption was only slightly increased, compared to the earlier two structures, the vault showed less unstable areas on the exterior. This was due to the long slow firing cycle which allowed the heat to penetrate deeply into the vault thickness. The upper part of the vault was better fired than the lower. The area that was fired well could be noticed and indicated that this didn't go all the way to the base of the vault.

Significant occurrences those were significant in developing the technology as a whole

As the end walls were eliminated altogether and as shuttering was used to support the vault, the problem of end walls leaning out and separating from the vault was tackled successfully.

As end walls were built later in fired brick, and were non-load-bearing, they could be thinner and with openings.

The movement similar to the bending outwards of end gable walls that occurred in the side walls of the structure upon firing, although much less pronounced, was monitored in Structure 3.

5.3.5 Fact File

Aim: The aim of this structure was to build a vault without resting it on the typical gable wall by eliminating the end wall altogether and therefore eliminating the end wall separation from the vault, and then to test its behaviour in firing.

Location: Golden Bridge Pottery, Pondicherry

Condition: Is in good condition and is being still used by the Golden Bridge pottery as a studio space. Vault 3 was later integrated architecturally with test vaults 4, 5 and 6 to form a single space.

Client: None

Year of Construction: 1986

Dimensions: 5 meters x 2.25 meters

Carpet Area: 11.25 sqm

Form of roof: vault of 2.25 meter span with a rise of 1.5 meters

Type of walls: 2.14 meters high, 450 cm thick mud walls

Fuel: Fire wood

Products: 13,000 bricks

Insulation: Burnt bricks.

Temperature reached: 960°C

Duration of Firing: 78 hours

Kiln description: Up-draught kiln

Special steps taken towards the technology: Eliminating the end wall all together and building a vault using a movable centering.

5.3.6 Conclusion

Though the fuel consumption was slightly increased the long slow firing cycle penetrated deeply into the roof and the vault exterior showed much less unstable areas.

Eliminating the end walls by introducing a shuttering for the vault eliminated the problem of the separation of end walls from the vault due to uneven temperatures on the outer and inner faces of the end walls. However using a shuttering to build a mud vault created enough complications due the shrinkage factor and was also not necessarily an ideal solution. In many ways a Nubian vault was much simpler.

5.4 Golden Bridge Pottery Vault 4

Fig. 5.12 GBP Vault 4,unloading product bricks, 1986, Source: Ray Meeker

In this structure (fig. 5.12) alternatives and improvements were attempted in four technical areas all of which proved to be successful as well as valuable improvements on the way to making this technology a viable one.

Firstly, it was concluded that the use of shuttering as in Structure 3, for vault construction with uncooked bricks was far too complicated, given that the vault continues to shrink as the days pass and makes it rather difficult to remove the shuttering. Thus the vault height gets lower and lower as one slides the shuttering along the length of the vault due to the advancing construction. An easier solution was essential to simplify the roof construction, and it was decided to build the vault by using a combination of the Nubian vault and a centering, so that the advantages of both these could be tapped while still eliminating the need for an end wall given fact that it would separate from the vault upon firing. This was done by building only a middle section of the vault with the shuttering, but thereafter on either side the vault was continued by leaning the brick courses on this central vault section in the Nubian style from either side.

Now that the leaning outwards of the end walls had been solved, by their removal, the second technical improvement attempted was to eliminate even the bending out of plumb in the side walls, after having monitored this in Structure 3. This was done by building the walls leaning slightly inwards.

Thirdly, in order to achieve a well-cooked vault through its entire thickness and length, it was felt that a much better insulation was needed. Normally this could be also attempted by firing the structure to a higher temperature on the inside, but as the local brick clays do not tolerate much over 950 degrees, this option would not be without weakening both structure and product. For this reason, a combustible insulation was introduced to test its effect on the firing result.

Fourthly, a further improvement in the quality of product brick was attempted to fetch a better price and recover the fuel expense, and thereby leading to the technique’s economic viability.

5.4.1 The raw mud structure

The side walls were built out of plumb, leaning slightly inwards. This was in order to counter the outward leaning of walls after firing as observed in structure 3. The vault was built bycombining the benefits of the Nubian vault technique with partial use of a wooden centering. 75 cm of the vault width was built over a catenary frame that was placed approximately midway between the ends of the side walls (Fig. 5.13). The vault was then continued to be built with the Nubian method, leaning bricks against the 75 cm section on either side of it. The frame was again used to finish the vault at the ends. (Fig. 5.14)

Fig. 5.13 Vault building technique, 1986, Source: Ray Meeker

Fig. 5.14 Neat end detail using the same frame, 1986, Source: Ray Meeker

No drawings were produced for this structure.

5.4.2 The products

13,000 bricks were to be fired in this structure. Of these 8,000 were table-moulded bricks of a relatively high quality. The bricks in the previous structures were of high quality but as they were ground-moulded, they didn't look too much better than the local bricks in appearance and as such didn't fetch the higher value of money that it deserved. Hence they were made as table-moulded in order to give them a distinctly better appearance, and if they fetched a far higher value of money in return, this could seriously lead to cost and fuel economy.

5.4.3 Preparation for firing, and the firing

A combustible insulating mixture of cow dung, straw and clay was applied over the structure. The idea was that during the firing process, when the outside surface of the vault would start heating up, even if it did not reach the adequate temperature required for transforming the mud brick to fired brick, the temperature would be enough to ignite the combustible cow dung contained in the insulation mixture. This mixture would self-burn and give the additional temperature rise needed to stabilize the vault.

It was hoped that this mixture would not begin to burn until quite late in the firing cycle when the interior was reaching its peak temperature, so that in the beginning it would serve as insulation and later when the vault had already started cooking from the inside, it would also catch fire and help it to be simultaneously cooked from the outside. This happened as predicted and proved to be a major breakthrough in the technique.

5.4.4 Finishing

End walls were added and exterior walls and vaults were waterproofed and finished with tiles. It should be noted that though the vault was stable and wouldn't have wash away, it is quite porous (as fired bricks) and does require treatment in order to make it water resistant.

5.4.5 Important firing results

Product

The bricks were of remarkable fired quality superior to most bricks made in the area, but also looked superior due to the better edges achieved by being table-moulded. The quality of the brick was tested[71]. The sale of these first quality bricks brought a return of Rs. 6,300 on the structure. These table-moulded bricks cost only a little more to produce, but fetched a much better return on the overall cost of producing the building as all the other process costs remained unchanged. In the first three structures, although the quality of the product bricks were of significantly higher than the local

[71] The strength was 12 MPa (Newton per millimetre square or Mega Pascal) as opposed to the local bricks that had strengths varying from 3-6 MPa.

ground-moulded brick, a higher price could not be procured as they still looked quite the same as the local inferior quality bricks and as such would fetch too low a price for the quality it offered. Although the sale of these bricks in no way recovered the building cost, it did indicate clearly the potential that lies in product development. This was a significant technical improvement in terms of making the technology economically viable.

The high quality bricks that became available as a consequence for the first time in the local area led to the first application of exposed brickwork in in Pondicherry, designed by Helmut Schmid[72] and built by Kanoo Mistry. This residential structure (Fig. 5.15a and 5.15b), Neena Devi`s residence, situated in a prominent location, on the main commercial street, Nehru Street, was made possible due to the high quality bricks that were achieved and found suitable for exposed use even in the high humidity and high rainfall area. This structure later led to further exposed brick houses being built in the area. As the project required far more bricks than what was produced inside the structure, the kiln was reused 3 more times only to produce more bricks to complete the order placed by that project. Of course, these 3 subsequent firings were much simpler as in these cases only the products had to be cooked and the heat did not need to reach the exterior surfaces of the structure's walls.

Fig. 5.15a and 5.15b Neena Devi's residence, the first exposed brick structure in Pondicherry, 2007, Source, photographed by Josephine Hansen

[72] This was the first house in Pondicherry that was built using exposed brick masonry as load bearing walls. The house was designed for Neena Devi by Helmut Schmid, a German architect living in Auroville and built by Kanoo Mistry.

Firing of the Structure

The idea of the combustible insulation was really effective and the firing proceeded as hoped. The vault cover did not ignite too early and continued to burn slowly for two full days after stoking of the fire was completed. The Vault number 4 was completely stable inside and out. After firing the side walls had moved, yet remained just slightly out of plumb (inward).

5.4.5 Occurrences those were significant in developing the technology as a whole

The success of the four areas of intended improvements led to a huge leap in the baked-*insitu* house experiments. The successful through and through stabilization of the vault achieved after 4 attempts was a major breakthrough and served as encouragement in continuing the research.

Vault construction

The use of a catenary frame enabled the construction of the vault in a Nubian technique as in Structure 1 and Structure 2 while eliminating the need for a continuous shuttering as in Structure 3. There was a problem though that by the time one would get to the end of the Nubian vault it would be lower due to shrinkage and so this problem was countered by simply building the vault in a negligibly downward sloping way.

Side walls

The side walls in the first three buildings showed a movement similar to, though less pronounced than the movement in the gable walls. This movement was monitored in Structure 3, and in Structure 4 the walls were built out of plumb- leaning slightly inwards. After firing, the walls had moved, yet remained just out of plumb (inward).

Product

Value addition of products could contribute significantly to the cost economy.

The first successful through firing

The vault was successfully fired through due to application of the combustible insulation. In several future buildings the same mixture was applied until the use of coal dust in the last three structures.

5.4.6 Fact File

Location: Golden Bridge Pottery, Pondicherry

Condition: Is in good condition and is being still used by the Golden Bridge pottery as a studio space. The vault was later integrated architecturally with test vaults 3, 5 and 6 to form a single space.

Client: None

Year of Construction: 1986

Dimensions: 5.25 meters x 2.25 meters

Carpet Area: 11.82 sqm

Form of roof: 15 cm thick vault of 2.25 meter span with a rise of 1.5 meters

Type of walls: 2.14 meters high, 450 cm thick mud walls

Fuel: Fire wood

Products: 13,000 bricks (5, 000 ground moulded and 8,000 table moulded)

The structure was stacked again with 13,000 bricks however 8000 of these bricks were table-moulded bricks of very high quality.

Insulation: The exterior of the fourth vault was insulated with a combustible mixture of one part cow dung, two parts straw and one part of clay in a 10 cm thick layer. In the first three structures, the attempt was simply to insulate the vault. In this case the insulation layer was mixed with combustible components so that in the initial phase the mixture would serve as insulation, but after a point would then ignite and thereafter contribute to the stabilization of the exterior of the vault.

Temperature reached: 960°C

Duration of Firing: unknown

Kiln description: Up-draught kiln

Special steps taken towards the technology: Eliminating of the end wall while also eliminating the need for a shuttering for constructing the vault was successfully achieved. Eliminating the leaning outward of the sidewalls after firing by building them sloping inwards was also achieved. Value addition of product made the technique take a big step in the direction of viability. The idea of using insulation over the vault during firing stage that was combustible led to the first through fired vault.

5.4.7 Conclusion

All four technical alternatives attempted succeeded and all proved valuable and helped to greatly improve the technology of firing houses.

The problem of the outward bending of side walls as well as end walls due to firing, were countered.

A simple way of combining Nubian vault building technique with a catenary frame centering was found to build vaults easily without either the problem of removing the shuttering after shrinkage, or without the need for end walls as supports in vault construction which would have brought back the problem of the end walls leaning out and separating from the vault due to uneven temperatures inside and outside.

A combustible insulation was a very effective way of achieving through and through firing of the vault. It was the first time a roof was fired all the way through adequately.

And finally the value addition of the product made the idea of attributing the fuel cost to the products an economic reality.

5.5 Golden Bridge Pottery Vault 5

Fig. 5.16 GBP Vault 3, the eliminated end wall area closed with raw bricks during firing, 1987, Source: Ray Meeker

As in the previous structure a satisfactorily fired building was already achieved, the aim of this structure was to further improve the economy generated by the product on one hand and to begin studying the fuel consumption and its potential optimization on the other.

5.5.1 The raw mud structure

A structure enclosing 5m in length and 3 meters in width was built again without end walls, resting only on 45 cm thick and 2.5 m high side walls made in composite brick masonry using fired bricks towards the outside and raw bricks towards the inside. A 15 cm thick vault of 3 meter span with a rise of 1.5 meters rested on the side walls. (Fig 5.16)

As it already proved to be successful in structure 4, the side walls were built out of plumb,leaning slightly inwards to counter the outward leaning of walls after firing. As in the structure 4 the vault in structure 5 was built by combining the benefits of the Nubian vault technique with partial use of centering to build a middle strip of the vault on both sides of which further courses of the vault can lean as it develops further without the use of shuttering. 75 cm of the vault width was built over a catenary frame that was placed approximately midway between the ends of the side walls. The vault was then continued to be built with the Nubian method, leaning bricks against the 75 cm section on either side of it.

However, a new improved steel centering was introduced with a mechanism that enabled it to be raised and lowered. This was required as significant shrinkage (37%) occurs in the mud vault which makes the removal of the centering difficult as was experienced in the vault number 4. This steel centering could be easily dropped to a lower rise and used to build the Nubian vault construction to its end and so this frame again served as a centering to finish the vault and achieve a better end detail. (Fig. 5.17)

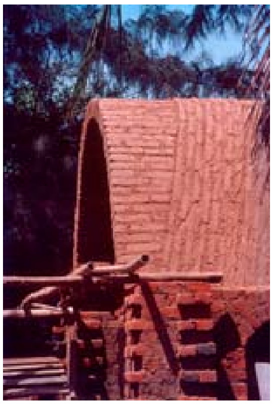

Fig. 5.17 GBP Vault 5, end detail, 1987, Source: Ray Meeker

5.5.2 The products

Based on the success and economic benefit of having produced table-moulded bricks in the structure number 4, this time all bricks were table-moulded. 12,000 bricks were produced. As was regular by now, the bricks were of first class quality, and helped significantly to recover the cost of fuel.

5.5.3 Preparation for firing and the firing

A combustible insulating mixture as in Structure 4 was used of cow dung, rice husk (instead of straw) and clay that was applied over the vault. This too began to burn quite late in the firing cycle as was desired when the interior reaching its peak temperature, so that in the beginning it served as insulation and later when the vault had already started being fired from the inside; the insulation would ignite and help it to be simultaneously cooked from the outside.

From this structure on, having already succeeded in firing the vaults through and through, fuel consumption was monitored. 10 tons of dry casuarina wood was used to stabilize this structure and its products by firing.

5.5.4 Finishing

Fig. 5.18 GBP Vault 5, after finishing, 1987, Source: Ray Meeker

End walls were added and exterior walls and vaults were waterproofed and finished with tiles (Fig. 5.18). It should be noted that though the vault was stable and won't wash away, it is quite porous and does require treatment in order to make it water resistant.

5.5.5 Important firing results

Product

As all the bricks were table-moulded and of fired quality superior to most bricks made in the area, 10,000 Rupees were recovered as opposed to the. Rs. 6,300 recovered in Structure 4. This was a significant improvement in the economic optimization of this technique.

Firing of the Structure

After firing, the walls had moved outwards, yet remained just out of plumb to the inside. Vault number 5 was completely stable inside and out. The difference with structure 4 was that this was fired to a lower temperature for a longer duration to allow deeper penetration of the fire and therefore better firing towards the external areas of the structure.

5.5.5 Occurrences those were significant in developing the technology as a whole

Now that the firing process and a relatively well fired structure was already achieved, the firing process was more closely monitored with the idea of taking up fuel efficiency as the next area of technical improvement beside capital generation through products fired inside the structure.

5.5.6 Fact file

Location: Golden Bridge Pottery, Pondicherry

Condition: Is in good condition and is being still used by the Golden Bridge pottery as a studio space. Vault was later integrated architecturally with test vaults 3, 4 and 6 to form a single space.

Client: None

Year of Construction: 1987

Dimensions: 5 meters x 3 meters

Carpet Area: 15 sqm

Form of roof: 15 cm thick vault of 3 meter span with a rise of 1.5 meters

Type of walls: 2.65 meters high, 450 cm thick mud walls

Fuel: 10 tons of dry casuarina wood

Products: 12,000 table moulded bricks. All bricks were now table-moulded.

Insulation: The exterior of the fifth vault was insulated with a combustible mixture of one part cow dung, two parts rice husk and one part of clay in a 10 cm thick layer. As a combustible insulation had proved to be successful in structure 4, this was repeated with the replacement of straw by rice husk.

Temperature reached: 945°C

Duration of Firing: 84 hours.

Fuel Consumption:

Heat required per 1000 bricks for products alone: 17,270 MJ

Heat required per 1000 bricks & structure: 12,300 MJ

Kiln description: Up-draught kiln

Special steps taken towards the technology: The wooden catenary centering was replaced by a steel structure that could be raised and lowered. There was a problem when one got to the end of the Nubian vault due to shrinkage and this end condition was changed by permitting the centering structure to be easily lowered.

5.5.7 Conclusion

The metal centering in combination with the Nubian technique was a further refinement in the easy and efficient building of a mud vault.

The recovery of capital generated by the products increased and the experiment was a step further in the direction of economic viability.

The idea of also taking up the fuel efficiency aspect of this technology as the next area of improvement was initiated and fuel consumption details were meticulously monitored.

5.6 Golden Bridge Pottery Vault 6

Fig. 5.19 GBP Vault 5 and 6, after finishing, 1987, Source: Ray Meeker

The aim of this structure was to increase the height of the structure to improve its use as a living space, by enabling the addition of a loft to make available a significant additional surface area at a correspondingly less cost increase.

5.6.1 The raw mud structure

The structure (Fig. 5.19), a meter longer than the previous experiment, enclosing 6m in length and 3 meters in width was built again without end walls, resting only on 45 cm thick but 3.15 meters high (65cms higher than structure no 5) side walls made in composite brick masonry using fired bricks towards the outside and raw bricks towards the inside. A 15 cm thick vault of 3 meter span with a rise of 1.5 meters rested on the side walls. The same span allowed the reuse of the newly developed improved steel centering for the vault construction and its easy removal.

As it already proved to be successful in structure 4 and 5, the side walls were built out of plumb- leaning slightly inwards to counter the outward leaning of walls after firing. As in the structure 4 and 5, the vault in structure 5 was built combining the benefits of the Nubian vault technique with partial use of centering to build to middle strip of the vault on which both sides of the vault can lean as it develops further without the use of shuttering. 75 cm of the vault width was built over this catenary frame that was placed approximately midway between the ends of the side walls. The vault was then continued to be built with the Nubian method, leaning bricks against the 75 cm section on either side of it. As in Structure 5, the new improved steel centering was used which had a mechanism that enabled it to be raised and lowered to facilitate its easy removal inspite of the shrinkage and therefore sinking of the raw earth masonry above. It was also again re-used to build the Nubian vault construction to its end to finish the vault and achieve a better end detail.

5.6.2 The products

Based on the success and economic benefit of having produced table-moulded bricks in the structure number 4, this time all bricks were table-moulded. 12,000 bricks were produced. As was regular by now, the bricks were of first class quality, and helped significantly to recover the cost of fuel.

5.6.3 Preparation for firing and the firing

A combustible insulating mixture as in Structure 4 and 5 was used of cowdung, rice husk (instead of straw) and clay that was applied over the vault. This insulation layer began to burn as hoped quite late in the firing cycle when the interior reaching its peak temperature, so that in the beginning it served as insulation and later when the vault had already started cooking from the inside, it also caught fire and help the vault at its final firing stage to be simultaneously cooked from the outside.

After the success of this method in Structures 4 and 5, there method led to a successful firing of the vault through and through. The fuel consumption was monitored as begun in Structure 5.

7.37 tons of dry casuarina wood and 1000 bundles of casuarinas malaar[73] were used to stabilize this structure and its products by firing. An up-draught scove-type kiln was used and the structure was fired for 77 hours.

[73] Malaar is a term that is used locally to describe the tops and large branches of the casuarinas tree includings its needle-like leaves. A bundle of malaar depending on the size, has roughly the calorific value of 7.5 kg of casuarinas wood- 4950 cal/kg. (From MEEKER, Ray. MUD: Towards a fire stabilized building Technology, Architecture & Design, Media Transasia, Delhi, March-April 1991)

5.6.4 Finishing

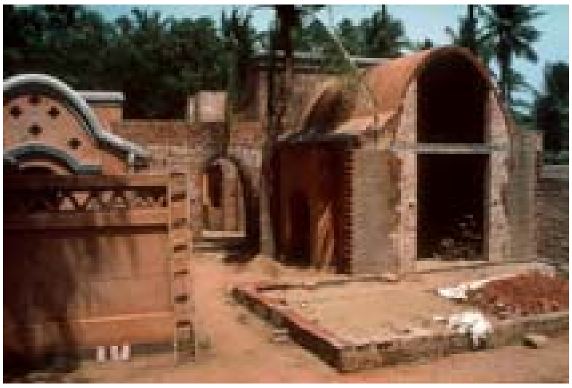

Fig. 5.20 GBP Vault 6, addition of loft during finishing, 1987, Source: Ray Meeker

End walls were added and exterior walls and vaults were waterproofed and finished with tiles. A loft was added in Reinforced Cement Concrete to significantly increase the utility of the space(Fig. 5.20). Internal walls were plastered and painted and the floors were laid with hand-made terracotta tiles that were fired within the structures. Ceramic gargoyles were added as water spouts to drain the rain water from the vault.

Structures 3, 4, 5 and 6 were inter-connected and used as part of the Pottery Studio’s working space. These earliest 4 surviving structures, the ones that were the most experimental, still stand in good condition and are very much in use as part of the Golden Bridge Pottery Complex (Fig. 5.19).

5.6.5 Important firing results

Product

As in Structure 5, all the bricks were table-moulded and of fired quality superior to most bricks made in the area. 19,000 bricks were produced. 15,800 Rupees were recovered as compared to Rs. 10,000 recovered in Structure 5. This was a significant improvement in the economic optimization of this technique.

Firing of the Structure

As in structures 4 and 5, after firing the walls had moved, yet remained just out of plumb (inward). Vault number 6 was completely stable inside and out. The difference with structure 5 was that this structure was fired to an even lower temperature for a longer duration. The structure was fired to 920° C for 77.5 hours.

Occurrences those were significant in developing the technology as a whole

As in Structure 5, now that the firing process and a relatively well fired structure was already achieved, the focus of the firing process was on improving fuel efficiency and capital generation through products fired inside the structure.

Due to the slow firing with reduced heat, a better fuel efficiency was achieved.

5.6.7 Fact file

Location: Golden Bridge Pottery, Pondicherry

Condition: Is in good condition and is being still used by the Golden Bridge pottery as a studio space. Vault was later integrated architecturally with test vaults 3, 4 and 5 to form a single space.

Client: None

Year of Construction: 1987

Dimensions: 6 meters x 3 meters

Carpet Area: 18 sqm without the loft that was added

Form of roof: 15 cm thick vault of 3 meter span with a rise of 1.5 meters

Type of walls: 3.15 meters high, 450 cm thick mud walls

Fuel: 7.37 tons of dry casuarina wood and 1000 bundles of casuarina malaar[74].

Products: 12,000 table moulded bricks. All bricks were now table-moulded.

[74] Casuarina malaar is the term used to describe the tops and large branches of the casuarinas tree including its needle like leaves. A bundle of malaar depending on the size, has roughly the calorific value of 7.5 kg of casuarina wood- 4950 cal/kg. (From MEEKER, Ray. MUD: Towards a fire stabilized building Technology, Architecture & Design, Media Transasia, Delhi, March-April 1991)

Insulation: The exterior of the sixth vault was insulated exactly as in the fifth with a combustible mixture of one part cow dung, two parts rice husk and one part of clay in a 10 cm thick layer.

Temperature reached: 920°C

Duration of Firing: 77.5 hours

Fuel efficiency:

Heat required per 1000 bricks for products alone: 16,292 MJ

Heat required per 1000 bricks & structure: 11,680 MJ

Kiln description: Up-draught kiln

Special steps taken towards the technology: There was the attempt to create a very tall space to accommodate a loft and significantly increase thereby the useable area. More financial returns were achieved from products, and an improvement in fuel efficiency was obtained.

5.6.8 Conclusion

The height of the structure was significantly raised and this increased the potential of using the space as a regular liveable one, as compared to the others in which constraints were imposed on the space due to the gradually evolving technology leading from safer smaller structures to larger ones. More quantity of first quality product bricks produced within the structure brought back more capital to offset the cost of firing the house. Fuel was being monitored for attempting efficiency. All the first 6 tests involved updraft kilns as firing systems.

With the sixth structure, the series of tests that were conceived for basic experience in building mud brick vaults and becoming familiar with the behaviour of large/brick structures during firing ended. These 6 experiments also focused on determining if a 15 cm thick vault could be thoroughly fire-stabilized, with which means and with how much fuel. Hereafter further optimisation was attempted within projects that were delivered to clients.

5.7 ‘Agni Jata’: House for Mallika and Dhruv in Auroville

Fig. 5.21 Agnijata, during firing, 1988, Source: Ray Meeker

Fig. 5.22 Agnijata, after finishing 1988, Source: Josephine Hansen

This structure, the seventh experiment, (Fig 5.21 and Fig 5.22) was the first to be built as an actual liveable house for a client after having successfully solved various challenging aspects of the technology in the previous six test experiments. ‘Agnijata’ as it was named, means ‘fire-born’ in Sanskrit. On the technical level, the aim was to achieve fuel efficiency through a combination of structures and through a more efficient kiln system. Until now, all of the first 6 structures were up-draught type kilns.

Product optimization was also attempted in order to increase capital generation and to be able to attribute all fuel costs to the products. The attempt was now to achieve the stabilizing of the mud house through firing without any additional cost, and only as a consequence of the ‘waste’ heat that is normally lost into the kiln walls.

In 1988, Mallika and Dhruv approached Meeker to build their house in the technique they had heard he was experimenting with. The agreement with Meeker was that he would bear the costs of firing the house, with the idea that he would produce the products within it and have to recover the fuel cost of the entire firing- of house and products- through the product sale. Mallika and Dhruv would pay for building the mud house and would get it transformed into ceramic, by letting it be used as a kiln for firing the ceramic products that Meeker was in charge of producing and selling.

This experimental house for Mallika, was a huge leap towards large and firing complex systems.

The plan of the house, although more complex than the earlier six test structures, was fairly simple, developed under a dome surrounded by four vaults. In earlier structures no drawings were necessary as they were very simple single vaulted structures being built only to solve the various basic aspects of firing a large earth structure successfully. In this case, plans, elevations and sections were produced to be presented to the client. While this structure was still a simple composition of vaults and a dome, it still had to function as a liveable house once it had served its function as a kiln. This was also the first structure involving the construction of a dome.

There were two main additions after firing, a fifth vault was added (2.5 m long and 3.5 m high) to serve as a canopy in fired brick and lime/sand mortar, and a partial loft was cast later in the highest vault.

As Meeker had intuitively guessed, this project would be a major breakthrough in proving that large earth structures can be successfully fired; could be affordable as well as fuel efficient. Meeker had thus arranged to get the significant steps of this construction filmed. Later on, in 1999 this film, produced by Ray Meeker went on to receive an international award in Ceramics Millennium at Amsterdam. Till date, this serves as one of the most valuable documentations providing an insight into the actual process involved especially the firing stage that is difficult to visualize only through written descriptions, as no further structures were filmed hereafter.

5.7.1 The raw mud structure

The entire structure was sunken 75cm below the surrounding ground-level to reduce the buttressing necessary for vault walls. This minimized the need for buttressing the vault walls and helped the house to maintain a low profile on a site which was rather prominent. The foundation walls were made of fired brick and lime mortar, with a damp-proof course administered in cement mortar. The walls were constructed as composite walls - of fired brick on the outside surface, and sun-baked earth bricks on the inside - but the vaults and dome were made entirely with unfired bricks.

The four arches supporting the Nubian vaults were constructed with the help of a frame developed along a catenary curve. The vaults are built without any centering – except for the initial supporting arch- beginning with an inclined course leaning on the base of the arch, and increasing the inclination with each successive course until the desired gradient is reached. For a vault 2m high with a 3m span 10 courses were required to reach the desired angle of 75 degrees, which was, then, carried through the rest of the vault length. The frame for arch construction, at this stage, served as a handy grid guide to maintaining the catenary shape. Bricks touched one another on the interior along each course their gaps widening towards the exterior. Mud mortar, which shrinks by as much as 37 percent in volume while drying[75], can cause distortion of the curve, cracking and, probably, failure. In the Nubian vault, the ends of the bricks should touch each other dry, with no mortar, and bits of dry brick should be tightly packed into the gaps between bricks.[76]

Dome bricks were 15 x 15 x 5 or 20 x 20 x 5 and vault bricks were 15 x 25 x 5. After having built a strip of the vault as in Structure 4, nubian vault construction, resting on this strip and necessitating no end wall, was followed for all vaults.

5.7.2 Products

Some 60,000 table-moulded bricks, 2,000 tiles, 35 decorative water spouts and 4 terracotta toilet-pans were stacked inside the structure. (Fig. 5.17 and 5.19)

[75] Fathy, Hassan. Architecture for the Poor, University of Chicago Press, Chicago, 1973

[76] Fathy, Hassan. Architecture for the Poor, University of Chicago Press, Chicago, 1973

Fig. 5.23 Production of ceramic toilet pan, 1988, Source: Ray Meeker

Fig. 5.24 Extrusion of Hollow roofing units, 1988, Source: Ray Meeker

The stacking of products was of prime importance as it determines the path of heat flow, and therefore, how evenly the products and the building would be fired. The stacking arrangement took about 4 weeks, in this structure, due to its huge volume.

The products were well fired and fetched a financial return of 75,000 Rupees. This was a significant contribution towards the total recovery of fuel costs due to the firing.

5.7.3 Preparation for firing and the firing

The form, so simple from the architectural point-of-view, was fairly complex from the point-of-view of firing as a kiln. Domes and vaults in combination and especially as the dome was surrounded by four vaults, was a new experiment in firing, but successfully fired in one operation.

A 10 cm coat - 2 parts rice husk - 1 part cow dung and 1 part clay - was applied over the dome and vaults. Initially, the layer served as insulation; later as an organic combustion layer. Hence, in effect, the vaults and dome are virtually fired from two sides as in the structures 4, 5 and 6.

The firing, begun at the four vaults, first involved the evaporation of water from the vaults and walls, and the products inside, for 2 days. The smoke was allowed to escape from holes high above on the vault. Then the holes were closed and the heat was directed towards the dome, which was finished as a down-draft system. The vaults were individually fired simultaneously but the dome benefited from the waste heat from the vaults and so was fired efficiently. A down-draft chimney placed in the centre of the dome rose 2 meters above the exterior height of the dome. This temporary chimney was dismantled after firing.

The temperature reached 900-980° C at the thermocouple points, but varied much more throughout the entire system – probably 800 degrees in the cold spots, and 1,100 where the bricks began to melt. The structure was fired for 108 hours. As compared to the earlier structures, this structure achieved a value of 13,270 MJ/1000 for product bricks alone, and 9,100 MJ/1000 bricks including the structure. This was significantly more efficient than the values previously achieved. (16,292 MJ/1000, and 11,680 MJ/1000 respectively).

The structure was fired for 4-1/2 consecutive days, (108 hours) with 23.5 tons of casuarina wood and 2,400 bundles of *malaar*. Once firing was over, every opening was tightly sealed for 3 days after which the structure was opened. Efficiency was gained by firing the 4 vaults simultaneously cross-draft that preheated the dome to 600° C only through flue gases from vaults.

5.7.4. Finishing

The structure was plastered on the inside and outside and painted. The tiles baked within the structure were used for flooring, and part of the bricks, in the external paving. Window openings were closed with *jaalis* or screens also made in ceramic and fired inside the structure.

The total living space is 65 sqm and has been occupied ever since. Even without fans, it is notably cool. This is because vaults and domes don’t have a single surface that constantly absorbs the suns radiation uniformly as in flat roof surfaces. Also the hot air is allowed to escape out of the high opening at the centre of the dome.

5.7.8 Important Firing Results

The 60,000 table-moulded bricks, 2,000 tiles, 35 gargoyles and 4 terracotta toilet-pans were well fired and fetched Rupees 75,000 from the sale. This was a significant contribution towards the total recovery of fuel costs due to the firing. The structure was well fired to satisfaction.

5.7.6 Occurrences that were significant in developing the technology as a whole

A big leap in fuel efficiency was achieved with the efficient - although complex kiln type - upon which this experiment was based. There was a significant improvement from the values that were previously reached.

5.7.7 Fact File

Location: Auromodel, Auroville

Condition: Is in a very good condition and is being still used by the same client and her son. Compared to all the structures this is the one that is still probably in the best condition, as it has been also very well maintained consistently, with the structure being painted regularly. As a result one sees clean white plastered surfaces, unlike the other structures where one sees dark patches of fungus, a common sight in also other unpainted buildings in the area, a result of the extreme humidity.

Client: Mallika and Dhruv

Year of Construction: 1988

Dimensions: Vault 1- 4 meters x 3 meters, 3.5 meters high
Vault 2- 4.5 meters x 3 meters, 3.5 meters high
Vault 3- 5 meters x 3 meters, 3.5 meters high
Vault 4- 6 meters x 3 meters, 4.5 meters high
Dome – 5meters diameter and 5 meters height

A Detached Vault was added after firing 5- 2.5 meters x 3.5 meters

Carpet Area: 65 sqm in the firing zone and 74.32 sqm useable area including the loft that was added

Form of roof: Four vaults linked to a central dome

Type of walls: 2.0 meters high walls, except one vault on 3.0 meter high walls that accommodates a loft. The dome sits on 45 cm walls and the vaults on 34 cm walls.

Fuel: 23.4 tons of casuarina wood and 2400 bundles of casuarina *malaar*.

Products: 60,000 table-moulded bricks, 20,000 tiles (for use as floor finish in the same structure), a number of decorative water spouts and several terracotta toilet pans.

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: varied from 900°C - 980°C in the 5 thermocouple points, but probably varied between 800°C in the cold spots to 1100°C in the areas where bricks began to melt.

Duration of Firing: 4 days.

Firing efficiency:

Heat required per 1000 bricks for products alone: 13,270 MJ

Heat required per 1000 bricks & structure: 9,170 MJ

Kiln description: The 4 vaults were simultaneously fired cross-draft towards the dome, and the dome itself as down-draft system. In terms of firing, a more complex combination of cross draft and down draft system was experimented in order to address the aspect of viability in relation to fuel efficiency.

Special steps taken towards the technology: Sinking the house below ground reduced the height of the walls that have to be thick and are difficult to fire through, and therefore reduced the number of fired bricks needed for the external faces of the composite brick masonry. The vaults as a result sprang up from a lower point. Vaults were built with a thickness of only 15 cms and were easy to fire through since the idea of using a combustible insulation had become a reality.

5.7.8 Conclusion

The successful firing of this scale of a project, for regular use as a house, for an actual client, was a big leap and a breakthrough in developing a technique, which indicated that in the right circumstances this could be one solution to building a low-cost, high quality, climatically appropriate house.

The economy generated by the products could fully absorb the fuel cost and the fired house could be delivered for the same price as a mud unfired house of that design.

The complex combination of cross-draft and down-draft kiln systems raised the fuel efficiency significantly.

5.8 A model village house in Uppalam, Pondicherry

Fig. 5.25 Model village house fired near thatch structures, 1988, Source: Ray Meeker

This structure, Meeker's eighth experiment (Fig. 5.25) was the first structure being built for a low-cost end use in the village. The aim was to find out specifically what it would cost to do a single vault for a single low cost house. It was located in the midst of a village very close to other structures with thatch roofs, which are known to be susceptible to fire. As in Agnijata, the previous project, this project was also being delivered to a client and the experiment had to be conducted within the framework of the responsibility that Meeker therefore had to also shoulder. But, in the case of this model village house in Upalam, it was also the first time that the project was being executed by a contractor.

The structure was originally planned to be a home for a leper, but as it proved later that no one wanted to have a leper living near them, it became a home for the aged and is now finally being used as a library for the Volontariat School[77].

While the building was being built, the village children were involved in the process and they were helped to build their own little structure on the side. (Fig. 5.26)

Fig. 5.26 Children build a tiny fired house beside the main project, 1988, Source: Ray Meeker

5.8.1 The raw mud structure

The structure was built like the previous experiment with no further new developments in any of the aspects. Planned as a long single vault the structure of 3m width and 7m length was meant to be divided into three areas after firing: a walled entry court, partially covered by the vault (1.56m x 3m), a living/ sleeping area (3.88m x 3m) and a kitchen area (1.56m x 3m). A W.C. and a bathroom (each. 92m x 1.35m) were to be accommodated in the rear courtyard. The remainder of the court was to be left open-to-sky (1.95m x 1.64m).

[77] Volontariat is an Indian non-sectarian, non-profit, charitable organization that was founded in 1962 by Mme. De Blic, a social worker originally from Liege, Belgium, who was very affected by the immense poverty of the inhabitants of Uppalam, Pondicherry. This organization is run by Indians and helped by Europeans. Its aim is to help the poorest and the most deprived people. (http://pagesperso-orange.fr/volontariat.inde)

5.8.2 The products

8,000 table-moulded bricks, 1,000 floor tiles, 1000 hollow roofing elements, 60 hollow wall elements and a terracotta mural of 2 sqm of surface area were produced for firing within the structure and as was established by now, all products were well fired. Rs. 16,000 were fetched by selling the products, which were substantial due to product diversity that was introduced to fetch more returns as in itself, a small updraft kiln is very inefficient.

Glazed tiles (Fig. 5.27) were produced for the first time within fired earth structures. Glaze is often applied after the first firing and stabilized in a second firing in the process of its production but in this case, a low temperature glaze was used which needed a temperature of 900°C. Hence it was possible to produce glazed tiles in a single firing.

Fig. 5.27 Glazed tiles were produced for the first time with low temperature glaze, 1988, Source: Ray Meeker

5.8.3 Preparation for firing, and the firing

The firing had to be conducted for the first time in the vicinity of neighbouring thatch houses. Meeker had asked Madame De Blic, the client to obtain permissions from the fire department which she did. Then the neighbouring structures kept being sprayed with water to prevent them from catching an accidental fire.

The structure and products were fired as a simple up-draught kiln, which in itself is known to be quite inefficient. This was compensated by increasing product diversity and better value from their sales. 6.6 tons of casuarinas wood and 600 bundles of *malaar* were used to fire the structure and products.

The stacking of products, closing of openings, insulating etc. were repeated as in the previous structures and there was no further innovation to report.

The structure was fired up to 940°C for 48 hours.

5.8.4 Finishing

After the single vault was fired as a kiln, the structure was completed and divided as planned into three areas using the fired bricks that were cooked within the structure: the walled entry court, partially covered by the vault, a living/ sleeping area and a kitchen area (1.56m x 3m). In the rear courtyard, a W.C. and a bathroom were added with the remaining area of the court being left open-to-sky.

All walls were plastered inside and out with lime/sand mortar. The vault was waterproofed with 5cm of brick jelly and lime covered by thin fired brick tiles. Cement mortar was used at all sensitive joints- on cornices where vault meets wall. The five necessary doors were built in prefabricated ferrocement[78], which seemed to be the most

[78] Ferrocement is defined by the A.C.I. (American Concrete Institute) Committee 549 on Ferrocement as ‘a type of thin-wall reinforced concrete construction, where usually a hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh. The mesh may be made of metallic materials or other suitable materials’.

Although ferrocement is a type of reinforced concrete construction, the amount and distribution of the reinforcement is such that a composite material is formed which exhibits behaviour completely different from the conventional reinforced concrete. According to the 1973 report of the U.S. Academy of Sciences, ferrocement is particularly suited to developing countries due to the fact that it is labour intensive, and easy to fabricate without machinery or expensive tools, and it uses much less amounts of steel in the form of mesh instead of heavy steel, which is more easily available and the skill can be easily acquired. It is also much cheaper than reinforced concrete

(SPENCE, David. COOK, David, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 Pg 219-220) cost-efficient option. Light and ventilation are provided by narrow vertical openings above and to the sides of the doors. The floor was finished with terracotta tiles fired in the building. Electrical connection with four light points and two plug points were provided.

5.8.5 Important firing results

The products were diverse and well fired and fetched a return of Rs. 16,000. The glazed tiles were introduced for the first time as a fired house product. This was the first time a local contactor was involved. The contractor was Kanoo Mistry, a reputed contractor from Pondicherry. The building of the mud vault was supervised by Meeker who produced and fired the product (and the building) independently of the construction cost of the house. In this project, the village children were involved into building a small house adjacent to the project which Deborah Smith referred to as the dog house due to its approximate size.

5.8.6 Occurrences those were significant in developing the technology as a whole

One important step in this experiment was that the test was located in the context of a village, and was surrounded by thatch roofs, which addressed the concern of fire hazard to adjacent structures.

The other was the focused effort to scale down the technique to arrive at a replicable model in a reduced size and simple form to serve as a small module that could suffice as a house in order to find out the cost and fuel efficiency.

Meeker used a low temperature glaze for the first time.

5.8.7 Fact File

Location: Pondicherry

Condition: It is still in good condition

Client: Madeleine De Blic, founder and director of Volontariat

Year of Construction: 1988

Dimensions: Vault 1- 7m x 3m x 3.5m

Carpet Area: 21 sqm

Form of roof: A single vault

Type of walls: 2.0 meters high, 35 cm thick mud walls

Fuel: 6.6 tons of casuarina wood and 600 bundles of casuarina *malaar*.

Products: 8,000 table-moulded bricks, 1,000 floor tiles, 1000 hollow roofing elements, 60 hollow wall elements and a terracotta mural of area of 2 sqm.

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: varied from 940°C

Duration of Firing: 48 hours

Fuel efficiency:

Heat required per 1000 bricks for products alone: 19,732 MJ

Heat required per 1000 bricks & structure: 14,250 MJ

Kiln description: An up-draught kiln system was adopted. Although it was known to be inefficient due to the small scale of the project, through the diverse range of products produced with the project, the fuel cost was recovered.

Special steps taken towards the technology: A structure was fired in the midst of thatch roof houses and measures for fire safety were adopted. It was the first test in the context of the village, and was the first example of a house for the target group for whom this technology was developed and the technique was scaled down to arrive at a replicable model in a reduced size and simple form. Glaze was tried out for the first time.

5.8.8 Conclusion

The cost ultimately came to Rs 861 per sqm of built-up area. This was a very successful model for the low-income village housing and this system was later repeated for other low income housing schemes.

It could be concluded that a typical single-vaulted structure of this size, built with the established method that was becoming typical, requires 6000 to 7000 bricks to build. The same structure accommodates 12,000 bricks as product.

5.9 GBP Structure No. 9

Fig. 5.28 GBP Vault 9, aimed at being an efficient kiln, 1989, Source: Ray Meeker

This structure, the ninth experiment (Fig. 5.28) aimed at attempting an alternative type of kiln for increasing fuel efficiency, particularly in the application for small village houses. In a test to develop an efficient, inexpensive kiln for the village potter, Meeker constructed a simple catenary vault on a low plinth of fired brick. The kiln, built in unfired brick, was 4 m long with a chimney at one end in fired brick. It was fired cross-draft to 950°C and required 11,800 MJ per 1000 bricks[79]. For such a small kiln, it was very economical[80].

The village potter could easily build a small kiln with this method and, after understanding its principle through a number of firings, put the same vault on 1.5 m walls and fire a room to live in. He would then become the equivalent of the local mason as a maker of houses. He would use the house as his kiln for firing floor tiles, jalis, chulas, pipes - any number of items which could contribute to the stock of locally

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[79] This kiln is not intended for bricks, but brick data is given for purpose of comparison.

[80] This is not unlike a small version of the CBRI Biomass kiln, which is quite economical, requiring 5,800 MJ per 1000 bricks. In a larger catenary vault system, fired longitudinally, it is conceivable that a figure of 6000 MJ per 1000 bricks can be reached.

available building materials. “Transfer of technology, always a stumbling block, might thus be handled with a minimum of difficulty” said Meeker.

5.9.1 The raw mud structure

The structure is a vault that is directly constructed over a high plinth built in fired brick. Walls are completely avoided. On one end there is a chimney in fired brick and on the other end is the firing box.

5.9.2 The products

3,500 table-moulded bricks were produced for firing within the structure

5.9.3 Preparation for firing and the firing

The combustible insulation mixture by now standard, of 2 parts rice husk, 1 part cow dung and 1 part clay was applied in a 10 cm thick layer.

2 tonnes of casuarinas were used as fuel and the structure reached 930°C and was fired for 36 hours

The cross-draught system of firing was tested and resulted along with the change in stoke hole positions, in a very efficient kiln for its small size.

5.9.4 Important firing results

The products, 3,500 table moulded bricks were well fired and fetched a return of Rs. 4,530. The structure cooked well and also very efficiently using only 2 tonnes of Casuarina.

5.9.5 Occurrences those were significant in developing the technology as a whole

The position of stoke holes was changed and a cross-draught system of firing was tested. This improved fuel efficiency.

5.9.6 Fact File

Location: Golden Bridge Pottery Campus, Pondicherry
Condition: It was taken down
Client: None
Year of Construction: 1989
Dimensions: Three vaults of 4m x 3m x 2m
Carpet Area: 12 sqm
Form of roof: A single small vault
Type of walls: Walls were totally avoided
Fuel: 2 tonnes of casuarinas
Products: 3,500 table-moulded bricks
Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.
Temperature reached: 930°C
Duration of Firing: 36 hours
Fuel efficiency:
Heat required per 1000 bricks for products alone: 11,850 MJ[81]
Heat required per 1000 bricks & structure: 8,457 MJ
Kiln description: cross draft system of firing
This kiln is not unlike a small version of the CBRI[82] bio-mass kiln which uses 5,800 MJ per 1,000 bricks. In a larger catenary vault system, fired longitudinally it is conceivable that a figure of 6000 MJ could be reached.[83]

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[81] This structure is not intended for firing bricks, but the data is given by Meeker for the purpose of comparison

[82] Central Builiding Research Institute of India

[83] MEEKER, Ray. Mud: Towards a Fire-Stabilised Building Technology, Architecture + Design, Media Transasia, Delhi, March-April 1991

Special steps taken towards the technology: The position of stoke holes was changed. This improved fuel efficiency. A chimney was provided at one end of the vault.

5.9.7 Conclusion

For such a small size of kiln this is a very efficient and inexpensive solution for the village potter's kiln.

5.10 Watchmen's shed in HiDesign Factory, Vilianur, Pondicherry

Fig. 5.29 Watchman's shed, first time using onsite clay, 1989, Source: Ray Meeker

This structure, the tenth experiment (Fig. 5.29) aimed at improving the structure 9 and increasing fuel efficiency by connecting vaults and using the 'waste' heat from one vault firing to preheat the next.

This was also the first structure where good onsite clay was available, to be used for brick making. Although this clay was still not good enough for high quality bricks, the clay was good enough for producing a reasonable quality of bricks.

This was a unique opportunity to test the economics under ideal conditions where on site clay would be used for building the structure, there by bringing little or virtually no material from outside. Coupled with the fact that the structure was planned as a series of three connected vaults to be fired as a semi-continuous cross-draught kiln, further economy was anticipated.

However the structure unfortunately suffered rain damage two or three times in spite of having been built during a dry month and the planned economic projection could not be tested.

The building was planned to serve as a watchman's shed located at the entrance of a Leather factory, HiDesign in Pondicherry.

5.10.1 The raw mud structure

The plan was made up of three vaults in a row, with two common walls. Primarily influenced by the attempt at achieving fuel efficiency through cluster structures, the design of the useable spaces below were largely influenced by the ideal kiln system rather than from the spatial requirements of the watchmen's residence. The three vaults were planned to be served through independent access into each.

The building was a series of vaults supported on common walls, to be fired as a semi-continuous chamber kiln. The on-site clay was of sufficient quality (just about) for brickmaking. All structural and product bricks were made at the site. The series of 3 connected vaults ended in a chimney. A chimney is quite a big component of building the structure although this may not be understood at once, especially since the chimneys get dismantled after the firing process. This chimney was not the most complicated one, but was still a tall and challenging structure to be built (Fig. 5.33).

Fig. 5.30 Vault built on the ground to determine reason for failure, 1989, Source: Ray Meeker

The common walls were initially designed and built as 35 cm thick walls, assuming that they would suffice for the interior walls, but they fell down twice after the vault was built. Meeker first supposed that that was due to the fact that the bricks were probably bad, but then found out that they did stand when vaults were built on the ground (Fig. 5.30) So then Meeker concluded that the wall thickness could not take the load of the vaults from two sides, and the walls were then eventually built as 45cm thick walls. This worked.

5.10.2 The products

Fig. 5.31 Product bricks were used to construct the main factory in show bricks, 1989, Source: Ray Meeker

35,000 table-moulded bricks were prepared as products for this structure. And were used to construct the main factory (Fig. 5.31)

Preparation for firing, and the firing

The firing was planned differently from all other structures until now, as the idea was to have a semi-continuous cross-draught kiln in which there was a series of 3 vaults in a sequence. This was the first time waste heat of one structure was being used to preheat the next. The vaults were fired cross-draught and semi-continuous[84] (Fig. 5.32). This meant that the structure needed a temporary chimney (Fig. 5.33) to be built at the last vault at the end furthest away from the vault where the fire was started.

[84] See Section 9.4 on Kiln Systems

Fig. 5.32 Cross-draft semi-continuous kiln system, 1989, Source: Ray Meeker

Fig. 5.33 Tall temporary chimney under construction, 1989, Source: Ray Meeker

The combustible insulation mixture by now standard, of 2 parts rice husk, 1 part cow dung and 1 part clay was applied in a 10 cm thick layer.

10 tonnes of casuarinas and 1,400 bundles of *malaar* were used as fuel and the structure reached 940°C and was fired for 96 hours

5.10.3 Finishing

The walls of the structure were finished externally with plaster and waterproofed with a finishing layer or terracotta tiles. The inside too was plastered. The floor was finished in cement IPS floor, and the end walls that were omitted were built post-firing with exposed brickwork with bricks procured from the products fired within the structure. Jaali work, that is brick work with voids were incorporated to cross-ventilate the structure without needing windows.

5.10.4 Important firing results

The products, 35,000 table-moulded bricks were well fired and fetched a return of Rs. 43,500. The structure cooked well. Even the internal common walls of 45cm cooked well given that they were able to be fired from both sides unlike the side walls in the exterior that had to be usually built by composite walls.

5.10.5 Occurrences those were significant in developing the technology as a whole

This was the first time that the on-site clay, was good enough for using as brick clay. Nearby the site Meeker had the opportunity to observe local brick makers at their own kilns during firing of the local brick produced there.

35 cm common walls were designed which fell down twice so then they were eventually also built as 45cm thick walls as it was concluded that the thickness of 35 cm was inadequate to take the load of vaults from two sides..



Fig. 5.34, Fig 5.35, Fig 5.36 Severe Rain Damage, 1989, Source: Ray Meeker

There was rain damage several times too. Here Meeker discovered that when it rains even if sizeable holes get carved out due to severe rain damage, the structure doesn’t collapse. There was after one severe downpour a hole that was 2m long and 1 meter high[85]. After the rain stopped, the damage was repaired but totally unexpectedly what followed was an even bigger downpour in which the structure lost whole walls (Fig. 5.34, 5.45, 5.36). One important lesson learnt here was that it can rain totally out of season.

The semi-continuous cross-draught kiln proved to be significantly fuel efficient.

5.10.6 Fact File

Location: Pondicherry

[85] This was in spite of the packing the structure with plastic sheets.

Condition: The structure is presently being used as a resting area for drivers and as a storage space too. The 3 vaults now 18 years later, are still in good condition and have been continuously used without any structural modification over time.

Client: Dilip Kapoor, HiDesign Leather Factory

Year of Construction: 1989

Dimensions: Three vaults of 6m x 3m x 3.5m

Carpet Area: 54 sqm

Form of roof: Three connected vaults

Type of walls: 2.0 meters high, 450 cm thick common walls and 34 cm thick external side walls

Fuel: 10 tonnes of casuarina, 1400 bundles of malaar

Products: 35,000 table-moulded bricks

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: varied from 940°C

Duration of Firing: 96 hours

Kiln description: Semi-continuous cross-draught kiln was used

Kiln efficiency:

Heat required per 1000 bricks for products alone: 12,193 MJ

Heat required per 1000 bricks & structure: 7,900 MJ

Special steps taken towards the technology: One important result was that by using common walls the structure could benefit from the waste heat of one vault for preheating the next. The other advantage was that the thick walls in some places could benefit from being fired from two sides and not resort to fired bricks to that extent as was being used previously.

5.10.7 Conclusion

It was an unfortunate lost opportunity to test the economics in the ideal conditions of good enough on-site clay. The structure should have been much cheaper but as there was significant rain damage caused by untimely rains, it was not possible to practically achieve this. In addition the wrong estimation of common wall thickness had also led to structural damage. There was a significant loss incurred due to additional labour expenses in rebuilding these collapsed areas. There were not many costing details available on this from which the actual cost of such a structure in a similar context could be derived. The availability of on-site brick clay makes significant savings in transport and cost. This also implies that skilled labour is likely to be available for brick making and firing. Thirdly, the structure made a big step in the direction of fuel efficiency. This was the first time waste heat of one structure was being used to preheat the next. Interconnected spaces therefore meant significant cost and fuel savings.

