

**A STUDY OF THE PERFORMANCE OF VARIOUS TYPES
SOLAR DESALINATION PLANTS IN DIFFERENT
WEATHER CONDITIONS.**



By-

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A STUDY OF THE PERFORMANCE OF VARIOUS TYPES SOLAR DESALINATION PLANTS IN DIFFERENT WEATHER CONDITIONS.

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ABSTRACT

Salinity in water poses a serious problem in the coastal region of Bangladesh. The major difficulty in developing appropriate water supply system for the communities in that region is that aquifers containing sweet water are not always found at convenient locations. There are various desalination techniques practiced all over the world but those are expensive for our rural areas. Renewable energy sources specially solar energy has appeared an attractive solution. The technology involved in desalination of saline water using the solar energy is relatively simple and maintenance can be carried out by semi-skilled or unskilled operators. Therefore, in this study, an attempt has been made to study the performance of various types household and low-cost solar desalination plants.

In this study, different types of single basin solar still were constructed. These designs differ in structure and material of construction, but basically, incorporate common elements for different functions. The principal criteria for selection of materials were cost involvement, efficiency, and ease of construction and maintenance. The stills were characterized by a single basin (base and wall) to store saline water and one or more transparent covers on the top of the basin. The study was carried out in a two phases. In phase 1, although different types of materials were considered for construction of still basins, only basins constructed with ferrocement and brick were operated as these produced reasonable amount of yield. In phase 2, field investigations were commenced in the coastal belt simultaneously with laboratory investigations.

A comparative study was conducted on the performance of the various types of the solar stills. Among all the materials studied, brick appeared to be cheap and durable materials for the construction of solar plants in comparison of other materials like ferrocement, steel etc. Glass and transparent plastic sheet were used as transparent cover of the plant. Glass was found superior to plastic sheets for use as transparent cover of solar stills from view point of productivity, efficiency and ease of operation, although glass required extra care and attention. Three plants were constructed with same design and dimension except different cover slope. The cover slope $10^{\circ}37'$ was found the optimum inclination of cover of the plant. Brick plant were constructed as single and double layers. Single layer brick plant was cost-effective in producing distill from saline water comparing to double layer brick plant.

It was evident from the study that, of all the plants studied, the design of Brick Plant 1 was the best suited solar desalination plant for Bangladesh. The plant was constructed with brick having base and wall thickness 3.25 inch and 3.50 inch respectively. 5 mm glass sheet was used as transparent cover with an inclination of $10^{\circ}37'$. The maximum, minimum and average yield of Brick Plant 1 was found 2.64 liter/m²/day, 0.28 liter/m²/day and 1.40 liter/m²/day respectively. The maximum, minimum and average efficiency of Brick Plant 1 was found 49.30%, 8.58% and 33.82% respectively.

The design life of Brick plants and Ferrocement Plant was considered 30 years. The lowest cost of water per liter was found Tk. 0.92 for Brick Plant 1. The water obtained from the plants was almost free from salinity. The salinity of water in the coastal areas of Bangladesh varies in general from 1,000 to 2,000 ppm and the acceptable limit for drinking purpose is 600 ppm. If, tubewell water was mixed with the distillate with an equal amount, then the cost of drinking

water would be half of the production cost.

Convective heat transfer (cover to air), convective heat transfer (basin to cover) thermal radiation (cover to air) and thermal radiation (basin to cover) were calculated. Convective heat transfer (cover to air) was the highest (an average 6.41 cal.cm^2) among four modes and convective heat transfer (basin to cover) was the lowest (an average 0.74 cal.cm^2) among the four modes.

A mathematical equation was developed for the prediction of the diurnal plant output from the climatic factors: average temperature, radiation, sunshine hour and relative humidity and plant temperatures: water temperature and glass temperature. This model could be satisfactorily used for the prediction of the diurnal yield of the plants. It was observed that the calculated average monthly diurnal yield had the maximum deviation of data within ± 14.60 for all cases and within ± 7.00 if 4 nos. data was excluded.

TABLES OF CONTENTS

ACKNOWLEDGEMENT	iii
ABSTRACT	iv
TABLES OF CONTENTS	vi
LIST OF TABLES	xi
LIST OF FIGURES	xii
CHAPTER 1 INTRODUCTION	
1.1 General	1
1.2 Objective of the Study	2
1.3 Scope of the Study	3
1.4 Organization of the Thesis	4
CHAPTER 2 LITERATURE REVIEW	
2.1 General	6
2.2 Historical Background	6
2.3 Basic Principle	8
2.4 Basic Heat and Mass Transfer Relations	14
2.4.1 General	14
2.4.2 Internal Transfer	14
2.4.3 External transfer	18
2.5 Single Basin Solar Still	19
2.5.1 General	19
2.5.2 Solar Radiation	19
2.5.3 Analysis of an Ideal Still	20
2.6 Still Materials Studies	21
2.6.1 Experience with Plastic Covers	21
2.6.2 Materials for Fabrication of Solar Stills	23
2.7 Effects of Meteorological Parameters	24
2.7.1 Effect of Ambient temperature	24
2.7.2 Effect of Wind Speed	25
2.7.3 Effect of Solar Radiation and Loss Coefficient	26
2.7.4 Effect of Brine Depth in Solar Still	27

2.7.5	Effect of Spacing between Brine and Cover	28
2.7.6	Effect of Salt Concentration on Output	28
2.7.7	Effect of Cover Slope	29
2.7.8	Effect of Thermal Capacity on Output	30
2.7.9	Effect of Charcoal Pieces in the Performance of a Still	30
2.7.10	Effect of Natural and Forced Convection	31
2.7.11	Effect of the Formation of Algae and Mineral Layers on Water and Basin Liner Surface on Productivity of a Still	31
2.7.12	Effect of Dropwise Condensation on Glass Solar Properties	31
2.8	Economic Aspects	32
2.9	Calculation of Efficiency	33
2.10	Various Approaches for Statistical Estimates	33
2.10.1	Freehand Method of Curve Fitting	33
2.10.2	The Method of Least Squares	33
2.10.3	The Least Square Parabola	34
2.10.4	Multiple Correlation and Non-Linear Multiple Regression	35
2.11	The Accuracy of Estimate	36
2.12	The Interpretation of Missing Data	37
2.13	Prediction of Solar Still	38
 CHAPTER 3 EXPERIMENTAL INVESTIGATIONS AND ANALYSIS		
3.1	General	39
3.2	Location of Study	39
3.3	Construction of Solar Still	41
3.3.1	Construction Phase	41
3.3.2	Selection of material	41
3.4	Construction Details of Plants	42
3.4.1	Ferrocement Plant	42
3.4.2	Brick Plant 1	42
3.4.3	Brick Plant 2	47
3.4.4	Brick Plant 3	47
3.4.5	Brick Plant 4	47
3.4.6	Brick Plant 5	47
3.4.7	Brick Plant 6	47

3.4.8	Brick Plant 7	47
3.4.9	Brick Plant 8	48
3.4.10	Clay Plant	48
3.5	Provision for Different Functions	48
3.5.1	Provision for Water Inlet	48
3.5.2	Provision for Distill Outlet	48
3.5.3	Provision for Thermometers	49
3.5.4	Placement of Transparent Cover	49
3.5.5	Distillate Storage Tank Connection	50
3.6	Constraints of Construction and Counter Measures	50
3.6.1	Casting of Ferrocement Plant	50
3.6.2	Cracks on the Still Wall of the Ferrocement Plant	50
3.6.3	Loss of Distillate	50
3.6.4	Brine Removal Provision	51
3.6.5	Leakage	51
3.6.6	Cutting and Placement of Outlet	51
3.6.7	Placement of Rubber Support	51
3.6.8	Attachment of Plastic Sheet with Wooden Frame	51
3.6.9	Placement of Wooden Frame	52
3.6.10	Handling and Protection of transparent Cover	52
3.7	Experimental Work	52
3.7.1	Feeding of Saline Water	52
3.7.2	Data Collection	52
3.8	Constraints of Operation and Counter Measures	53
3.8.1	Damage of Glass and Plastic Cover	53
3.8.2	Detachment of Glass Strip	53
3.8.3	Displacement of Rubber Strip	53
3.8.4	Mixing of rain water with Out let	54
3.8.5	Cleaning of Plant	54
3.8.6	Cracks in Distill Collection Container	54
3.9	Experimental Results	54
3.9.1	Plant Yield	54
3.9.2	Relative Plant Yield	55
3.9.3	Measurement of Air, Water and Glass Temperature	59
3.9.4	Measurement of Salt Concentration in the Distilled Water	62

3.9.5	Convective heat Transfer	63
3.9.6	Thermal Radiation	64
3.10	Climatic Data Collection	65
3.11	Statistical Analysis of the Climatic Parameters	66
3.12	Plant Efficiencies	76
3.13	Prediction of Still Yield	76
 CHAPTER 4 DISCUSSIONS AND DESIGN, OPERATION AND MAINTENANCE GUIDELINES		
4.1	Introduction	85
4.2	Performance of Different Types of Plants	85
4.2.1	Construction and Installation	85
4.2.2	Design Life	86
4.2.3	Operation and Maintenance	87
4.2.4	Plant Yield	87
4.2.5	Cover Slope	88
4.2.6	Transparent Cover	88
4.2.7	Layer of brick Wall	89
4.2.8	Efficiency of Plants	89
4.2.9	Yield in Different Location	90
4.3	Capacity of Desalination Plants to Supply Drinking Water	90
4.4	Cost of Production	91
4.5	Plant Selection	92
4.6	Use of Desalination Plants during the Rainy Season	92
4.7	Heat Transfer	92
4.8	Mathematical Equations for Prediction of Yield	92
4.9	Guidelines	101
4.9.1	General	101
4.9.2	Guidelines for Design and Construction	104
4.9.3	Guidelines for Operation and Maintenance	104
4.10	Remarks	105
 CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY		
5.1	General	106
5.2	Conclusions	106

5.3 Recommendations for Future Study	107
--------------------------------------	-----

REFERENCE	108
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APPENDIX A

APPENDIX B

APPENDIX C

LIST OF TABLES

2.1 Effect of Angle of Incidence on Radiation Parameters	20
3.1 Schedule of Data Collection from Different Types of Plants	53
3.2 Maximum, Minimum and Average Yield of different Plants	55
3.3 Maximum, Minimum and Average Water temperature of different Plants	62
3.4 Maximum, Minimum and Average Glass temperature of different Plants	62
3.5 Maximum, Minimum and Average Convective Heat Transfer (Cover to Air)	63
3.6 Maximum, Minimum and Average Convective Heat Transfer (Basin to Cover)	63
3.7 Maximum, Minimum and Average Thermal Radiation (Cover to Air)	64
3.8 Maximum, Minimum and Average Thermal Radiation (Basin to Cover)	64
3.9 Statistical Analysis of Average Temperature at Dhaka	75
3.10 Maximum, Minimum and Average Efficiencies of Different Plants	75
3.11 Errors for Calculated And Actual Yield	78
4.1 Materials and Cost Involvement of Different Types of Plants	86
4.2 Average and Range of Yield of Different Types of Plants	87
4.3 Cover Slope with Average and Relative Yield	88
4.4 Transparent Cover with Average and Relative Yield	88
4.5 Efficiencies of Plants	89
4.6 Yield and Environmental Conditions of Different Plants	90
4.7 Cost of Production over Design Life	91

LIST OF FIGURES

2.1 Basic Elements of a Solar Still	09
2.2 Energy flow Diagram of A Basin Type Solar Still	10
2.3 Evaporative, Radiative and Convective Energy Fractions	17
2.4 Still Production for Different Average Ambient Temperatures	24
2.5 Still Production for Different Average Wind Velocities	25
2.6 Effect of Solar Radiation and Loss Coefficient on Predicted Still Output	26
2.7 Effect of Ambient temperature and Loss Coefficient on Predicted Still Output	27
2.8 Still Production for Varying Water Depths with and without Insulation	28
2.9 Still Production as function of Salt Concentration	29
2.10 Still Production for Varying Cover Slope	30
2.11 Method of Least Square	34
3.1 Study Location	40
3.2 Design Details of Ferrocement Plant	43
3.3 Design Details of Brick Plant 1	44
3.4 Design Details of Brick Plant 2	45
3.5 Design Details of Brick Plant 3	46
3.6 Yield of Brick Plant 1	56
3.7 Relative Yield of Brick Plant 1 and Ferrocement Plant	57
3.8 Relative Yield of Brick Plant 6 and Brick Plant 7	58
3.9 Glass Temperature of Brick Plant 1	60
3.10 Water Temperature of Brick Plant 2	61
3.11 Daily Average Temperature at Dhaka during the Period of Operation	67
3.12 Daily Solar Radiation at Dhaka during the Period of Operation	68
3.13 Daily Sunshine Hour at Dhaka during the Period of Operation	69
3.14 Daily Relative Humidity at Dhaka during the Period of Operation	70
3.15 Daily Wind Speed at Dhaka during the Period of Operation	71
3.16 Daily Rainfall at Dhaka during the Period of Operation	72
3.17 Daily Average Temperature at Kaliganj during the Period of Operation	73
3.18 Daily Sunshine Hour at Kaliganj during the Period of Operation	74
3.19 Variation of Calculated Yield with Actual Yield of Brick Plant 1	80
3.20 Variation of Calculated Yield with Actual Yield of Ferrocement Plant	81
3.21 Variation of Calculated Yield with Actual Yield of Brick Plant 3	82

Chapter 1
INTRODUCTION



CHAPTER 1 INTRODUCTION

1.1 GENERAL

Water is a fundamental need for the existence of life. At present, it is one of the most scarce resources on the earth. In Bangladesh, the main source of water for human consumption is ground water. Around 85% of all rural households have a tubewell within 150 meters and another 5% are located within 200 meters. In Urban areas, only 47% of total population have access to public water supplies (UNDP/World Bank Water Sanitation Program report, 1994). In the coastal belt of the country covering seventeen districts, the major obstacle in the use of ground water has been identified as high salt content (in excess of 1,000 mg/l). It has however been possible to pump sweet water from deep seated aquifers by the use of deep tubewells. But, installations of the deep tubewells are costly. Shallow shrouded and very shallow shrouded tubewells have also been used to extract water from sweet water aquifer lenses at shallow depths. However, they cannot completely solve the problem of sweet water shortage in the coastal areas since such aquifers are not always found at convenient locations.

On the other hand, surface water is available in abundance in most part of the coastal belt albeit with high salt content. It can be an attractive sources of potable water by developing an appropriate desalination technology option. There are various desalination techniques practiced all over the world such as the vertical tube distillation or multistage flash distillation, reverse osmosis or hyper filtration, electrodialysis, freezing process etc. (Rahman, 1994). Electrically or diesel powered desalination units or reverse osmosis units or electrodialysis system are not feasible in the rural areas of Bangladesh for their huge cost involvement and complex technological level.

The choice of renewable energy sources like solar energy has become even more attractive on account of the ten-fold rise in petroleum crude oil prices as compared to that in the beginning of 1970. But, the cost of conversion of brackish water to fresh water by use of solar energy is still relatively high even with the present state of knowledge and technology. However, solar energy is not a monopoly and is renewable, inexhaustible and free of cost although available only in a form of low heat. The application of solar distillation process has promising potentials because the technology involved in distillation of saline water using solar energy is relatively simple. Solar stills possess the advantage of having the least possible moving parts, and operation and maintenance can be carried out by

semiskilled or unskilled operators. It is applicable where conventional water treatment methods may not be feasible especially to meet small scale demands of villages or isolated communities, and most important of all operation costs are low because the source of energy is free.

Presently, solar stills for desalination are not used in Bangladesh. It is revealed that solar desalination plant has further scope for detail study whether the cost of still construction would offset the savings from free solar energy. The study has been undertaken with a view to studying the applicability of different types of solar distillation plants in the coastal areas of Bangladesh and recommending options for design, construction and operation of such plants. In the study, an attempt would be also made for synthesis of related meteorological data like radiation, sunshine hour, temperature etc.

1.2 OBJECTIVE OF THE STUDY

The main objectives of the study were as follows:

i) Development of different small size solar desalination stills.

Different types of solar stills had been used in the different parts of world for desalination purpose. The study was aimed at designing small solar distillation units utilizing technologies available and information from previous research works carried out elsewhere. Different types of solar stills would be constructed with different features from locally available, least costly but suitable materials making use of local tradesman.

ii) Comparative study of the performance and output of different solar desalination plants.

The workability of a solar desalination plant depends on various aspects. These include cost of construction, availability of materials, ease of operation and maintenance, amount of output, efficiency and removal efficiency of salinity of the feed water in solar desalination plant. The constructed units would be operated with adjustments and data would be collected from measurements of conditions, performance and output. These data would be analyzed to get a comparative idea on the different stills performance and output.

- iii) **Simulation of real plant operation sequences to encounter the various problems in construction and maintenance phase.**

The application of solar desalination plant was still limited on experimental stage. It revealed a details investigation on the problems encountered on different solar stills during construction, operation and maintenance at laboratory and field conditions.

- iv) **Study the seasonal variation of various climatic parameters in relation to solar desalination process.**

The solar desalination process was directly related to the different climatic factors such as solar radiation, air temperature, sun shine hour etc. These climatic parameters vary season to season. The knowledge of the variation of these factors over the year helped to get an idea about the plant yield through out the year.

- v) **Development of mathematical model (equation) for generating the amount of the plant yield from the various climatic parameters.**

The amount of plant yield varies with the variation of the different climatic parameters. Mathematical model (equation) would be developed by correlating the climatic factors with output, it would be possible to estimate the amount of yield in a different climatic conditions.

- vi) **Preparation of guideline for design, operation and maintenance of solar distillation plants in the coastal areas of Bangladesh.**

There have been several designs of solar desalination plant proposed by researchers in different countries. The performance of different plants would be investigated in order to develop a desalination plant suitable for the coastal areas of Bangladesh. The guidelines would be prepared intending to help construction, operation and maintenance of such a plant.

1.3 SCOPE OF THE STUDY

The following tasks were carried out to achieve the objectives stated above:

- i) Comprehensive study of different solar desalination plants already exists in different countries.

- ii) Design of solar desalination units utilizing the information from previous research carried out elsewhere.
- iii) Construction of different types solar stills with different features from locally available, least costly but suitable materials and utilizing local tradesman.
- iv) Stepwise study of these plants operation with daily adjustments.
- v) On time data collection of the plants output, glass & water temperature and the relevant meteorological data from Bangladesh Meteorological Department (BMD).
- vi) Determination of the daily plants efficiency for a span of the total study period.
- vii) Estimation of plant's design life and cost in involvement per unit production.
- viii) Establishment of a empirical equation with multiple degree for estimation of plant yield considering the climatic parameters and plants conditions.

1.4 ORGANIZATION OF THE THESIS

The thesis presents the analysis, results and findings of the study in five chapters with three appendix. In addition, a bibliography of related publications has also been presented.

Chapter 1 presents a brief introduction to the study along with its objectives and scope.

Chapter 2 compiles all relevant literature and makes reference to previous studies in related areas.

Chapter 3 provides a detail description of experimental investigations and analysis.

Chapter 4 presents the discussion on the study and provides guide lines for design, operation and maintenance of solar still.

Chapter 5 summaries the lists of conclusions drawn up and provides some recommendations for future study in this area.

Reference provides a list of relevant publications and reports which were reviewed in the study and may be useful for any future researcher in this area.

Appendix A contains the figures referred in the main text.

Appendix B provides the tables referred in the main text.

Appendix C presents the relevant computer programs.

Chapter 2
LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

A solar still is a simple device which can be used to convert saline, brackish, polluted or other water into drinking water. Solar stills operate on the principle of using solar energy to increase the relative humidity in a confined area and, in effect, distilling the feed water without boiling. The classic still is a form of solar radiation increases the temperature of the water to be desalinated. The resultant water vapor produced is allowed to contact a cooler surface, where it condenses (as fresh water) and is then collected for use. This is, of course, the same basic principles as the conversion of sea water to rain water in nature.

The loss and utilization of heat at various stages of it and the amount of distilled water obtained as calculated from the fundamental laws of heat and mass transfer are described briefly in this chapter. Detailed description of a single basin solar still has been presented. The various methods of desalination with their working principles are also reported in this chapter.

There are several factors that affect the performance of a solar still (Rajvanshi, 1979). Among those factors are: solar radiation, depth of brine in the still, cover material and its shape, ambient temperature, wind velocity and temperature of the condensing surface. Some of these are related to local conditions, while others are dependent on the physical design of the still. The factors affecting the output of the still are summarized in this chapter.

Statistics is a strong tool for estimation of probability, correlation of various interdependent parameters, forecasting and predicting the error of such estimations. The basic approaches of statistics in this context are also depicted in concise form in this chapter.

Different mathematical equations were developed to calculate the yield of the solar plants. Some equations and the relevant factors are also mentioned in this chapter.

2.2 HISTORICAL BACKGROUND

Of all the renewable energy sources available, solar energy has received the most attention in connection with desalination. Using solar energy for desalination was mentioned as early as the seventeenth century by the Italian scientist Della Porta (United Nations report, 1985).

Various experimenters have mentioned and tried on solar distillation for at least the past four centuries (Nebbia and Menozzi, 1966). One of the first successful, well-documented solar stills was first designed and fabricated in 1822 near Las Salinas in Northern Chile by Carlos Wilson, a Swedish Engineer (Kumar et al., 1982). This was a large basin-type solar still, meant for supplying fresh water to a nitrate mining community (Harding, 1883) as reported by Malik (1982). This device was in operation for about 40 years and yielded more than 4.9 kg of distilled water per square meter of the still surface on a typical summer day. It is worth noting that this output compares very high with the distilled water output from the present day solar stills.

It used plate glass, which was then a recent invention, and is a necessity for most modern solar stills. Other stills were built at about that time and in the years that followed. They were used in various arid areas such as Chile, the Sahara and other locales in North Africa (United Nations report, 1985).

No work on solar distillation seems to have been published after 1880's till the end of the First World War. With the renewal of interest, several types of devices have been described, e.g. roof type, V-covered, tilted wick, inclined tray, suspended envelope, tubular and air inflated stills etc. Use of metal coated reflectors as solar concentrators for application in solar distillation has been described by Kausch (1920); Pasteur (1928) also used several concentrations to focus solar rays onto a copper boiler containing water.

During the second world war, efforts were increased to produce a solar still that could be utilized on life-rafts for ships and aircraft. Maria Telkes (1945) invented a small inflatable plastic unit for that purpose and hundreds of thousands of the units were produced. Her research efforts in this field continued after the war.

Many investigators have attempted to improve the operating efficiency by using the latent heat of vaporization in either multiple-effect systems or for preheating the brine to increase the output of the stills. Several large scale distillation plants and integrated schemes for combining electric power generation and desalination of water have also been suggested as way of improving the overall operating efficiency of the plant.

In the 1960s, the United States Office of Saline water undertook an extensive program to investigate the potential use of solar energy for distillation. A significant part of the OSW program consisted of construction and field testing at a station operated by Battelle Institute near Daytona Beach, Florida. Various designs of solar stills included glass-covered basins, inflated-plastic basins, tilted wicks and trays, and all-plastic double tubes. The OSW solar

still program, conducted from 1952 to 1970, produced design data that have been used in numerous stills built around the world since 1960 (Eibling, 1980).

More attention now a days has been paid on basin type solar-still and also on several other types as follows:

- Multiple-effect stills (Oltra, 1972; Bartali, 1976)
- Tilted tray or inclined-stepped solar stills (Howe, 1961; Akhtamov et al., 1978)
- Tilted wick type and multiple wick type solar stills (Frick and Somerfield, 1973; Sodha et al., 1980; Moustafa and Brusewitz, 1979)
- Solar film covered still and wiping spherical stills (Norov et al., 1975; Umarov et al., 1976; Menguy et al., 1980)
- Solar still greenhouse combination (Selcuk, 1970, 1971; Sodha et al., 1980)
- Indirectly heated solar stills (Soliman, 1976; Malik et al., 1973, 1978; Sodha et al., 1981)

Depending upon their expected life span and application, the various solar stills are categorized into 'permanent' (e.g. glass stills), 'semi-permanent' (e.g. plastic stills) and 'expandable' (e.g. double-tube and floating stills) type solar stills.

2.3 BASIC PRINCIPLE

Solar distillation has four basic elements. These are: i) Incoming radiation (energy); ii) Water vapor production from brine; iii) Condensation of water vapor (condensate); and iv) Collection of condensate.

A conventional solar still is simply an airtight basin, usually made out of galvanized iron sheet in a rectangular shape (Figure 2.1). It operates when solar radiation, passing its transparent cover, heats the saline water in the basin to a temperature higher than that of the cover. The resulting temperature gradient and associated vapor-pressure gradient within the still causes water vapor to condense on the underside of the transparent cover. This thin film condensate is drained to the collecting channels and runs to storage.

The most important parameter affecting the output of a solar still is, the intensity of the solar radiation on the still. If Q_t (in Joules/m² day) is the amount of energy incident on the glass cover of a still and Q_e (in Joules/m² day) is the energy utilized in vaporizing water in the still, then the daily output of distilled water M_e (in kg/ m² day) given by

$$M_e = Q_e / \zeta \quad (2.1)$$

where ζ (in Joules/kg) is the latent heat of vaporization of water.

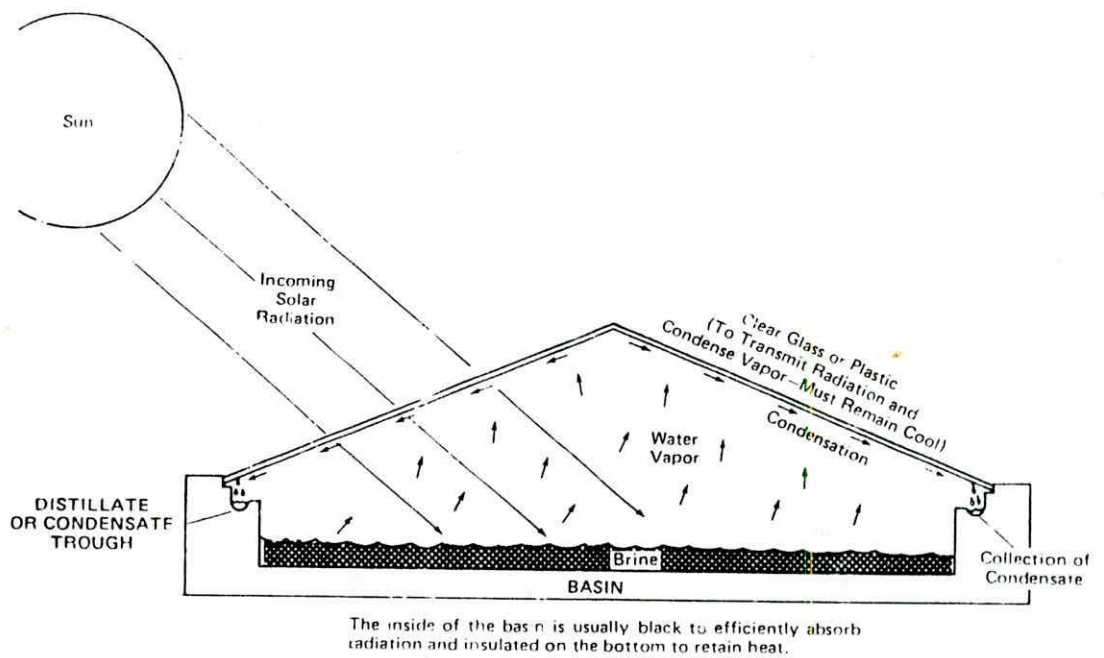


Figure 2-1: Basic Elements of a Solar Still (United Nations report, 1985)

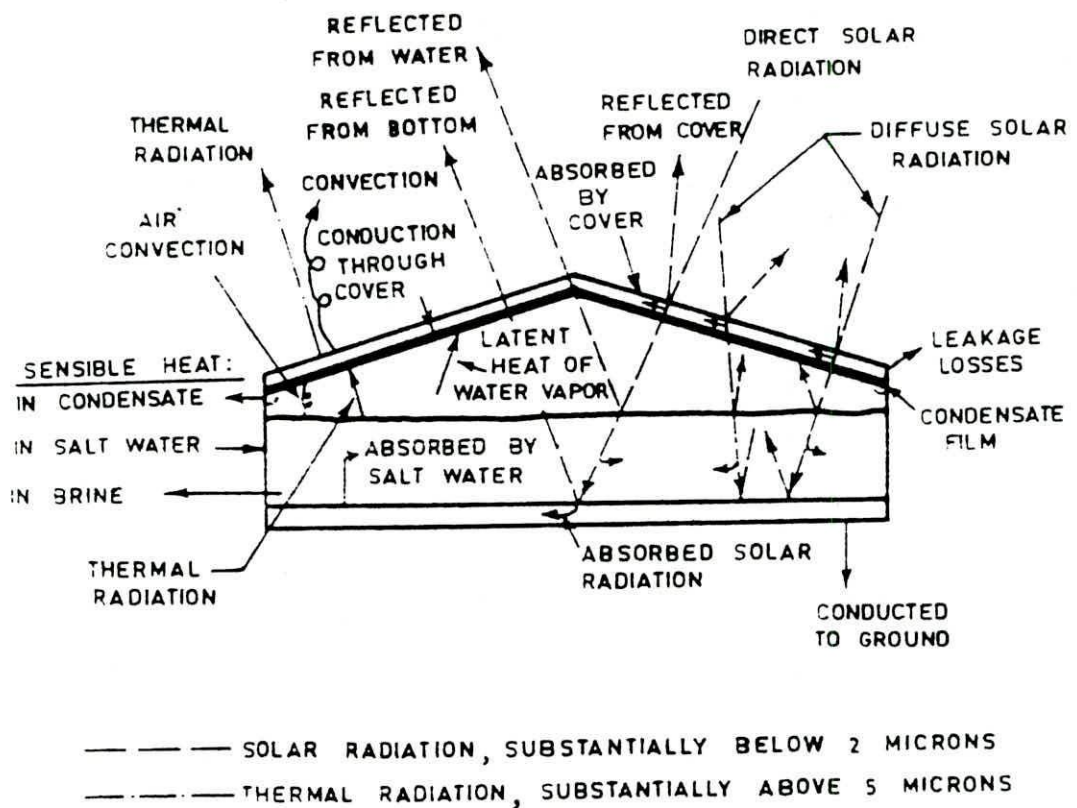


Figure 2-2: Energy Flow Diagram of a Basin Type Solar Still (After Lof, 1961b)

The Figure 2.2 illustrates the principal energy exchange mechanisms in a basin-type solar still. A very large part of the solar radiation, direct and diffuse, falling on the still is absorbed in the blackened base. Small reflection losses occur at the glass surface and to a very small extent at the base. The energy absorbed at the base is largely transferred to the water in the still and a small fraction of it lost to the ground by conduction through the base. Energy is transferred from the water to the glass cover principally by the water vapor evaporating from the water surface and then losing its heat of vaporization to the glass cover upon condensation. Heat is also transferred to the glass cover from water by free convection of the trapped air in the still. The glass cover absorbs a part of the heat radiated from the water surface. A small part of the solar energy is also absorbed by the glass cover. The heat thus absorbed by the glass cover is lost to the atmosphere by convection and radiation. Energy exchange also occurs on the account of change of sensible heat content of the saline water entering the still, the distillate leaving the still and the brine that accumulates in the still. Thermal losses may also occur due to the leakage of water vapor and the water from the still.

The energy related to the solar still can be summarized as below:

Incoming energy

1. Solar radiation
2. Atmospheric radiation

Outgoing energy

1. Convection to atmosphere
2. Radiation to atmosphere
3. Reflection to atmosphere
4. Ground conduction
5. Edge conduction and convection
6. Vapor leakage
7. Brine leakage from basin
8. Sensible heat of condensate and overflow

The efficiency of the utilization of energy in the solar still depends on the on the percent of total incident solar radiation utilized for the distribution process. Lof et al. (1960) identified the energy leaving the basin as follows:

1. Thermal radiation from salt water and basin bottom to cover.
2. Sensible heat transferred from brine surface to cover via circulating air in the enclosure.
3. Conduction losses to the ground or other surroundings.

4. Sensible heat in effluent distillate and brine streams.
5. Enthalpy in any vapor or liquid streams which may escape the enclosure and recovery facilities.

The values of the above factors are influenced by the temperatures of the basin salt water (t_b), the cover (t_g), and the ambient air temperature (t_a). The basin salt water temperature (t_b) influences the thermal radiation from the basin to the cover and the sensible heat transfer between the salt water and cover which accompanies the useful transfer of water vapor.

The cover temperature (t_g) affects the distillation rate and efficiency. All the heat transferred to the underside plus the solar absorption in it must be dissipated by convection and radiation to the surroundings.

Ambient air temperature (t_a) and other factors such as wind velocity and atmosphere clarity all affect the heat transfer rate from the desalination plant.

Neglecting the absorption of solar energy by the transparent cover and temperature drop through the cover, the heat balance on the cover per unit area in:

$$(h_{c,o} + h_{r,o})(t_g - t_a) = (h_{c,i} + h_{r,i})(t_b - t_g) + E\lambda \quad (2.2)$$

where,

$h_{c,o}$ = Convection heat transfer coefficient from cover to atmosphere, $\text{cal hr}^{-1} \text{cm}^{-2} \text{°C}^{-1}$

$h_{r,o}$ = Radiation heat transfer coefficient from cover to atmosphere, $\text{cal hr}^{-1} \text{cm}^{-2} \text{°C}^{-1}$

$h_{c,i}$ = Convection heat transfer coefficient from salt water surface to cover of still, $\text{cal hr}^{-1} \text{cm}^{-2} \text{°C}^{-1}$

$h_{r,i}$ = Radiation heat transfer coefficient from salt water surface to cover of still, $\text{cal hr}^{-1} \text{cm}^{-2} \text{°C}^{-1}$

E = Water evaporation (and condensation) rate, $\text{kg cm}^{-2} \text{hr}^{-1}$

λ = Latent heat of condensation at basin temperature (plus difference in sensible heat of condensate at basin and cover temperature), cal/kg (equals approx. $584 \times 10^3 \text{ cal/kg}^{-1}$)

Assuming the cover area to equal the basin area and that the effective sky temperature for radiation to equal the ambient atmospheric temperature, the overall energy balance on the distillation plant can be represented as follows:

$$Q_{sh}/24 = (h_{c,o} + h_{r,o})(t_g - t_a) + E(t_a - t_g) + L \quad (2.3)$$

where,

Q_{sh} = Net solar radiation rate absorbed on basin bottom, $\text{cal cm}^2 \text{ day}^{-1}$

L = Net miscellaneous heat loss rate, $\text{cal hr}^{-1} \text{ cm}^{-2}$

Utilizing the information collected by Lof (1960) from California study individual terms in equations (2.2) and (2.3) may be represented as follows:

$$\text{convective heat transfer (cover to air)} = 1.514(t_g - t_a) \quad (2.4)$$

$$\text{thermal radiation (cover to air)} = 0.461 \times 10^{-8}(T_g^4 - T_a^4) \quad (2.5)$$

$$\text{convective heat transfer (basin to cover)} = 0.145(t_b - t_g)^{1.25} \quad (2.6)$$

$$\text{thermal radiation (basin to cover)} = 0.444 \times 10^{-8}(T_b^4 - T_g^4) \quad (2.7)$$

$$\text{heat of condensation (basin to cover)} = 0.336(t_b - t_g)^{0.25}(W_{H_2O}/W_{da})\lambda \quad (2.8)$$

where,

T_g = Temperature of transparent cover, $^{\circ}\text{K}$

T_a = Atmospheric temperature, $^{\circ}\text{K}$

T_b = Temperature of salt water basin, $^{\circ}\text{K}$

W_{H_2O} = Mass of water distilled per unit time, kg hr^{-1}

W_{da} = Mass of dry air circulating per unit time, kg hr^{-1}

Substituting the above information into equations (2.2) and (2.3) yields the following relationship for heat balance of transparent cover per unit area:

$$\begin{aligned} &1.514(t_g - t_a) + 0.461 \times 10^{-8}(T_g^4 - T_a^4) \\ &= 0.145(t_b - t_g)^{1.25} + 0.444 \times 10^{-8}(T_b^4 - T_g^4) + 0.336(t_b - t_g)^{0.25}(W_{H_2O}/W_{da})\lambda \end{aligned} \quad (2.9)$$

and assuming heat conduction losses of $13.56 \text{ cal/cm}^2 \text{ day}$ ($50 \text{ Btu/ft}^2 \text{ day}$) the following relationship for the overall energy balance on the distillation plant per unit area:

$$\begin{aligned} Q_{sh}/24 = & \\ &1.514(t_g - t_a) + 0.461 \times 10^{-8}(T_g^4 - T_a^4) + 0.605(t_b - t_g)^{1.25}(W_{H_2O}/W_{da}) + 13.56/24 \end{aligned} \quad (2.10)$$

This represents the total radiation incident on the basin cover less the reflection from the cover, reflection from water surfaces reduction from the basin bottom, and the losses due to structural shadowing.

Bloemer et al. (1964) showed that the radiation from the basin water to the cover is the largest (26%) single heat loss in a solar still.

2.4 BASIC HEAT AND MASS TRANSFER RELATIONS

2.4.1 GENERAL

The operation of a solar still is governed by various heat transfer modes. Convection and radiation are the predominant modes of heat transfer in a solar still. A very small amount of energy is also lost to the ground (or atmosphere) due to heat conduction through the base.

The heat transfer modes can be divided into 'internal transfer' and 'external transfer'. The heat transfer within the still is termed as internal transfer and heat transfer between the still and the environment is referred as external transfer. It is however, important to note that the heat transfer problem as such cannot be decoupled. The essential distinction between the modes of heat transfer in these two regions is that, while, within the still convective heat transfer occurs simultaneously with evaporative mass transfer, no such mass transfer occurs outside it. Radiative heat transfer occurs in both the regions along with other modes.

Thermal convection is the process by which heat transfer takes place between a solid surface and the fluid surrounding it. The rate of heat transfer by convection between the fluid and the boundary surface is described by equation.

$$q = h.A.\Delta T \quad (2.11)$$

which looks disarmingly simple. However, the crux of the problem lies in evaluating the heat transfer coefficient h , which is a complicated function of the geometry of the surface, the flow characteristics of the fluid and the physical properties of the fluid. In most practical cases the heat transfer coefficients are evaluated from empirical equations obtained by correlating empirical results using methods of dimensional analysis.

2.4.2 INTERNAL TRANSFER

The modes of heat exchange inside the still between the water surface and the glass cover are convection accompanied by evaporative mass transfer (in the form of water vapor) and radiation.

Convection

Heat is transported across the bulk of the humid air inside the still by free convection of air. It then releases its enthalpy upon coming into contact with the glass cover, which is at a lower temperature.

The amount of heat transferred per unit area per unit time from water to the glass cover is given by Dunkle (1961) with the following relationship :

$$q_{cw} = 0.884 \left[T_w - T_{gi} + \frac{(P_w - P_g)(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right] \cdot (T_w - T_{gi}) \quad (2.12)$$

$$= h_{cw} (T_w - T_{gi}) \quad (2.13)$$

where,

q_{cw} = Amount of heat transferred per unit area per unit time from water to the glass cover by convection, W/m²

P_g = Partial pressure of water vapor at glass temperature, Pa

P_w = Partial pressure of water vapor at water temperature, Pa

T_w = Water temperature, °C

T_{gi} = Temperature inside glass surface, °C

h_{cw} = Convection heat transfer coefficient from water surface to glass cover, W/m², °C

Evaporation

Baum and Bairamov (1964) found that bulk of the air did not have any significant rate of exchange of water vapor with the boundary layers at the water and glass surface. Then the net mass of water vapor transferred per unit area per unit time is given by the difference of mass of water vapor transferred from the water surface and mass of water vapor transferred from the glass surface.

The amount of heat transferred on account of the mass transfer of the water vapor per unit area per unit time is,

$$\begin{aligned} q_{ew} &= h_e (P_w - P_a) \\ &= 16.273 \times 10^{-3} h_{cw} (P_w - P_a) \end{aligned} \quad (2.14)$$

where,

q_{ew} = Amount of heat transferred per unit area per unit time from water to the glass cover by evaporation, W/m²

h_e = Evaporation heat transfer coefficient from water surface to glass cover, $W/m^2, ^\circ C$

and mass transfer rate i.e. mass evaporated unit area per unit time, $Kg/hr m^2$ is:

$$\dot{m}_e = q_{ew}/\zeta \quad (2.15)$$

Radiation

The water surfaces and the glass cover are considered as infinite parallel planes in usual solar stills analysis. This is valid approximation for stills with small cover slopes and large dimensions in both the horizontal directions. This would not be valid for stills consisting of essentially unconnected strips or long rectangles.

For the infinite case:

$$q_{rw} = \frac{\sigma (T_1^4 - T_2^4)}{(1/\varepsilon_1) + (1/\varepsilon_2) - 1} \quad (2.16)$$

where,

q_{rw} = Amount of heat transferred per unit area per unit time from water to the glass cover by radiation, W/m^2

σ = Stefan-Boltzman constant, $5.6697 \times 10^{-8} W/m^2 K^4$

$\varepsilon_1, \varepsilon_2$ = Emissivity of inside surfaces of two infinite parallel planes (in still $\varepsilon_1 = \varepsilon_g$ and $\varepsilon_2 = \varepsilon_w$)

$\varepsilon_g, \varepsilon_w$ = Emissivity of glass and water respectively

Absolute values of total solar energy transfer rate are obtained by the addition of the equations (2.12), (2.14) and (2.16). To provide an insight into the relative magnitudes of each mode, the heat transferred by evaporation, radiation and convection, expressed as a fraction of the total, is shown in Figure 2.3 for various water temperatures and water-glass temperature differences. The important characteristic of the figure that, for high mean temperatures of operation, the evaporation fraction is large and hence the internal efficiency is high.