5.11 EWS House Prototype at Auroville Visitors' Information and Reception Center (AVIRC)

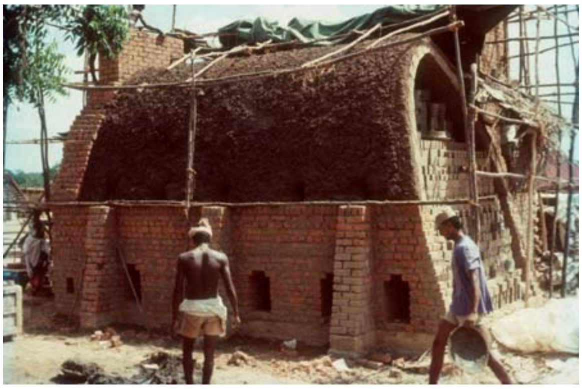

Fig. 5.37, AVIRC prepared for firing, 1990, Source: Ray Meeker
Fig 5.38, AVIRC finished, present condition, 2007, Source: Josephine Hansen

In 1988, while working in Auroville on Agnijata, his first project for a client, Meeker was asked to participate in the building of the Auroville Information and Reception Center (AVIRC) to demonstrate the potential of fire-stabilized mud construction for low-cost housing. Given the HUDCO[86] specifications for the EWS 'Economically Weak Section', the challenge was to build two houses within Rs 20.000 (Fig 5.37 and 5.38).

[86] Housing and Urban Development Corporation, India

This was the eleventh test since 1985 and was conceived to demonstrate the potential for income generation, and also improving the efficient use of fuel in a necessarily small building-system.

That a mud structure could be adequately stabilised by in-situ firing, had been amply demonstrated over the first 10 tests. However, small intermittent up-draft kilns[87] as he had had to use for these tiny one-room, low-cost houses did not utilise fuel efficiently. From the point of view of fuel consumption, it was clear that a large housing project could achieve fuel efficiency by connecting a long series of vaulted rooms with flues through the common walls. Larger structures could be fired as semi-continuous chamber kilns, with 'waste' heat from one room, pre-heating the next. The high-quality bricks, produced on site, would find an easy ready market and a significant portion of the product brick could go right back into the housing project- in its foundations, compound walls and infrastructure. In such a large scale, working at all levels; the economics of scale would ensure a cost-effective solution. But, whether a similar effective solution could be developed for a small one- or two-house system, was the main question to be answered in this test. That is, knowing that small structures would not be as fuel efficient, it was to be explored how the costs could be offset for this kind of a target group, by investigating further returns on product sales.

In terms of kiln systems, this test was to demonstrate the longitudinal draft system in two connected vaults. Meeker thought that if Habla (or Zig-zag) efficiency[88] could be approached in this test, then fire-stabilizing a single house would indeed be economically viable.

5.11.1 The raw brick structure

The structure was composed of two vaulted rooms sharing a common wall. The vaults were laid in the Nubian style leaning on a supporting arch on 1.5 meter high walls.

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[87] See section 9.4 on Kiln Systems

[88] See section 9.4 on kiln systems

The buttressed side walls were 34cm thick and composite - mud and fired brick laid in mud mortar- as in the previous structures.

When structures are fired from the inside out the required temperature for stabilizing the mud into brick could not reached beyond 20 cm through the external walls in the best situation. In order to allow maximum heat penetration into the wall, the vertical joints in the brickwork on the inner face of the wall were not filled with mortar. Fired bricks were used in the exterior face of the side walls to ensure a stable exterior. The common wall was built only with mud bricks as they would get fired from both sides.

Foundations up to 80cm below ground level, were in cement-stabilised site soil - the excavated earth, mixed with 5 percent cement and 20 percent gravel, was compacted in 10cm thick layers. For the site soil to be stabilised with cement, the clay content of the site soil is required to be at least 10-20 percent. As there was a larger project being executed at this site, the Auroville Information and Visitors' Center[89] in cement stabilized compressed earth blocks, Meeker was able to use the technique to replace some of the fired brick that was previously needed at the beginning of his structures to build the foundations.

Above the ground level, the foundations were raised up to the building's plinth level by using 20cm granite blocks with a concrete DPC[90]. The DPC was applied slightly below plinth-level to avoid over-heating while under fire. Above it, two courses of fired brick were laid in cement-stabilised site soil, and two additional courses of fired brick, in mud mortar, as the bottom course of brick could be under-fired.

5.11.2 The products

[89] The architect of the project was Suhasini Aiyer- Guigan and the Technical Consultant for Earth Construction was Satprem Maini, with a previous work experience in CRATerrre, Grenoble. His technical support enabled that the soil from the site was also useable for the construction of the building's foundation reducing the need for fired bricks to be purchased to initiate the building, where as the previous buildings still required brick foundations.

[90] Damp Proof Course

In the first 10 experiments products were restricted to high-quality table-moulded bricks and tiles. Diverse products such as hand-extruded drain pipes glazed toilet-pans, gargoyles, window *jaalis* and glazed tiles were tested in small quantities. Unlike bricks and tiles, such sophisticated products do pay for themselves, and also partly cover the cost of firing the structure. (Fig 5.39 and 5.40)

Fig 5.39 and 5.40, Product diversification, 1990, Source: Ray Meeker

Fig 5.41 Smokeless chula, 1990, Source: Ray Meeker

Given the challenge of building these houses at Rs 10,000 each over such a small-scale two vault system, a much-higher return had to be fetched from the product sales. The product would have to subsidise the cost of building as well as that of firing the house.

Value addition to the products was attempted by designing a series of simple household items that could be produced by training a group of local potters. Candle-stands, hanging planters, oil lamps, garden stools and lanterns were made and transported to the building site for firing. Some, 250 smokeless *chulas*[91] (Fig. 5.41), to serve the needs of a nearby village, were also fired. The *chulas* did not yield a great return, but demonstrate the use of the house-kiln to fire appropriate items for village economy.

Table moulded bricks and tiles constituted about 60 percent of the product load. Even though the sophisticated products fetch better returns, sufficient quantities of ‘heavy’ clay ware must be fired to create the thermal mass necessary to penetrate walls and vaults through and through.

5.11.3 Preparation for the firing and the firing

[91] Local term for fire wood cooking stove

Fuel consumption can be kept to the minimum when the flame path, or heat path, is stretched to the maximum. For this two-vault test the attempt was to minimise fuel consumption by using the longest flame path for the given size of the structure- by firing horizontally down the length of Vault No 1, passing the heat into Vault No 2 reversing the direction of the flame and, once again, firing horizontally in Vault No 2. Temporary chimneys were built at the end of each vault, to provide the necessary draft.

The vaults were insulated with the typical combustible mixture of rice husk, cow dung and clay. When the temperature of the interior reached 500°C the insulation began to burn as expected. This slow combustion continues until the firing is completed or even longer, and resulted in a well-stabilised vaulted roof exterior.

The AVIRC houses were slowly and continuously fired for 5 days. A slow fire minimises the damage to the sensitive products by thermal shock, and penetrated more deeply into the walls and vaults while minimising structural distortions. The fuel, in this structure, was wood –Acacia Auriculiformis, 4,800-4900 kcal/kg and harvested from the now-abundant Auroville forest[92]. 8 tons of wood and 655 bundles of *malaar*- casuarina tree tops- were needed to fuel a fire that sufficiently heated the two-vault system to 950° C.

Fuel consumption of 6,800 MJ/1,000 bricks was achieved for bricks and structure combined.

5.11.4 Finishing

The fired structure was finished by a variety of conventional techniques. Standard cement based plaster was applied to the exterior of all vaults and walls; with special care at the critical points where two vaults meet, and at cornices over the walls. A small courtyard

[92] As part of the successful reforestation program these trees were abundantly planted on barren and soil-eroded land as pioneer species. The barren land was completely regenerated and is unrecognisably green within a span of 25 years. This tree has a very short life, quick growing and is intended to be replaced by appropriate diversity of other tree species.

with kitchen, bathroom and toilet were added in fired brick and cement-stabilised soil mortar after firing.

5.11.5 Important Firing Results

The products fetched a large sum of Rs. 105,000 due to the amount of sophisticated products that could be supplied to boutiques. These products cost Rs. 65,000 to produce and generated a profit of Rs. 40,000 which covered the cost of fuel as well as Research and Development expenses of Rs. 5,000. The important result was that the production of appropriate products was able to actually subsidize the entire process of stabilization and a stable house could be provided within the budget allotted for the Economically Weaker Section of Rs. 10,000 per house.

The structure was overall well fired. But due to one area not sufficiently fired, was damaged after firing in a 14cm unseasonal downpour. Though enough fuel was used to stabilise the structure, Meeker's faulty placement of the fireboxes left the common wall insufficiently fired. Water saturated it. Nearly a third collapsed. Both vaults, well fired, stood. The wall was repaired with fired brick. Meeker felt fortunate though to experience this- to underline the importance of firebox placement. This experiment was important in striking a balance between an efficient and sufficient use of fuel.

5.11.6 Occurrences that were significant in developing the technology as a whole

A longitudinal cross-draught kiln was tested and resulted in further fuel efficiency: The importance of firebox placement was learnt. The inclusion of sophisticated products to the tune of 40% could offset costs and actually substantially subsidize the cost of the house, over and above the recovery of fuel costs by the products alone.

5.11.7 Fact File

Location: Auroville, Tamil Nadu

Condition: The two vaults are being used since construction as a watchman's residence. The vaults are not in good condition, and his toilet bathroom and kitchen are leaking, as the watchman said that the open to sky courtyards were later covered with *kadappa* stone slabs to gain space. This was not part of the original project. The leakage in the vaults could be due to settlement in the extremely clayey soil, as was estimated to have occurred in the adjacent buildings which also faced floor cracks and also cracks in the load bearing walls.

Client: Auroville Visitors' Information and Reception Centre

Builder: CSR, Center for Scientific Research, Auroville

Year of Construction: 1990

Construction time: Prior to firing: 1 month
Loading, firing, cooling, unloading: 3 weeks
Finishing: 6 weeks

Dimensions: Two vaults of 6m x 3m x 3.5m

Carpet Area: 36 sqm.

Form of roof: Two connected vaults

Type of walls: 1.5 meters high, 340 cm thick mud walls

Fuel: 8 tonnes of acacia auriculiformis, harvested from the now abundantly planted local forest, 655 bundles of casuarinas *malaar*

Products: 60% of the products consisted of table-moulded bricks and tiles. The rest were boutique products such as candle stands, hanging planters, oil lamps, garden stools and lanterns. Around 250 smokeless *chulas*[93] were made to serve the local area's need for improved cooking conditions.

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: varied from 950°C

Duration of Firing: 5 day slow firing

Fuel Efficiency:

Heat required per 1000 bricks for products alone: 12,193 MJ

Heat required per 1000 bricks & structure: 6,800 MJ

Kiln description: Longitudinal cross-draft kiln

[93] Local term for firewood stove

Special steps taken towards the technology: The most important step was the value addition of sophisticated products that could fetch a much higher return and make the technology truly an affordable one.

5.11.8 Cost Accounting

Total cost of const ruction:

Material: Rs. 33,000

Labour: Rs. 22,000

Total: Rs. 55,000

Cost: Rs. 85/sqft

Return on product: Rs. 40,000

R&D expenses: Rs. 5,000

Total profit: Rs. 35,000

Cost of built-up area: 75,000

Product -subsidised: Rs 55,000

Total cost of built-up area: Rs20.000 or Rs 31/sqft

To understand the cost accounting figures, it must be noted that these would apply to small systems specifically, and that the experiment was specially targeted at such small systems as simple houses, and that the accounting would be very different in a larger scale.

The built-up area of the two houses of approximately 60 sqm was estimated to cost Rs 55.000 with finishing, which if achieved would mean Rs 90 per sqm, inclusive of all post-firing costs of waterproofing, toilet, bath, kitchen, doors, flooring, electricity, septic tanks, and plastering inside and out. These figures were based on the assumption that all the fuel would be accountable to the product, with no additional returns from the product sales.

However as only Rs 20,000 was earmarked for the two houses, an additional Rs. 35,000 had to be generated from the product sales. The Center for Scientific Research (CSR), in Auroville coordinated the funding of the project and provided a loan of Rs 50,000 towards the making of the product fired in the two rooms.

Ray Meeker himself raised the question, “How realistic is this accounting?” which he answers thus: “Perhaps, not very. There is no contractor's percentage, and nothing for the considerable effort required to orchestrate the near-improbable mélange. Yet, further development of the process will reduce building costs and increase the product value.”

And yet Meeker felt the value in pursuing his research and pointed out that a further fifteen percent could be have been saved on building costs if suitable clay for the fired brick would have been available at, or very near the site, which, unfortunately was not available in this case. All the building and product clay had to be transported from 20-30 km. In a larger site-and-service scheme, the waterproofed vault-and-service core could have absorbed a variety of the fired products in their finishing. The client could have finished the house as his income permitted.

A further challenging implication of the products successfully subsidizing the cost of the house emerged. This way of financing housing is highly unconventional given that an additional amount of Rs 40,000 - 50,000 would have to be made available in advance to be able to produce the product, to have a house that costs Rs. 20,000.

In spite of these reflections, for Meeker it was enough for the moment to confirm and demonstrate that the potential to generate income exists. How to distribute them after production would have yet to be worked out.

5.11.9 Conclusion

Reasonable fuel consumption was realised. Though not as efficient as a Hoffman, Habla or Bull's Trench Kiln[94], the two-vault system fired longitudinal cross draft, for its size, was quite efficient and comparable to the local scove.

This was the first time true economy in money terms was achieved through high profits from product sales.

[94] See section 9.4 on kiln systems

At this stage Meeker having solved that earth structures can be stabilized *insitu* and be subsidized through product generation, was preoccupied with fuel efficiency, and was beginning to worry about technology transfer. Realising that he was in a rather unique position, developing the fired building process, Meeker worried that “the transfer of technology would pose problems; as will, quality control. Under-firing could prove to be disastrous. The traditional builder cuts costs by lean cement mixtures; the maker of fired houses may cut costs by inadequate firing.”

5.12 Golden Bridge Pottery: Coal Firing Experiment, Pondicherry

Fig 5.42 Test in coal-dust firing, 1990, Source: Ray Meeker

Fig 5.43 Coal dust in combustible insulation, 1990, Source: Ray Meeker

Meeker initiated this experiment on his pottery site in order to look into the prospect of fuel efficiency that can be achieved if the bricks themselves contained a combustible material (Fig 5.42). The idea is then that the additional fuel could be reduced to the amount needed to light the structure at the base. Thereafter the fuel content in the bricks of the structure as well as the products would be able to keep the fire going by self burning and thereby spread into the subsequent upper layers. The mortar too would be made of the same mixture.

Coal dust was procured from Neyveli, for this experiment and 5% of it by volume was mixed in the brick clay mixture.

5.12.1 The raw mud structure

The main difference in the construction of this structure was that the brick clay was had to be prepared by adding 5% of coal dust into it. The mortar too had the same proportion of coal dust. Apart from this the structure was a simple single vault that was built in the standard way.

5.12.2 The products

The main difference in the products was that the table-moulded bricks too were prepared by adding 5% of coal dust into the brick clay.

5.12.3 Preparation of the firing and the firing

The plan was to start a fire in the kiln by stoking as in a regular wood firing to get the products to begin to ignite and burn with their own fuel content, but this didn't happen as hoped. Meeker was not able to understand at once what made it not work, and eventually after having given up, it was fired using the regular method with wood as fuel, even though fuel (coal) had already been added into the brick clay.

5.12.4 Finishing

5.12.5 Important Firing Results

Meeker couldn't get the fire going and he knew he was doing something wrong but in spite of several attempts he couldn't manage to get this to work. It could be that there was insufficient air movement in the draft system.

Later on in 1999 in Bina Saxena's house, when he did manage to succeed in firing a structure with coal dust as fuel, he had placed a bed of coal at the bottom layer of the structure to get it to catch fire. In this structure he had been stoking like in a wood firing but in vain. Finally he gave up and had to fire the structure and products as a regular wood firing in spite of the fuel content. The figures of this experiment therefore are not important as the project used twice the fuel as intended due to failure of the original experiment.

This example is still relevant in that it was the first structure in which Meeker had already began to test the potential of coal dust as a fuel alternative in his quest to improve fuel efficiency. It becomes all the more relevant as he did not fully abandon this idea, but returned to it first in the Nrityagram Temple at the outskirts of Bangalore, and later in the last two projects: house for Bina Saxena and Bina Saxena's pottery studio.

5.12.6 Occurrences those were significant in developing the technology as a whole

As the fire would not ignite, the effect of using coal dust could not be known on the structure and products and neither could it be compared for fuel efficiency and cost efficiency.

It was understood that if the idea of coal dust as fuel was to be further pursued then some other solution would have to be proposed that would sustain the initial fire until the clay products and walls containing coal dust would catch fire and begin to burn from its own fuel content.

5.12.7 Fact File

Location: Pondicherry
Condition: It has been taken down and no longer exists
Client: None
Year of Construction: 1990
Construction time: 2 months
Dimensions: 4m x 3 m
Carpet Area: 12 sqm
Form of roof: single catenary vault
Type of walls: none

Fuel: lignite coke dust as an additive in the brick mixture, apart from fuel to start the fire at the base. Later when this didn't work, then wood was used as usual

Products: mostly bricks, but some hollow conical roofing tube units, an order placed by the author, architect for a 'House for Pierre Tran' in Auroville

Insulation: A combustible mixture of 2 parts rice husk, 1 part coal dust and 1 part clay in a 10 cm thick layer (Fig 5.43)

Firing system: The products and structure were to be fired not by allowing heated air to circulate, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact.

5.12.8 Conclusion

The experiment had failed as the fire didn't manage to get going as planned, but it was not clear what was wrong. It was only understood that some other solution would have to be proposed that would sustain the initial fire until the clay products and walls containing coal dust would catch fire and begin to burn from its own fuel content.

However in spite of the failure of firing the structure as intended, the structure and products were then salvaged by investing a lot of wood as fuel again and firing it in the regular way.

5.13 Satyajit's House, Auroville

Fig 5.44, 5.45, 5.46 The plan for Satyajit's house is freed from looking like a kiln, 1991, Source: Ray Meeker

By 1991, when this project was undertaken, the most important technical problems in firing a house were solved.

The aim in this project was to come up with a more liveable and friendly house plan (Fig 5.44, 5.45, 5.46) given the limitations the technique had to accept in terms of roof forms of vaults and domes and serving the function of a kiln.

At the same time there was an attempt to optimize the fuel efficiency by opting for a semi-continuous kiln firing system.

5.13.1 Description and plan of the proposed structure

The house was composed around a central vault containing the living space (8m x 3m wide and 4.6 m high) flanked by two domes placed on either side of the vault at either end. At the end of the living room vault, another vault was placed. The domes were supported on leaning thick walls. The dome to the left of the central living space accommodates a bedroom. Squinches convert the square plan into an octagon, creating corner niches that partly absorb shelves. All corners we rounded off in the interior to harmonise with the rounded shapes originating from the roofs. The other domed room was planned as the study. A vaulted room was attached to the study.

5.13.2 The raw mud structure

The leaning walls themselves were also a new feature. Normally external buttresses would be necessary to support the load bearing walls upon which a dome sat, and these buttresses would mean a lot of extra mass of earth walls and there was also no space for them. Hence leaning walls were introduced.

The leaning walls further enabled that the square plan below the dome could in fact be much bigger than the dome diameter itself and thereby provide a larger useable area for the same span. For example, a 4 meter dome could enable a square plan of 5 meters x 5 meters. The base of the leaning walls therefore began at the outer edge of where the buttresses would have spread, and the leaning walls become self buttressing and remaining in total compression.

There was a challenge to be solved in constructing these leaning walls after a point though. As a result of leaning walls the radius of the squinch was different from the base towards the top and the center itself also keeps changing, as it shifts progressively backwards towards the top due to the leaning wall. The fabrication of the doubly-curved raised leaning squinch trammel[95] enabled the construction of the squinch in a context of leaning walls.

Another step was the acceleration of vault construction that was enabled through the development of a light steel frame catenary guide of 6mm rods which helped to ensure that the shape was being strictly adhered too. This did speed things up to be able to build up to 2 meters of vault length per day.

5.13.3 Products

Table-moulded bricks, glazed tiles, and terracotta planters were the main products. The planters that were part of the products were used as saggers (containers to protect sensitive glazed articles from the dusty and dirty atmosphere within the inside of kilns). Products have thus to be thought in terms of their stacking and firing within the kiln. Later the planters as well as the glazed tiles fired within could be sold.

5.13.4 Finishing

Built in furniture was added after firing and ferro-cement louvers were introduced in the upper part of the vault to cut the glare and rain while allowing ventilation. Within the thickness of the buttresses window seats were accommodated. A wooden staircase was added to access the loft. The loft procured light from the vault opening at its tip. The study had built in counters for worktops.

[95] Meeker was so challenged with solving this tool and so satisfied with the trammel that he mentions it as probably the most interesting thing that he had enjoyed developing in all those 12 years.

Meeker hadn't agreed to a lot of what Satyajit wanted to do with but finally reflects that maybe some of the things turned out to be better than his own proposals.

5.13.5 Important firing results

The structure was well cooked. The products were well cooked and sold off.

5.13.6 Occurrences those were significant in developing the technology as a whole

This was the first time that a house plan began to look like a house rather than an efficient kiln.

5.13.7 Fact File

Location: Auroville, Tamil Nadu
Condition: Still in good condition. Find out who now lives in it after Satyajit moved.
Client: Satyajit
Builder: Meeker delivered the raw structure but Satyajit, the client stepped in and took responsibility for the finishing
Year of Construction: 1991
Carpet Area: 100 sqm
Form of roof: Two vaults and two domes
Type of walls: Leaning walls were introduced below domes instead of buttresses.
Fuel: Casuarina fire wood, quantity was not recorded
Products: Table moulded bricks, glazed tiles and terracotta
Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.
Temperature reached: not recorded
Duration of Firing: not recorded
Kiln description: semi-continuous kiln

Special steps taken towards the technology: Freeing the plan from the technical limitations was the main point of this exercise.

5.13.8 Costs

The house with a total area of 100 sqm cost just Rs. 2,00,000

5.13.9 Conclusion

The house from freed from the typical kiln-based plan and its restrictions. A reasonably large house was created with this technology for a client that didn't come with the cost limitations of some of the previous targeted low-cost housing sector.

5.14 Marta's House, Kottakarai, Auroville

Fig. 5.47 Marta's house, a composition of 2 domes, 1991, Source: Ray Meeker

This was mainly the attempt to do a small and modest but comfortable house for a person who is not so much in need for a low-cost solution as a solution towards being able to live with as less as possible. (Fig. 5.47)

5.14.1 Description and Plan of the structure

A 5 meter diameter dome sitting on a square base with rounded corners is the principle structure containing the main living space, and at the outer edge of one of its corners, there is a projection containing the bathroom. The bathroom is roofed by a smaller dome of 2.25 meter diameter. The leaning walls introduced in Satyajit's house were repeated.

5.14.2 Products

Apart from fired bricks and tiles, a terracotta mural designed by Vineet Kakar, one of Meeker's students at that time working on the project was produced to fire along with the house to later adorn the entrance area. (Fig. 5.48 and Fig. 5.49)


Fig. 5.48 and 5.49, murals and tiles baked in the house, 1991, Source: Ray Meeker

5.14.3 Finishing

The dome has an opening at its tip which is covered with a ferrocement cap leaving a gap for letting out the hot air and facilitating the ventilation. A water channel surrounds the house which while being a pleasant feature also intends to act as a barrier to ants. This is often seen in houses in Auroville, referred to commonly as 'ant channel' and has been also included in the finishing of this house. Outdoor wide built in seats allow the living space to expand to the outdoors in two areas, one of which is the entrance. Blue glazed *jaali* were built in to protect the windows without preventing ventilation, and eliminating the need to use glass or any other shutters.

5.14.4 Important firing results

The structure was well cooked. The products were well cooked and sold off.

5.14.5 Fact File

Location: Auroville, Tamil Nadu

Condition: Presently abandoned and not maintained. After the client, Marta, returned to Columbia, this place was home to several people. One of them was Harini who left it in 1999. Harini in an interview expressed her happiness and joy to have lived there. She particularly mentioned that the space was always cool inside, comfortable and very spacious. She fondly remembered the built-in benches inside which she liked and used a lot. The structure is still in good condition, except for one spot between the 2 domes which seemed to be leaking. This can result when structures are abandoned, and if the leaves that are shed on the rooftop are not swept out periodically and block the drainage of storm water. It was not possible to determine if the structure was leaking due to this or other cracks.

Client: Marta

Year of Construction: 1991

Carpet Area: 45sqm

Form of roof: A 5 meter diameter dome with a tiny 2.25m dome beside it

Type of walls: 2.4 meters high, 340 cm thick leaning mud walls

Fuel: Casuarina fire wood, amount not recorded

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: 900°C to 1000°C

Duration of Firing: just over 2 days

Kiln description: semi-continuous kiln

Special steps taken towards the technology:

Firing of the structure: The house was fired for just over 2 days.

5.13.10 Conclusion

Marta’s house was a simple structure to fire. It was also probably the easiest to repeat with a relatively untrained crew.

5.14 Housing for Minolta Aquatech ITC[96], at Tuticorin

Fig. 5.50 and Fig 5.51 The large scale housing project at Tuticorin allowed further fuel efficiency, 1993, Source: Ray Meeker

This was a project that would allow the testing of the technology in terms of efficiency that can be achieved at a larger scale. This however would not be for the low-cost sector but rather for a middle-income group housing example for the corporate sector. Minolta Acquatech was a shrimp farm venture, a pilot project they wanted to initiate in Tuticorin and the hence there was the need for the middle-income housing project.

5.15.1 Description and plan of the structures

The housing project comprised of 4 family houses, five bachelor apartments with a common kitchen and recreational area, an office and a laboratory (Fig. 5.50 and 5.51).

5.15.2 Firing results

The products, mainly bricks with a usual assortment of other terracotta products including a mural, were well cooked. A significant portion of product bricks were used to build the foundations, compound walls, etc in the subsequent structures on the same site. The structures were well cooked.

[96] Indian Tobacco Company

5.15.3 Occurrences those were significant in developing the technology as a whole

This was an experience in working for ‘corporate India’ which though not as bureaucratic as the Government, was still inconvenienced greatly by the bureaucracy. For example they had got held up for months on making raw bricks because they insisted on paying brick-makers by cheque. Brick makers usually don’t have bank accounts and it took them months to clear cash payments to brick-makers so much so that they then ran into the monsoon period.

Ray Meeker had given them rough estimates based on built-up area. He has said it would cost Rs 150 to 200 and if there was no nearby clay then it may go up to 15-20% more. It did go over budget but only slightly.

In May there was an untimely rain and cyclone.

The project of shrimp farming too faced a big disaster. The first batch of shrimps caught a virus and all died. And immediately the project was converted into a training center on shrimp farming and it was decided to train others on shrimp farming and themselves only be involved in buying and selling of shrimps.[97]

5.15.4 Fact File

Location: Tuticorin, Tamil Nadu

Condition: All the structures A, B and C still exist in fairly good condition[98], but presently not in use with the exception of one vault that is being occupied by the watchman. After the shrimp farm project was abandoned these structures were left locked and unhabited. Yet these locked structures, as is still clearly visible, seem to be in good condition.

[97] Ray Meeker remarked during the interview in this regard “how people give up very easily the moment they see a loss.” He himself doesn’t give up so easily, but that’s why they are making money!

[98] The structures are in excellent condition even though they haven’t been inhabited for years. Meeker commented upon being shown the pictures taken recently, in his humorous style that he wondered if they would have been still in that good condition had they been inhabited!

Client: Minolta Acquatech, a subsidiary of the Indian Tobacco Company (ITC)

Builder: The clients paid the material and labour directly while supervised the whole thing.

Year of Construction: 1993

Construction time: 15 months

Carpet Area: 80000sqft

Form of roof: 20 vaults and domes

Fuel: Casuarina fire wood, amounts not recorded

Products: Mainly bricks a lot of which were used in the same campus and for foundations of subsequent structures, and the usual assortment of other terracotta products including a mural

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Kiln description: semi-continuous kiln

Special steps taken towards the technology: The first experience in large scale, and the possibility of a larger village enterprise in product manufacture.

Firing of the structure: The series of vaults are connected with flues through the common walls to divert the waste heat of one space to preheat the next.

5.15.5 Conclusion

The project needed half a million bricks for building the structures alone, and then the products that would have to be stacked inside the spaces before firing. Fuel efficiency was optimum due to good use of 'waste heat' from firing process being diverted to preheat the subsequent structure. This demonstrated the potential for a small village enterprise.

The project proved that through this new dimension to earth architecture stabilized by fire, a high quality and climatically comfortable space was definitely possible in low-moderate cost budget. However this scale of project also stressed that availability of brick clay on or near site was a major factor in the appropriateness of this technology.

5.16 Low-cost Housing in Ayothiyapatinam, Salem


Fig 5.52, Low-cost housing, after firing, 1993, Source: Ray Meeker

Fig 5.53, Low-cost housing, present condition, 2007, Source: Josephine Hansen

This project was an attempt at low-cost housing for the rural poor supported by the District Rural Development Agency (DRDA) of Tamil Nadu Government. (Fig 5.52 and 5.53)

This was a jump from a corporate context of the previous experiment to a government context and it ended in a disaster after the original interested officer, the Additional Collector was transferred to another place. The officer had had some special budget to spend and was keen on fired housing and after Meeker had submitted detailed estimates, he received the go ahead to start the project.

The interesting thing about this project was the opportunity of attempting a technology transfer that could test if other persons could develop the skills to use this technology.

5.16.1 Description and plan of the structures

50 single-vault houses were laid out and construction commenced. While some bricks were produced, uncooked bricks were also bought directly from brick-makers.

5.16.2 The raw mud structure

Ten single vault attached structures were built out of 50 planned units in what by now was the standard design for low cost housing units. The exception was that the wall height was reduced to 1.25 meters to economise the costs.

5.16.3 Firing results

Six structures were fired and the other four were left to be fired by the engineers who had trained on the site, but was never actually continued after Meeker's commitment was delivered. The products and structure were well cooked.

5.16.4 Occurrences that were significant in developing the technology as a whole

Although Ray Meeker had expected there to be good enough on-site clay, it turned out not to be so, and when he had scanned the area, the price quoted for raw bricks seemed to be really cheap. Later by the time the construction started however, the brick was only available at twice the cost. Meeker had warned the client that the whole thing may not be viable at all, as it implied a significant cost increase. But they wanted to go ahead anyway.

There was a lot going on due to the fact that there was an exchange between golden bridge potters and village potters, The Tuticorin engineer had been there to teach this to the new engineers. School kids from the villages made beads for necklaces, and whistles and little Ganeshes (idol of a deity) with the help of moulds provided by Meeker. It was quite enjoyable as Meeker would go there in the mornings with clay and come back in the evenings with all kinds of products.

Next to the site there was a standard concrete technology housing that was provided also by the Government. It was interesting that the villagers had upon seeing the new project had wondered why they couldn't have had beautiful houses such as those, as their own houses all leaked. Every single house leaked, they told him, and that in the day time the workers came and put in all this steel and in the night time, every other bar was removed, or that they used for a truck load of sand only one cement bag. There was evidently mistrust in the area and also corruption. But Meeker was of the opinion that the prices at which they are expected to produce a low-cost but permanent house are also so unrealistic that it would be anyway impossible to do it well.

5.16.5 Fact File

Location: Salem, Tamil Nadu

Condition: The structures are still inhabited by the families that inhabited them, and they have maintained their houses really well, white-washing the surfaces regularly with lime. The people finished the houses themselves after seeing the way Meeker had finished one vault. One lady remembered him very fondly and recalled the time of the construction which was 14 years ago. As the space requirements of the family grew, the families started extending the structures on their own.

Client: DRDA, Tamil Nadu

Year of Construction: 1993

Construction time: Within six months, as per Meeker's contract with them, 10 houses were built, six were fired and 1 was finished. Since it was a technology transfer project Meeker felt that it was fine to leave them to continue as they had learnt each stage and one had reached its finishing, and so he stopped his engagement. Meeker found out that they didn't continue after he terminated his visits there and the houses which were not fired probably were left to melt in the rain.

Dimensions: Single vaults of 3 m x 7 m each

Carpet Area: 50 vaults of 21 sqm each, 1050 sqm

Form of roof: single vaults

Type of walls: 1.25 meters high, 340 cm thick mud walls

Fuel: Casuarina fire wood, amount not recorded

Products: Bricks and assorted products

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: not recorded

Duration of Firing: not recorded

Kiln description: Semi-continuous

5.16.6 Costs

The estimated cost per unit was Rs 15,000.

5.16.7 Conclusion

The technology transfer aspect of the project was really successful and DRDA engineers were taught how to do it and they managed very well. This was a project with a lot of potential but Ray Meeker hadn't had the patience needed to work with Government and their ways and so it was not possible to realize this potential fully. The fact that there was a change in leadership had also affected the project badly and it didn't make the situation any easier, and sadly after Meeker finished his 6 month term, in spite of the team having learnt all processes by then, the project did not see completion.

It did prove in spite of being unfinished that the technology could be transferred, since young Indian engineers managed the construction as well as the firing.[99] Labour could be allotted even upto 80% as material cost is minimal.

5.17 Housing for Volontariat Farm Workers, near Saiderapeth, Pondicherry

A row of low cost single vaults for housing of farm workers, this project was like picking up from where the left at Salem. It was a project about doing what well what was already known how to do. It was for the same client Mme. De Blic, of Volontariat[100] whom Meeker had already built test structure 8 for.

[99] DANISCH, Jim. Ray Meeker's Fired Houses, *Ceramic Monthly*, a publication of the American Ceramic Society, Ohio, January 2001 (pg 49-52)

[100] Detailed description is provided in Section 5.8

The structure consists of 9 interconnected vaults interspersed with courtyards and would house 6 families (Fig. 5.54 and Fig. 5.55).

Fig. 5.54 and Fig. 5.55, Housing for Volontariat farm workers, 2007, Source: Josephine Hansen

Occurrences those were significant in developing the technology as a whole

The project was severely affected by an unexpected cyclone in the month of May. The tarpaulin was blown off in spite of having been securely tied over the structure. 20cm of rainfall was received that night, over the mud structures that had lost their tarpaulin protection. It was a complete washout, far beyond any rain damage seen in the HiDesign factory project. Nothing was salvageable and the loss was immense, as 5 vaults had been completed and 3 or 4 were even stacked with products. The project had to be started afresh all over again.

Fact File

Location: Tutiput, Pondicherry

Condition: A group of gypsy families are living in these houses and up to 8 children sleep in one vault. The houses were notably cool inside. As it has never been repainted - since completion 13 years ago- a few dark patches of fungus can be seen although the structures themselves seemed to be in very good condition.

Client: Volontariat Aid Organisation, Pondicherry

Builder: ‘Creations’, Gautam Chatterjee

Year of Construction: 1994-1995

Construction time: unknown

Dimensions: 3m span vaults of varying lengths of 5.5 meters to 7.5 meters

Carpet Area: 255 sqm

Form of roof: single catenary vaults

Type of walls: 1.25 meters high, 340 cm thick mud walls

Fuel: Casuarina fire wood, amounts not recorded

Products: Bricks and clay whistles for export

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: not recorded

Duration of Firing: not recorded

Kiln description: semi-continuous

Special steps taken towards the technology: There was a local contractor who took up the responsibility of the construction, with Meeker holding less responsibility.

Costs

The cost was a disaster, due to the severe damage in the cyclone.

Conclusion

Even though the client was very happy with the houses themselves, they were very unhappy with the costs. Ray Meeker didn't feel responsible towards this and also didn't think that this was the contractor's fault as he had been regularly wrapping the structure with tarpaulin.

5.18 Temple for Nrityagram Dance Village, Hessaraghatta near Bangalore


Fig. 5.56 Fired Temple, 2002 Source: Anupama Kundoo

Fig. 5.57 Terracotta decoration, 2002, Source: Anupama Kundoo

This project was again a major breakthrough as the bricks for building the structure were mixed with combustible material, as in the attempt of Golden bridge coal firing experimental vault, so that they would be able to fire themselves once enough starting heat was provided. This meant that fired structures could be produced for no more fuel than the local brick-makers. This time it succeeded.

The fact that it was a temple and not a regular house; it gave the opportunity to do all sorts of additional things in terracotta to adorn the temple.

5.18.1 Description and plan of the structures

Protima Gauri, a well known classical dancer had approached Meeker to design a temple for her dance village, Nrityagram, on an existing plinth which was planned for a temple that had always been part of her total vision for the colony. Although Ray Meeker had hesitated in taking up the project saying, “I mentioned the fact that 1 was not quite up on the relevant Shastra, to which she gave her most dismissive wave of the hand”, and he recalls, “Gerard D'Cunha's[101] plinth looked "Shastra-ish" — full of number nines — and I did maintain that much in dimensional integrity.”

[101] previous architect of the project who had put up the plinth

On one of his earliest visits to the site, when Meeker had been scouting around for local brick-makers, he discovered that the bricks in this area were fired by incorporating coal dust in the clay mixture. This opened up a whole new area of experimentation as this development he felt could really make the whole technology viable. The clay mass burned with its own internal fuel and needed only a small quantity of wood to start the fire. This gave Ray Meeker the enthusiasm necessary to experiment further, as he was sure that this was a way to save a lot of energy, the most important of several flaws in the technology. In fact he had tried this method- with limited success- in a small test structure in the pottery compound in Pondicherry, but when the brick maker Govindaswamy agreed to supply sun dried bricks- coal filled- as well as mud and coal dust for mortar and coal for the firing itself, Ray was confident that a stable structure could be achieved.

5.18.2 The raw mud structure

The structure was built with coal infused bricks and similar mortar. The structure was a tapering square plan, with leaning walls of 34 cms thickness, and held a very high corbelled dome of 5 meters height.

5.18.3 The products

The products were all bricks. The terracotta pieces used to adorn and finish the structure were later produced in Golden Bridge Pottery and brought for installation.

5.18.4 The preparation of the firing, and the firing

The heat moved from the base where the fire was introduced and when sufficient temperature was reached both the product bricks as well as the structure bricks would burn by themselves and pass the fire to the next levels above. When the combustible coal dust in the brick was spent, the brick would begin cooling. A 5% of coal dust was tested to be the adequate amount of coal dust to be added for transforming the vulnerable clay into durable brick.

5.18.5 Finishing

The outside surfaces were plastered.

Meeker adorned the temple with terracotta murals, relief sculptures and other decorative elements at the tip, spines, cornices and important edges some terracotta cladding. Ray had never really done sculpture. This was inspired to some extent by the ancient terracotta temples of Bengal. Ray admits that these were his first sculptures of actual people. His murals were 'Mirrors of the five senses', in terracotta, adorn the four faces of the dome. Preparation for the dance applying the make-up is reflected in five oval mirrors with accompanying hand mudras, the conch for sound, a bee landing on a lotus for taste, putting jasmine in the hair for smell, applying the bindi on the forehead for touch and applying kajal in the eyes for sight. The patterns on the Odissi saree borders influenced the design of the dome, spines, bells are used in a band between the double cornice and the base of the shikhara -the crown - is ringed in jasmine. When Ray Meeker heard of Protima's death, he had been working on the last of the mirrors, and in response to the landslide had added the water, mountain and cloud to the already shaved head in a kind of 'out of this world' headdress to try to incorporate a feeling of that final pilgrimage. The two large reliefs were finished -full figures - one of Kelucharan, planned for the inside of the temple and the one of Protima for the outside, Kelucharan representing more or less the soul and/or revival of the Odissi form and Protima the propagator. It seemed to Ray appropriate to reverse this with the death of Protima, emphasising the temple as Protima's parting gift to Nrityagram and to her many friends and well-wishers.

5.18.6 Firing results

The product bricks were well cooked. The structure was well cooked overall but the dome was probably slightly under-fired in some parts in Meeker’s estimation.

5.18.7 Occurrences those were significant in developing the technology as a whole

Self burning of product bricks and structure bricks were attempted again after the failure of the previous experiment of the kind in Golden Bridge Pottery, and this time it proved successful.

This simplified the complex procedure of stacking the products to allow air flow. Instead what was now desired was compaction and contact between products. Another significant difference was that the structure didn't need to be constantly fed fuel according to the temperatures recorded. In this process it was enough to start a good fire and monitor it occasionally. There were no sleepless nights involved. And in any case if the temperatures were not adequate or too high, there was no way in which any adjustments could be made as there was nothing to be done after the products had begun firing. There were no controls possible in this mechanism and the only purpose for monitoring would be to rectify certain decisions in the next experiment.

5.18.8 Fact File

Location: Hessaraghatta, Bangalore
Condition: In very good condition. Is being used as planned
Client: Protima Gauri
Year of Construction: 1997-1999
Construction time: One and a half year
Dimensions: 3m x 3m on 2 m high walls with a catenary corbelled dome of 5m height
Carpet Area: 9 sqm
Form of roof: A single very high corbelled catenary dome
Type of walls: 35 cm thick leaning walls composite (fired bricks on the outside and clay bricks on the inside)

Fuel: Coal dust[102] mixed into the brick clay, in the structure bricks, mud mortar and product bricks. The proportion was as recommended by the brick makers in that area according to their conventional practice.

Fuel efficiency: Heat required per 1000 bricks: 3000 MJ

Products: only bricks

Insulation: A combustible mixture of 1 part coal dust, 2 parts rice husk, and a part clay in a 10 cm thick layer. Rice husk was omitted and it was later felt that the dome could have benefited from this addition as it would have opened up the structure of the insulation mixture and led to better firing of the dome.

Temperature reached: records missing

Duration of Firing: 3 days

Firing system: The products and structure were to be fired not by allowing heated air to circulate, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact.

5.18.9 Conclusion

It was a clear step in equalizing the fuel efficiency in bricks produced through in situ firing and those produced locally. The experiments had come a long way, starting with the basic construction, to product development, to increasing cost efficiency and fuel efficiency, from freeing the plan for liveable houses to now this step that included art, craft and decoration in architecture produced through this technology.

[102] Coal dust is usually procured from industries that need to use coal, by sweeping the floors, as it still combustible.

Coal is actually a nasty material, it is polluting and non-renewable, and its not just CO2 emissions, it is horrible for breathing, and coal mining is also deadly.

It would be interesting to find out how many trees you have to plant to absorb these emissions, to find out what the trade of is. How much CO2 a tree absorbs in how many years compared to how much CO2 it release when burned.

5.19 House for Bina Saxena, Bommaiyarpalayam, near Auroville

Fig. 5.58, Central dome of the residence, 1999, Source: Anupama Kundoo

In the previous structures Ray Meeker was able to reduce his level of involvement progressively as the technology evolved, the last experiments being taken up by outside contractors and in one case by local engineers in a technology transfer programme. In this structure it was the first time that even the architectural design was handed out and Meeker continued to supervise in particular the making of bricks, important stages in construction, and product stacking. He adopted the role of Firing Consultant and was responsible for conducting the firing, producing the additional products other than the bricks and as a consultant; he was involved in approving the architectural design.

The aim of this structure was to build upon the Nrityagram experiment and test the result of the coal dust mixture in the clay content.

5.19.1 Description and plan of the structures

Twinkie was a potter who lived in Pondicherry and had recently bought a piece of land adjacent to the canyons in Auroville. As that area was very sensitive not only environmentally but also visually, due the beauty of the natural landscape that was made up of the red textured surfaces of soil eroded land, the house was planned to merge into the settings as far as possible. The concept was that visually the red of the earth landscape would be carried into the house and the organic shaped walls would resemble that of the eroded canyon surfaces and furrows as if a natural extension of the same. As the structure had to be built around compression forms like domes and vaults, the leaning walls that became necessary, were continued even in the rest of the structure and helped to emphasise the structure of the canyons themselves.

As it was decided that the structure would be fired by the combustible content in the structure clay bricks as well as the mortar and products, the chief product to be built would be bricks. As this would be the first experiment of coal dust in the clay mix in that area and as ready bricks wouldn't be procured from local brick makers as this was not the usual practice in the area, it was decided that the experiment, which was a moderate to large size private house, would be too big an area to test and that it would need too many product bricks to fill. It was therefore concluded that the test would be contained in a 5meter dome which would be central to the house, and here bricks for the rest of the house would be produced.

5.19.2 The raw mud structure

The central dome structure to be fired had a 5m diameter and was built in composite brick work with external bricks being fired bricks and internal facing bricks being raw. The walls were 34 cms thick and leaning inwards to act as a buttress but without creating any additional mass. A catenary dome sat on these walls and was built by creating a internal frame for guiding the shape. A skylight was left at the top which also served as an outlet for the steam during firing.

5.19.3 The products

Products were mostly bricks, with some floor tiles interspersed in them.

5.19.4 The preparation of the firing, and the firing

The first row of product bricks were stacked by creating tunnels for carrying the coal layer that would initiate and sustain the fire until the coal in the bricks above would begin to burn. These tunnels were curved to reach the various external walls to end at openings that would source air for combustion. Sufficient voids were left for the steam to escape out from the chimney.

5.19.5 Finishing

The rest of the house was finished with product bricks and terracotta tiles made in the structure were used in floors. The client passed away during this phase, and the house did not get completed as per the original intention. The finishes were high budget as compared to the rest of the fired structures.

5.19.6 Firing results

The structure was well cooked with the exception of some patches in the exterior face of the dome that was under cooked, and some spots that were over cooked in the internal walls. The products were extremely well cooked with the exception of some bricks that were over-cooked.

5.19.7 Fact File

Location: Bommaiyarpalayam, near Auroville, Tamil Nadu

Condition: The structure is in good condition but after the sudden death of the client even before the house was complete, the project unfortunately was stalled for years and later completed gradually and randomly by her boyfriend Subhash, who proceeded to complete it without the architects and hence it did not even get built as intended.

Client: Late Ms. Bina Saxena

Architect: Anupama Kundoo

Builder: Kolam, a contracting unit headed by the architect, supervised by M. Vinayagam

Year of Construction: 1999

Construction time: 4 months for the test part

Dimensions: 5m dome

Carpet Area: 100 sqm

Form of roof: Catenary dome

Type of walls: 2 m high, 340 cm thick leaning composite walls

Fuel: coal dust infused in the brick

Fuel efficiency: Heat required per 1000 bricks: 3000 MJ

Products: mostly bricks, in two sizes, and some tiles

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: record lost

Duration of Firing: 4 days

Firing system: The products and structure were to be fired not by allowing heated air to circulate, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact.

Special steps taken towards the technology: The success of coal dust as a self contained fuel in bricks led to a leap in the fuel efficiency figures, and therefore also cost figures. It was the first time that a catenary dome was built.

Conclusions

New horizons opened through the success of coal dust as a self contained fuel in bricks. Fuel efficiency figures, and therefore also cost figures.

5.20 Pottery for Bina Saxena, Bommaiyarpalayam, near Auroville

Fig. 5.59 Pottery structure, 2006, Source: Anupama Kundoo

Fig. 5.60 Low wall height with composite walls, 1999, Source: Anupama Kundoo

5.20.1 Description and plan of the structures

The structure was a very small pottery studio (Fig. 5.59) built a few months after the house for the same client but finished earlier, being smaller and simpler, but also as unlike the house the whole structure was built in this technology.

5.20.2 The raw mud structure

The structure was a 16 sqm square plan with rounded corners, with a spherical dome sitting on it upon low 75 cm walls (Fig 5.60).

5.20.3 The preparation of the firing, and the firing

Fig. 5.61 Pottery being fired under a temporary thatch structure, 1999, Source: Anupama Kundoo

The description is exactly as the previous structure 19. A thatch structure was built temporarily during firing as unexpected rains were predicted. (Fig. 5.61)

5.20.4 Finishing

The building was finished with external plaster and paint with some over cooked bricks left un-plastered as a record of the process. The floor was tiled with terracotta tiles.

5.20.5 Firing results

The structure and products were cooked.

5.20.6 Fact File

Location: Bommaiyarpalayam, near Auroville, Tamil Nadu
Condition: The structure is in good condition but abandoned after the sudden death of the client just after the finishing of the structure, but even before the finishing of the main residence that was begun before the pottery.
Client: Late Ms. Bina Saxena
Architect: Anupama Kundoo
Builder: Kolam, a contracting unit headed by the architect, supervised by M. Vinayagam
Year of Construction: 1999
Construction time: 4 months
Dimensions: 3.5m dome
Carpet Area: 16 sqm
Form of roof: Catenary dome
Type of walls: 0.75 m high, 340 cm thick leaning composite walls
Fuel: coal dust infused in the brick

Fuel efficiency: Heat required per 1000 bricks: 3000 MJ

Products: mostly bricks, in two sizes, and some tiles

Insulation: A combustible mixture of 2 parts rice husk, 1 part cow dung and 1 part clay in a 10 cm thick layer.

Temperature reached: record lost

Duration of Firing: 3 days

Firing system: The products and structure were to be fired not by allowing heated air to circulate, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact.

Special steps taken towards the technology: The success of coal dust as a self contained fuel in bricks led to a leap in the fuel efficiency figures, and therefore also cost figures. It was the first time that such low walls were built to reduce the walls and firing mass.

5.20.7 Conclusion

The structure was more or a smaller version of the previous test.

6. Evolution of the Technology

As in the accompanying table, it can be noticed that at the earliest stage of development, i.e. Structure 1 to 6 the focus was on improving the earth construction to allow it to withstand fire and to improve the extent of firing through of the structure, which was first achieved in Structure 4.

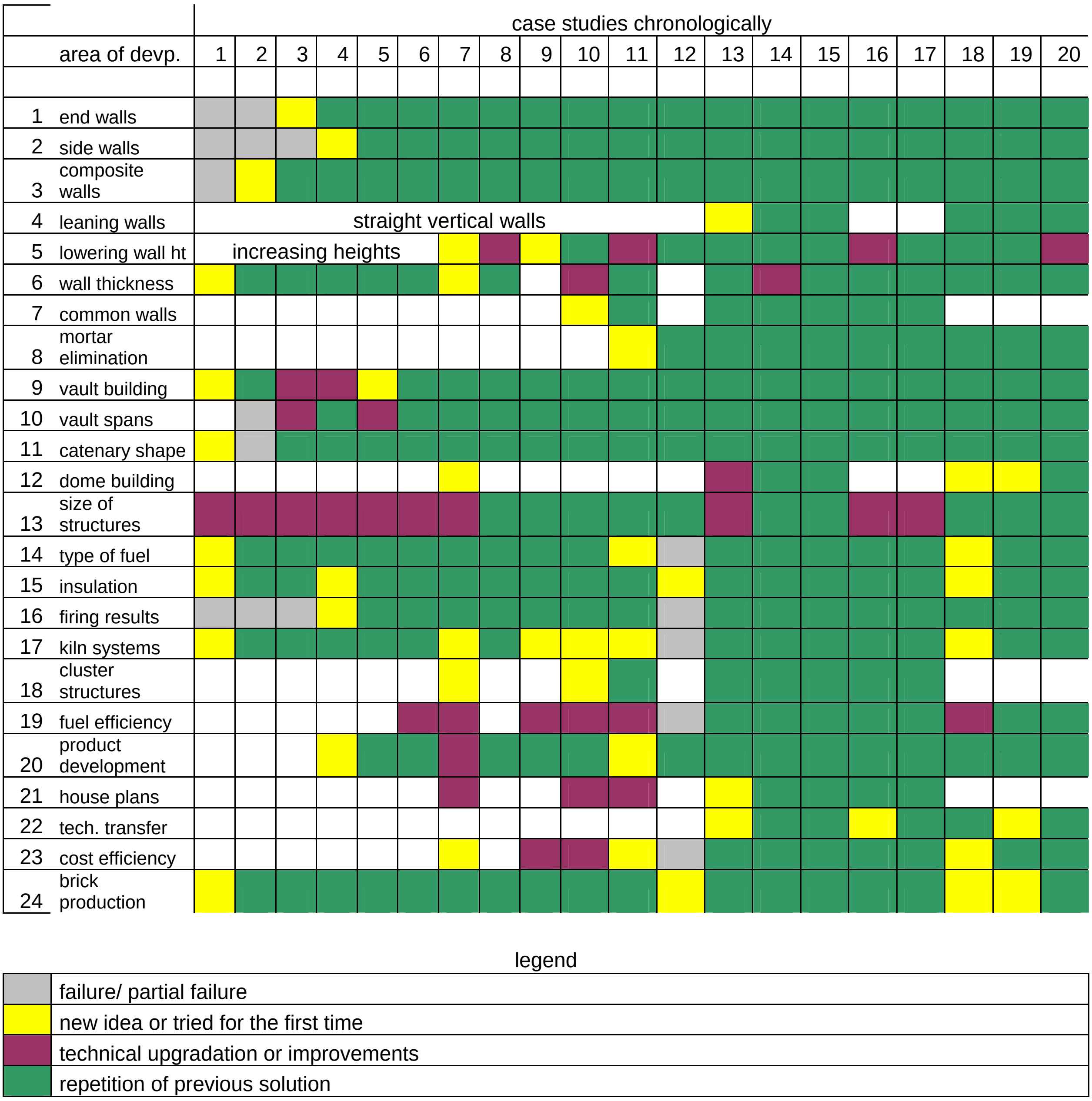
Structure 7 was the first time a regular house was built for a client and from Structure 7 onwards, the fact that large earth structures could be sufficiently stabilized by fire was established. From here on the focus of research and experimentation shifted to improvements in fuel efficiency and cost efficiency. Fuel efficiency directly addressed ecological concerns and cost efficiency was closely interwoven not only with fuel efficiency but also product development as the products carried the fuel costs to a great extent and socio-economical factors of generating employment. Structures 7 to 12 were experiments that were based on improving fuel efficiency through different kiln firing systems. And later again in Structure 18, the failed experiment of Structure 12 an experiment in improving efficiency by infusing fuel into the bricks was again taken up leading this time to a break-though and a significant improvement in fuel efficiency figures. Product development and research contributed to the economical sustainability of this technology, and Structures 4 to 11 were mainly focused on this aspect. Structure 11 had the biggest returns due to product diversification and was a breakthrough in that the products were for the first time not only able to bear their own fuel costs, but they also subsidized the fuel costs of the whole structure.

Structures 13 to 17 were mainly base on improving the plans of the houses to make them stretch beyond the restrictions imposed on them by kiln systems and make them comfortable and appropriate living spaces.

In Structure 18, there was another breakthrough with a successful firing using coal dust as fuel that was part of the brick. This was a second attempt in the same direction as tried in Structure 12. This gave further hope to the technology and it’s potential as a cost-effective as well as energy efficient housing solution that had been Meeker's pursuit. Structures 19 and 20 were tests along similar lines.

The following subsections take up each area of technological advances separately.

Table 2: Overview of the advances made in each experiment



6.1 Walls

6.1.1 The problem of end walls bending outwards and separating

From the very first structure, the attempt was to build in the simplest way with raw earth bricks. The focus was to find out if a house could be stabilized by fire. Therefore the easiest and tested method of vault-building was adopted, making it possible to construct vaults without centering. This meant that although the vault structure needed side walls to support the weight of the vault, it would also need the end walls to support the vault building process, as Nubian vaults are begun by leaning the courses of uncooked bricks on the buttressed end walls at an angle.

However the result of the first fired vault, GBP Structure 1, built on the typical buttressed end walls that go with the Nubian vaults proved that this common building technique, ideal for mud building or even other kinds of bricks, do not withstand the *insitu* firing process. As a result of the firing the end walls had altogether separated from the vault, even though this separation did not affect the vault in any other way. This separation occurred due to uneven temperatures on either side of a structure, being only fired from one side, the inside. The interior reaches high temperatures between 850°C and 1000°C, while the exterior surface of the end walls remains cool. This leads to significant expansion of the inner surface while the outer surface remains the same. This naturally leads to the walls bending outwards and leaning out of plumb, and then separating altogether from the vault (Fig 5.5). Upon cooling, though the walls move back, they don’t quite return to their original position and a gap is left between the vault and wall, which is easy to fill with plaster, and doesn’t affect the vault.

In spite of this occurrence, the same end detail was continued in GBP vault 2 with the end walls (gable walls) ending horizontally just above the height of the highest point of the vault. As predicted, the end walls responded exactly in the same manner as they had behaved in GBP Vault No. 1, with the end walls separating from the vault.

By now it was felt that the gable walls, although convenient for vault construction in the Nubian way, were quite bothersome for fired buildings as they meant a lot of extra mass for nothing. There was also the added problem that the 45 cm external walls were not receiving enough heat at the exteriors and therefore remaining largely uncooked. So it was concluded that the end walls should be subsequently eliminated altogether.

For the following experiment, in GBP Vault No 3, it was decided to eliminate the end walls altogether. The vault had to be constructed in some other way. The Nubian Vault, a shuttering-free vault building technique as in the previous structures had to be left behind, and a centering had to be introduced for vault construction. A movable centering section of 1m vault length was made for the purpose and had to be moved as and when a 1 meter length of vault was constructed. This method couldn't compete with the simplicity of the Nubian technique as was already known before. This came with added costs. The most complicated aspect of using a centering for mud vaults is that the vault tends to shrink over the centering, as the mortar and bricks continue to shrink in place as they keep losing moisture, and this makes the centering very hard to remove. This can be minimized by using no mortar towards the inside and using pebbles towards the outside (add sketch), but in any case, this remains an area that needs constant attention. There were benefits of this too, apart from preventing end wall separation. The centering was an excellent way of maintaining the shape of the catenary curve that is so necessary for the structural stability.

GBP Vault No. 3 thus constructed successfully countered the problem of end wall separation from the vault. End walls were added later in fired brick using bricks produced inside the structure. These end walls being non-load bearing, didn't have to be as thick as 45 cm as in the previous 2 structures and could be limited to 23 cm. Further they could smaller and cheaper foundations and also have openings wherever functionally needed.

All further structures were built without end walls but the quest for simpler vault construction methods was identified as the area of further investigation and improvement. These are further discussed in 6.2.1 under the sub-section on vault construction.

6.1.2 Side walls bending outwards

Similar to the behaviour of end walls as explained above in sub-section 6.1.1, the side walls too are exposed to uneven temperatures on the inside and on the outside as they receive heat only from the inside. However unlike the end walls which lean out so much that they separate from the vault altogether, the side walls in GBP Vault 1 were seen to lean out much less. This is due to the fact that the weight of the vaults sitting on it counters this expansion to a great extent. After cooling, these walls were almost back to the original position, and this expansion of the side walls did not cause much worry as there was no separation and only minimal falling out of plumb.

The second experiment, GBP Vault 2 had made no change on account of this result, and again the firing results showed the same extent of leaning out of plumb. In the third experiment, GBP Vault 3, the focus was on eliminating the end wall separation, a bigger concern. So the side walls were again left unchanged, and met with the expected result on account of firing, which in this third test were in fact monitored.

In the fourth Experiment GBP Vault 4, this issue was addressed, and the technical improvement attempted to solve the outward bending out of side walls was to build the walls leaning slightly inwards in the first place. This was seen to expand slightly after firing and remained out of plumb inwards. Hereafter this improvement was repeated by building external walls slightly out of plumb inwards.

6.1.3 Composite brick walls

Meeker had doubted from his very first test structure that such a thick external load bearing wall[103] had any chance of being fired through totally, especially when

[103] The external walls referred to here were 45 cm thick as is necessary to bear the load of a mud vault including buttressing

being only fired from one side, the inside. This guess proved to be a fact, and in the first structure, the external load bearing walls were insufficiently fired to the exterior.

Although a number of methods do exist of stabilizing the mud walls externally through plasters, Meeker opted for a composite brick wall, in the external load bearing walls, by replacing the mud bricks that are exposed to the outside with fired bricks while leaving all the other bricks towards the inside of the structure with raw mud bricks. Thus the outer surface would look like being constructed in fired brick, while the inner face would still be raw mud.

In his second test, GBP Vault 2, Meeker had built the exterior walls as composite. Though this did raise the cost to some extent, Meeker felt that this was justified given the increased durability the structure would gain thereby. This seemed a perfectly secure solution, where even if walls wouldn't be fired through, unfired areas would restricted to the middle region of the wall thickness, providing stabilized fired surfaces on both external and internal faces. About a third of the volume of bricks in the external wall would then be made of external bricks.

Hereafter all external walls, whether 34 cm thick or 45 cms thick, continued to be built in this way, even though further evolution occurred in trying to reduce the volume of composite walls by attempting to reduce their height and by introducing common internal walls in structures with adjacent vaults that could be fired from two sides and therefore all in raw mud bricks.

6.1.4 Leaning Wall as Alternative to Buttress

The first twelve structures were built on straight walls of 34 or 45 cm thickness, although from Structure4 onwards the side walls were built very slightly leaning inwards to counter the side wall movement after firing and bending out of plumb. The external walls always were provided with buttresses in brick masonry to counter the thrust introduced by the vaults and domes.

In the thirteenth structure, by when the focus was trying to free the plan to serve as a comfortable house rather than an efficient kiln, the external walls that supported the dome were for the first time built as leaning walls (Fig. 6.1) that were significantly leaning, so as to continue the line of the dome above it. Thereby, a lot of extra mass that the buttresses would create was eliminated, while also gaining extra space in the interior useable area. The walls ended in a square, increasing the area within the dome's circular footprint. The walls, by leaning out, further contributed to an even enabled larger useable area; that is, a 4m diameter dome led to a useable area of square plan of 5m x 5m.

Fig. 6.1 Leaning walls in the thirteenth test, Satyajit's house, 1991, Source: Ray Meeker

Leaning walls were hereafter included wherever it was useful, such as in the fourteenth structure Marta's House, the fifteenth experiment, staff quarters for Minolta Aquatech; the eighteenth structure, temple at Nrityagram Dance Village; the nineteenth structure, House for Bina Saxena; and the twentieth structure Pottery for Bina Saxena.

6.1.5 Lowering of Wall Height

In the first six experiments, the walls were 1.65, 2.00, 2.14, 2.14, 2.64 and 3.15 meters respectively. The rising height in subsequent experiments were mainly with the aim of trying to successfully stabilize larger and larger structures in order to be eventually serve the requirements of a regular house. The sixth structure, with the highest vaults intended to allow the addition of a loft slab so as to gain more useable space.

However when Meeker started the design of his seventh structure, an actual house for a client, he opted for reducing the wall heights again. The seventh experiment Agnijata, was built using 3 vaults sitting on 2.0 meter high walls and 1 vault sitting on a 3.0 meter high vault. Further, these spaces were sunk 75 cms below ground in order to make the structure blend into its natural surroundings more discreetly. The other advantages of this reduced walls and sunken space were to minimize the buttressing required and thereby reduce the mass of masonry. A further saving results as the 45cms external load bearing walls get heat from only one side and do not suffice to stabilize the wall through its entire thickness and hence, fired bricks are introduced in the brick masonry on the external surface of these thick walls. The vaults and domes themselves being thinner, 15 to 20 cms thick, get fired through. By lowering the walls, the structure has a reduced need for fired bricks in the external surface, and can be built with a greater percentage of uncooked bricks.

The structures that followed continued wherever possible to reduce the height of walls while achieving the necessary height through the height of the vaults and domes.

The eighth structure, the model village house in Uppalam had 2 meter high walls.

The ninth structure, Golden Bridge Pottery Vault No 9, was a structure that was an attempt in increasing fuel efficiency by introducing a cross-draft kiln system. In this structure, the walls were completely omitted and the structure was purely a vault sitting on its foundation walls. This meant that the structure could completely avoid the 45cm thick walls and therefore also the composite walls including fired bricks.

The tenth structure, the watchman’s space at HiDesign Factory had 2 meter high walls as well.

The eleventh structure, the two-vault low cost house at Auroville Visitors Information and Reception Center had walls reduced to 1.5 meters.

The twelfth structure, an experiment in coal dust as additive in mud brick as fuel, was also built with no walls as a single vault directly placed on the foundation walls.

The thirteenth structure, Satyajit’s House had vaults resting on 2.5 m high walls and the domes on 2.10 meters. Here leaning walls were introduced for the first time in areas where the dome alone was supported while the walls supporting vaults and domes were kept straight. And the leaning walls that supported the dome, were reduced from 45 cms to 34 cms thickness after a height of 1 meter.

The fourteenth structure, Marta’s House, had 2.5 m high walls supporting two domes. The walls were all leaning and were 34cms thick.

The fifteenth experiment, Staff Quarters for Mintolta Aquatech in Tuticorin, were a series of domes and vaults built in combinations very similar to Satyajit’s House and Marta’s House and the vaults and domes rested on walls ranging from 2 meters to 2.90 meters high.

The sixteenth experiment, low-cost housing for DRDA in Ayothiapatinam, Salem was a series of single vaults that were supported on 1.25 meter high walls. Here the walls were further lowered to 1.25 cm and the vault that normally had a rise of 1.5 meters was further raised to 2.00 meters.

The seventeenth structure, Housing for Volontariat farm workers, were similarly built with 34 cm walls of 1.25 cms supporting single vaults with a rise of 2.0 meters, a higher rise as compared to the earlier structures.

The eighteenth structure, a temple at Nrityagram, Hessaraghatta, had a catenary corbelled dome of 5 meter height built on 2 meter high walls.

In the nineteenth structure, House for Bina Saxena, the central catenary dome was supported on 2 m high walls.

In the twentieth structure, Pottery Studio for Bina Saxena, the structure was a simple dome that sat on low walls that were reduced to 75 cm only. This was done in order to reduce the volume of thick brick walls that would require fired brick content in the external face as well as the to reduce the mass of thick walls that would need the fire to penetrate deeper. Hence it was attempted to increase the proportion of the structure that could be built as a 15cm thick dome, with minimum walls.

6.1.6 Wall thicknesses

The first six experimental vaults were built in increasing wall heights of 45cms thickness. But from the seventh structure when the heights of walls were reduced according to the function, the wall thicknesses could also be reduced.

The seventh experiment Agnijata, had 34 cms thick walls for the vault bearing walls, while the dome sat on 45cms walls.

The eighth structure, the model village house in Uppalam had 2 meter high walls resting on 35cm thick walls.

The ninth structure, Golden Bridge Pottery Vault No 9, completely avoided the walls and was a single vault resting on foundation walls directly.

The tenth structure, the watchman’s space at HiDesign Factory had 2 meter high walls as well. These walls were initially all planned as 34 cm thick, but after two collapses, it was realized that the internal walls which supported vaults from two sides required to be 45cms and were thus rebuilt.

The eleventh structure, the two-vault low cost house at Auroville Visitors Information and Reception Center had walls reduced to 1.5 meters. The walls were built as in the previous structure with 34 cms for external walls and 45cm for internal common walls supporting 2 vaults.

The twelfth structure, an experiment in coal dust as additive in mud brick as fuel, was also built with no walls as a single vault directly placed on the foundation walls.

The thirteenth structure, Satyajit's House had 45 cm thick walls with the unique case that the walls the leaning walls that supported the dome, were reduced from 45 cms to 34 cms thickness after a height of 1 meter.

The fourteenth structure, Marta's House, had all leaning walls of 34cms thick.

The fifteenth experiment, staff quarters for Mintolta Aquatech in Tuticorin, were a series of domes and vaults built in combinations very similar to Satyajit's House and Marta's House and the vaults and domes rested on walls of 34 cms as well as 45 cms in places.

The sixteenth experiment, low-cost housing for DRDA in Ayothiapatinam, Salem was a series of single vaults that were supported on 1.25 meter high walls which were 34 cm thick.

The seventeenth structure, Housing for Volontariat farm workers, were similarly built with 34 cm walls of 1.25 cms height too.

The eighteenth structure, a temple at Nrityagram, Hessaraghatta, had a catenary corbelled dome of 5 meters height built on 2 meter high walls that were leaning and 34 cm thick.

In the nineteenth structure, House for Bina Saxena, the central catenary dome was supported on 2 m high 34 cm thick leaning walls.

In the twentieth structure, Pottery Studio for Bina Saxena, the structure was a simple dome that sat on low leaning walls of 34 cms thickness.

6.1.7 Load-bearing Walls Fired from Two Sides

The first time this occurred was in the tenth experiment, in the watchman's space at HiDesign Factory, where 3 single vaults were stacked together sharing two common walls. The idea was to achieve fuel efficiency through a semi-continuous cross-draft kiln, in which the heat of one vault could preheat the next. The common walls were thus heated from two sides, and could be fired through even though the thickness was 45 cms. The first time that that a thick wall of 45cms was entirely built with mud bricks was successfully thus stabilized.

Hereafter in all the subsequent structures, where there occurred internal load bearing walls bearing vaults or domes, the walls were built in 45 cm thickness and entirely in mud bricks, and the composite wall detail was exclusively used in external load bearing walls.

6.1.8 Elimination of Mortar in Vertical Joints

In the first ten structures, the external walls were built with raw and cooked bricks laid in mud mortar, and it was an established fact that the walls couldn't be stabilized on the external surface as the required temperature could not penetrate beyond the wall thickness of 20 cms.

In the eleventh experiment, Low-cost housing units at Auroville Visitor's Information and Reception Center, in order to allow maximum penetration of heat into the walls, the vertical joints in the brickwork on the inner face were not filled with mortar, and left open to be filled later.[104] Khalili mentioned this in his book of 1983.

[104] Khalili had thought of this idea already and mentioned it in his book, Racing Alone, Harper and Row, San Francisco, 1983

Hereafter in all the subsequent structures elimination of vertical joints in the external wall was repeated.

6.2 Roofs

6.2.1 Vault-building Technique

The Nubian vault building technique is known to offer several advantages in raw mud brick construction, the principal one being that this technique enables vault-building without any centering, by allowing courses of brick to lean at an angle upto 70° over a supporting gable wall[105]. Further advantages are that if the mud vault continues to shrink in place, there is no problem of removal of the centering etc. Yet another advantage of not having a centering is the cost savings, as well as the liberty to use

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[105] Jan de Rooden was asked by Meeker to go and visit Hassan Fathy and his structures as part of this preparation. Hassan Fathy (1900-1989), an Egyptian architect was the first to revive the use of mud brick and ancient vaulting techniques and to adapt them to present-day building requirements, and to show how suitable they still are in response to climate, local materials and existing building skills. His book 'Architecture for the Poor' describes in detail the way he introduced the Nubian vault technique for construction of the village of New Gourna in the 1940s. Although he had already started building with mud bricks, as the war began, steel and timber supplies were cut off, and it occurred to him that if he had mud bricks and nothing else, he was no worse off than his forefathers.

Typically the building of a vault would need a strong wooden centering, running through the entire length and supported on wooden props, which has to be removed when the vault is made. Fathy had known that in ancient times in Egypt vaults were constructed without centering and after several failures, he discovered that in Nubia this ancient technique had survived. In Nubia, he discovered a village whose architecture had been preserved for centuries uncontaminated by foreign influences. Later he found masons from Aswan who still knew how it was done.

A Nubian vault is rests on side walls but during construction is supported on an end wall that is somewhat higher, against which the vault leans while being built. Masons roughly outline a catenary arch with handfuls of mud. Then the first brick course stands on its end on the side wall. The second course is laid after a wedge shaped packing that allows the next course to lean slightly towards the end wall instead of standing up straight. The third course inclines even more acutely, and so on till the two curved lines of brick meet at the top. The inclination holds the bricks in place, till the vault is completely spanned.

This is the simplest and cheapest way of building vaults with mud bricks as it avoids the use of centering, and is not affected adversely by the 37% shrinkage that occurs when the mud mortar dries. In Nubian Vaults the gable walls are needed for the brick courses of the vault to lean during construction and so the end walls are typically raised higher than the height of the vault and buttressed to support the leaning load, even though after construction the buttresses are only needed in the side walls where the vault would exert a thrust.

spans according to the appropriateness rather than because one happens to possess a centering of a specific size.

The very first structure GBP Vault No. 1 was built as a Nubian Vault leaning on its typical gable end walls. After firing though, it became evident that this method of vault building though ideal for adobe structures, was not without problems in the case of fire-stabilized mud structures, as due to uneven temperatures on the outside and inside surfaces, the inner surface of the end wall expanded more than the outer surface, causing their bending outwards and eventual separation from the vault altogether.

In the second experiment, the vault shape deviated to a curve that was outside of the catenary shape. This proved to be a disaster and the vault eventually collapsed and had to be rebuilt. A major lesson was learnt about the importance of the catenary shape for vault building.

The rebuilt vault followed the catenary curve and the Nubian method was used once again for vault building as in the first experiment. As noted in the first experiment, the structure behaved predictably after firing and the end wall separated once again from the vault. This led to a valuable conclusion that the end wall had to be reconsidered and in subsequent structures another way of supporting the vault during construction had to be attempted in order to do away with end walls altogether.

In the third experiment, GBP Vault no. 3, the vaults were constructed on a movable centering that was 1 meter long and was slid along the length as the vault construction progressed. Although this experiment did solve the problem of end wall separation, the centering created complications due to the shrinkage factor of raw mud masonry, and not considered to be an ideal solution. At this stage it was concluded that further investigation into vault construction methods would be necessary to be able to address the problem of easy removal of the centering.

For the fourth experiment, the vault was used by combining the benefits of the Nubian vault technique with the partial use of a 75 cm wide wooden centering of 3m span and 1.5 m rise. First a 75cm wide vault width was built over the catenary wooden centering frame that was placed approximately midway between the length of the vault. Then the vault was constructed from either side of this middle strip by leaning brick courses on it as in the Nubian technique. The problem of having to slide the centering below a shrinking mud vault was solved and the catenary frame was reused to finish the vaults at the end neatly. The problem of shrinkage of the vault was countered by building the vault in a negligibly downward sloping shape, with the vault being negligibly lower by the time one reached the end of the vault on either side.

In the fifth experiment, new improved steel centering of 3m span and 1.5 m rise was introduced with a mechanism that would allow it to be raised and lowered. This enabled the easy removal of the centering after the freshly constructed vault strip shrank slightly in place. Further the centering could be dropped to a lower rise, and be used to finish the last part of the vault neatly achieving a better end detail. Except for this technical improvement, the rest of the vault construction proceeded exactly as in the fourth experiment. With this improvement the results were satisfactory, the end wall problem was solved without creating complications through the use of centering, and this satisfactory vault building technique, a combination of adjustable centering and nubian method was hereafter used as a standard technique.

The vault construction in the sixth experiment on wards proceeded in the same way. In the seventh experiment of a large house, Agnijata, the 4 vaults surrounding a dome, were built by first building four arches with the steel centering adjacent to the dome and the rest of the vaults were completed in the Nubian technique.

Only again in the thirteenth experiment, Satyajit's House was the vault building technique furthered. A light steel frame catenary guide of 6mm rods was introduced. This helped ensure that the catenary shape that is so essential to the structural stability could be adhered to. This accelerated the speed of construction significantly and up to 2 meters of vault length could be built per day by one mason team.

Subsequent vaults were built using the above technique.

6.2.2 Spans

The first vault was built with a 2m span, and increased to 3m in the second structure. But after the second vault had almost collapse on Meeker's head (due to deviation form the catenary shape), Meeker preferred to build a smaller span of 2.25 meters in the third experiment and also fourth experiments in GBP Vault 3 and 4. In the fifth and sixth structures the span was increased to 3 meters. As by this stage the vault building method had also stabilized, it was convenient to use the steel centering to build further vaults and in the subsequent structures vaults were 3m spans. As the 3m span also provided the basic requirement of a living space, the span didn't need to be increased hereafter, but the requirement for more living space was rather met by increasing either the length of the vault or building several vaults in a sequence and gaining further advantage of fuel efficiency.

6.2.3 Catenary Shape and the Deviation from It

From the very first studies undertaken to be able to build the very first mud vaults easily and correctly, it was decided to use the Nubian vault method in a Catenary shape as was revived by Hassan Fathy in Egypt. There is no history of mud vault construction in the area traditionally and the methods had to be learnt anew by all especially the masons.

The first vault successfully built in a catenary shape was questioned in the second test, by Jan de Rooden who wanted to have a better looking shape for the vault and had convinced Meeker to deviate from the catenary for the second test. This was done, but faced regular vibrations when trains passed the nearby railway track, and developed a crack horizontally along the entire length and even while Meeker had gone in to look at it and had decided to take it down, it collapsed and he himself had a narrow escape. The lesson learnt was that the catenary shape must be adhered to and hereafter all the further structures were strictly catenary shaped vaults.

6.2.4 Domes: Construction Method; Supporting Walls; Buttresses and Tools

The first six structures were vaults, and the first dome was only built in the seventh experiment, Agnijata. This was a house built using four vault structures surrounding a central dome. The dome had a clear span of 5m and a thickness of 15 cms using square dome bricks of 15cm x 15cm x 5 cm and rested on 45cm thick walls that were 2.5 meters high from a sunken floor level of -75cm. The walls were as yet not leaning walls and the vault structures served as buttresses from all the four sides. This dome was fairly simple to build with the help of a trammel placed at the center of the dome.

The next dome was built only in the thirteenth Structure, Satyajit’s House. But in this case, the dome was supported on leaning walls, which were a new feature. They were introduced in order to minimize the extra mass needed for buttresses that counter a dome’s thrust. The useable space was thereby extended and for the same span of dome a larger area of floor space could be gained.

The other change was that the previous dome, round in plan sat on straight walls that were also circular in plan. In this structure, as the attempt was to create a better plan for the effective functioning of the house, the dome was planned over a square space with smoothly rounded off corners. The dome therefore sat on squinches that converted the square plan below to an octagon on which the dome could be easily supported.

This brought up the challenge to be solved in constructing the leaning walls, especially as the squinches begin. As a result of the leaning walls the squinches had a radius that not only differed from the base towards the top, but also had a shifting center that moved towards the center of the dome with each progressive course. Till today, Meeker takes pride in the double leaning raised squinch trammel that he fabricated specially for the purpose of building squinches in the context of leaning walls as one of the most satisfying and interesting highlight he experienced in those twelve years of experimenting.

The fourteenth experiment, Marthas House, had two domes of 5m and 2.25 m sitting beside each other on leaning walls that originated from a square plan with rounded off edges and was built in very much the same manner as in Satyajit's House.

The fifteenth experiment of Staff Quarters for Minolt a Aquatech was also similar.

The eighteen experiment, Temple at Nrityagram Dance Village was the next dome built and is the unique example of a catenary shaped corbelled dome. This was built by simply recessing subsequent courses of brick work inside as the dome grew higher and sat on a 3m x 3m square base with offset corners. The dome was 5m high, and resulted in the highest structure yet (7m above plinth) that was built in this technique.

The nineteenth structure, House for Bina Saxena, was a central catenary dome, the first one ever built, the previous ones being spherical domes, around which the organic shaped house was later built with bricks that were fired within the dome. The centering was a mesh of steel bars temporarily put together to guide the shape of the dome.

The twentieth structure, Pottery Studio for Beena Saxena, was a spherical dome of 3 meter diameter sitting on low 75cm high leaning walls built using the standard trammel.

6.3 Size of Structures

The first structure with a useable area of 6sqm, of 3m length, 2m span and 3m height began as a small and humble experiment to find out what happens in trying to stabilize an earth structure by fire. In spite of several areas of difficulties that emerged there was sufficient success to encourage developing the idea further and a second experiment was undertaken by building a much larger structure with 15 sqm useable area, pf 5m length, 3 m span and 4m height. After having faced one vault collapse and finally losing the whole structure, the third structure was again smaller, with 11.25 sqm useable area, an increased length of 5 m but a reduced span of 2.25 m and 3.64 meters height. The fourth structure was not much bigger with a useable area of 11.82 sqm with the length being 5.25 meters and all other dimensions being the same.

In the fifth and sixth structures larger useable areas were attempted with 15 and 18 sqm respectively, with the span also increased in both cases to 3m and the vault lengths to 5m and 6m respectively. By the end of the sixth experiment the various problems were sufficiently solved to begin building actual projects with a client to suit the specific uses envisaged within the structures.

In the seventh experiment, there was thus a leap jump and 65 sqm of built up area was successfully fired. The spans of all vaults built here were 3 m as in the previous two tests, but a dome spanning 5m and reaching a height of 5 m was built.

Hereafter the question of being able to fire earth structures or build sizes sufficient for the purpose of residential use was not an issue and the following structures were built big or small more according to the need that arose from the project. The eighth structure a model village house was 21 sqm with a 3m span and 7 m vault length and the ninth structure a test in cross draft kiln system was a small structure of 12 sqm with a 3m span and 4m vault length. The tenth structure, a Watchman’s shed for Hidesign Factory, was 54 sqm achieved through three vaults of 3m span and 6 m length. The eleventh structure had 36 sqm built with 2 vaults of the size as in Hidesign Factory of 3m span and 6 m length. The twelfth structure again a test in fuel efficiency was 12 sqm of the 3m span that was standard by now.

The thirteenth structure, House for Satyajit, was again a leap in the size of structures undertaken until then and was a regular spacious house of 100 sqm. Marta’s House, the fourteenth test was again small according to Marta’s need with an area of about? 40 sqm.

Hereafter, the sizes that could be built were no longer an area of increase although the fact that larger projects followed, and the attention shifted to a larger scale rather than a larger size of structure.

The fifteenth structure, a large staff quarters housing project for Minolta Aquatech, was the largest scale of structure undertaken by Meeker with a useable area of 800 sqm and reaching a scale that permitted the understanding of economics that could result out of largeness of scale of the project.

The sixteenth structure, low-cost housing at Ayothiapatinam, Salem, was much smaller, but being a low-cost housing project for the Government as opposed to the above example that was for the Corporate client, was by no means insignificant with a total planned useable area of 1000 sqm of around 20 sqm per housing unit. Meeker built 10 out of 50 planned structures, of 200 sqm useable area, and the rest that were meant to be continued by the site engineers trained for the job during the building of the first structures, were never completed after Meeker left.

The seventeenth structure, Volontariat farm-workers housing, was smaller, with nine single vaults of varying lengths totaling to an area of 225 sqm, but were built entirely and thus the project assumes the same scale as the previous project.

The eighteenth, nineteenth and twentieth structures were again new experiments with the successful attempt at using coal dust as a fuel mixed into the raw mud mixture, and also by their own particular requirements had much smaller areas.

The Nrityagram Temple was a 7 m tall structure with a corbelled dome with a square plan of 3m x 3m and 9 sqm area. The House for Beena Saxena was a 5m diameter catenary dome of 6 m height and the Pottery Studio was a very small structure, a spherical 3 m dome on a square plan with leaning low walls of 75 cm.

6.4 Firing Issues

6.4.1 Type of fuel

The first structure was fired using casuarina wood. Casuarina Equisetifloria is a commonly grown crop that is fast growing and planted extensively in the area specifically for using as fuel. This was also the standard practice in the Pottery. The nine following structures also were fired using the same fuel, casuarinas wood. The treetops of the casuarinas, called *malaar* locally, is also available in bundles including their needle like leaves that dry in place after harvesting, and were also used as fuel for the firing. These are very useful in creating a large fire immediately when added.

In the eleventh test, low-cost housing units at the Auroville Visitors and Information Center, firewood was still the fuel although the locally sourced Acacia Auriculiformis was used instead of the Casuarina Equisetifloria. In the twelfth test, there was an attempt to use coal dust from the nearby coal industries, as a fuel that would be mixed homogenously into the brick mixture as well as the mortar and the products contained within the structure, so that the mass of the house would burn by self-burning as soon as a fire could be ignited, and apart from the fuel needed to start the fire, it was hoped that the coal dust would suffice and that this would lead to major improvement in the fuel efficiency figures. Unfortunately this couldn’t be tested at all, as the fire wouldn’t ignite, and after several attempts it was cooked as the previous structures implying that the fuel was double in consumption, considering that in spite of having used coal dust, the usual firewood had to also be consumed to salvage the failed experiment.

All following structures until Structure 16, except Structure 12, continued with firewood.

In the seventeenth experiment, there was a major breakthrough of a success in coal dust firing, an idea that had failed in the twelfth experiment but retried five structures later. This was because when Meeker inspected the area to find some local brick kilns, he saw that bricks were being locally produced by infusing coal dust into the mud brick mixture. So he had the confidence to try this again with the assistance of the local brick manufacturer who was ready to supply the uncooked bricks that contained coal dust. This experiment was successful this time around and as expected made a huge difference in the fuel efficiency.

The following two experiments for Residence and Pottery Studio for Bina Saxena, were built using coal dust firing.

6.4.2 Insulation

Fig. 6.2, cow dung in insulation, 1986, Source: Ray Meeker
Fig. 6.3, coal dust in insulation, 1990, Source: Ray Meeker

The very first test structure was insulated with a 10cm layer of a mixture of clay sand and ash.[106] The second and third test structures were also similarly coated with the 10 cm layer. In spite of this layer, and other improvements in firing, the results remained that the vaults could not be sufficiently fired through its entire thickness.

In the fourth structure, there was a big achievement through the use of a combustible insulation that included cow dung, straw and clay in a mixture (Fig. 6.2). As the structure reached about 500°C during the firing process, this layer caught fire, and continued to burn slowly for two days, even after the stoking was completed. This

[106] The proportion of clay, sand and ash in the mixture were not recorded.

resulted in a uniformly fired vault that for the first time was cooked through its entire thickness.

Hereafter the subsequent structures were thus insulated with the combustible mixture as explained above. In Structures 12, 18, 19 and 20, coal dust replaced cow dung in the same proportion (Fig 6.3).

6.4.3 Firing results

The vaults of structures 1, 2, and 3 were not sufficiently stable towards the exteriors. The walls too were only being stabilized towards the inside, but were already solved by adding fired bricks in the outer face since the second experiment.

The fourth test was the first breakthrough in terms of achieving a stable vault through the entire thickness of 20cms and this was successful due to the application of a combustible insulation that upon reaching 500°C began to burn and provide the necessary additional heat to fire the vault during the second half of the firing period from two sides.

Hereafter Structures 5-17 were well fired with the exception of Structure 12 which was a new experiment in Coal Dust as a fuel infused into the brick mixture, and had failed as the fire couldn’t be triggered.

Much later in Structures 18, 19 and 20 which were also fired with coal dust as the self contained fuel, the results were much better and stable structures were achieved with the exception of some external patches in the domes of Structures 18 and 19 that were insufficiently stable.

6.4.4 Kilns and Firing Systems

In the earliest structures, the focus was on simplicity of firing with the aim of being able to successfully stabilize large earth structures *insitu* by firing only from the inside. Once this was proven to be achievable the focus shifted to attempting more complex kiln systems that could contribute to fuel efficiency. The later structures from Structure 13 to Structure 17, the focus was on trying to go beyond the structure’s need to serve as an efficient kiln, and to achieve comfortable and efficient house plans. The last 3 tests were again more experimental as they were attempts in self burning of combustible bricks and products.

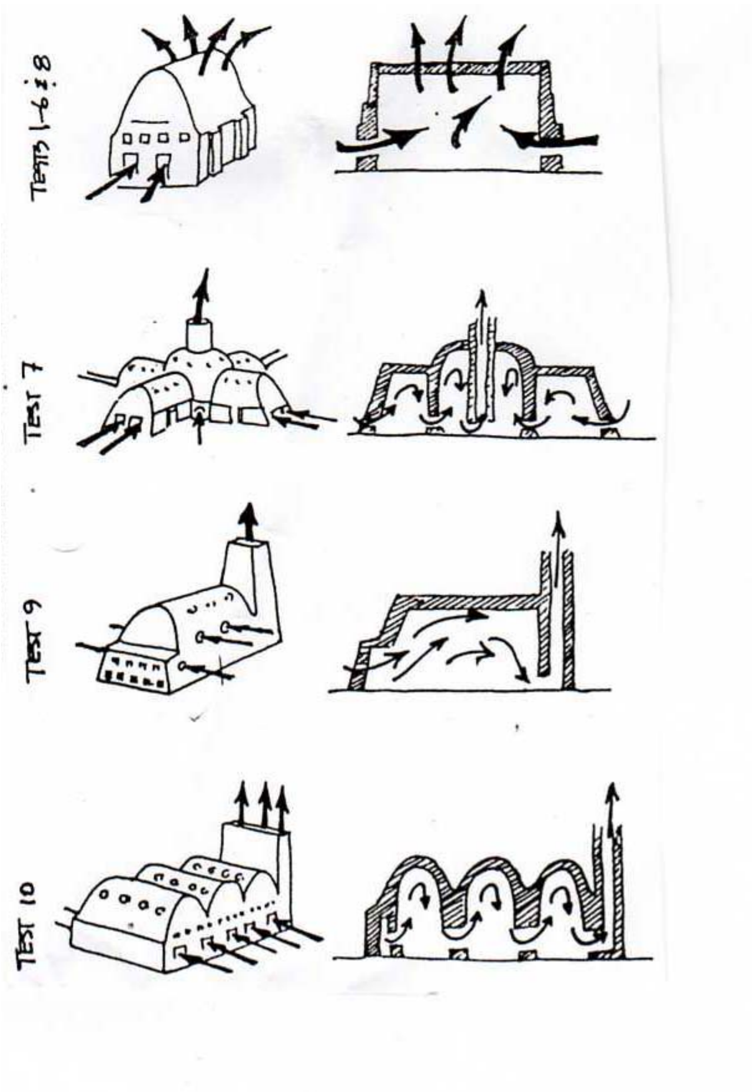

Fig. 6.4, sketch by Meeker comparing kiln systems, 1990 Source: Ray Meeker’

Structures 1 to 6 and 8 were fired as simple up-draught kiln types.

In Structure 7, Agnijata, the first house for a client, a cross-draught and down-draught kiln system was tested. The four vaults surrounding the central dome were fired cross draft towards the central dome and this led to preheating the dome significantly. The dome itself was fired down-draught; so that the heat was led up to the dome and the down again and finally out through the chimney at the centre.

Structure 9, was fired cross draft, and was a test specifically undertaken at Meeker's own Pottery to test the efficiency of a cross draft kiln. It proved to be significantly effective as compared to the up-draught kiln that was being used until then.

The up-draught kilns in Structures 1 to 6 had led to a fuel consumption of 17,270 MJ/1000 Bricks for structure and 12,300 MJ/1000 Bricks for structure and products together. The cross-draught down-draught kiln in Structures 7 had led to a fuel consumption of 13,270 MJ/1000 Bricks for structure and 9,170 MJ/1000 Bricks for structure and products together. The down-draught kiln in Structures 9 had led to a fuel consumption of 11,850 MJ/1000 Bricks for structure and 8,457 MJ/1000 Bricks for structure and products together.

Structure 10 was the first example of a semi-continuous cross-draught kiln that involved a series of 3 vaults that were fired in a sequence so that the heat from one vault was used to preheat the next. This led to a further fuel efficiency with a fuel consumption of 12,193 MJ/1000 Bricks for structure and 7,900 MJ/1000 Bricks for structure and products together.

Structure 11 was a similar composition of two attached vaults and was fired as a longitudinal cross-draught kiln.

Structure 12 was a special experiment for testing coal dust infused bricks and similar products that were stacked as a mass and were expected to self burn, but failed.

From Structure 13 onwards, the houses began to be designed primarily as houses with the intention of freeing the plans from having to serve as an efficient kiln as had been the focus at this time.

Structure 18 was a second attempt at stabilizing the structure through addition of coal dust in the brick mixture and produce combustible bricks which when ignited would be self burning. The products and structure were to be fired not by allowing heated air to circulate, as in previous structures and kiln systems, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact. This test had been successful, and found to be extremely fuel efficient. This led to an extreme reduction in fuel consumption of 3,000 MJ/1000 Bricks. The following two structures, 19 and 20 were further tests in the same technique.

6.4.5 Cluster structures for fuel efficiency

It was always known that clusters of vaults and domes would lead to better fuel efficiency as in the case of efficient kilns by profiting from the waste heat of one structure directed into the next and thereby preheating it. Yet the early structures and several later low-cost or small models had to be built as single standing vaults or domes which would have to be built in the simplest way that would not necessarily be the most fuel efficient option. However as Meeker developed the technology further over successive experiments, he had the opportunity to build some cluster structures and compare their efficiencies.

The earliest 6 structures were single vaults built to test the basic idea of firing large earth structures from inside and as such were fired as up-draught type kilns.

In structure 7, for the first time 4 vaults were combined around a dome, and the combination of cross draft and down draft kiln type led to significantly reduced fuel consumption. The cross draft down draft kiln in Structures 7 had led to a fuel consumption of 13,270 MJ/1000 Bricks for structure and 9,170 MJ/1000 Bricks for structure and products together while the earlier 6 used 17,270 MJ/1000 Bricks for structure and 12,300 MJ/1000 Bricks for structure and products together.

In Structure 10, 3 vaults were combined in a series and was the first example of a semi-continuous cross draft kiln, with a fuel consumption of 12,193 MJ/1000 Bricks for structure and 7,900 MJ/1000 Bricks for structure and products together. This was significantly more efficient that Structure 7, Agnijata.

In Structure 11, only 2 vaults were combined but instead of semi-continuous cross draft kiln, as in Structure 10, it was fired as a longitudinal cross-draft kiln and resulted in a fuel consumption of 6,800 MJ/1000 Bricks for structure and products together. This was the lowest fuel consumption that was reached until that time.

Structures 13, 14, 15 and 16 were combinations of vaults and domes and Structures 17 and 18 series of several vaults. The fuel consumption data hereafter was not meticulously monitored as in the previous structures and in several of the above cases contractors were involved, and Meeker did not receive all the data as in the structures that he executed himself previously.

6.4.6 Fuel efficiency

The evolution of Fuel Economy is what Meeker calls ‘the Ecological crunch’. Table x gives a comparison of the fuel consumption for six fired structures (structure number 5 to 10) and for seven conventional firing systems.[107]

Up-draught kilns are known to be extremely inefficient. The house fired up-draught house arrives at almost the same figures as the conventional up-draught kiln. Compared to the best firing systems available - the Hoffman, Bull's Trench, or Habla- that consume up to 3000 MJ/1000 product bricks, the results of the fired houses may be still far behind, but the tests do show a remarkable progress towards reaching an

[107] These figures are reasonably accurate, and, though peak temperature and soaking time vary somewhat, the trend is quite evident and is consistent with general knowledge of firing systems.

acceptable level of fuel consumption. From 13,400 MJ to 7,900 MJ in the 3-vault system of Structure 10, and 6,800 MJ in the 2 vault structure 11 was is an impressive advance considering the technology being still at its infancy. And even if the brick itself may consume fuel than the efficiently produced fired brick, to what extent this technique makes the use of other high energy materials (steel and cement) redundant or significantly reduced still remains to be assessed.

There is certainly a limit up to which kiln economy principles can actually be followed through. A trade-off has to be made because this structure is not only a kiln- after firing it becomes a living space. In this context Meeker mentioned that he heard of chamber kilns being used for shelter in Europe during and just after WWII, but he does not think that the most efficient kiln will make an ideal living space. There are severe limitations architecturally as well. Roofs must be vaulted or domed, and interior spaces must not be complex, in order to ensure adequate draft.

FUEL EFFICIENCY COMPARISON								
Case study	5	6	7	8	9	10	11	18-20
Year	1987	1987	1988	1988	1989	1989	1990	1998-9
Size l/w/h	5/3/4.14	6/3/4.65	4/3/3.5 4.5/3/3.5 5/3/3.5 6/3/4.5 5 dia. 5 h	6/3/3.5	4/3/2.0	6/3/3.5		
Kiln type	updraft	updraft	fired simult. cross draft into dome down draft	updraft	cross draft	semi-con cross draft	longitud. cross draft	compact product mass
Product	tmb 12000	tmb 19000	tmb 60000 tiles 2000 toilet pans 4 spouts 35	tmb 8000 tiles 1000 roofing units 1000 wall units 60 mural 18 sqft	tmb3500	tmb 35000	diverse	bricks tiles
Firing temp.	945°C	920°C	900-1000°C	940°C	930°C	940°C	950°C	940°-980°C
Firing time	84 hrs	77.5 hrs	108 hrs	48 hrs	96 hrs	36 hrs	120 hrs	96 hrs
Fuel Cons.	ca. 10 tons	ca 10 tons ma 1000 bd	ca 23.4 tons ma 2,400 bd	ca 6.6 tons ma 600 bd	ca 2 tons	ca 10 tons ma 1400 bd	aa 8 tons ma 655 bd	

MJ/1000 Product	17270	16292	13270	19732	11850	12193		3000
MJ/1000 Prod + Str	12300	11680	9100	14250	8457	7900	6800	3000
Value of Product Rs	10000	15800	75000	16000	4530	43500	40000	3000

Note: These fiqures are somewhat misleading as structure bricks are well fired on the inner face and progressively less well fired toward the outer face 23 cm is assumed to be in the firing zone in the walls. However figures for the cross draft 3 vault system are real as walls are fired from both sides. ‘Ma’ stands for malaar and ‘Bd’ stands for bundles

Table 3: Fuel efficiency comparison

Fuel Efficiency in Standard Kilns

TYPICAL FUEL REQUIREMENT FOR KILNS (Source: Appropriate building materials SKAT)				
Type of kiln	Heat requirement	Quantity of fuel required		
	MJ/1000 bricks	Tonnes/1000 bricks		
		Wood	Coal	Oil
Intermittent				
Clamp	7000	(0.44)	0.26	(0.16)
Scove	16000	1.00	0.59	0.36
Updraught	16000	1.00	0.59	0.36
Downdraught	15500	0.97	0.57	0.35
Continuous				
Original Hoffmann	2000	0.13	0.07	0.05
Modern Hoffman	5000	0.31	0.19	0.11
Bull's Trench	4500	0.28	0.17	(0.10)
Habla (high draught)	3000	0.19	0.11	(0.07)
Tunnel	4000	(0.25)	(0.15)	0.09
CBRI Biomass kiln	5800			
Note: figures in brackets mean that fuel is unsuitable for kiln type. The CBRI figure is from Satyaprkash and FU Ahmed, Use of rice husk as fuel for building bricks, CBRI, Roorkee				

Table 4: Fuel efficiency in Standard Kilns

The Auroville house was certainly not a typical kiln and posed real questions (doubts) as to whether or not it could be fired in one single operation. In the 3-chambcr test, the vaults are higher than they are wide, which slows the draft. Heat tends to stagnate in the top of the vaults. Interestingly, heat loss to the structure, an unfortunate waste in ordinary kiln operation, is an advantage when firing a house, more especially when the loss is through the roof.

Long, multi-chambered structures are unquestionably most efficient. It is conceivable that a ten-vault system will prove economical. But even ten vaults will require producing some two lakh bricks, inclusive of structure and product. This is way beyond the means of individual families and probably necessitates government subsidy and supervision.

In a test to develop an efficient, inexpensive fuel-burning kiln for the village potter, Meeker has constructed a simple catenary vault on a low plinth of fired brick. The kiln, built in unfired brick, is 4 m long and has a chimney at one end in fired brick. It is fired cross-draft to 950°C and requires 11,800 MJ per 1000 bricks. (This kiln is not intended for bricks, but brick data is given for purpose of comparison) For such a small kiln, it is very economical. This is not unlike a small version of the CBRI Biomass kiln, which is quite economical, requiring 5,800 MJ per 1000 bricks. In a larger catenary vault system, fired longitudinally, it is conceivable that a figure of 6000 MJ per 1000 bricks can be reached. The next test, EWS model house in AVIRC, demonstrated the longitudinal draft system in two connected vaults and required 6,800 MJ per 1000 bricks. This along with the products that recovered the entire cost of fuel demonstrated that fired houses could be considered economically viable even for small single houses provided that there was money available to invest for product manufacture and outlets to sell the same as an integral part of the housing project.

6.5 Product Development

In the case of baked *insitu* houses, the development of products to be fired within the house is an equally important area of research that could make the technology viable for application in the mainstream. Apart from the fact that it is inconceivable to fire structures empty given the high demand and inefficient use of fuel that this would imply, the products were ideally expected to carry all the fuel cost thereby providing a fired mud structure for the price of a raw mud structure. The house was meant to in exchange first serve the function of a kiln, and the heat that would normally be wasted into the kiln structures during firing the products was meant to be tapped for stabilizing the house for free.

Thus the development of products evolved through the various structures with two main objectives. The first and most immediate aim was to generate income. The second was to produce as many building components as possible and necessary in the completion of the structure. Thirdly, that a small scale, labour intensive, rural building industry, would evolve producing a wide variety of fired clay building components, and this would lead to secondary benefits in the region going beyond the project of the fired structure and its own direct benefits. This would provide work opportunities to the village potter who holds a great potential for creating rural clay based building industry, and "whose livelihood is now threatened by mass produced plastic and aluminium vessels, and whose knowledge and skill with earth and fire are no longer fully utilized".

The product in the first 3 test were ground-moulded bricks and even though they were of extremely high fired quality as compared to the local bricks, they didn't fetch more than the same price as they didn't look too much better in appearance. In the 4th structure 8000 out of the 13000 product bricks were table moulded and brought a financial return of Rs. 6,300. The products in the subsequent tests were restricted to high-quality table-moulded bricks and tiles. Product sales from structure 5 fetched Rs 10,000, Structure 6 15,800, structure 7, a larger house fetched Rs 75,000, Structure 8 fetched Rs. 16,000. Structure 9 Rs, 4530 and Structure 10 fetched Rs. 43,500.

In the first 10 structures, test runs were conducted on hand-extruded drain pipes glazed toilet-pans, gargoyles, window *jaalis* and glazed tiles Such products did pay for themselves, and partly covered the cost of firing the structure.

In Structure 11, given the challenge of building twin houses at Rs 10,000 each along a small two-vault system, a much-higher return had to be realised from the product sales. The product had to subsidise the cost of building as well as that of firing the house. The product value increased, by designing a series of simple household items; and training a group of local potters. Candle-stands, hanging planters, oil lamps, garden stools and lanterns were made and transported to the building site for firing. Some, 250 smokeless *chulas*, to later serve in a nearby village, were also fired. The *chulas* do not yield a great return, but demonstrate the use of the house-kiln to fire appropriate Items for village economy. Brick and tile constituted about 60 percent of the product load. Enough 'heavy' clayware must be fired to create the thermal mass necessary to penetrate walls and vaults through and through. Rs 40,000 were recovered from product sales and the houses were achieved at the planned costs.

Given the number of potential products: Table moulded bricks, Glazed facing brick, Terracotta and glazed tiles, drain pipes, Jaalis, Toilet pan in glazed earthenware, Terracotta biogas plant and burner, Decorative and ritual elements of the house such as altar and deepam niches, Smokeless chulas and Terracotta "refrigerators" it would seem that practically the whole dwelling could be done out in fired clay[108].

A project in a "backward" area, far from industrialized urban centres, will not have to compete with mass produced clay building products as the generally do not reach these areas. Producing with labour intensive methods, the products will no doubt be of somewhat inferior quality, but if quality is sufficient for utility, then a market-albeit a limited one- does exist.

In areas adjacent to urban population with broad market potential, if local raw materials are good, a more sophisticated process and product could be considered.

6.6 Freeing the house plan from being a kiln

[108] The Center of Science for Villages Wardha, had already produced terracotta[108] bio-gas burner and glazed earthenware toilet bowls and had been experimenting with bio-gas digester systems. At Gramodaya Sangh Bhadravati, terracotta drain pipes were being made. At the Indian Institute of Sciences, Bangalore, a "smokeless"stove had been made in terracotta by the ASTRA Group. They had developed a light press for soil blocks which Ray was then testing as a tile press[108].

After the first six test structures achieved sufficient success for Meeker to be ready to begin building an actual house for a client, Meeker had shifted the focus of his further research on improving the fuel efficiency and cost efficiency by attempting to fire the structures as efficient kilns. Thus the architecture that resulted was restricted not only to the limits of building with earth as the basic material, meaning that all roofs had to be restricted to compressive structures, combinations of vaults and domes, but also that the structures had to function as efficient kilns.

Structures 7, and 10 and 11 had plans that were accommodated into these efficient kilns, and hence the watchman's space in HiDesign Factory and the EWS House in the AVIRC had to be fitted below the vaults in a sequence.

By the 11th test, extreme cost efficiency had also been achieved through product diversification that absorbed all the fuel cost of firing the house, and fuel consumption of 6,800 MJ/1000 bricks including structure and products was achieved.

Hereafter the focus shifted to freeing the plan from looking like kilns and more like houses. Structures 14 Satyajit's house, 15 Marta's house and 16 staff quarters for Minolta Aquatech, were examples of better and freer house plans where a wider range of architectural possibilities found expression. These projects had built up areas of 100, 40 and 8000 sqm respectively, and were not limited by the cost constraints of some of the other projects, and these structures technical improvements were not the focus.

Structures 17 and 18, were again low cost housing projects, and went back to being series of vaults, the requirements being multiple small living spaces.

6.7 Technology transfer and local skills

Structures 1 to 14 were not only designed but also built by Meeker through his own team of labourers under his own supervision. In Structures 13 and 14, Meeker had been responsible until the raw structures were fired and the clients Satyajit and Marta were themselves were responsible for the finishing of the house.

In Structure 15, Staff Quarters for Minolta Acquatech, there was no contractor, and Meeker had spent a lot of time living at the site himself.

In Structure 16, Low cost housing for DRDA in Ayothiapatinam, it was the first time a technology transfer was attempted to test of other persons could develop the skills to use this technology. As per Meeker's contract, 50 single vaults were planned, 10 were built, six were fired and one was finished during his involvement with them, and his supervisory visits to the site. Meeker found out only later that the houses were sadly discontinued after his term with them was finished. This was rather unfortunate as the young Indian engineers had managed the construction as well as the firing well to Meeker's satisfaction.

Structure 17, Housing for Volontariat Farm workers once again involved a local contractor, Gautam Chatterjee, and Meeker had reduced responsibilities.

Structure 18, the temple at Nrityagram dance village, was built by a local labour contractor with the materials provided directly by the management. The construction of the raw structure was supervised in Meeker's absence by Dharmesh Jadeja, an apprentice then at Golden Bridge, and by myself after the firing. Meeker himself was present at certain stages and mainly supervised the firing.

In Structures 19 and 20, Meeker had even handed over the architectural design and reduced his role to design consultant and guided the construction at important stages. He remained responsible for firing the structure. The architectural design as well as the construction responsibility of these two structures was taken up by me and my team.

The village potter could easily build a small kiln with this method and, after understanding its principle through a number of firings, put the same vault on 1.5 m walls and fire a room to live in. He would then become the equivalent of the local mason as a maker of houses. He would use the house as his kiln for firing floor tiles, *jaalis*, *chulas*, pipes — any number of items which could contribute to the stock of locally available building materials. Transfer of technology, always a stumbling block, might thus be handled with a minimum of difficulty.

6.8 Cost Efficiency

If on-site, or very-near-site, clay suitable for making fired bricks is available, material cost for the superstructure will be negligible. Foundation costs are somewhat high, as walls are thick (common walls 45 cm, end walls 34 cm with buttresses) and the vaults fairly heavy.