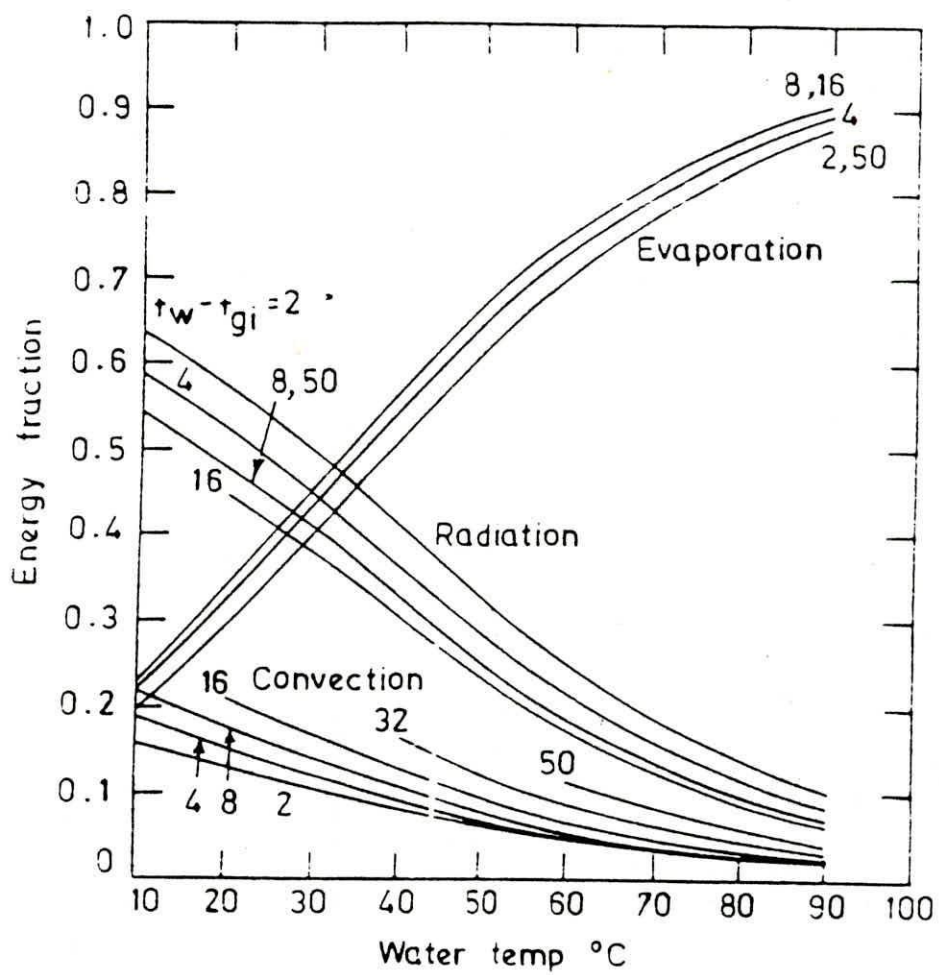


Figure 2-3: Evaporative, Radiative and Convective Energy Fractions (After Cooper, 1973b)

2.4.3 EXTERNAL TRANSFER

The modes of heat exchange between the still and the environment are convection and radiation accompanied by periodic heat transfer in conducting media.

Convection and Radiation

Due to small thickness of the glass cover, the temperature in the glass may be assumed to be uniform. The external radiation and convection losses from the glass cover to outside atmosphere can be expressed as,

$$q_{ra} = \varepsilon_g \sigma [(T_g + 273)^4 - (T_{shy} + 273)^4] \quad (2.17)$$

where,

q_{ra} = Total heat transferred per unit area per unit time from water to glass, W/m²

T_g = Temperature of glass surface °C

T_{shy} = Sky temperature °C (assumed to be 12°C below ambient)

and

$$q_{ca} = h_{ca} (T_g - T_a) \quad (2.18)$$

where,

h_{ca} = Convection heat transfer coefficient from water surface to glass cover, W/m², °C

T_a = Ambient air temperature °C

Hence, Total heat transferred per unit area per unit time from glass to ambient, W/m² is given by,

$$q_a = q_{ra} + q_{ca} \quad (2.19)$$

The external convection coefficient h_{ca} is a function of wind velocity and given below (Duffie, 1974).

$$h_{ca} = 5.7 + 3.8g \quad (2.20)$$

where,

g = Wind speed, m/sec

Periodic Heat Transfer in Conducting Media

Energy transfer through the base of the still occurs through thermal conduction. Since the solar insulation is a periodic phenomenon, the heat transfer into the ground is also of periodic nature. The periodic heat transfer through a conducting medium depends on the periodic boundary conditions.

2.5 SINGLE BASIN SOLAR STILL

2.5.1 GENERAL

A single basin solar still is characterized by a single basin having saline water; it may, of course, have more than one transparent cover. The various designs of solar still differ in structure and materials of construction, but basically, incorporate common elements of different functions. The glass/plastic cover is transparent to the incoming solar radiation, but blocks the long wavelength radiation emitted by the water surface and the base of the still. Besides this, the cover prevents the escape of the humid air trapped inside the still and also provides a cool surface for condensation of water vapor. The cover should be sloped on one side at an angle large enough to facilitate an easy flow of water droplets, that condense on it, into condensate trough. The trough is also inclined so that the collected water flows out of the still to be collected in bottles. Obviously, the condensate trough should extend all along the lower edge of the sloped cover. It is important to note that the angle at which the cover is inclined should not be too large as to present a grazing surface to the solar rays at noon, when the solar intensity is maximum; this would cut off a very large fraction of the total daily insulation.

The basin of the still should be watertight and the entire still should be airtight, except for the inlets and outlets. Durable materials such as metals, concrete etc. can increase the life span of still.

2.5.2 SOLAR RADIATION BALANCE

The amount of solar energy absorbed by the saline water and the base of the still depends on the amount of energy reflected and absorbed by the transparent top cover and on the amount reflected by the saline water surface and the base of the still. The water film formed due to the condensation of water vapor on the interior surface of the top cover also contributes to the reflection of solar energy. Since reflectivity is a function of the angle of incidence on any surface, it is natural to expect that the energy absorption by the base of

the still should vary with the time of the day, because the angle at which sun's rays are incident on a stationary still varies with time. Fortunately such temporal variations in the reflectivity at the various surfaces of the still are quite small. Cooper (1970) has shown that, for places confined within latitudes 0 to 45 degrees and for the angle of inclination of the top covers ranging from 0 to 60 degrees, the variation is very small. Consequently, the reflection and transmission coefficients may be treated as constants for any particular still.

Cooper (1969a) reported the effect of angle of incidence on radiation parameters which is summarized in Table 2.1.

Table 2-1: Effect of Angle of Incidence on Radiation Parameters

<i>Angle of incidence, deg.</i>	0	30	45	60
Cover reflection	5	5	6	10
Cover absorption	5	5	5	5
Cover transmission	90	90	89	85
Water reflection	2	2	3	6
Water absorption	30	30	30	30
Water transmission	68	68	67	64
Basin reflection	5	5	5	5
Basin absorption	95	95	95	95
Basin transmission	0	0	0	0

The values are expressed as percentage of fractions.

2.5.3 ANALYSIS OF AN IDEAL STILL

An ideal solar still is one with zero conductive heat losses and a saline water level shallow enough to enable one to neglect the sensible heat stored in the saline water. Consequently, an ideal still would attain a steady state almost instantaneously corresponding to the prevailing circumstances. Cooper (1973a) has studied the performance of such a still.

The interior heat transfer rates (i.e. heat transfer rates inside the still) q_{cw} , q_{ew} and q_{rw} are given by equations (2.12), (2.14) and (2.16) respectively. The solar radiation absorbed by the top cover, together with the heat transferred to it by the condensing water vapor, is rejected to the atmosphere through convection and radiation; the convection would be strong function of the wind velocity outside the still. Under steady state conditions, the heat balance on the saline water surface may be expressed as

$$\alpha_w H_s = (q_{cw} + q_{ew} + q_{rw}) + \frac{C_{pw}}{\zeta} (T_w - T_a) \cdot q_{ew} \quad (2.21)$$

In the above equation, it is assumed that, a steady inflow of saline water at temperature T_a replaces the water lost through evaporation. Thus, the second term on the right hand side of the equation represents the heat used up in raising the temperature of the incoming saline water from T_a to T_w the steady state temperature of the saline water in the still.

In order to relate the temperature on the interior surface of the top cover, T_{gi} , to the ambient temperature T_a , it is assumed, as a first approximation, that the temperature of the solar radiation absorbed by the cover. If the thickness of the cover is small, this absorption may be considered as having occurred at the external surface of the cover. Then it can be written as

$$(q_{cw} + q_{ew} + q_{rw}) = \frac{K_g}{\ell_g} (T_{gi} - T_{go}) \quad (2.22)$$

where,

T_{gi} = Temperature of interior surface of the transparent cover

T_{go} = Temperature of exterior surfaces of the transparent cover

α_g = Absorption coefficient of glass

K_g = Thermal conductivity of glass, W/m °C.

ℓ_g = Thickness of glass, m

The total energy balance may be expressed as

$$\begin{aligned} 0.85 \sigma [(T_{go} + 273)^4 - (T_a + 261)^4] + h_{ca} (T_{go} - T_a) \\ = \sigma_g H_s + \frac{K_g}{\ell_g} (T_{gi} - T_{go}) \end{aligned} \quad (2.23)$$

Although no explicit solution exists for this equation, one may always calculate the distillation rate approximately by iteration. Based on such a simplified model, Cooper (1973b) has shown that the efficiency of an ideal solar still may be as high as 60% for high values of solar isolation.

2.6 STILL MATERIALS STUDIES

2.6.1 EXPERIENCE WITH PLASTIC COVERS

The acceptance of solar still in a large scale depends on its cost and the ease with which it can be transported, installed, operation and maintenance. The transparent cover is a major item of cost in solar still construction. Its magnitude may vary from as little as 20 percent of the material cost where glass is very cheap such as in Australia, to over 50 percent where

glass is expensive such as in the USA. Transparent plastic film seems to be a logical substitute for glass due to its possible lower cost per unit surface cover area, flexibility and elimination of joints necessary in glass construction. Keeping these points in view, several small solar still have been designed suitable for short term use (particularly in the developing countries (Lof, 1966)). In all these designs, plastic sheets are used as the transparent covers and either concrete or black plastic film is employed for the basin of the still.

For convenience these systems may be classified into three general types:

1. Inflated or wire-supported all plastic tabular condensing surface with enclosed saline water tray (Bloemer et. al., 1964).
2. Conventional horizontal basin with separate plastic covers supported by frames (Daniels, 1965).
3. Circular basin with vertical or inverted plastic conical cover (Howe, 1964).

Design possibilities with sheet glass are quite inflexible. About the only advance in glass-cover technology during the past 100 years is the expansion of scientific data on the effects of glass thickness, cover slope, sealing materials, and transmittance through single and multiple covers (Hay, 1973). Substitution of plastic for glass is, in itself, not basically innovative even though major advantages are obtained, such as elimination of joints at which vapor leakage occurs or elimination of misfortunes concurrent with breakage. But, the plastic sheets suffers some limitations during the operation of the plants.

The following are the some common problems encountered during the operation of the systems:

1. Fragility and short service life of plastic sheets.
2. Leakage of water vapor and the condensate.
3. Over-heating, and hence melting, of the plastic bottom of the still due to development of dry spots in course of time. In the extreme case, the black polyethylene sheets used as the basin liner may get heated beyond its melting point.
4. The plastic cover surface does not get wetted and this leads to reduce transmission of incoming solar energy and also to dripping of distilled water back into brine liquid.

5. Susceptibility to damage by wind and other elements of nature.
6. Occasional unforeseen mixing of brine and distilled water in some of the designs.

Moreover, the productivity of the plastic cover stills is lesser than that of the glass cover stills. One factor contributing to the lower productivity of plastic-covered solar still is the transmission of the plastic cover in the infrared spectrum (Telimat et al., 1969). The transmittance of plastic (Tedlar Type 20) is vary between a high of 80% to a low of 10% in the range 6-12 μ m wavelength, with an average transmittance of 40%. The spectral energy distribution for the temperatures involved in solar saline-water stills, according to Wein's displacement law, has a peak value at 9.3 and 8.5 μ m for the water temperature of 37.8°C (100°F) and 65.6°C (150°F) respectively. Glass, on the other hand, is completely opaque in this infrared region of the spectrum. On this basis, it may be expected that the radiation loss from the water surface will be larger for the plastic-covered stills than glass-covered stills.

It appears that plastic sheets may not be the right choice for meeting the fresh water requirements of a community or family on a long term scale, mainly because of its low productivity and doubtful reliability. However, these can be used in cases of emergency, war and in general for short time applications.

2.6.2 MATERIALS FOR FABRICATION OF SOLAR STILLS

There are so many options in selecting the materials for fabrication of solar stills. The deciding factors are the cost, availability, productivity and constraints peculiar to any particular location. Achilov et. al. (1973a) have conducted extensive studies on the use of several materials such as concrete, sand concrete, ferrocements, foamed plastic, various types of sheet, plate and window glass, zinc coated and rubber piping, various types of steel, duralumin, various types of thermal insulators, asbestos cement, reinforced cement, dyes, lacquers and other cementing compounds in the fabrication of a still. An important outcome of these studies has been that, if the still is to be installed at any location permanently it is best to construct the basin of the still using sand concrete or water proofed concrete; Baum et. al. (1970) also arrived at the same conclusion.

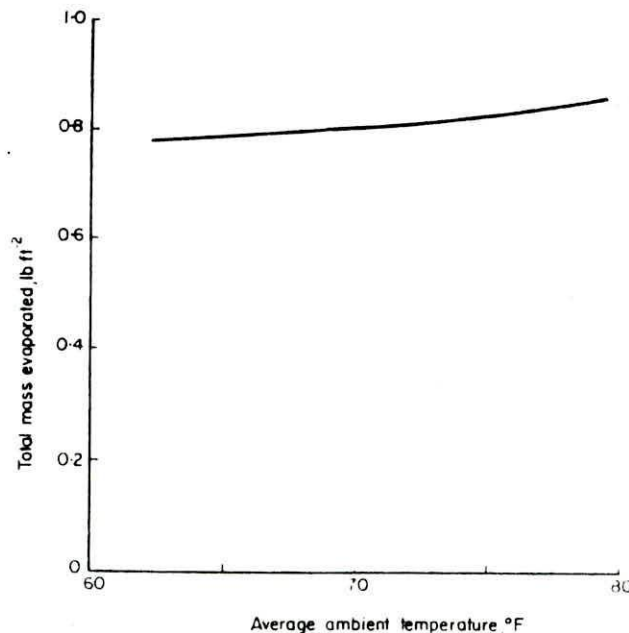
In the case of factory manufactured system, prefabricated ferroconcrete is more convenient. The extensive use of prefabricated ferroconcrete offers several important advantages, including the mechanization of constructional work, possibility of construction work throughout the year, reduction in fabrication time, improvement in quality, and reduction in cost. Above all, prefabricated ferroconcrete still basins are transportable, convenient to use and independent of local conditions.

According to Baum et. al. (1970) the type MP5-XII-2 insulating paste has been found to give the best results when used as a sealing compound. It exhibits good adherence to iron, various concrete types, wood, glass etc., is noted for its marked elasticity, undergoes no cracking and does not peel off under the effect of heat or moisture.

2.7 EFFECTS OF METEOROLOGICAL AND STILL PARAMETERS

2.7.1 EFFECT OF AMBIENT TEMPERATURE

Morse and Read (1968) have shown that an ambient temperature change from 26.7°C (80°F) to 37.8°C (100°F) causes an 11% increase in the output and a change from 26.7°C (80°F) to 15.6°C (60°F) causes a 14% drop. This is for a still with smaller thermal loss coefficient base of still to surroundings, but in higher smaller thermal loss coefficient base of still to surroundings, the effect of ambient temperature is greater. Cooper (1969a) also concluded that decreasing the average ambient temperature decreases the output. Figure 2-4 represents still production for different average ambient temperature. In this case, even though both water and glass temperatures decrease and the difference increase, it is not sufficient to compensate the general fall in the overall temperature of the system. This effect becomes evident at relatively lower temperatures. This is in agreement with the earlier work of Lof et. al. (1961b).



**Figure 2-4: Still Production for Different Average Ambient Temperatures
(After Cooper, 1969)**

2.7.2 EFFECT OF WIND VELOCITY

Cooper (1969) concluded that for average wind velocities from 0 to 2.15 m/sec the output gets increased by 11.5%, while from 2.15 m/sec to 8.81 m/sec the increase was only 1.5%, indicating the decreasing influence of wind at higher velocities on distillation rate. Figure 2-5 shows the still production for different average wind velocities.

A suggested fall in productivity with increasing wind velocity by Lof et. al. (1961b) is not consistent with the present understanding of the heat and mass transfer modes. Morse and Read (1968) concluded that the influence of wind on still output may be unimportant.

Soliman (1972) has studied the effect of wind velocity on output in detail, considering all heat and mass transfer modes. He has concluded that at high water temperature, the increase in the difference between water and cover temperature by increasing wind speed causes an increase in the rate of evaporation.

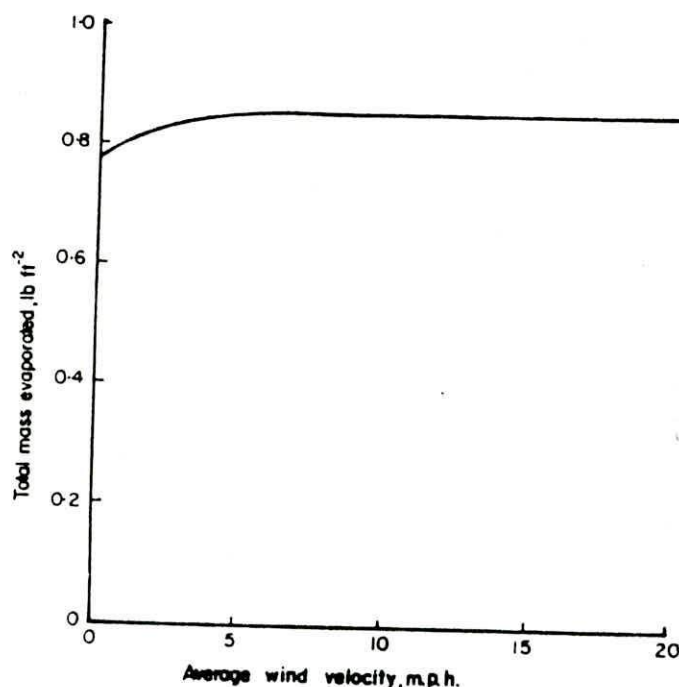


Figure 2-5: Still Production for Different Average Wind Velocities (After Cooper, 1969)

2.7.3 EFFECT OF SOLAR RADIATION AND LOSS COEFFICIENT

The effect of solar radiation (total) and the loss coefficient on the daily output have been shown (United Nations report, 1970) in Figure 2-6 and 2-7 respectively. It is clear from Figure 2-6 that in determining the output of a still (having different loss coefficients) solar insolation is the single most important parameter. It will depend to some extent upon how the radiation is distributed throughout the day (United Nations report, 1970). However, this is a second order effect and it is usually sufficient to consider only the total radiation received each day. The best situation for a solar still is one where both the daily insolation (Akinsete *et. al.* 1979) and the mean ambient temperature are consistently high. The loss coefficient has less influence at higher ambient temperatures. The decrease in loss coefficient by a factor of 5 increases the output by about 45% which is in close agreement with the work of Morse and Read (1968).

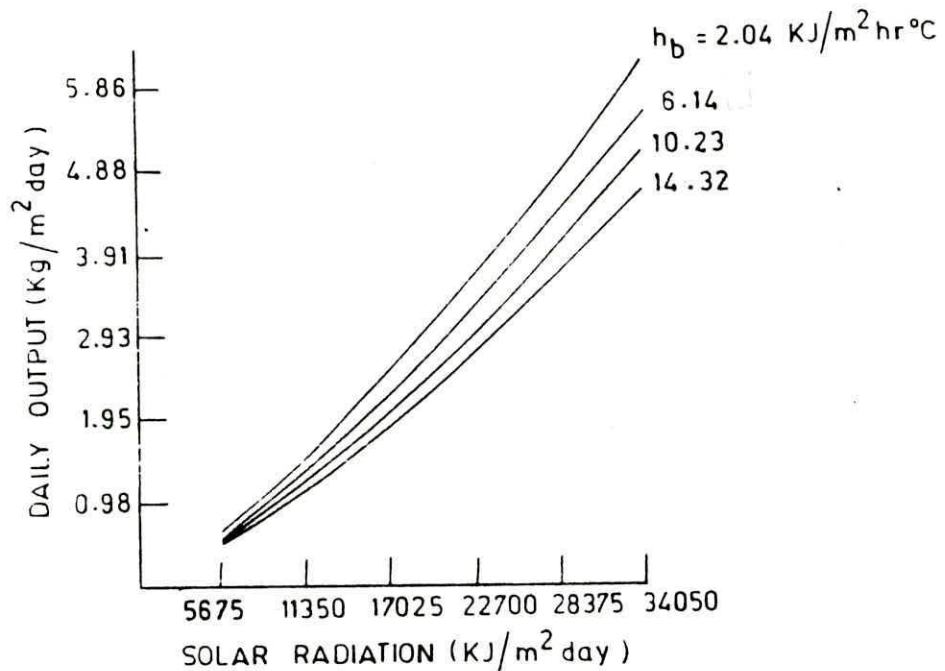


Figure 2-6: Effect of Solar Radiation and Loss coefficient on Predicted Still Output at Ambient Temperature $T_a = 27^\circ\text{C}$ Heat capacity $M_{wo} = 327 \text{ KJ/m}^{20}\text{C}$ Wind Velocity $\theta = 2.23 \text{ m/sec}$. (After United Nations, 1970.)

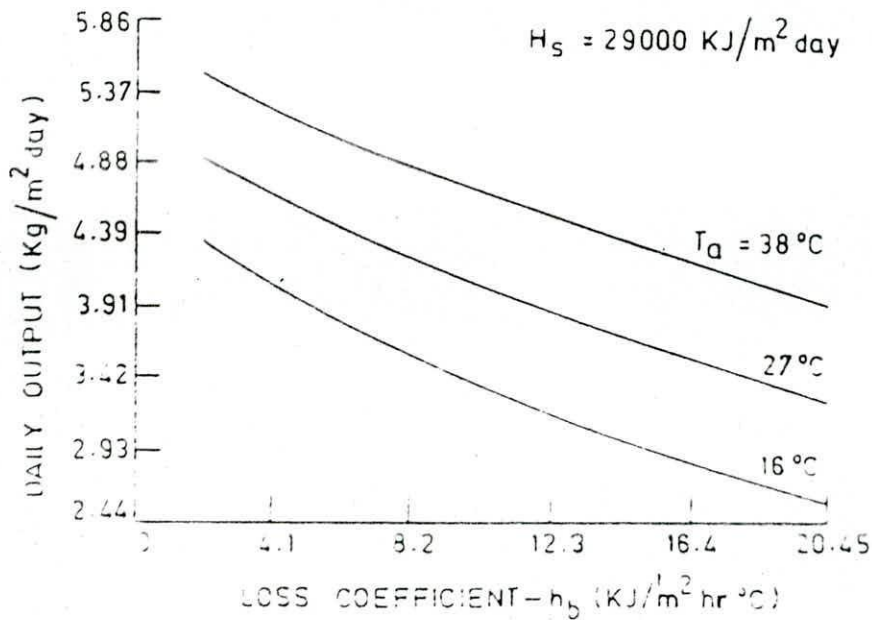


Figure 2-7: Effect of Ambient Temperature and Loss Efficiency on Predicted Still Output at $H_s = 29000 \text{ KJ/m}^2 \text{ day}$. (After United Nations, 1970.)

2.7.4 EFFECT OF BRINE DEPTH IN SOLAR STILL

Lof (1966) found that the total production increased approximately 8 percent by reducing the water depth from 1 foot to 6 inches and furthermore the production increased approximately by another 25 percent when the water depth was reduced from 6 inches to 2 inches. Cooper (1969a) has also studied the effect of water depth on the distillate output. He suggested that without insulation, the gains from decreasing the water depth are only marginal, but with the insulation the difference is more marked, especially at shallow water depths. A 30% variation was found for water depths from 5 inch (12.7 cm) to 12 inch (308 mm). Still production for varying water depths with and without insulation has been shown in Figure 2-8.

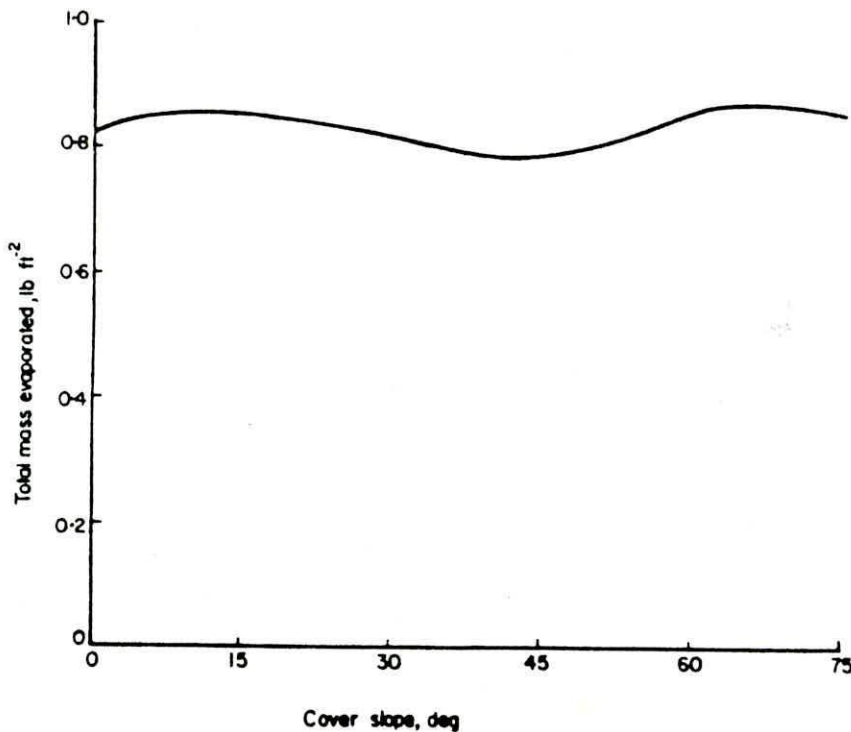


Figure 2-10: Still Production for Varying Cover Slope. (After Cooper, 1969a.)

2.7.8 EFFECT OF THERMAL CAPACITY ON OUTPUT

Morse and Read (1968) have studied the effect of thermal capacity of water on the output of the still. They recommended a water depth of about 7.6 cm (3 inch), corresponding to thermal capacity of 1.41 (KJ/m² for the CSIRO ground-based still (Australia) with bottom insulation and 2.54 cm (1 inch) water depth for the still resting on the ground without any insulation. For a daily insulation of 225 KJ/m² hr, reducing thermal capacity from 1.41 KJ/m² to 5.64 KJ/m² °C (equivalent to 0.3m depth of water) would reduce the output by 7%. It follows therefore that, while the water depth is not a critical parameter, it should be as small as possible (Morse and Read, 1968).

2.4.9 EFFECT OF CHARCOAL PIECES IN THE PERFORMANCE OF A STILL

Akinsets and Duru (1979) have studied the effect of charcoal pieces on performance of a still because of its wettability, large absorption coefficient for solar radiation and their property to scatter, rather than reflect, the solar radiation. It was concluded that the effect of charcoal is most pronounced in the mornings and on cloudy days when the values of direct

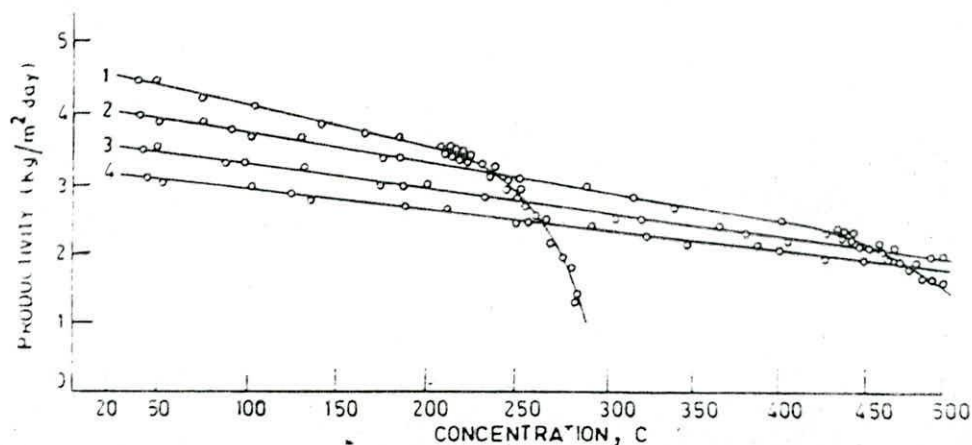


Figure 2-9: Still Production as Function of Salt Concentration in the Initial Water ($C = 100\%$ for Natural Water in Each Lake): 1-4 Lakes Khulis, Tudakul, Makhankul, and Kum-Mazar. (After Baibutaev et al., 1970.)

As reported by Lof (1966), the distillate decreased put 10 percent as salinity was increased from 0 to 20 percent. With the normal range of salinity of 3 to 8 percent, the effect was found to be negligible.

2.7.7 EFFECT OF COVER INCLINATION

The variation of distillate production with glass cover inclination has been studied by Cooper (1969b) in detail and the variation of production with cover slopes is shown in Figure 2-10. It was found that the evaporation rate decreases with cover slope variation from 0° to 45° , rises at about 60° and falls again beyond 75° . According to Lof (1966), the productivity is not affected by increasing the slope from 10° to 45° and the United Nations (1970) reported that the slope of the glass cover must be between 10° to 18° to the horizontal to avoid the dripping of condensate back into saline water and to keep capital cost minimum. Garg and Mann (1976) has suggested that the optimum angle of glass cover for Indian climates is 10° - 15° .

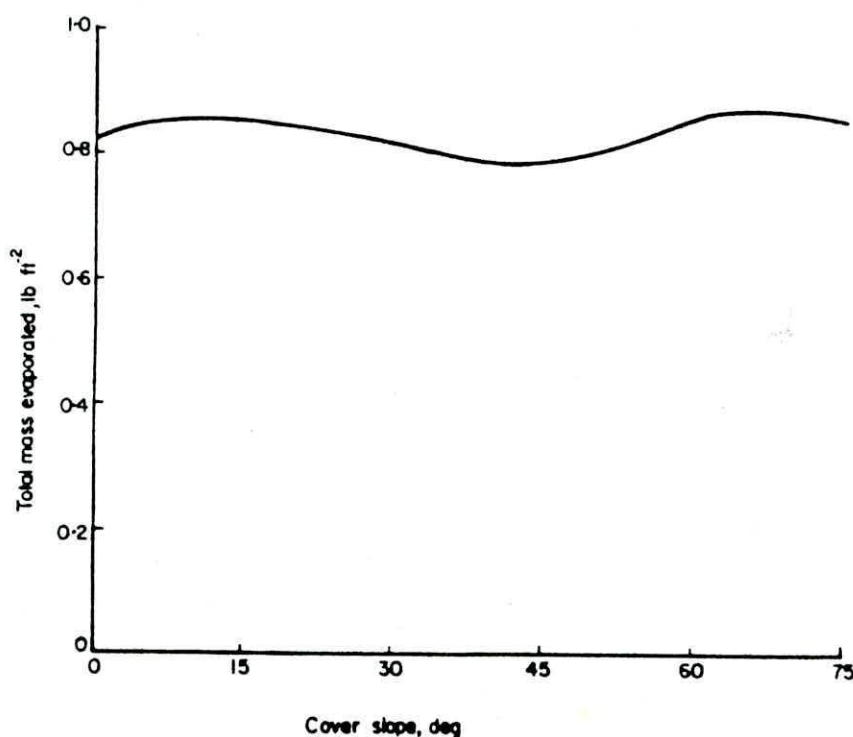


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radiation are low. This result implies that the presence of charcoal pieces reduces the start up time and utilizes the diffuse radiation much better than the conventional unlined still. They have also concluded that the charcoal lined still is relatively insensitive to basin water depth as long as a good amount of the charcoal remains uncovered.

2.7.10 EFFECT OF NATURAL AND FORCED CONVECTION

According to Crune (1962), natural convective stills gave efficiencies from 13.9% for a deep-basin unit with a 30° roof-type mylar cover to 38.2 percent for a still with an extended wick-type and a wettable glass cover. On the other hand, forced convection stills gave efficiencies from 50 and 60%. Cooper (1973) tested an "ideal still" and concluded that the maximum attainable ideal efficiency over one day operation will rarely exceed 60% and for a practical still during the period of high solar radiation intensity and ambient temperature, the efficiency would be about 50%.

2.7.11 EFFECT OF THE FORMATION OF ALGAE AND MINERAL LAYERS ON WATER AND BASIN LINER SURFACE ON PRODUCTIVITY OF A STILL

Cooper (1972) has shown that the presence of deposits on the surface of the basin water and basin liner have a detrimental effect on the output, assuming that no other factor becomes significant. He pointed out that surface reflection appears to be more detrimental than basin liner (bottom of still) reflection because of the absorbing properties of the basin liner except at normal incidence of insulation. There is an increase of 8-15% in the measured albedo as taken on some black surface relative to the scaly surfaces in the solar still. For example a reflection of 21.7% was found by Cooper (1972) with a thin, floating, whitish surface scale. The reflection of a identical location at approximately the same time, but a reasonably clean water surface and a black butyl rubber liner gave a measured reflection of only 13.7%.

2.7.12 THE EFFECT OF DROPWISE CONDENSATION ON GLASS SOLAR PROPERTIES

The change of heat transfer characteristics of surface covered with water condensation has been a subject of intense research only insofar as it is related to heat convection. In fact in the flat plate solar collector, especially in the solar distillation, dropwise condensation on glass surface often occurs and can be a dominating factor affecting the performance of the device. There are two factors which make the study of surface radiative characteristics of dropwise condensation less than trivial. The first is the rapid variation of water absorption coefficient with wavelength. With the water droplets varying in size in practice, its

transmission and reflection cannot be predicted with reasoning. The second complication is the fact that when radiation enters into the water droplet and crosses the water-air interface, because of the smaller refractive index occurring at the air side, total reflection will take place for rays of large incident angles. These may also experience longer path length of traveling, thereby attenuating more energy. As a result the multi-reflections in the water droplet cannot be neglected and this complicates the formulation.

Hsieh and Rajsvanishi (1975) studied the effect of dropwise condensation on glass solar properties. According to him a clean glass surface has a surface solar transmittance of 0.958 and reflectance of 0.042 whereas a clean glass plate has bulk transmittance 0.853 and (the term "bulk glass" has been used to mean the glass having water drops on its surface) bulk reflectance of 0.075. Thus with dropwise condensation occurring on one surface, the bulk solar transmittance of glass drop about 11 percent while reflectance increases 79 percent for the size of the water droplet studied. The presence of dropwise condensation has thus proved to present a serious problem reducing the actual energy that can be received in a solar energy device.

The above discussion enables to know what the real amount of radiation is that enters the solar still. So once the true transmittance and reflectance values of the bulk glass are known the truly extracted energy can be evaluated.

2.8 ECONOMIC ASPECTS

Distillation of brackish/sea water for supplying fresh water is thought of obviously, only for those regions that do not have a nearby supply of natural fresh water. The capital costs and water production costs depend upon the design, quality of materials, cost and availability of labor, maintenance cost, life span etc. and vary from place to place. The first significant economic analysis of solar distillation systems was made by Lof (1962). In that study the cost of production of distilled water from sea water by solar distillation was compared with that by vapor compression and multi-stage flash distillation techniques. Solar still construction costs were obtained from previous estimates and the prices of the other two systems from manufacturers. Operational costs were worked out from estimates of labor requirements and the manufacturers data. An optimistic life span of 50 years was assumed for the asphalt-glass solar still.

Capital costs of basin-type solar stills range from \$0.60-\$2.00/ft² and water costs range from \$3 to \$6 per 1000 gallons (3780 liters) as reported in the United Nations report (1970).

2.9 CALCULATION OF EFFICIENCY

The conventional efficiency terms represents the efficiency (output/input) as follows :

$$\eta = \frac{57.78 \times 10^2 \times Y}{R} \quad (2.24)$$

Where,

η = efficiency values expressed as percentage

Y= distillate produced by the plant (l/m² day)

R= incoming solar radiation (cal/cm² day)

It is worthwhile to note that the efficiency of a typical basin-type solar still is quite low and is not greater than 35% (Farid, 1992).

In the Section 2.7.12, it is seen that the presence of dropwise condensate on the glass cover causes an obstruction for the solar energy to enter into the plant through the condensate cover. So, the total solar radiation measured by the pyranometer is not actually coming in to the solar still and hence not received by the stored water. So, in reality, the actual plant efficiency is somewhat higher than the value found by the equation. (2.24).

2.10 VARIOUS APPROACHES FOR STATISTICAL ESTIMATIONS

2.10.1 FREEHAND METHOD OF CURVE FITTING

Individual judgment can often be used to draw an approximating curve to fit a set of data. This is called a *freehand method of curve fitting*. If the type of equation of this curve is known it is possible to obtain the constants in the equation by choosing as many points on the curve as there are constants in the equation. For example, if the curve is a straight line, two points are necessary and if it is a parabola, three points are necessary. The method has the disadvantage that different observers will obtain different curves and equations (Spiegel, 1981).

2.10.2 THE METHOD OF LEAST SQUARES

To avoid individual judgment in constructing lines, parabolas or other approximating curves to fit sets of data, it is necessary to agree on a definition of a "best fitting line", "best fitting parabola", etc.

To motivate a possible definition, consider Figure 2.11 in which the data points are given by (X_1, Y_1) , (X_2, Y_2) , (X_N, Y_N) . For a given value of X , say X_1 , there will be a difference between the value Y_1 and the corresponding value as determined from the curve C . As indicated in the figure this difference is denoted by D_1 , which is sometimes referred to as a deviation, error or residual and may be positive, negative or zero. Similarly, corresponding to the values $X_2, \dots, X_N$ the deviations are $D_2, \dots, D_N$.

A measure of the "goodness of fit" of the curve C to the given data is provided by the quantity

$D_1^2 + D_2^2 + \dots + D_N^2$. If the above is small the fit is good, if it is large the fit is bad. Of all curves approximating a given set of data points, the curve having the property that $D_1^2 + D_2^2 + \dots + D_N^2$ is a minimum is called a best fitting curve (Spiegel. 1981).

A curve having this property is said to fit the data in the *least square sense* and is called a *least square curve*. Thus a line having this property is called a least square line, a parabola with this property is called a least square parabola, etc.

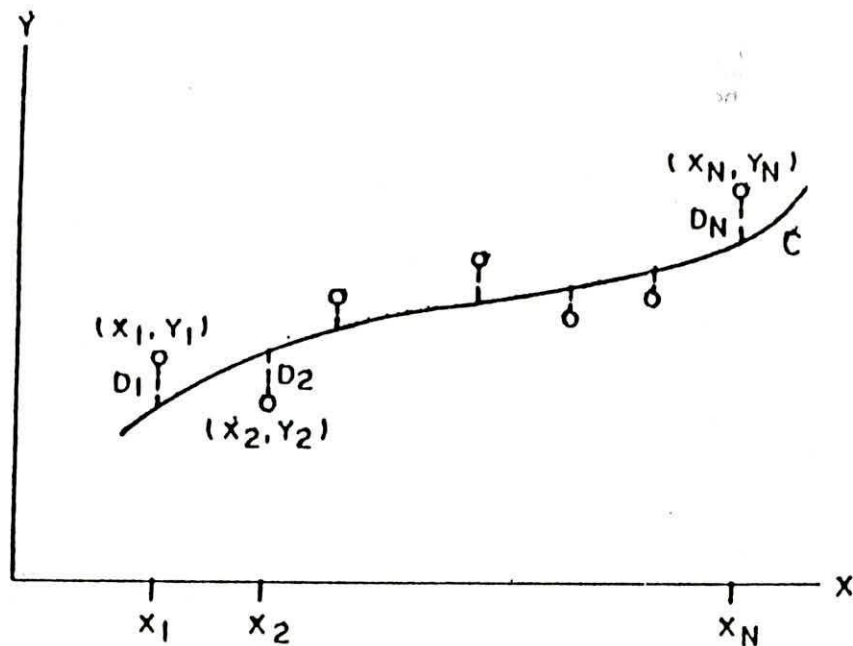


Figure 2-11: Method of Least Squares.

2.10.3 THE LEAST SQUARE PARABOLA

The least square parabola approximating the set of points (X_1, Y_1) , (X_2, Y_2) , $\dots$, (X_N, Y_N) has the equation

$$Y = a_0 + a_1 X + a_2 X^2 \quad (2.25)$$

where the constants a_0 , a_1 and a_2 are determined by solving simultaneously the equations

$$\sum Y = a_0 N + a_1 \sum X + a_2 \sum X^2 \quad (2.26)$$

$$\sum XY = a_0 \sum X + a_1 \sum X^2 + a_2 \sum X^3 \quad (2.27)$$

$$\sum X^2 Y = a_0 \sum X^2 + a_1 \sum X^3 + a_2 \sum X^4 \quad (2.28)$$

called the normal equations for the least square parabola.

2.10.4 MULTIPLE CORRELATION AND NON-LINEAR MULTIPLE REGRESSION

The degree of relationship existing among three or more variables is called multiple correlation. The fundamental principles in problems of multiple correlation are analogous to those of simple correlation.

It is however clearly understood that in multiple regression there will be one dependent variable and more than one independent variables. For examples if the dependent variable Y depends on X_1, X_2, X_3 linearly then it can be written

$$Y = a + bX_1 + cX_2 + dX_3 \quad (2.29)$$

The normal equations corresponding to the least square plane are given by,

$$\sum Y = aN + b \sum X_1 + c \sum X_2 + d \sum X_3 \quad (2.30)$$

$$\sum YX_1 = a \sum X_1 + b \sum X_1^2 + c \sum X_1X_2 + d \sum X_1X_3 \quad (2.31)$$

$$\sum YX_2 = a \sum X_2 + b \sum X_1X_2 + c \sum X_2^2 + d \sum X_2X_3 \quad (2.32)$$

$$\sum YX_3 = a \sum X_3 + b \sum X_1X_3 + c \sum X_2X_3 + d \sum X_3^2 \quad (2.33)$$

For given set of values of X_1, X_2, X_3 and Y the above set of equations can be solved for a, b, c, d .

In the equation (2.29) the independent variables have exponent one and hence the equation is multiple linear equation. When these linear terms are replaced by the non-linear terms (i.e. terms of multiple degree) then this equation becomes a non-linear multiple regression equation which again can be solved for its coefficients in the similar fashion.