The projected costs for the three-vault system with on-site clay being used for all brick, structural and product, the original estimate looks quite good at Rs. 35/- per ft2 or plinth area. With the inevitable overruns, it should remain within Rs. 45/- per ft2, which is certainly very reasonable, considering the quality of the building. This was unfortunately not possible due to unforeseen factors and rain damage that upset all the figures.

The process is labour intensive. Most of the work is unskilled- moving bricks, loading/ unloading the structure, adding cow dung/rice husk/clay over the vaults, removing it after firing. The firing labour itself, continuous for 60 hours or more in structures fired by firewood, even on small houses, was exhausting, but the coal dust structures required no labour after the fire had sufficiently stabilised.

Many people get employment, and a high percentage of cost goes to labour rather than material. Meeker says that it can also be seen as negative- labour cost is high even though wages are low, as is productivity. “Evidently, labour intensive does not mean work intensive.”

All fuel and firing cost can be considered accountable to the product, or a percentage can be added to the structure (house mass relative to product mass).

Post-firing finishing costs vary depending on treatment. All structures need proper waterproofing over the vaults. Exterior walls need to be plastered with cement of lime base mixtures. (Walls that have an exterior face are composite: a mud brick on the interior face and a fired brick on the exterior face). Interior walls can be treated according to budget. Floors can be tiled with fired product. Windows can be filled with fired *jaali* elements and drain pipes, toilet pans, smokeless *chulas* installed.

Where these conditions are met - good on-site clay and a local fuel source it is reasonable to conclude that a house of relatively high quality can be built for technological transfer.

Long, multi-chambered structures are unquestionably most efficient. It is conceivable that a ten-vault system will prove economical. But even ten vaults will require producing some two lakh bricks, inclusive of structure and product. This is way beyond the means of individual families and probably necessitates government subsidy and supervision. It must also be remembered that until the building is fired, it is all mud. Large scale mud building projects arc extremely vulnerable to "unseasonable" rain-more especially when a large quantity of mud product has to be protected as well. Process infrastructure would include a significant and not inexpensive area of canvas tarpaulin.

6.9 Production of Raw Earth Bricks

The production of raw earth bricks for the structures were usually ground moulded hand made bricks produced on the site with locally sourced clay.

Table moulded bricks were produced only as products to be sold for offsetting the fuel costs of the stabilized structure by attributing all of it to the products. This was produced for the first time in Structure 4.

The only difference in brick production occurred in Structures 12, 18, 19 and 20 where coal dust that was procured from sweeping floors of coal factories and thus collected was used as a fuel that was mixed into the clay mixture for producing structure bricks, product bricks as well as the mortar for the raw brick masonry. The volume of coal dust that was mixed into the clay mix was 5% and was determined by trying several mixed brick samples in a regular oven.

Summary of problems faced, solutions found and relevant case studies

In Walls		
Problem	**Solution**	**Relevant Case Studies**
End Walls bending outward	Eliminating end walls	4
Need to eliminate end wall	Not resting nubian vault on end wall	4,5,6
Side walls bending outward	Built as leaning walls sloping inwards	5
Walls not firing through	Composite walls with cooked bricks on outer face and mud bricks on inner face All mud brick walls in interiors double-sided firing in continuous kiln no mortar in vertical joints	3 11 11
To build squinches on leaning walls	double leaning squinch trammel	14
Increase in mass of external walls and consequently the need for fired brick	reduction of wall height	7,8, 9,10, 14, 15, 20
To gain more space and to eliminate buttresses	leaning walls below domes	14, 15

Size and Scale		
Being able to fire a big space	progressive increase with firing experience	2,3,4,5,6,7,8
Fuel and Firing Technique		
Firing through of 15-20 cm thick vaults	Combustible insulation	5
Inefficient use of fuel as compared to ready brick	Using ‘waste heat’ to preheat a subsequent space in a continuous kiln structure or down draft kiln Coal dust	8,10,11,12 12,18, 19 and 20
Achieving socio-economic benefits through value addition of products		
Fuel cost was significant	Products absorb total fuel cost and more Table moulded bricks fetch more money for the same fuel consumption 40% of the products are sophisticated smokeless chulas etc half a million bricks advantage of scale	5,8,16 5 8 8 16
Achieving fuel efficiency		
Fuel cost was significant	efficient kilns choice of fuel: coal dust infused self- burning bricks	8,10,11,12 13,19,20,21

7. The Building Process

"There is nothing quite so exhilarating as a very large kiln; a series of six or eight volumes, connected with a winding tongue of flame - a coiling dragon of incandescent fire - restrained by an undulating roof-scape of mud vaults and domes."

Ray Meeker[109]

Fundamentally the building process is as follows:

1. Building a structure (that also works as a kiln) in unfired mud bricks, including the roofs which would either have to be vaulted or domed due to the restriction of mud as the only building material to be used above the plinth level of the structure.
1. Filling the inside space of the structure with ceramic products (bricks, tiles, any other appropriate product) to be fired, as if the structure were a kiln.
2. Firing the kiln structure to temperatures between 900°C and 1000°C depending on the locally available clay. (Pondicherry clay required 950°C).
3. Unloading the fired products.
4. Using a part of the fired products for finishing the kiln as the house or other planned use. This includes tiling floors and maybe roofs, building partition walls and compound walls, paving outdoor spaces, installing toilet fixtures and water spouts, '*jaalis*' window screen elements, etc .
5. Selling the remaining products to recover fuel costs and if possible even more.

7.1 Building the Mud Structure

7.1.1 Locating Suitable Clay

[109] MEEKER, Ray. Attitude, Imagination, Innovation Pg 12-15, Magazine of the Kamala Raheja Vidyanidhi Institute of Architecture, 1998

While it is acknowledged that earth as a building material is one of the planet's most abundant resources, and mud may still be the most widely used material in today's world for building houses[110], each earth building technique does require the appropriate type of earth.

While the earth building technology that is built for firing is very much like the conventional adobe structures, meaning that it is built using unfired mud bricks bonded together in mud mortar, the earth that is suitable for adobe construction may not be suitable for fired earth buildings

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In fired buildings the end desired result is the conversion of clay into ceramic just as in the case of the fired brick, and so the most ideal clay suitable to this technique would be good brick clay.

Soil Suitable for Adobe Buildings

Adobe is the term for a commonly used method of earth construction that uses sun dried earth bricks. The soil is brought to a semi-liquid consistency, and then formed into blocks. The blocks are allowed to dry in the sun during which period, they gain strength and at the same time shrinkage takes place. The selection of soil is crucial: the best soils have clay content high enough to give good strength but not so high as to cause moisture movement problems. In central Africa, ant-hill soils are well-known to have suitable properties. To some extent, an excess of clay can be overcome by adding vegetable fibres to control movement, and absence of clay can be remedied by adding bitumen or some other binder. The great advantage of adobe construction over other earth construction techniques is that blocks previously made, and stored so that drying shrinkage can take place before they are built into a wall. The major disadvantage is that

[110] "…and it is probably true to say that there are today more buildings in the world whose walls are built with soil than with any other material." SPENCE, Robin. *Building Materials in Developing Countries*, John Wiley and Sons, Chichester 1983 (pg 35)

some moisture movement does occur, particularly in wet climates, making adhesion of renderings difficult.[111]

Soil Suitable for Fired Earth Buildings

Adobe mixture for fired earth structures differs from a common adobe mixture in its higher clay content and purity of the mix.

To make fired earth structures, the soil suitable for bricks, a wide range of soils called clay or brick-earth is suitable. The essential property is plasticity- the ability to be moulded under pressure- and this is imparted by clay particles. But the proportion of clay in the soil needed to give plasticity is not great, and soils with a very high clay content often exhibit high shrinkage and cracking, making them unsuitable for brick making. Some of the best brick-earths contain only about 30-40 percent clay material, the remainder being sand or silt particles.[112] Alluvial soils are most commonly used for brickmaking, and the Indian Standard IS: 2117 gives the following preferred soil composition by weight Clay 20-30 %, silt 20-35 % and sand 35-50%. Total weight of the clay and silt particles should preferably not exceed 50%. Where a soil with these properties is not available, mixing of two soils or the admixture of sand, or ash, or finely ground fired clay (grog) can be used to obtain a suitable particle size distribution[113].

Indian Standard IS: 2117also gives a preferred plasticity index[114], (PI) between 15 and 20 %. The soil grading and plasticity properties are found by use of the particle

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[111] From SPENCE, David and COOK, Robin, Building Materials in Developing Countries, John Wiley and Sons, CHichester, 1983 (Pg 42-43)

[112] SPENCE, Robin. *Building Materials in Developing Countries*, John Wiley and Sons, Chichester 1983 (pg 37, 68). More on material properties is discussed in Chapter 8 and Section 8.1

[113] A Compendium of Information on Selected Low-Cost Building Materials, UNCHS (Habitat)

[114] The plasticity of a soil refers to the extent to which a soil will absorb water. The tests for this are carried out only on fine material. The water content by weight at which the soil passes from the rigid to the plastic state is called the plastic limit, the water content at which the soil passes from the plastic state to the liquid state is called liquid limit. The difference between these two water contents is the plasticity index. The standard methods of measurement of the liquid and plastic limits are the Attenberg tests. (A Compendium of Information on Selected Low-Cost Building Materials, UNCHS (Habitat)

size distribution and plasticity tests. The plasticity of a soil refers to the extent to which a soil will absorb water.

Description	Grain size (equiv. particle diameter, mm)
Gravel	2.0 – 60
Sand	0.60 – 2.0
Silt	0.002 – 0.06
Clay	Less than 0.002

Table 5: Size classification of soil grains

All brick-earths contain a certain amount of impurities. Some of these, such as iron oxides, are responsible for the colour of the burnt brick, which, depending on the type of oxide present and the conditions of burning, may be red, yellow, brown or blue. One undesirable impurity is limestone; this can occur in nodules in the soil which subsequently expand and crack the brick. Others are gypsum and other salts which can dissolve and be re-deposited on the surface of the brick causing efflorescence.

The Importance of Proximity of the Site to the Clay Source

Ideally the soil is best sourced from the site itself or from nearby. Bringing the earth from outside or buying earth-clay is not like buying steel, concrete or timber. It may be dug in a nearby area or purchase it from other spots. The major cost would be transportation. Even buying blocks can sometimes be justified, since the earthen material is the only major material needed.[115]

Good brick clay on or very near the site is essential to realizing the full economic potential of the process. Mud is generally considered to be an abundant resource (it definitely is when it rains on an unfired structure) but clay suitable for making fired bricks is not to be found everywhere. The tenth test, the first building to be done in nearly 'ideal conditions is a series of three vaults on common walls. It was fired as a semi-continuous

[115] KHALILI, Nader. Ceramic Houses and Earth Architecture: How to Build Your Own Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (pg 67)

chamber kiln. The on-site- clay is of sufficient quality (just) for brick making. All structural and product bricks were made at the site.[116]

A typical single-vaulted structure will require 6000 to 7000 bricks to build. The same structure will contain 12,000 bricks as product. Good brick clay on or very near, the site is essential to realizing the full economic potential of the process. Mud is generally considered to be an abundant resource, but clay suitable for making fired bricks is not to be found everywhere[117].

Locating Clay

The best way is to ask natives, potters, brick makers, farmers. And if we see any brick kilns in the area there is probably lots of clay.

Brick Clay used in Meeker's Case Studies

There is a great deal of latitude in the quality of earth appropriate for use in an unfired mud wall. Clay suitable for firing (i.e. brick clay), though certainly not a scarce material as such, is not likely to be found at many building sites. The first eight structures were built by Meeker on three different sites, all of which were composed of clayey soils. Yet none of the on-site clays were suitable for making fired brick. At the first site, (where the first six test structures, structure 9 and structure 12 were built) the clay substance was very good but could not be used because it was riddled with limestone nodules. At the second site (Structure 7 Agnijata) the sand content was much too high; at the third site, about a mile from the sea (Uppalam), the clay contained too much salt. Meeker had been buying raw (unfired) bricks from the brick yards or transporting clay and making the bricks on site. This raised construction cost and Meeker found it very difficult to find someone who will sell their brick clay. To them it is a very valuable

[116] MEEKER, Ray. MUD: Towards A fire Stabilised Building Technology, Architecture & Design, Media Transasia, Delhi, March- April 1991

[117] MEEKER. Ray. Fire Stabilised Mud Structures. *Moving Technology* Vol.4 No.4, CAPART, Delhi, August 1989 (pg 27-31)

resource. Brick makers, at least in that area, which is developing rapidly, did not consider good brick clay abundant. The cost of this material is rapidly on the increase. The tenth Structure was built on a site with excellent clay, and provided an opportunity to determine the importance of proximity to the clay source. Bearing in mind that these structures are filled with a product (normally bricks) before firing, it is clear that *a* tremendous amount of material is used in the process and the transportation cost alone of that much material is significant.[118]

7.1.2 The Manufacture of Bricks on Site



Fig. 7.1 Brick making using slop-moulding, 1999, Source: Anupama Kundoo
Fig. 7.2 Brick making using slop-moulding with an addition of coal dust, 1999, Source: Anupama Kundoo
Fig. 7.3 Square bricks for vaults or domes, more surface area and grooves for better adhesion, 1999, Source: Anupama Kundoo

Preparation of the clay for moulding requires a thorough intermixing of the clay with the right amount of water. In the simplest brickworks, as in India, this is done by treading. At the mixing stage, ash or sand may be added to control shrinkage. Fuel may also be mixed into the clay; in Lesotho, coal dust is added; in Egypt, chopped straw.

As in traditional brickmaking, bricks may be moulded by hand in simple wooden moulds. The clay is formed into a clot by the moulder, thrown into the mould with sufficient force to take up its shape accurately, and the excess is scraped off. The mould is then removed leaving the brick to dry. Clean release of the mould is crucial, and in the slop-moulding method, the mould is kept wet, and sufficient water is added to the clay to prevent sticking, bricks made in this way are prone to slumping and distortion. In the

[118] MEEKER, Ray. Geltaftan: A Second Thought, An undated and unpublished essay.

sand-moulding method, the clot is rolled in sand before moulding to aid release, firmer, more regular bricks can be made this way.[119]

Bricks for the structure were ground-moulded using a gang mould producing 2 bricks to increase productivity.

Table moulded bricks were manufactured as product to get a better finish and fetch a better return by selling them for use as exposed brick masonry.

Bricks are dried in the open under the sun. This usually means that brickmaking is seasonal as bricks cannot be allowed to dry in the rainy season. Initially bricks are left in rows on the ground, just as they were moulded, and later turned on edge to allow drying uniformly. To save space, they are then stacked with space for ventilation, and covered with rain protecting sheets. Drying takes up to four weeks after which, the bricks are ready for burning. This means that they are ready for the brick masonry of the earth structure to be fired, or to be stacked into the kiln as the case may be.

7.1.3 Foundations

Fig. 7.4 and 7.5, Strip foundation in Agnijata, 1988, Source: Ray Meeker

[119] SPENCE, Robin. *Building Materials in Developing Countries*, John Wiley and Sons, Chichester 1983 (pg 69)

Foundations remain unaffected by fire, and the fire is ignited at the base of the interior of the structure. As such the foundations of the buildings may be done in the most appropriate materials according to the site circumstances.

In most of Meeker's buildings, foundations were strip foundations in brick masonry (Fig. 7.4 and 7.5). In the AVIRC, the eleventh test, the structure was built on a cement stabilized rammed earth foundation using the same earth that was excavated out of the foundation pit (Fig. 7.6). In the eighteenth experiment, the building was built on an existing foundation and plinth built with stone masonry as was the standard practice in local area of Hessaraghatta near Bangalore.

Fig. 7.6 Cement-stabilised rammed earth foundation from site soil in AVIRC, 1990, Source: Ray Meeker

7.1.4 Wall Construction

Load bearing walls initially 45 cms thick, and later 35 cms were being constructed in mud bricks with mud mortar, but as they were not met with any success in being cooked through, the later structures were built as composite masonry with mud mortar using fired brick in the outermost face and green bricks towards the inner sides.

In cluster structures, common walls bearing vaults on either side, would benefit from firing from two sides and hence would get sufficiently stabilized even if it were built entirely in green bricks. In such common walls, composite masonry is unnecessary.

The vertical joints in the inner brick layer are left open without mortar to encourage the heat to penetrate deeper.

23 cms could be considered as the depth to which the fire could be expected to penetrate. Therefore it is more advantageous to reduce the wall depth and to build as much of the structure with the 20 cm thick vaults and domes as possible. The reduction has the benefit of saving building mass and material, but also enables it to be built with fewer fired bricks, and a larger volume of the earth structure can be achieved as an insitu fired building.

Side walls maybe built slightly leaning so as to avoid their bending outwards on firing and end walls in vault structures are best avoided altogether as their bending will be greater due to the fact that they are not loaded.

Buttresses are important not only due to the thrust introduced by the vaults and domes but also due to the expansion that will occur during firing. According to the plan of the structure below, it may be advantageous to have leaning walls that could displace buttresses and claim more useable space.

7.1.5 Vaults and Domes and their Centering

Vaults cannot be constructed in the simplest and classic Nubian method as this method requires an end wall to lean the vault during construction without centering. This method of construction had in the early structures resulted in the bending outwards of the end walls upon unequal expansion of inner and outer faces during firing, and their separation from the vault altogether.

Vaults maybe constructed on centering, which is convenient to raise and lower as the vault is likely to settle after shrinkage, even if the mortar joints to the inside face reduce to 0. Working with centering is going to be difficult if this shrinkage of the vault is not taken into account in the planned building process.

One of the most satisfactory ways to build vaults was the use of centering for building a 75cm strip of vault, upon which the brick courses of the remaining vault could lean and be developed just as in the Nubian Vault technique.

Domes may be built in a wide variety of established methods, none of which met with any unfavourable results in the series of Meeker's experiments.

In order to gain more useable space under a dome, it proved to be advantageous to lean the supporting walls outwards towards the base, and also to end in a square plan. This meant though that the squinches were also leaning (Fig. 7.7) and required the development of a doubly-curved leaning squinch trammel which enabled the construction.

Fig. 7.7 Leaning walls meant leaning squinches, which needed the fabrication of a doubly-curved leaning squinch, 1999, Source: Anupama Kundoo

7.1.6 Protection from water

Mud construction is very vulnerable to rain damage, and in spite of the fact that the raw earth construction should be planned in dry seasons; there is every possibility that unseasonable rain showers may occur and pose as a serious threat to the yet unstabilised structure.

The structure must be packed carefully with waterproof sheets of plastic daily at the end of each work day. This is quite a task and also creates substantial expenses both in terms of material and labour, as the structure must be unwrapped each morning and repacked in the evening[120].

7.2 Products

7.2.1 Choice and Production of Products

The clay products chosen to be fired in the structures could range from simple table-moulded or ground-moulded bricks to more complex ceramic objects that could be useful in finishing the house like terracotta and glazed tiles, glazed facing brick, drain pipes, *jaalis*[121] (Fig. 7.8) toilet pans (Fig. 7.9) and wash basins in glazed earthenware, terracotta biogas plant and burner, decorative and ritual elements of the house such as altars and *deepam*[122] niches



Fig. 7.8, Glazed jaalis (window screen elements), Marta's house, 1991, Source: Anupama Kundoo
Fig. 7.9, Toilet pan, model village house, Uppalam, 1988, Source: Ray Meeker
Fig. 7.10, Planters and lampshades, etc. for boutiques, AVIRC, 1990, Source: Ray Meeker

Products may also be developed that may benefit the quality of life in the local area such as smokeless *chulas*[123], or in areas adjacent to urban population with broad market potential products may be highly sophisticated products produced primarily for

[120] There were so many cases of unseasonable rain damage to Meeker's experiments that Meeker said he was being popularly known as "Rain Maker" instead of Ray Meeker.

[121] Permanent window screen elements as they are called in India

[122] Local term for oil lamps

[123] Local term for Fire wood stoves for cooking

generation of capital like planters (Fig. 7.10), candle stands, oil lamps, garden stools, lanterns and other such products that may be well received at boutiques.

7.2.2 Stacking of Products


Fig. 7.11 Brick stacking in wood fired kiln systems, Agnijata, 1987, Source: Ray Meeker

Fig. 7.12 Brick stacking in coal-dust kiln systems, Bina Saxena's residence, 1999, Source: Anupama Kundoo

In case of wood firing, the products should be stacked as they would be in a kiln, providing sufficient air movement and well balanced arrangements to protect the products through the firing process.

In case of combustible material infused in the brick clay as in the last three structures, product bricks are stacked as close as possible to have maximum contact and help spread the fuel in the product to ignite easily. Such a kiln is stacked compactly with the structure as well as products intended to burn as one mass. Sufficient spaces are provided within the stacked products to allow the steam that will be expelled to find its way outside the structure without creating any pressure and without letting the rising humidity affect the structural stability. The other are to be considered is that the first few layers need to be provided with sufficient coal (fuel) at the base of the structure so that a strong and stable fire is sustained initially until the coal content in the bricks actually begin to burn. These voids in the product stacking where fuel is contained must find their way to the doors where openings are provided to light the fire and also to allow oxygen into the tracks for combustion.

7.2.3 Ceramic Glazing

Glaze is a glass-like waterproof protection, usually 0.15 to 0.3 mm thick, fired on to the surface of ceramic ware. By glazing ceramic products, it is possible to give the products a pleasing appearance and to increase its imperviousness to water. According to the baking temperature, it is customary to distinguish high-melting glazes (1100°C to 1350°C) and low-melting glazes (900°C to 1100°C). High melting glazes are usually applied without preliminary fusion (fritting). They are mainly composed of quartz, kaolin, clay, feldspar, and natural carbonates of metals (like dolomite). These form what are called wet mixes. Low-melting glazes are usually frittedbefore application. In addition to quartz, feldspar, and dolomite, they contain borax, strontium carbonate, magnesite, and some other substances. Glazes may be transparent or opaque. Transparent glazes are coloured by fusion with colouring oxides. Colour to opague glaze is given by mineral pigments.[124] The most important of all these elements is silica, which when fired to the melting point and cooled, makes glass. But it takes a very high temperature to melt silica. So, to lower the melting point of the silica, it is mixed with other minerals (oxides) such as sodium, calcium, potassium. Much lower-temperature oxides, like lead are used as flux. Flux (e.g. lead) is the agent that reduces the need for high firing temperatures. High temperature glazes are more durable than low-temperature ones. But the products fired in the structures need may not be dealing with an intensive use factor- as in a cup or a plate- a high-fired glaze may not be needed. In areas of use such as a bathroom or a counter top, however, a more durable glaze may be desired. Glazing an entire room, like covering a room with conventional ceramic tile, is not desirable. The room would not be able to "breathe," nor would it be acoustically suitable for a living environment.

Khalili's writes that during his experiments, Ali Agha, his kiln specialist, made a homemade glaze by grinding broken Coke bottles and adding a couple of oxides. He then applied it, within twenty-four hours of mixing, with an insecticide sprayer over the room

[124] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (pg 133-134)

surfaces. The decorative parts were covered with glaze applied by a brush. Care had to be taken as far as safety[125] was concerned.

The idea of glazing a building interior is negated by Meeker by the difficulty of getting even temperatures and protecting the raw glaze from damage during brick loading. It makes better sense to fire glazed tiles in saggars and to install them after the firing. However in Structure 8, the model village house in Uppalam, Pondicherry, and Meeker did use a low temperature glaze on some products, such as tiles and seating elements.

7.3 Firing the Structure

7.3.1 Choice of Fuel and Firing systems

The firing system depends mainly on the availability of the fuel. It is good to compare the available alternatives and calculate the tradeoffs. Coal, firewood and oil are the commonly used fuel in brick-making, and the optimum choice is to be made based on availability and on kiln system adopted. The best firing system is usually the system that would for a specific area be the most fuel efficient option given the fuel availability and the most efficient kiln system that could be adopted according to the scale of the project. However, a kiln designed for efficiency may not be the most ideal place to live in, and so a compromise has to be reached between fuel-efficiency and spatial requirements.

Section 9.4 discusses in detail the design considerations due to the structure having to perform as an efficient kiln, and also explains the principal types of brick kilns and their fuel consumption.

7.3.2 Sealing the openings

[125] Lead oxide, which is used all over the world as part of the glazing mix, has tremendous advantages over other fluxes. But since lead is poisonous, handling it in raw form must be done with great care. Spraying the lead and breathing it is very dangerous and must be either completely avoided or done with adequate protection. There is no hazard once lead glaze is properly fired.

First the products are stacked and flues are provided as necessary. Door and window openings are then blocked by piling green bricks, standing them next to each other and using small broken pieces to fill the corners, without using any mortar. Then a thin layer of mud plaster is applied on the outside to close the open joints and prevent the heat escaping.

7.3.3 Insulating

The vaults and domes are insulated with a 10 cm layer of a mixture of 2 parts of rice husk, 1 part of cow dung and 1 part of clay, (earlier structures used clay sand and ash, but the walls weren't stabilizing through the entire thickness and then an advance was made with the successful attempt of a combustible insulation). The cow dung may also be replaced by coal dust in case the firing is fuelled with coal dust as part of the brick mix.

7.3.4 The firing itself

Fig. 7.13 Meeker starting the fire, Bina Saxena's residence, 1999, Source: Anupama Kundoo
Fig. 7.14, after the fire is stable, Bina's Saxena's Pottery, 1999, Source: Anupama Kundoo

A fire is started at the bottom, according to the interior floor level and the fire box that is planned with respect to the kiln system to be adopted.

In case wood is used as a fuel, the structures need to be closely monitored throughout the duration of firing. During firing, the temperature inside the room can be measured. Pyrometers can be left in the specific positions of the room for the entire baking time, with an outside indicator to show the temperature rise.

In case of coal dust as a fuel, the interior space is compactly packed with products except at the base the structure, which contains tunnels filled with coal to initiate the fire. About six hours are required to ignite the coal layer in the base, after which it is allowed to burn at leisure. It burns till the fuel is spent, and can take a few days. There is no possibility to control the fire in this kind of firing, as the firing is mainly dictated by the fuel content in the bricks, and if it was inaccurate, then the products may be over-fired and the structure under-fired.

The twenty-four to thirty hours of firing is enough to create a fired-shell structure; however, with slower and longer firing systems, deeper penetration of the fire and more solidification of adobe and mortar are ensured. The best handmade bricks sometimes take as long as three to five days of slow firing.

It is important to get the building as dry as possible before introducing a higher temperature fire. A low fire is started at first. During the early firing, all flues and access holes on top of the roof should remain open. It may even be better to leave the stack of adobe in front of the door or window unplastered for few hours to help the early steam escape. Using mud-straw plaster during the fire is possible. The idea is to let the adobe and clay dry outside and inside, and let water that is trapped between its molecules escape as easily as possible.

After ten to fourteen hours, when the steam is all out the top access holes are closed by when the system of updraft and downdraft circulation changes to downdraft. This means that the only way fire and hot gases can escape is from the flues at the base of the wall, or below the floor. Flues at the top must be open and clear of any obstructions. After all the steam is out, the fire can be raised to its highest temperature and heat can be allowed to build up.

When the fire reaches 960°C (or suitable temperature according to the brick clay) the fire is continued for about two hours or so before turning it off.

7.3.5 Cooling the structure

After the fire is stopped comes the cooling period. The only openings should be flues on the roof, through which the air and heat exchange occurs. Through these shafts, and through the roof and wall surfaces, the room cools off very slowly. Khalili let it sit for forty-eight hours or more before opening it up Early opening creates cracks[126].

7.3.6 Opening the Kiln and Recovering the Fired Products

When the room is cooled and opened, the simplest and yet the most profound sight can be seen and touched: The entire adobe and clay room has changed to solid brick. The structure now is water resistant. The products are individually loaded. The structure gradually reveals itself. The structure is then analysed for under-fired and over-fired areas.

Fig. 7.15 opening the kiln, model village house, Uppalam, 1988, Source: Ray Meeker

[126] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg 163-164)


Fig. 7.16, Meeker starting the fire, Bina Saxena's residence, 1999, Source: Anupama Kundoo

Fig. 7.17, after the fire is stable, Bina's Saxena's Pottery, 1999, Source: Anupama Kundoo

7.3.7 Waterproofing and Finishing


Fig. 7.18, exterior finishing, Agnijata, 1987, Source: Ray Meeker

Fig. 7.19, interior finishing, Satyajit's house, 1992, Source: Ray Meeker

The fired structure is finished by a variety of conventional techniques; "admittedly, an anti-climax to the 5-day firing", according to Meeker, given the excitement of the process so far. All structures will need proper waterproofing over the vaults. This is most important. The structure is stable, will not slake in the rain, but, like a fired brick, it is porous. The vault will absorb a large amount of water, increasing its weight tremendously, and of course, will eventually leak. Standard cement or lime-based plasters must, therefore, be applied to the exterior of all vaults and walls; especially those critical points where Two vaults meet, and at cornices over the walls. Interiors can be finished according to one's budget - with cement or lime-based plaster, mud plaster, no plaster; simply whitewashed. Electrical conduits can be cut into the fired walls if concealed wiring is preferred. In the EWS demonstration houses, a small courtyard with kitchen, bathroom and toilet were added In fired brick and cement-stabilised soil mortar alter firing. Agnijata has a sleeping loft, cast in concrete, in a 4.5m high vault.

Post-firing finishing costs will vary depending on treatment. Interior walls can be treated according to budgets: cement or lime plaster, mud plaster, or whitewashed with no plaster at all. Floors can be tiled with fired product. Floors can be tiled with fired product. Windows can be filled with fired *jaali* elements and drain pipes, toilet pans, smokeless-*chulas* installed.[127]

[127] MEEKER. Ray. Fire Stabilised Mud Structures. *Moving Technology* Vol.4 No.4 CAPART, Delhi, August 1989 p 27-31

8. Material Properties of the Structure and Their Implications

"Fire is the cement in this technology"

Ray Meeker[128]

Fired clay is the earliest man-made material that is in use since the early human civilization, and still used widely. With their attractive appearances and superior properties such as high compressive strength and durability, excellent fire and weather resistance, good thermal and sound insulation, bricks are widely used for building, civil engineering work and landscape design.

Fired clay products are one of the earliest man-made materials to be used in architecture[129] and both sun-dried as well as fired bricks have been in use since at least 3000 and 1500 BC respectively. From the earliest times, fired bricks were used mainly for buildings of public or religious significance; one reason for this is the large quantities of fuel required for firing. It is only in recent times that burnt-clay bricks have replaced other less durable materials for ordinary house-building.[130] The material

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[128] MEEKER, Ray. Geltaftan: A Second Thought, Unpublished essay, Undated

[129] At first ceramics, (from the Greek Kéramos, meaning Clay) was chiefly employed to suit everyday domestic necessities. In 5000 BC people in various parts of the world began to burn clay products to strengthen them still mainly for cooking and storage pots. It is commonly believed that man began using clay for buildings about 4000 or 3000 BC. The mud houses he built were burnt by bonfires outside and then some of them were even painted. (AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 Page 69-70)

The earliest known bricks are those found in archaeological excavations in the cities of Mohenjo-Daro and Harappa in the Indus Valley, in present day Pakistan, which flourished between 2500-1500 BC. At roughly the same period, bricks were also used in the Sumerian cities on the Tigris and the Euphrates rivers in present day Iraq. These bricks were flat on one side, convey on the other measuring approximately 250 x 150 x 500 mm. Mesopotamia continued for a long time, to be a centre if brickmaking, at least for monumental structures. In the first millennium BC, the Assyrians and Babylonians used bricks of an even larger size which they laid up in bituminous mortar. (Ishtar Gate of Babylon is a magnificent surviving example from that period). From the first century AD onwards, Romans made considerable use of bricks as a facing material, square up to 600mm and flat, not more than 50 mm thick. It was through them that the bricks reached Northern Europe. In India bricks continued to be used, and from there spread through South and South-East Asia. Bricks in ancient Egyptian civilization, but these were sun-dried and not burnt. Around 1500 BC the Babylonians started using coloured glaze for earthenware. (SPENCE. R, COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 65-67)

[130] Indeed in some parts of India and Africa, the proportion of burnt brick homes in a village can be used as some sort of measure of its level of prosperity. However, there are other parts of the world where,

properties of the structure of baked-*insitu* earth houses are the same as the age-old fired brick structure known to man since at least 3500 years. However in the case of this technique the structure and the method of construction directly involve three distinct three stages of the material and its properties: before, during and after firing. Moreover, as the firing is done after the structure is built, the behaviour of not only the material itself, but also the large structure as a whole to the firing process is extremely significant to understand.

8.1 Before firing: As raw earth

The primary raw material for the bricks, the mortar as well as most of the products of the structure is 'brick clay'. Brick clays[131] are secondary earths derived from sedimentary rocks, considerably varying in mineral and granulometric composition. They are made up of clay minerals (kaolinite, hydromica, and montmorillonite with a substantial proportion of quarts, carbonates, iron oxides, etc)[132]. For the production of tiles, hollow bricks, facing bricks, terracotta articles, majolica, various kinds of porcelain and earthenware the clay used is called 'potter's clay'.[133]

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although the necessary raw materials are available, brick burning has never been introduced. (SPENCE. R, COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 65-67)

[131] Brick clays serve as raw material for clay and clinker (paving?) brick, masonry units, roofing tile, facing tile, and expanded clay aggregates. They also find application as water-proofing materials in dams and road-building, and in rural areas, they are used to make mortar (surkhi in India), plaster, stucco, sun-dried bricks, adobe and mud walls.

[132] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pages 130-132)

[133] Other ceramic clay types than the brick clay and potter's clay are *bentonite clays*, finely dispersed earths formed from the chemical disintegration of volcanic tuff, ash and lava mainly composed of montmorillonite mixed with some quartz, kaolinite, hydromica, gypsum, biotite, and iron oxides, and primarily used for waterproofing and sealing materials and underground construction but also as plasticizers for porcelain masses; and *fireclays* are finely dispersed earths consisting of kaolinite with quartz, feldspar, hydromica, and carbonates in them and mostly used to fabricate wall and lightweight insulating fire brick used in masonry and furnace lining.

The properties of raw clay and clay products can be markedly improved by adding non-plastic substances such as quartz sand, grog and slag[134] to highly plastic clays which require much water to be worked into a uniform plastic mass. This is done to reduce shrinkage and to facilitate moulding. Combustible organic admixtures such as saw dust and coal dust are also added to improve the clay products.[135]

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Until the building is fired the structure will be all mud- and so also the products that are being simultaneously manufactured to be fired inside. This means that the structure will have the limitations that unfired clay has for building until the point that the structure is fired and thereby transformed into ceramic. Sun dried bricks for the structure may be manufactured on the site or sourced from nearby brick makers, and can be moulded in a variety of ways.

The principle limitation is the vulnerability to water. The structure will have to be built during a dry season, and in spite of that will need to be carefully protected from water during the period of construction until firing, just in case. This is a major consideration, as it will not be possible to build throughout the year, and it even then it may not be exactly possible to pre-plan the time schedule. Unseasonable rain is still potential threat to a mud house, and wrapping and unwrapping the structure with thick plastic sheets and rope is a tedious work that has to be meticulously done daily.

The dry compressive strength of mud bricks ranges upto 2.0[136] MPa[137]. Local bricks have the compressive strength of 3 to 8 MPa[138]. For 2 storey structures a

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[134] Slag is the waste glass like product from a metallurgical furnace. The slag most used in building and civil engineering are blast-furnace slags obtained from iron smelting. The products of solid fuels (coal, wood, etc.) that have ceased to flame are known as cinder and ash.
AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 144)

[135] This is according to AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 133)

[136] Air dried soil bricks have a compressive strength of upto 2 MPa, according to AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986

[137] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 121)

compressive strength of 3 MPa is sufficient and the design of baked insitu structures will have to accept the limits of the dry compressive strength of the raw brick as it will have to bear its weight as such, even though it will eventually acquire the strength of a brick upon firing. In single or two storey structures this may not matter. The structures will have the limitation of the dry compressive strength of a Structures will have to be designed in total compression, but the same principles would have to also be followed in the case of a fired brick-only structure.

In a fired brick structure, it is possible to add other structural material such as stone lintels and wood in order to deviate from arches and domes. In the case of a baked-insitu structure, as it will be subject to firing after construction, and subsequently transformation of the material as well as expansion, the entire structure would be best built with mud as the only material. And hence the necessity to use arches, vaults and domes is all the more basic.

Another characteristic that requires consideration is that during construction, the mud bricks are put together using mud mortar, which has the property that it is subject to upto 37% shrinkage[139]. Even though the final structure behaves as fired brick structures, the baked-insitu structure must take this difference into account in the way the arches domes, and vaults are constructed. Shrinkage would lead to sinking of the form upon drying if the proper precautions are not taken. The construction of arches vaults and domes have to follow the principles of raw earth brick building techniques. Pieces of brick need to be packed on the outer edges while on the inner edges the bricks need to touch each other[140]. The second implication of shrinkage is that it makes the removal of formwork very difficult. The choice and design of formwork has to be paid the necessary attention.

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[138] SPENCE. R, COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, (Pg 78)

[139] FATHY, Hassan. Architecture for the Poor, The University of Chicago Press, Chicago, 1973 (Pg 10)

[140] FATHY, Hassan. Architecture for the Poor, The University of Chicago Press, Chicago, 1973 (Pg 10)

8.2 During firing: An Unstable State

Fig. 8.1, Steam escaping, Bina's Saxena's Pottery, 1999, Source: Anupama Kundoo

Fig. 8.2, Structure expanding, products contracting, Bina's Saxena's residence, 1999, Source: Anupama Kundoo

The burning of clays requiring from 60 to 100 hours may be divided into three main stages: dehydration or water smoking; oxidation; and vitrification.

During the initial stage of dehydration, the chemically bound water is driven off, the clay minerals decompose, the clay becomes amorphous, and the ware shrinks. The speed at which these processes occur depends on the water and the mineral content of the clay, its porosity, texture, and on the method of handling the kiln. Too rapid heating causes cracking or bursting of the ware. On the other hand, if alkalis are contained in the clay or if much sulphur is present in the coal, too slow heating produces a scum on the surface of the product. The process is completed before the temperature rises from 450°C to 600°C[141]. No matter how old or dry adobe and clay buildings are, even centuries old, they still contain more than 15 percent moisture[142].

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[141] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 134)

[142] KHALILI, Nader, Ceramic Houses and earth Architecture: How to Build Your Own, Cal-Earth Press, Hesperia, 2000 (pg 154)
According to AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 134), the green ware may contain 7 to 30% moisture.

The de-oxidation process is nearly always completed at 900°C[143]. From 450-500°C dehydroxylation begins to take place, an irreversible reaction. The hydroxyl groups present in the clay are driven off as steam. This results in expansion of bricks, and the material becomes very soft, almost like wet clay. The structure is at its weakest at this point (and one should avoid going on the roof).

After all the steam has escaped, the blow holes are closed, and the heat directed to the path planned. It is important to fire the structure gradually; otherwise it may burst or crack. After 10-14 hours or more depending on the structure, the blow holes are closed. It can even take up to 2 days for all the steam to escape in case of slow-firing. Slow firing minimizes structural distortions, but consumes more fuel.

Carbonaceous organic matter from plants etc. will burn off in the temperature ramge of 400-700°C provided sufficient air is allowed in to convert it to carbon dioxide gas. If this organic matter is not burnt off completely before the temperature rises to the point at which glassy material forms, the diffusion process will not be possible and carbon will remain within the bricks as undesirable black cores.

Carbonates and sulphides present decompose at the top of the temperature range at which organic matter is burnt, carbon dioxide and sulphur dioxide being given off.

Silica, which is a common constituent, is in the form of quartz, changes its crystal form at 573°C. This inversion is accompanied by expansion.

During the third stage, vitrification[144], the clay is baked and the finished product is formed. This happens at 900°-1100°C with low-melting clays and between 1150°-1250°C with high-melting clays. The burning temperature and the duration of firing depend to the character of the raw material and the purpose of the ware. Glass particles which is necessary to bond particles together and make the product strong and durable

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[143] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 (Pg 121)

[144] in which fluxes react to form a liquid

commences at approximately 900°C. The higher the temperature, the more liquid is formed and the more the material shrinks. Therefore overheating should be avoided to avoid melting of bricks and distortion of form.

To attain uniformity, a few hours soaking at the finishing temperature is recommended to ensure that the whole brick has attained uniformity. Other substances like mullite, etc, if present also solidify at this soaking temperature.

Once the fire is over, every opening should be sealed for 3 days, to allow for gradual cooling. As cooling commences, the liquid solidifies to glass, bonding other particles together. Great care is necessary in cooling the products to avoid cracking. Hastening the annealing process may destroy the product of an otherwise successful firing.

Expansion of the Structure and its Consequences

There will be a significant expansion during the firing and the structure must be able to withstand this expansion. Apart from the static load on the structure and the thrust introduced by the vaults and domes on the walls, there will be this additional dynamic expansion force that the structure will counteract. In case of the domes and vaults themselves, the structure simply expands outwards, and then upon cooling the structure contracts back to its original position and probably even shrinks after have lost moisture. The walls that support the load of the vault or dome and the buttress that they may have usually withstands the expansion very well as the load on the walls prevent them from moving outwards at the junction with the roof due to the heavy weight of the roof itself, and the structure does not move out at the bottom due to its firm anchoring into the foundation. However, in the case of side walls of the vault that are non load-bearing but do support the vault courses during construction in the Nubian style of vault-building, the walls did not manage to withstand the firing load. In Structures 1 and 2, the end walls expanded unevenly on the inside and outside and then eventually separated from the vault altogether. After cooling the wall returned nearly to its original position but still left a gap, which was easy to fill, and did not cause a structural threat being non-load bearing. However, such non load-bearing elements were eliminated in the subsequent experiments and are discussed in greater detail in Section 6.1.1. In Structure 19, there was a small arched dormer opening in the catenary dome, (sketch or photo) and knowing that this wouldn't fire well as an addition on the dome that couldn't receive sufficient heat, this sunshade to the opening was built in fired brick. This additional structure expanded to such a great extent as the dome expanded, that the vaulted sun shade couldn't withstand the firing and collapsed altogether. This showed that the expansion is really significant although in the various structures this was never measured.

8.3 After firing: Stable Ceramic State

The term 'ceramics' refers to polycrystalline materials and products formed by baking natural clays and mineral admixtures at a high temperature, and also by sintering the oxides of various metals and other high-melting-point inorganic substances. Building and decorative ceramics, or structured clay products as they are called in the trade, are basically fabricated by moulding, drying, and burning a clay mass. Clay products form one of the most important classes of structural materials. In building construction, brick and terracotta are desirable due to their strength, durability and pleasing appearance and resistance to fire. Paving bricks, floor and wall tiles, sewer pipes, sanitary ware, are some of the popularly used applications of ceramics in buildings.[145]

According to the manner of manufacture and structure, the products are specified further[146]. Terracotta[147] is a yellow to brownish red or even nearly black clay of porous

[145] The above definition is from AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986 Pg 129-130

[146] Terracotta is described in the above text as it is the relevant material for the structure and products in this technique. The other forms of ceramic are as follows: *Faience* or *Earthenware*, which is glazed terracotta essentially. It is white and differs from porcelain in that it has a greater porosity and water absorption, which is why it is always glazed; *Majolica*, Italian earthenware coated with an opaque white enamel ornamented with metallic colour. In Russia, it was used architecturally in doorways, friezes, window casings facing tiles, far back in the 11th C.; *Porcelain*, is the finest and hardest kind of earthenware, conventionally white and having zero absorption. It consists largely of widely dispersed clay, kaolin, quartz, and feldspar, baked at a high temperature and usually covered with a coloured or transparent glaze. Faience is made of the same materials but the proportions and the firing process are

texture, used generally unglazed. Even unglazed terracotta is very durable. Generically, the broadest definition of terracotta refers to a high grade of weathered or aged clay which, when mixed with sand or with pulverized fired clay, can be molded and fired at high temperatures to a hardness and compactness not obtainable with brick. Simply put, terracotta is an enriched molded clay brick or block. The word terracotta is derived from the Latin word terracotta-literally, "cooked earth."

The structure that was made with sun-dried mud bricks and mud mortar had bricks with a dry compressive strength up to 2 MPa[148]. Upon firing successfully the material transformed into ceramic has an increased strength. Local fired bricks have the compressive strength in the range of 3 to 8 MPa, and the fired mud structure can be at least assumed to have that strength. But in the case of Meeker's structures, product fired bricks were tested and noted to have the strength be 12 MPa.

The water resistance of the material is also significantly improved. The structure will no longer melt away, dissolve or crumble. The structure would remain stable when exposed to water. But this does not mean that water-proofing will be redundant. The fired brick is known to be porous. Water absorption is a measure of the porosity of the brick and it can be measured by a boiling or vacuum test, and expressed as a percentage of the dry weight of a brick. For use as damp-proof courses the maximum average absorption limit is specified as 4.5 (percentage by weight)[149]. For load-bearing brickwork[150] and for load bearing brickwork 'not-designed', no specific requirements are stated for water absorption properties of fired brick.

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slightly different; *Stoneware*, is a hard ceramic material resembling porcelain but differing from the latter in colour and opaqueness. Coated with glaze, it is also used for decorative purposes as well as for road paving, drains, channels, etc.

[147] From Latin *Terra* meaning earth and *cotta* meaning burnt

[148] Air dried soil bricks have a compressive strength of up to 2 MPa, according to AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986

[149] SPENCE. R, COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 76-77

[150] designed in accordance with CP 111, Structural Recommendations for Load bearing walls

Soluble salts in bricks, which may derive from the original clay body can cause staining and efflorescence. Efflorescence is the crystallisation of the soluble salts at the surface of the bricks and occurs when bricks dry after a prolonged period of wetting. It is unsightly but not damaging unless it occurs below the surface when it may cause crumbling.[151]

Generally bricks have a high resistance to chemical attack, and fire resistance is normally good.


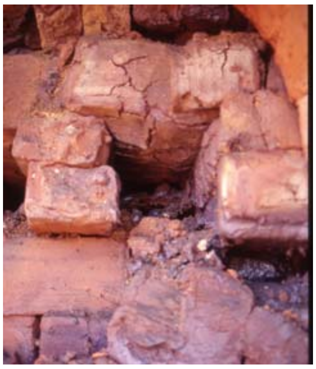


Fig. 8.3, overcooked structure areas, 1999, Source: Anupama Kundoo

Fig. 8.4, overcooked product areas, 1999, Source: Anupama Kundoo

Fig. 8.5, bricks extracted from under-fired areas showing changing material through firing penetration, 1999, Source: Anupama Kundoo

Under firing: This is one of the commonest reasons for bricks being unable to stand up to normal use and also shows in the colour of the brick which is lighter than the well burnt bricks. The traditional test is to knock two bricks together and if the sound made is a dull ‘clunk’ instead of a metallic ring, it is probably under-fired and will have a low compressive strength. In Structure No. 19, in the house for Bina Saxena, there were under-fired areas in the dome. A few bricks were removed to show the material and its colour transformations over the thickness. The dark black areas are the most under-fired, the light brown areas are fired better but still not enough and the red areas

[151] Potentially more serious is the reaction of sulphates on Portland Cement in mortars which is expansive and can cause disintegration. Normally sulphate content should be limited in cases where the bricks are to be exposed, and according to British standards, this limit is specified to be 0.30 % by weight. However, as in these structures, the use of Portland Cement is redundant, this problem is not a concern, although it is good to know in case the product bricks are made to be sold for other purposes.

are well fired. (Fig. 7.21) The areas of different colour are very distinct and abrupt and not gradual.

Over-firing: According to the brick clay, there is an ideal temperature to be reached to arrive at a well fired product, which has the optimum compressive strength for the given brick clay. But it may happen that areas of the structure or products may turn out to be over fired. In such cases the compressive strength would be less than the optimum and is not desirable, however it may not be structurally problematic as the strength of the material is already higher than the minimum strength required. In Structure 19, areas of product bricks and certain spots in the interior of structural walls were overfired and appeared like frothy volcano lava.

9. Design Considerations

> *"And it does work. I mean, it is possible to stabilize a mud house by firing it, and though the energy audit was not what I hoped for[152], an aesthetic was born from the process that met with wide appeal. To fire what is essentially a large mud-walled kiln, full of heavy clay product - bricks, tiles, drain pipes, etc. - and finish it post-firing, as a house, presents an unusual and extremely limiting set of design parameters."*
>
> Ray Meeker[153]

Due to the unique way in which these fired mud buildings are made, this technology comes together with its unique set of design limitations, and some advantages.

Structurally, in the first stage of the construction when the building is as yet unfired, the fire-stabilized buildings are similar to the adobe buildings which also use adobe bricks for the building of roofs. Prior to firing, the "house" or "kiln" must conform to the limits of the unfired mud brick masonry. During firing, the structure must be able to withstand the changing and unstable states of the material before its vitrification into ceramic, as well as the significant thermal expansion that occurs due to high temperatures which are moreover uneven with the inner faces being much hotter than the external surfaces. The structure must also be adequately designed for the use as an efficient kiln in which a whole lot of other clay building materials and decorative

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[152] The article was written before Structure 18, Temple for Nrityagram Dance Village and at that time Meeker had not yet succeeded with coal dust as a fuel. He was at this time quite disappointed that the fuel efficiency was not as advantageous as he had hoped it could be. During this time he also wrote: "I spent 13 years firing houses. I have stopped, for several reasons, but in the main because I viewed the process as an experiment in the pursuit of an eco-technology, and in fact it proved to be too energy intensive for sustainable development. But, living in the thrall of the process- on technical and aesthetic levels, I continued to fire houses long after I realised that it was not going to work as I had hoped". Later there was another breakthrough in fuel efficiency figures in Structures 18, 19 and 20 which realised Meeker's hope in terms of meeting the energy consumption figures.

[153] 'Attitude, Imagination and Innovation' published in the College Magazine of Kamala Raheja Vidyanidhi Institute of Architecture, Mumbai, 1998

objects will be fired. Finally the design of the products is an integral part of the design of the house due the several interdependencies between the house and the products within. This however produces the house with a unique opportunity to be finished in all kinds of interesting terracotta products ranging from floor, wall and roof tiles to water spouts, sanitary fittings and window screen elements.

9.1 Due to mud being the only building material including the roof: Shapes and forms ideally suited to building baked-in-situ houses

Mud is a building material that is only strong in compression; it has no tensile strength. Without the addition of tension-carrying materials such as steel or timber, flat roofs are impossible to be constructed. As the structure will be subject to firing, the entire structure will have to be built in mud bricks including the roofs, and hence they will have to be restricted to vaults and domes using the principle of the arch. Such structural forms, use the material properties of earth with maximum efficiency, are the appropriate structures that work in total compression.

A *vault* is a roof in which the spanning is all done in one direction, creating a side ways thrust in that direction at the springing point. A *dome*[154] is a roof with curvature in two directions, and usually with radial symmetry, which thrusts outwards on its support in all directions.[155] The vault must be strictly shaped as a catenary so as to avoid any tension from being introduced in the structure, which the mud bricks will not be able to bear. In the Case Study 2, a small deviation from this shape was attempted in the vault building and led to a collapse.

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[154] SPENCE. R, COOK. D, Buildiing Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 288-291

[155] The use of vaults and domes is of great antiquity, and the largest spanning structures of ancient times such as the Pantheon in Rome were built on this principle. For small buildings, vaults and domes are used in arid areas where timber is scarce, the construction tends to be massive, and thus to be appropriate to the climate of these areas. But the traditional techniques seem to be in decline wherever modern materials can be obtained. SPENCE. R, COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 288

The vaults and domes also perform a practical function, keeping the house cool in summer – a curved roof has a shaded zone and a sun zone, which creates two different temperatures, resulting in a constant movement of air and also is the most efficient forms for a kiln.

Meeker has used high vaults sometimes to accommodate a partial loft. Square rooms, "squinched" to octagons in a variety of ways, carry domes on walls that are .leaning, or not, depending on structural necessity. Rooms support each other on a common wall or connect on the diagonal through a squinch, some playfully rotated 45 degrees. Squinches, forming niches at the corners of domes make good cupboard spaces or bookshelves or a desk nook.

Similarly, all openings in the masonry for doors and window have to be shaped by arches in order to avoid lintels in any other material.

In order to carry the thrust introduced into the structure by vaults and domes, very thick walls and often buttresses are necessary. Meeker has addressed this by building 45 cms and 34 cm thick walls, and by adding buttresses of a further masonry mass of 34 cm and projecting by 23 cm occurring at every 2.5 meter intervals of wall length in case of walls supporting vaults. In case of domes, he has integrated the buttress as a leaning wall element so as to gain interior useable area.

As the structure will be built in raw mud masonry, there will occur a significant shrinkage in the mud mortar.[156] This is particularly relevant in the construction of vaults, domes and arches as if the appropriate measures are not taken, they will sink upon drying and loose their form. This also makes the removal of shuttering very complicated. The Egyptian Architect Hassan Fathy, had revived the ancient knowledge of vault building techniques by which it was possible to build them without centering, popularly known now as the Nubian Vault Construction Technique[157]. However, Meeker's use of the Nubian Vault Construction proved that it could not be applied directly, as the gable end wall that the courses of the Nubian vault need to rest on, although a perfect solution for a mud structure, could not withstand the firing process, as the non load-bearing end wall leaned outwards after firing due to uneven expansion of

[156] FATHY, Hassan. Architecture for the Poor, University of Chicago Press, Chicago, 1973 (Pg 10)

[157] In his book, Architecture for the Poor, he describes the way he introduced the Nubian Vaulting technique for the construction of the village of New Gourna in Upper Egypt in the 1940s. This has been explained in detail in Chapter 6 Section 6.2.1

inner and outer faces and separated from the structure in earliest three case studies. Meeker worked on alternative vault construction techniques but the use of centering led to complications in removal, and eventually Meeker arrived at compromise in Structure 4, which he then upgraded in subsequent structures. The phenomenon of shrinkage of mud mortar is also countered by touching bricks at the interior surface and packing brick pieces at the outer surface, but nevertheless, the design of centering for Vault construction as well as domes thus are an area of design that must not be neglected.