2.11 THE ACCURACY OF ESTIMATE

When one variable is dependent on the other variables then the dependent variables are expressed in terms of the independent variables by an equation. In case when sufficient data is available for these dependent and independent variables collected under the same conditions and corresponding to the same situation then from those available data a relation can be generated by the statistical approach. A such regression equation is developed which is nothing but a line of least square. Say $Y = f(X_1, X_2, \dots)$ and sufficient data of $Y, X_1, X_2, \dots$ under the similar condition are available. Then a least square line or a regression equation of Y in terms of $X_1, X_2, \dots$ is developed which predicts the nearest possible Y values. The accuracy of the estimated Y value (Y_{cal}) can be tested by calculating the mean bias error (MBE), root mean square error (RMSE) and mean percentage error (MPE) etc. and the measure of how good the regression equation is fit is estimated by the coefficient of correlation. The MBE, RMSE, MPE and coefficient of correlation are defined as follows :

$$MBE = (\sum [Y_{cal} - Y_{act}])/n \quad (2.34)$$

$$RMSE = (\sum \frac{\{Y_{cal} - Y_{act}\}^2}{n})^{1/2} \quad (2.35)$$

$$MPE = \sum \left[\frac{Y_{cal} - Y_{act}}{Y_{act}} \right] \times \frac{100}{n} \quad (2.36)$$

$$\begin{aligned} \text{Coefficient of correlation (r)} &= \sqrt{\frac{\text{explained variation}}{\text{total variation}}} \\ &= \pm \sqrt{\sum (Y_{cal} - \bar{Y})^2 / \sum (Y_{act} - \bar{Y})^2} \end{aligned} \quad (2.37)$$

Where,

Y_{act} = actually measured value

Y_{cal} = value of Y calculated by using the regression equation.

$\bar{Y}$ = arithmetic mean of the actually measured Y values and

n = number of observations

The lower the RMSE value the more accurate the estimate is. A positive MBE shows over estimation while a negative MBE shows under estimation. While calculating the MPE value, the sign of the error are neglected in many cases and the percentage errors are added up to calculate the mean. The smaller the value of square of residuals fraction better is the estimation and a value of zero represents perfectly realistic situation. The coefficient of

correlation varies between -1 to +1. The sign (+,-) are used for positive correlation and negative linear correlation respectively. This is a dimensionless quantity and does not depend on the unite employed. For the case of linear correlation, the value of coefficient of correlation is the same regardless of whether X or Y is considered as the independent variable. Thus this is a very good measure of the linear correlation between the two variables.

2.12 THE INTERPRETATION OF MISSING DATA

In developing the regression equation consisting of one dependent variable and few independent variables continuous data set of all these variables is needed. Say, while developing the regression equation of distilled water amount (produced by a solar still) in terms of the days of operation of the solar plant, the distillate production data of the plant on various days for a span of period has to be collected. This may not be possible uninterruptedly for a long time. What really happens in most of the practical cases is there occurs a break or interruption of measurement on few occasions. Some common techniques are generally adopted to minimize the statistical deviations due to such occurrences. Unless any drastic change of these parameters is expected on these occasions the following methods are adopted for prediction of such missing data for the purpose of providing a continuation of the data set :

Averaging Method

Say in a study of 365 days data lost or missed values for any two intermediate days can be assigned equal to the average value of the rest 363 days.

Linear Interpolation

For the above mentioned case the value against the two lost days can be assigned by interpolation method. The interpolation is being done with respect to the two adjacent days just before and after such lost days. An extrapolation may however be needed if these lost days are not the intermediate days but are the terminating test days. Such extrapolation is generally done with respect to the two days just preceding these two lost days.

Graphical Method

This requires the variation of dependent variable to be plotted against the independent variable excluding the values of the lost days (i.e. ordinates corresponding to the lost days are kept blank in the graph). Then a smooth curve is drawn over the available points of the

graph. Now, the value represented by this curve corresponding to those lost days interpret the missing value. This method has the major short coming regarding the fact that it can be applied when there is only one independent variable.

Polynomial Interpolation

This is almost the same as the graphical method but the difference is that instead of drawing a curve with the available data, here the attempt is to generate a polynomial equation. The value given by this polynomial for those lost days represent the lost value. This method is considered to be the most accurate and the major advantage lies in the fact that this has the benefit of using multiple independent variables against one dependent variable. Again this method needs sufficient tools for developing the polynomial equation against the given set of data.

2.13 PREDICTION OF STILL YIELD

Rahman (1994) has developed different mathematical models (equations) for the prediction of still yield from the available meteorological data for the ferrocement plant. Among the models, the following three may be noted.

$$Y = 0.706 + 3.362T + 0.696S^2 - 3.383R \quad (2.38)$$

$$Y = 0.641 + 2656.18T^6 + 0.304W^3 + 371.959 R^5 \quad (2.39)$$

$$Y = 0.719 - 213.901T^4 + 0.044H^5 + 119.892R^4 \quad (2.40)$$

where,

Y = Yield of ferrocement plant (liter/m²)

T = Air Temperature (degree Celsius/100)

S = Sunshine Hour (hours/10)

R = Radiation (cal/cm² day/1000)

W = Wind Speed (knots/10)

H = Relative humidity (value/100)

Gauss's Elimination process was used to solve the equations for the coefficients in the computer program based on FORTRAN (Davis and Hoffman, 1986; Kumar, 1986).

The program was developed with very short duration data and for a specific plant.

Chapter 3
EXPERIMENTAL INVESTIGATIONS
AND ANALYSIS

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EXPERIMENTAL INVESTIGATIONS AND ANALYSIS

3.1 GENERAL

The construction and use of solar still as a desalination unit is still in research stage in Bangladesh. This chapter describes the design and construction details of family size solar still plant with special attention on materials of still. The principal criteria for selection of materials and developing the design of still was local availability of materials and cost involvement, efficiency, and ease of construction and maintenance. Family size solar stills suitable for application on small scale were designed, constructed and installed at Department of Civil Engineering, BUET. Such type of stills, six in number, each with some difference in design characteristics were tested. Four stills were also constructed at Kaliganj, Satkhira to study their performance in the coastal area. The emphasis is given on the various steps to be followed for the still construction and its smooth operation. The different parameters such as water and glass surface temperature within the still has also been reported in this chapter. The efficiencies of solar stills in producing drinking water in terms of incoming radiation were investigated. The convective heat transfer, thermal radiation and heat condensation were calculated for the solar stills.

The performance of a solar still is directly related on the climatic factors such as solar radiation, air temperature, sun shine hour etc. These climatic parameters vary season to season. The variation of these factors over the year were studied to get an idea about the plant yield through out the year. These parameters were used to predict the still output for a given period. This prediction could provide an idea of the solar still output that is helpful in decision making process for the installation of solar still as a provision for fresh water from saline water. Attempt was made to predict the solar still output using the different climatic factors.

3.2 LOCATION OF STUDY

The laboratory test were carried out at the top of the Civil Engineering Building, BUET, Dhaka. Dhaka is situated as 9 m above the MSL and is located at 23°46' N latitude and 90°23' E longitude (Figure 3.1). The field test was carried in the premises of Department of Public Health Engineering, Thana: Kaliganj, District: Satkhira. Satkhira is situated as 4 m above the MSL and is located at 22°43' N latitude and 89°05' E longitude (Figure 3.1).

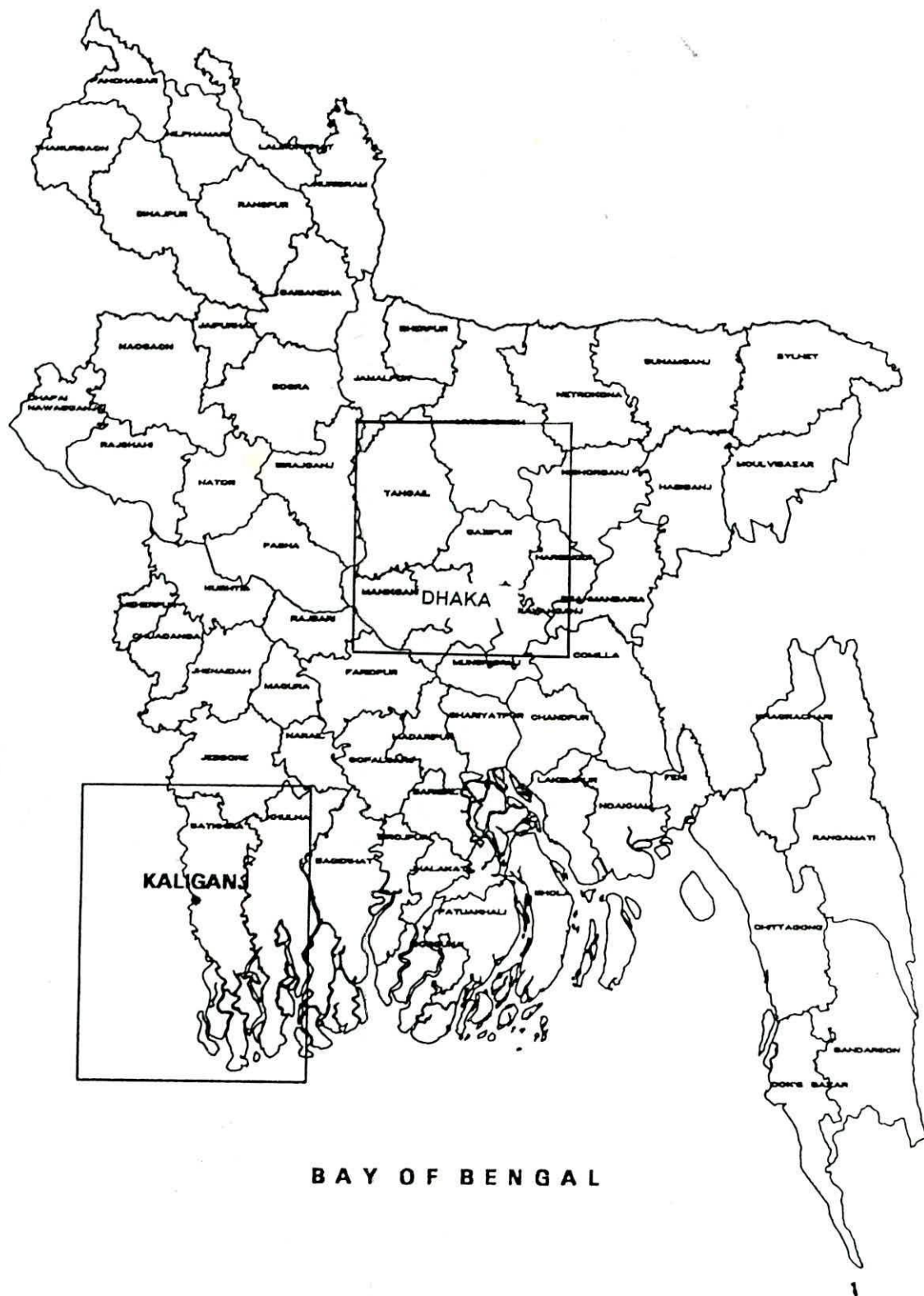


Figure 3-1: Study Location

3.3 CONSTRUCTION OF SOLAR STILL

3.3.1 Construction Phase

The study was carried out in a two phases. In the first phase of the study, different types of materials were considered for construction of solar stills. However, only plants constructed with ferrocement and brick (two types) were operated as these produced reasonable amount of yield. The other constructed and tested plants were wooden plant, mild steel plant and Ryan Foundation type plant [Ryan Foundation (1990)].

In the phase 2, field investigations were commenced in the coastal areas while laboratory investigations continued at BUET. Three types brick plants and one clay plant (cement plastered) were constructed at Kaliganj. Experimental investigations at BUET were continued with six plants. These comprised three plants of phase 1 and three new constructed brick plants.

3.3.2 Selection of Material

The principal criteria for selection of materials and developing the design of still was local availability of materials and cost involvement, efficiency, and ease of construction and maintenance.

Still base and wall Material : Different types of materials were considered for construction of solar stills. However, ferrocement and brick were selected for this purpose. Mild steel and wooden solar stills were reviewed earlier. The wall and base of the still were made of the same material. Ferro cement and brick plants were given preference for their durability, cost-effectiveness and easy maintenance facilities. The brick plants were cement plastered. Clay was also used in one plant as base and wall materials. The clay was also cement plastered.

Cover Material : Glass or transparent plastic sheet can be used as cover material. Glass and transparent plastic sheet both suffers breakage or damage problems. But, glass sheet enjoys some advantage over plastic sheet such as non-leakage of water vapor and condensate and can normal withstand wind. Glass was given preference over plastic because of short service life of the latter. Seven plants were constructed using ordinary window glass of 0.197 inch (5 mm) thickness and other three were constructed using transparent plastic sheet.

Sealant Material : Sealant material was required to prevent leakage of water vapor and condensate. Butyl rubber strip was used for this purpose. Rubber gasket was also used in Ferrocement Plant as sealant Material. A sealant material prepared from adequate mixer of Chalk dust and Tarpin oil was also used at the edge of the glass to prevent any losses of heat and evaporation.

Insulation Material : Various insulation materials were available but none was used for the following reasons.

- to minimize the construction cost,
- to eliminate construction complexities,
- to avoid the materials which were not easily available in different parts of the country.

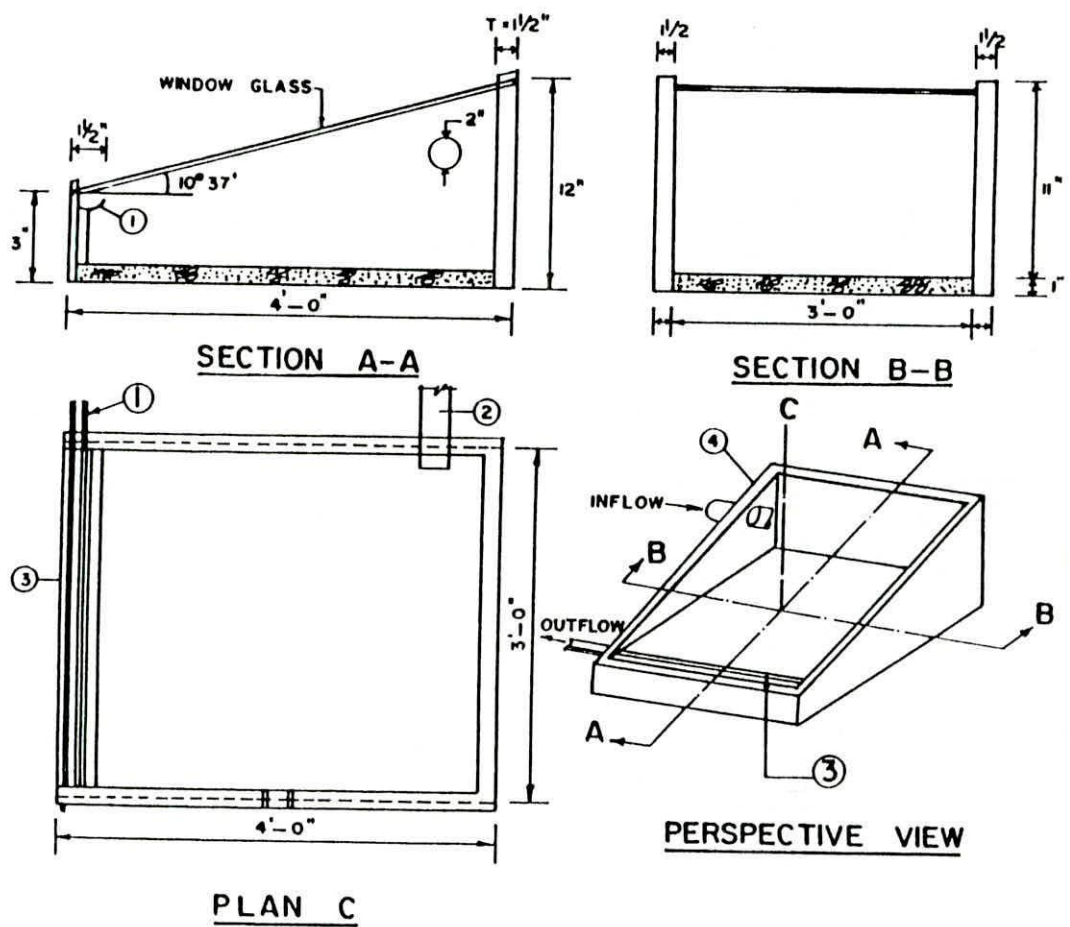
3.4 CONSTRUCTION DETAILS OF PLANTS

3.4.1 Ferrocement Plant

Ferrocement was constructed with a cement sand ratio of 1:2 and water : Cement ratio of 0.6 along with 1/2 inch sized wire mesh. Construction works were carried out at different stages in the Concrete Laboratory of the Civil Engineering Department of BUET. Casting of a single plant was carried out in a single day without any break of work. The thickness of the base was 1 inch and that of the wall was 1.5 inch. Figure 3.2 shows the construction details of the Ferrocement Plant. This plant was operated at BUET campus from January 01, 1994 to December 28, 1995.

3.4.2 Brick Plant 1

The brick plant was constructed on the roof of the Civil Engineering Building of BUET. Figure 3.3 shows the design details of this plant. In this plant, the thickness of the base and the wall were 3.25 inch and 3.5 inch respectively. The transparent glass cover of the plant was made to rest on the three side walls and to the inner face of the brick wall. A one-third-cut section of a plastic pipe was attached to the same face of the wall beneath the edge of the glass cover. This plant was constructed in August, 1994 and operated up to December, 1995.



1. OUTLET GUTTER
2. INLET PIPE (G.I. PIPE)
3. GLASS STRIP
4. BASIN WALL (1/2" Thick)

Figure 3-2: Design Details of Ferrocement Plant

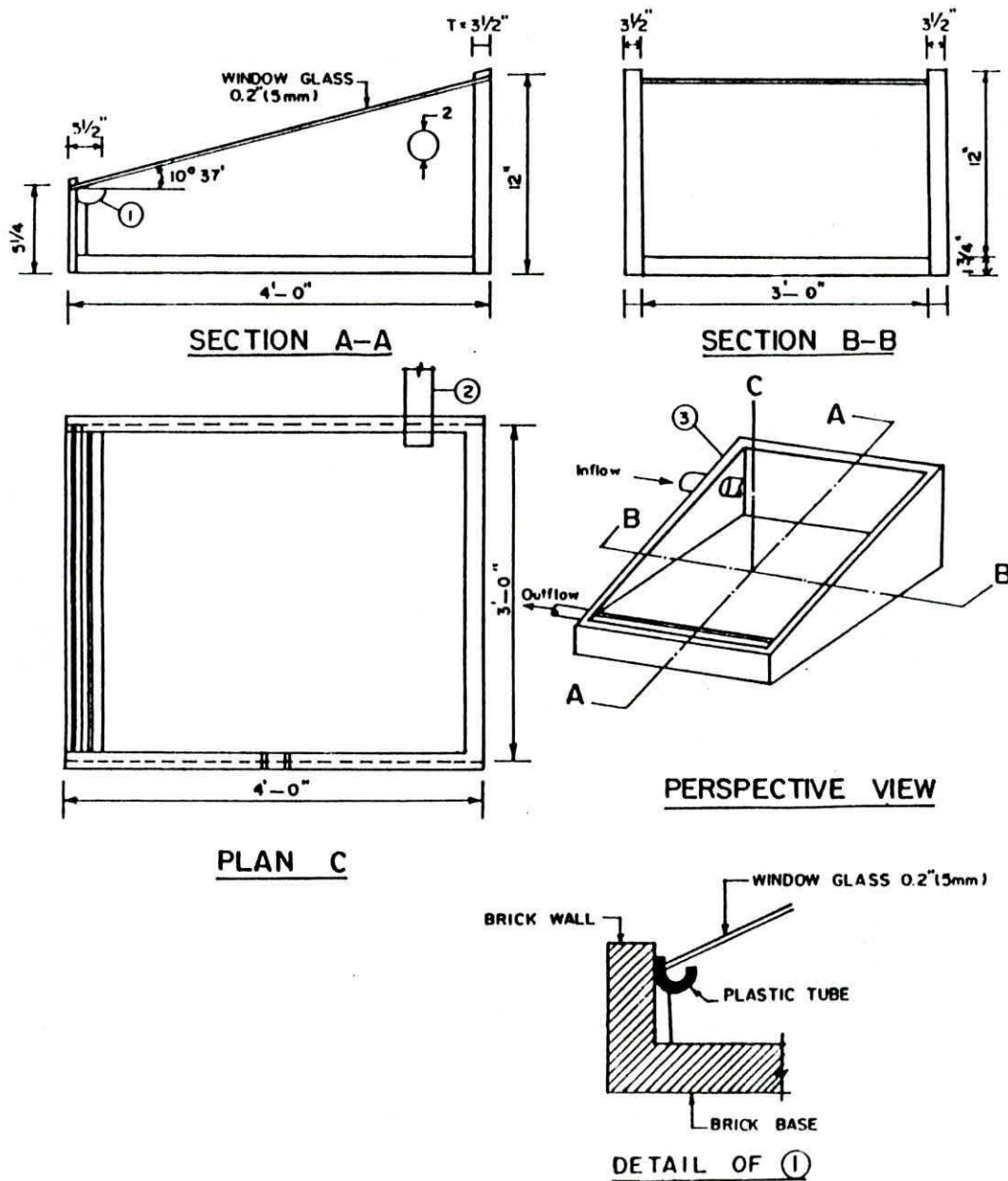


Figure 3-3: Design Details of Brick Plant 1

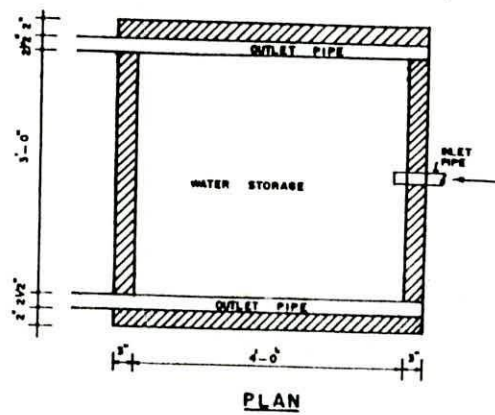
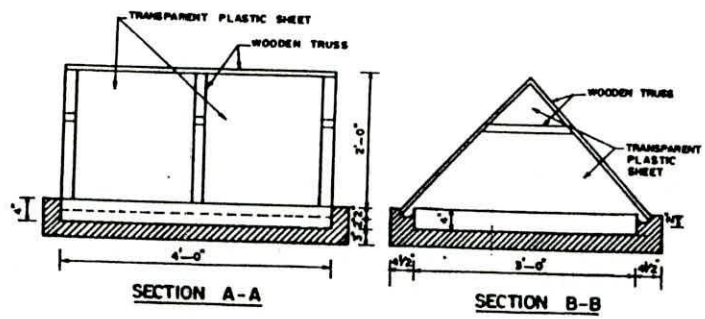
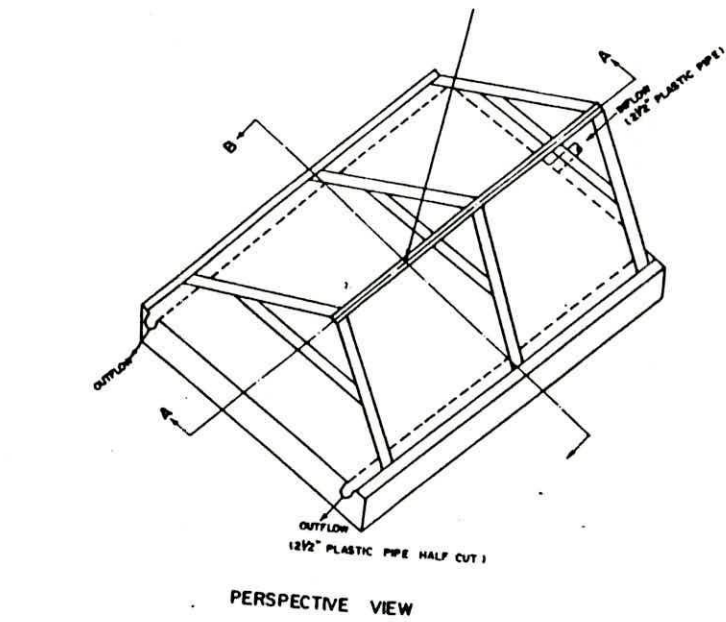


Figure 3-4: Design Details of Brick Plant 2

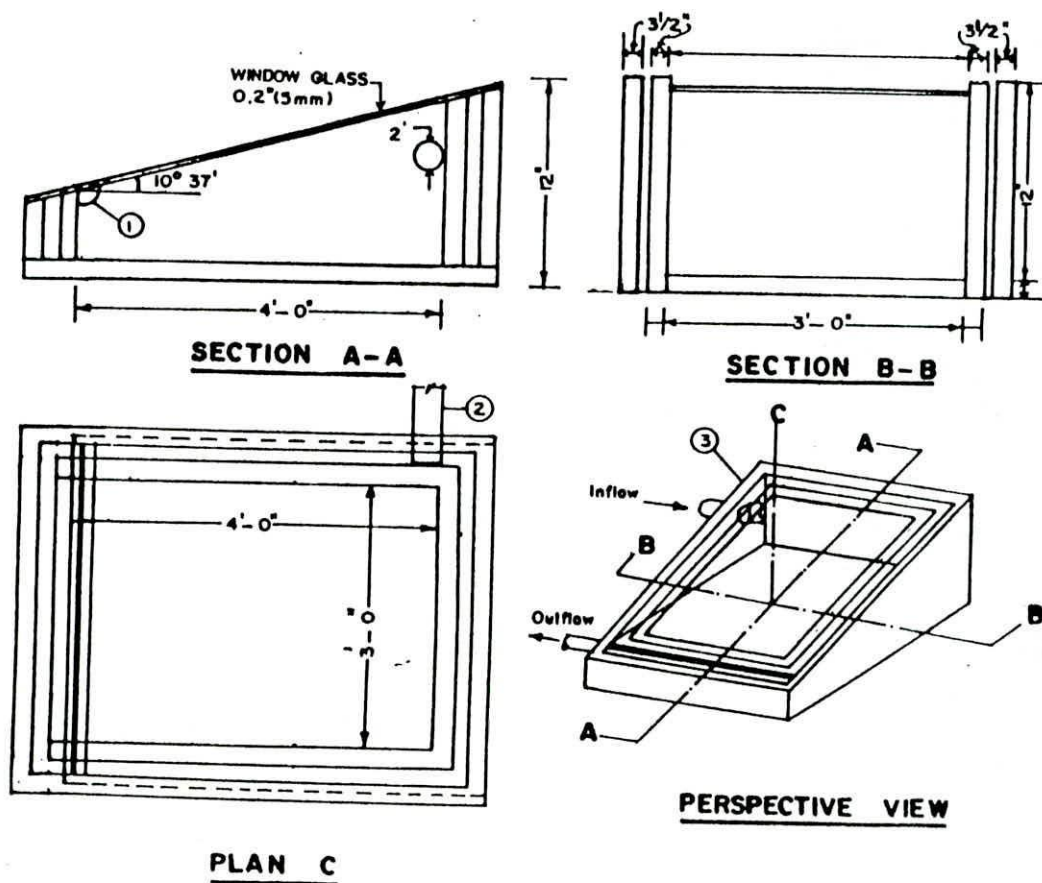


Figure 3-5: Design Details of Brick Plant 3

3.4.3 Brick Plant 2

Plastic sheet was used as transparent cover in the second brick plant. It had a double slope. The plastic cover was held in place with the help of a wooden frame. The plastic cover was tightened with wooden frame with board pin. Two half-cut section of a plastic pipe was attached to the inner face of the longitudinal side wall beneath the edge of the wooden frame and subsequent plastic sheet. The thickness of the base and the wall were same as Brick Plant 1. Design details of this plant is shown in Figure 3.4. This plant was constructed during September, 1994 and operated up to December, 1995.

3.4.4 Brick Plant 3

This plant was similar to brick plant 1 but with double layer of brick wall with air gap between them (Figure 3.5). The inner dimension was same as that Brick Plant 1. Double layer brick wall was provided to prevent loss of heat through the walls resulting in greater amount of yield. The increase in cost involvement was studied with increase in distillate production. This plant was constructed during November, 1994 and operated up to December, 1995.

3.4.5 Brick Plant 4

This plant was similar to Brick Plant 1 with a different slope angle. The slope angle was 13° . The slope angle was changed to study its effect on yield. This plant was constructed during December, 1994 and operated up to December, 1995.

3.4.6 Brick Plant 5

This plant was similar to Brick Plant 1 with a different slope angle. The slope angle was 15° . The slope angle was also changed to study its effect on yield. This plant was constructed during December, 1994 and operated up to December, 1995.

3.4.7 Brick Plant 6

This plant similar to Brick 1 and it was constructed at Kaliganj, Satkhira during March, 1995 and operated up to March, 1996.

3.4.8 Brick Plant 7

This plant was similar to Brick Plant 3. It was constructed at Kaliganj, Satkhira during March, 1995 and operated up to March, 1996.

3.4.9 Brick Plant 8

This plant was similar to Brick Plant 2 but the length was increased to 6 ft to study the increased amount of yield vis-à-vis the increased cost of construction. It was also constructed at Kaliganj, Satkhira during March, 1995 and operated up to March, 1996.

3.4.10 Clay Plant (Cement Plastered)

This plant was similar to Brick Plant 2. However the wall was made of clay and plastered with cement-sand mortar. This plant was constructed and operated at the field for the period of March, 1995 - March, 1996. Clay was selected as construction materials for its less cost involvement and easy availability.

3.5 PROVISION FOR DIFFERENT FUNCTIONS

3.5.1 Provision for Water Inlet

A 2 inch (50.8 mm) diameter GI pipe with 12 inch length was used as inlet of saline water for the Ferrocement Plant. 2 inch (50.8 mm) diameter PVC pipes with 18 inch length were used as inlets for the brick plants. The length of water inlet for Brick Plant 2, Brick Plant 8 and Clay Plant were 12 inch. The inlet had a slope of 25° and inclination towards its inside. The outer side opening of the inlet was sealed with cotton and covered tightly with simple plastic covers to prevent heat and vapor losses during the normal operation period of the plants.

3.5.2 Provision for Distillate Outlet

A 1.5 inch (38.1 mm) diameter half-cut PVC pipe was used as a gutter which assisted in getting fresh water out of the Ferrocement Plant. For Brick Plants, the diameter of the PVC pipe was 2.0 inch. The gutter with 1.5° slope and an inclination towards its projection outside had its one long edge slightly embedded in the basin wall. The portion of PVC within the brick plant was one-third-cut, but the portion inside the side brick wall and outside the plant were not cut. The portion of outlet PVC was cut by saw machine of Carpentry Laboratory of BUET. The portion of outlet PVC was cut by hand saw at Kaliganj.

3.5.3 Provision for Thermometers

Two grooves were provided on the side wall for inserting two thermometers to measure the water and glass surface (inner face) temperature. These were positioned at the top edge of the wall exactly below the glass cover. For Brick Plant 2, Brick Plant 8 and Clay Plant, there was only one groove to measure the water temperature. The temperature of transparent plastic sheet cover was not recorded for difficulties in reading. The grooves were sealed with cotton during the normal operation period of the plants.

3.5.4 Placement of the Transparent Cover

To place the transparent cover properly the following points were taken into consideration.

Angle of Inclination

As suggested by the earlier research works, the optimum angle of tilt of the transparent cover should be kept between 10° to 15° for Indian region. Ferrocement Plant, Brick Plant 1, Brick Plant 3, Brick Plant 6 and Brick Plant 7 were constructed with an angle of tilt of about $10^{\circ}37'$. In Brick Plants 4 and 5, the angles were 13° and 15° respectively. The angle used for Brick Plant 2, Brick Plant 8 and Clay Plant for transparent Plastic cover were $57^{\circ}13'$.

Additional Glass Strip

An additional glass strip of 0.12 inch thickness, 0.39 inch width and 2 ft 9 inch length was attached inside the glass cover. This was attached with the glass cover just above the outlet gutter keeping the strip length along the width of the basin. It facilitated the water vapor that condenses on the interior surface of the glass cover to trickle into the outlet gutter. However, in the Brick Plants, no such additional glass strip was necessary as the edge of glass sheet were inserted into PVC outlet.

Rubber Support on the Wall

The glass cover was placed on a rubber support to avoid damages. The rubber was placed on top of the four side walls of Ferrocement Plant. However, in Brick Plant 1 and 3-7 rubber was placed on top of the three side walls. No rubber support was required in Brick Plant 2, Brick Plant 8 and Clay Plant.

Rubber Gasket around the Glass Cover

In addition to a rubber support fixed with the basin wall the glass cover also had a rubber gasket attached with its front edge for better leakage prevention in Ferrocement Plant. This

also increased the convenience of operation covering the sharp edges of the glass sheet. Brick Plants did not have rubber gusset.

Wooden Frame for Plastic Sheet

Transparent plastic sheets were placed over a wooden frame for the Brick Plant 2, Brick Plant 8 and Clay Plant. The plastic sheets were attached with the wooden frame by board-pin.

3.5.5 Distillate Storage Tank Connection

Plastic jars were used which were connected with the outlet gutter by rubber tubes. To prevent leakage at both ends of the rubber tube, its ends were covered tightly with simple plastic covers at the opening of the jar and the outlet gutter respectively.

3.6 CONSTRAINTS OF CONSTRUCTION AND COUNTERMEASURES

3.6.1 Casting the Ferrocement Plant

It was found very difficult to maintain the wall thickness of 1 inch everywhere during the casting of ferrocement. The main difficulty, however, was to keep the mesh in position for the entire work. These difficulties were mainly caused due to unskilled labor handling which was explored later when the initially constructed plant was rejected and the second was constructed with a skilled mason.

3.6.2 Cracks on the Still Wall of the Ferrocement Plant

After casting of the plant, various cracks of about 0.12 inch (3 to 4 mm) width were found on the still wall. These were developed due to high heat of hydration because of the excess use of cement in the paste. All these cracks were filled up by patch work instantly.

3.6.3 Loss of Distillate

It was found for few consecutive days that the smaller front wall of the Ferrocement Plant was wet. This was overcome by the installation of the glass strip attached to the interior front side of the glass cover. But the use of such a glass strip was avoided in constructing Brick Plants by proper placing of glass into outlet.

3.6.4 Brine Removal Provision

In the plant construction no extra provision was employed for removing brine and other precipitation deposited at the base of the basin. There could be an extra opening at the bottom of the plant which could be opened occasionally to be cleaned. But, this was not done to prevent complexities and increase in chance of leaking.

3.6.5 Leakage

Leakage problems were mainly observed during the operation of Ferrocement Plant. The loss of water through the gap of glass edges was encountered many times. Initially the rubber gasket was attached only at the front side of the glass cover and hardly any leakage was found all around. With time, due to differential settlement of support rubber all around, there were prominent gaps for air entrainment and vapor loss. To counter this problem, rubber support of greater thickness was provided at the necessary places under the glass cover. This problem was in consideration during the construction of Brick Plants.

Loss of water vapor through the inlet pipe was stopped by using cotton covered with normal plastic, tied tightly at its exterior opening. The both the ends of the rubber tube which carried the distillate from the outlet gutter to the storage container were also covered tightly with plastic.

3.6.6 Cutting and Placement of Outlet

A problem was arisen during cutting one-third portion of the outlet by maintaining alignment. One PVC pipe was rejected for not maintaining the alignment. The problem was minimized by paying due attention.

The placement of PVC pipe was done very carefully by maintaining the slope and facilities for placing the transparent glass.

3.6.7 Placement of Rubber Support

During the placing of the glass, a portion of rubber supports was displaced. The glass was removed and by replacing the rubber support, the glass was replaced very carefully.

3.6.8 Attachment of Plastic Sheet with Wooden Frame

The plastic cover should be straight over the wooden frame. So, that condensate easily goes to the outlet. In practical, it was very difficult to make the plastic straight over the

wooden frame. Extra care was taken to minimize the problem in construction of Brick Plant 2, Brick Plant 8 and Clay Plant.

3.6.9 Placement of Wooden Frame

The lower portion of wooden frame of Brick Plant 2, Brick Plant 8 and Clay Plant were placed over the outlet. But there was a slippery tendency and the frame was displaced from the outlet. To overcome this problem, the wooden frame was tighten with outlet by cement sealing.

3.6.10 Handling and Protection of Transparent Cover.

Glass sheets as transparent cover needed special care in handling and placement on the still as they broke very easily. The plastic sheet did not have any problem with handling and placement but was vulnerable to attack by crows.

3.7 EXPERIMENTAL WORK

3.7.1 Feeding of Saline Water

The saline water was supplied to the plant through the inlet pipe. It was done four times a day (at 8 am, 12 noon, 3 pm and 5 pm) initially, but with the increase of plant number, it was done twice a day (at 8 am and 5 pm). The amount of the water supply was supplied in the stills to maintain a fixed water depth of 1 inch (25.4 mm) based on the objective.

3.7.2 Data Collection

Distillate amount, air temperature outside the still and on inner side of the glass cover, and water temperature inside the still were measured at the site four times a day (at 8 am, 12 noon, 3 pm and 5 pm) initially but, later on measured two times a day (at 8 am and 5 pm). Schedule of data collection is shown in Table 3.1.

Table 3.1: Schedule of Data Collection from Different Types of Plants

<i>Still Type</i>	<i>Start of Operation</i>	<i>End of Operation</i>
Ferrocement Plant	January 1, 1994	December 28, 1995
Brick Plant 1	August 21, 1994	December 28, 1995
Brick Plant 2	September 13, 1994	December 28, 1995
Brick Plant 3	November 5, 1994	December 31, 1995
Brick Plant 4	December 12, 1994	December 31, 1995
Brick Plant 5	December 12, 1994	December 31, 1995
Brick Plant 6	March 24, 1995	March 08, 1996
Brick Plant 7	March 24, 1995	March 08, 1996
Brick Plant 8	March 24, 1995	March 08, 1996
Clay Plant	March 24, 1995	March 08, 1996

3.8 CONSTRAINTS OF OPERATION AND COUNTERMEASURES

3.8.1 Damage of Glass and Plastic Cover

The greatest and the costliest of all the operational problems was the loss or damages of glass during the study period. The loss of glass due to mishandling happened only once out of three times. Once it was broken due to hailstorm and other occasion was stormy weather. The plastic transparent sheets were sometimes perforated by crows. The plastic transparent sheets were also perforated by heavy rainfall. For practical operations, the stills have to be placed in such a way that they are safe from these and at the same time the children have to be made aware so that they will not break the glass or perforate the plastic sheet. Glass sheet may be removed during the periods of hailstorm and stormy weather to protect it from natural damage. An extra wooden cover may also be placed over the glass sheet during those periods without removing the glass sheet.

3.8.2 Detachment of Glass Strip

The glass strip inside the glass cover of the Ferrocement Plant at front was attached by glue. Due to high heat generation inside the plant, this joint was frequently detached. Its frequency was however reduced by using a new and better brand of glue (Aerolite).

3.8.3 Displacement of Rubber Strip

The rubber strip inside the glass cover was slightly displaced due to over heating under high temperature. This might increase the chance of heat losses. The glass was removed and the rubber strip of Brick Plant 1 was replaced.

3.8.4 Mixing of Rain Water with Output

During the period of heavy rainfall, the rain water was some times mixed with output in Brick Plant 2 from the outer edge of the wooden frame. The problem was minimized by proper placing of wooden frame on outlet and sealing it.

3.8.5 Cleaning of Plant

No extra provision was employed for removing brine and other precipitation-deposited at the base of the plants. So, the cleaning was done by removing the glass where there was a chance of mishandling. The plants were cleaned when the glasses were removed for other purposes. A plant required cleaning in every four month on an average. In practical, the glass may be removed during the rainy season to safe from the hail storm and cleaning can be done during that period.

3.8.6 Cracks in Distill Collection Container

The plastic containers used for collection of distill suffer problems due to exposure in bright sunshine conditions. Cracking was found at and around the opening of the containers. The rubber tubes were also cracked by sun rays. The containers and rubber tube were changed twice in a year on an average.

3.9 EXPERIMENTAL RESULTS

3.9.1 Plant Yield

The yields of each plant were recorded twice a day (8 am and 5 pm). The yields were calculated for each plant in liter per square meter. Yield versus time graph for each type of plant was plotted. These graphs are shown in Figure 3.6 and Appendix A1 to A9. The diurnal variation of yield varies from 0.10 liter/m² to 2.68 liter/m². The maximum yields occurred during March-May with an average yield 1.91 liter/m² for the Brick Plant 1 and 1.89 liter/m² for the Brick Plant 3. Table 3.2 shows the maximum, minimum and average yield of all the plants during their respective time of operation. The maximum yield recorded was 2.68 liter/m² for the Brick Plant 3. This yield was recorded in the month of May, 1995. The minimum yield recorded was 0.1 liter/m² for the ferrocement plant. This yield was recorded in a rainy day of June.

Brick Plant 3 had the highest average daily production capacity of 1.42 liter/m². The daily production capacity of Brick Plant 1 was 1.40 liter/m² which was very close to the production capacity of brick Plant 3. The daily production capacity of Brick Plant 4 and Brick Plant 5 were close to Brick Plant 2. The production capacities of Brick Plants with transparent plastic cover were much lower than Brick Plants with glass cover. Brick plants had higher production capacity than Ferrocement Plant. The plants located at Kaliganj had produced lower yield than those located at Dhaka.

Table 3.2: Maximum, Minimum and Average Yield of Different Plants

<i>Still Type</i>	<i>Minimum Yield (liter/m²/day)</i>	<i>Maximum Yield (liter/m²/day)</i>	<i>Average Yield (liter/m²/day)</i>
Ferrocement Plant	0.0987	2.1780	1.0617
Brick Plant 1	0.2804	2.6410	1.3921
Brick Plant 2	0.2000	2.0750	0.8848
Brick Plant 3	0.2200	2.6800	1.4200
Brick Plant 4	0.2860	2.6640	1.3612
Brick Plant 5	0.2692	2.5800	1.3103
Brick Plant 6	0.2000	2.1310	0.9470
Brick Plant 7	0.2200	2.6560	1.0920
Brick Plant 8	0.2000	2.1520	0.7040
Clay Plant	0.2000	1.4860	0.6470

3.9.2 Relative Plant Yield

The relative yields of plants were calculated. The relative yields of plants those located at Dhaka were calculated on the basis of the yield of Brick Plant 1, i.e., the yield of Brick Plant 1 was taken as unit. The result shows that the yield of Ferrocement Plant varied from 0.22 to 1.58 times of yield of Brick Plant 1 with an average of 0.76 times. It varied from 0.22 to 1.08 times, if 5 points were ignored. The yield of Brick Plant 2 varied from 0.19 to 1.62 times of yield of Brick Plant 1 with an average of 0.64 times. Neglecting only 4 points, it varied from 0.22 to 1.35 times. The yield of Brick Plant 3 varied from 0.24 to 2.83 times of Brick Plant 1 with an average of 1.02 times. It varied from 0.50 to 1.50, if 13 points were excluded. The yield of Brick Plant 4 varied from 0.37 to 2.75 times of yield Brick Plant 1 with and average of 0.98 times. Ignoring only 3 points, it varied from 0.37 times to 1.35 times. The yield of Brick Plant 5 varied from 0.27 times to 1.93 times of yield of Brick Plant 1 with an average of 0.94. It varied from 0.5 to 1.3 times, if 13 points were excluded.

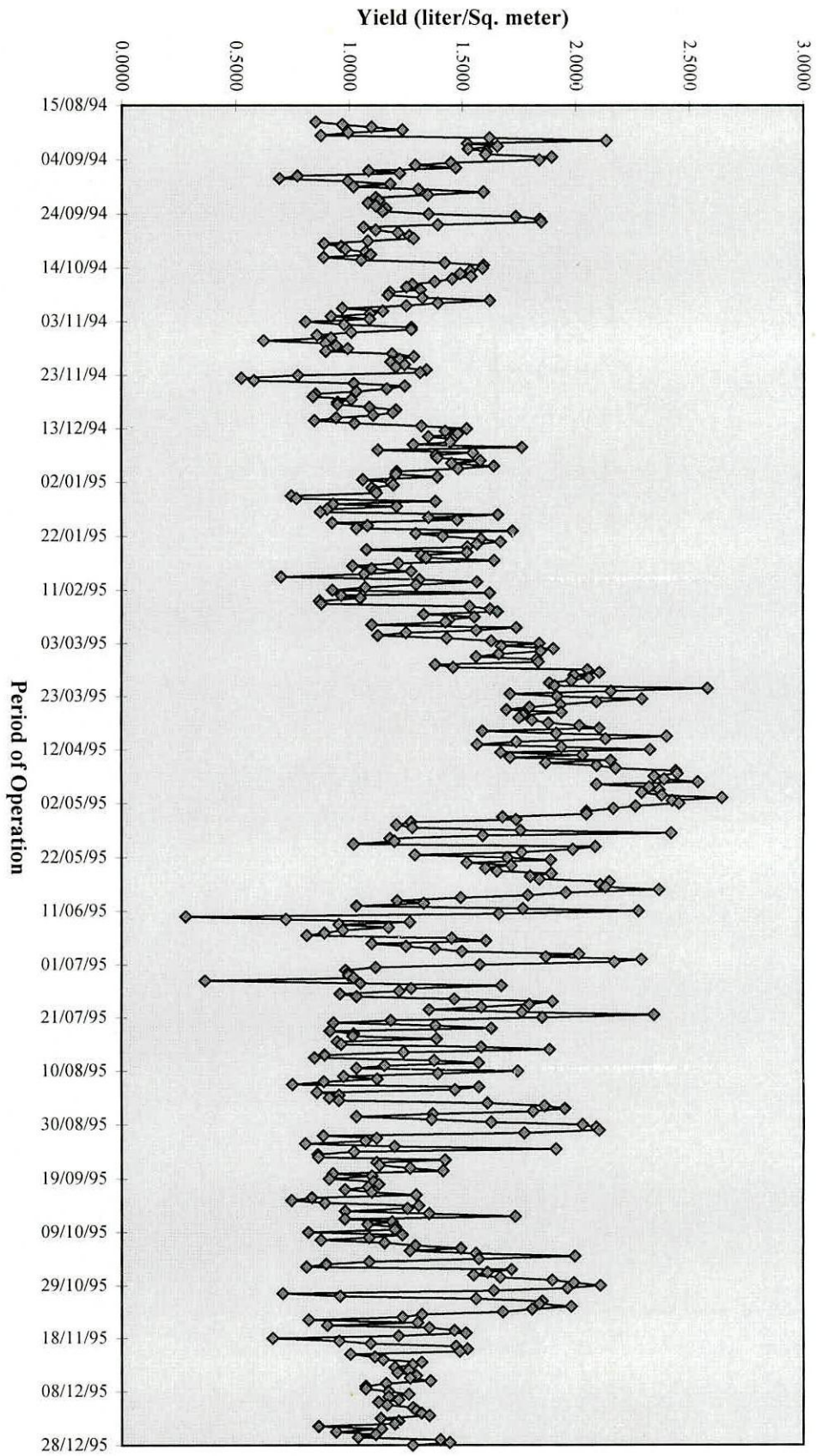


Figure 3-6: Yield of Brick Plant 1

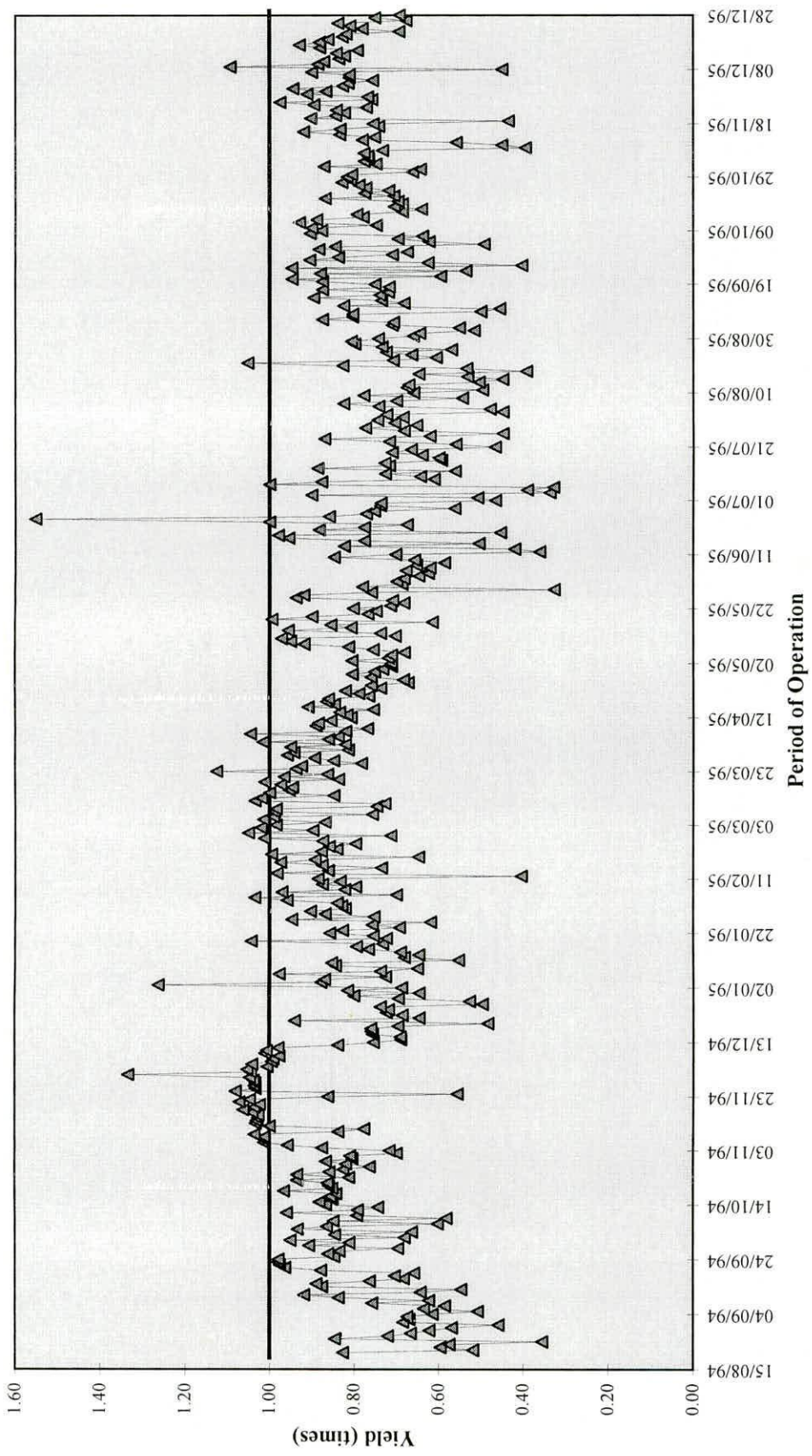


Figure 3-7: Relative Yield of Brick Plant 1 and Ferrocement Plant (Yield of Brick Plant 1 is taken as unit).

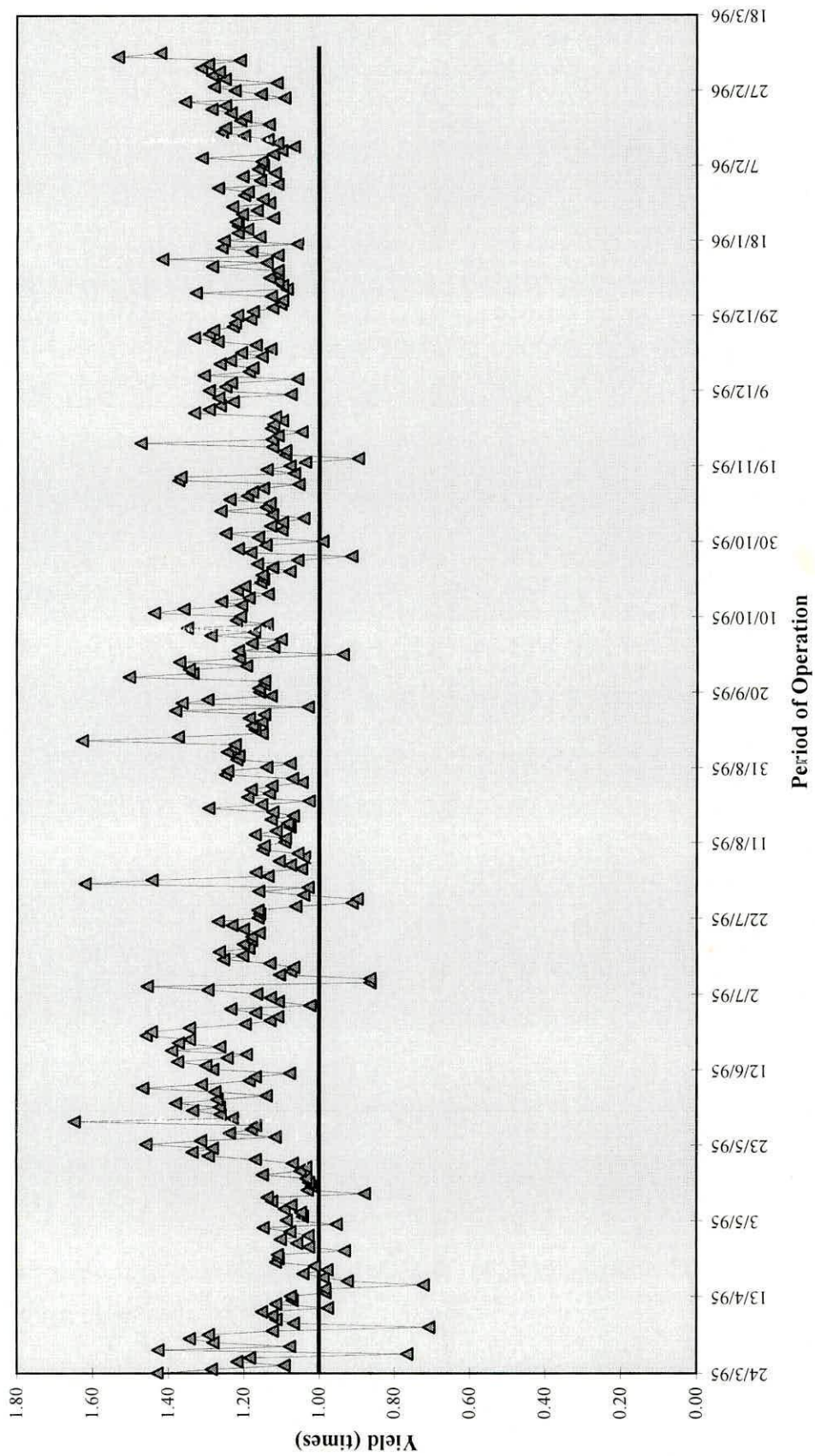


Figure 3-8: Relative Yield of Brick Plant 6 and Brick Plant 7 (Yield of Brick Plant 6 is taken as unit).

The relative yields of plants those located at Kaliganj were calculated on the basis of the yield of Brick Plant 6, i.e., the yield of Brick Plant 6 was taken as unit. The yield of Brick Plant 7 varied from 0.71 to 1.69 times of yield of Brick Plant 6 with an average of 1.15 times. Neglecting only 6 points, it varied from 0.84 to 1.52 times. The yield of Brick Plant 8 varied from 0.24 to 1.46 times of Brick Plant 6 with an average of 0.74 times. It varied from 0.24 to 1.18, if 11 points were excluded. The yield of Clay Plant varied from 0.20 to 1.78 times of yield Brick Plant 6 with and average of 0.68 times. Ignoring only 12 points, it varied from 0.38 times to 1.03 times. Relative yields versus time graph for different type of plants are shown in Figure 3.7-3.8 and Appendix A9 to A15.

3.9.3 Measurement of Air, Water and Glass Temperature

The air temperature data measured at the plant site of Dhaka was found to be in well agreement with the BMD data except in very few occasions. For the entire experimental period the air temperature (outside the still), water and glass cover temperature inside the still measured at 8:00 am and 5:00 p.m.

The glass and water temperature in side the plants at 8:00 am and 5:00 pm versus time graph for Brick Plant 1 were plotted. These graphs are shown in Figure 3.9 and Figure 3.10. Table 3.3 and 3.4 show the average maximum, minimum and average temperature of water and glass of all the plants respectively. The temperatures of transparent plastic sheet were not measured. The water and glass temperatures measured at 5 pm were found higher than those measured at 8 am. The temperature of water and glass increased during the sunshine hour and decreased during the rest period. The water temperature varied from 16.25°C to 47.25°C and the glass temperature varied from 15.00°C to 43.19°C. Brick Plant 3 attained these maximum water temperature and glass temperature during April. The lowest water temperature was observed at Ferrocement Plant and the lowest glass temperature was observed at Ferrocement and Brick Plant 5. The water temperature of Brick Plant 1 varied from 19.50°C to 47.00°C with an average of 33.14°C. The water temperature of Brick Plant 1 varied from 16.50°C to 43.00°C with an average of 29.35°C.

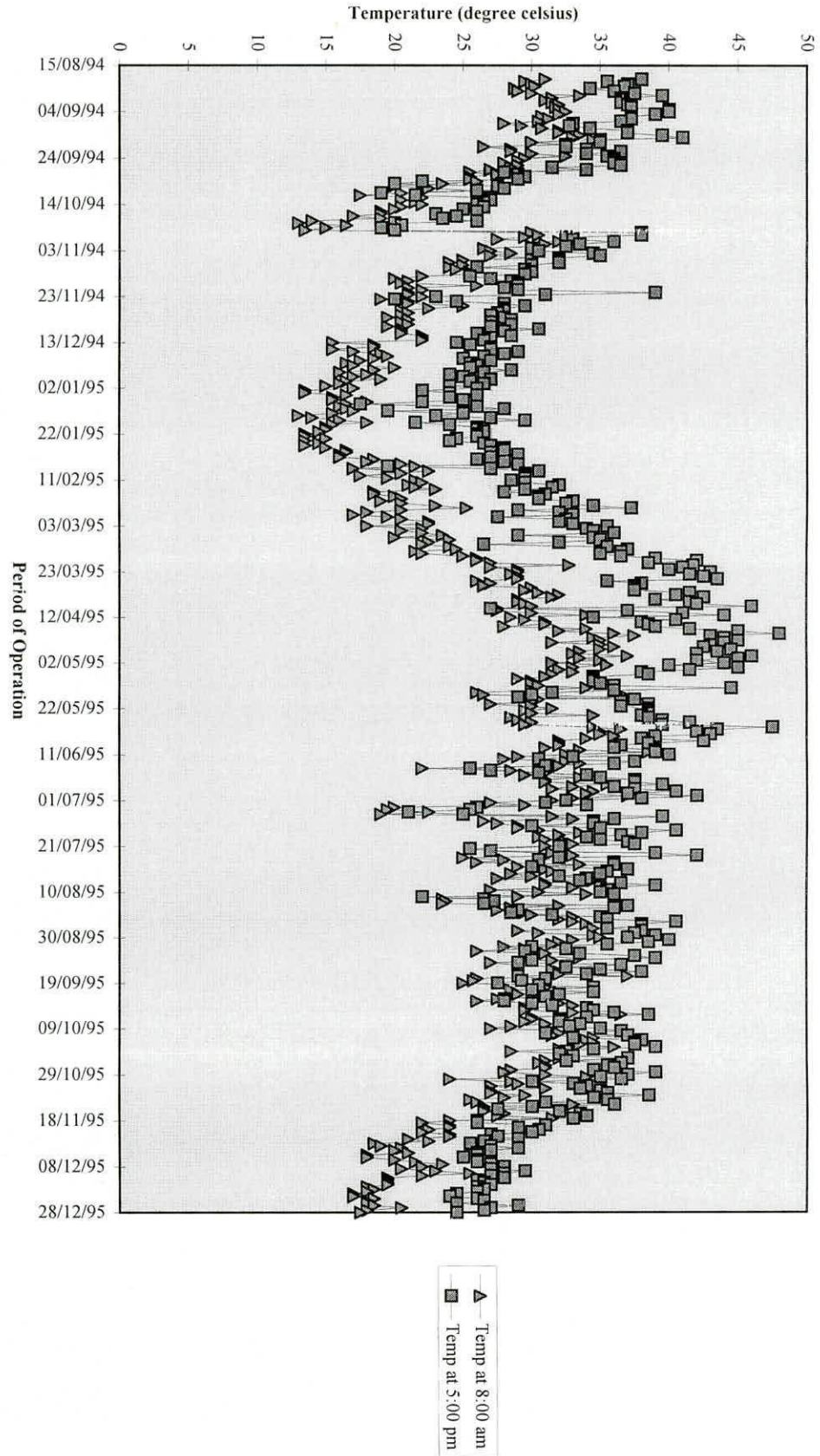


Figure 3-9: Glass Temperature of Brick Plant 1

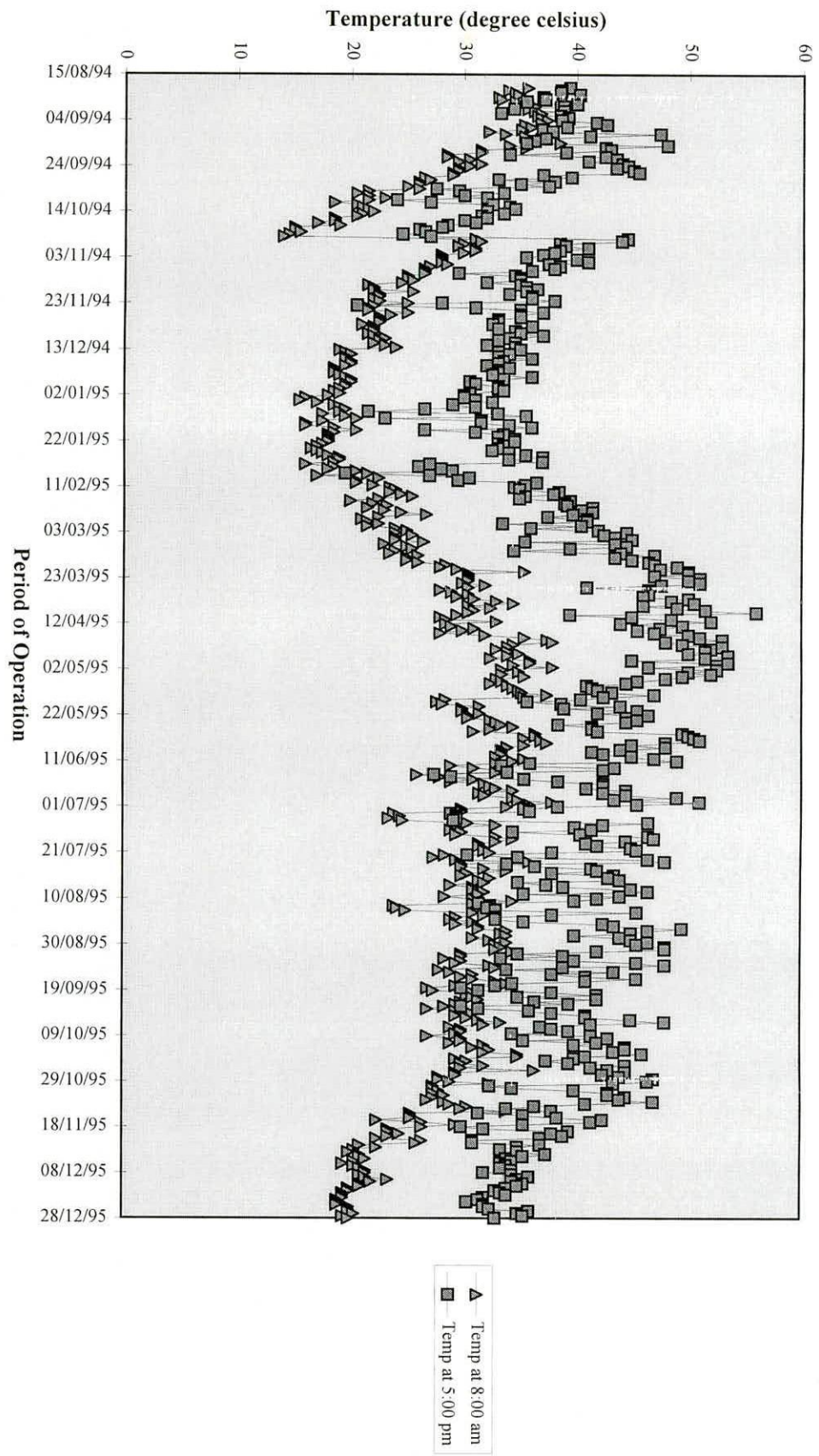


Figure 3-10: Water Temperature of Brick Plant 1

Table 3.3: Maximum, Minimum and Average Water Temperature of Different Plants

<i>Still Type</i>	<i>Minimum Temperature (°C)</i>	<i>Maximum Temperature (°C)</i>	<i>Average Temperature (°C)</i>
Ferrocement Plant	16.25	42.25	31.04
Brick Plant 1	19.50	47.00	33.14
Brick Plant 2	20.25	41.50	30.71
Brick Plant 3	16.50	47.25	34.65
Brick Plant 4	19.75	44.50	33.00
Brick Plant 5	19.00	42.25	32.03
Brick Plant 6	20.50	43.00	33.82
Brick Plant 7	21.00	44.50	34.37
Brick Plant 8	20.50	42.75	32.60
Clay Plant	19.00	40.00	29.30

Table 3.4: Maximum, Minimum and Average Glass Temperature of Different Plants

<i>Still Type</i>	<i>Minimum Temperature (°C)</i>	<i>Maximum Temperature (°C)</i>	<i>Average Temperature (°C)</i>
Ferrocement Plant	15.00	39.75	28.35
Brick Plant 1	16.50	43.00	29.35
Brick Plant 3	15.75	43.19	30.48
Brick Plant 4	17.00	40.00	29.36
Brick Plant 5	15.00	38.75	28.71
Brick Plant 6	18.50	38.50	30.85
Brick Plant 7	18.00	39.13	31.70

3.9.4 Measurement of Salt Concentration in the Distilled Water

The salt concentration of the distilled water production was investigated against feed water having salinity of the order of 3,000 ppm to 25,000 ppm. The salt concentration of the distilled water was found to be of the order of 15 ppm to 25 ppm irrespective of the input salinity, as measured at the end of each day. Therefore, salinity of feed water was almost totally removed.

3.9.5 Convective Heat Transfer

The convective heat transfer - cover to air and basin to cover were calculated for each plant (except Brick Plant 2, Brick Plant 8 and Clay Plant) by using equations 2.4 and 2.6 respectively. The calculation shows that maximum convective heat transfer (cover to air) was 20.23 cal.cm² and maximum convective heat transfer (basin to cover) was 3.20 cal.cm². The minimum convective heat transfer (cover to air) was 0.00 cal.cm² and minimum convective heat transfer (basin to cover) was 0.00 cal.cm². The average convective heat transfer (cover to air) of various plants varied from 5.00 cal.cm² to 7.83 cal.cm². The average convective heat transfer (basin to cover) of various plants varied from 0.54 cal.cm² to 0.89 cal.cm². Table 3.6 and 3.7 show the maximum, minimum and average convective heat transfer for cover to air and basin to cover respectively.

Table 3.5: Maximum, Minimum and Average Convective Heat Transfer (Cover to Air) of Different Plants

Still Type	Minimum Heat Transfer cal.cm ²	Maximum Heat Transfer cal.cm ²	Average Heat Transfer cal.cm ²
Ferrocement Plant	0.00	18.40	6.31
Brick Plant 1	0.00	18.55	6.12
Brick Plant 3	0.23	19.87	7.83
Brick Plant 4	0.00	16.65	5.70
Brick Plant 5	0.08	16.28	5.00
Brick Plant 6	0.00	19.10	6.37
Brick Plant 7	0.17	20.23	7.55

Table 3.6: Maximum, Minimum and Average Convective Heat Transfer (Basin to Cover) of Different Plants

Still Type	Minimum Heat Transfer cal.cm ²	Maximum Heat Transfer cal.cm ²	Average Heat Transfer cal.cm ²
Ferrocement Plant	0.00	2.74	0.54
Brick Plant 1	0.03	2.42	0.78
Brick Plant 3	0.00	2.45	0.89
Brick Plant 4	0.00	2.26	0.75
Brick Plant 5	0.00	3.07	0.67
Brick Plant 6	0.00	2.37	0.76
Brick Plant 7	0.04	3.20	0.81

3.9.6 Thermal Radiation

The thermal radiation - cover to air and basin to cover were calculated for each plant (except Brick Plant 2, Brick Plant 8 and Clay Plant) by using equations 2.5 and 2.7 respectively. The calculation shows that maximum thermal radiation (cover to air) was 6.67 cal.cm² and maximum thermal radiation (basin to cover) was 5.18 cal.cm². The minimum thermal radiation (cover to air) was 0.00 cal.cm² and minimum thermal radiation (basin to cover) was 0.00 cal.cm². The average thermal radiation (cover to air) of various plants varied from 1.67 cal.cm² to 2.65 cal.cm². The average thermal (basin to cover) of various plants varied from 1.33 cal.cm² to 2.12 cal.cm². Table 3.8 and 3.9 show the maximum, minimum and average thermal radiation for cover to air and basin to cover.

Table 3.7: Maximum, Minimum and Average Thermal Radiation (Cover to Air) of Different Plants

<i>Still Type</i>	<i>Minimum Heat Transfer cal.cm²</i>	<i>Maximum Heat Transfer cal.cm²</i>	<i>Average Heat Transfer cal.cm²</i>
Ferrocement Plant	0.00	5.91	1.76
Brick Plant 1	0.00	5.96	2.06
Brick Plant 3	0.07	6.67	2.65
Brick Plant 4	0.00	5.53	1.91
Brick Plant 5	0.00	5.40	1.67
Brick Plant 6	0.03	6.01	2.15
Brick Plant 7	0.09	6.45	2.42

Table 3.8: Maximum, Minimum and Average Thermal Radiation (Basin to Cover) of Different Plants

<i>Still Type</i>	<i>Minimum Heat Transfer cal.cm²</i>	<i>Maximum Heat Transfer cal.cm²</i>	<i>Average Heat Transfer cal.cm²</i>
Ferrocement Plant	0.00	5.01	1.33
Brick Plant 1	0.12	4.97	1.90
Brick Plant 3	0.07	4.82	2.12
Brick Plant 4	0.00	4.45	1.81
Brick Plant 5	0.00	5.18	1.64
Brick Plant 6	0.21	5.02	2.05
Brick Plant 7	0.32	5.13	2.22

Among the previous four discussed heat transfer modes, it was revealed that convective heat transfer (cover to air) was the highest (an average 6.41 cal.cm^2) among four modes and convective heat transfer (basin to cover) was lowest (an average 0.74 cal.cm^2) among the four modes.

3.10 CLIMATIC DATA COLLECTION

The following daily climatic data were collected from the Bangladesh Meteorological Department (BMD) for Dhaka for the year 1994 and 1995.

- Maximum daily air temperature
- Minimum daily air temperature
- Global solar radiation (at Joydevpur)
- Sunshine hour
- Relative humidity
- Wind speed
- Rainfall

Presently, the Bangladesh Meteorological Department (BMD) is not collecting solar radiation data at Dhaka. Joydevpur is a nearer station to Dhaka where solar radiation data is recorded. The data recorded at Joydevpur was used at the study. The air temperature, sunshine hour, relative humidity, wind speed and rainfall data were measured at Agargaon, Dhaka. Both these locations are different from where the plants were set (BUET). However, in absence of data in the plant location, these data provide an estimate.

No solar radiation data is recorded at Kaliganj nor Satkhira. The daily average temperature and sunshine hour were recorded at the field.

Some data for few days were not available as those were missed. These missing data were predicted by the polynomial interpolation (Section 2.12) method. Due to unavailability of average daily temperature at BMD, the average of daily maximum and minimum temperature are considered as average daily temperature.

3.11 STATISTICAL ANALYSIS OF THE CLIMATIC PARAMETERS

The climatic parameters in this country vary in a wide range over the year. So the plant output also varies as it is directly dependent on these climatic parameters. The variation of the daily average temperature, radiation, sunshine hour, relative humidity, wind speed and

rainfall for the year 1994 and 1995 for Dhaka are shown in Figure 3.11 to Figure 3.16. The daily average temperature and sunshine hour for Kaliganj are shown in the Figure 3.17 to 3.18.

The minimum, maximum, average, median and standard deviation (Sukla and Gulshan, 1978) were calculated for the average temperature for each month and each year. The Table 3.9 shows this statistical analysis. The same statistical calculations were carried out on radiation, sunshine hour, relative humidity, wind speed and rainfall data for Dhaka (Appendix B1 to B5) and on average temperature and sunshine for Kaliganj (Appendix B6 to B7).

It was observed from Figure 3.11 that the variation of temperature during the different months of the two particular years had a similar trend. The average temperature varied from 16.90°C to 32.00°C with an average 25.89°C for the year 1994. It varied from 18.00°C to 34.50°C with an average 26.50°C for the year 1995.

The daily solar radiation varied from 54.70 cal/m² to 370.50 cal/m² with an average 238.23 cal/m² for the year 1994. It varied from 63.80 cal/m² to 376.20 cal/m² with an average 230.46 cal/m² for the year 1995. The maximum average daily solar radiation was observed during the month April. These were 370.50 cal/m² and 376.20 cal/m² for the year 1994 and 1995 respectively. The daily sunshine hour varied from 0.00 to 11.30 with an average 6.23 for the year 1994. It varied from 0.00 to 11.20 with an average 6.18 for the year 1995. The maximum average daily sunshine hours were observed during March and April. These were 7.33 and 7.44 for the month March, 1994 and April, 1995 and 8.77 and 8.57 for the month March, 1995 and April, 1995. The daily relative humidity varied from 31% to 93% with an average 70.32% for the year 1994. It varied from 36% to 95% with an average 75.30% for the year 1995. The daily wind speed varied from 0.01 knots to 6.90 knots with an average 2.02 knots for the year 1994. It varied from 0.00 knots to 7.50 knots with an average 2.03 Knots for the year 1995. The daily rainfall varied from 0.00 mm to 74.00 mm with an average 4.18 mm for the year 1994. It varied from 0.00 mm to 83.00 mm with an average 3.29 mm for the year 1995. The average temperature of Kaliganj varied from 18.50°C to 35.00°C with an average 27.49°C. The daily sunshine hour of Kaliganj varied from 0.80 to 9.20 with an average 6.16.