The baked-insitu mud structure allows the integration of built in furniture to be built as part of the house in the same material. Benches built into deep arched windows between buttresses, raised seating areas and beds, have been seen in the various case studies as simple, unobtrusive, and inexpensive elements of interior design comfortably integrated with the structure. This is not to say that all furniture must necessarily be built in but that much can be and very little more is necessary.

9.2 Due to the Exposure to High Temperatures and its Consequent Expansion and Contraction

Apart from the static compressive load the structure must bear, and the thrust introduced by vaults and domes, the structure is also subject to the dynamic load introduced through the thermal expansion while firing. Firing the house puts the structure under considerable additional stress given that the high temperature it is subject to is between 900 and 1000 degrees centigrade. Furthermore, as the mud structure is fired only from within, and remains cooler on the outside even though the structure is coated with an insulation layer, there is a significant temperature difference in the inner and outer faces of the structural walls causing them, especially if not loaded with the weight of a vault or dome, to bend outwards and in cases separate altogether from the structure. Then again upon cooling most of the deviations nearly return to their former positions before firing as contraction occurs.

In order to resolve these forces without exterior buttresses or concrete ring beams, which would crack during firing, Meeker has put the domes on "leaning" walls which, becomes the buttress. Using canted walls, rather than external buttresses, was a technical innovation that simultaneously resisted thermal expansion during firing, increased interior space, and added dynamism to the elevation.

One of the earliest challenges were the problem that the end gable walls, the non-load bearing walls that were an important part of the mud structure, were bending outwards on firing, and after cooling although they did tend to return towards their original position upon cooling, they didn't quite return and they left a complete separation from the vault and the rest of the structure. This got solved, by eliminating the end wall altogether, but this meant that the vaults had to be built by more complex methods than the simple age-old Nubian technique which absolutely needed the end walls in order to rest the leaning vault brick courses.

9.3 Due to the Limited Depth of Penetration of High Temperature

Meeker found out very early in his experiments that there was no way that a 45cm wall (34 cm thick in subsequent experiments) that may be required for a raw mud structure roofed with a vault or dome, was going to fire through its entire thickness with the structure being fired from the inside only. In fact, he even struggled to try to fire the entire thickness of the much thinner vault or dome structure (15 -20 cms thick).

It was only in the fourth test that he managed to fire the entire vault thickness satisfactorily through the success of the combustible insulation that he had applied to the outside vault surface containing two parts of rice husk, one part of cow dung and one part of clay.

For the external wall thickness for load bearing walls he had introduced a kind of composite brickwork with bricks that touch the external faces being fired brick and the rest being raw bricks. This protected the external faces from the exposure to rain in view of the vulnerability of raw mud bricks to moisture, while still using a substantial volume of raw mud bricks in the external structural walls.

To increase the penetration of heat into the walls Meeker eliminated vertical mortar joints towards the inside of the structure so that the heat would have better access into the thick mass of external brickwork.

As the external walls depend on some portion of fired bricks, and are the only component that is difficult to fire through entirely, in subsequent structures the height of these walls have been reduced wherever the function permitted it and in 2 cases were eliminated altogether with the vault resting directly on the foundation. These measures may be adopted if the program permits and if the structure needs to have as less use as possible of fired bricks. In cluster structures, though this is not as much a concern given that each firing will produce some amount of fired bricks that can be used for the subsequent structures, either for foundations, compound walls, or composite external walls.

Cluster structures have the further advantage that some of the thick load bearing walls will fall within the interior of the structure, and those walls will receive firing from both sides, and as such may be entirely built of raw mud bricks. It would be therefore advantageous to plan cluster structures of vaults and domes with common walls and thereby significantly reduce the need for fired bricks in the construction of a baked-*insitu* mud structure.

9.4 Due to Having to Serve as a Kiln, moreover, an Efficient One

> "But nobody really wants to live in a kiln."
>
> Ray Meeker[158]

One of the strongest motivations for pursuing the challenge of baking a mud structure was the fact that in regular brick kilns, about 40% [159]of the heat is wasted into

[158] MEEKER, Ray. Attitude, Imagination, Innovation Pg 12-15

[159] MEEKER Ray, Kiln Technology, Indian Architect and Builder, Business Press, Mumbai, November 1990

the kiln walls themselves, and the kiln walls keep getting re-fired over and over again. If this heat could be tapped; then a mud structure could be fired without costing any additional fuel and for the price of a mud house, a fired structure would be attained that would be water resistant and overcome the most significant weakness of raw mud as a building material. But for this to work, the structure must first perform as a kiln and enable the interior space to lend itself for stacking the products that will be fired within it, and will in fact bear the cost of the fuel that enables this material transformation. Moreover, the structure cannot be fired empty in any case, as the mass of products are very helpful in providing the thermal mass that retains the high temperature over a sufficient time period that allows the heat to penetrate through the wall thickness of the structure. Furthermore, the more efficient the structure performs as a kiln, the better the figures of fuel consumption and therefore also the cost implications are likely to be.

Based on the program for the structure's intended use, the most efficient kiln on the other hand may not at all be suitable. Therefore the most optimum choice must be made after considering the spatial needs of the structure and the knowledge of kiln types and firing systems.

The size of the structure is another aspect that may prevent the application of known efficient firing systems. Particularly if the structure is very small as in the case of a stand-alone low cost housing unit,[160] the firing system would have to settle for the acknowledged inefficient kilns.

Cluster structures would lead to significantly improved fuel efficiency figures, and when the project has a large program, or if small housing units can share common walls and be composed as a series of vaults and domes, then the firing can become very efficient, by using the 'waste' heat of one structure to preheat the next structure.

[160] This is a rather ironical situation. On one hand this technology targets the low income sector in order to provide them with an efficient and economical way of getting the strength of a fired structure for the price of a mud structure, by tapping the 'waste' heat that would other wise go in to the kiln walls during fired brick manufacture. On the other hand it is the very case of the low cost house program that would not be able to serve as an efficient kiln, as the size restriction would lead to the selection of inefficient kiln systems. This can be optimized significantly and even reversed if several cluster structures are planned in single operations.

The kiln requires that the structures are restricted to simple shapes. Very complex flame paths are out of the question, as all corners of the interior space must be well fired. Domes and vaults, the structural forms that are the result of structural limitations of mud as a building material, luckily do make good kilns.

Temporary structural elements required in the firing stage only

During the firing stage of the construction process of a baked-*insitu* mud structure, the structure needs to be completely closed with the exception of fire boxes and air inlets for the combustion process, and blow holes and openings planned in the structure to release the steam that is expelled in the firing process.

The openings are usually closed with mortar less stacking of unfired brick, which will later be fired to varying degrees and maybe used as part of the composite wall construction in the external walls of further structures. In the case of end walls of vaults that may be altogether absent, the whole surface is similarly closed by stacking unfired bricks in a closely packed assembly.

The structure is sealed and insulated with a mud mortar layer and at the stage when steam has completely been eliminated the cracks and gaps in the structure is again tightly sealed.

Depending on the firing system decided upon, chimney structures may have to be erected in strategic places temporarily to improve fuel efficiency, and taken down after the firing is completed. These structures must not be underestimated in the complexity of their erection, as they are fairly taller than the rest of the mud structure and need to be stable enough.

Standard brick kiln types and kiln types[161] used in Meeker's test structures

[161] From MUKERJI, Kiran. And STULZ, Roland. *Appropriate Building Materials: A Catalogue of Potential Solutions (Revised Enlarged Edition)* SKAT(Swiss Cneter for Appropriate Technology) Publications, St. Gallen, 1988 Pg 41; PARRY, JPM. Brickmaking in Developing Countries, BRE

There are two basic types of kilns for burning bricks: intermittent[162] kilns and continuous[163] kilns. The common kiln types are as follows:

Clamps: Clamps are basically a pile of green bricks carefully stacked in such a way that bricks are interspersed with combustible material such as crushed coal, rice husk and cow dung. Some holes are left at the base of the clamp, where the fire is lit. The holes are closed and the fire is allowed to burn itself out, a process which can take a few days for a small one or several weeks. The bricks near the centre of the clamp are the hardest. The quality of the bricks is variable since close control of the temperature of the kiln is impossible and sorting out is necessary. About 20-30 % are not saleable. These are refired or reused in the clamp base, sides or top. Clamps are the simplest technique of burning bricks, cheap to construct and used throughout the world with some interesting regional variations[164]. Archaeological excavations suggest that a very similar technique may have been used to fire the earliest bricks at Mohenjo-Daro.

Scove kilns: These kilns are principally the same as clamps, but plastered on all the sides with mud, and with tunnels built across the base of the pile, in order to feed additional fuel. This is the best method for burning wood.

(Building Research Establishment), Watford, 1979; SPENCE. R, COOK. D, Buildiing Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 71-74

[162] Intermittent refers to the fact that each firing is a new operation, the fire burns for a period and then goes out, so that all the heat developed is lost. Examples of intermittent kilns are clamps and scoves which are traditional field kilns, and updraft kilns. Clamps, scoves and up-draught kilns are very suitable for small-scale rural brick production; they vary in size from 10,000 to 100,000 bricks, but being intermittent

[163] Continuous kilns are permanent kiln structures in which an ongoing heat is maintained and used continuously to fire various batches of products, which leads to better fuel efficiency. Various versions of the Hoffmann kiln, (particularly the Bull’s Trench kiln), Zig zag or Habla and vertical draft kilns come under this category. Tunnel kilns, in which bricks are passed through a stationary fire, are too sophisticated and capital-intensive to be considered here. Continuous kilns have fires alight in some parts of the kiln all the time. Fired bricks are continuously removed and replaced by raw bricks.

The kiln heat is efficiently reused in two ways: the incoming air is warmed by leading it through bricks that have already been fired, and are cooling; and the bricks waiting for firing are heated up by passing the hot gases from the fire through them. These heat exchange processes are made possible by slowly moving the fire around the trench, unloadin bricks behind it, and adding them in front. To benefit from the continuity of production, these kilns need a much larger output in the range of 10000 bricks per day.

[164] One regional variation is due to the use of available fuel. In Southern India, clamps are burned with a mixture of cinder coal (with 20% of un-burnt carbon remaining) and cow dung, in Indonesia rice husk and abundant waste product, and in most of Africa, firewood. In some monsoon regions as in Kerala, clamps are constructed with permanent side walls and a thatched roof.

Up-draught kilns (also known as Scotch kilns)*:* These kilns have permanent walls but function in the same way as scoves, except that the fire is located in a separated firing chamber below the kiln. Updraft kilns were used in ancient Mesopotamia and Rome and are used today in parts of Africa, Indonesia and China. They have the advantage that they can create a much more uniform temperature, and can be used to fire pottery and roofing tiles as well as bricks.

Downdraft kilns: These kilns have a permanent arched roof. The hot gases from the fuel burnt at the sides of the kiln, rise to the arched roof and are drawn down between the bricks by chimney suction through the perforated floor and out through the chimney.

The Hoffman Kiln: Originally circular, but now more commonly oval, this kiln is a multi-chambered kiln in which the combustion air is preheated by cooling bricks in some chambers and passes through the firing zone, from which the exhaust gases preheat the green bricks. While the cool bricks are removed from one side of the empty chamber, the green bricks are stacked from the other side. The fuel is fed from the top, through holes in the permanently arched roof. The daily output is about 10,000 bricks. The Hoffman Kiln like the Bull's trench kiln serves the urban brickwork market but is used where the climate is unsuitable for the open-topped trench as in the Bull's Trench. Being enclosed, it has a complex arrangement of flues and fixed chimneys and is therefore considerably more expensive to set up than the Bull's trench kiln.

The Bull's Trench Kiln: This derivation from the Hoffmann Kiln, is commonly used in India, and is mainly different from the Hoffmann in that the expensive arched roof is omitted and the exhaust gases are drawn off through 16m high movable metal chimneys with a wide base, which fit over the openable vent hole set in the brick and ash top of the kiln. The fuel, generally crushed coal, is fed through the holes on the top. The position of fire is controlled by the feed holes and the lightweight movable chimnex sitting on the top of the bricks to create a draft. Depending on the size of the kiln, daily outputs can be between 10,000 and 28,000 bricks, 70% of which are of high quality. This kiln is ideal for the needs of the brick-built towns and cities of the Punjab and the Ganges plain, where excellent brick clay is available. It is a good example of a technology where rural industries can serve urban markets, although they are widely used in rural areas too.

The high-draft kiln (Habla): This kiln is the further development of the Bull's Trench kiln whereby temporary cross-walls of green bricks leave openings on the on alternate sides, thus making the hot air travel a longer distance in a zigzag fashion, achieving a larger transfer of heat from a given quantity of fuel (wood and coal). Fans are installed to provide the necessary draught. Daily outputs of 30,000 bricks are possible.

Wood, coal and oil are the main types of fuel used. Coal is suitable for all purposes while wood is less suited to clamps and oil is unsuitable for clamps, downdraught, Bull's Trench and high draught kilns.

TYPICAL FUEL REQUIREMENT FOR KILNS (Source: Appropriate building materials SKAT)				
Type of kiln	Heat requirement	Quantity of fuel required		
	MJ/1000 bricks	Tonnes/1000 bricks		
		Wood	Coal	Oil
Intermittent				
Clamp	7000	(0.44)	0.26	(0.16)
Scove	16000	1.00	0.59	0.36
Updraught	16000	1.00	0.59	0.36
Downdraught	15500	0.97	0.57	0.35
Continuous				
Original Hoffmann	2000	0.13	0.07	0.05
Modern Hoffman	5000	0.31	0.19	0.11
Bull's Trench	4500	0.28	0.17	(0.10)
Habla (high draught)	3000	0.19	0.11	(0.07)
Tunnel	4000	(0.25)	(0.15)	0.09
Note: figures in brackets mean that fuel is unsuitable for kiln type				

Table 6: Typical fuel requirements in standard kilns

Kiln Systems used in Meeker's Structures

Structures 1 to 6 and 8 were fired as simple up-draught kiln types. In Structure 7, Agnijata, the first house for a client, a cross-draught and down-draught kiln system was tested. The four vaults surrounding the central dome were fired cross draft towards the central dome and this led to preheating the dome significantly. The dome itself was fired down-draught; so that the heat was led up to the dome and the down again and finally out through the chimney at the centre. Structure 9, was fired cross draft, and was a test specifically undertaken at Meeker’s own Pottery to test the efficiency of a cross draft kiln. It proved to be significantly effective as compared to the up-draught kiln that was being used until then. The up-draught kilns in Structures 1 to 6 had led to a fuel consumption of 17,270 MJ/1000 Bricks for structure and 12,300 MJ/1000 Bricks for structure and products together. The cross-draught down-draught kiln in Structures 7 had led to a fuel consumption of 13,270 MJ/1000 Bricks for structure and 9,170 MJ/1000 Bricks for structure and products together. The down-draught kiln in Structures 9 had led to a fuel consumption of 11,850 MJ/1000 Bricks for structure and 8,457 MJ/1000 Bricks for structure and products together. Structure 10 was the first example of a semi-continuous cross-draught kiln that involved a series of 3 vaults that were fired in a sequence so that the heat from one vault was used to preheat the next. This led to a further fuel efficiency with a fuel consumption of 12,193 MJ/1000 Bricks for structure and 7,900 MJ/1000 Bricks for structure and products together. Structure 11 was a similar composition of two attached vaults and was fired as a longitudinal cross-draught kiln. Structure 12 was a special experiment for testing coal dust infused bricks and similar products that were stacked as a mass and were expected to self burn, but failed. From Structure 13 onwards, the houses began to be designed primarily as houses with the intention of freeing the plans from having to serve as an efficient kiln as had been the focus at this time. Structure 18 was a second attempt at stabilizing the structure through addition of coal dust in the brick mixture and produce combustible bricks which when ignited would be self burning. The products and structure were to be fired not by allowing heated air to circulate, as in previous structures and kiln systems, but rather by letting the whole mass burn as a whole, through the self contained fuel which would burn and spread by contact. This test had been successful, and found to be extremely fuel efficient. This led to an extreme reduction in fuel consumption of 3,000 MJ/1000 Bricks. The following two structures, 19 and 20 were further tests in the same technique.

Up-draught kilns are known to be extremely inefficient. The house fired up-draught house arrives at almost the same figures as the conventional up-draught kiln. Compared to the best firing systems available - the Hoffman, Bull's Trench, or Habla-that consume up to 3000 MJ/1000 product bricks, the earlier results of the fired houses may be still far behind, but the tests do show a remarkable progress towards reaching an acceptable level of fuel consumption. From 13,400 MJ to 7,900 MJ in the 3-vault system of Structure 10, and 6,800 MJ in the 2 vault structure 11 was is an impressive advance considering the technology being still at its infancy. And even if the brick itself may consume fuel than the efficiently produced fired brick, to what extent this technique makes the use of other high energy materials (steel and cement) redundant or significantly reduced still remains to be assessed. In Structures 18-20, Fuel Consumption of 3000 MJ per 1000 Bricks was achieved, that makes the technology very efficient in terms of fuel efficiency.

FUEL EFFICIENCY COMPARISON								
Case study	5	6	7	8	9	10	11	18-20
Year	1987	1987	1988	1988	1989	1989	1990	1998-9
Size l/w/h	5/3/4.14	6/3/4.65	4/3/3.5 4.5/3/3.5 5/3/3.5 6/3/4.5 5 dia. 5 h	6/3/3.5	4/3/2.0	6/3/3.5		
Kiln type	updraft	updraft	fired simult. cross draft into dome down draft	updraft	cross draft	semi-con cross draft	longitud. cross draft	compact product mass
Product	tmb 12000	tmb 19000	tmb 60000 tiles 2000 toilet pans 4 spouts 35	tmb 8000 tiles 1000 roofing units 1000 wall units 60 mural 18 sqft	tmb3500	tmb 35000	diverse	bricks tiles
Firing temp.	945°C	920°C	900-1000°C	940°C	930°C	940°C	950°C	940°-980°C
Firing time	84 hrs	77.5 hrs	108 hrs	48 hrs	96 hrs	36 hrs	120 hrs	96 hrs
Fuel Cons.	ca. 10 tons	ca 10 tons ma 1000 bd	ca 23.4 tons ma 2,400 bd	ca 6.6 tons ma 600 bd	ca 2 tons	ca 10 tons ma 1400 bd	aa 8 tons ma 655 bd	
MJ/1000 Product	17270	16292	13270	19732	11850	12193		3000
MJ/1000 Prod + Str	12300	11680	9100	14250	8457	7900	6800	3000
Value of Product Rs	10000	15800	75000	16000	4530	43500	40000	3000

Note: These fiqures are somewhat misleading as structure bricks are well fired on the inner face and progressively less well fired toward the outer face 23 cm is assumed to be in the firing zone in the walls. However figures for the cross draft 3 vault system are real as walls are fired from both sides. Ma stands for Malaar and Bd stands for bundles

9.5 Design of Products and Their Stacking

The unique fact of the technique of the baked-insitu mud structure is that a huge quantity of products has to be manufactured to be fired inside the structure. This production is central to the technology and it does require the due design considerations as an integral part of the design of a structure to be produced in this technique.

The production of other bricks and terracotta products within the structure offers the unique opportunity to meet the direct demands of the structure itself in its finishing stage. Floor tiles, window screens, water spouts, wash basins, toilet pans, facing tiles and murals, friezes and decorative elements, and an unlimited range of other products can be conceived, and produced as part of the integral concept of the house. The design of these elements needs to be taken up as part of the design of the structure.

Depending on the circumstances and the budget of the proposed project, the products may play the role of capital generation to a certain degree. Accordingly the terracotta products proposed to be produced within the structure may have to be decided accordingly. More sophisticated products such as planters, lanterns, candle stands and boutique products may be added in order to fetch better returns especially if the project is located close to urban areas which may provide the suitable market.

9.6 Due to Choice of Fuel

In cases where wood is used for firing, the raw bricks produced are standard mud bricks, and the products are stacked in a complex way that allows for heated air to move through the stacked arrangement according to the chosen firing system needed by the kiln type. The wood fired structures need to be closely monitored throughout the several days of its firing to control the fire according to readings obtained from the various pyrometers that are appropriately positioned.

But in case coal dust is used as a fuel, then the brick making has to take this into account and a 5% of coal dust is to be added as an admixture in the mud mixture with which the raw bricks are produced. In this case, the products, mostly bricks made of the same mixture are stacked in close compaction as opposed to leaving air gaps for heat movement. Much more product is produced due to the compact stacking. Voids in the stacking are created as required according to the shape and size of the structure, to function as chimneys and to allow the steam to escape out of the structure. The base of the structure contains a layer of tunnels filled with coal to initiate the fire. About six hours are required to ignite the coal layer in the base, after which it is allowed to burn at leisure. Five or six days later, the doors are opened, and the fired product is unloaded. The use of coal dust as a fuel actually solves the problem of efficient fuel consumption, but the control of fire is sacrificed. If you get it wrong you either under-fire the structure or overfire the product brick - or both."

10 Assessment of the Present State of 'Baked-Insitu' Technology

10.1 Structural stability; Properties and Strength of Material

The technology has already advanced enough so that after firing, the mud structures get sufficiently stable on the exterior faces of domes and vaults. Thus it may be concluded that the structure achieved is similar to fired brick masonry structure with the exception that the mortar joints are made of the same material as the fired brick and therefore has the same properties as that of fired brick masonry. However, until the structure is fired successfully the structure would have the material properties and vulnerabilities of adobe or sun dried mud brick masonry.

Compressive Strength: Fired clay products can have high compressive strengths, even when wet, and are thus resistant to impact and abrasion. The strength of locally fired bricks[165] ranges between 3 MPa[166] and 8MPa. Strength of industrially made fired bricks can be as high as 100 MPa, but such strengths are needed only for exceptional load-bearing situations, and for normal two-storey houses an average of 3.0 – 3.5 MPa is adequate for load bearing walls while even lower strength may be acceptable for non-load bearing internal walls[167]. In Meeker's structures, the products bricks that have been tested were found to have a strength of 12 MPa[168], almost twice that of the locally available ground moulded brick in Pondicherry area[169]. The compressive strength can be considered to be more than adequate. Yet, the buildings

[165] In the local area of South India hand made bricks have a strength ranging from 3 MPa to 8 MPa, according to SPENCE, Robin. Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (Page 78),

[166] Mega Pascal is a unit for compressive strength, and is the term used for Newtons per square millimeters.

[167] SPENCE, Robin. Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983 (Page 76)

[168] This was tested in Structure 4, when bricks were sold to contractor Kanoo Mistry for Neena Devi's house in Pondicherry, the very first exposed brick house in the local area designed by German architect Helmut Schmid. In this kiln structure 3 more batches of fired brick were produced before its finishing.

[169] For the comparison of brick quality achieved, product bricks were tested but also local bricks were tested. The local bricks tested had strength of 6 MPa.

have to be designed within the structural limits of mud brick masonry since the structure is only fired after it is completely built, and hence must be able to stand even as a mud structure. The dry compressive strength of sun dried bricks is about 2 MPa, which however falls abruptly when the bricks are saturated with water.[170]

Water Resistance

The main limitation of sun dried bricks, their low water resistance, and wet compressive strength, is overcome after the firing to achieve the water resistance material of fired brick. It must also be remembered that until the building is fired, it is all mud. Large scale mud building projects are extremely vulnerable to "unseasonable" rain-more especially when a large quantity of mud product has to be protected as well. Process infrastructure would include a significant and not inexpensive area of canvas tarpaulin. The mud structure after firing will no longer melt away, dissolve or crumble, but will remain stable when exposed to water. But this does not mean that the structure will automatically be water-proof. The fired brick is known to be porous, and will absorb water. Water absorption is a measure of the porosity of the brick and it can be measured by a boiling or vaccum test, and is expressed as a percentage of the dry weight of a brick. For use as damp proof courses the maximum average absorption after boiling or vaccum treatment is specified as 4.5 (percentage by weight) [171], where as no specific requirements are specified for load bearing brick work. Any of the waterproofing treatments may be applied as a surface finish for roofs, where as walls maybe plastered or left unplastered as per the design and climatic requirement.

Other Properties

The porosity of fired clay permits moisture movement, without significant dimensional changes. Bricks and tiles can ‘breathe’.

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[170] AIRAPETOV, D. Architectural Material Sciences, Translated from the Russian by Alexander Kuznetsov, Mir Publishers, Moscow, 1986, Pg 121

[171] SPENCE, R. COOK. D, Building Materials in Developing Countries, John Wiley and Sons, Chichester, 1983, Page 76-77

Solid bricks have a thermal capacity, beneficial for most climates, except for the predominantly humid zones.

Fired bricks provided excellent fire-resistance.

Generally bricks have a high resistance to chemical attack.

10.2 Cost Implications

> *Anybody in this world should be able to build a shelter for his or her family with the simplest of materials available to all: the Elements- Earth, Water, Air and Fire. A family should be able to learn the techniques, move to an empty piece of land, and then- with some water and simple tools- build themselves a house using the earth under their feet."*
>
> Nader Khalili[172]
>
> "*The fired earth house concept is both simple and potentially revolutionary in its economic implications*"
>
> Ray Meeker[173]

The motivation driving the development of this technology was always the idea of a achieving a high quality but low-cost house affordable by those needing it the most. However several circumstantial factors such as availability of clay and fuel, as well as several design factors such as product development could affect the economical viability of the technique particularly in attempting to be a high quality housing alternative for

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[172] KHALILI, Nader. Ceramic Houses and Earth Architecture: How to Build Your Own Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg ix)

[173] MEEKER, Ray. Fired Houses: A Concept for Stabilizing Earth Structures, Moving Technology Volume 2 No 1, CAPART, New Delhi, February 1987

the ‘low-income’ category of people. These factors affecting the overall cost are discussed below separately. Apart from them, there are other variable costs that influence the total cost of the project: Research and Development costs; Foundations and Finishing.

Research and Development costs have been part of the cost of each structure and as such the costs involved in replicating the technology are likely to be less. In the early experiments this technique had certainly not proved to be inexpensive. However costs came down with each subsequent test and in the eleventh test an extremely low cost house was achieved, but this was largely due to the fact that it was possible to create and sell sophisticated products to a boutique. As the technology is still in its infancy (or maybe childhood) it may be appropriate to separate the R&D costs from the cost of the structures to obtain more comparable figures.

Foundation costs are somewhat higher than the rest of the structure as, as walls are thick (common walls 45cm, end walls 35cm with buttresses) and the vaults fairly heavy. However they are not higher than the foundation cost of regular buildings of the same scale. They only cost more in proportion to the structure than the standard brick masonry house, as the rest of the structure is cheaper. The foundation is not affected by the firing, and hence it can be built in any suitable method. The main effect of the foundations being built with other materials and technology than the rest of the house is that, some material has to be brought in to the site for the foundation alone: fired bricks, cement, and steel if it is needed to have a plinth beam for seismic factors. However in large scale projects, the product bricks produced in the first structure are used in further structures. The import of outside materials can be reduced as in the eleventh structure if the soil conditions are appropriate. In this structure, rammed earth foundations were used which was stabilized by adding 5% of cement. The earth from the foundation was simply put back into the pit in layers after adding cement moisture and rammed in place. This was a case of an inexpensive foundation.

Post-firing finishing costs depend on the treatment. This need not be expensive if the budget is small, as many elements can be sourced from ceramic products produced within the building during firing. Partition walls and compound walls maybe added in fired brick. The floors may be finished in brick tiles, and the walls maybe left unplastered from the inside. Sanitary ware, water spouts and drain pipes maybe also produced in the house. The most important element is the external waterproofing of the dome or vault and external wall plasters to prevent dampness from entering even though the structure is water resistant and wont melt away, fired brick is porous and needs to be sealed on the outside for water penetration.

Given an 'ideal' building situation- good on-site clay; available fuel; availability of local labour; and a long, dry building season- baked-insitu mud structures look quite promising economically. The above constellation of circumstances may be somewhat rare. But there are certainly places, where this technique could indeed be economically appropriate, and depending on the exact site circumstances more or less economical.

Products and Financial Returns

> *"The client funds the building. I fund the product. Assuming the contractor and administrative fees can be met, it still is a highly unconventional way to finance housing. Who, after all, will part with the Rs. 40,000 -50,000 generated by their labour in making the product, so that someone else can have a cheap house? Frankly, I don't know. For the moment, it is enough to show, and know, that the potential to generate income exists. How the distribution is to be arranged, and through what mechanism, has to be worked out at a later date."*
>
> Ray Meeker[174]

One key to the full realization of the economic potential is the development of product and the production process. The fact that production of products to be fired

[174] MEEKER, Ray. Kiln Technology: A Demonstration and a Challenge, *Indian Architect and Builder*, Business Press, Bombay, November 1990

within the structure is an integral part of the housing economics, and totally interwoven with all other decisions made in the production of such a house is one of the most unique and unusual aspects of this technology. The structure must contain a full product load not only to provide monetary return on total process[175].

Typically, depending on size, Meeker's single vaulted rooms held between 10,000 and 20,000 bricks. All structures fired by Meeker have been fully loaded: table-moulded bricks, floor tiles; window screen elements, toilet pans; hollow wall and roof modules and glazed tiles were produced inside houses. Initially, however, Meeker found it very difficult to compete in the local marketplace with these products. In order to ensure adequate firing of the structure in the initial structures Meeker had used twice the amount of fuel per brick (inclusive of structure and product) as the local brick maker. He had also achieved twice the strength and less wastage. The fuel cost alone made his product non-competitive. He had to develop a very good brick which could be sold at a very high price. This has at least made it possible for the brick to pay for itself including the firing cost. This was significant. No fuel cost was being made accountable to the structure.

Several products that are would be needed to finish a house, can be made within the house, such as further bricks, window screen elements, floor tiles, water spouts, toilet pans, wash basins, benches and murals. This can lead to cost savings on materials that would have to be purchased. Further, the house can rely on product sales to recover the total fuel cost and theoretically achieve the fired structure for the price of a mud structure. The house becomes a producer of building materials rather than a consumer. According to the location of the project and circumstances, the house could supply the judiciously selected appropriate money-generating products that could be sold in the surrounding area. High quality fired bricks, hollow roofing and wall units, and floor tiles can form the bulk of the products, and in areas with nearness to urban markets and boutique outlets, the house can also be a producer of sophisticated terracotta products such as planters, candle stands, etc. In structure eleven, Meeker was able to diversify his

[175] but very importantly, to ensure adequate and even firing of the structure. An empty kiln does not fire well. The thermal mass of 30 to 60 tons of material at between 900 and 1,000 degrees centigrade penetrates deeply into the wall and roof

product range to include such sophisticated products that were sold at a boutique and had achieved the cheapest structures[176] by offsetting their costs. With the right product, at least in theory, the building could cost nothing except labour and finishing. Theoretically it is even possible lo make a profit on making a house by selling the product.

If all fuel and firing costs are justifiably borne by the products fired within, the house will cost as much as one in unbaked mud and mud mortar.

But what remains a challenge is the capacity of low cost house client to finance the production of such a quantity of products that he can only recover when the products are sold. And even in a 10 vault project, by no means a large project, will require producing some two lakh (200,000) bricks, which is surely beyond the means of individual families and requires subsidies and support from the government. This remains the main obstacle in main-streaming this technology, but if the project is acknowledged for its capacity to generate socio-economic benefits, it is not unimaginable that this could be probably subsidized or assisted as a policy to facilitate the building of low cost environmentally sound houses in appropriate areas.

10.2.2. Nearness to brick clay source

If onsite or very near to the site suitable brick clay for making fired bricks is available, material cost for the superstructure will be negligible. Meeker calculated that in the eleventh structure he built in Auroville that was already quite cost-efficient, fifteen percent could be saved on building costs if suitable clay for the fired brick could have been sourced from the site or very near the site, which, unfortunately, was not the case. All the building and product clay had to be transported some 20-30 km.

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[176] In the eleventh structure, Meeker was competing with the HUDCO (Housing and Development Corporation of India) national standard budget allotted for an EWS (Economical Weakest Section) unit and achieved the structures of a better quality within the given price, and even managed to recover some money for R and D. The two structures of 18 sqm each cost Rs. 10,000 each in 1990

If not, the transport of clay has to be taken into account, and depending on the distance, it may be still affordable for the low-cost housing sector or not. Alternatively, green bricks may be ordered from nearby brick sites.

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10.2.3. Cost of labour vis-à-vis material

The baked-insitu mud house construction process is labour intensive. Most of the work is unskilled: moving bricks, loading/unloading the structure, adding cow dung/rice husk/clay over the vaults, removing it after firing. The firing labour itself is significant in case of firewood as a fuel, needed continuously for 60 hours or more, even on smalI houses. This can be seen as positive: many people get work, and a high percentage of cost goes to labour rather than material. In places where labour is cheap[177] and materials expensive, this technique will be low-cost compared to the other conventional house-building techniques. Expensive materials like cement and steel, which are often in low supply at exhorbitant prices, are also avoided.

10.2.4. Cost efficiency through fuel efficiency

Fuel costs are a significant part of the cost of the baked-*insitu* mud structures and any step made in fuel-efficiency will directly reflect in the cost of the building. Fuel efficiency can be realized by increasing the length of the heat-flow path as much as possible to allow a larger heat transfer to take place from the given quantity of fuel. Fuel efficiency is discussed in detail in 10.3. Although there are various efficient kiln-systems available for application, an efficient system may not always be applicable A small room fired up-draught is prohibitively inefficient as seen in Section 9.4, whereas clustering of structures allow for efficient kiln systems, that use the waste heat of one part to preheat the next. However, depending on the size of the project or the scale of the project this is not possible, and if one has to build a single standing small house, an inefficient kiln system may have to be opted for, in spite of knowing that it would not lead to the optimum fuel efficiency. Long, multi-chambered structures are unquestionably most efficient.

[177] Meeker warns though that labour cost may still prove to be high, even if wages are low, as productivity is often low, and “labour-intensive doesn’t mean work-intensive”

"Economy begins to develop when there are several vaults in a line - improved fuel efficiency occurs by connecting the series of vaulted rooms with flues through common walls; the waste heat from one room pre-heating the next." There is a huge advantage of scale.

All fuel and firing cost may be considered accountable to the product, or a percentage can be added to the structure (house mass relative to product mass) as per the desired accounting. In Meeker's structures, all fuel costs were accountable to the project, as he principally wanted to make the economy work such that the products that were being fired within the house-kiln would absorb all the fuel costs and the house-kiln would be fired from the 'waste-heat' of the firing, as it were.

The choice of fuel can also lead to cost economy. In the earlier structures, Meeker used firewood, and in the last three structures, 18, 19 and 20, 5% of coal dust by weight was added as an additive in the brick mixture, producing thereby combustible bricks. Fuel efficiency almost doubled, with the fuel consumption drastically reduced to 3000 MJ/ 1000 bricks, and therefore further economy resulted. However these figures were not available in detail, and as the projects themselves were not low-budget projects, and resorted to expensive finishing details, the total expenditure figures do not easily lend themselves to deriving the comparative cost of the structures due to coal dust as a fuel instead of firewood.

10.3 Fuel consumption and energy implications

Embodied energy in fired clay products

Energy consumed by building materials, although smaller than household energy use, is by no means insignificant in national and global energy budgets: the materials industries, of which building materials comprise a large proportion, are in general, energy-intensive, and have been shown to account over 20% of world fuel consumption.[178]

[178] Source: Chapman, 1975. Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8

Fired clay products are known for their relatively high fuel consumption in the firing process.[179] (See the comparative energy[180] table for building materials.) Yet, these materials are of great importance in developing countries because they can be produced from local materials using relatively simple technologies and whatever fuels are locally available. In case of this material, the bulk of the energy used in all production processes is the kiln fuel required to fire the bricks. This can represent more than 95 per cent of the energy requirement of the entire process[181] in cases where ambient energy is used for drying. In other cases, significant amounts of energy may be needed for drying, mixing, moulding and handling, but these will rarely exceed 10 percent of the total process-energy requirement[182].

Comparative energy requirements for various building materials	
Material	Primary energy requirement (GJ/Tonne)
Very high energy	
Aluminium	200-250
Stainless Steel	50-100
Plastics	100+
Copper	100+
High energy	

[179] MUKERJI, Kiran. STULZ, Roland. Appropriate Building Materials: A Catalogue of Potential Solutions (Revised Enlarged Edition) SKAT(Swiss Center for Appropriate Technology) Publications, St. Gallen, 1988 (page 45)

[180] The embodied energy or the energy content of a building material comprises all the energy consumed in acquiring and transforming the raw materials into finished products and transporting them to the place of installation or the building sites. It symbolizes the quotient of its environmental friendliness reflecting the material's closeness to earth. The more it is refined or processed, the more energy it 'contains' and hence more environmentally 'expensive'

[181] A great variety of technologies are used for each of these stages ranging from simple manual technologies which have been unchanged for centuries to highly sophisticated mechanized operations. In most developing countries relatively small-scale labour-intensive methods are mostly used, and it has been found that the introduction of mechanized methods, even if they may be more energy-efficient and produce bricks and tiles of higher quality, are not successful because the high capital costs lead to higher prices for bricks than those produced by traditional producers. Thus emphasis is now being placed on ways to upgrade the techniques used by the small-scale traditional producers.
Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (pg 28)

[182] Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 28)

Steel	30-60
Lead	25+
Glass	12-25
Cement	5-8
Plasterboard	8-10
Medium energy	
Lime	3-5
Clay bricks, tiles	2-7
Gypsum plaster	1-4
Concrete in situ	0.8-1.5
Concrete blocks	0.8-3.5
Concrete precast	0.1-5
Low energy	
Sand, aggregate	Less than 0.5
Fly ash	Less than 0.5
Blast furnace slag	Less than 0.5
Source (UNCHS 1991)	

Table 7: Comparative embodied energy of building materials

Types of fuel

Wood, coal and oil are the main types of fuel used in brickmaking. Coal is suitable for all purposes, while wood is less suited for clamps and oil is not used for clamps, down-draught, Bull's Trench and high-draught kilns. Section 9.4 elaborates on Basic Kiln Types, the suitable fuel, and the energy requirement per 1000 bricks.

Within the range of technologies available for producing any particular material, there is often the scope for replacing high-grade energy, such as electricity and liquid fuels with relatively low-grade energy such as solid fuels, agricultural waste and other unconventional fuels. In many countries, where firewood is used, large forest areas have disappeared causing serious ecological damage. Where firewood is still available, it is extremely expensive, but this is also true for other fuels[183]. Efficient brick kilns require

[183] Therefore good quality fired clay products tend to be expensive.

high capital investments and produce good bricks that are often too expensive for small scale uses for which a lesser quality is sufficient. In most developing countries, simple field kilns which are the common practice, which operate with low fuel efficiency but also low capital investment.

Scarcity and rising prices of coal, the predominant fuel used for brick firing is forcing brick producers everywhere to look for cheaper fuel substitutes as well as energy economies. Increasing numbers of producers in Delhi area[184] are using a proportion of unconventional fuels, fuel wood, rice husk, sawdust and agricultural waste, and that these producers were able to reduce costs without detriment to the quality of the bricks, though at the cost of a rather small lowering of energy efficiency. A small number of producers have eliminated coal entirely, with a resulting increase in energy consumption of only 14 percent compared with the producers using coal alone. Rice husk and other agricultural wastes have long been used as fuels for firing of rural clamps. Waste engine oil has been used to fire a small kiln in the United Republic of Tanzania.

Another way to reduce the conventional energy consumption of kilns is to add carbonaceous wastes (agricultural or industrial wastes containing some combustible material) to the clay mixture. Fly ash and rice-husk ash are both suitable if they have a significant amount of un-burnt carbon. Fly ash in India has been found to have typically 6 percent un-burnt carbon; rice husk has a calorific value of 2 - 2.5 MJ/kg. In Vietnam, small rural clamps are fired with fuel bricks which are made from a mixture of coal ash and lake mud. The effect of these additions is to alter the characteristics of the clay and to affect the properties of the bricks. They can also improve the workability of the clay allowing otherwise unsuitable soils to be used[185]. The resulting bricks are lighter than normal clay bricks and the savings in fuel could be as high as 35 percent. Some special clays such as the Oxford clay in the UK contains significant amounts of carbon

[184] Source Lawson 1991, Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 32)

[185] Source Rai, p 45 Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 32-33)

naturally. This accounts for the very low fuel consumption of Fletton bricks in the UK. Unfortunately such clays are not common.

Variables affecting the energy requirements of brick kilns

The principle variables affecting the consumption of brick kilns: are whether the firing is intermittent or continuous; the size and heat transfer efficiency of the kiln; and whether the brick clay used contains combustible material.[186] It is important to note that clamp processes for brick firing use two or more times as much fuel as continuous kilns such as the Bull's Trench kiln; this is because they are fired intermittently, and all the energy used to heat the bricks and the combustion gases is lost, where as in continuous processes the heat in bricks is transferred to the incoming air, and the heat in the combustion gases preheats the next batch of bricks for firing.

Replacement of intermittent kilns by continuous kilns is not always possible, however, for a variety of reasons: demand may not be large enough to justify continuous production; the capital costs of continuous kilns is higher; the amount of land needed may not be available; the technology of clamp burning is simpler, particularly when only biomass fuels are available.

Thus it is important to look for ways to improve the fuel efficiency of intermittent kilns. The main objectives should be: to obtain even temperatures throughout the kiln; to reduce heat losses through the sides and top surface of the kiln; and to recover heat from the combustion gases. Research on the kiln process at the Central Building Research Institute in India has led to the development of an improved high-draught kiln design, which is reported to reduce energy consumption by a further 25 percent compared with a typical trench kiln.[187] But the capital cost of such a kiln is

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[186] Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 28)

[187] Source Rai, 1986. Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 32)

ten times that of the traditional kiln, and consequently it is considered unlikely to be widely adopted at current energy prices.[188]

Energy saving opportunities in brick kilns:

The following is a summary of opportunities to save energy in brick kilns: wherever possible continuous kilns should replace intermittent kilns; where continuous processes are used, low movable chimneys should be replaced by higher permanent chimneys; improving the insulation of kilns if intermittent kilns have to be used; carbonaceous wastes should be added to clay bodies to reduce the requirement for conventional fuels, high grade fuels such as coal should be replaced with lower grade alternatives such as sawdust, agricultural waste and waste oil; reuse waste heat from combustion; use of simple manual equipment for manufacture rather than mechanical equipment.

In India, the addition of coal washery rejects could save 25-75 percent of coal. The other energy savings possible through changes in brickmaking technology in India are as follows:

Process description	**Coal saving percentage**
High-draught kiln	15-20
Addition of fly-ash (30 per cent) to clay	10-30
Addition of coal washery rejects (50-60%)	25-75
Use of rice husk in firing bricks	20-25

Table 8: Energy savings possible through changes in brickmaking technology in India[189]

[188] Source Gandhi, 1986. Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 32)

[189] Source Rai. Energy for Building: Improving energy efficiency in construction and in the production of building materials in developing countries, UNCHS (United Nations Centre for Human Settlements) Habitat, HS/250/91 E. ISBN 92-1-131- 174-8 (Pg 37)

Tapping wasted energy in brickmaking in baked-*insitu* houses

For Meeker, the fuel consumption always remained a major concern. From the very beginning ever since he took up the challenge of firing *insitu* large houses energy efficiency has a Meeker's continuous preoccupation. Moreover, the idea was driven by the prospect of tapping the energy that is wasted in conventional brick pottery kilns where up to 40 % of the heat is absorbed by the kiln walls themselves, and each time products are baked, a part of the fuel is spent in baking and re-baking the same kiln structure. With the wasted fuel of a modern brick kiln several thousand two-room houses could be fired- because in this process every time the kiln is fired, it remains as a house.

Fuel and energy implications in Meeker's test structures

In the first seventeen structures, with the exception of Structures 11 and 12, Meeker used casuarina wood to fire his houses. Casuarina[190] is grown as a fuel crop in the region. It has a high calorific value, grows quickly, and is a renewable resource.

His first test structure was a small vaulted room, three meters in length and two meters wide fired as an updraft kiln, in spite of it being inefficient as the test structure was too small, and the primary focus was on testing if it was at all possible to stabilize the mud house-kiln. Each year of testing brought new ideas. The quest for firing efficiency lead to larger combined structures with common walls and connecting flues between rooms- not unlike standard multi-chambered kilns. Fuel consumption is the minimum when the flame path is the maximum; and in these structures Meeker tried to extend the heat path as much as possible to allow maximum heat transfer from the given fuel.

In a test to develop an efficient, inexpensive, fuel-burning kiln for the village potter, Structure 9, Meeker had constructed a simple catenary vault on a low plinth of fired brick. The kiln built in unfired brick, is 4m long and has a chimney at one end in fired brick. It was

[190] The botanical name is Casuarina Equisetifloria

fired cross draft to 950° C and requires 11,800 MJ per 1000 bricks. For such a small kiln, it is very economical. This is not unlike a small version of the CBRI bio-mass kiln, which uses 5,800 MJ per 1000 bricks. In a larger catenary vault system, fired longitudinally, it is conceivable that a figure of 6,000 MJ can be reached.

Meeker also managed to build a small twin vault structure, the eleventh experiment, to demonstrate the longitudinal draft system in two connected vaults for 6,800 MJ/1000 bricks, even though he used fire wood as fuel. Over and above, he was able to recover all the fuel cost through the product sales, and as per his intention was able to achieve the ideal economic condition, in terms of total fuel attribution to product alone, and get the earth structure fired for ‘free’. Meeker hoped that if Habla kiln efficiency (3000 MJ/1000 bricks) can be approached in this test, and then fire-stabilizing a single small house will indeed be economically viable.

Table 9 gives a comparison of fuel consumption for six fired structures and for seven conventional firing systems. These figures are reasonably accurate, and though peak temperature and soaking time vary somewhat, the trend is quite evident and is consistent with the general knowledge on firing systems. The up-draught house and up-draft kiln data are nearly identical and it should be noted that up-draught kilns are notoriously inefficient. Compared to the best firing systems available — the Hoffman, Bull's Trench, or Habla — there is certainly no future for firing houses up-draft (or down-draft). However, the tests do show a remarkable progress towards reaching an acceptable level of fuel consumption: From 13,400 MJ to 7,900 MJ/1000 bricks in the 3 vault system is not an unimpressive advance.

In the eleventh structure, a two vault structure was fired by using the longest flame path for the given size of the structure, and by slow continuous firing for 5 days to minimize damage to products by thermal shock and penetrate deeply into the walls. Reasonable fuel consumption was realised. Though not as efficient as a Hoffman, Habla or Bull's Trench Kiln, the two-vault system was, for its size, quite efficient and comparable to the local skove. The quality of the fired product was, in fact, far superior lo the locally-available brick. The fired quality of the structure is of similar quality as the local brick

FUEL EFFICIENCY COMPARISON								
Case study	5	6	7	8	9	10	11	18-20
Year	1987	1987	1988	1988	1989	1989	1990	1998-9
Size l/w/h	5/3/4.14	6/3/4.65	4/3/3.5 4.5/3/3.5 5/3/3.5 6/3/4.5 5 dia. 5 h	6/3/3.5	4/3/2.0	6/3/3.5		
Kiln type	updraft	updraft	fired simult. cross draft into dome down draft	updraft	cross draft	semi-con cross draft	longitud. cross draft	compact product mass
Product	tmb 12000	tmb 19000	tmb 60000 tiles 2000 toilet pans 4 spouts 35	tmb 8000 tiles 1000 roofing units 1000 wall units 60 mural 18 sqft	tmb3500	tmb 35000	diverse	bricks tiles
Firing temp.	945°C	920°C	900-1000°C	940°C	930°C	940°C	950°C	940°-980°C
Firing time	84 hrs	77.5 hrs	108 hrs	48 hrs	96 hrs	36 hrs	120 hrs	96 hrs
Fuel Cons.	ca. 10 tons	ca 10 tons ma 1000 bd	ca 23.4 tons ma 2,400 bd	ca 6.6 tons ma 600 bd	ca 2 tons	ca 10 tons ma 1400 bd	aa 8 tons ma 655 bd	
MJ/1000 Product	17270	16292	13270	19732	11850	12193		3000
MJ/1000 Prod + Str	12300	11680	9100	14250	8457	7900	6800	3000
Value of Product Rs	10000	15800	75000	16000	4530	43500	40000	3000

Table 9: Fuel Efficiency Comparison in Meeker's test structures

There is certainly a limit as to how closely continuous kiln economy can be approached. There is a trade-of because this structure is not only a kiln — after firing it becomes a living space. Ray states, "I have heard of chamber kilns being used for shelter in Europe during and just after World War II, but I do not think the most efficient kiln will make an ideal living space." In the 3-chamber test, the vaults are higher than they are wide, which slows the draft. Heat tends to stagnate at the top of the vaults. Interestingly heat loss to the structure, an unfortunate waste in ordinary kiln operation, is an advantage when firing a house, more especially when the loss is through the roof.

By 1998, Meeker had solved most of the challenges, except the unresolved attempt at coal dust as a fuel of Structure 12. By this time he was quite sceptic about further pursuing the firing of earth houses due to his doubts about their environmental sustainability. In his article Attitude, Imagination, Innovation, he wrote, “I spent 13 years firing houses. I have stopped, for several reasons, but in the main because I viewed the process as an experiment in the pursuit of an eco-friendly technology, and in fact it proved to be too energy intensive for sustainable development. But, living in the thrall of the process - on technical as well as aesthetic levels -I continued to fire houses long after I realised that it was not going to work as I had hoped.”

Around this time, he was asked to build another fired building, this time a temple for a dance village, Nrityagram in Hessaraghata near Bangalore. He went on to develop this project in spite of his earlier reservations, and on inspecting the brick production in nearby kilns, Meeker was overjoyed to have discovered that in that area bricks were being produced with an admixture of coal dust in the brick mixture as combustible bricks. This opened up new doors to the continuation of a process that he had thought had no further reason to go on. This technique of brick making was already attempted by him in his twelfth experiment and he hadn’t pursued this further.

The successful firing of the eighteenth structure with the support of the local brick maker who supplied the project with the green coal mixed bricks, lead to a breakthrough in competitive fuel consumption figures and had brought a significant reduction in the previous figures. 3000 MJ per 1000 bricks as against the 6,800 MJ achieved in the eleventh structure through longitudinal cross draft firing in a twin vault. This figure makes the technique reach the fuel efficiency figures of the Zigzag or Habla kiln, and just when Meeker was about to stop firing houses, the technique of coal dust infused combustible bricks opened up new horizons.

10.4 Socio-economic implications

"When a mud house is being stabilized by fire, it is at the same time serving as a temporary kiln. The house, born of earth and fire, gives back a product of earth and fire."

Ray Meeker[191]

A sustainable habitat is one that is considered to be economically viable, socially acceptable and environmentally benign. The environment aspects are taken up for discussion in Section 10.5, and the Socio-Economic aspects are covered separately under this section.

The dimensions of Economic Sustainability are listed as: creation of new markets and opportunities for growth of sales; cost reduction through efficiency improvements and reduced energy, and raw materials use; and creation of additional added value[192]. The baked-insitu mud construction technology addresses all these issues by creating a small scale building material industry along with the production of a house, by reusing the heat 'wasted' into kiln walls in normal brick manufacture, and thereby reducing energy consumption and cost, by using locally available low energy materials and helping the money to remain in the local economy by increasing the labour component of the building cost, and by creating value addition in both, the structure as well as the products that are baked within the house.

The dimensions of Social Sustainability are listed as: worker health and safety; impacts on local communities, quality of life; and benefits to disadvantaged groups. This technology also addresses each of these issues as the technology is mainly focused on providing high quality of affordable houses to those who cannot afford the 'standard' house, and it gives unskilled labour ample opportunities to find work, while also providing jobs to the local potter whose lively hood is threatened by the plastics and

[191] MEEKER, Ray. Just Plain Geometry 29, July 1993, unpublished essay

[192] Source http://enertia.com/envirac.html Sustainable Building Design Manual: Vol. 2 Sustainable Building Design Practices, ICAEN, TERI, New Delhi, (2004 Pg3)

metal industries that are replacing the products that potters used to provide. These benefits are separately discussed below:

10.4.1 Generating employment

"The village potter, whose livelihood is now threatened by mass-produced plastic and aluminium vessels, and whose knowledge and skill with earth and fire are no longer fully utilised, holds in his hand great potential for spinning the rural clay-based building industry" Meeker says. There is no short-age of labour in India and Ray's project could potentially provide work for brick makers, potters, and masons as well as manual labourers. This process is labour intensive. Most of the work is unskilled-moving bricks, loading/ unloading the structure, adding cow dung/rice husk/clay over the vaults, removing it after firing. The firing labour itself, continuous for 60 hours or more, even on small houses, is exhausting. This technique can be seen as employment generating, with a high percentage of cost going into labour rather than material.