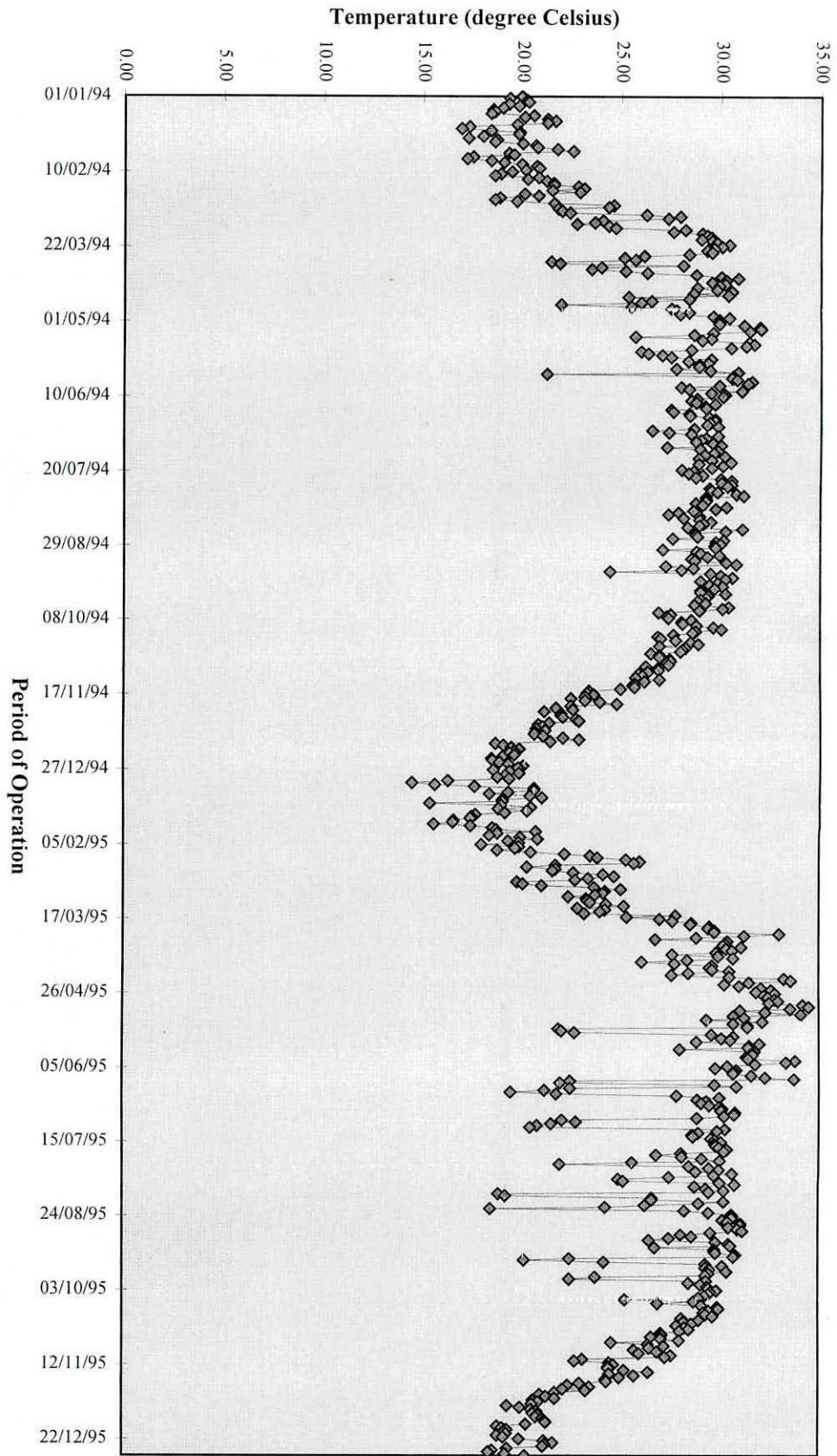


Figure 3-11: Daily Average Temperature at Dhaka during the Period of Operation

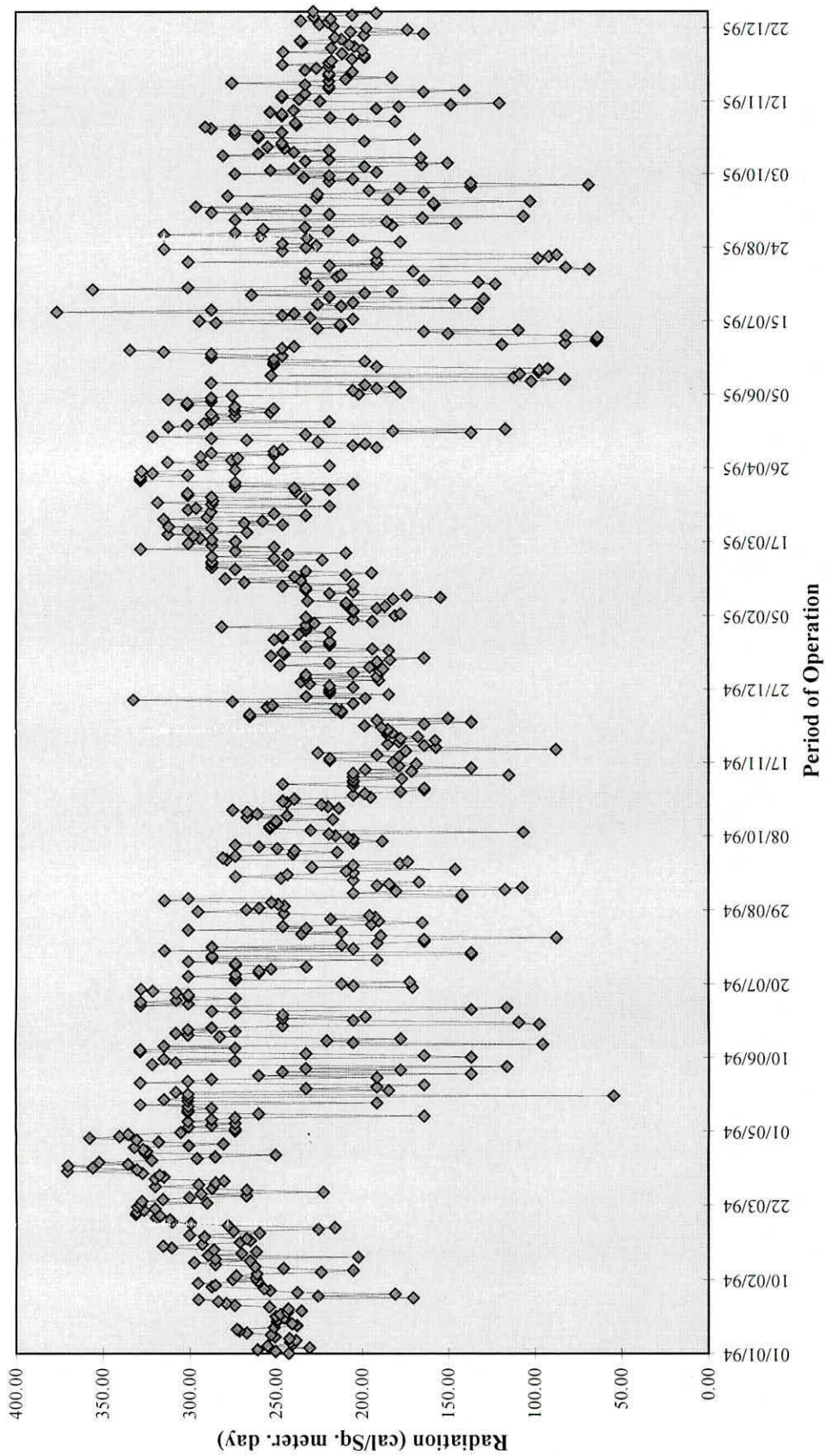


Figure 3-12: Daily Solar Radiation at Joydevpur during the Period of Operation

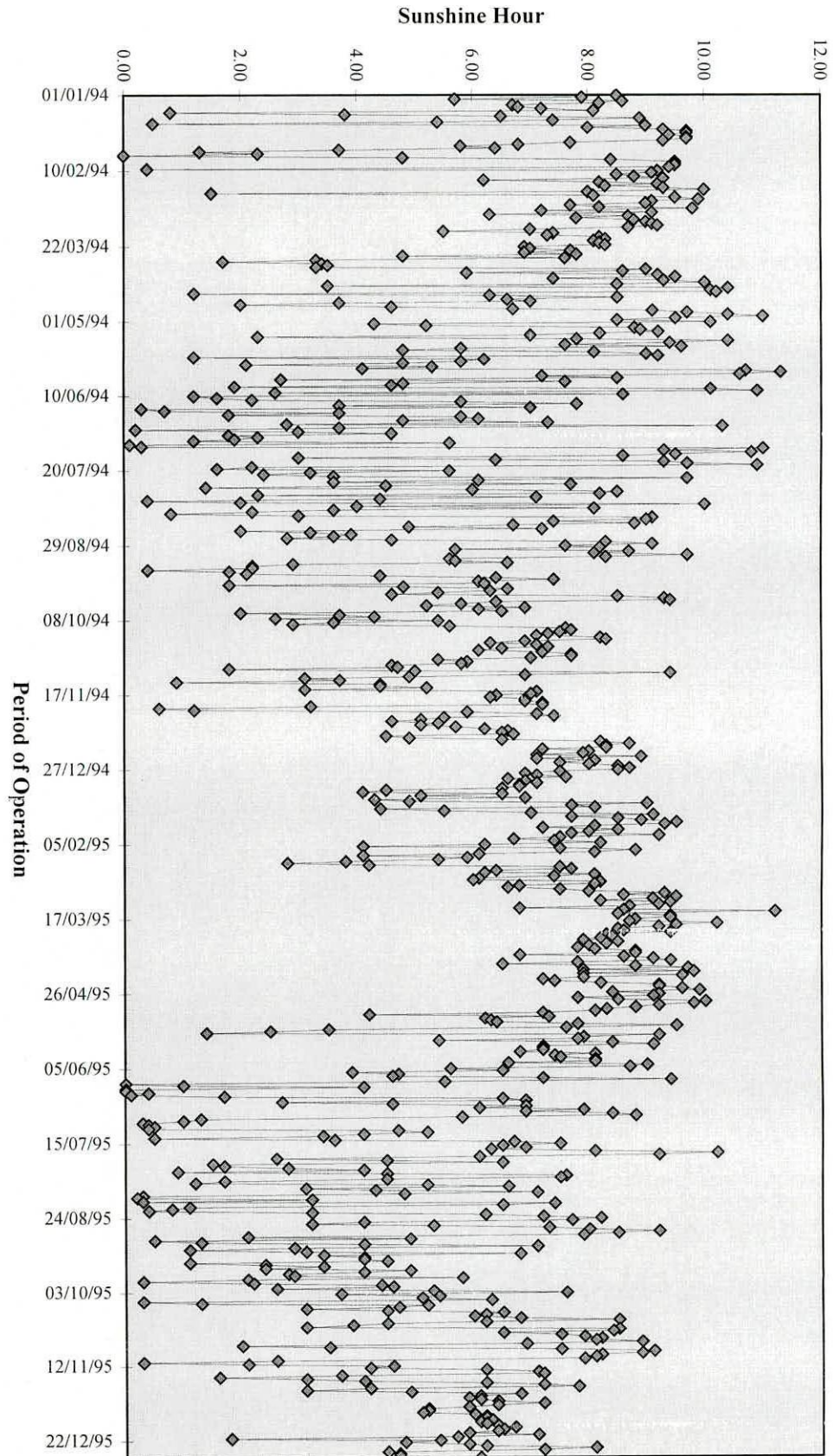


Figure 3-13: Daily Sunshine Hour at Dhaka during the Period of Operation

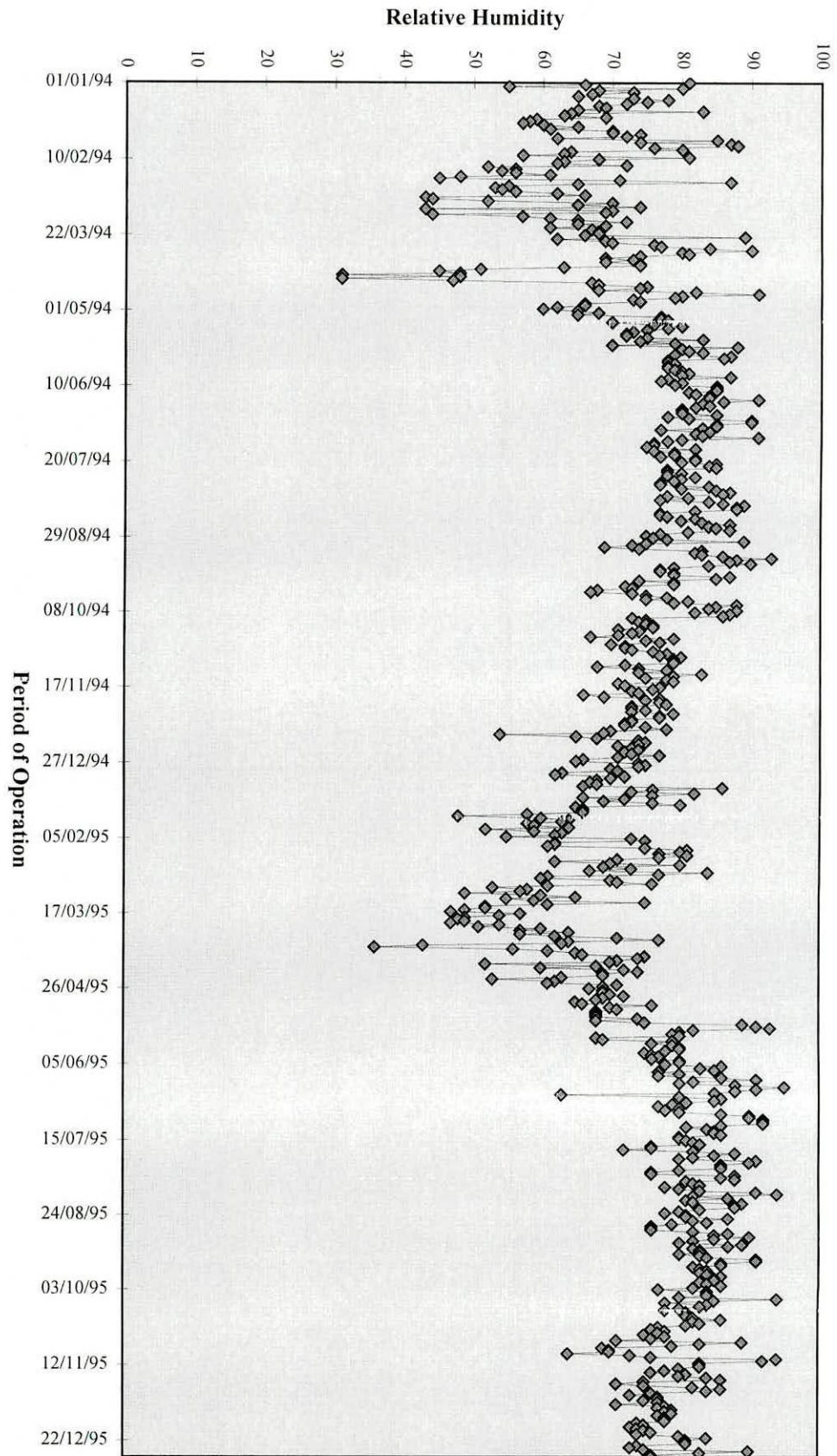


Figure 3-14: Daily Relative Humidity at Dhaka during the Period of Operation

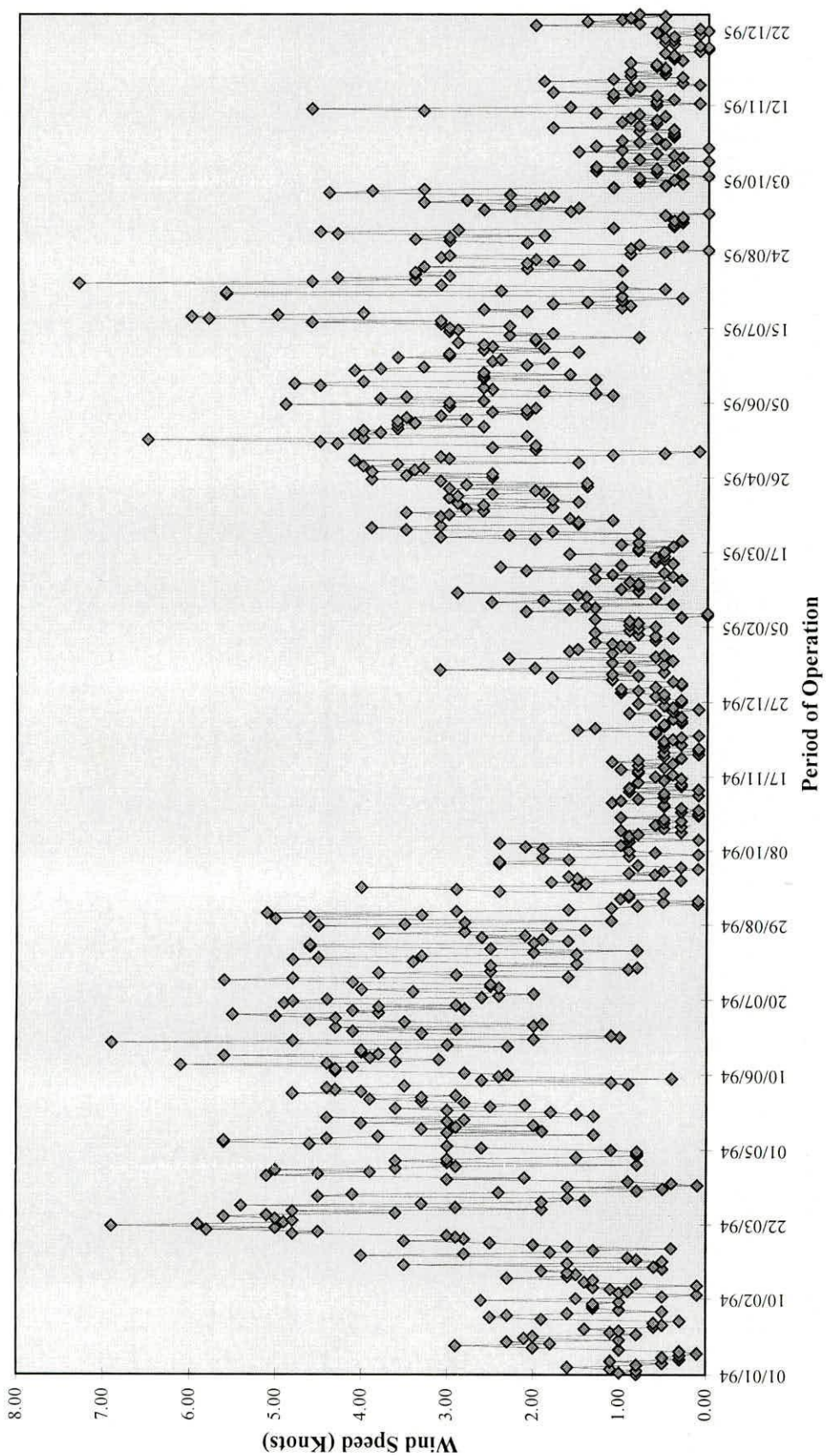


Figure 3-15: Daily Wind Speed at Dhaka during the Period of Operation

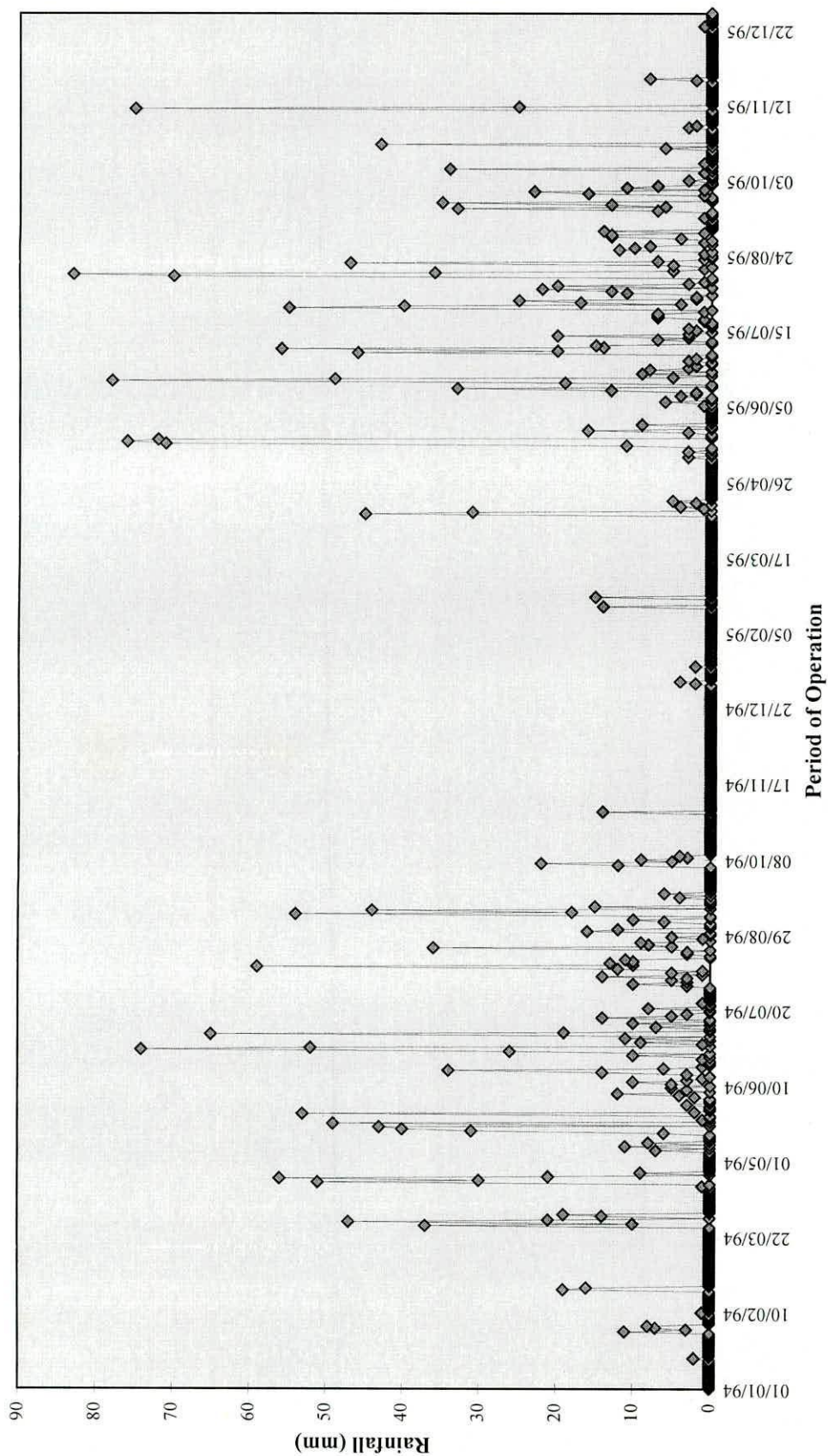


Figure 3-16: Daily Rainfall at Dhaka during the Period of Operation

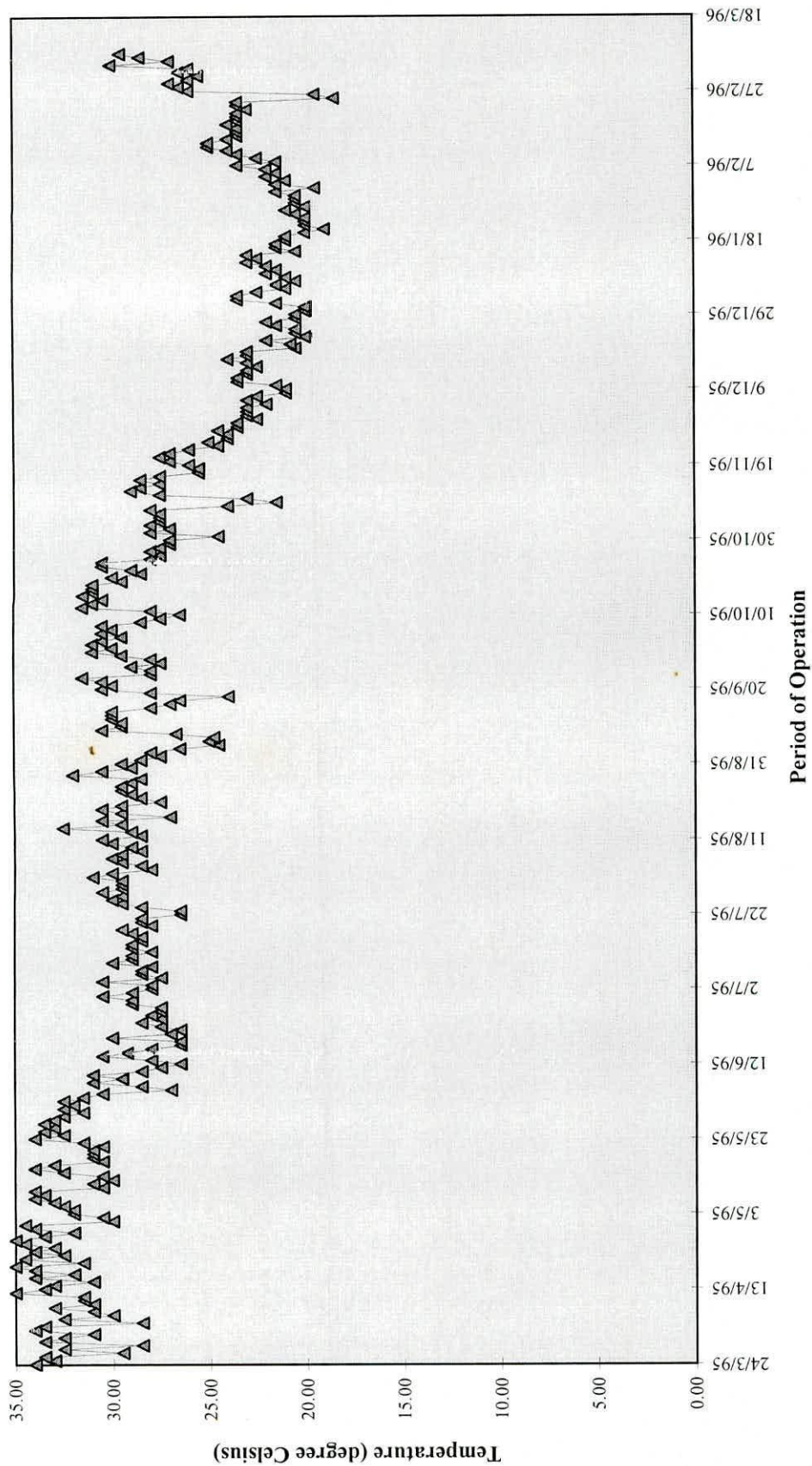


Figure 3-17: Daily Average Temperature at Kaliganj during the Period of Operation

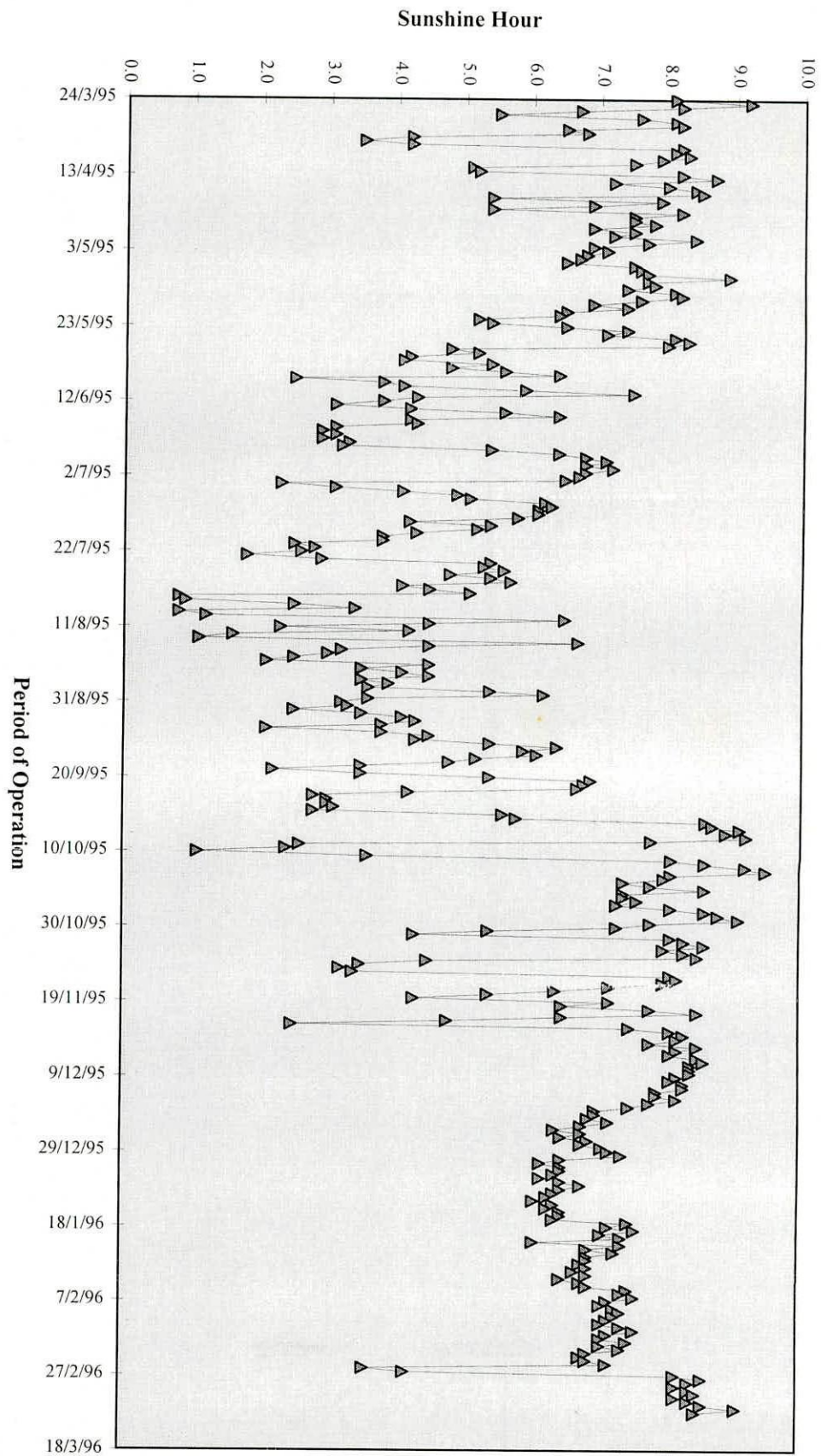


Figure 3-18: Daily Sunshine Hour at Kaliganj during the Period of Operation

**Table 3.9: Statistical Analysis of Average Temperature (Degree Celsius)
at Dhaka**

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St. Dev.</i>
January, 94	16.90	22.50	19.60	19.80	1.37
February, 94	17.20	24.60	20.37	20.20	1.74
March, 94	21.45	30.40	26.49	27.35	2.97
April, 94	21.95	30.85	28.00	28.50	2.35
May, 94	21.25	32.00	29.35	29.60	2.23
June, 94	26.55	31.55	29.18	29.28	1.18
July, 94	27.30	30.55	29.43	29.55	0.76
August, 94	27.10	31.15	29.20	29.15	1.00
September, 94	24.45	30.80	29.17	29.28	1.18
October, 94	26.50	30.40	28.05	28.00	1.04
November, 94	21.15	27.40	24.38	24.38	1.89
December, 94	18.50	22.90	20.10	19.85	1.23
1994	16.90	29.43	25.89	28.03	4.41
January, 95	24.50	21.05	18.37	18.75	1.77
February, 95	18.00	26.00	21.83	21.68	2.20
March, 95	22.40	33.00	26.70	26.80	3.02
April, 95	26.10	33.60	30.59	30.58	1.91
May, 95	21.90	34.50	30.53	31.40	3.12
June, 95	19.50	33.80	28.86	30.05	3.96
July, 95	20.50	30.40	27.74	28.95	3.23
August, 95	18.50	31.10	28.09	29.50	3.62
September, 95	20.20	31.20	28.28	29.38	2.84
October, 95	24.60	30.00	28.44	28.75	1.34
November, 95	21.00	27.60	24.45	24.48	1.91
December, 95	18.40	21.65	20.13	20.30	0.96
1995	18.37	30.59	26.50	27.92	4.57

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

3.12 PLANT EFFICIENCIES

The efficiencies of different plants were calculated from the radiation data using the equation 2.2.4. A simple computer program was developed to calculate this efficiency (Appendix C-3). Table 3.10 shows the maximum, minimum and average efficiencies of all the plants during their respective time of operation. The efficiencies of plants at Kaliganj were not calculated due to non-availability of solar radiation data. The efficiencies of various plants varied from 4.23% to 52.05%. Maximum, minimum and average efficiencies of Ferrocement Plant were found 38.17%, 4.23% and 22.57%. The corresponding figures for the Brick Plant 1 were found to be 49.30%, 8.58% and 33.82%. For Brick Plant 3, these were found 52.05%, 9.03% and 34.50%. The average efficiencies of Brick Plants were comparable to that of Farid and Hamad (1992) and Samy and Hasan(1992). These were 30% and 40%. However, the plant base could be blackened (as done by Farid and Hamad) to increase efficiency but that involved additional cost and might change the quality of the distill.

Table 3.10: Maximum, Minimum and Average Efficiencies of Different Plants

<i>Still Type</i>	<i>Minimum Efficiency</i>	<i>Maximum Efficiency</i>	<i>Average Efficiency</i>
Ferrocement Plant	4.23	38.17	22.57
Brick Plant 1	8.58	49.30	33.82
Brick Plant 2	7.27	41.25	19.77
Brick Plant 3	9.03	52.05	34.50
Brick Plant 4	8.36	48.28	33.14
Brick Plant 5	8.27	49.90	31.80

3.13 PREDICTION OF STILL YIELD

A mathematical equation was developed for the prediction of still yield from the available meteorological data and plant temperatures. For the development of different equations, the experimental data for the Brick Plant 1 had been used.

This model was based on the 4 climatic factors and 2 plant factors. The climatic factors are: daily average temperature, radiation, sunshine hour and humidity. The plant factors are glass temperature and water temperature. The equation was developed in taking into consideration of the yield of Brick Plant 1 and tested the other plants. For the accuracy of

the calculation and result given by the computer program, the factors were taking into consideration in the following form.

- temperature in degree Celsius/100
- solar radiation in (cal/cm² day)/1000
- bright sunshine hours in hours/10
- relative humidity in fraction i.e., 0.80 (say) when the true value is 80%
- glass temperature in degree Celsius/100 and
- water temperature in degree Celsius/100

The generation of the models was accomplished through the sequential stepwise processes of model generation and screenings as follows:

Step 1: At this stage, a program was developed in computer C program (Balagurusamy, 1992) for the equation that takes care of the combination of multiple degree of each of the six parameters. The program actually took into consideration up to the 6 th degree of each of the parameters and all the possible combinations of multiple degree for each of parameters up to this 6 th degree. The number of iteration required for a single set of data was 6⁶ or 46656. This program generated the constants and power of the initially assumed trial equation that is as follows:

$$Y = a_0 + a_1(\text{Temperature})^t + a_2 (\text{Radiation})^r + a_3 (\text{Sunshine hours})^s + a_4(\text{Humidity})^h + a_5 (\text{Glass Temperature})^{gt} + a_6 (\text{Water Temperature})^{wt}$$

This program also calculated the MBE, RMSE and MPE as the fraction of the actual value for each values of exponents up to 6. Then the program developed a chart with the combination of the degree values and the coefficients corresponding to each term of the trial equation. The constant a_0 was taken as 0.25 as the average lowest yield was 0.25 liter/m².

Step 2: This was the part of first screening. Screening was done considering degree variation with the respective statistical estimates of deviation. Attention was given to search for the combinations having the least error.

Step 3: The next step was to develop and to use of another program considering the supplied data. The degrees of polynomial and coefficients of the parameters having the least error were picked at step 2. This program then used these constants and power to

generate the yield (l/m²). The estimates of accuracy were then measured and given as an output file by the program in the same way.

Step 4: This was actually another screening, performed in the same way as in Step 2. This screening was done to pick up the best combinations based on the MBE, RMSE and MPE expressed as a fraction of actual value. From this second screening again the best combinations were taken.

Step 5: This was the final screening step and also the decision making step. Here the graphical method was followed which aids the screening procedure. In this screening process graphs were plotted for the selected combinations the graph being plotted with model calculated values along Y-axis and the actual value along the X-axis. The best equation was then selected looking at the figures depending on how close the true points were near the 45° line (line of perfect agreement). The graphs found for the finally selected mathematical models are shown in Figure 3-19. The finally developed and selected equation is as follows :

$$Y = 0.25 + 1.0 (\text{Temperature})^5 + 0.1429 (\text{Radiation})^4 + 1.7143 (\text{Sunshine hour})^2 + 1.285 (\text{Relative humidity})^6 + 1.7413 (\text{Water Temperature})^3 + 1.4286 (\text{Glass Temperature})^4 \quad (3.1)$$

The Table 3.11 shows the errors for the calculated and actual yields for the plants operated at Dhaka.

Table 3.11: Errors for Calculated and Actual Yield

Plants	MBE	RMSE	MPE	Coefficient of Correlation
Ferrocement Plant	-0.29	0.35	-30.08	± 1.120
Brick Plant 1	-0.14	0.19	-12.43	± 0.850
Brick Plant 3	-0.22	0.29	-18.69	± 0.714
Brick Plant 4	-0.24	0.31	-21.15	± 0.745
Brick Plant 5	-0.18	0.24	-15.96	± 0.805

Again the units used in these equations (discussed earlier in this Section) should be remembered.

In the programs the Gauss's Elimination process [Scarborough, (1966)] was used to solve the equations for the coefficients.

The graphs containing the line of perfect agreement for the different plants were drawn and shown in Figure 3.20 to Figure 3.23. It was revealed from the figures that the equations predicted a better between the actual yield of 0.75 liter/m² to 1.75 liter/m². The calculated yields of ferrocement plant were found higher than actual yields.

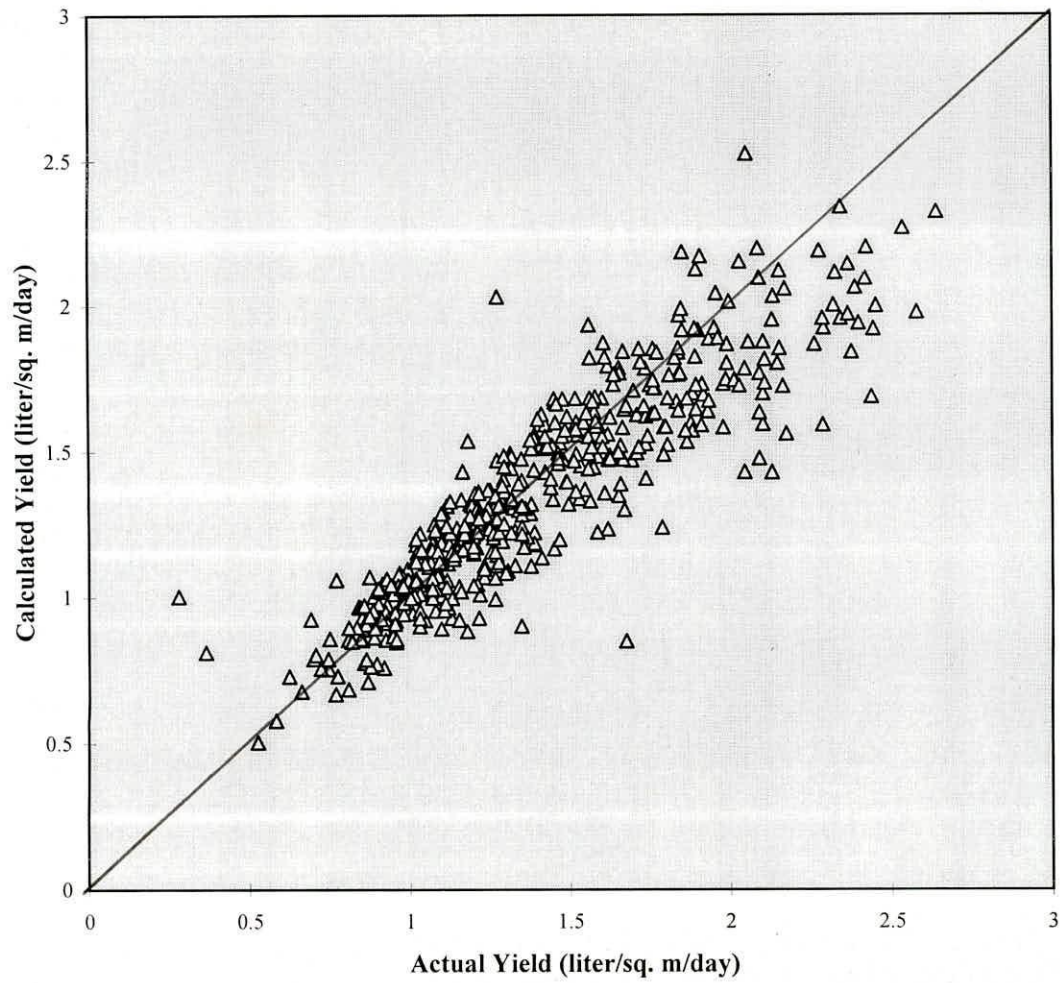


Figure 3-19: Variation of Calculated Yield (Calculated from Developed Equation 3.1) with Actual Yield of Brick Plant 1

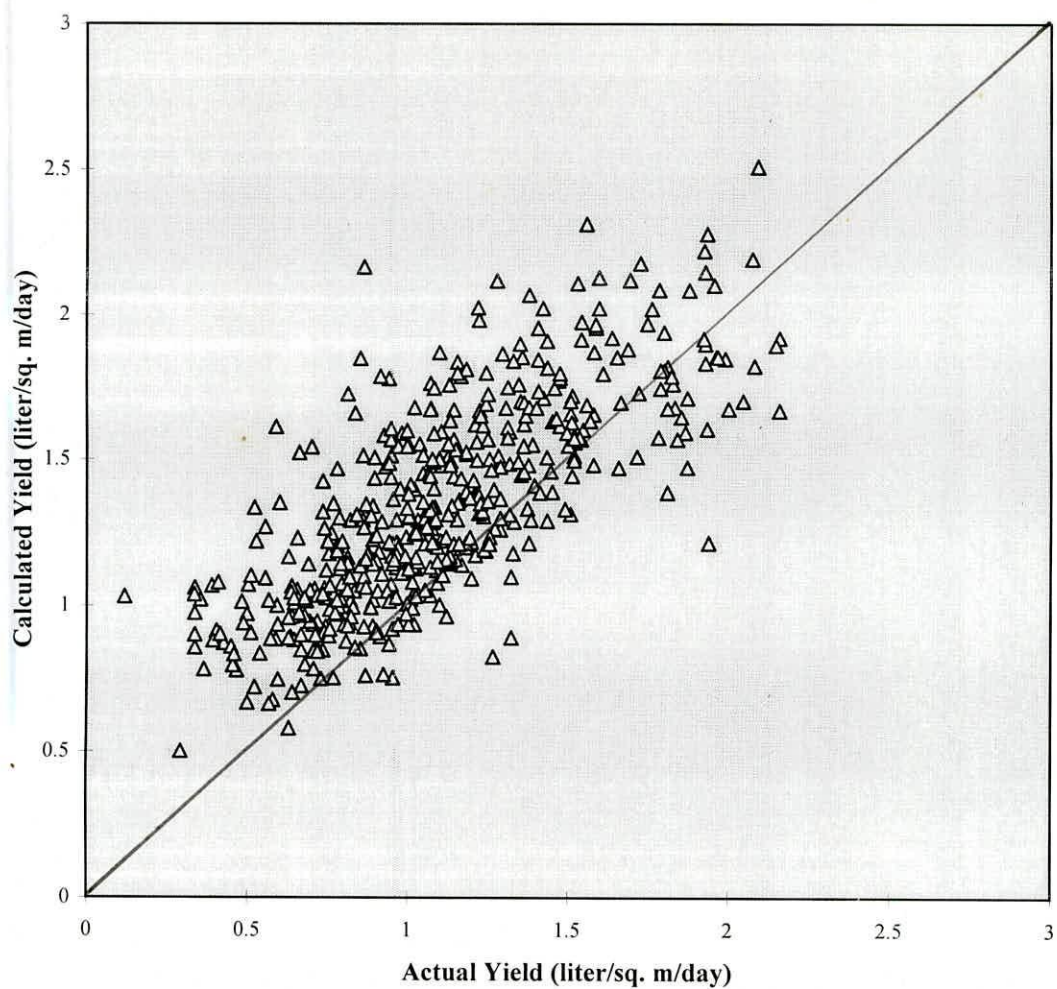


Figure 3-20: Variation of Calculated Yield (Calculated from Developed Equation 3.1) with Actual Yield of Ferrocement Plant

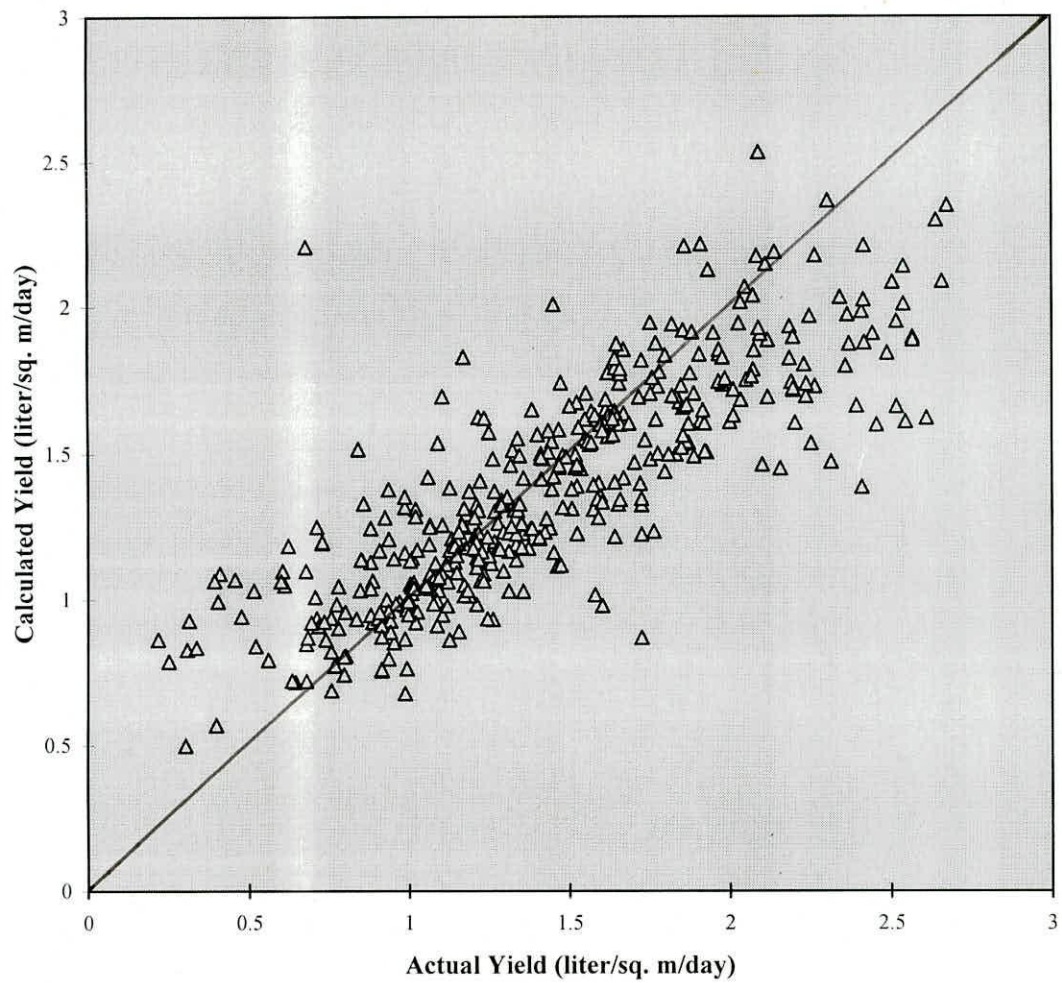


Figure 3-21: Variation of Calculated Yield (Calculated from Developed Equation 3.1) with Actual Yield of Brick Plant 3

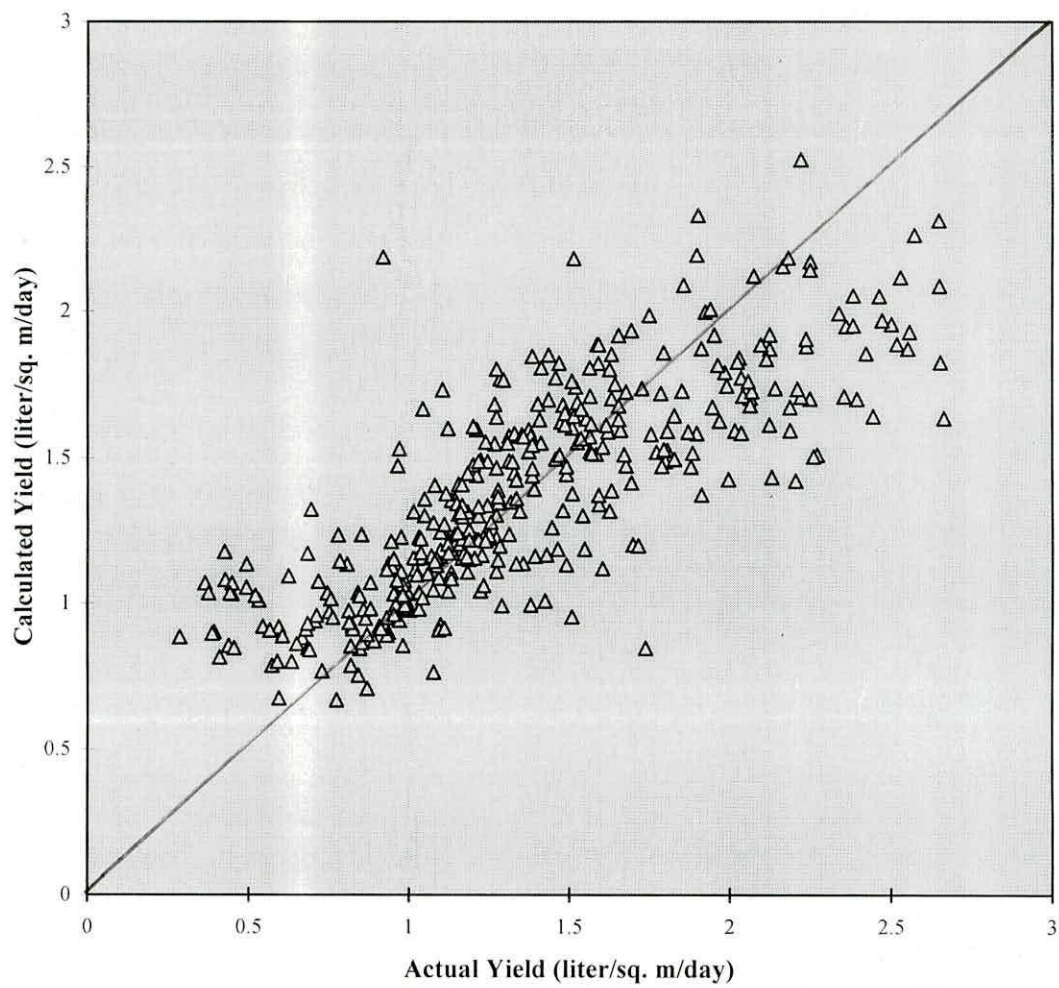


Figure 3-22: Variation of Calculated Yield (Calculated from Developed Equation 3.1) with Actual Yield of Brick Plant 4

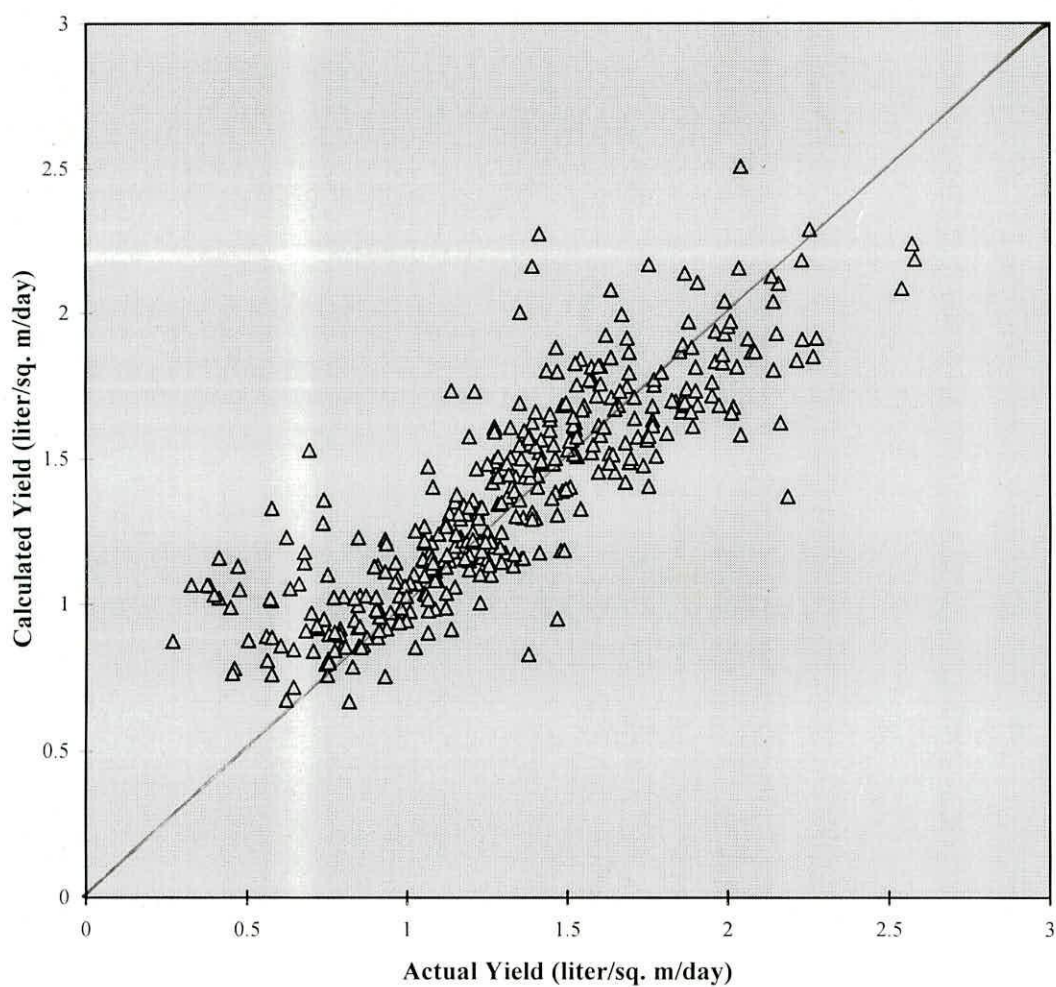


Figure 3-23: Variation of Calculated Yield (Calculated from Developed Equation 3.1) with Actual Yield of Brick Plant 5

Chapter 4

DISCUSSIONS AND DESIGN, OPERATION
AND MAINTENANCE GUIDELINES

CHAPTER 4

DISCUSSIONS AND DESIGN, OPERATION AND MAINTENANCE GUIDELINES

4.1 INTRODUCTION

An elaborate experimental and analytical program was carried out in connection with this study. The experimental investigation dealt with detail construction, installation, maintenance and operation of the different types of desalination plants. Experimental works were conducted both at Dhaka (BUET campus) and at a coastal location (Kaliganj, Satkhira). In the analytical works, variation of yields and climatic factors with period of operation were studied. The measured yields were compared with predicted yields for different types of plants. On the basis of the experimental works and analysis, discussion and guideline for design, operation and maintenance of solar stills are presented in this chapter.

4.2 PERFORMANCE OF DIFFERENT TYPES OF PLANTS

4.2.1 Construction and Installation

In this study, different types of single basin solar still were constructed. These designs were differed in structure and material of construction, but basically, incorporate common elements for different functions. The principal criteria for selection of materials were cost involvement, efficiency, and ease of construction and maintenance. The stills were characterized by a single basin (base and wall) to store saline water and one or more transparent covers on the top of the basin. From a review of the literature, at first attempt was made to construct stills that could be fabricated with skilled labor and shipped to the remote areas. It was decided that mild steel, wood and ferrocement would be used to construct still basins. Experimental investigation with these solar stills indicated that their construction cost were much more higher compared to their output. On the basis of market survey, detailed analysis and installation, the cost involvement of different types of solar desalination plants are presented in Table 4.1.

Table 4.1: Materials and Cost Involvement of Different Types of Plants

<i>Still Type</i>	<i>Materials Used</i>	<i>Installation Cost (Tk.)</i>
Mild Steel Plant (operated for a little period)	3/4" sheet of mild steel and glass cover.	4,090
Ferrocement Plant	Cement : sand ratio of 1:2, water : cement ratio of 0.6, 1/2" sized wire mesh. Base thickness 1.5". Glass cover.	3,000
Brick Plant 1	Thickness of wall and base are 3.25" and 3.5" respectively. Glass cover.	1,085
Brick Plant 2	Double slope of transparent plastic sheet	800
Brick Plant 3	Same as brick plant 1 but double layers of brick.	1,610
Brick Plant 4	Same as brick plant 1 but slope of glass cover is 13°.	1,085
Brick Plant 5	Same as brick plant 1 but slope of glass cover is 15°.	1,085
Brick Plant 6	Same as brick plant 1. Constructed and operated at field.	1,085
Brick Plant 7	Same as brick plant 3. Constructed and operated at field.	1,610
Brick Plant 8	Same as brick plant 2. but with increased dimension. Constructed and operated at field.	1,220
Clay Plant (Cement Plastered)	Same as brick plant 2 but made with clay and plastered with cement sand mortar. Constructed and operated at field.	435

4.2.2 Design Life

Design life of the plants could be estimated rather easily as the construction materials and types were used widely. From experience of using ferrocement and brick masonry in construction works, it was considered they would provide service at least for a period of 30 years without any major repair or rehabilitation (Rahman et al. 1996). The design life of the clay plant was considered 10 years. Routine cleaning and maintenance with nominal cost involvement would suffice during that period. However, the transparent cover would need to be changed periodically. The transparency of plastic sheet would reduce with time. Glass sheets, because of their brittleness, was likely to be broken several times during the design life. It was evident from the study that transparent covers would need replacement once a year. The sealant materials would need to be changed once in two years.

4.2.3 Operation and Maintenance

The difference in performance between the different types of plant were more obvious during the periods of operation. Generation of heat within the desalination basin and the glass caused damage to the sealant. The glass sheets used as transparent cover required special care in handling and placement on top of solar stills as they breaks easily. The plastic sheets as a transparent cover did not have such problems but they were vulnerable to attacks by crows. The still was placed in such a way that they were safe from the above mentioned problems and at the same time the children had to be made aware so that they would not break the glass or perforate the plastic sheet. The plants (base and wall) constructed with ferrocement and bricks had the advantage that these were safe against natural catastrophe and unfavorable climatic conditions. Their lifetime was much higher than the mild steel plants. The plants required cleaning in every four month on an average. In practical, the glass might be removed during the rainy season to safe from the hail storm.

4.2.4 Plant Yield

Outputs or yields of the plants were measured during the experimental investigation. The summarized form of the outputs are presented in Table 4.2. The average maximum yield was obtained from of Brick Plant 3 (1.42 liter/m²/day) and followed by Brick Plant 1 (1.40 liter/m²/day), Brick Plant 4 (1.36 liter/m²/day) and Brick Plant 5 (1.31 liter/m²/day). The minimum average yield was obtained from Clay Plant (0.65 liter/m²/day). The yields of different types of plants are shown in Figures 3.6 and Appendix A1 to A9. The plant output varies with seasons and the maximum average outputs were obtained during the March-May (for Brick Plant 1, the average output 1.91 liter/m²/day).

Table 4.2: Average and Range of Yield of Different Types of Plants

<i>Still Type</i>	<i>Average Yield (liter/m²/day)</i>	<i>Range of Yield (liter/m²/day)</i>
Ferrocement Plant	1.1	0.10-2.18
Brick Plant 1	1.40	0.28-2.64
Brick Plant 2	0.89	0.20-2.68
Brick Plant 3	1.42	0.22-2.68
Brick Plant 4	1.36	0.29-2.66
Brick Plant 5	1.31	0.27-2.58
Brick Plant 6	0.95	0.20-2.13
Brick Plant 7	1.09	0.22-2.66
Brick Plant 8	0.70	0.20-2.15
Clay Plant	0.65	0.20-1.49

4.2.5 Cover Slope

Brick Plant 4 and 5 were constructed in similar design of Brick Plant 1 with different slope of glass cover to study the effect of cover slope. The slopes were varied from 10° to 15° for the three plants as the suggested slope range by Grag and Mann (1976) was 10° - 15° (Article 2.7.7). The cover slope of the three plants with their average and relative yield are shown in the Table 4.3. Experimental results showed that Brick Plant 1 with cover slope 10° provided average higher yield (1.40 liter/m²/day) among the three plants.

Table 4.3: Cover Slope with Average and Relative Yield

<i>Still Type</i>	<i>Cover Slope</i>	<i>Average Yield</i>	<i>Relative Yield</i>
Brick Plant 1	10°	1.40	1.00
Brick Plant 4	13°	1.36	0.98
Brick Plant 5	15°	1.31	0.94

4.2.6 Transparent Cover

The study was carried out by using two types of transparent cover. These were 5 mm glass and transparent plastic sheet. Plastic sheets had many outstanding advantages over the other materials. An important advantage was that as their density was lower than most engineering materials, they had higher strength-to-weight ratios, a useful feature where reduction in weight was required. Plastic provided flexibility in design of solar stills. On the other hand, glass was a brittle material that required extensive care in handling and design possibilities with glass were quite inflexible. Average yield of plants with glass and plastic sheet are shown in Table 4.4. Experimental results showed that plants with glass cover had higher yield (an average 1.44 times) than the plants with transparent plastic cover sheet.

Table 4.4: Transparent Cover with Average and Relative Yield

<i>Still Type</i>	<i>Cover Material</i>	<i>Average Yield</i>	<i>Relative Yield</i>
Brick Plant 1	Glass	1.40	1.00
Brick Plant 2	Plastic Sheet	0.89	0.64
Brick Plant 6	Glass	0.95	1.00
Brick Plant 8	Plastic Sheet	0.70	0.74

Moreover, the plastic sheets were often perforated by crows. These were also perforated by heavy rainfall. It may be concluded that glass is superior to plastic sheets for the use as transparent cover of solar stills from the view point of productivity and ease of operation. However, glass sheet require special attention and care in handling and operation.

4.2.7 Layer of Brick Wall

Brick Plant 3 was constructed in similar design to brick plant 1 but with double layer of brick wall with air gap between them (Figure 3.5). The inner dimension was same as that Brick Plant 1. Double layer brick wall was provided to prevent loss of heat through the walls resulting in greater amount of yield. The experimental results shows that Brick Plant 3 had produced maximum average yield (1.42 liter/m²/day). But, the increase in the productivity of Brick Plant 3 was lower than the cost involvement. On the basis of installation cost, the cost of production per liter (without considering design life) for Brick Plant 3 was Tk. 1,133.80 and for Brick Plant 1 was Tk. 775. The single layer Brick Plant was found cost-effective in producing distill from saline water.

4.2.8 Efficiency of Plants

The efficiencies of various plants varied from 4.23% to 52.05%. Maximum, minimum and average efficiencies of Ferrocement Plant were found 38.17%, 4.23% and 22.57%. The corresponding figures for the Brick Plant 1 were found to be 49.30%, 8.58% and 33.82%. For Brick Plant 3, these were found 52.05%, 9.03% and 34.50%. The average efficiencies of Brick Plants were comparable to that of Farid and Hamad (1992) and Samy and Hasan(1992). These were 30% and 40%. The overall efficiency of solar still was found by Aftab (1975) was 25.20% at Bangkok. However, the plant base could be blackened (as done by Farid and Hamad) to increase efficiency but that involved additional cost and might change the quality of the distill. Table 4.5 summarizes the efficiencies of the plants.

Table 4.5: Efficiencies of Different Plants

<i>Still Type</i>	<i>Average Efficiency %</i>	<i>Range of Efficiency %</i>
Ferrocement Plant	22.57	4.23-38.17
Brick Plant 1	33.82	8.58-49.30
Brick Plant 2	19.77	7.27-41.25
Brick Plant 3	34.50	9.03-52.05
Brick Plant 4	33.14	8.36-48.28
Brick Plant 5	31.80	8.27-49.90

4.2.9 Yields in Different Location

The three brick plants with similar design and dimension were constructed at Dhaka and Kaliganj. The yield of these plants were compared with the daily average temperature and sunshine hour. The average temperature and sunshine hour of Kaliganj were found slight higher than those of Dhaka. The average temperature of Kaliganj was 27.55°C and that of Dhaka was 25.89°C. The average sunshine hour of Kaliganj was 6.16 and that of Dhaka was 6.05. But the average yield of the plants of Kaliganj was lower than those of Dhaka. It might be due to the reason that the plants at Dhaka were placed on the roof of the Civil Engineering Building (6th storied Building) and the plants were placed on the ground at Kaliganj. The heat transfer from the basin might be higher for those located at Kaliganj. The variation also might be created due to variation of environmental factors of Kaliganj specially solar radiation. There also might be an effect of MSL.

The Table 4.6 gives the yield, average temperature and sunshine hour during the plant operation.

Table 4.6: Yield and Environmental Conditions of Different Plants

<i>Still Type</i>	<i>Yield (Liter/m²/day)</i>	<i>Average Temperature (°C)</i>	<i>Sunshine Hour</i>
Brick Plant 1	1.40	26.10	6.03
Brick Plant 6	0.95	27.55	6.16
Brick Plant 2	0.89	25.97	6.05
Brick Plant 8	0.70	27.55	6.16
Brick Plant 3	1.42	25.60	6.08
Brick Plant 7	1.1	27.55	6.16

4.3 CAPACITY OF DESALINATION PLANTS TO SUPPLY DRINKING WATER

The water obtained from the plants was totally free from salinity (15-25 ppm). The salinity of water in the coastal areas of Bangladesh varied in general from 1,000 to 2,000 ppm and the acceptable limit for drinking purpose was 600 ppm. Therefore, an equal amount of tubewell water might be mixed with the output of the plants to increase the stock of water (considering salinity of 1,000 ppm) (Rahman et al. 1997).

The average yield of Brick Plant 1 was 1.40 liter/41/m²/day. With an area of 1.15 m² (12 ft²) the output would be 1.61 liter/day. If tubewell water of salinity 1,000 ppm was mixed with

this yield in 1:1 ratio, the volume obtained was 3.22 liter/day. However, three such plants might be required for drinking purposes for a family.

4.4 COST OF PRODUCTION

Both Brick plant and Ferrocement Plant could be considered to have a design life of 30 years with routine cleaning and maintenance involving nominal cost. However the transparent cover (glass sheet) would need replacement several times (say once a year) during the design life because of its brittle nature. The maintenance cost involves cost of transparent cover, cost of sealant materials and labor involves in cleaning of the plant. Assuming that the plants would be able to provide yield for 30 year with changes of transparent glass once in a year and plastic twice a year (for Brick Plant 2, Brick Plant 8 and Clay Plant), changes of sealant materials once in a two year and cleaning with own labor, the cost of production over the year could be estimated as shown in Table 4.7. As earlier mention, the design life of Clay Plant was 10 years.

Table 4.7 : Cost of Production over Design Life

Still Type	Installation Cost (Tk.)	Per Year Maintenance Cost (Tk.)	Total Maintenance Cost (Tk.)*	Per Annum Average Yield (lit)	Cost per Liter (Tk.)
Ferrocement Plant	3,000	470	16,920	445	1.49
Brick Plant 1	1,085	450	16,200	584	0.92
Brick Plant 2	800	300	10,800	371	0.97
Brick Plant 3	1,610	500	18,000	596	1.00
Brick Plant 4	1,085	450	16,200	588	0.98
Brick Plant 5	1,085	450	16,200	571	0.98
Brick Plant 6	1,085	450	16,200	550	1.05
Brick Plant 7	1,610	500	18,000	458	1.30
Brick Plant 8	1,220	300	14,000	442	1.15
Clay Plant	435	300	3,150**	272	1.16

* The total maintenance cost includes 20% extra for probable increase in the cost of materials for the 30 years.

** The total maintenance cost includes 5% extra for probable increase in the cost of materials for the 10 years.

The cost per liter would be just half if we considered mixing of tubewell water with the yield with a ratio of 1:1. Then the cost of drinking water would be half of the production cost. Again, if proper care and attention would be paid in handling the transparent glass cover, one glass cover might serve more than one year that would reduce the cost output per liter.

4.5 PLANT SELECTION

From the foregoing discussion, it appeared that the Brick Plant 1 performed well during the experimental investigation period. The plant had glass as cover materials with slope $10^{\circ}37'$ and single layer brick wall. The plant was easy to construct, operate and maintain and involved less cost. Though the installation cost of Brick Plant 2 and Clay Plant were lower than Brick Plant 1, but those were not convenient to operate and maintain.

4.6 USE OF DESALINATION PLANTS DURING THE RAINY SEASON

The desalination plants with proper cleaning could be used to collect rain water during the rainy season. Then a tap of Tk. 10 had to be provided with the plant for collecting rain water to minimize contamination of storage water. This might minimize the lower output during the rainy seasons.

4.7 HEAT TRANSFER

The average convective heat transfer (cover to air) of various plants varied from 5.00 cal.cm^2 to 7.83 cal.cm^2 . The average convective heat transfer (basin to cover) of various plants varied from 0.54 cal.cm^2 to 0.89 cal.cm^2 . The average thermal radiation (cover to air) of various plants varied from 1.67 cal.cm^2 to 2.65 cal.cm^2 . The average thermal (basin to cover) of various plants varied from 1.33 cal.cm^2 to 2.12 cal.cm^2 . Among the previous four discussed heat transfer modes, it was revealed that convective heat transfer (cover to air) was the highest (an average 6.41 cal.cm^2) among four modes and convective heat transfer (basin to cover) was lowest (an average 0.74 cal.cm^2) among the four modes.

4.8 MATHEMATICAL EQUATION FOR PREDICTION OF YIELD

The developed mathematical equation (equation 3.1) could be used to predict the yield of solar still with transparent glass cover. The equations predicted a better yield between the actual yield of 0.75 liter/m^2 to 1.75 liter/m^2 . The actual average monthly diurnal yield for the Brick Plant 3 (the equation was developed using the data of Brick Plant 1) was plotted against calculated average monthly diurnal yield in the Figure 4.1. The figures indicated that calculated average monthly diurnal yield varies from -14.56% to $+13.14\%$. So, it provided a better prediction for the average monthly diurnal yield. The equation could also be used to predict the effect of single parameter on the yield of solar plant. To predict the

effect of single parameter, other parameter should be kept fixed. The following average data were taken for this calculations.

Average Temperature 30°C

Radiation = 250 Cal/m² .day

Sunshine Hour = 6.5

Relative Humidity = 75

Glass Temperature = 30°C

Water Temperature = 34°C

The effect of single parameter on yield were plotted and shown in Figure 4.2 to Figure 4.7. With the increasing of the parameters, the yield is found increasing. The effect of average temperature on yield had a similar trend as shown by Cooper (Figure 2.4). The figures may be used in sensitivity analysis of yield.

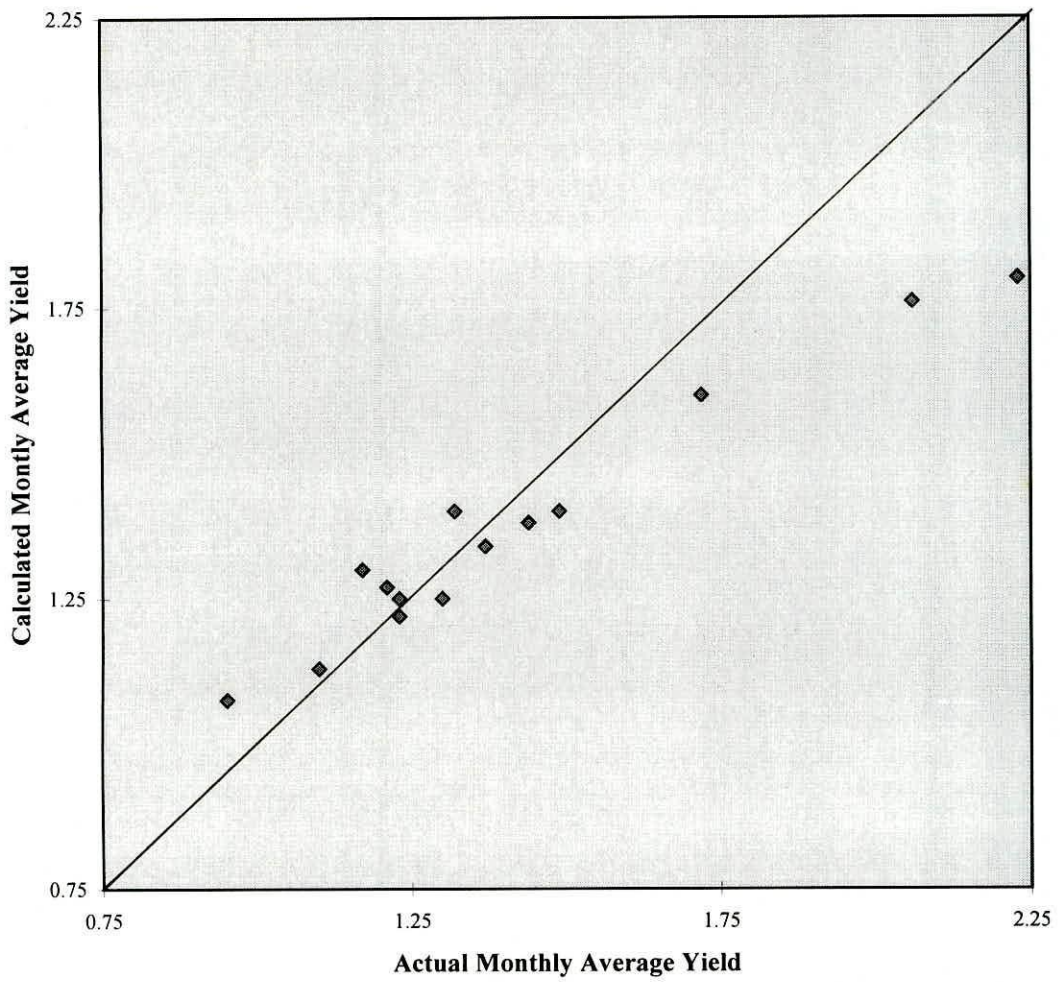


Figure 4-1: Variation of Calculated Average Monthly Diurnal Yield with Actual Average Monthly Diurnal Yield of Brick Plant 3

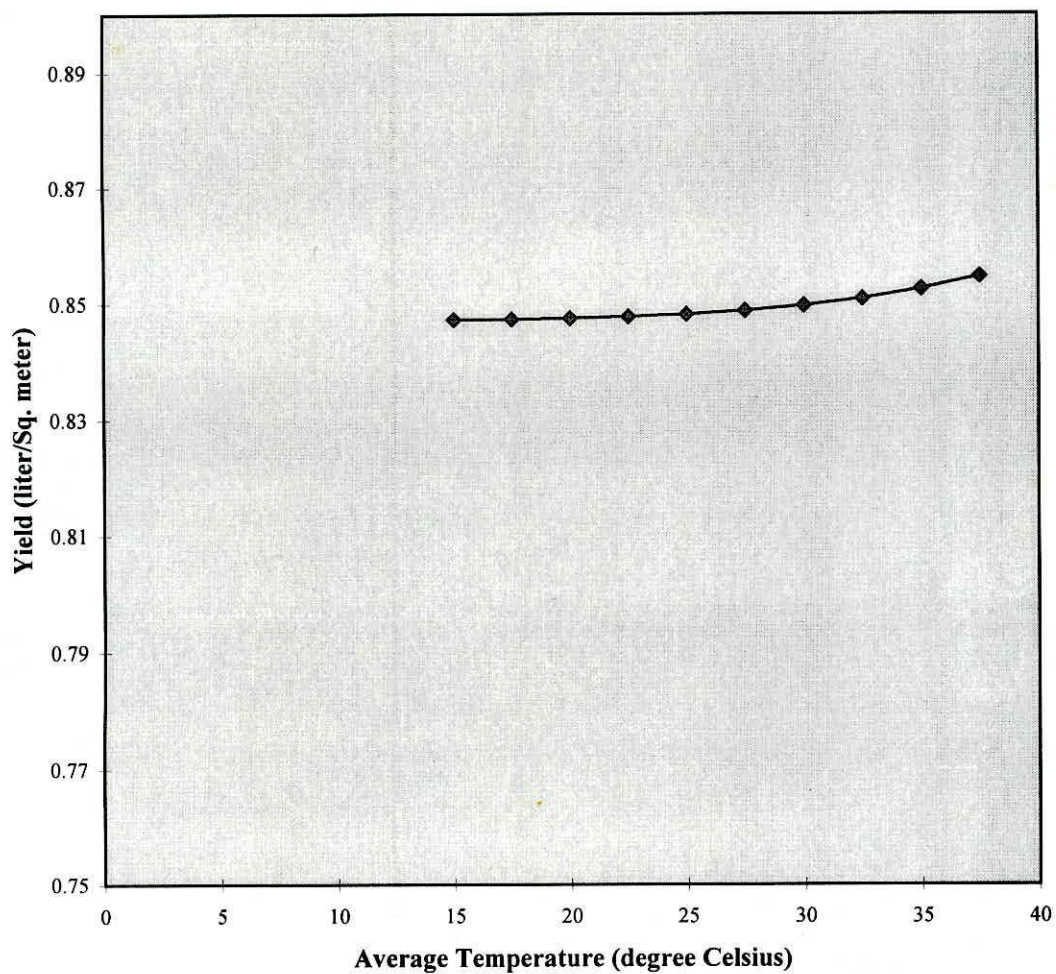


Figure 4-2: Effect of Temperature on Plant Yield (Calculated by Developed Equation 3.1)

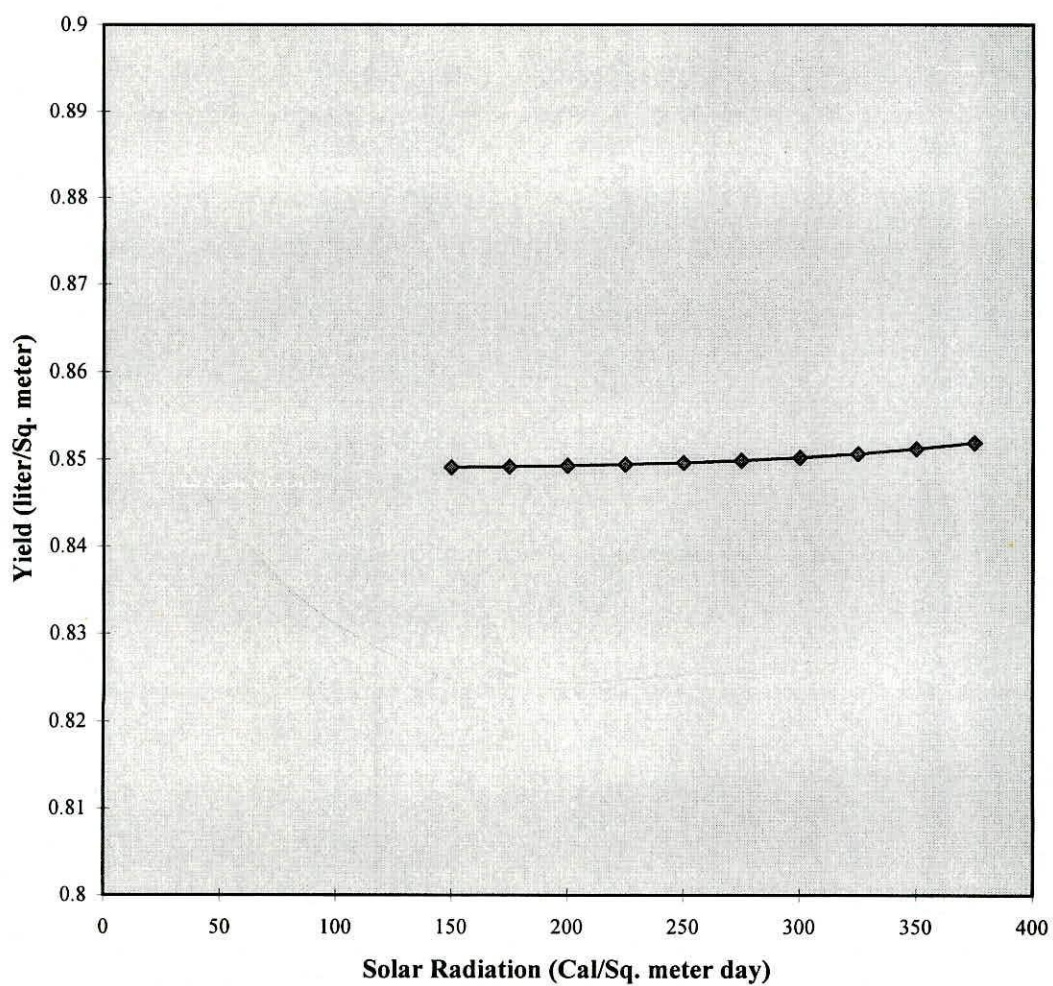


Figure 4-3: Effect of Radiation on Plant Yield (Calculated by Developed Equation 3.1)

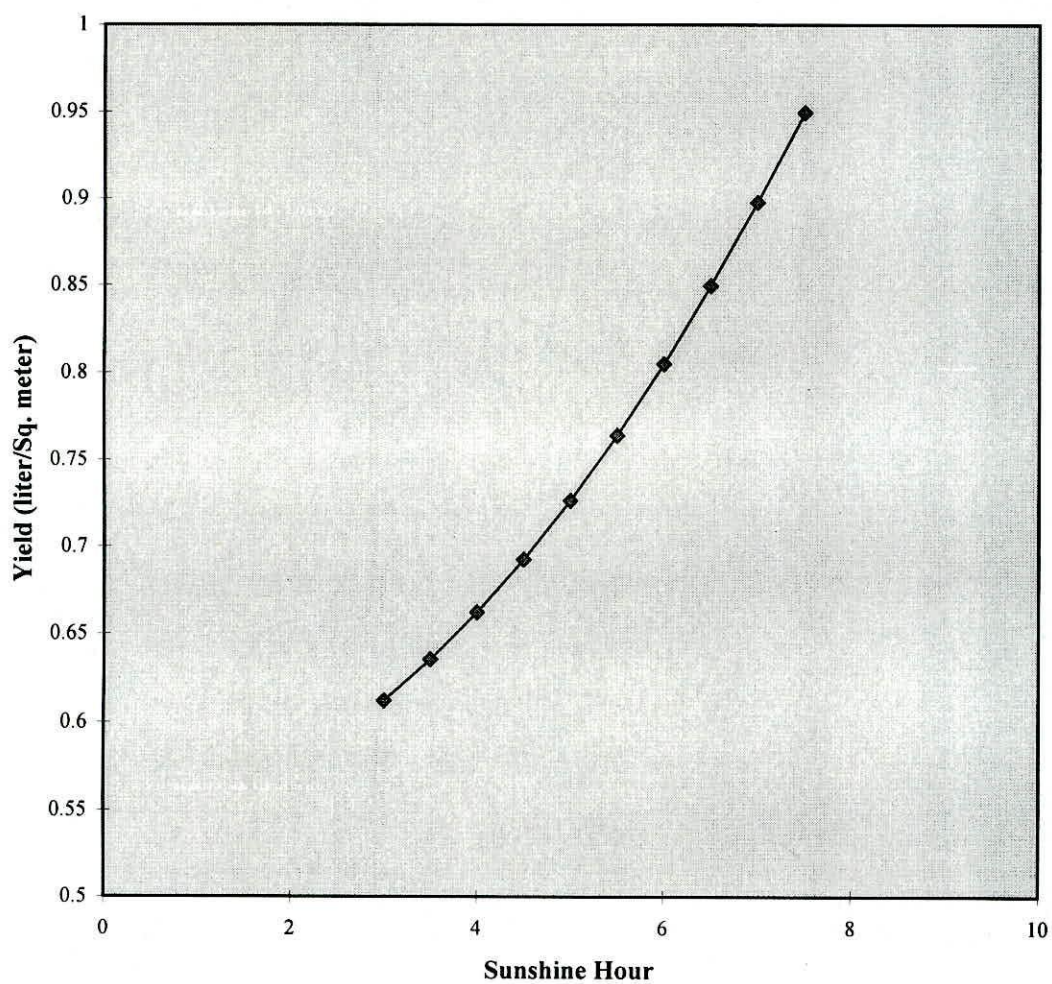


Figure 4-4: Effect of Sunshine Hour on Plant Yield (Calculated by Developed Equation 3.1)

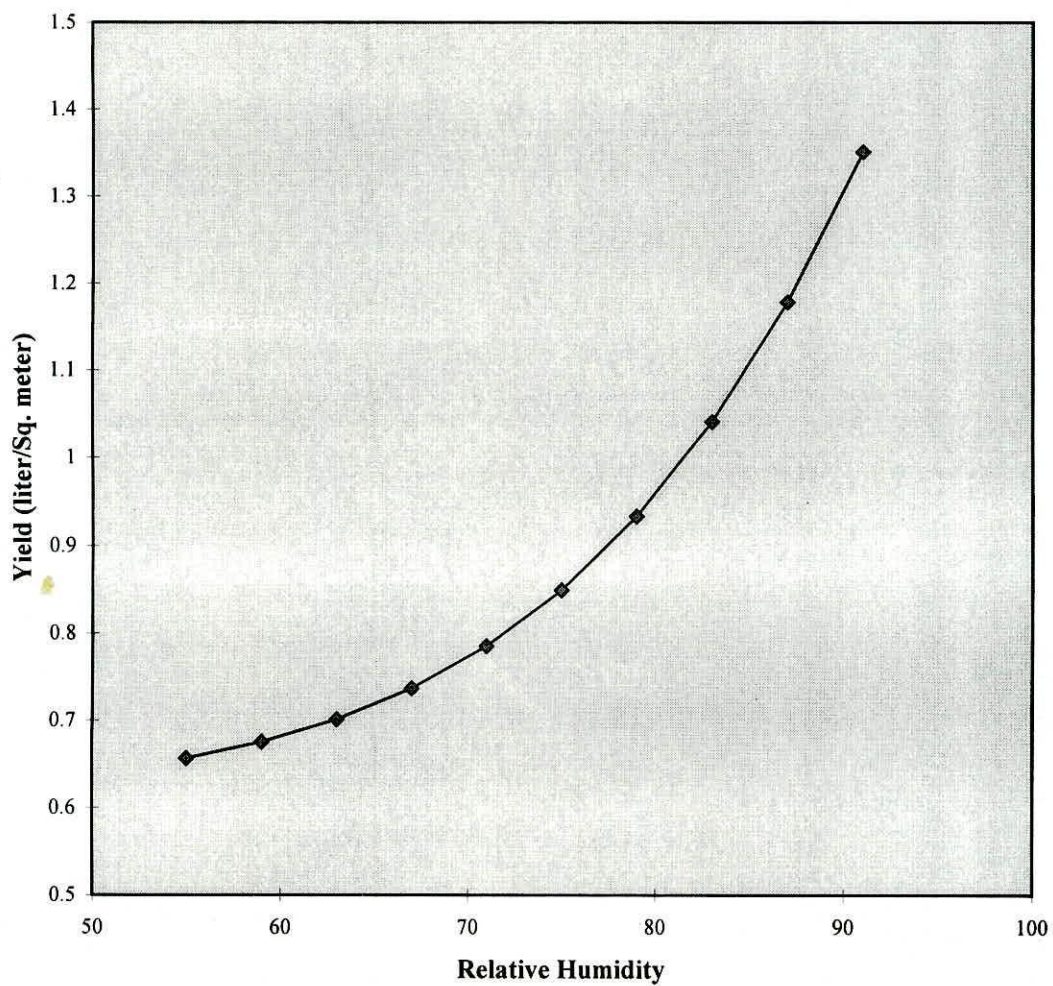


Figure 4-5: Effect of Relative Humidity on Plant Yield (Calculated by Developed Equation 3.1)

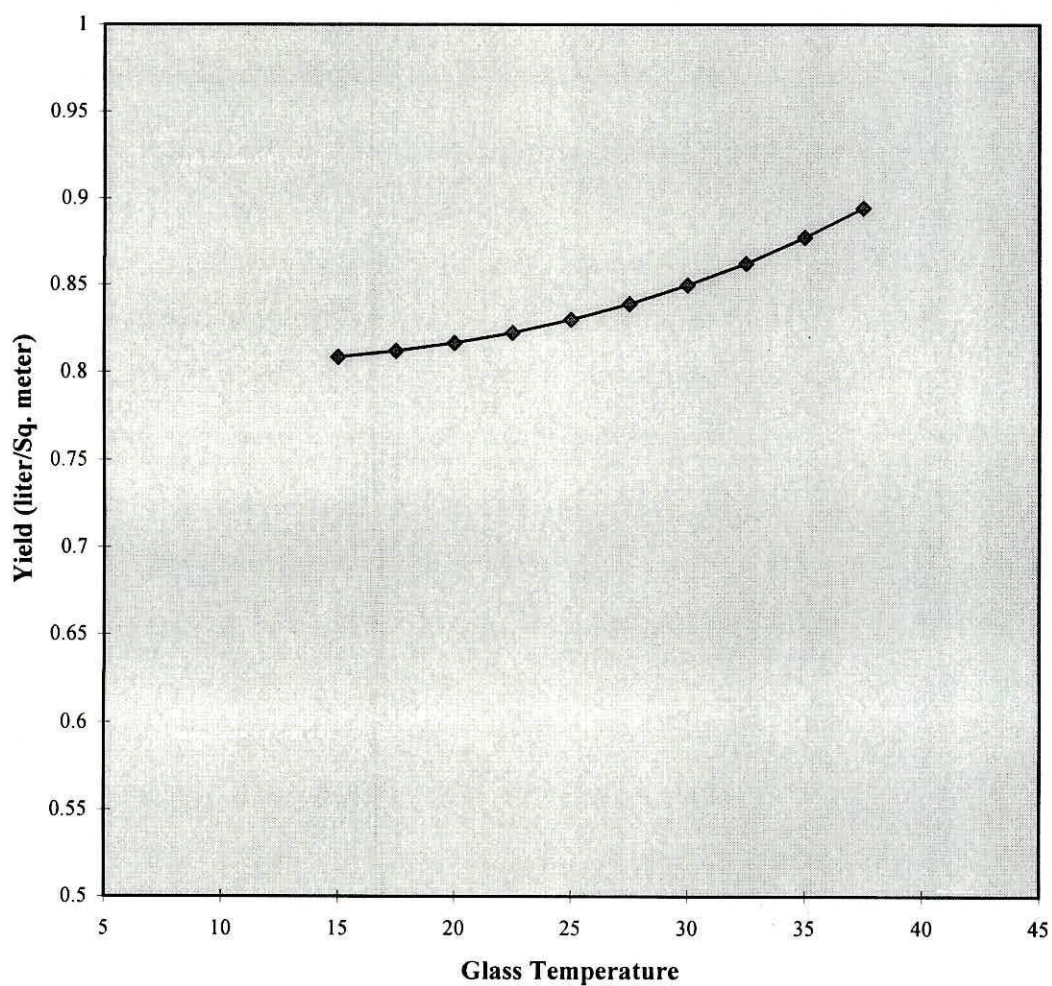


Figure 4-6: Effect of Glass Temperature on Plant Yield (Calculated by Developed Equation 3.1)

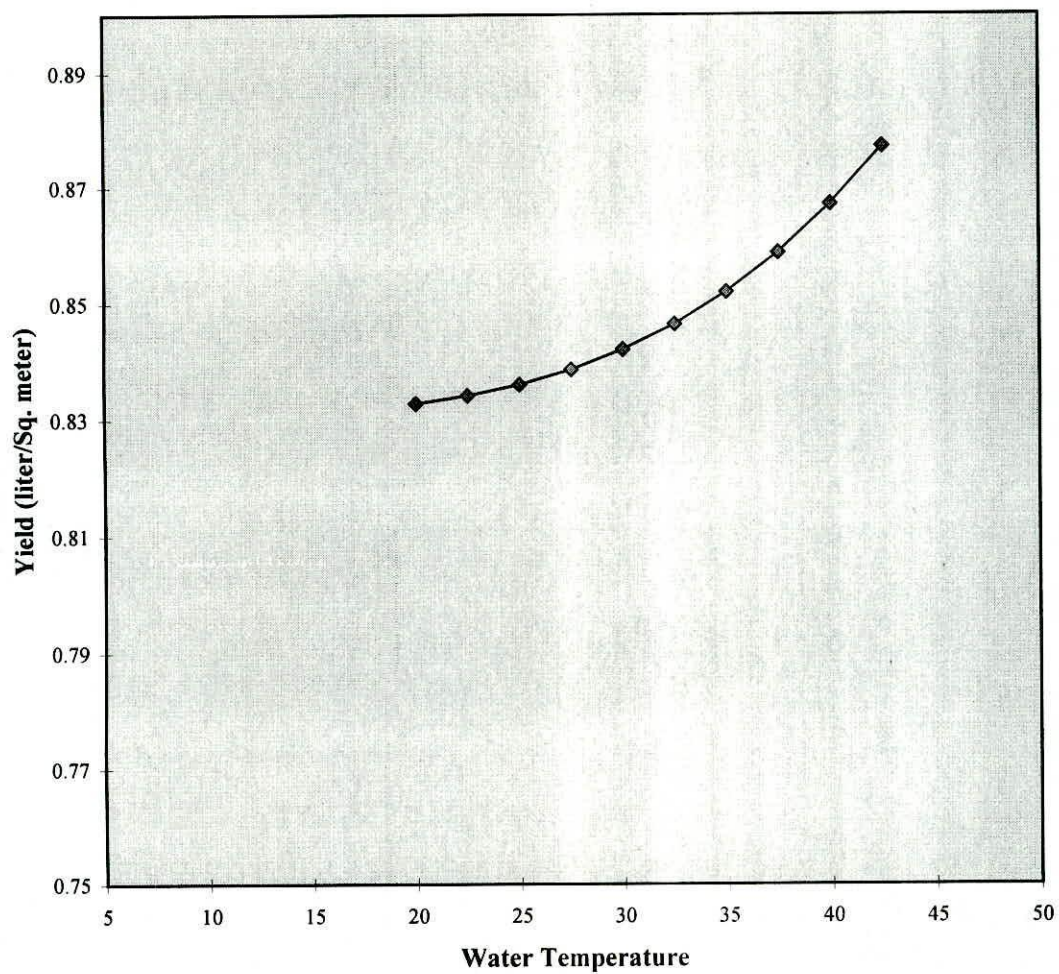


Figure 4-7: Effect of Water Temperature on Plant Yield (Calculated by Developed Equation 3.1)

4.9 GUIDE LINES

4.9.1 General

The development of solar still in Bangladesh is still in the research stage. On the basis of literature review, experimental work and analysis, guidelines for solar still design, operation and maintenance were prepared. The guidelines presented is intended to construct, operate and maintain such a desalination plant in Bangladesh.

There are certain basic requirements which must be met. In general, the following specifications should be adhered to :

- The unit should be made of locally available materials;
- The cost of the materials should be within reasonable limits;
- Local technology should be adequate to construct and maintain the plant;
- The unit should have an effective life of 25 to 30 years with normal maintenance;
- The unit should be able to withstand the effects of severe storms and surges; and
- The materials used in the plant will not contaminate the input saline water or the distillate.