10.4.2 Local materials replacing building materials from industries

As the technology is mainly dependant on availability of local earth and local fuel, the only building materials except for the foundations and finishes, the production of baked insitu houses help the money spent on the house to remain within the local economy. Even if the house is low cost, this fact that the production of houses directly benefits the local economy is one of the most interesting advantages that give this technology an edge over others (wherever this technology has the ideal circumstances of appropriate clay and fuel) in terms of economic sustainability..

10.4.3 House as a generator of building materials, rather than a consumer[193]

[193] KHALILI, Nader. *Ceramic Houses and Earth Architecture: How to Build Your Own* Cal-Earth Press, California 2000 ISBN 1-889625-01-9 (Pg 21-26)

While working on the first rehabilitation project, Khalili writes, it occurred to him that the house itself was becoming a kiln and that if this kiln could be filled with sun-dried blocks, tiles, water jars and flower pots, they could be baked along with the house. The products could be used for courtyards and walls, or sold. The house could thus become the producer as well as the consumer of building materials. And if done right, then each time a house was fired the sale of products could pay for the house. *"The dream of making no-cost housing instead of low-cost housing with earth architecture could become a reality."* Yet surprisingly he fired both his structures empty.

According to Meeker, large buildings cannot be fired empty. The most practical load is brick, which can be stacked in ways to channel the fire where it is needed. Tiles and pots may be included as a secondary load. Brick and tile have tremendous thermal mass, resulting in a mammoth heat reservoir that radiates deeply into walls and roof. And there is a market for high-quality, table-moulded brick, which is more profitable than the ordinary slop-moulded product. In addition a whole range of products including a range of ceramic building products can be produced within the house to provide high quality locally produced materials for house building.

Meeker's dream, in fact, is to develop a viable small scale, rural base, clay building industry which will also produce a wide range of terracotta building components. He had hoped that by using exclusively local materials both for the house and fired together with local labour, the fire stabilised mud building could help decentralise the construction industry.

Given the small scale of buildings that were relatively few in number, Meeker's products did have a visible effect in the local area of Pondicherry and Auroville. In the year 1986, the first exposed brick masonry house, Neena Devi's house was built on an important commercial street in the centre of Pondicherry with table-moulded bricks produced in Meeker's fourth test structure. This created a demand for high quality and even for wire cut bricks in the area. Other buildings followed, such as the HiDesign Factory whose bricks were produced in Test Structure 7, Agnijata. In 1990, in Structure

9, Meeker produced hollow terracotta conical roofing units for Pierre Tran's House (Fig. 10.1, 10.3 and 10.4), based on an order placed by the architect and author of this dissertation in Auroville, to enable a high quality insulating roof to be built without using timber or steel. In 1998, Meeker produced hollow trapezoidal roofing units, for the author's own house in Auroville where terracotta units were designed within jack arches for insulated flat roofs (Fig. 10.2, and 10.5).


Fig. 10.1 Pierre Tran's House using hollow terracotta units as structural elements, 1993, Source: Anupama Kundoo

Fig. 10.2 Author's House using terracotta units as structural elements in a variety of ways, 2006 Source: Anupama Kundoo


Fig. 10.3 Terracotta Units produced for Pierre Tran's House, 1993, Source: Anupama Kundoo

Fig. 10.4 Pierre Tran's House using hollow terracotta units as structural elements, 1993, Source: Anupama Kundoo


Fig. 10.5 Terracotta Units produced for use within Jack arches, 2004, Source: Anupama Kundoo

Fig. 10.6 Creativity: Urban Eco-Community using hollow terracotta units as structural elements, 2004, Source: Anupama Kundoo

Fig. 10.7 Terracotta units as lost shuttering in filler slabs to reduce steel, Sangamam Community Center, Low-cost Housing Project, Auroville, 2002, Source: Anupama Kundoo

Fig. 10.8 Terracotta units as lost shuttering in filler slabs to reduce steel, Author's own house, Auroville, 2002, Source: Anupama Kundoo

10.4.4 The role of products and their implications

Although products are required to be able to fire a large structure that technically cannot be fired empty, products also play an important role in the socio-economic implications of this technology, as they offset fuel costs involved in firing a structure and thereby economizing the cost of the house.

The proportion of products to be produced within the house compared to the bricks needed for the structure is significant. Over 6000 bricks are required to build a typical single vaulted house. The same structure contains l2, 000 bricks as product. But the bricks are of much superior quality are more expensive than the local bricks. Since the traditional brick is of sufficient quality for intended use there is little sense in making it better when the local economy cannot afford a better brick! But there could be a small market for high quality bricks in the local area. Even higher value products such as floor tiles, window jalis, pipes and so on, of terracotta as well as other objects such as lamps, gargoyles, garden seats and stools, even murals - can be produced and sold or used in the house. Given the number of potential products, it would seem that practically the whole dwelling could be done in fired clay.

A project in a "backward area", far from industrialized urban centres, will not have to compete with mass produced clay building products as they do not generally reach these areas. Producing with labour intensive methods, the products will no doubt be of somewhat inferior quality, but if quality is sufficient for utility, then a market- albeit a limited one- should exist. In areas adjacent to urban population with broad market potential, if local raw materials are good, a more sophisticated process and product could be considered.

Product development, in the context of fired building technology, has two main objectives: First, and most immediate, to generate income from the process, and produce as many building components as possible for completion of the kiln as a house, while offsetting fuel costs; Second, to generate a small-scale, labour-intensive, rural building industry, producing a wide variety of terracotta building components. It can be argued that this is a dream- that it will not be possible to compete with existing industry either in terms of product quality or cost. This may be true. However, if a number of products and processes are developed, appropriate to different economic conditions, these objections might be overcome.

10.4.5 Local skills and expertise

> *"Apart from the considerable experience required to become a knowledgeable and capable fireman, (except for local brick makers and potters) there is doubt concerning maintaining a standard for adequate firing. Fire is cement in this technique. Contractors in our area are notorious for fattening their wallets on lean cement mixtures. The obvious place to cut the cost of a fired building is in fuel consumption. Whether the contractor maximizing profit (This, by the way, is true for government as well as private contractors.) or the poor man who simply cannot afford the fuel what will be the consequence of an underfired house?"*
>
> Ray Meeker[194]

[194] MEEKER, Ray. Geltaftan: A Second Thought, undated and unpublished paper.

Whether the average homeless villager in the "developing" world can actually build their own ceramic house is a major question. The early structures naturally needed Meeker's complete involvement and in the subsequent structures, he began to involve contractors and local engineers and eventually even an architect to take up the design aspect. More R & D would be needed before the technology could be transferred.

From the tests conducted in Pondicherry it seems that with skilled masons (Skilled masons in South India have very little experience with arches and generally none at all with domes and vaults) and perhaps eventually with unskilled and semi-skilled labour, building the mud structure will pose no insurmountable difficulty.

Transfer of the firing technique does, however, raise interesting questions. The village potter could easily build a kiln with this method and, after understanding its principle through a number of firings, put a similar vault on 1.5 m walls and fire a room to live in. He would then become the equivalent of the local mason as a maker of houses. He would use the house as his kiln for firing floor tiles, *jaalis, chulas,* pipes — any number of items which could contribute to the stock of locally available building materials. Transfer of technology, always a .stumbling block, might thus be handled with a minimum of difficulty.

10.5 Environmental Implications and Sustainability

> *"Still, there are those who feel, given the fuel crisis, even firing common brick should be stopped. Perhaps. But, I do not see that as an immediate prospect. In standard kiln operation, as much as 40 percent of the heat available may be absorbed by the kiln structure. Why not stabilise a structure with that waste heat? And then, suppose it really is possible to do a completely finished, pucca house for Rs30/sqft?"*
>
> Ray Meeker[195]

[195] MEEKER, Ray. Kiln Technology, Indian Architect and Builder, Business Press, Mumbai, November 1990. (pg 61)

Development always has some environmental impact. Sustainable development can be defined as development with low environmental impact, while maximizing environmental, economic and social gains.[196] Sustainable development is a very broad subject that goes beyond conserving the environmental capital. It can be considered to have four main objectives: social progress, recognizing the needs of everyone; effective protection of the environment; prudent use of natural resources; and maintenance of high and stable levels of economic growth and employment. The first and the fourth objectives are discussed at length in Section 10.4 under 'Socio-economic implications' of this technology and the second and third namely effective protection of the environment and prudent use of natural resources are issues that fall under environmental sustainability, and will be discussed in this section.

The awareness of environmentally sustainable architecture began around the seventies in response to a visible evidence of environmental damage and rising fuel costs. Buildings as they are designed today, symbolize unrestrained consumption of energy and other natural resources, with a consequent negative environmental impact. In India, the residential and commercial sectors consume 25 per cent of the total electricity usage of the country, and a major portion of this is utilized in buildings. Most buildings that are presently being designed and used are far from being eco-friendly or sustainable. Their energy consumption and imposition on natural resources is massive[197]. According to the World Watch Institute,[198]about 40% of the total energy use is dedicated to buildings. In 1990, residential, commercial and institutional building sectors globally consumed 31% of the global energy and emitted 1900 mega tonnes of carbon. By 2050, this share will rise to 38%, emitting 3800 mega tonnes of carbon.[199]

The basic principles of sustainable building design are:

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[196] Sustainable Building Design Manual: Vol. 2 Sustainable Building Design Practices, ICAEN, TERI, New Delhi, (2004 Pg 1)

[197] Sustainable Building Design Manual: Vol. 2 Sustainable Building Design Practices, ICAEN, TERI, New Delhi, (2004 Pg 2)

[198] Details available on http://www.worldwatch.org/about/

[199] Source: Watson, Zinyowera, and Moss (eds) 1996, Sustainable Building Design Manual: Vol. 2 Sustainable Building Design Practices, ICAEN, TERI, New Delhi, (2004 Pg 1)

- Maximising the use of renewable and natural resources in the building environment
- Minimising energy and water use and the negative environmental effects of buildings
- Ensuring processes to validate-building system functions and capabilities for proper maintenance and operation.

Assessment of the environmentally sustainable parameters of the baked-insitu mud building technology:

Measures listed to be adopted in environmentally sustainable buildings[200]	**Baked-insitu technology**
Improved building envelope and system design	Roof forms are climatically comfortable as the curved surface prevents absorption of radiation and thick walls provide necessary thermal mass
Water conservation and efficiency measures	Not applicable
Energy conservation and efficiency measures	Wasted heat in brickmaking is tapped, high energy materials like cement and steel are avoided
Increased use of renewable resources	Fuel crop is used as fire wood
Reduction or elimination of toxic and hazardous substances in facilities, processes and their surrounding environment	Natural materials are used
Improved indoor air quality and interior and exterior environments, leading to increased human productivity and performance and better health	Structure can breathe
Efficient use of resources and materials	Local clay and local fuel are used efficiently. Energy efficiency is

[200] Comprehensive list of parameters to be adopted in the integrated approach to sustainable building design. Sustainable Building Design Manual: Vol. 2 Sustainable Building Design Practices, ICAEN, TERI, New Delhi, (2004 Pg3)

	achieved in comparison with other small scale brick production
Selection of materials and products that minimize safety hazards and cumulative environmental impacts	yes
Increased use of recycled contents and other environmentally preferred products	Coal dust, an industrial waste is used to replace conventional fuel in brick making
Salvage and recycling of waste building materials created during construction and demolition	Partly burnt bricks are reused in the next structure, brick masonry is without cement joints and is easy to reuse
Prevention of generation of harmful materials and emissions during construction, operation and demolition	yes
Implementation of maintenance and operational practices that reduce or eliminate harmful effects on people and the natural environment	Not applicable
Reuse of the existing infrastructure, identification of facilities near public transport systems, and consideration of redevelopment of contaminated properties.	Avoids the need for truckloads of material to be delivered and therefore the need for adding infrastructure for development

Table 10: Assessment of the environmentally sustainable parameters of the baked-insitu mud building technology

11 Summary/ Conclusion

"Fire-stabilized mud building, when perfected, will no doubt be limited to a very specific set of circumstances. However, where these conditions are met (good on-site clay and a local fuel source), it is reasonable to conclude that a house of relatively high quality can be built for a very low cost. Being extremely labour intensive, the fired building process will create jobs and, using almost exclusively local materials both for house and fired product, will help to decentralize the construction industry. Hopefully, the next experiment will bring this process into a new phase: transfer of technology."

Ray Meeker[201]

11.1 Advantages

11.1.1 In terms of environmental sustainability

High compressive strength and durability

The principle material, fired clay, is acknowledged to have excellent properties as a building material, a high compressive strength, and durability. It is water resistant, permits moisture movement, can 'breathe', and provides excellent resistance to fire and chemical attacks.

Climatically comfortable

The technique limits the structure to vaults and domes that are in total compression. Vaults and domes provide sun and shade zones, which creates two

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[201] MEEKER, Ray. MUD: Towards A fire Stabilised Building Technology, Architecture & Design, Media Transasia, Delhi, March- April 1991

different temperatures and thus a draft, as opposed to flat roof that are exposed to the sun all day, and are climatically effective in areas with a high diurnal temperature variation. Under these conditions, they keep the house warm in winter and cool in summer. A flat roof is exposed to the sun all day, but a curved roof always has a shade and a sun zone which create two different temperatures and are thus a constant movement of air. The thick walls necessary to bear the load of the mud roofs provide the thermal mass that also leads to natural climatic comfort.

Mostly local materials, mainly earth

The structure makes use of mainly locally available brick clay and locally available appropriate fuel.

Reduction of high energy imported materials

The technique also involves a considerable saving of cement and, particularly, steel, high energy materials which are hard to procure, expensive, sell at prices inflated by transport and habitually used in modern building even simple houses. Even roofs, an area of dependency on high energy material or timber, are made in locally procured brick clay.

Low-tech equipment and tools, and mainly labour-intensive construction

The technique does not involve huge investments in tools and equipment and is very simple to learn, with the main expense being labour, rather than expensive building material.

Energy Conservation and Efficiency

About 40% of 'waste' heat that goes into the kiln walls in conventional kilns is tapped and used to stabilize a mud structure that is vulnerable to water if not baked. Conventionally efficient large-scale brick kilns such as Bull's Trench Kiln consume

4,500 MJ/1000 Bricks while small-scale rural intermittent brick kilns consume 16,000 MJ/1000 bricks. These small scale kilns are the only ones that are affordable in rural economies given the investment and scale of production needed to support efficient kilns. In Meeker's structures, through using fire wood form fuel crop, the consumption was 6,800 MJ/1000 bricks and by using coal dust in combustible bricks, the fuel consumption was 3000 MJ/1000 bricks. The bricks thus made by firing mud structures insitu can thus be considered energy efficient as compared with other small scale but also large scale brick production.

This is furthermore energy efficient by using non-conventional fuel sources, as the fuel used is either a renewable resource, sourced from fuel-crop or in the case of coal dust, by mixing an industrial waste that contains carbonaceous material into the brick mixture.

Yet another area of energy saving is due to not requiring Portland cement, a high energy material for mortar.

Use of environmentally preferred material with recycled content

This technique uses several locally found 'waste' material into the construction process such as cow dung, rice husk, coal dust, an industrial waste that contains carbonaceous material and calorific value.

Waste generated and Building materials after demolition

Partly burnt bricks, and broken bricks generated in the construction from areas within the openings and other areas, are reused in the construction of subsequent structures, or for packing during vault and dome construction. Once these structures are demolished they can be readily absorbed in building activities as broken bricks are used, the further advantage being that these bricks are not even bonded by cement but are a monolithic ceramic material.

Reduced load on existing infrastructure and not necessitating creation of new infrastructure

The technique does not import large quantities of material like conventional building techniques that usually call in polluting trucks into virgin lands for facilitating developments, and demand the creation of roads without proper planning. In this technique most of the material can be moved by bullock cart, and transportation energy is kept to the minimum as also the creation of new infrastructure as it is a low impact building technique mainly depending on local labour and no mechanized tools or equipment.

11.1.2 In terms of economic sustainability

Low-cost technology

Given conditions of availability of suitable brick clay and fuel, in areas with long dry season, and availability of local labour, the technique can prove to be really low cost and extremely cost-effective for the quality of construction achieved.

Labour intensive

As the technique is labour-intensive and not material-intensive, in rural areas in most developing countries, the technique is very cost-effective.

Financial returns fetched by products baked in the structure

The right choice of products could lead to the realization of the full economic potential of the technique. In this case, the fuel cost is carried by the product, and the strength of a brick house is achieved for the price of a mud house. Theoretically, the products may even make a profit and further subsidise the cost of the house.

Creation of small scale industry for production of building materials

In this technique, the manufacture and supply of high quality building material and ceramic products used in building are an integral part of the technique. Houses become suppliers of products to the local area, rather than the conventional houses that are consumers of building materials.

Value addition

By tapping the heat generated by firing ceramic products within the house-kiln, the structure gains an added value of transforming into ceramic from brick, by becoming water resistant and durable. On the other hand, the structure also produces high quality building products such as bricks, hollow roofing units, and floor tiles. These high quality products become available in remote areas where industrial products do not often reach, and when they do then they come with a high transportation cost. The surrounding structures and secondary development also sees value addition in the products that are brought into the local economy, and possibly can be exported into close by urban areas.

11.1.3 In terms of social sustainability

Employment generation

The technique has a vast employment potential. For this is a highly labour intensive process, involving a whole range of skilled and semi-skilled workers, ranging from brick makers, potters and masons to scores of manual labourers. Potters who are threatened by the plastic and metal industries are particularly favoured in this technique.

Housing solution that is affordable for those who cannot afford a 'standard' house

In 'ideal' conditions of availability of appropriate brick clay and fuel, this technique could really be a viable option for those who are willing to put their own labour into house building, and they could profit from having a durable ceramic house instead of the vulnerable mud house that is the only affordable option.

11.2 Limitations

The risk of rain damage and the need for protection

Though a mud building can be sufficiently stabilized with fire to resist deterioration from erosion, in a monsoon climate, there will be a relatively short and somewhat insecure building season. Rain during construction can be disastrous. Though it is possible to protect structures while under construction, it does add significantly to the cost. This need not however, invalidate the process. It probably precludes it from use on very large projects. But, in fact, many villages in India are small, and I do not believe that each and every building technique evolved must necessarily be appropriate for covering hectares of land with literally thousands of houses. And in fact, traditionally, in rural areas, building and planting, respect the cyclic monsoon pattern.

Structures built in mud are extremely vulnerable until they are fired. The building and product must be protected from unseasonable rain during construction. Large tarpaulins are expensive and cumbersome, but are absolutely necessary in areas with erratic monsoons. It is worthwhile to consider the problem of "unseasonable" rain when discussing mud building of any kind. All mud products as well as the whole of the structure must be protected until it is fired. A single canvas tarpaulin large enough to cover a small room of 180 square feet can cost as much as half the cost of the finished fired room. The villager is not going to be able to afford to lose his time and labour.

Nearness to brick clay

Brick clay may not be easily found in many places, and if sourced from further away, this will come with substantial added costs. There are many problems for its wide-spread application.

Design Limitations due to Compression Structures and Kiln Function

The structural design is also limited by the strength of unbaked earth to stand till fired. Mud has no tensile strength, and so there can be no flat roofs; the structure is also subject to dynamic load of thermal expansion while firing. Roofs must be either vaults or domes. On vaults built in the 'Nubian ' technique, the structure is susceptible to cracks either due to unresolved tension at the top of the curve or to thermal expansion in hot climates. The latter generally appear along the weakest vertical joints[202].

Then there are also design limitations, as the houses must be designed for optimal firing and heat transference. Other architectural limitations also exist as the house must be primarily designed as a kiln and interior spaces must not be complex in order to ensure adequate draft during firing. But a kiln is not necessarily the most function living space. Going beyond the basics of firing efficiency to design a house always compromised fuel consumption. Very complex flame paths are out of the question, as all corners of the interior space must be well fired

Fuel Consumption

Fired clay products are known for their relatively high fuel consumption. Yet these materials are of great importance in developing countries because they can be produced from local material using relatively simple technologies and whatever fuel is locally available. However materials such as compressed earth blocks use a far reduced amount of energy in comparison.

Technical Supervision and Quality Control

Another drawback is that the technique requires the supervision of a specialist for scientific thermal applications which must be precisely monitored at every stage. Although potters can be trained to handle this, much simpler guidelines will have to be developed. Fire is the cement of this process. Either the factor of the contractor cutting costs, or the poor villager unable to afford sufficient fuel to dully stabilize the structure could lead to structural failures with serious consequences. Far more serious will be the problem of maintaining adequate construction standards. Criteria can be established, even codified for proper building procedures.

[202] Meeker said, “Many of the vaults I have tested have developed post-firing cracks. I have been concentrating on developing the firing economy of the system, and as yet have not had time to worry about these cracks. Mud vaults of this type, cracked and otherwise, have been standing for centuries.”

Financing of the products

Even if the cost will be recovered, the production of products to be fired in the structure requires a substantial investment, which no house economy can bear. Other ideas have to be found to be able to advance financial resources for the production of the products. While economy is achievable in larger scale projects, the procedures for making the product load need to be financed. This could mean government assistance and many houses taking the process out of the hands of the individual family.

11.3 Appropriateness

> *"This book is an appeal for a new attitude to rural rehabilitation. The standard of living and culture among the world's desperately poor peasants can be raised through cooperative building, which involves a new approach to mass housing. There is much more in this approach than the purely technical matters that concern the architect. There are social and cultural questions of great complexity and delicacy…"*
>
> Hassan Fathy[203]
>
> *"If I tend to dwell on the "owner built" house it is simply because that is still how most houses in the world are built. By comparison, government mass housing pales to insignificance."*
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> Ray Meeker[204]

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[203] FATHY, Hassan. Architecture for the Poor, The University of Chicago Press, Chicago, 1973

[204] MEEKER, Ray. Geltaftan: A Second Thought, Undated Unpublished article.

Earth buildings have been built all over the world: in the hottest deserts of the Middle East, in the freezing and snowy climate of Scandinavia, in the tropical countries such as Costa Rica in Central America, which has an annual rainfall of 180 cms. Thus to build with earth is appropriate everywhere in the world. But it is not earth alone that makes a building. Skills, availability of the earth itself, local tradition, acceptance and socio-economics play a great part in the whole process.

11.3.1 Availability of suitable soil and fuel, lack of steel or timber for roofs

The technique is particularly suitable in areas where brick clay is available. In most countries of the world large clay deposits are shown in geological survey maps, but those are only regional deposits. Clay pockets are everywhere and can easily be found. If we look at a good structural factory fired brick, we will see that it is dense and has few impurities, but there are other grades of bricks that have lasted centuries- handmade, less pure and less dense. In this technique clay need not be of the best quality, but a quality that suits the manufacture of much weaker local bricks is sufficient as its strength is adequate for upto two storey load bearing structures.

It is especially appropriate, however, for more isolated areas where building products are difficult to get and sell at prices inflated by transportation. In remote areas, that are struggling to get sophisticated materials like structural steel, given the non-availability of timber, this technique provides ways to build roofs in compression and does not require lintels. It may be argued that the same kind of structure could also be achieved in brick masonry, but even for that cement, or lime would be required. In this case the principal material is locally available brick clay; with fire being the cement. The other basic material required is fuel to sustain the fire, but a range of locally available unconventional fuel sources may be used.

11.3.2 Availability of skills and know-how

This technique is labour intensive, with plenty of work for unskilled labour, and is low-cost where labour is cheap, relatively unskilled and easily available. Thus it is likely to be suitable in almost all the developing countries because of their availability of cheap and relatively unskilled labour. In places where there are skilled potters and local brick makers, (which means there is also clay), fired earth building will be easier to handle. The potters community widespread over India, for example, who have still a good knowledge of fired clay are unable to sustain their profession as people are moving away from the use of terracotta cooking pots and other articles, and turning to metal or plastic substitutes.

These places could profit from developing a local economy and if close to urban areas, the products inside could be diversified to contain a larger quantity of sophisticated products that could fetch larger returns and the house building activity could generate the production of high quality environmentally friendly basic as well as sophisticated building material for the local area.

11.3.3 In places of acute housing shortage due to affordability

In places where there is an acute housing shortage (as in India) where there is simply not enough money to build a 'standard' house[205] and where self building could be a conceivable way to be able to offset costs.

The supply of low cost but durable building materials is almost universally recognized as a major obstacle to improved housing conditions in developing countries, whether in urban or rural areas. There is a growing interest in the use of building

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[205] "We are constantly reminded that when it comes to building a new house, for those who can afford it, the first choice will be a box-like R.C.C. frame filled in with fired brick and cement mortar and plastered. This all-pervasive solution, aesthetically and technically Western, forms the norm for both private and government sector construction and has left a built environment of shockingly drab conformity." In Feb 1987, in Ray's article in Moving Technology, Ray writes: "A good deal has been said over the past fifty years on the need for a revival and/or upgrading of mud building technique in order to produce a durable "low cost" house. The call, strident in the past decade, as housing demand increases, energy costs rise and natural resource reserves seem to be on decline, has yet to yield a totally satisfactory solution. To be sure, there has also been strong opposition to mud as a viable material for building in the twentieth century. The resistance, not unjustified, stems form technical, cultural, and no doubt political and economic prejudices. Without getting bogged down in the mud vs. cement rhetoric, it should be sufficient to say that any technique which might produce a reasonably low cost solution to today's housing shortage is certainly worth serious investigation."

materials that can be produced entirely from local resources, using simple small-scale production technologies to provide durable building materials at a cost that is affordable by the majority of potential builders.

11.3.4 Environmental appropriateness

> *"Still, there are those who feel, given the fuel crisis, even firing common brick should be stopped. Perhaps. But, I do not see that as an immediate prospect. In standard kiln operation, as much as 40 percent of the heat available may be absorbed by the kiln structure. Why not stabilise a structure with that waste heat? And then, suppose it really is possible to do a completely finished, pucca house for Rs30/ft2?"*
>
> Ray Meeker[206]

In the quest for meeting the increasing shelter demand with sustainable solutions, there is a focused attention on the importance of local building materials and techniques. Research on building materials and technologies were identified as core mandates of UN-HABITAT following the United Nations Conference on Human Settlements (Habitat II) convened in Istanbul, 1996.[207] Methods of improving such materials and technologies and for combining them in new ways are constantly being developed.

The rich variety of traditional building technologies has been replaced by the standard technology of Reinforced Cement Concrete roof with brick or block walls in a Reinforced Concrete frame structure. This is due to the unavailability of some resources and due to the lack of new methods of using local materials in ways that are effective and affordable.

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[206] MEEKER, Ray. Kiln Technology: A demonstration and a challenge, Indian Architect & Builder, Business Press, Bombay, November 1990

[207] Building materials and construction technologies: annotated UN-HABITAT bibliography http://www.unhabitat.org

In places where local clay is found to be suitable, this technique can be considered environmentally appropriate due to the various advantageous this technique offers in terms of overall sustainability, including environmental, economic and well as social sustainability issues as discussed in Section 10.5 and Sub-section 11.1.1.

The environmental appropriateness can however been summarised thus: the technique offer a strong and durable structure with a proven long life; with a good solar passive performance that will reduce the energy demand for artificial heating and cooling; that is principally built with local materials which have automatically less embodied energy than the manufactured materials that use energy not only for manufacture but also transportation; that uses significantly less energy that the small-scale locally produced fired bricks**,** but offering a far better strength and quality, but in addition significantly reduces embodied energy in the structure by enabling that roofs are also built in earth, and makes no (or very little) demand on high energy materials like steel and cement; is mainly a labour-intensive construction requiring very simple and inexpensive tools; even the reduced energy required to produce the fired earth relies largely on unconventional fuel sources like fuel crop or industrial waste with carbonaceous content, produces no “waste” during construction or demolition, and makes no significant demand on existing infrastructure such as roads and energy for construction.

This technique addresses two areas innovation: on one hand it offers a way to stabilize a raw earth structure, a problem that really has not been solved satisfactorily; and on the other hand it can be seen as an attempt to reduce the firing and transportation energy consumed in conventional fired brick construction. Sanjay Prakash, an Indian architect renowned for his contributions towards sustainable building reflects[208], “… on the whole it is probably best to see these experiments as representing a branch of building technologies sufficiently distinct from either raw earth or improved earth construction techniques on the one hand and from fired brick building on the other so as to merit exploration in its own

[208] MEEKER, Ray. MUD: Towards A fire Stabilised Building Technology, Architecture & Design, Media Transasia, Delhi, March- April 1991

right. In modem times, reports of in situ fired structures have been trickling in from the Middle East where they use oil-fuelled blow torches to stabilize raw earth buildings, a shocking prospect in our context. Meeker's work is much better suited to our environmental context, utilizing biomass fuels which are, at least in principle, renewable. In practice, of course, this may still entail a heavy price in the short and medium term, unless married with sound afforestation practices.” [209]

11.3.5 Regarding Earthquakes and Flood prone areas

Baked insitu structures are not likely to withstand seismic loads and measures can be taken to reinforce foundations by adding a plinth beam. As the firing takes place above the plinth level it does not pose a problem to overheating other materials used in the foundations. However, steel and concrete may not be added as reinforcement in the brick masonry, as the steel and concrete will not be able to withstand the high temperatures.

This technique is also not ideal in flood prone areas as the unbaked structure would be highly susceptible to damage.

11.4 Areas of further experimentation and research and future prospects for upgrading and overall optimization

[209] Sanjay Prakash continues, “At first sight it seems that the energy savings in the techniques described are the result of firing only the finished masonry face. But this is not so. As Meeker candidly admits, a kiln designed for efficiency is not the greatest of places to live in, and a compromise has to be reached between efficiency of fuel burning and spatial requirements and use. Also, since the firing has to be from inside but the heat must reach outside in order to stabilize the face that matters most; the entire mass of the building has to be fired. All this results in a structure whose energy cost is actually somewhat higher per unit volume than that built in efficiently fired kiln bricks, except that there is a substantial saving of cement by its virtual elimination in the building, especially in the mortars. Therefore, the justification for the technique really centres around the other fired products that can come out of the 'house-kiln'. These pottery products can be used in the house itself, or sold. If the technique were to be propagated on a larger scale, it is in this area that the implementors would have to concentrate, and this probably makes the idea fairly untenable for sale to the bureaucracy. Unfortunately, integrated concepts addressing a range of problems simultaneously, such as employment, local self-reliance, energy, distribution of natural resources, and housing, as this one does, tend to slip between the cracks in diverse institutions, and be forgotten.”

"I have done all what I can do. I have taken this project up to a point. It must be taken up by others. Somebody should step in and say, yes, we are interested."

Ray Meeker[210]

11.4.1 One interesting question remains unanswered: The extent to which Khalili's structures actually got stabilized. Given the experiments made and monitored by Meeker, there are reasons to doubt that they were fired through and Khalili makes no mention in his books about the depth to which he estimated that they got fired. Firstly, Khalili fired his structures empty, which doesn't make a good kiln, and doesn't get the heat to penetrate due to the lack of thermal mass. Secondly, he didn't mention combustible insulation which Meeker found was the only way to get the vault thickness to get baked through. Thirdly, he fired existing adobe houses which are not likely to have been the appropriate clay to be fired. It would be worth visiting the two experiments conducted by Khalili and to inspect the structure for extent of firing.

11.4.2 In the midst of current construction trends in India, there have sprouted certain experimental uses of terracotta systems that have been largely the work of a few inspired enthusiastic architects and individuals. These structures have been more or less tried and tested over the past 15 years in their own individual capacities and still await theoretical and comparative analysis. This prevents them from being applied on the mainstream and being incorporated in the building standards although they are apparently more efficient than most technologies of that scale. It would be interesting to explore the possible terracotta building components that could be produced within the house that could be beneficial to the surrounding area, while generating capital for the house itself.

11.4.3 To make a comparative energy audit of the structure as a whole compared to other conventional as well as alternative energy –efficient building technologies. In this dissertation, only energy comparisons of building materials have been made, and not of their combination.

[210] in interview with T. Manivannan, Indian Express Sunday magazine, November 3, 1991

11.4.4 It would be interesting to find out how much compare how much carbon dioxide trees absorb compared to what it gives off when you burn it including the time involved in their growing. A carbon trading study could prove to be quite useful.

Conclusion:

The technique of baked-insitu mud construction has several advantages.

The structures this built have high compressive strength, have good thermal properties, use mainly local materials and mostly local earth thereby significantly reducing imported materials with high embodied energy. The technology is energy efficient, uses environmentally preferred materials as fuel, and does not generate unwanted 'waste' even upon demolition. The construction involves low-tech equipment and tools, and is labour-intensive, and does not add to the demand on existing infrastructure or necessitate the creation of new infrastructure. Thus the technique can be considered to be environmentally sustainable.

The technology is low-cost and labour-intensive, and its production generates financial returns through simultaneous manufacture of building materials and ceramic products to be fired inside it. The process of firing products inside the house brings added value to the structure by turning it into ceramic and making it durable as compared to other mud structures. Thus the technique can be considered to be economically sustainable.

As the process of its construction is labour-intensive and generates further more employment through the simultaneous production of building material, and provide direct benefits in upgrading the quality of life of those who couldn't have afforded a 'standard' house; the technique can also be considered as socially sustainable.

There are also several limitations. Until it is stabilised by fire, the structure is prone to rain damage being extremely vulnerable to water. It can also therefore not be built throughout the year. The technique depends on nearness to brick clay source, but this is not common and so the technique is not suited to wide-scale application. The structure is limited to forms suited to compression structures and also to kiln systems. Even though the fuel consumption may have been drastically lowered in the last three structures and is quite energy efficient for being ceramic, fired clay products are not the most energy-efficient building materials. The problem of technical supervision and quality control is not to be under-estimated and the pre-financing of products to be fired within, until they are sold, is a major financial hurdle that cannot be afforded particularly by the poor and require financial support or government assistance.

The technique could be considered appropriate in areas where suitable soil and fuel are locally available, in areas where there is a lack of steel or timber for roofs, and in remote areas where the supply of Portland cement is expensive and unreliable. In places where there is plenty of labour, even unskilled labour, and in places with an acute housing shortage due to affordability, this technique is also suited. The technique may not be ideally suited to earthquake and flood prone areas. Environmentally, the technique is also appropriate as it uses the age-old benign materials, with the innovation being the new ways in which they are combined.

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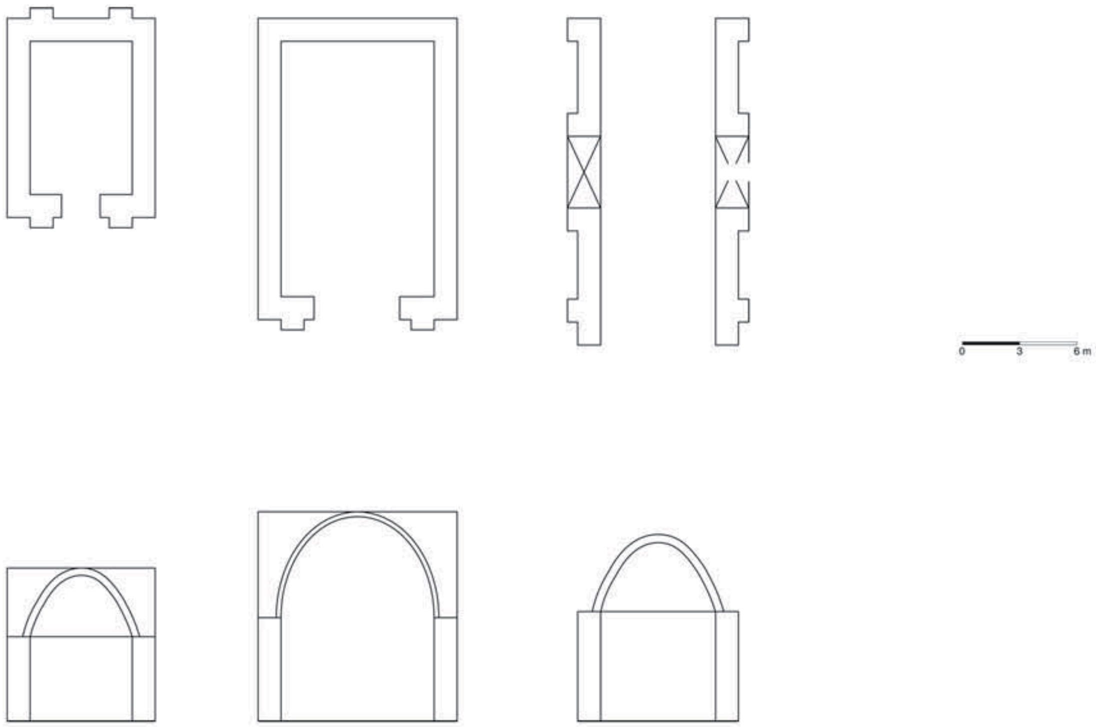
APPENDIX 1: CASESTUDIES

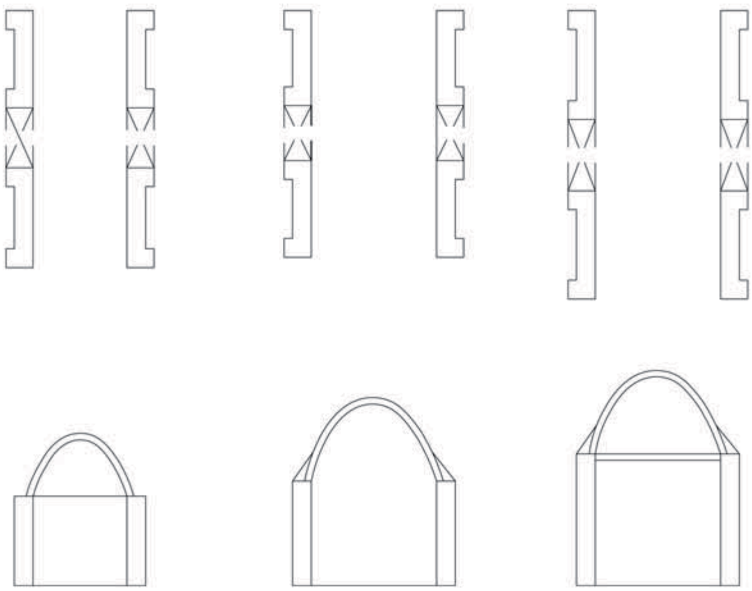
Casestudy 1-6 - Golden Bridge Pottery Structure 1, 2, 3, 4, 5, 6, Pondicherry

Project plans

structure 1 structure 2 structure 3



structure 4 structure 5 structure 6



Casestudy 1 - Golden Bridge Pottery Vault 1

Photos


A1-1


A1-2


A1-3


A1-4


A1-5


A1-6


A1-7


A1-8

Casestudy 2 - Golden Bridge Pottery Vault 2

Photos


A2-1


A2-2


A2-3


A2-4


A2-5


A2-6


A2-7


A2-8

Casestudy 3 - Golden Bridge Pottery Vault 3

Photos

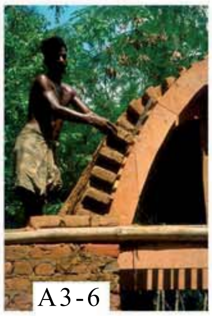

A3-1


A3-2


A3-3


A3-4


A3-5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A3-7


A3-8


A3-9


A3-10


A3-11


A3-12


A3-13


A3-14

Casestudy 4 - Golden Bridge Pottery Vault 4

Photos


A4-1


A4-2


A4-3


A4-4


A4-5


A4-6


A4-7


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Casestudy 5 - Golden Bridge Pottery Vault 5

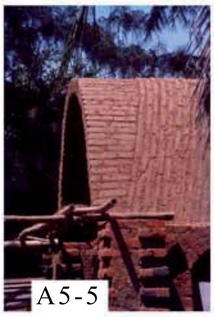
Photos


A5-1


A5-2


A5-3


A5-4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Casestudy 6 - Golden Bridge Pottery Vault 6

Photos


A6-1


A6-2


A6-3


A6-4


A6-5


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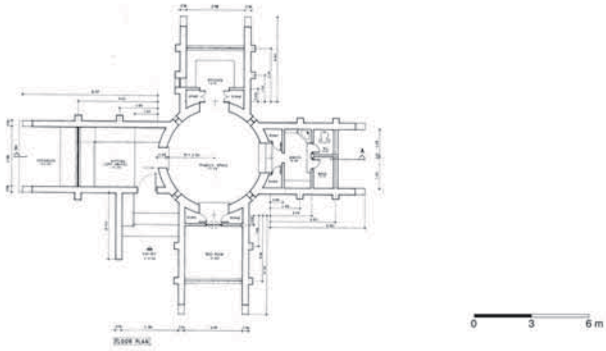
A6-9

Casestudy 7 - Agni Jata: Mallika's residence, Auroville

Project plans - Pg 1

floor plan



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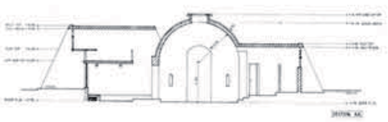

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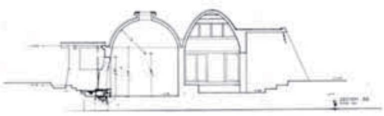
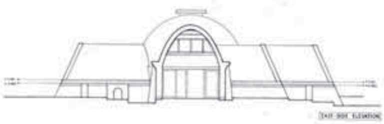


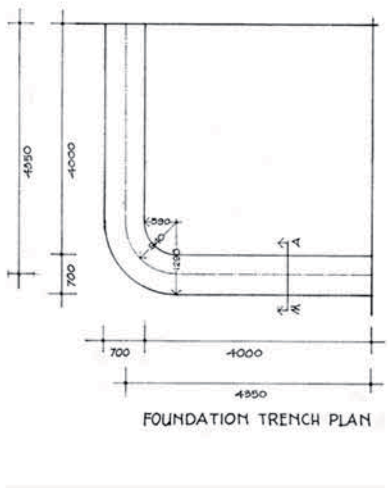
elevation 1

elevation 2

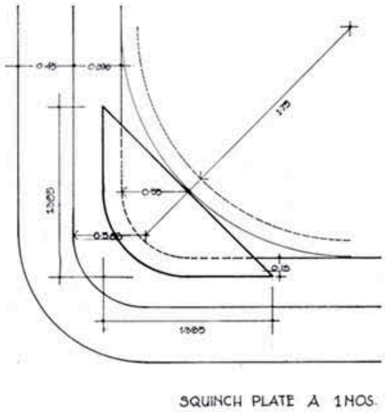


elevation 3

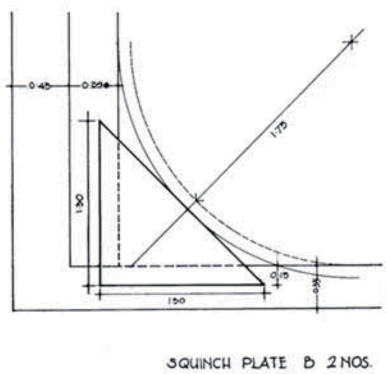
plan 2



squinch plate 1



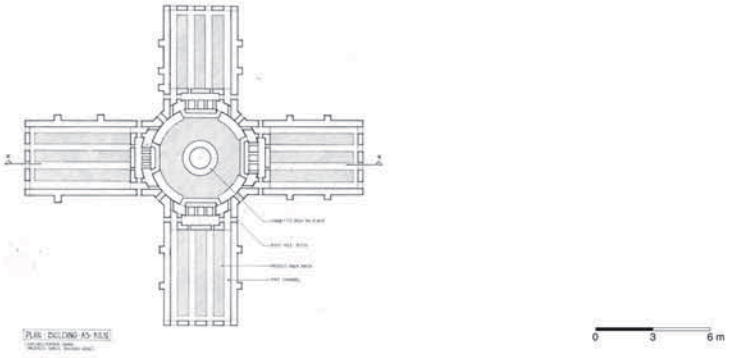
squinch plate 2



Casestudy 7 - Agni Jata: Mallika's residence, Auroville

Kiln systems - Pg 2

plan



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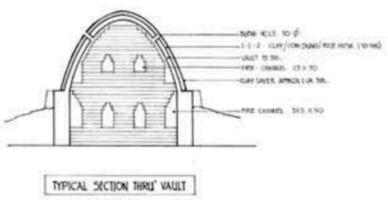

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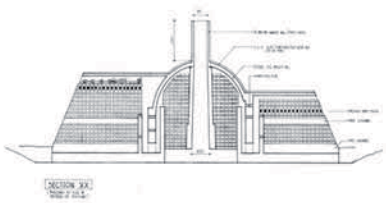

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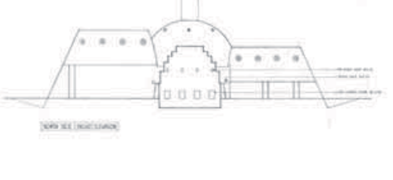

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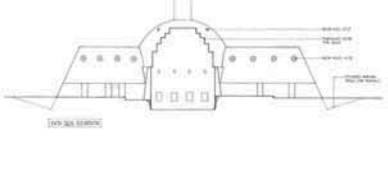

Casestudy 7 - Agni Jata: Mallika's residence, Auroville

Photos I


A7-1


A7-2


A7-3


A7-4


A7-5


A7-6


A7-7


A7-8


A7-9


A7-10


A7-11


A7-12


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A7-14


A7-15


A7-16


A7-17


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A7-19


A7-20

Casestudy 7 - Agni Jata: Mallika's residence, Auroville

Photos II


A7-21


A7-22


A7-23


A7-24


A7-25


A7-26


A7-27


A7-28


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Casestudy 7 - Agni Jata: Mallika's residence, Auroville

Photos III


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A7-38


A7-39


A7-40


A7-41


A7-42


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A7-46


A7-47

Casestudy 8 - Model village house at Upalam, Pondicherry

Photos


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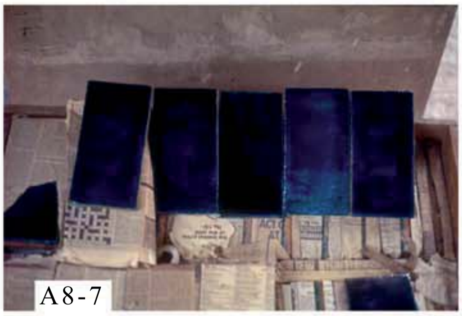
A8-5


A8-6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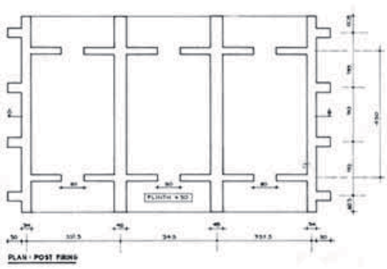
A8-9

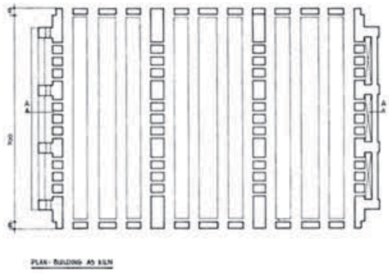
Casestudy 9 - Watchman shed at Hidesign factory, Pondicherry

Project plans & kiln systems

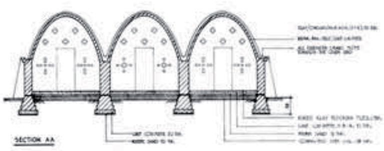
plan 1



plan 2



section 1



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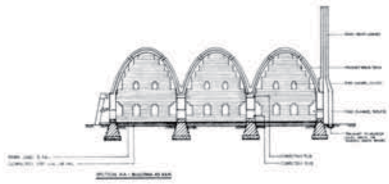
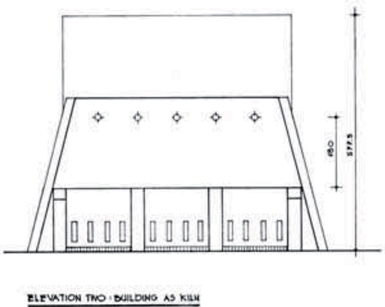
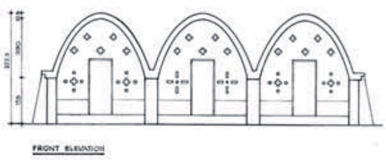


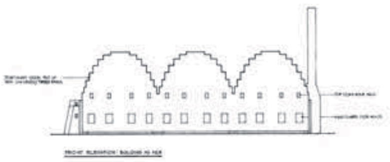
elevation 1



elevation 2



elevation 3



Casestudy 9 - Watchman shed at Hidesign factory, Pondicherry

Photos I


A9-1


A9-2


A9-3


A9-4


A9-5


A9-6


A9-7


A9-8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A9-16

Casestudy 9 - Watchman shed at Hidesign factory, Pondicherry

Photos II


A9-17


A9-18


A9-19


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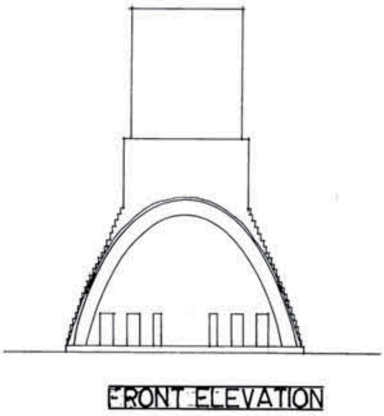
A9-21


A9-22

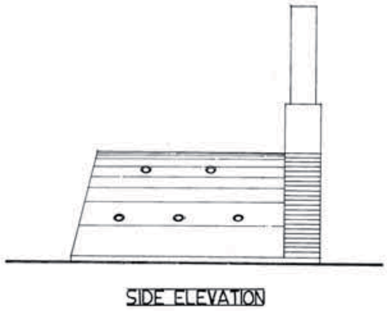
Casestudy 10 - Golden Bridge Pottery Structure 10, Pondicherry

Project plans

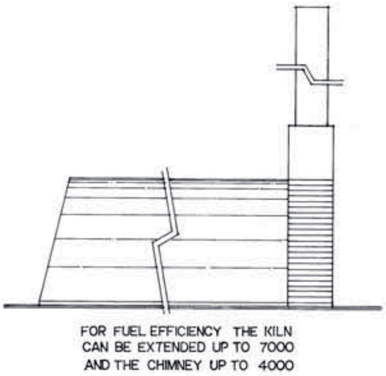
elevation 1



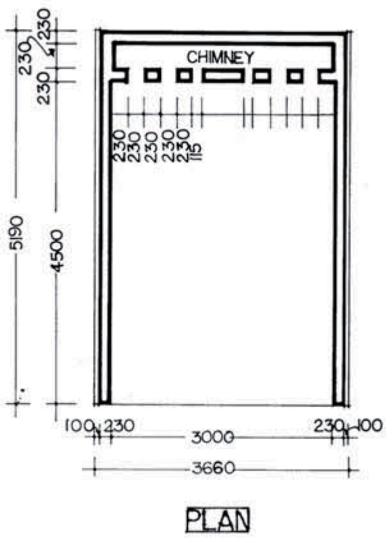
elevation 2



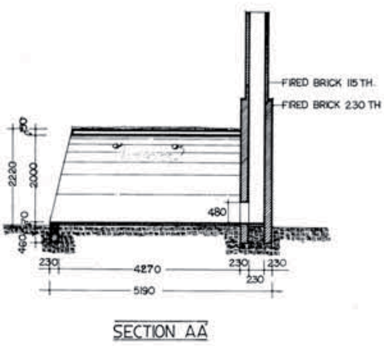
fuel efficiency



plan



section 1



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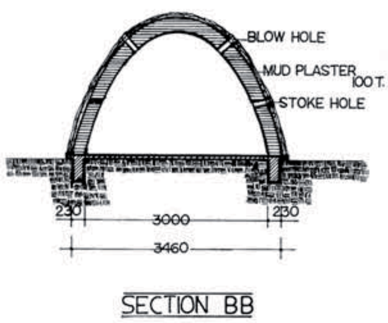
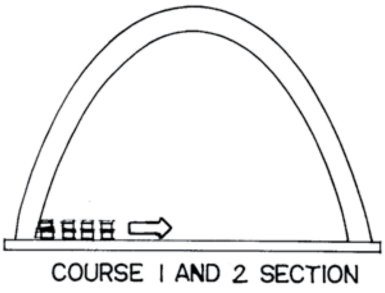


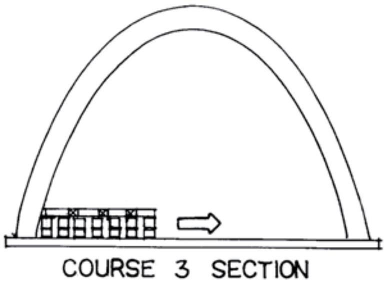
Casestudy 10 - Golden Bridge Pottery Structure 10, Pondicherry