Transparent Cover

This serves to cover the equipment and permit access of solar radiation to the interior. Required properties of the transparent cover are listed below :

- The material must withstand the effects of weather - wind, sunshine, rain, dust etc.;
- The material must have a transitivity of short wave solar radiation (between the limits of 0.3 to 3.0 microns) of over 85% and preferably higher;
- Essentially, it must be nearly opaque to long wave (over 3.0 microns) radiation;
- The solar reflectivity at normal incidence should not exceed 10%;

- The solar reflectivity at normal incidence should not exceed 10%;
- The heat capacity should be high in order to reduce the cover temperature;
- The material properties should not alter with age;
- The cover must be able to withstand the ravages of small animals; and
- The cover must be able to withstand a wind load of up to 50 m/sec.

Evaporator Liner

The evaporator of basin liner serves as the absorbing surface for solar radiation as well as a container for the saline water. Materials used for this purpose should have the following properties and characteristics :

- The liner must be impervious to water;
- The liner must have a solar absorptivity of the order of 0.95. Generally black materials are used;
- The surface would be fairly smooth so as to discourage the deposition of scale from the saline water. It also becomes easier to clean when necessary;
- As liners are often placed directly on the ground, the materials should not deteriorate or decompose on contact with normal soils;
- The material must withstand the effects of continuous emission in hot saline water. Temperature should not exceed 80°C to 100°C upon being heated, and
- The basin liner should not emit any gases or vapors which could taint the taste of fresh water distillate.

Solar Still Frame

This section refers to materials which are used to form the frames of the evaporators. Any material used in this fashion should possess the following characteristics :

- They should be sufficiently heavy so as to anchor the plant to the ground during periods of high winds;
- The materials should not be affected by direct contact with the ground or exposure to normal weather conditions; and
- The material should be free from corrosion in the expected weather conditions.

Sealants

This section includes materials used to seal transparent cover materials to another as well as the other components of the plant. In addition, it includes any members used to support the superstructure of the distillation units as they will invariably come in contact with the transparent cover.

- The material should not be adversely affected by exposure to the weather on one face and by the possible exposure to the interior of the evaporator in the internal face; and
- If structural cover supports are not used, the transparent cover material sealants must withstand the effects of wind of up to 50m/sec.

Insulation

The insulation used in solar distillation units is used beneath the sea water evaporator basins in order to reduce ground heat losses. The materials used for this purpose require the following properties :

- They must be water proof and basically water impermeable;
- They should insulate the edges as well as the base of the evaporator;
- The insulation must withstand temperatures of up to 80°C and must not warp or change shape; and
- The insulation must withstand the effects of the ground on which it is placed.

Auxiliaries

This section includes all fluid systems- gutters for condensate collection, piping for feed lines and outlets. All internal gutters or piping systems should have a protective coating of inert material in order to avoid contamination or damage to the system.

4.9.2 Guide lines for Design and Construction

Installation

The site of the still should be so selected that the still receives unobstructed sunshine from at least 8 am to 4 pm everyday. The still should be placed in such a way that the inclination lies toward the equator. Large areas are needed to produce significant quantities of pure water.

Depth of Water

The depth of water that is evaporated each day is about 1/8 inch, so nowhere should the water in the tray be less than about 1/4 inch deep. The maximum desirable depth is 1 inch.

Spacing between Brine and Cover

The productivity is not affected by the spacing between brine and cover in the range of 0.5 to 1.5 ft.

Effect of Cover Inclination

The optimum angle of inclination of the transparent cover is 10 to 15°.

Collection of Condensate

Condensate should be collected in covered and contaminant-free containers.

4.9.3 Guidelines for Operation and Maintenance

Operation and maintenance of a solar still is simple. Adherence to the following points would suffice in smooth operation and maintenance of a still :

- The still would be filled with clean fresh water to a height of approximately 1 inch. Early every morning, about 6 to 7 am, the still must be drained of the remaining water and fresh water added in its place to the specified height in order to prevent salt deposition in the basin.
- When initially starting up the still, the first few days of production should be rejected to avoid contamination. The collecting bottles should be washed out in fresh water and then in distilled water. The collecting bottles must be of sufficient size to hold from 1 to 2 liters. The top should be loosely stoppered to prevent contamination.
- The surplus distilled water shall be stored in a clean container for emergencies.
- Special care should be taken to minimize the maintenance cost of solar still with glass cover. Glass cover should be handled carefully during the time of cleaning the still and during stormy weather.
- During rainy season, the still should be properly cleaned before rain. Storms and the clean rain water should be collected for adding to the reserve stocks.
- During the winter season, the transparent cover should be cleansed in the morning so that it is not obscured due to condensation of fog.
- Performance of the still should always be monitored and if any leakage or any other problem with the plant components is found, it should be fixed as soon as possible.

4.10 REMARKS

It is apparent from the study that Brick Plant 1 performed well during the experimental investigation period, provided the highest amount of yield in terms of cost of production. It was easy to construct, operate and maintained by very low cost. The cost per liter of yield was found to be lowest and it was Tk. 0.92. If, tubewell water was mixed with the distillate, then the cost of drinking water would be half of the production cost. The Brick Plant 1 had 5 mm glass cover with cover slope of $10^{\circ}37'$. This plant had single layer side brick wall.

The site of the still should be so selected that the still receives unobstructed sunshine from at least 8 am to 4 pm. The depth of water that was evaporated each day was about 1/8 inch, so nowhere should the water in the tray be less than about 1/4 inch deep. The maximum desirable depth was 1 inch. The spacing between brine and cover should be in the range of 0.5 to 1.5 ft.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS
FOR FUTURE STUDY

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

5.1 GENERAL

On the basis of the detail experimental work, analysis and discussion, conclusions are drawn and future recommendations for future study are presented in this chapter.

5.2 CONCLUSIONS

The study has led to the following conclusions:

1. Brick appeared to be cheap and durable materials for the construction of solar plants in comparison of other materials like ferrocement, steel etc. (Table 4.1).
2. Glass was superior to plastic sheets for use as transparent cover of solar stills from view point of productivity, efficiency and ease of operation (Section 4.2.6 & Table 4.4).
3. The cover slope $10^{\circ}37'C$ was found the optimum inclination of cover of the plant (Section 4.2.5 & Table 4.3).
4. Single layer brick plant was cost-effective in producing distill from saline water comparing to double layer brick plant (Section 4.2.7).
5. It was evident from the study that, of all the plants studied, the design of Brick Plant 1 was the best suited solar desalination plant for Bangladesh (Section 4.5).
6. The maximum, minimum and average yield of Brick Plant 1 was found 2.64 liter/m²/day, 0.28 liter/m²/day and 1.40 liter/m²/day respectively (Table 4.2).
7. The maximum, minimum and average efficiency of Brick Plant 1 was found 49.30%, 8.58% and 33.82% respectively (Table 4.5).

8. The lowest cost of water per liter was found Tk. 0.92 for Brick Plant 1. If, tubewell water was mixed with the distillate in 1:1 ratio, then the cost of drinking water would be half of the production cost. Section 4.4 & Table 4.7).
9. Convective heat transfer (cover to air) was the highest (an average 6.41 cal.cm²) among discussed four modes and convective heat transfer (basin to cover) was the lowest (an average 0.74 cal.cm²) among the four modes (Section 4.7 & Table 3.5-3.8).
10. The yield of different solar stills could be predicted by using the equation 3.1. From Figure 4.1 it was observed that the calculated average monthly diurnal yield had maximum deviation of data within ± 14.60 for all cases and within ± 7.00 if 4 nos. data was excluded.
11. The mathematical equation 3.1 could be used to study the effect of a single parameter to the yield (Figure 4.2 to Figure 4.7). The effect of average temperature on yield has a similar trend as shown by Cooper (Figure 2.4).

5.3 RECOMMENDATIONS FOR FUTURE STUDY

The following recommendations are made to extend the present study:

1. The effect of latitude, longitude and MSL on plant productivity and efficiency can be studied.
2. The effect of dye in increasing the productivity of plant can be studied for Bangladesh.
3. Studies may be carried out with different geometric design of solar stills.
4. The developed equation can be verified with the climatic data for different region.

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APPENDIX A
FIGURES REFERRED IN TEXT

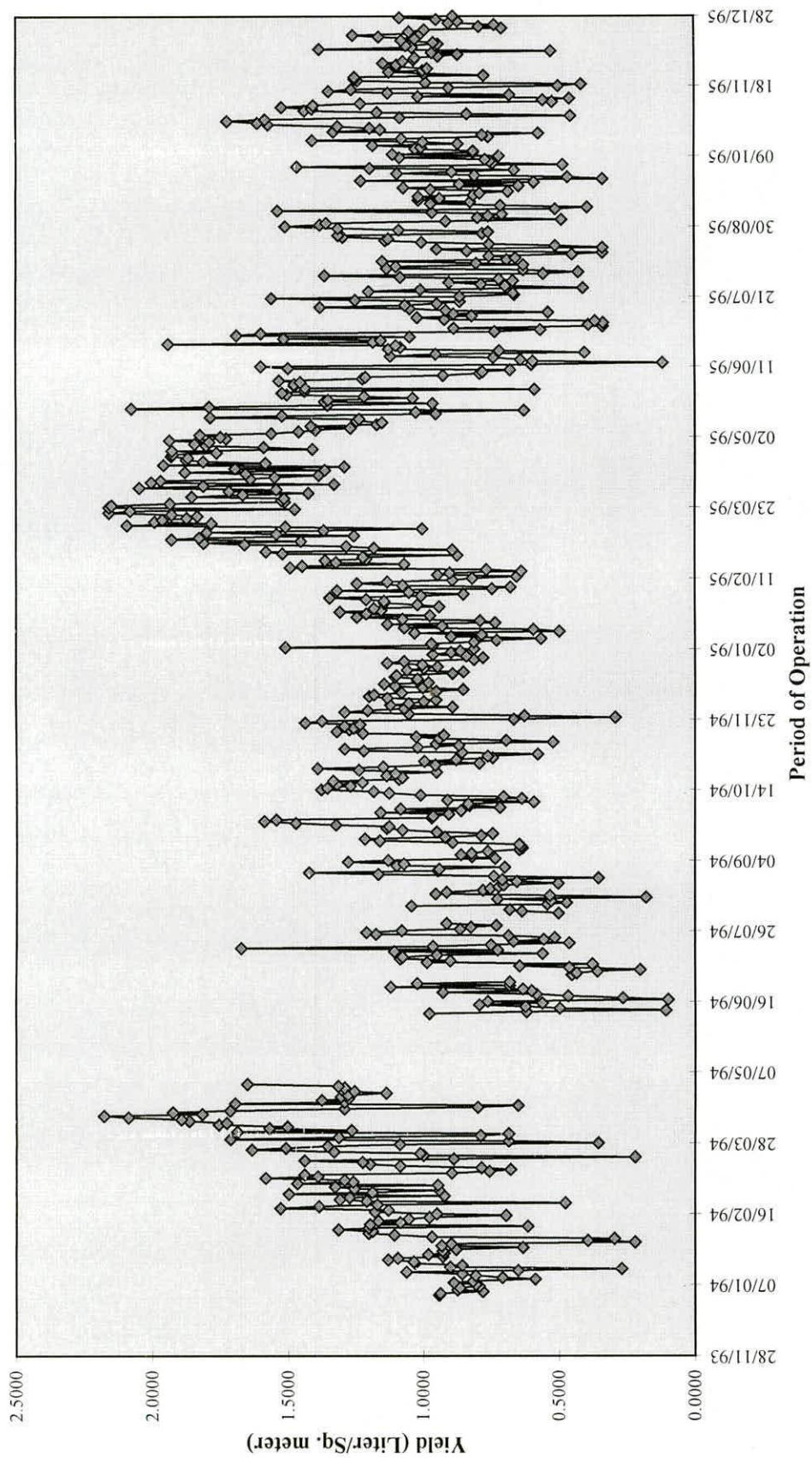


Figure A 1: Yield of Ferrocement Plant

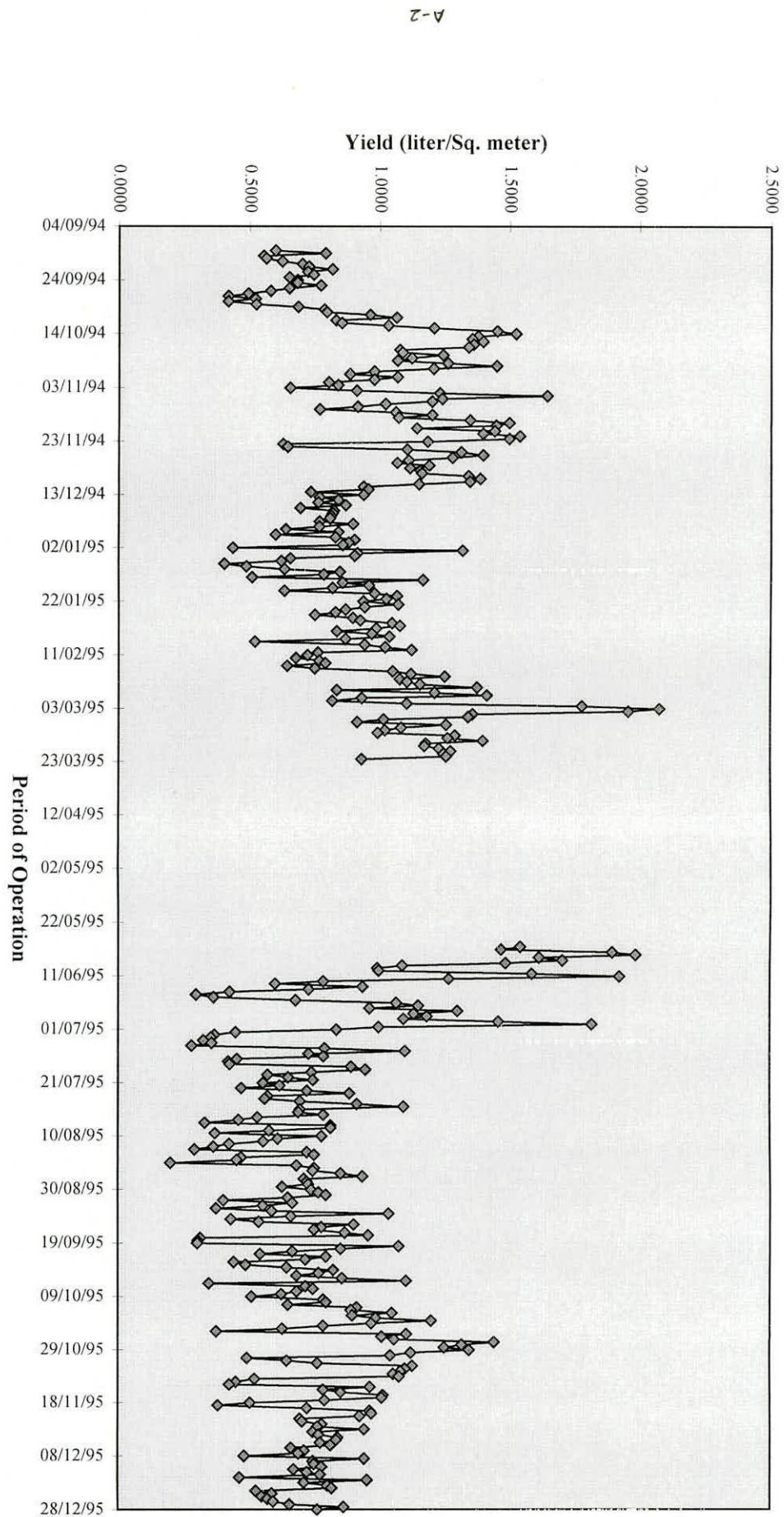


Figure A 2: Yield of Brick Plant 2

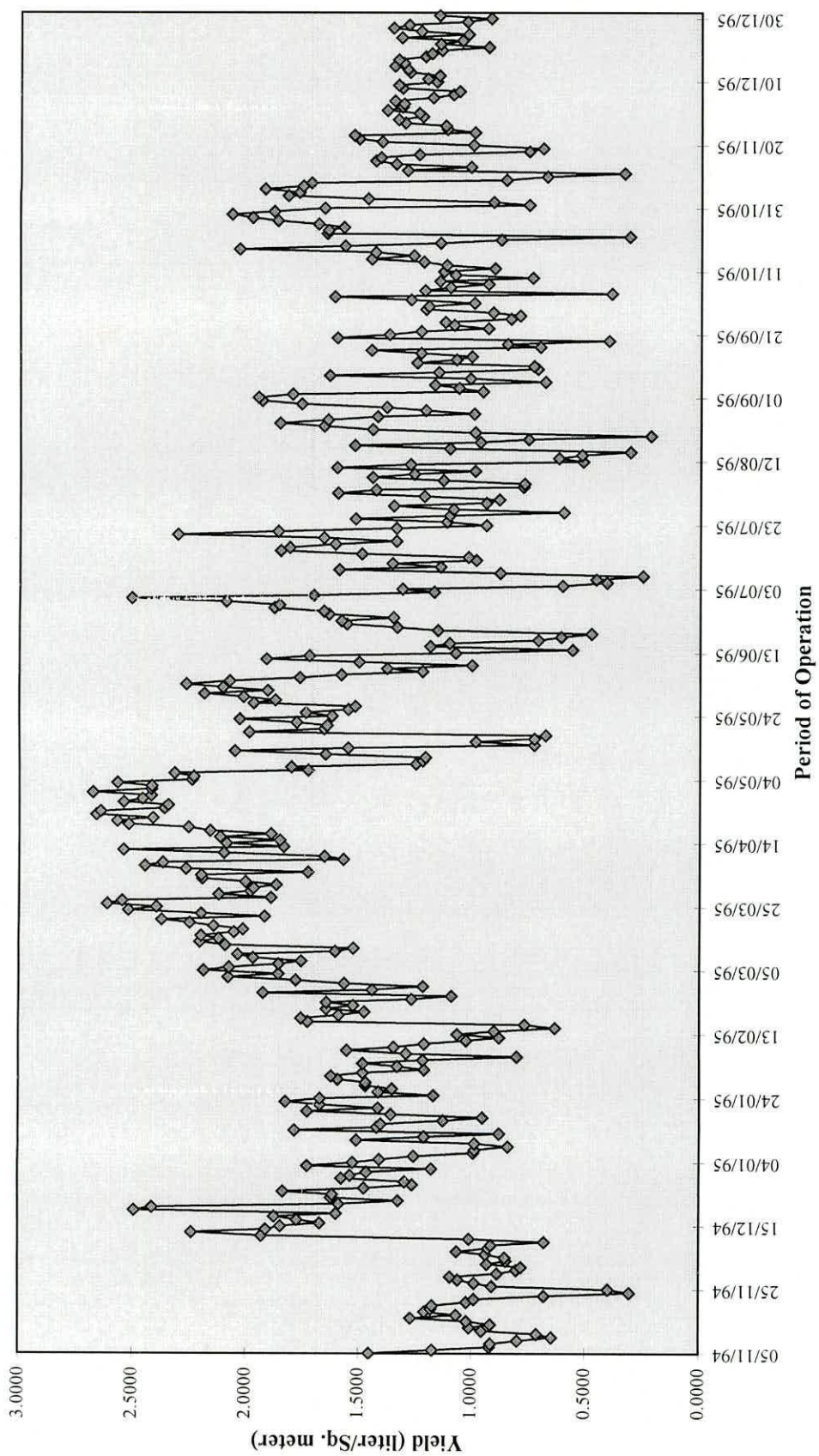


Figure A 3: Yield of Brick Plant 3

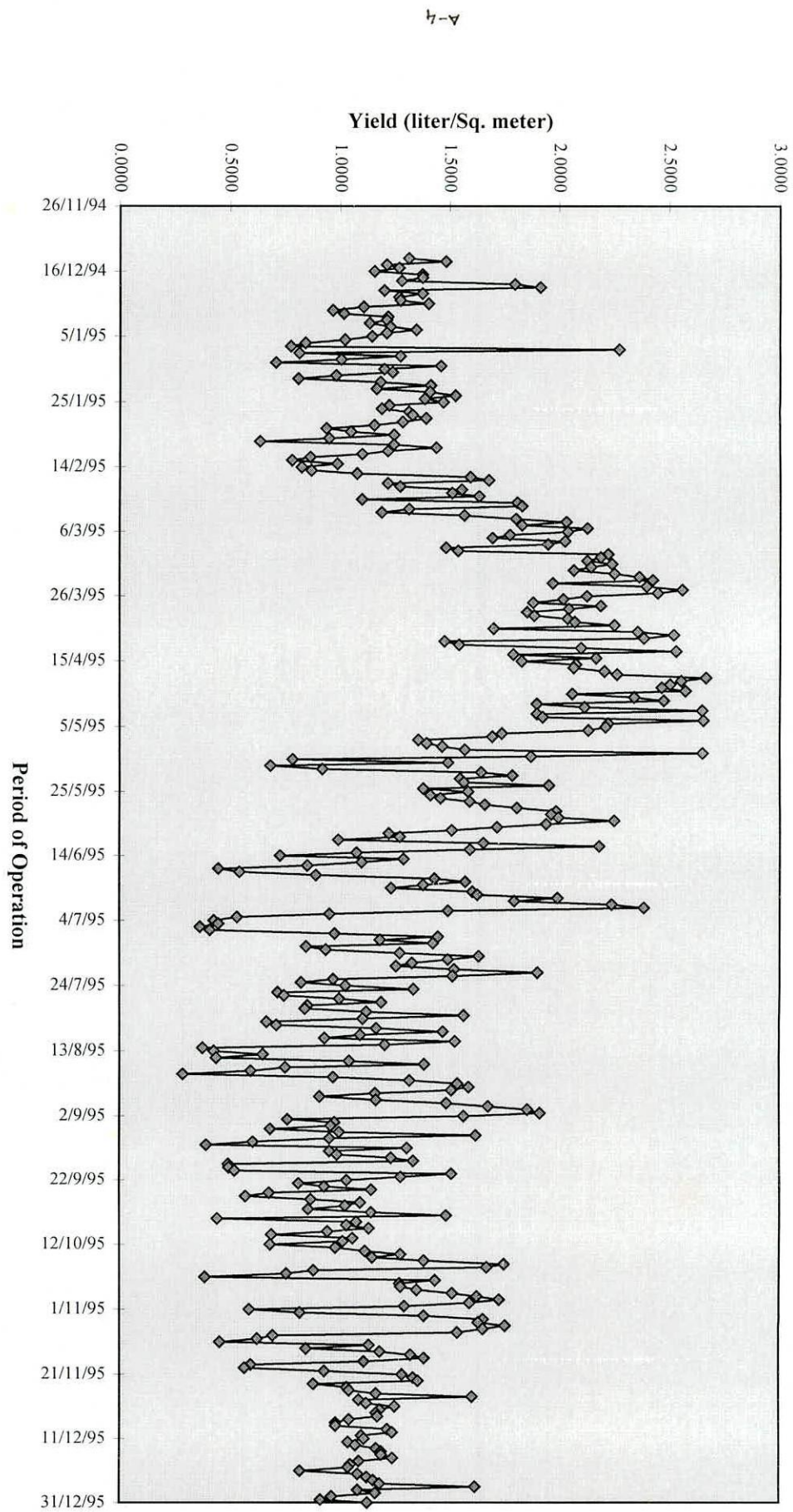


Figure A 4: Yield of Brick Plant 4

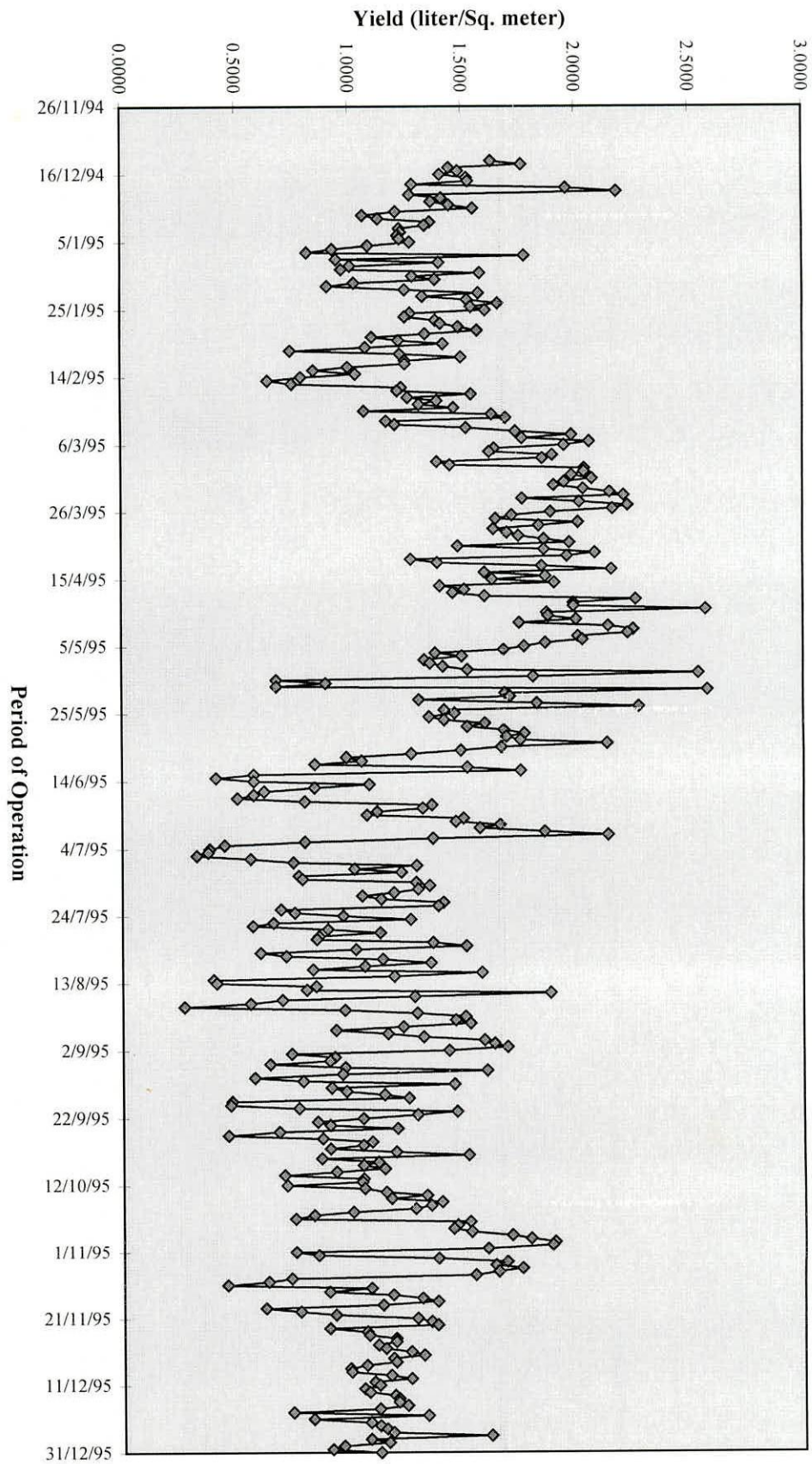


Figure A 5: Yield of Brick Plant 5

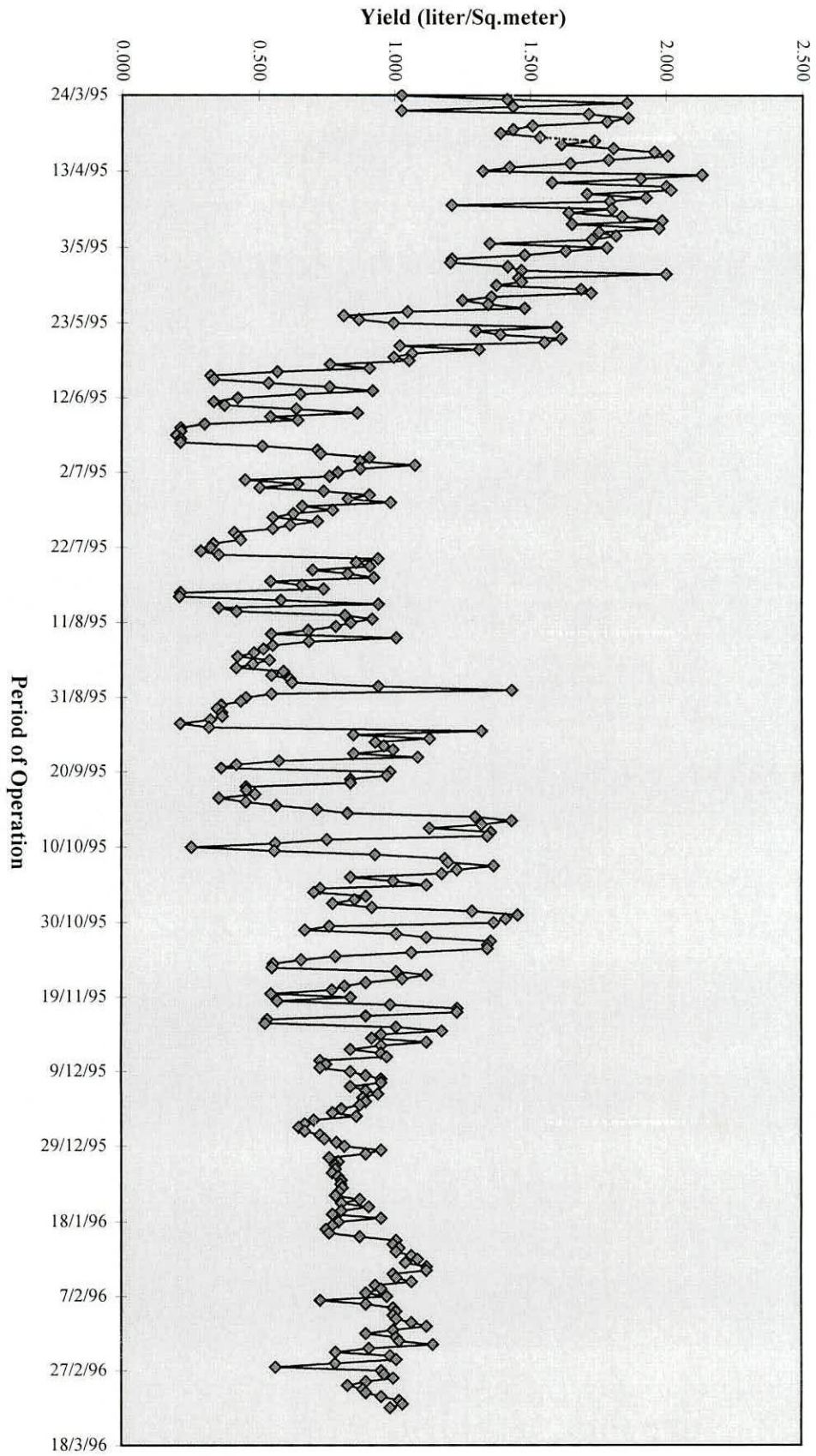


Figure A 6: Yield of Brick Plant 6

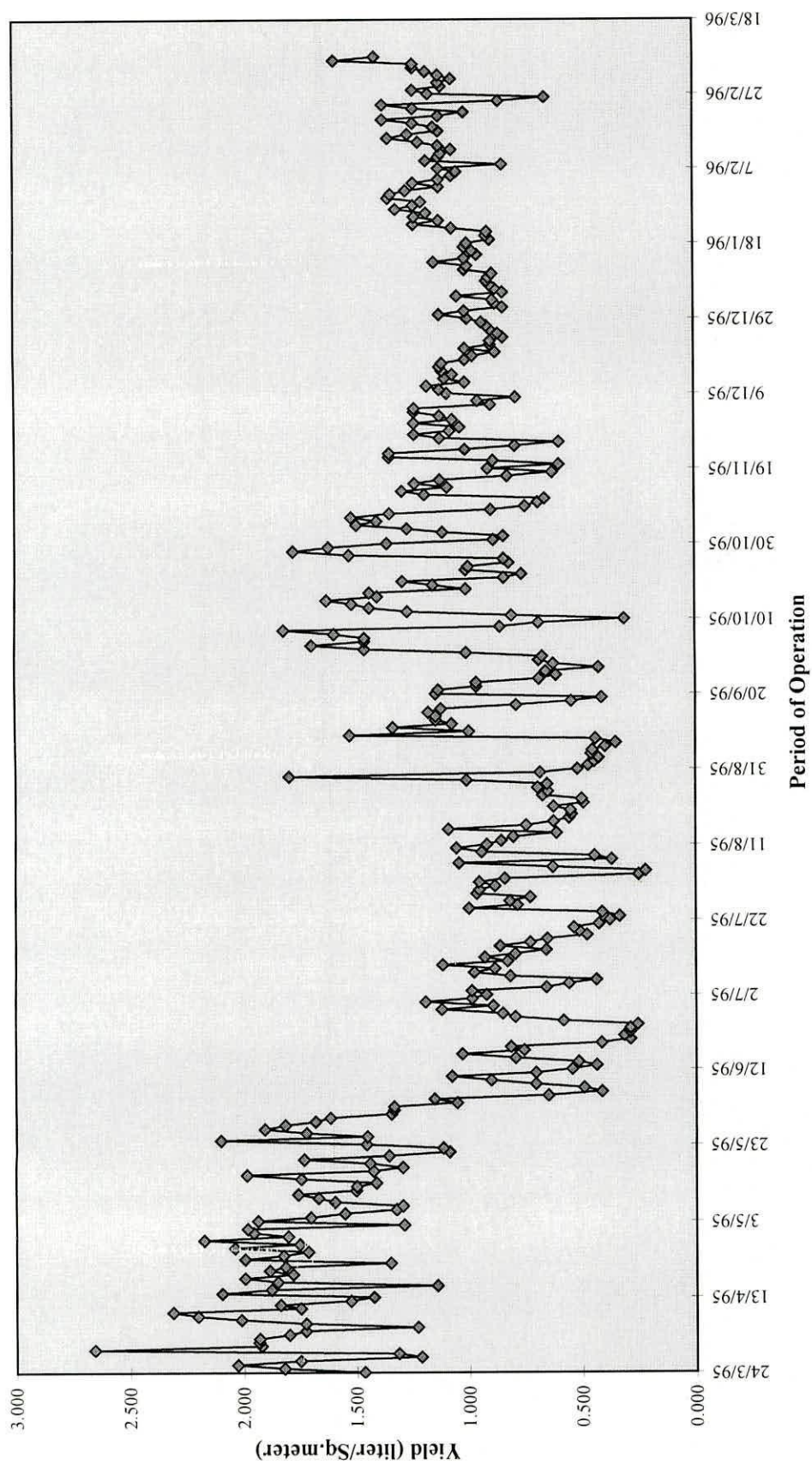


Figure A 7: Yield of Brick Plant 7

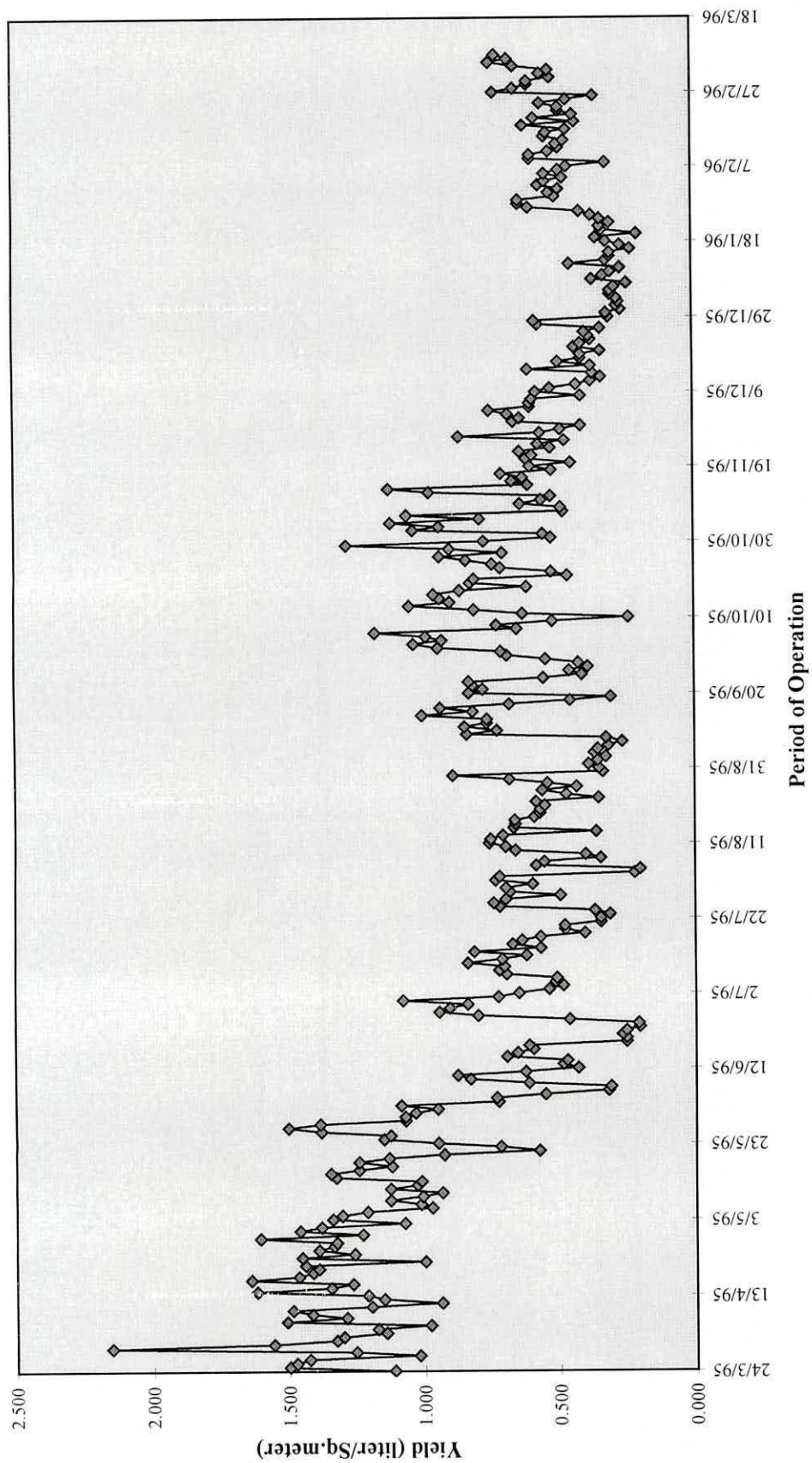


Figure A 8: Yield of Brick Plant 8

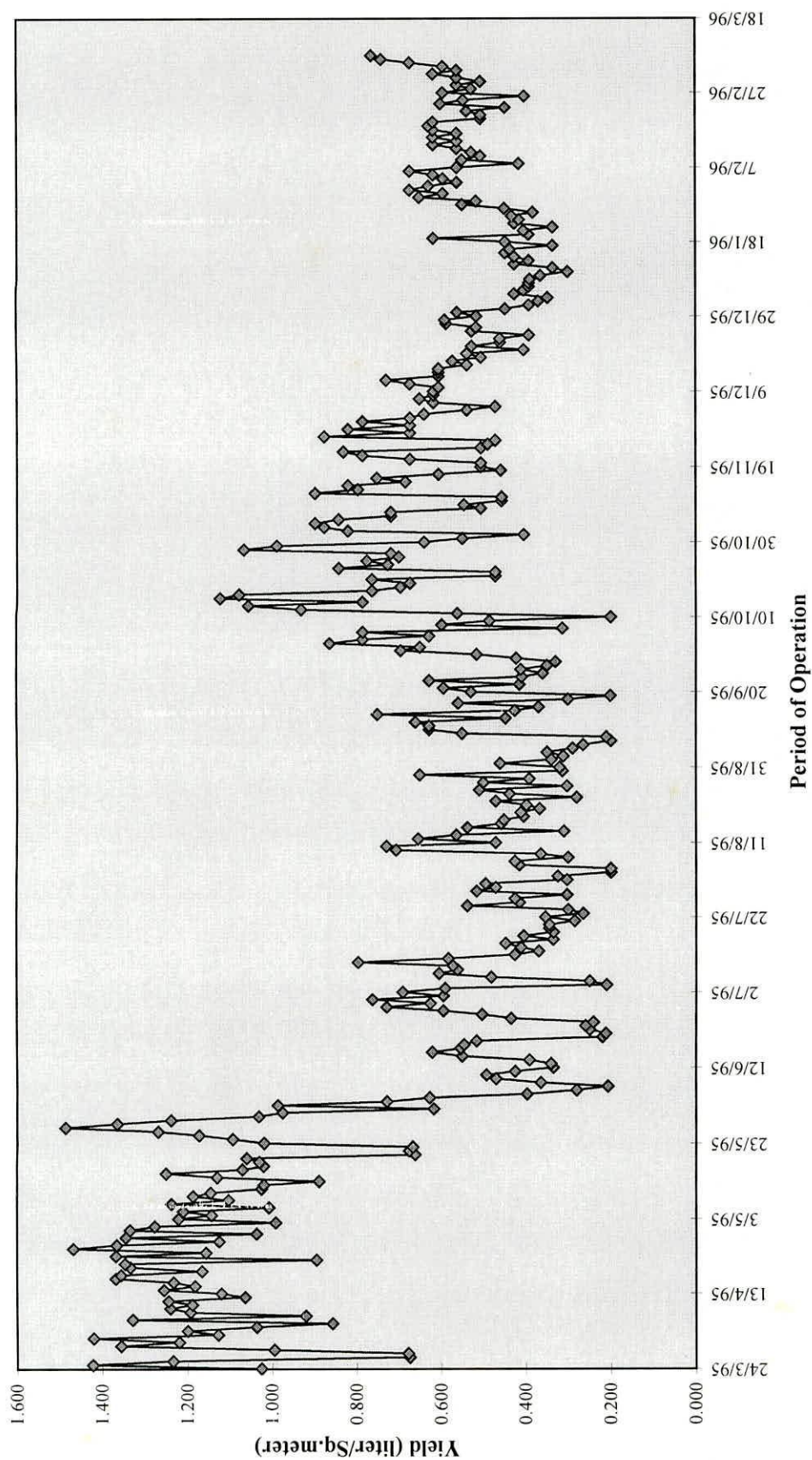


Figure A 9: Yield of Clay Plant

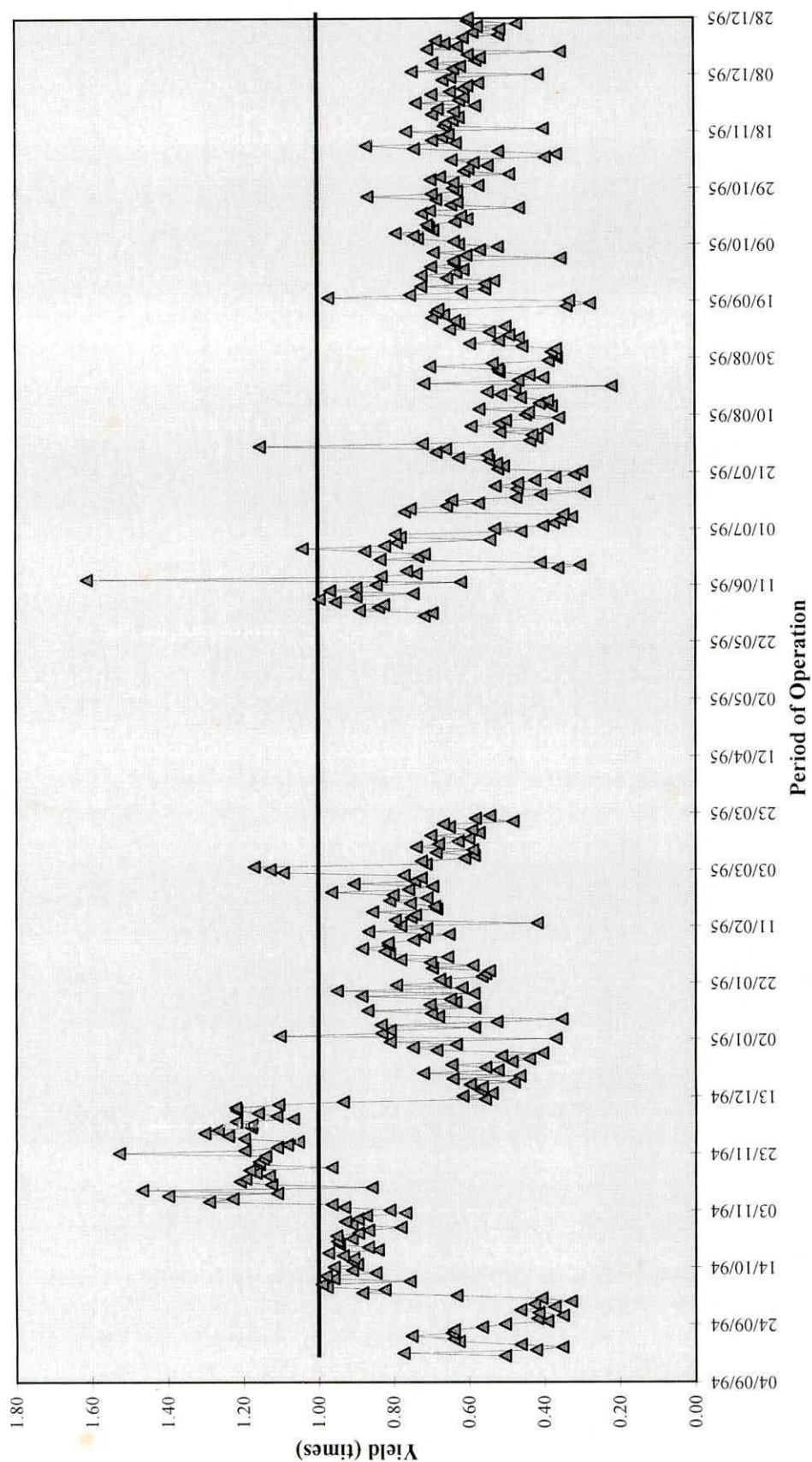


Figure A 10: Relative Yield of Brick Plant 1 and Brick Plant 2 (Yield of Brick Plant 1 is taken as unit).