Kiln systems & stacking plans Pg 2

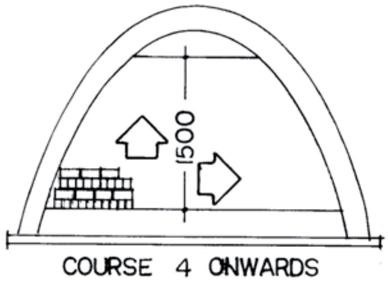
course i, 2



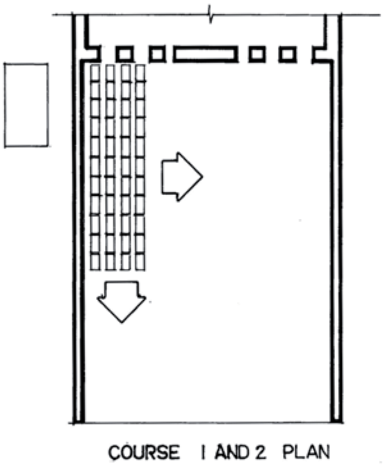
course 3



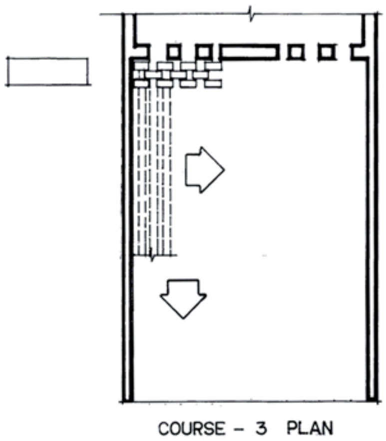
course 4



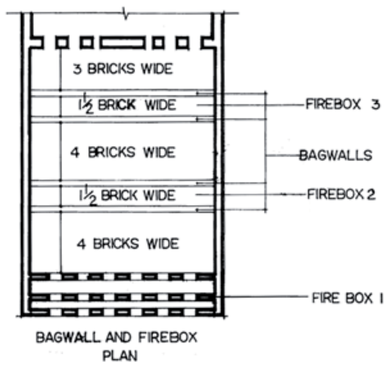
course 1, 2 plan



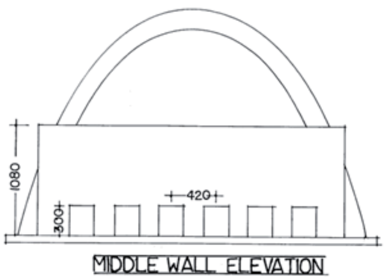
course 3 plan



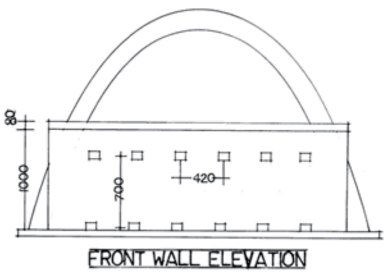
bagwall, firebox plan



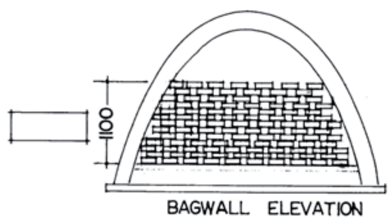
elevation 1



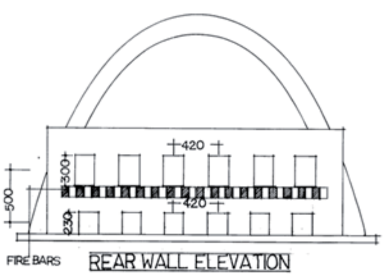
elevation 2



elevation 3



elevation 4



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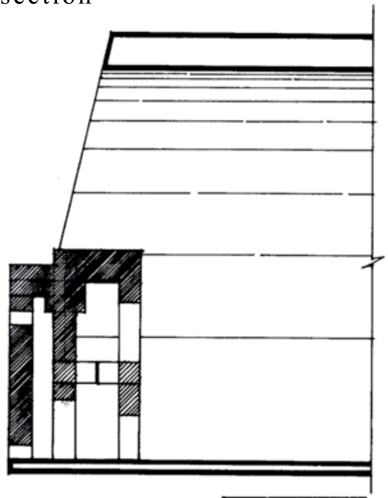

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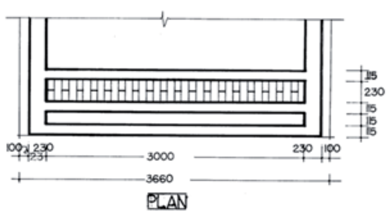


Casestudy 10 - Golden Bridge Pottery Structure 10, Pondicherry

Photos

A10-1

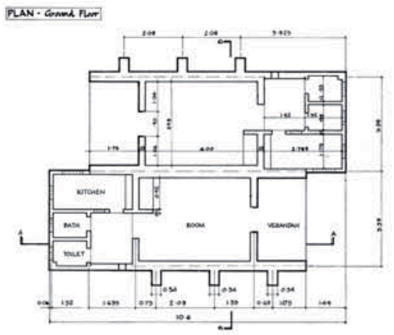
A10-2

A10-3

Casestudy 11 - Visitor's Information and Reception Center, Auroville

Project plans Pg 1

plan



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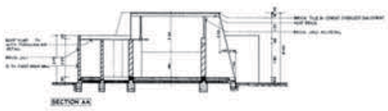
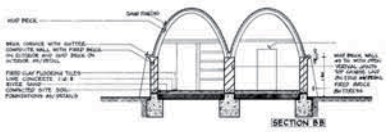
section 2





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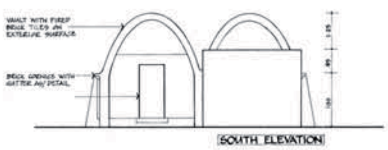
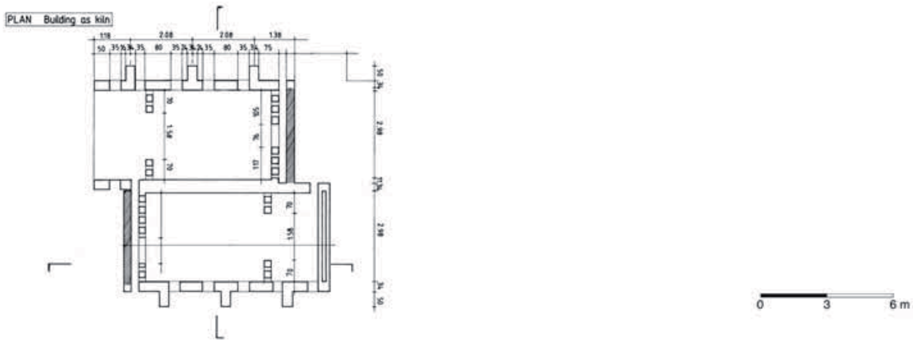
elevation 2



Casestudy 11 - Visitor's Information and Reception Center, Auroville

Kiln systems Pg 2

plan



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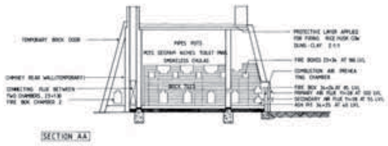

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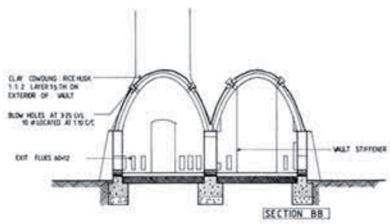

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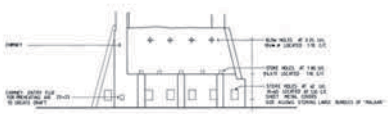
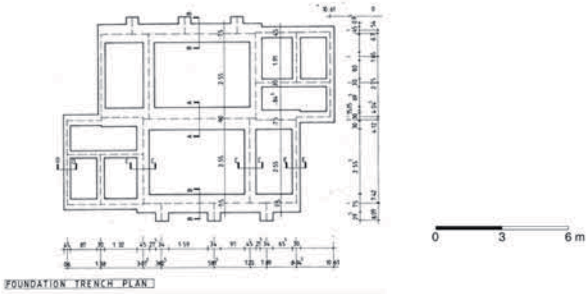


Casestudy 11 - Visitor's Information and Reception Center, Auroville

Foundation plans Pg 3

plan



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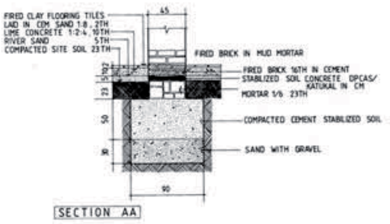

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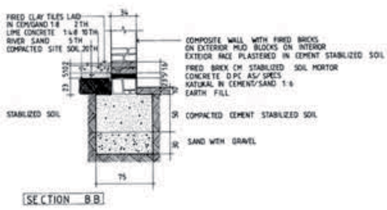

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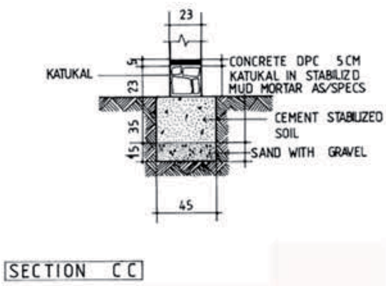

Casestudy 11 - Visitor's Information and Reception Center, Auroville

Photos


A11-1


A11-2


A11-3


A11-4


A11-5


A11-6


A11-7


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A11-9

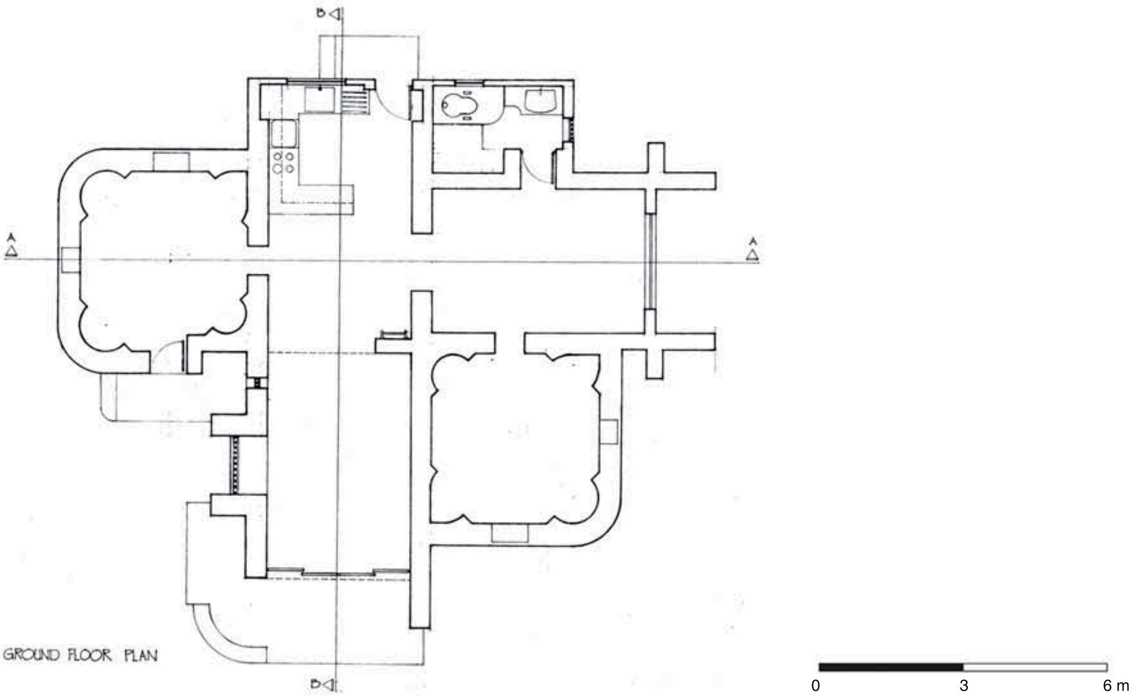

A11-10


A11-11

Casestudy 12 - Satyajit's House, Auroville

Project plans Pg 1

plan



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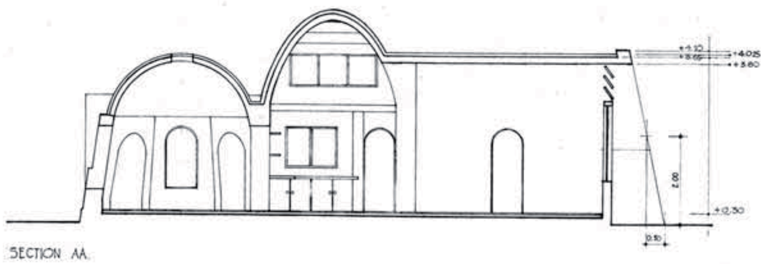

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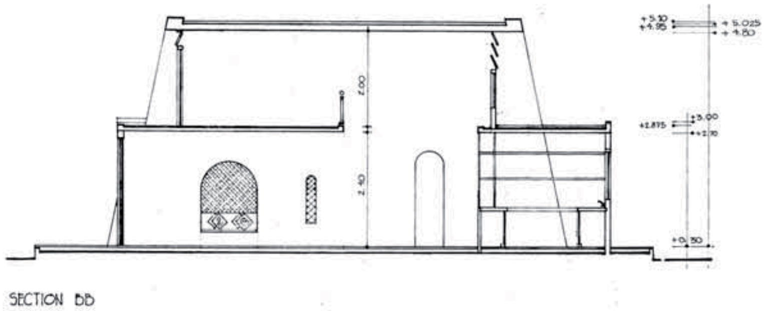
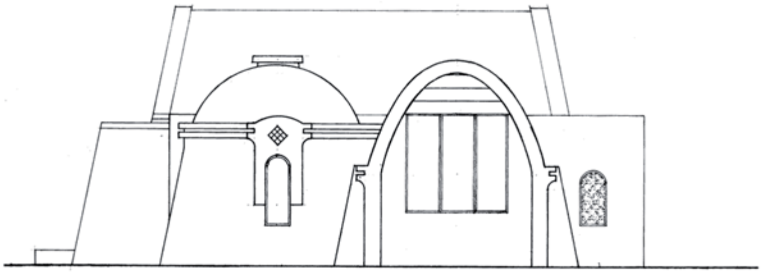


Casestudy 12 - Satyajit's House, Auroville

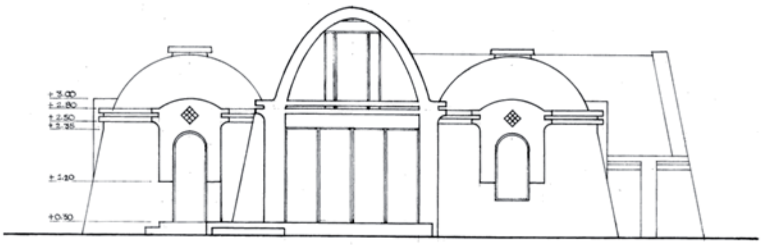
Project plans Pg 2

elevation 1



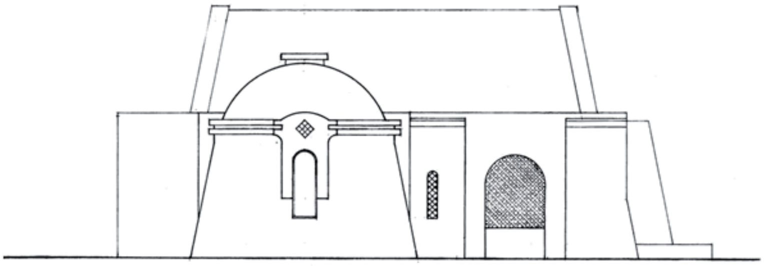
NORTH ELEVATION

elevation 2



EAST ELEVATION

elevation 3

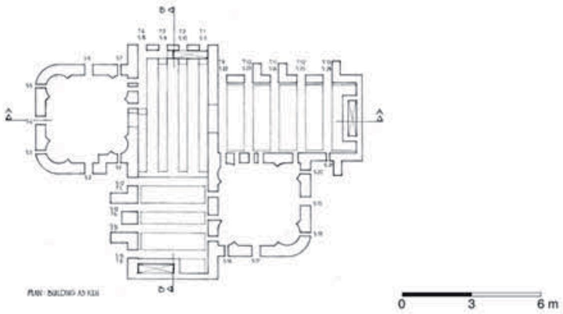


SOUTH ELEVATION

Casestudy 12 - Satyajit's House, Auroville

Kiln systems Pg 3

plan



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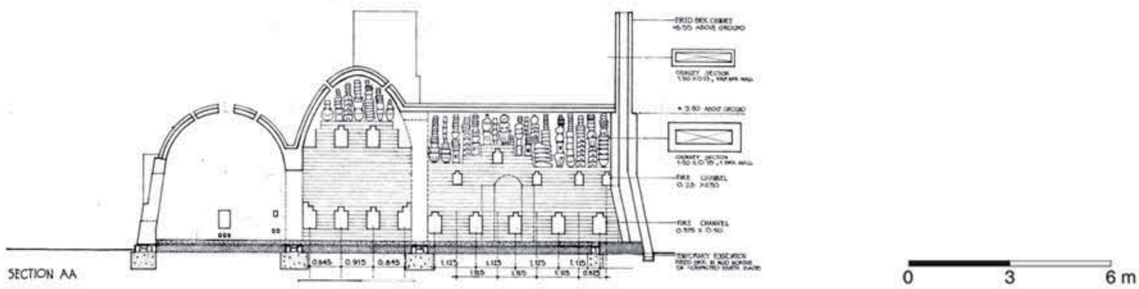

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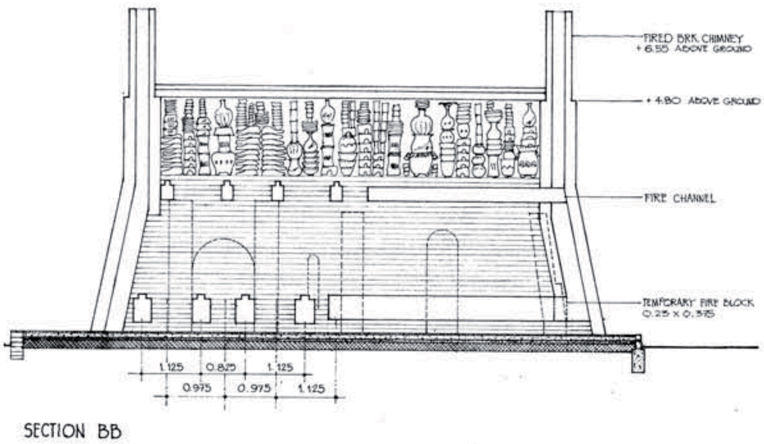
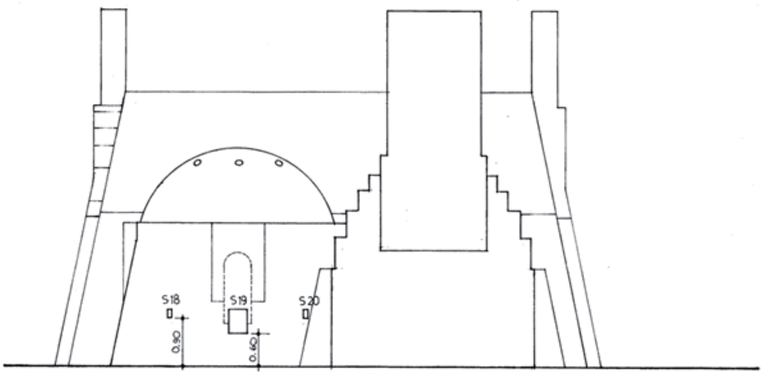


Casestudy 12 - Satyajit's House, Auroville

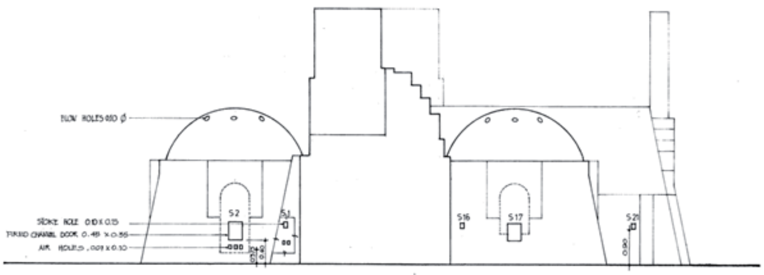
Kiln systems Pg 4

elevation 1



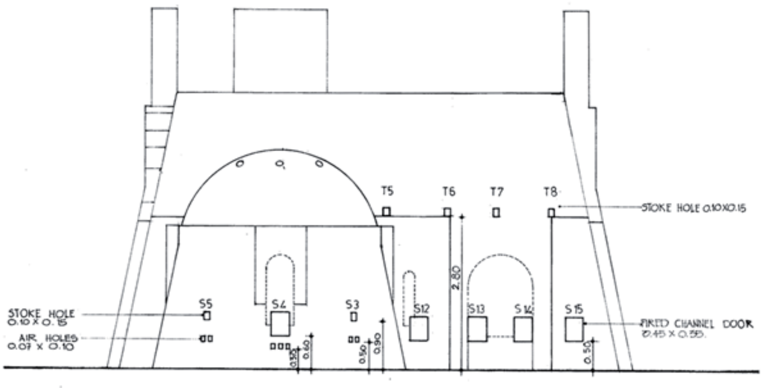
NORTH ELEVATION

elevation 2



EAST ELEVATION

elevation 3



SOUTH ELEVATION

Casestudy 12 - Satyajit's House, Auroville

Photos


A12-1


A12-2


A12-3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A12-9


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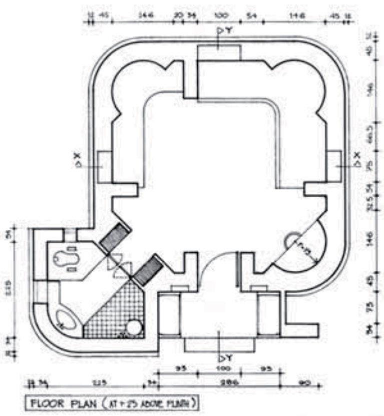
A12-11

Casestudy 13 - Marta's House, Kottakarai

Project Drawings Pg 1

plan



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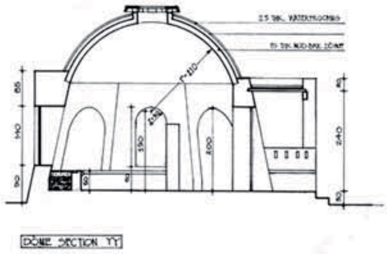

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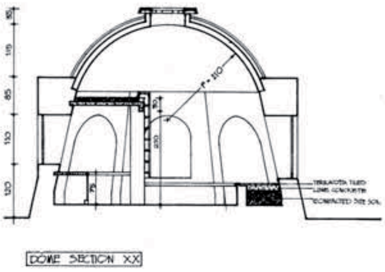

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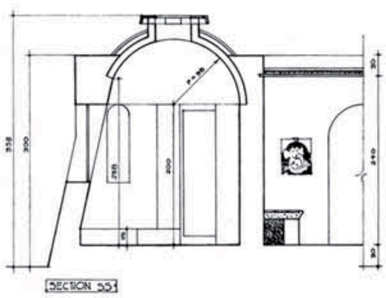

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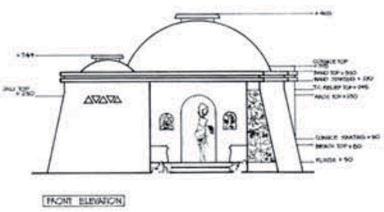
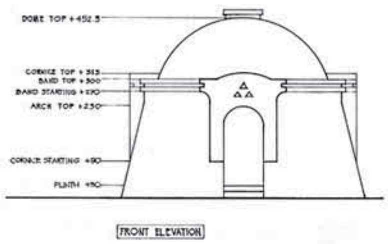


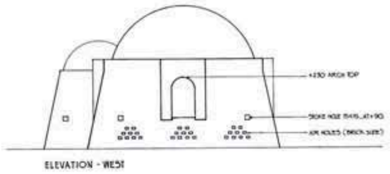
elevation 2



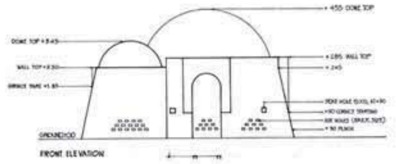
Casestudy 13 - Marta's House, Kottakarai

Kiln Systems Pg 2

elevation 1



elevation 2



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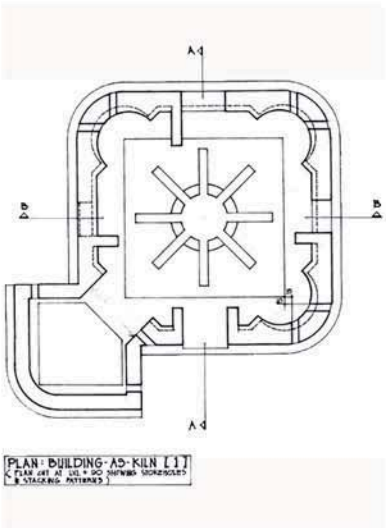

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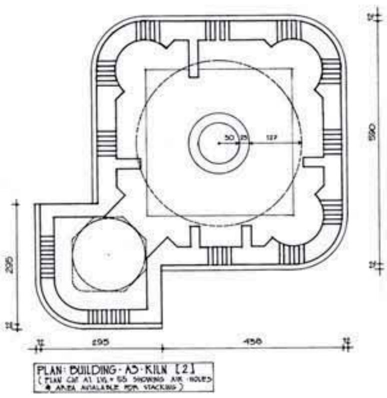

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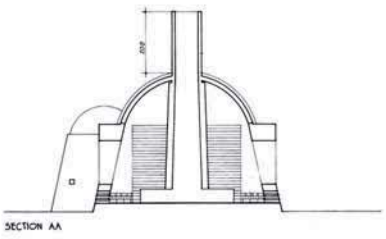

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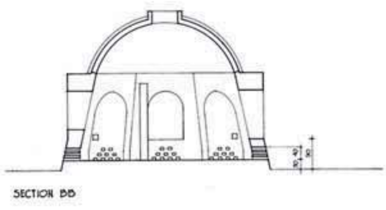
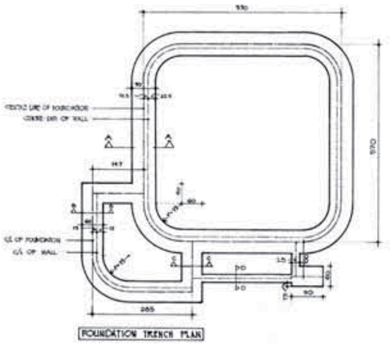


Casestudy 13 - Marta's House, Kottakarai

Details Pg 3

plan



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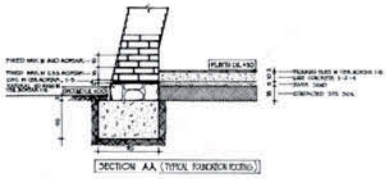

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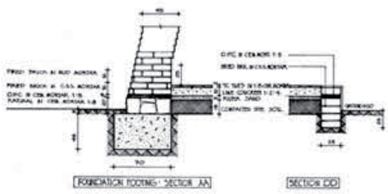
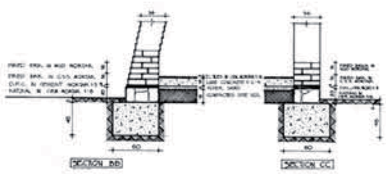


section 3, section 4



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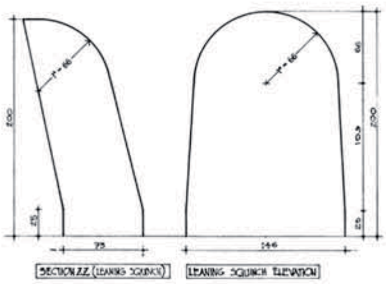
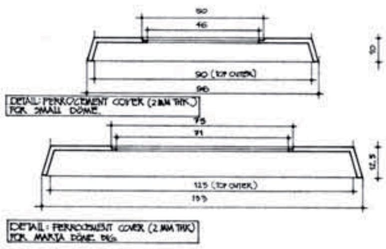
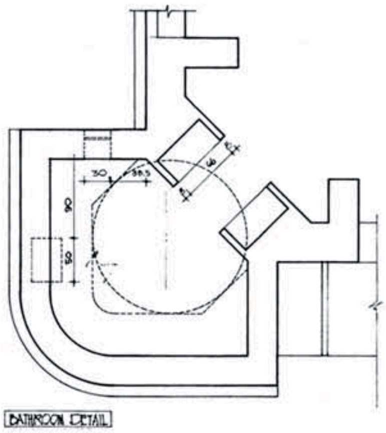


ferrocement cover



bathroom



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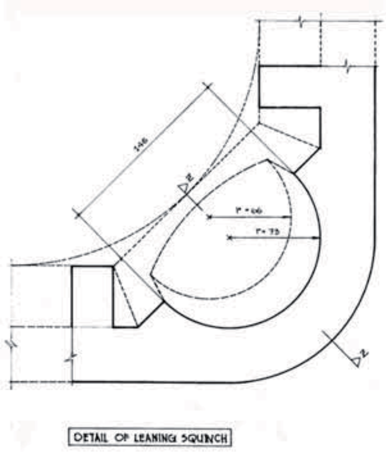

Casestudy 13 - Marta's House, Kottakarai

Photos


A13-1


A13-2


A13-3


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A13-5


A13-6


A13-7


A13-8


A13-9

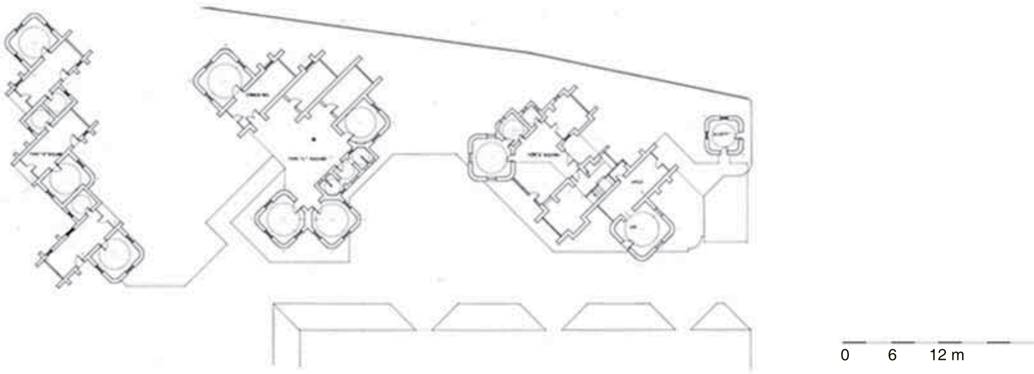

A13-10


A13-11

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Site Plan A B C D Pg 1

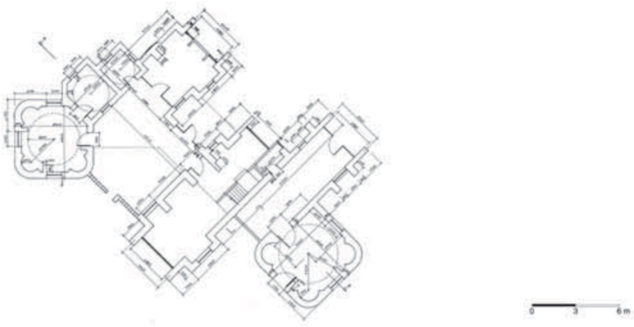
plan



Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

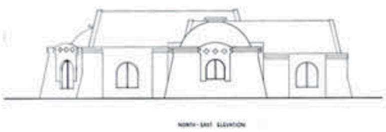
Project plans A Pg 2

plan



section 1

elevation 1

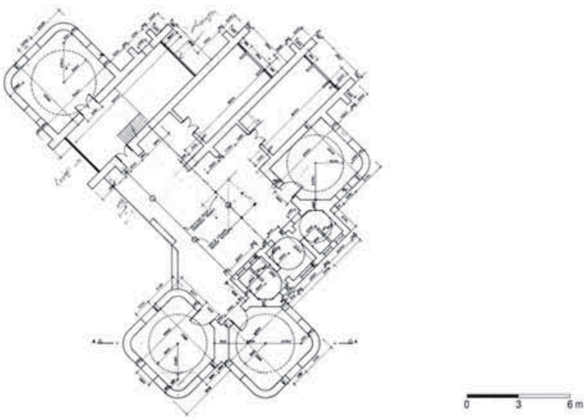


elevation 2

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Project plans B Pg 37

plan



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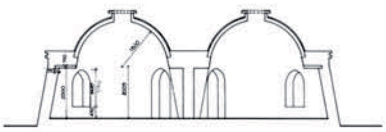
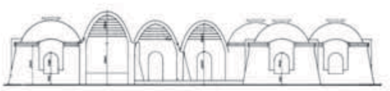


SECTION AA

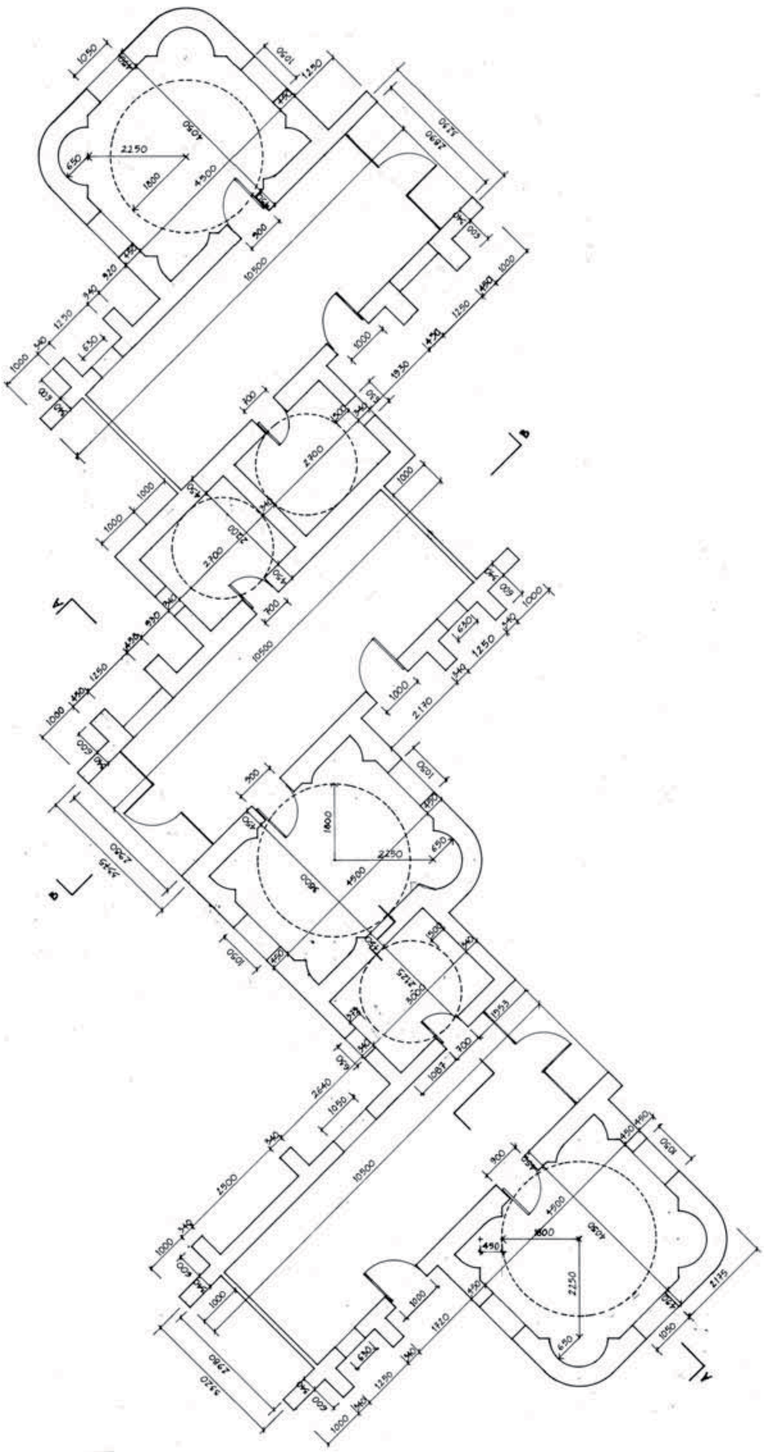
elevation



Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Project plans C Pg 4

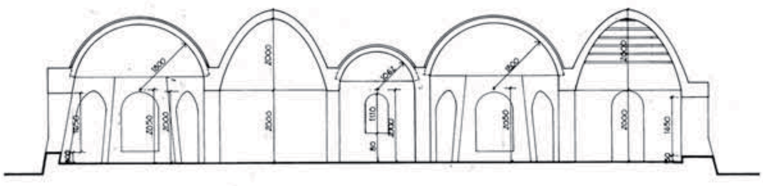
plan



Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Project plans C Pg 5

section 1



SECTION AA

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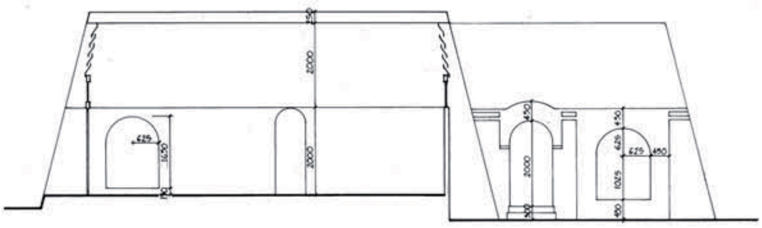

SECTION BB

0 3 6 m

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Kiln systems A Pg 6

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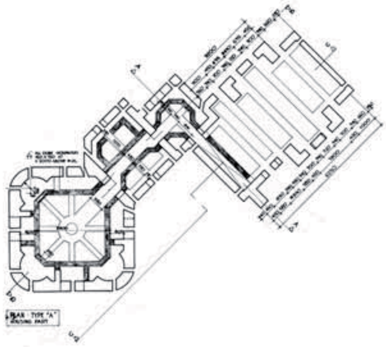

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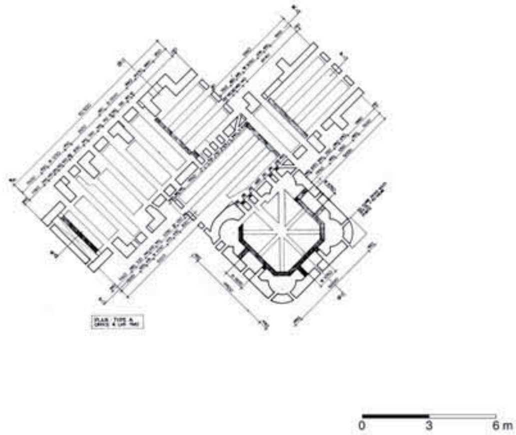

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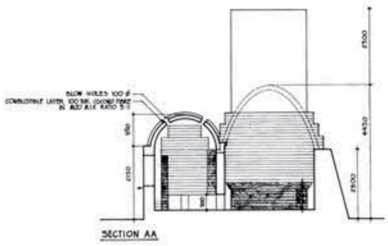

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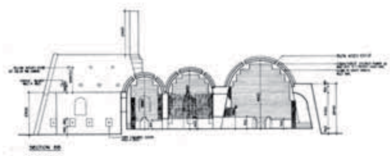

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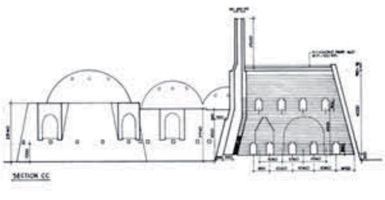

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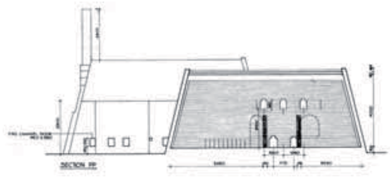

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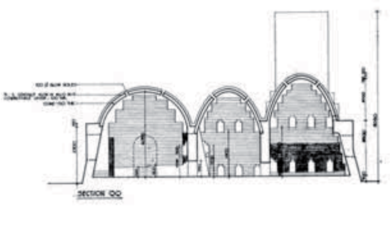

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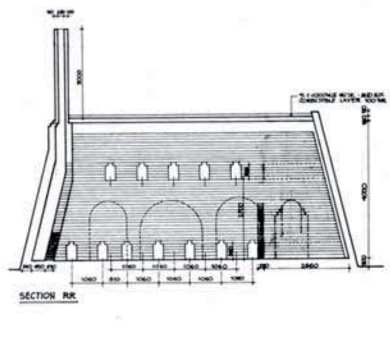
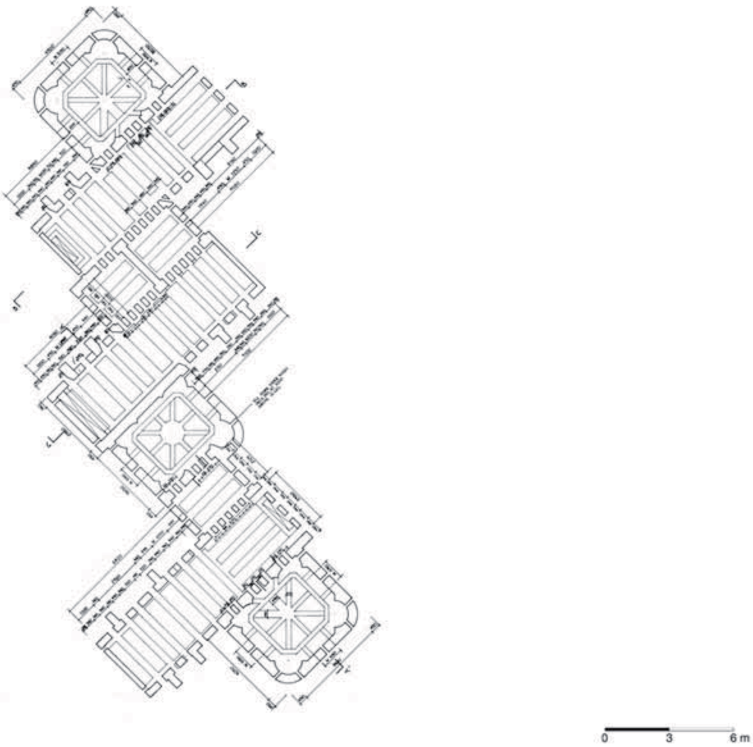


Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Kiln systems C Pg 7

plan



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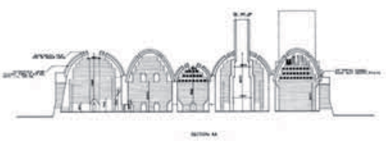

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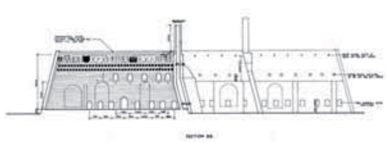

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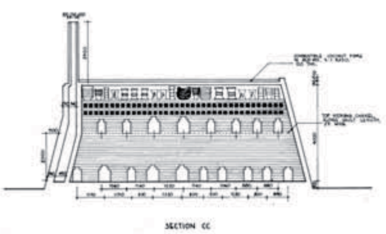
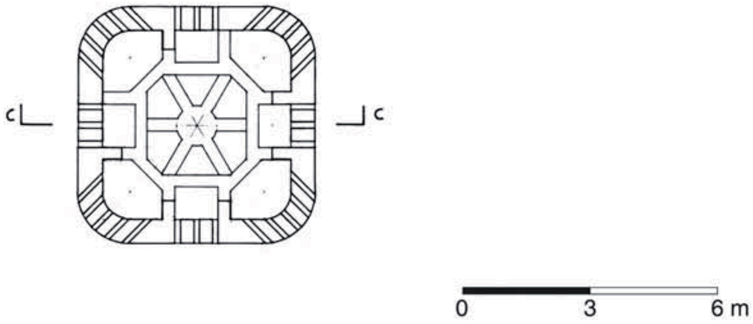


Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Kiln systems D Pg 8

plan



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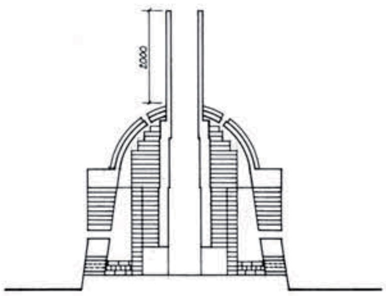

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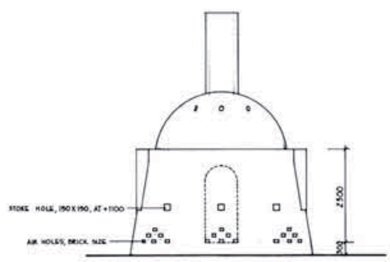
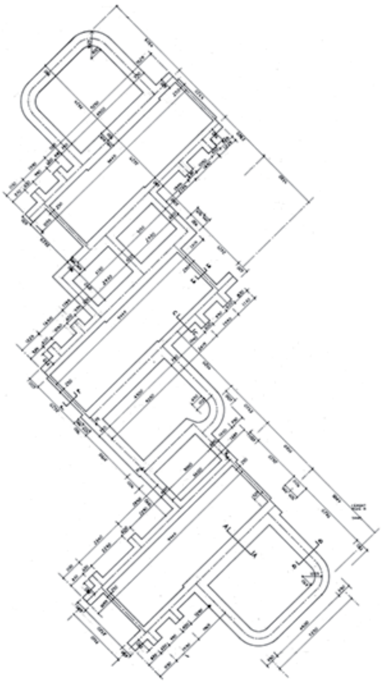


Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Foundation plans C Pg 9

plan



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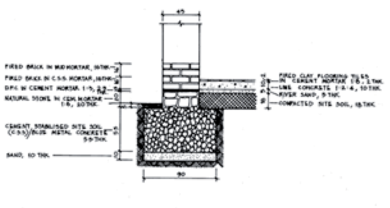

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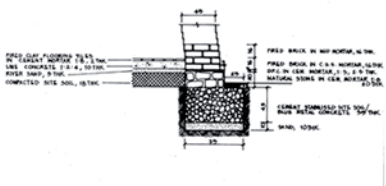
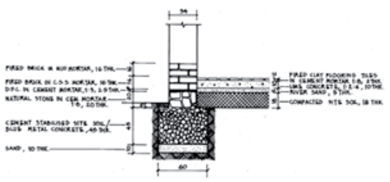


SECTION BB

section 3

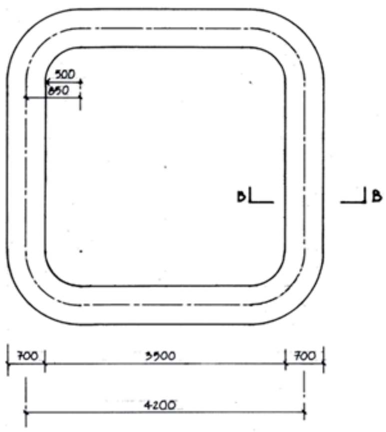


SECTION CC

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Foundation plans D Pg 10

plan 1



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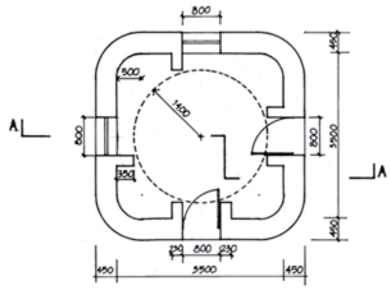

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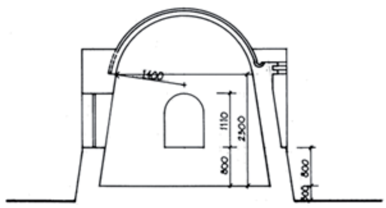

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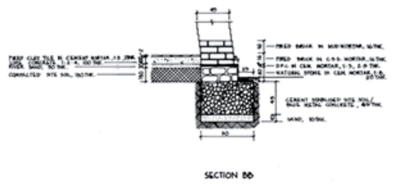
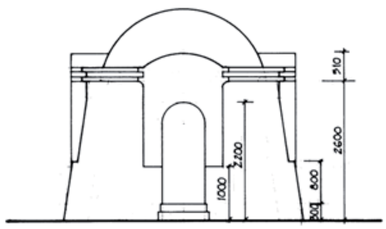


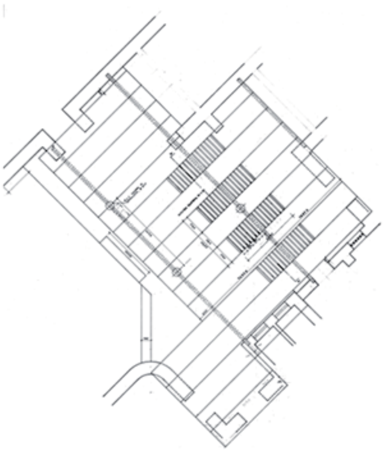
elevation



Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Details Pg 11

plan 1



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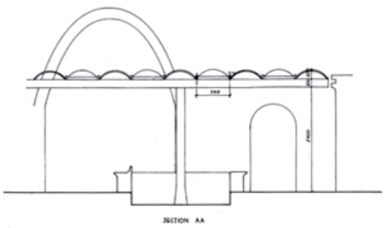

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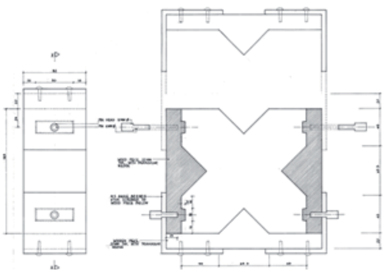

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Photos I


A14-1


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A14-15


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A14-17


A14-18

Casestudy 14 - Housing Project for Minolta Aquatech, Tuticorin

Photos II


A14-19


A14-20


A14-21

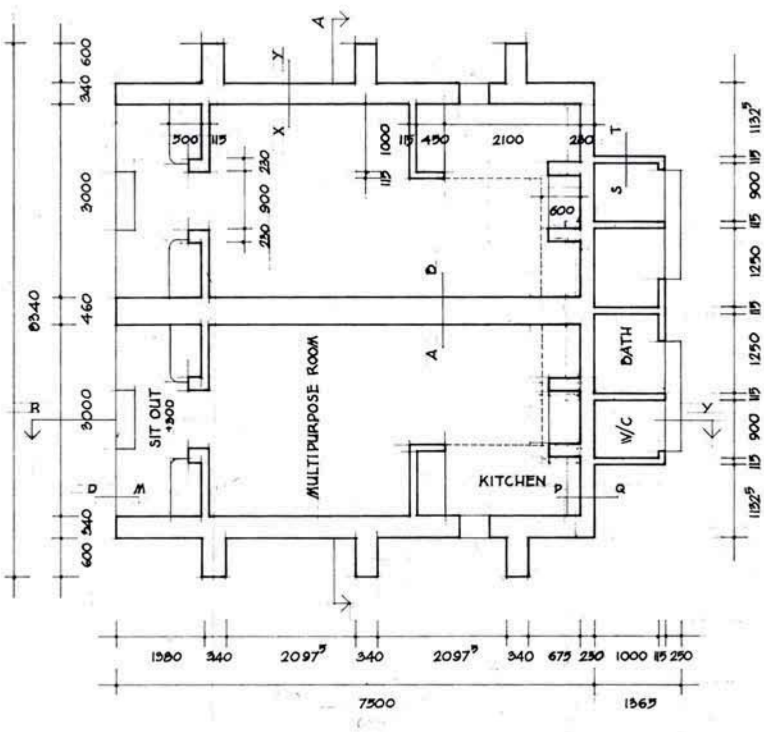

A14-22


A14-23

Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

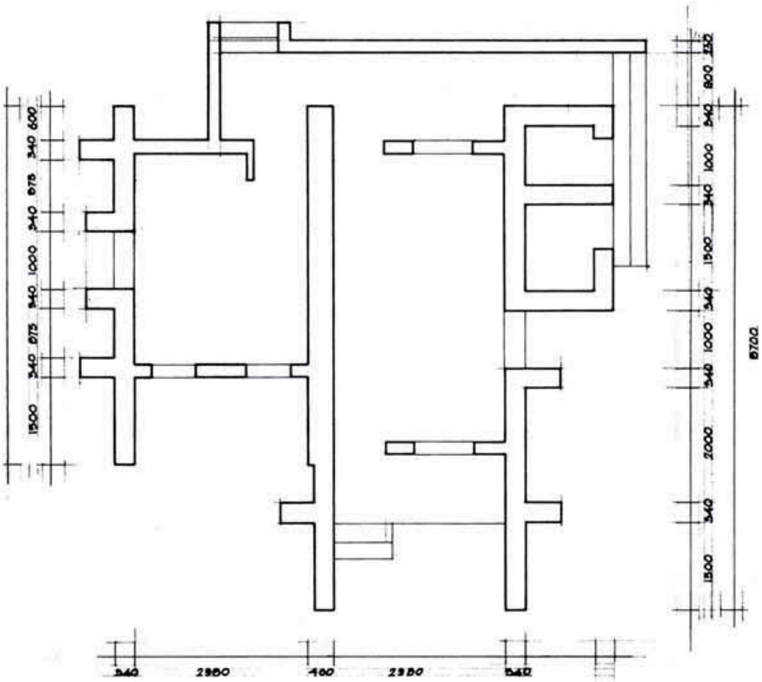
Project plans Pg 1

plan 1



PLAN

plan 2

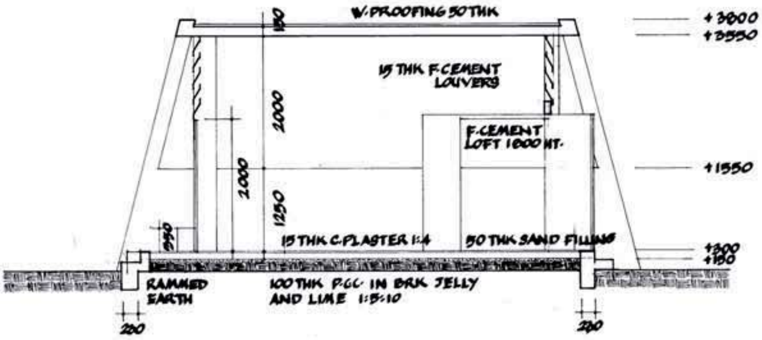


PLAN
FIRED STRUCTURE

Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

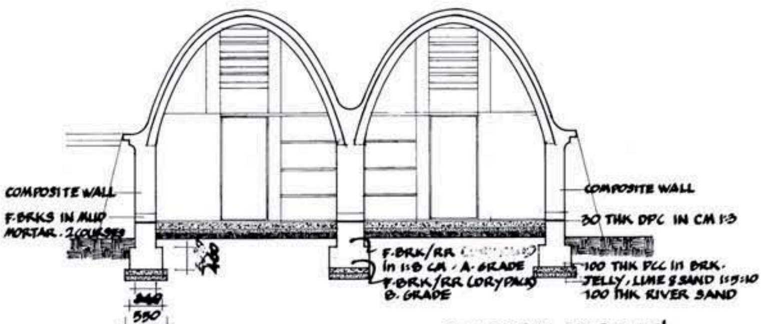
Project plans Pg 2

section 1



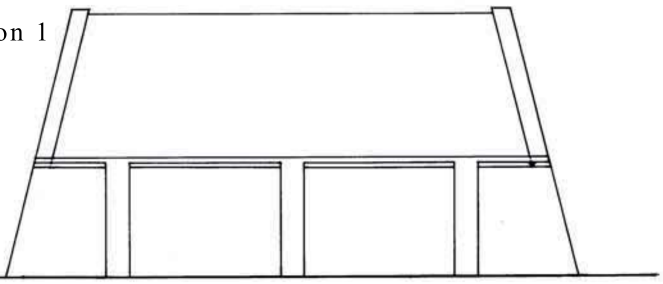
SECTION THRO AA'

section 2



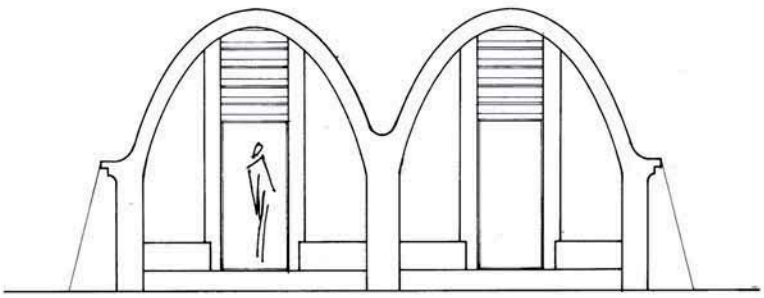
SECTION THRO BB'

elevation 1



SIDE ELEVATION

elevation 2

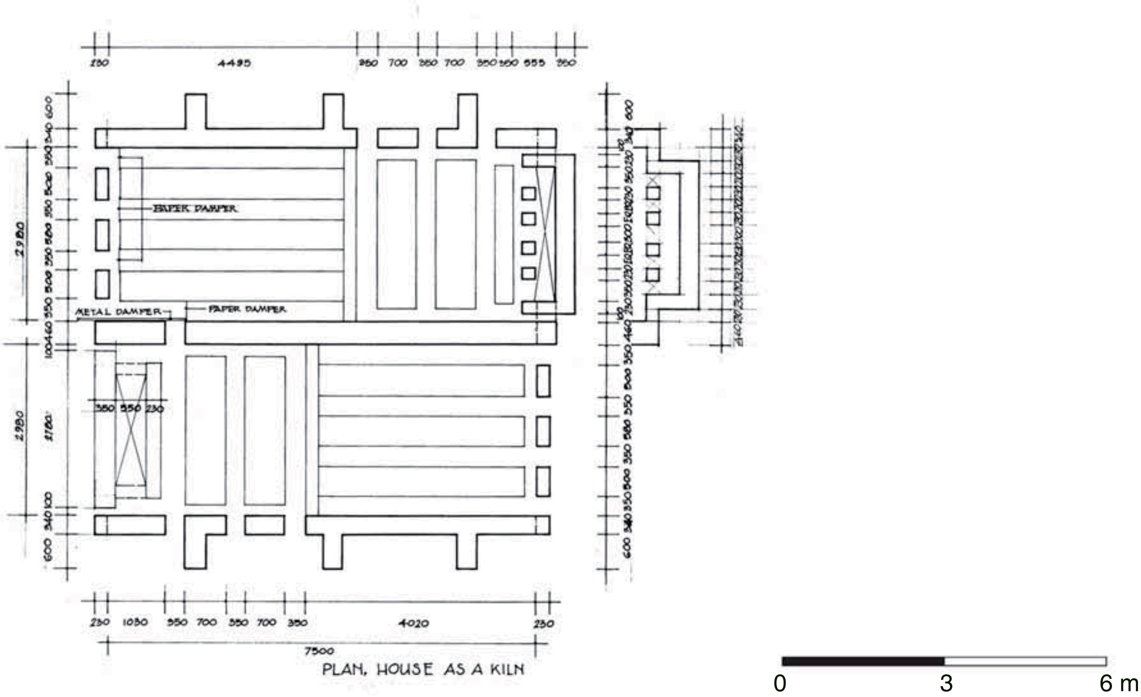


FRONT ELEVATION

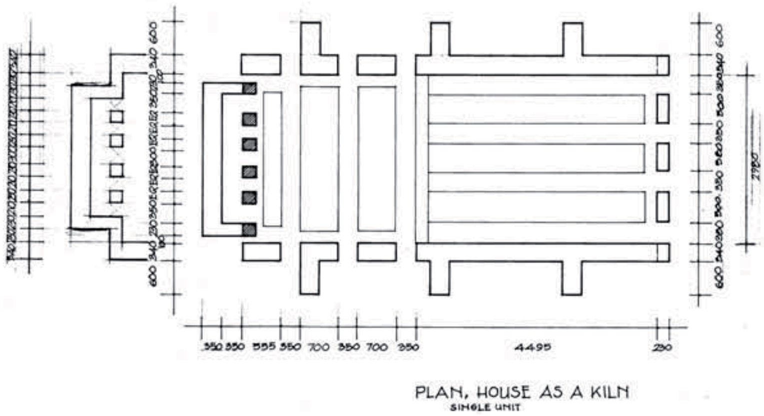
Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

Kiln systems Pg 3

plan 1



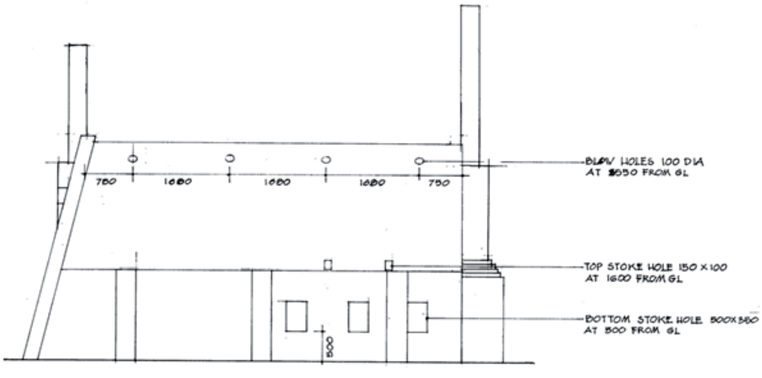
plan 2



Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

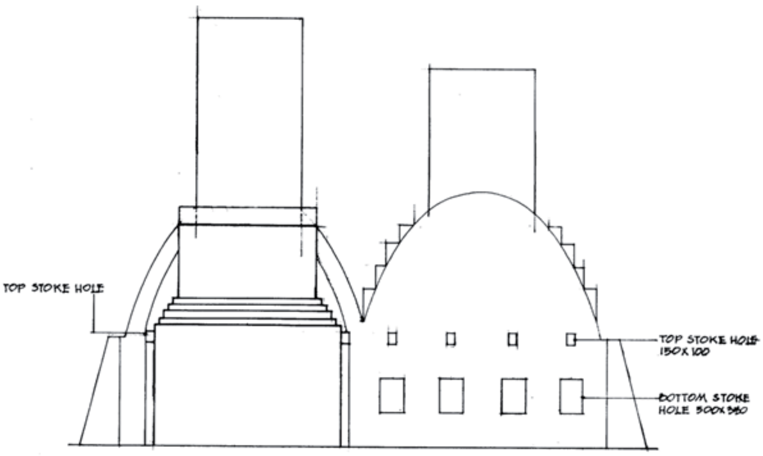
Kiln systems Pg 4

elevation 1



ELEVATION

elevation 2

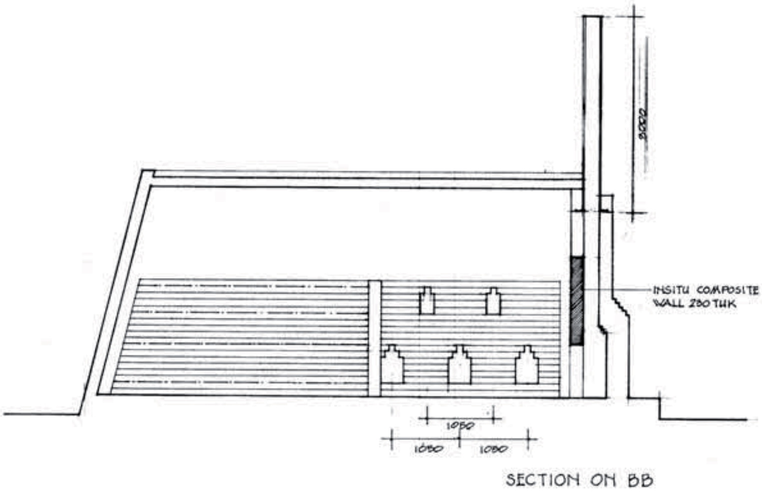


ELEVATION

Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

Kiln systems Pg 5

section 1



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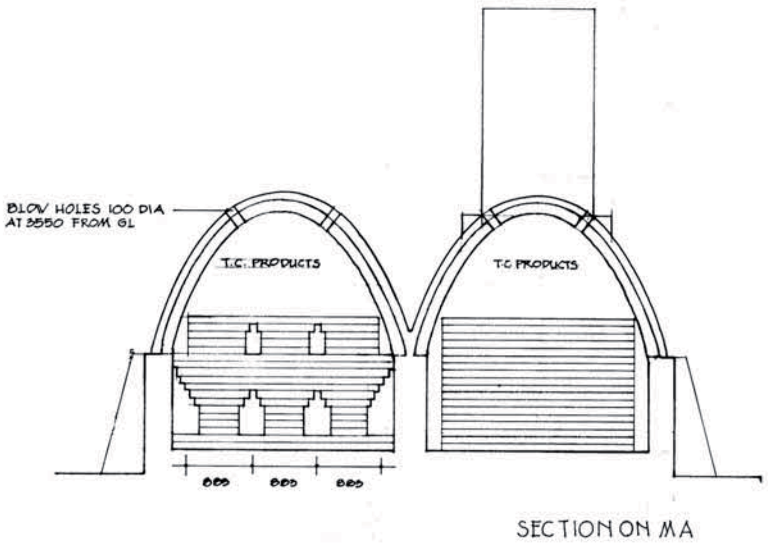

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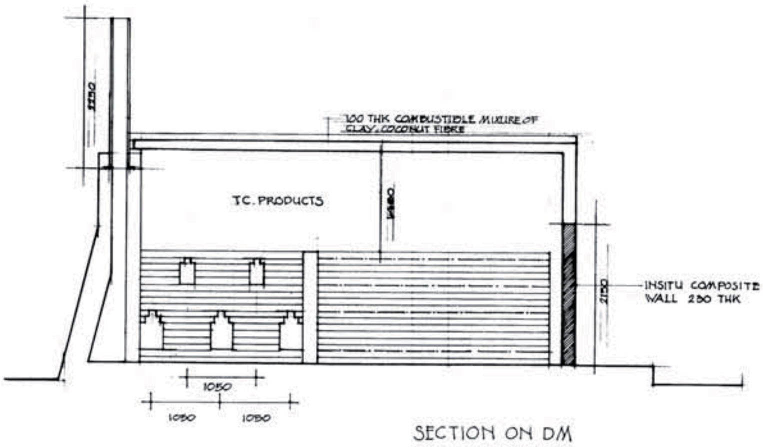

Casestudy 15 - Low cost housing, Ayothiapattinam, Salem

Photos


A15-1


A15-2


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A15-5


A15-6


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A15-8

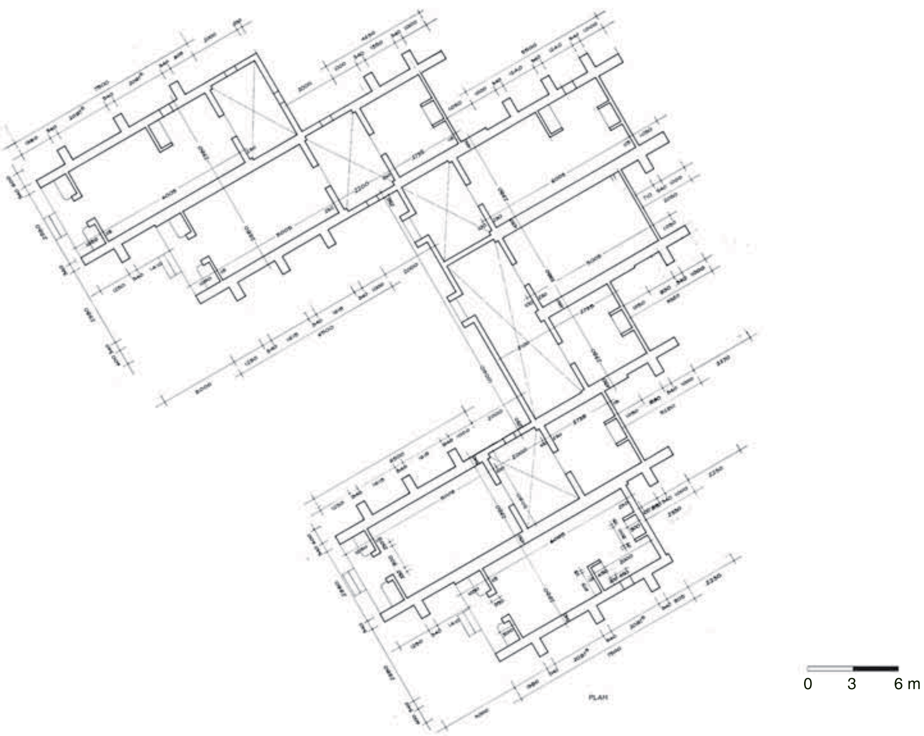

A15-9


A15-10

Casestudy 16 - Volontariat Farm Housing, Pondicherry

Project plans Pg 1

plan



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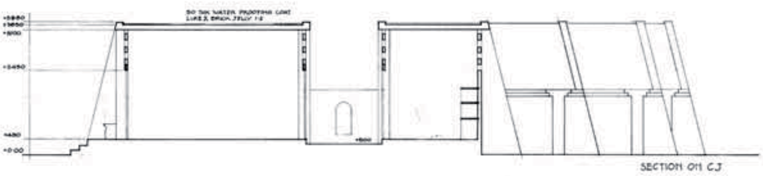

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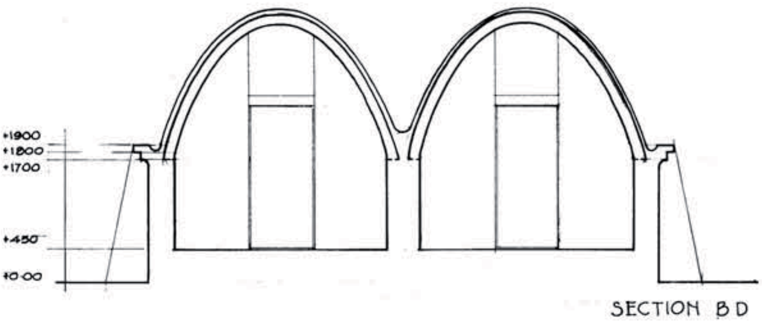
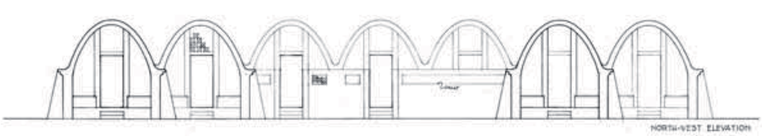


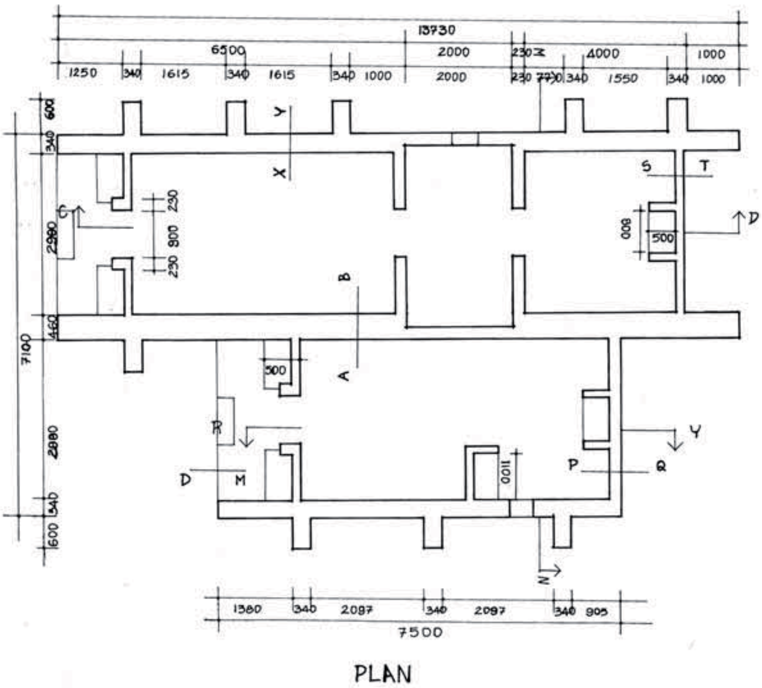
elevation



Casestudy 16 - Volontariat Farm Housing, Pondicherry

Project plans Pg 2

plan



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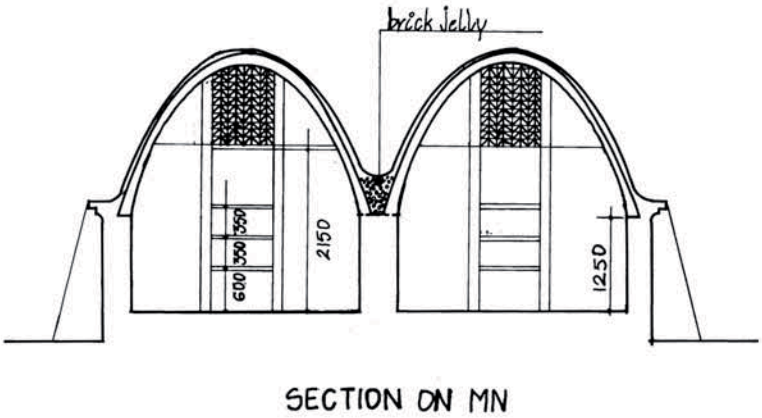

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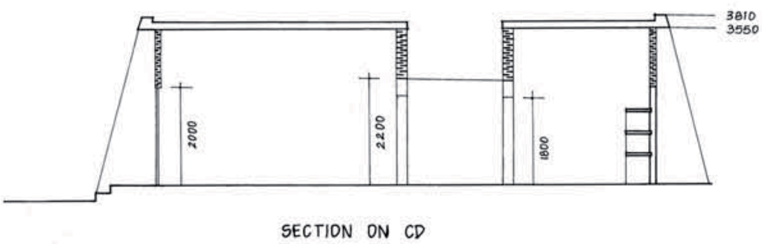
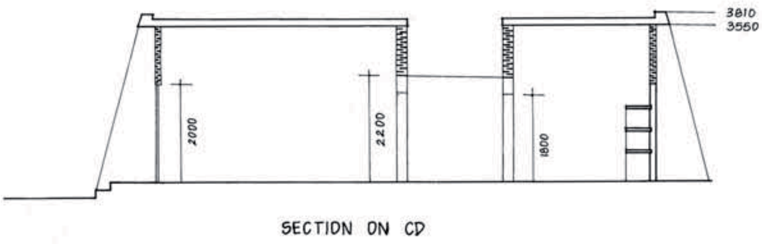


Casestudy 16 - Volontariat Farm Housing, Pondicherry

Project plans Pg 3

section 3



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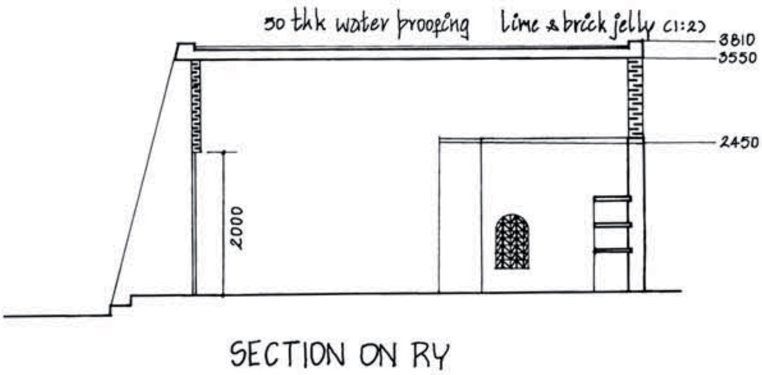

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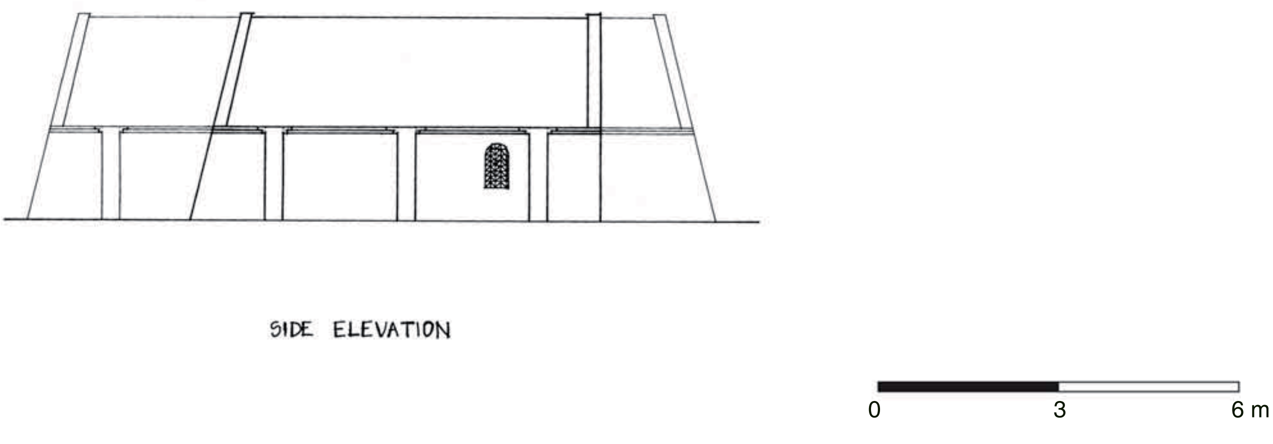
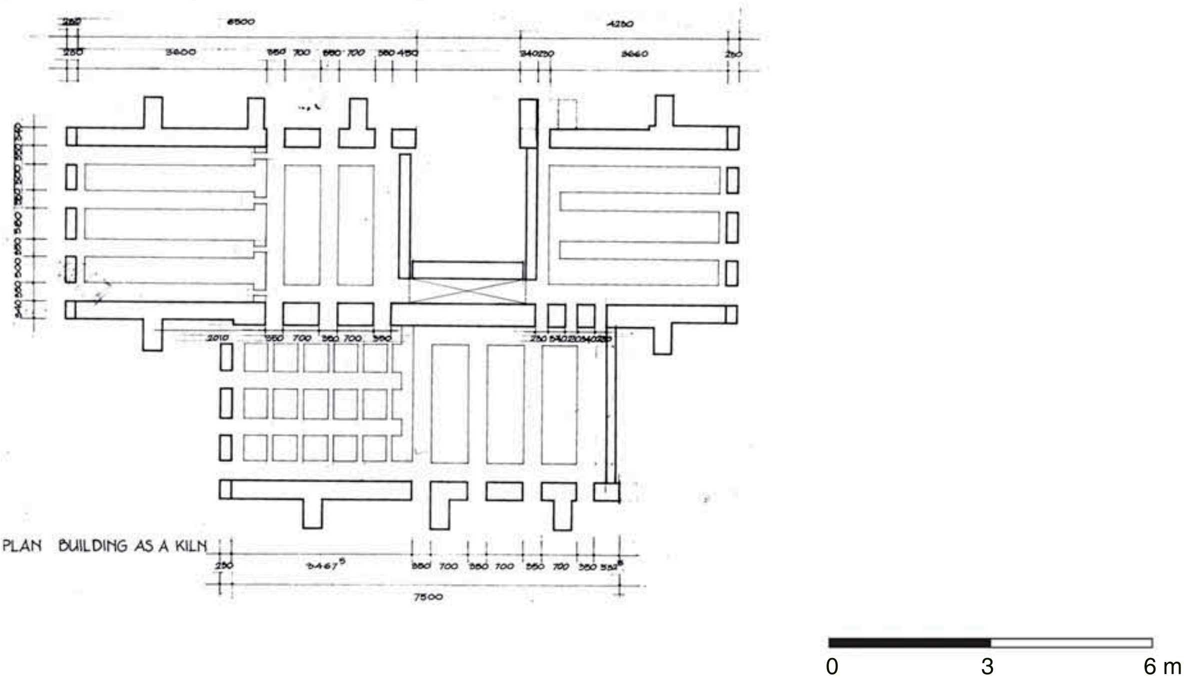


Casestudy 16 - Volontariat Farm Housing, Pondicherry

Kiln systems Pg 4

plan



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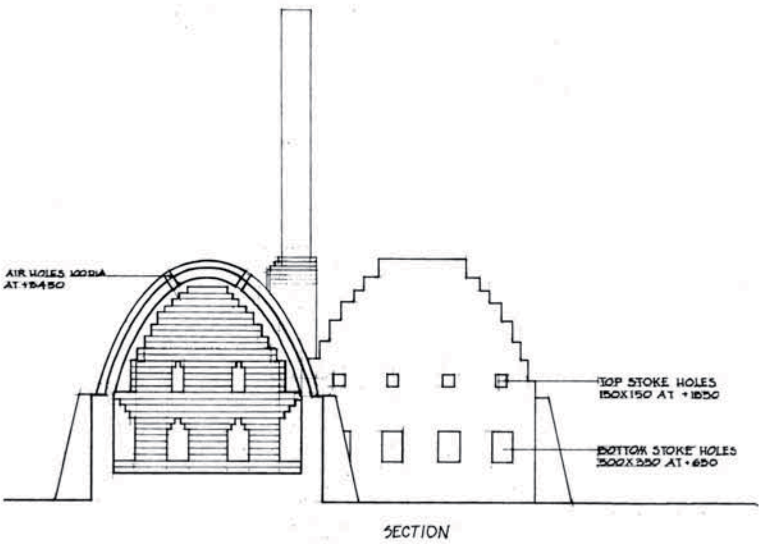
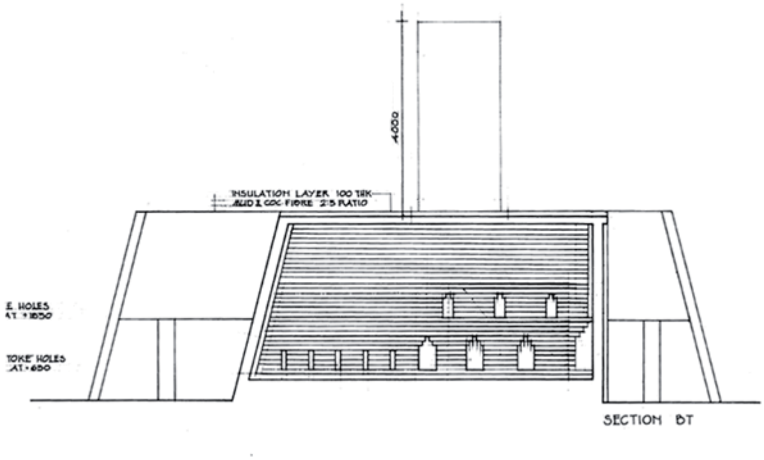


Casestudy 16 - Volontariat Farm Housing, Pondicherry

Kiln systems Pg 5

section 2



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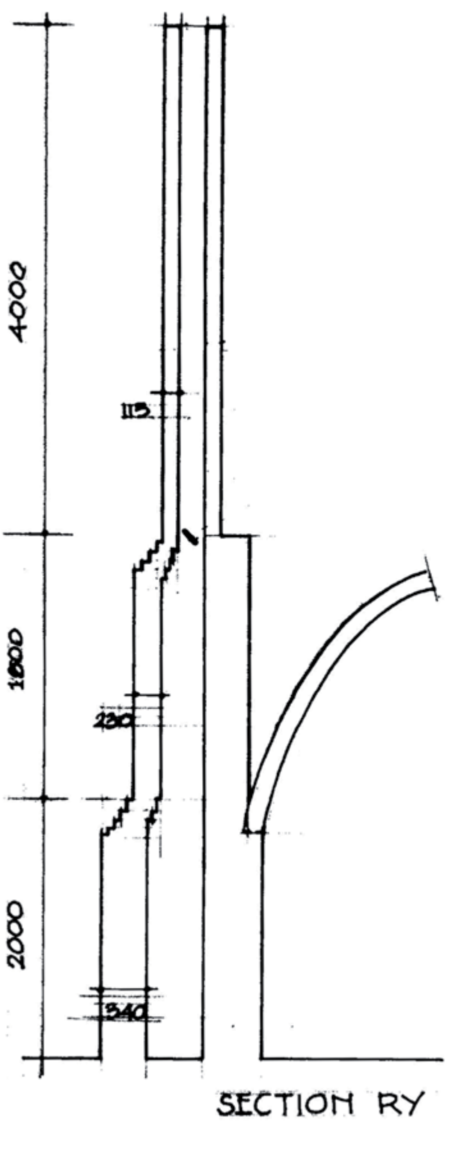

Casestudy 16 - Voluntariat Farm Housing, Pondicherry

Photos


A16-1


A16-2


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A16-4

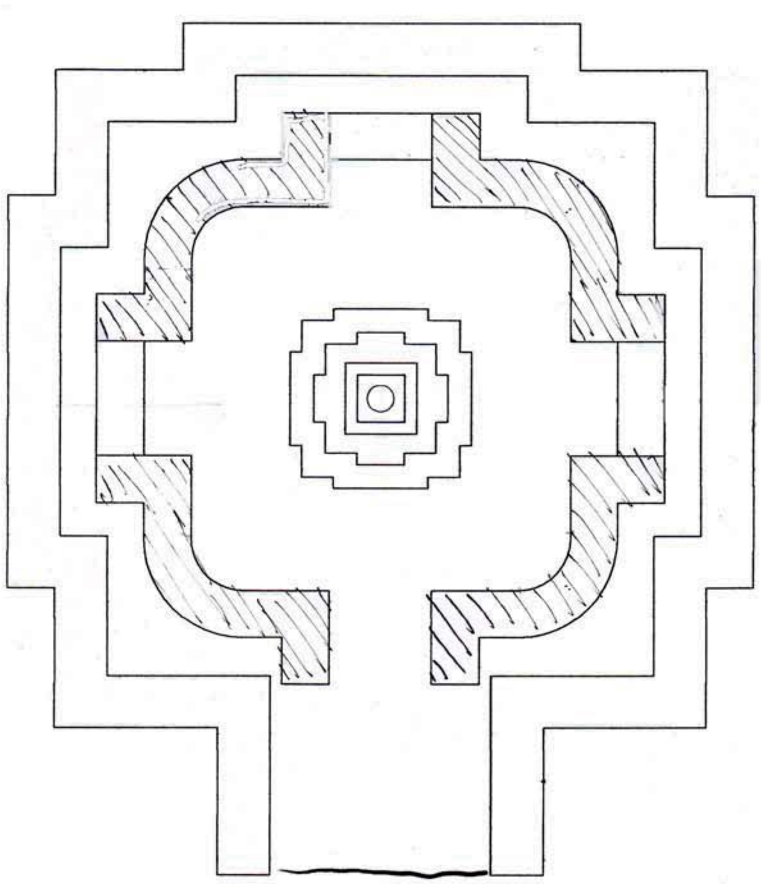

A16-5


A16-6

Casestudy 18 - Temple in Nrityagram Dance Village, Hessaraghada

Project plans Pg 1

plan



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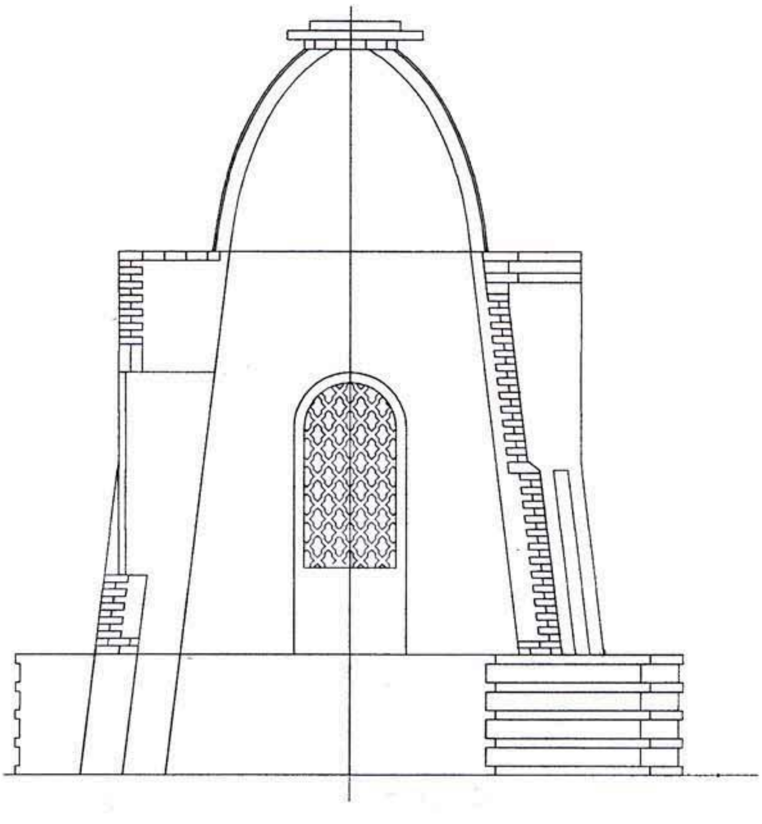
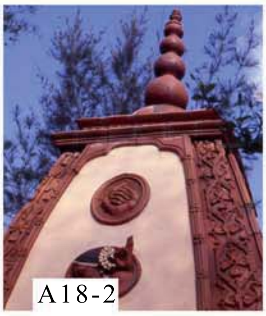


Casestudy 18 - Temple in Nrityagram, Dance Village, Hessaraghatta, near Bangalore

Photos


A18-1


A18-2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A18-4


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A18-6

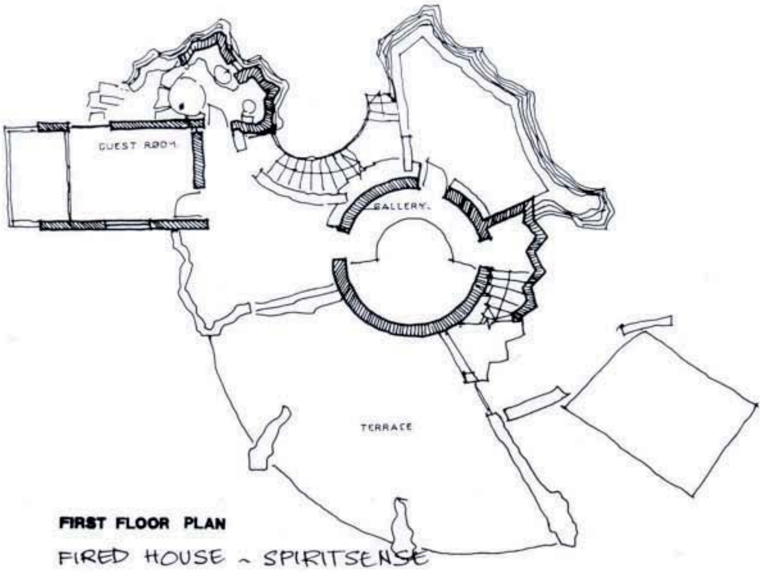

A18-7


A18-8

Casestudy 19 - Bina Saxena's residence, Bomnayarpalayam, near Auroville

Project plans Pg 1

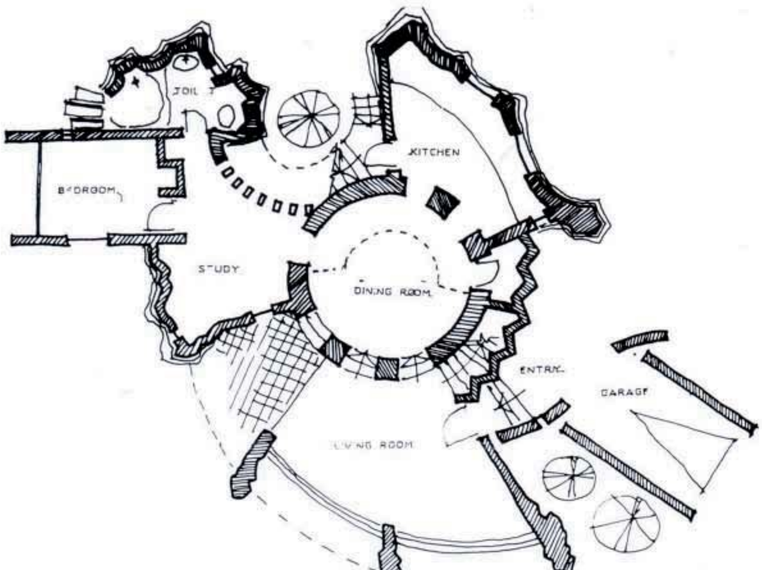
plan 1



FIRST FLOOR PLAN

FIRED HOUSE ~ SPIRITSENSE

plan 2

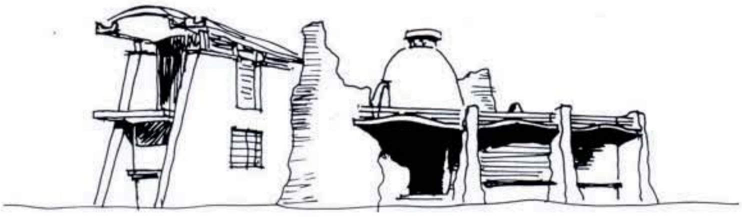


GROUND FLOOR PLAN

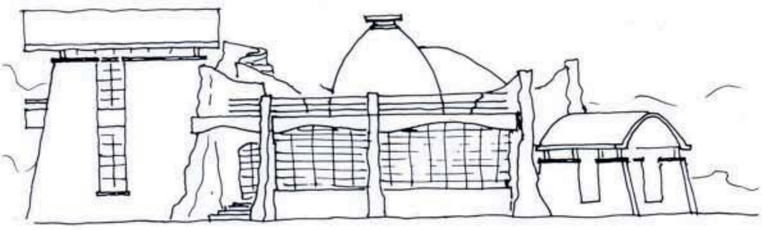
Casestudy 19 - Bina Saxena's residence, Bomnayarpalayam, near Auroville

Project plans Pg 2

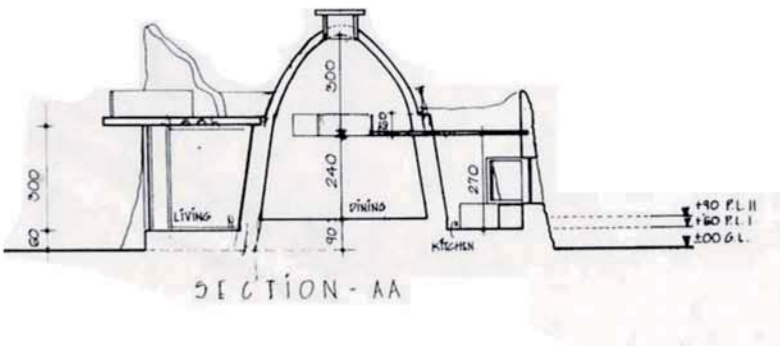
elevation 1



elevation 2

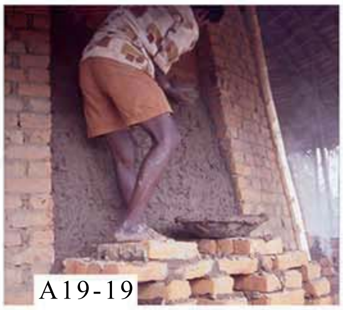


section



Casestudy 19 - Bina Saxena's Residence, Bomnayarpalayam, near Auroville

Photos II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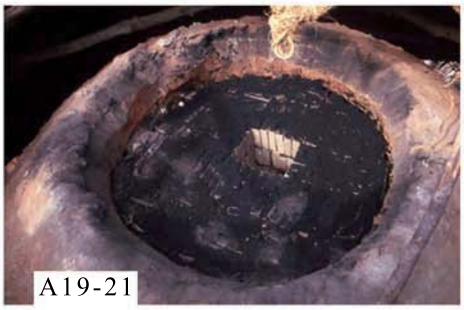
A19-20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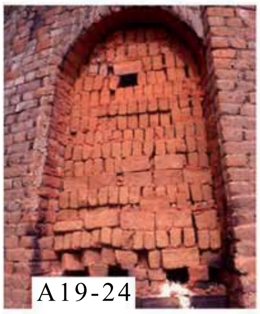
A19-22


A19-23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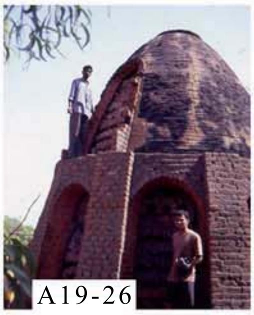
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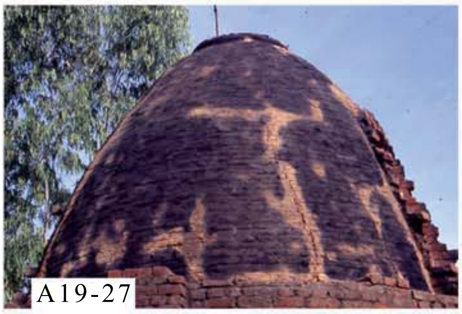
A19-27


A19-28


A19-29


A19-30

Casestudy 19 - Bina Saxena's Residence, Bomnayarpalayam, near Auroville

Photos I


A19-1


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A19-6


A19-7


A19-8


A19-9

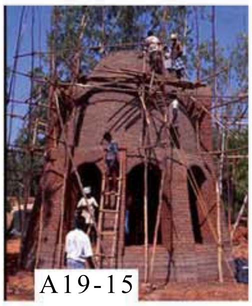

A19-10


A19-11


A19-12


A19-13


A19-14


A19-15


A19-16

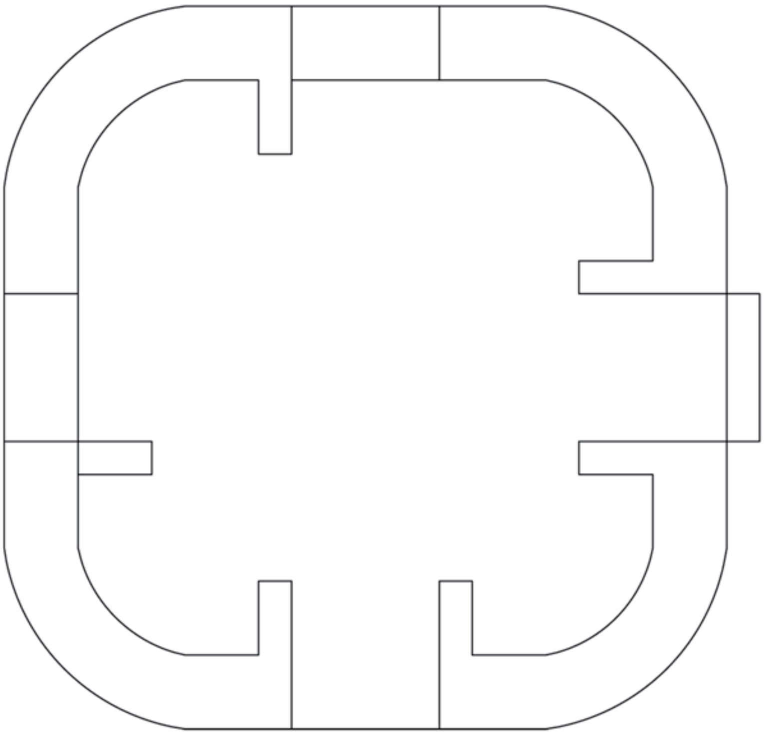

A19-17


A19-18

Casestudy 20 - Bina Saxena's Pottery, Bomnayarpalayam, near Auroville

Project plans Pg 1

plan



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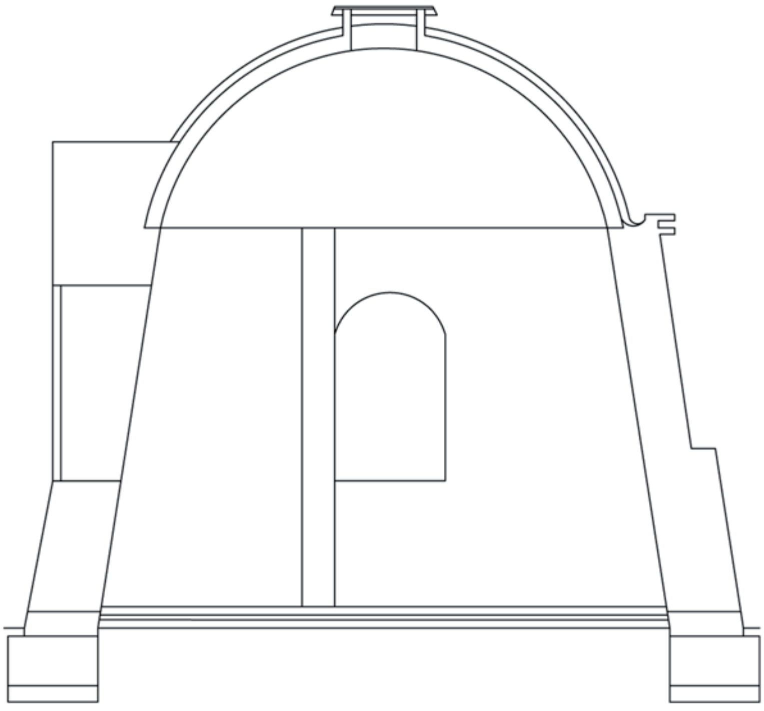
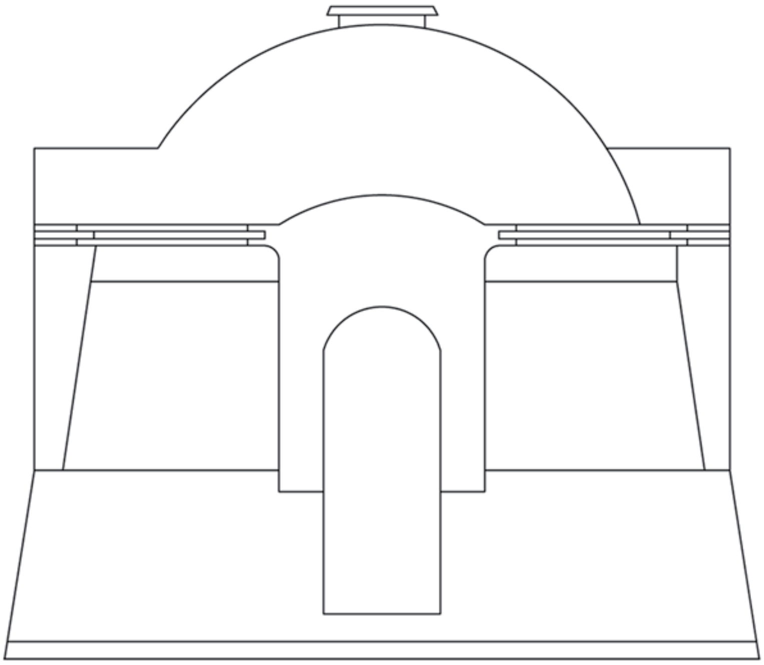


Casestudy 20 - Bina Saxena's Pottery, Bomnayarpalayam, near Auroville

Project plans Pg 2

elevation



Casestudy 20 - Bina Saxena's Pottery, Bomnayarpalayam, near Auroville

Photos I


A20-1


A20-2


A20-3


A20-4


A20-5


A20-6


A20-7


A20-8


A20-9


A20-10


A20-11


A20-12

Casestudy 20 - Bina Saxena's Pottery, Bomnayarpalayam, near Auroville

Photos II


A20-13


A20-14

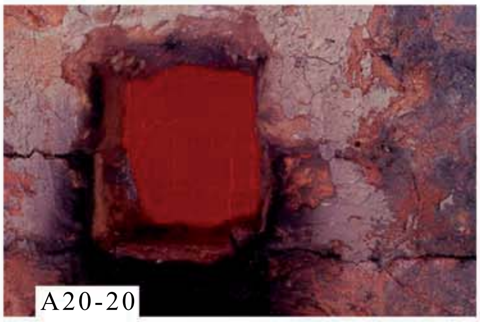

A20-15


A20-16

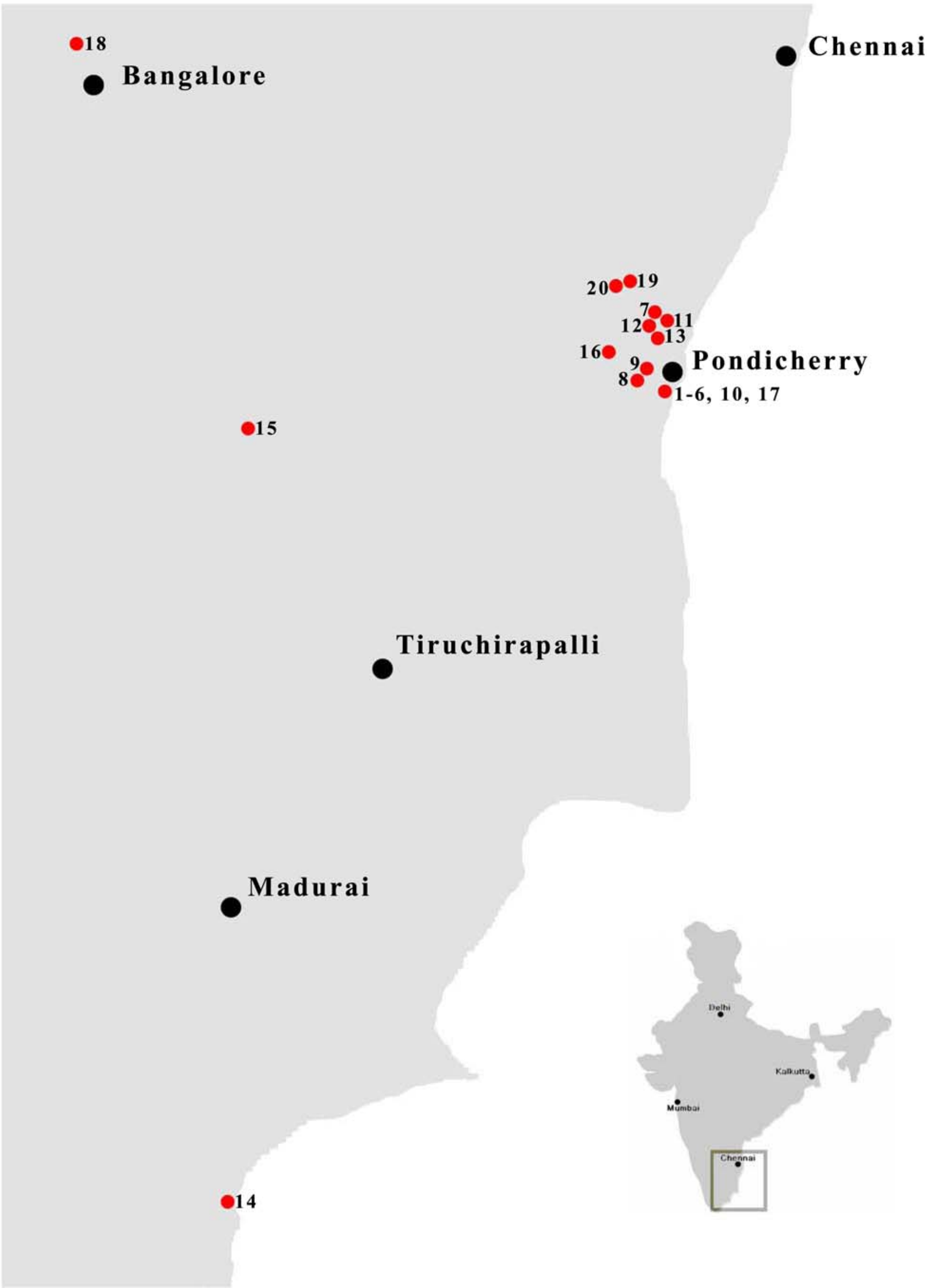

A20-17


A20-18


A20-19


A20-20

APPENDIX 2: LOCATION OF THE CASESTUDIES



1 GBP 01
2 GBP 02
3 GBP 03
4 GBP 04
5 GBP 05
6 GBP 06
7 Mallika's Residence
8 Upalam
9 Hidesign
10 GBP 10
11 AVIRC
12 Satyajit's House
13 Martha's House
14 Minolta Aquatech
15 Low cost housing
16 Voluntariat Farm
17 GBP Coal Firing
18 Nrityagram
19 Bina Saxena's Residence
20 Bina Saxena's Pottery