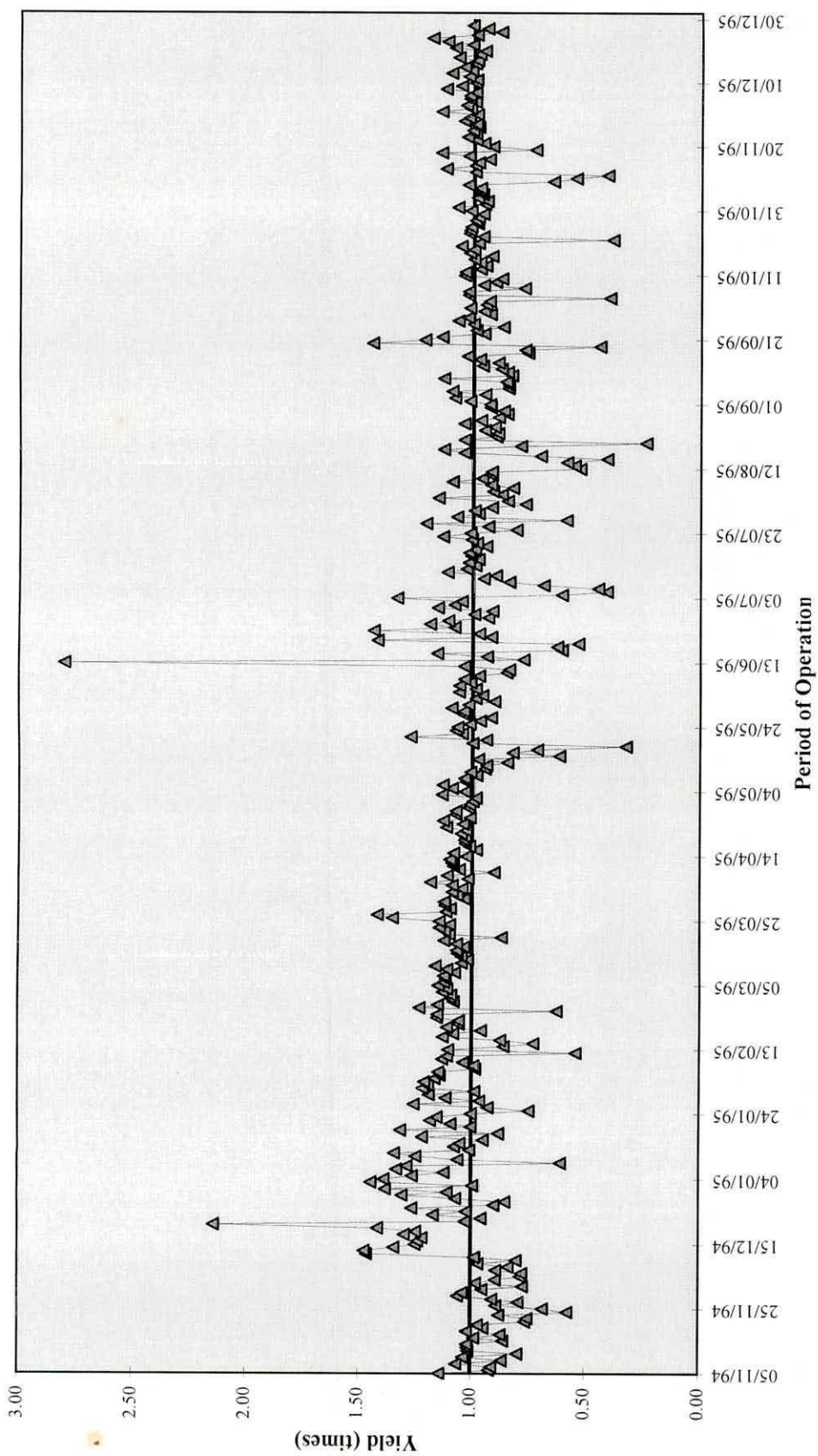


Figure A 11: Relative Yield of Brick Plant 1 and Brick Plant 3 (Yield of Brick Plant 1 is taken as unit).

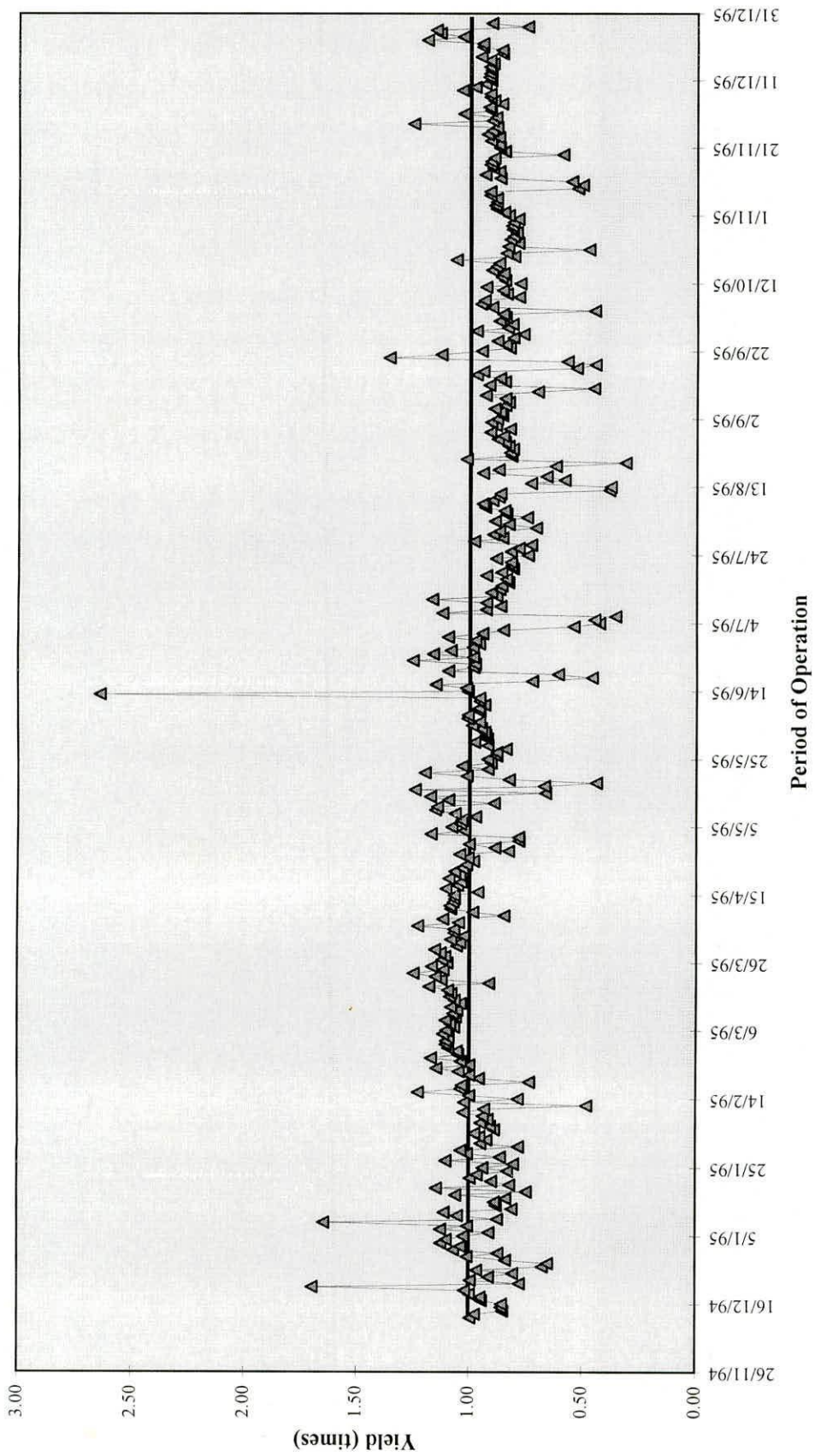


Figure A 12: Relative Yield of Brick Plant 1 and Brick Plant 4 (Yield of Brick Plant 1 is taken as unit).

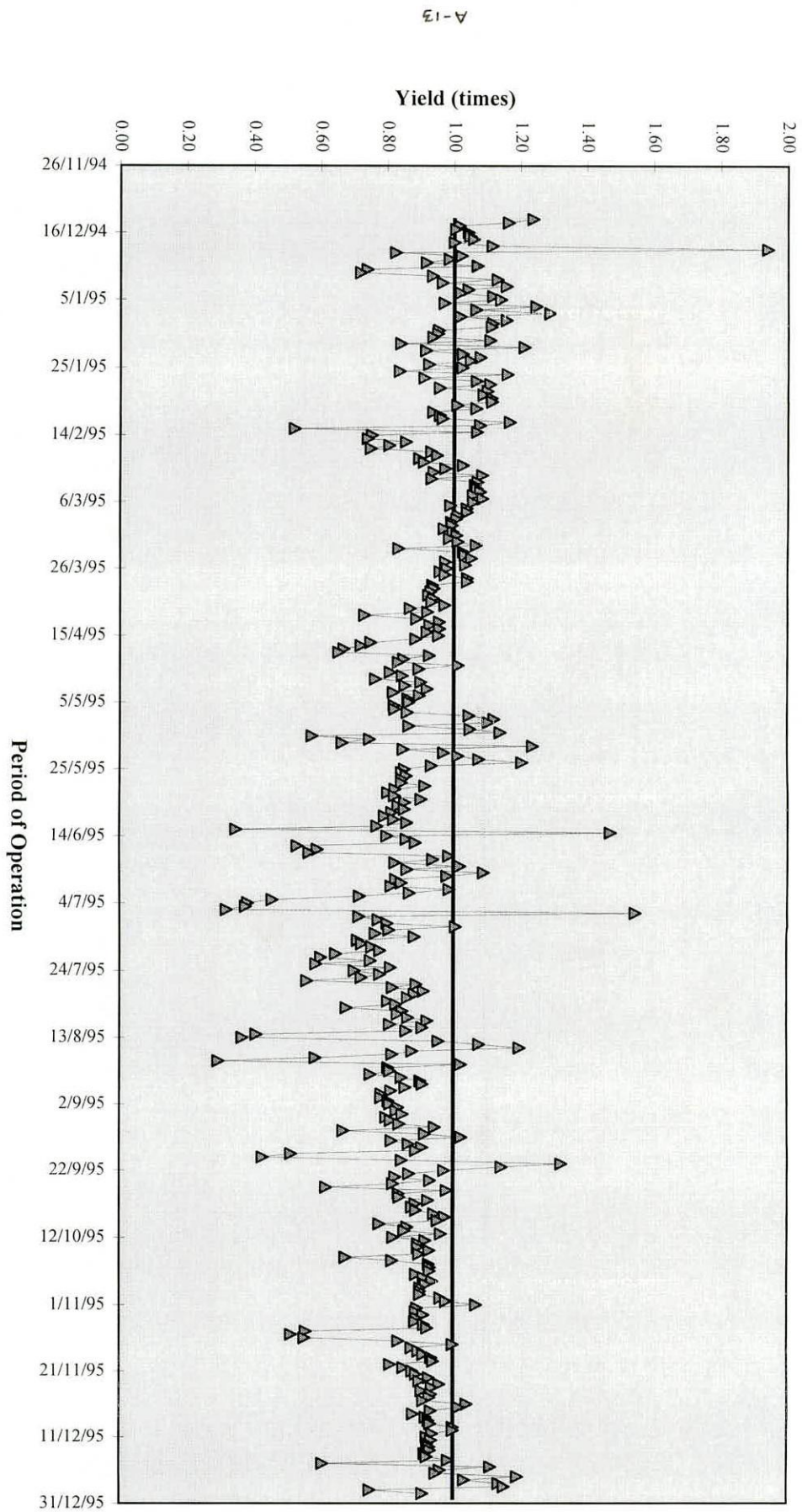


Figure A 13: Relative Yield of Brick Plant 1 and Brick Plant 5 (Yield of Brick Plant 1 is taken as unit).

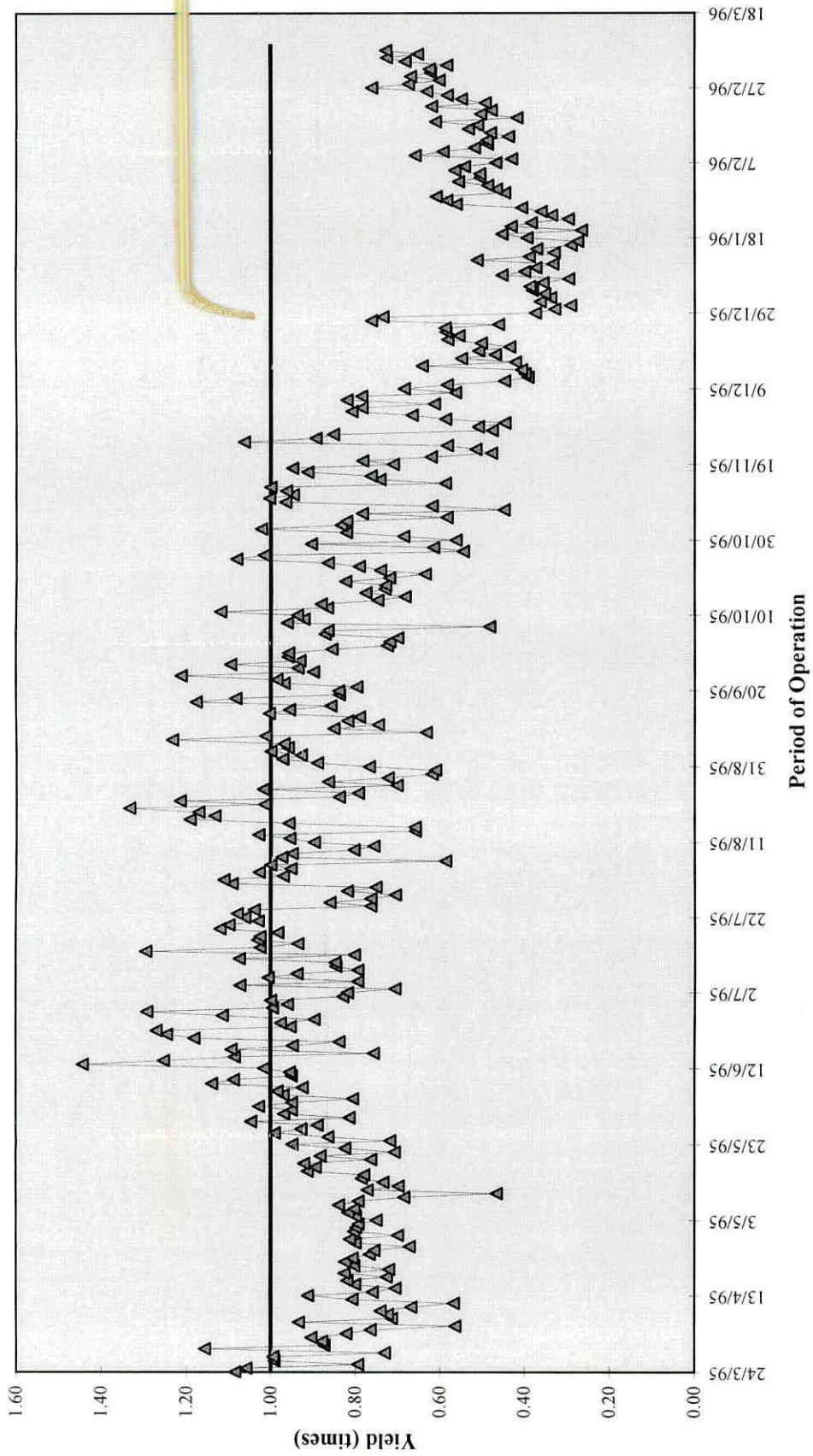


Figure A 14: Relative Yield of Brick Plant 6 and Brick Plant 8 (Yield of Brick Plant 6 is taken as unit).

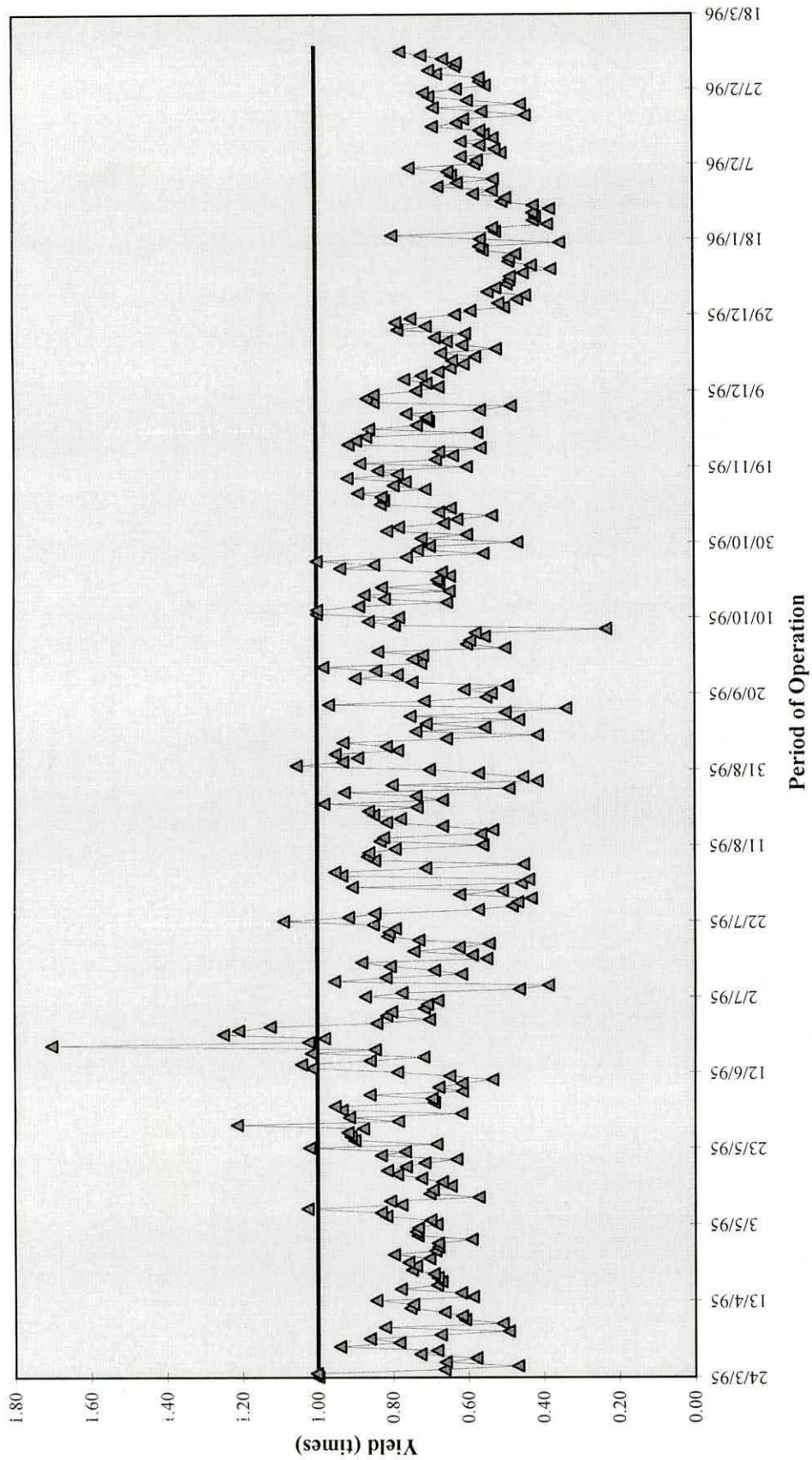


Figure A 15: Relative Yield of Brick Plant 6 and Clay Plant (Yield of Brick Plant 6 is taken as unit).

APPENDIX B
TABLES REFEREED IN TEXT

Table B 1: Statistical Analysis of Solar Radiation (Cal/m² day) at Joydevpur

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
January, 94	170.50	295.00	250.55	249.60	21.34
February, 94	180.95	315.40	262.93	263.75	32.56
March, 94	215.90	331.20	291.57	293.60	32.43
April, 94	250.30	370.50	320.19	323.45	27.84
May, 94	54.70	328.30	262.07	287.20	61.71
June, 94	95.70	328.30	233.85	246.20	76.01
July, 94	116.20	328.30	259.28	273.60	55.61
August, 94	87.50	314.60	221.07	212.00	55.92
September, 94	107.30	314.60	213.29	207.30	53.58
October, 94	106.80	275.20	230.19	239.40	33.80
November, 94	87.80	246.20	180.80	178.80	32.01
December, 94	136.80	332.50	212.50	212.00	40.00
1994	180.80	320.19	244.86	242.20	37.86
January, 95	164.10	281.50	220.09	218.90	27.16
February, 95	154.70	279.40	212.01	207.30	28.46
March, 95	209.40	328.30	274.55	287.20	29.18
April, 95	205.20	328.30	279.23	287.20	37.20
May, 95	117.00	321.20	254.06	272.00	49.75
June, 95	82.70	334.10	213.64	225.70	76.45
July, 95	63.80	376.20	189.28	205.20	77.00
August, 95	68.40	355.60	204.51	214.50	73.88
September, 95	68.90	296.20	199.39	200.45	58.64
October, 95	150.40	290.50	234.40	239.40	37.38
November, 95	120.40	275.00	212.52	218.90	35.66
December, 95	164.10	245.80	212.59	215.40	18.34
1995	189.28	279.23	231.12	213.20	39.63

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

Table B 3: Statistical Analysis of Relative Humidity (Percentage) at Dhaka

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
January, 94	55.00	85.00	68.61	68.00	7.71
February, 94	45.00	88.00	64.64	62.50	12.12
March, 94	43.00	90.00	66.32	68.00	12.11
April, 94	31.00	91.00	65.43	68.50	14.59
May, 94	65.00	88.00	76.84	78.00	5.70
June, 94	77.00	91.00	82.73	82.00	3.69
July, 94	75.00	91.00	80.42	80.00	3.56
August, 94	75.00	89.00	82.19	82.00	4.38
September, 94	67.00	93.00	78.93	79.00	6.67
October, 94	67.00	88.00	77.06	76.00	5.60
November, 94	66.00	83.00	75.20	75.00	3.84
December, 94	54.00	79.00	71.97	73.00	4.85
1994	64.64	82.73	74.22	76.02	6.59
January, 95	48.00	86.00	67.13	66.00	8.25
February, 95	55.00	84.00	69.93	70.50	8.11
March, 95	47.00	77.00	57.61	57.00	8.41
April, 95	36.00	75.00	64.47	67.50	9.02
May, 95	65.00	93.00	75.10	75.00	7.35
June, 95	63.00	95.00	81.80	80.00	6.00
July, 95	72.00	92.00	84.35	85.00	5.02
August, 95	76.00	94.00	82.90	82.00	4.70
September, 95	76.00	91.00	84.37	84.00	3.25
October, 95	71.00	94.00	81.06	81.00	4.54
November, 95	64.00	94.00	78.67	78.50	1.03
December, 95	71.00	90.00	77.42	77.00	3.84
1995	57.61	84.37	76.89	79.87	10.10

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

Table B 3: Statistical Analysis of Relative Humidity (Percentage) at Dhaka

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
January, 94	55.00	85.00	68.61	68.00	7.71
February, 94	45.00	88.00	64.64	62.50	12.12
March, 94	43.00	90.00	66.32	68.00	12.11
April, 94	31.00	91.00	65.43	68.50	14.59
May, 94	65.00	88.00	76.84	78.00	5.70
June, 94	77.00	91.00	82.73	82.00	3.69
July, 94	75.00	91.00	80.42	80.00	3.56
August, 94	75.00	89.00	82.19	82.00	4.38
September, 94	67.00	93.00	78.93	79.00	6.67
October, 94	67.00	88.00	77.06	76.00	5.60
November, 94	66.00	83.00	75.20	75.00	3.84
December, 94	54.00	79.00	71.97	73.00	4.85
1994	64.64	82.73	74.22	76.02	6.59
January, 95	48.00	86.00	67.13	66.00	8.25
February, 95	55.00	84.00	69.93	70.50	8.11
March, 95	47.00	77.00	57.61	57.00	8.41
April, 95	36.00	75.00	64.47	67.50	9.02
May, 95	65.00	93.00	75.10	75.00	7.35
June, 95	63.00	95.00	81.80	80.00	6.00
July, 95	72.00	92.00	84.35	85.00	5.02
August, 95	76.00	94.00	82.90	82.00	4.70
September, 95	76.00	91.00	84.37	84.00	3.25
October, 95	71.00	94.00	81.06	81.00	4.54
November, 95	64.00	94.00	78.67	78.50	1.03
December, 95	71.00	90.00	77.42	77.00	3.84
1995	57.61	84.37	76.89	79.87	10.10

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

Table B 4: Statistical Analysis of Wind Speed (Knots) at Dhaka

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
January, 94	0.10	2.90	1.13	1.00	0.74
February, 94	0.10	3.50	1.30	1.30	0.75
March, 94	0.40	6.90	3.35	3.00	1.80
April, 94	0.10	5.40	2.44	2.25	1.59
May, 94	1.10	5.60	3.10	3.00	1.19
June, 94	0.40	6.90	3.45	3.70	1.51
July, 94	1.10	5.60	3.56	3.80	1.15
August, 94	0.80	4.80	2.59	2.50	1.22
September, 94	0.10	5.10	1.63	1.05	1.48
October, 94	0.10	2.40	0.89	0.80	0.74
November, 94	0.10	1.10	0.59	0.50	0.29
December, 94	0.10	1.50	0.48	0.50	0.31
1994	0.48	3.56	2.04	2.04	1.17
January, 95	0.30	3.10	1.01	0.90	0.63
February, 95	0.00	2.90	1.08	0.90	0.68
March, 95	0.30	3.90	1.31	0.90	1.02
April, 95	1.10	3.90	2.50	2.60	0.80
May, 95	0.10	6.50	3.06	3.30	1.28
June, 95	1.10	4.90	2.83	2.60	1.03
July, 95	0.30	6.00	2.57	2.50	1.38
August, 95	0.00	7.30	2.48	2.10	1.74
September, 95	0.00	4.50	1.97	1.90	1.39
October, 95	0.00	1.80	0.67	0.60	0.44
November, 95	0.10	4.60	1.03	0.85	0.92
December, 95	0.00	2.00	0.52	0.50	0.42
1995	0.52	3.06	2.04	1.64	1.62

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

Table B 5: Statistical Analysis of Rainfall (mm) at Dhaka

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
January, 94	0.00	11.00	0.42	0.00	2.00
February, 94	0.00	19.00	1.93	0.00	4.85
March, 94	0.00	47.00	3.71	0.00	11.09
April, 94	0.00	56.00	6.70	0.00	14.82
May, 94	0.00	53.00	8.19	0.00	16.15
June, 94	0.00	74.00	8.87	2.50	16.95
July, 94	0.00	65.00	4.94	0.00	12.22
August, 94	0.00	59.00	7.94	5.00	11.98
September, 94	0.00	54.00	5.63	0.00	12.84
October, 94	0.00	22.00	1.77	0.00	4.70
November, 94	0.00	14.00	0.47	0.00	2.56
December, 94	0.00	0.00	0.00	0.00	0.00
1994	0.00	8.87	4.21	4.33	3.27
January, 95	0.00	4.00	0.26	0.00	0.86
February, 95	0.00	15.00	1.04	0.00	3.81
March, 95	0.00	0.00	0.00	0.00	0.00
April, 95	0.00	45.00	2.93	0.00	9.78
May, 95	0.00	76.00	8.52	0.00	21.79
June, 95	0.00	78.00	7.97	2.00	17.08
July, 95	0.00	56.00	11.42	3.00	16.55
August, 95	0.00	83.00	11.65	2.00	20.57
September, 95	0.00	35.00	6.63	1.00	9.75
October, 95	0.00	43.00	29.4	0.00	9.65
November, 95	0.00	75.00	3.73	0.00	14.27
December, 95	0.00	1.00	0.03	0.00	0.18
1995	0.00	11.42	10.38	3.34	21.08

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

**Table B 6: Statistical Analysis of Average Temperature (Degree Celsius)
at Kaliganj**

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St. Dev.</i>
March, 95	28.50	34.00	32.13	32.75	2.01
April, 95	28.50	35.00	32.80	33.00	1.64
May, 95	30.00	34.00	32.08	32.50	1.31
June, 95	26.50	32.50	28.78	28.50	1.76
July, 95	26.50	30.50	28.77	29.00	0.96
August, 95	27.00	32.50	29.47	29.50	1.17
September, 95	24.00	31.50	28.27	28.00	2.01
October, 95	24.50	31.50	29.27	30.00	1.75
November, 95	21.50	29.00	26.13	27.00	1.96
December, 95	20.00	24.00	21.93	22.00	1.23
January, 96	19.00	23.50	21.23	21.00	1.12
February, 96	18.50	27.00	23.07	23.50	1.97
1995-96	21.23	32.80	27.83	28.78	3.95

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

Table B 7: Statistical Analysis of Sunshine Hour at Kaliganj

<i>Period</i>	<i>Min.</i>	<i>Max.</i>	<i>Avg.</i>	<i>Median</i>	<i>St.. Dev.</i>
March, 95	5.50	9.20	7.70	8.10	1.13
April, 95	3.50	8.70	7.04	7.50	1.45
May, 95	4.20	8.90	7.02	7.40	1.11
June, 95	2.50	7.50	4.81	4.30	1.52
July, 95	1.80	6.80	4.70	5.10	1.43
August, 95	0.80	6.70	3.46	3.50	1.64
September, 95	2.10	6.90	4.32	4.15	1.43
October, 95	1.10	9.50	7.35	8.00	2.16
November, 95	2.50	8.60	6.67	7.65	1.93
December, 95	6.40	8.60	7.61	7.80	0.72
January, 96	6.10	7.60	6.71	6.50	0.43
February, 96	3.60	8.60	7.08	7.20	1.00
1995-96	3.46	7.70	6.21	6.87	1.46

Note: Monthly analysis is carried on the basis on daily data and yearly analysis is carried on the basis of monthly average data.

APPENDIX C
RELEVANT COMPUTER PROGRAMS

/* This is program to establish model equation for the water treatment plant in the following form:

$y = a_1 + a_2 T^{\text{poer } a} + b_1 S^{\text{pow } b} + \dots$

*/

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <conio.h>
#include <time.h>
#include <io.h>
#include <dos.h>
#include <float.h>
```

```
main()
```

```
{
```

```
FILE *fp,*fp1,*fp4,*datafile;
float ydiff,temp,rad,shine,humd,rf,ws, gt, wt, y[500],yac;
int sp,tp,rp,hmdp,rfp,wsp,gtp,wtp;
int i=0,m=0,k,ln;
long l;
float a0=.25;
float a1,a2,a3,a4,a5,a6,a7,a8,perror,mbsum,MBE,rmsum,RMSE,mpsum,MPE;
char fname[17];
strcpy(fname,"C:\\tc\\out.dat");
randomize();
clrscr();
if( ( fp=fopen(fname,"w+"))==NULL)
{ printf("Cannot open file 1");
getch();
exit(0);

}
strcpy(fname,"c:\\tc\\good.dat");

if( ( fp1=fopen(fname,"w+"))==NULL)
{ printf("Cannot open file 2");
getch();
exit(0);

}
if( ( datafile=fopen("c:\\msc\\plant2a.txt","r+"))==NULL)
{ printf("Cannot open Plant data file ");
getch();
exit(0);
rewind(datafile);

}

strcpy (fname,"c:\\tc\\test.dat");
if( ( fp4=fopen(fname,"w+"))==NULL)
{ printf("Cannot open file 4");
getch ();
exit (0);
```

```

}

clrscr();
printf(" Enter a key to read data from file and process");
getch();

ln=0;

while(!feof(datafile)) {
fscanf(datafile, "%f%f%f%f%f%f%f%f", &yac, &temp, &rad, &shine, &humd, &ws, &rf, &gt, &wt);
temp=temp/100.0;
rad=rad/1000.0;
shine=shine/10.0;
humd=humd/100.0;
ws=ws/10.0;
rf=rf/100.0;
gt=gt/100.0;
wt=wt/100.0;
clrscr();
ln++;
gotoxy(30,14);
printf(" Iteration needed/record : %0.0f ", pow(6.0,6.0));

fprintf(fp1, " For the yield of %f \n\n\n", yac);
fprintf(fp, " for the yield of %f \n ", yac);
/*fclose(fp1);
fclose(fp);
fp1=fopen("good.dat", "a"); */
i=0;
l=0;

for(tp=1; tp<=6; tp++)
{ for(rp=1; rp<=6; rp++)
{ for(sp=1; sp<=6; sp++)
{ for(wtp=1; wtp<=6; wtp++)
{ for(hmdp=1; hmdp<=6; hmdp++)
{ for(gtp=1; gtp<=6; gtp++)
{
i++;

l++;
a1=random(15)/7.0000;
a2=random(15)/7.0000;
a3=random(15)/7.0000;
a4=random(15)/7.0000;
a5=random(15)/7.0000;
a6=random(15)/7.0000;
gotoxy(30,13);
printf("Record number on process Û %d ", ln);
gotoxy(30,15);+
printf("Running on %li\n ", l);
gotoxy(30,12);

```



```

printf("For actual yield(yac) of: %f",yac);

y[i]= a0+ a1*pow(temp,tp)+a2*pow(rad,rp)+a3*pow(shine,sp)+a4*pow(humd,hmdp)
+a5*pow(wt,wtp)+a6*pow(gt,gtp);
ydiff=fabs(yac-y[i]);
gotoxy(30,20);
printf(" The Yield is = %0.4f ",y[i]);
perror= (ydiff/yac)*100;

if (perror<0.2)

    fprintf(fp1,"%6d %5.4f %5.4f %4d%4d%4d%4d%4d %6.4f %6.4f %6.4f %6.4f %6.4f
%6.4f\n", i, y[i], yac, tp,rp,sp,hmdp,wtp,gtp,a1,a2,a3,a4,a5,a6);

    if(i==499)
    { i=0; }

    }
    m=0;

    mbsum=0;
    rmsum=0;
    mpsum=0;
    for(k=1;k<m;k++)
    { mbsum+=-ydiff[k];
      rmsum+=pow(ydiff[k],2);
      mpsum+=-(ydiff[k]/yac);
    }
    MBE=mbsum/i;
    RMSE=sqrt(rmsum/i);
    MPE=mpsum*100/i;

    fprintf(fp4,"\n\n MBE          RMSE          MPE \n");
    fprintf(fp4,"%6.4f %6.4f %6.4f\n", MBE,RMSE,MPE);

    if(m==499)
    {m=0;}

    }
    }
    }
    }
    }
    }

    getch();

    fcloseall();

```

/* This is program to establish model equation for the water treatment plant in the following form:

$y = a_1 + a_2 T^{\text{poer } a} + b_1 S^{\text{pow } b} + \dots$

*/

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <conio.h>
#include <time.h>
#include <io.h>
#include <dos.h>
#include <float.h>
```

```
main()
```

```
{
```

```
FILE *fp, *fp1, *fp3, *datafile;
```

```
float temp, rad, shine, humd, rf, ws, gt, wt, y[600];
```

```
float ydiff[600], yac;
```

```
int sp, tp, rp, hmdp, rfp, wsp, gtp, wtp;
```

```
int i=0, j, k, ln;
```

```
long reject=0, totdata=0;
```

```
float a0=.25;
```

```
float a1, a2, a3, a4, a5, a6, a7, a8, perror, mbsum, MBE, rmsum, RMSE, mpsum, MPE, rfsum, REFA;
```

```
char fname[17];
```

```
strcpy(fname, "C:\\tc\\out.dat");
```

```
randomize();
```

```
clrscr();
```

```
if( ( fp=fopen(fname, "w+") )==NULL)
```

```
{ printf("Cannot open file 1");
```

```
getch();
```

```
exit(0);
```

```
}
```

```
strcpy(fname, "c:\\tc\\good.dat");
```

```
if( ( fp1=fopen(fname, "w+") )==NULL)
```

```
{ printf("Cannot open file 2");
```

```
getch();
```

```
exit(0);
```

```
}
```

```
if( ( datafile=fopen("c:\\msc\\plant2a.txt", "r+") )==NULL)
```

```
{ printf("Cannot open Plant data file ");
```

```
getch();
```

```
exit(0);
```

```
rewind(datafile);
```

```
}
```

```
strcpy(fname, "c:\\tc\\outdata.dat");
```

```
if( ( fp3=fopen(fname, "w+") )==NULL)
```

```
{ printf("Cannot open file 3");
```

```

    getch();
    exit(0);

}
clrscr();
printf(" Enter a key to read data from file and process");
getch();

i=0;
fprintf(fp3," Ycal Yact Error \n");
while(!feof(datafile)) {
    fscanf(datafile, "%f %f %f %f %f %f %f %f %f %f",
    %f",&yac,&temp,&rad,&shine,&humd,&ws,&rf,&gt,&wt);
    printf(" Actual Calculated and Error: %f %f %f\n ",yac, temp,rad) ;
    temp=temp/100.0;
    rad=rad/1000.0;
    shine=shine/10.0;
    humd=humd/100.0;
    ws=ws/10.0;
    rf=rf/100.0;
    gt=gt/100.0;
    wt=wt/100.0;
    clrscr();
    totdata++;

    tp=5;
    rp=4;
    sp=2;
    wtp=3;
    hmdp=6;
    gtp=4; /* powers of the variables */
    a1=1.0; a2=.1429;a3=01.7143;a4=1.285;a5=1.7413;a6=1.4286; /* selected constant terms */

    y[i]= a0+ a1*pow(temp,tp)+a2*pow(rad,rp)+a3*pow(shine,sp)+a4*pow(humd,hmdp)
    +a5*pow(wt,wtp)+a6*pow(gt,gtp);

    printf("%li data on process %f is the yield %d are rejected \n", totdata, y[i], reject);

    ydiff[i]= fabs(yac-y[i]);

    perror= (ydiff[i]/yac)*100.0;

    fprintf(fp3," %f %f %f\n",y[i],yac, perror) ;

    if ( perror>30.0 ) reject++;

    i++;
}

```



```

mbsum=0;
rmsum=0;
mpsum=0;
rfsum=0;
for(k=1;k<i;k++)
{
    mbsum+=-ydiff[k];
    rmsum+=pow(ydiff[k],2);
    mpsum+=-(ydiff[k]/yac);
    rfsum+=pow(mpsum,2);
}
MBE=mbsum/i;
RMSE=sqrt(rmsum/i);
MPE=mpsum*100/i;
REFA=rfsum/i;
fprintf(fp3,"\n\n MBE      RMSE      MPE      REFA \n");

fprintf(fp3," %f  %f  %f  %f\n",MBE, RMSE, MPE,REFA) ;

clrscr();
printf(" %li data out of %li are not matched with the formula",reject,totdata);
getch();

```

```

fcloseall();

```

```

}

```



```
#include <stdio.h>
#include<math.h>
#include<io.h>
```

```
main()
{
```

```
float y,r,eta;
char fname[20], fname1[20];
int i=0;
FILE *fp,*fp1;
```

```
clrscr();
strcpy(fname,"data4.dat");
strcpy(fname1,"out4.dat");
```

```
if((fp=fopen(fname,"r+"))==NULL)
{
printf("Cannot open File\n");
getch();
exit(0);
}
```

```
if((fp1=fopen(fname1,"w+"))==NULL)
{
printf("Cannot open File\n");
getch();
exit(0);
}
```

```
while ( !feof(fp))
{
fscanf(fp,"%f%f\n",&y,&r);
eta=57.78*100*y/r;
fprintf(fp1,"%12.3f %12.3f %12.f\n ", y,r,eta);
i++;
/*if( i%100==0) getch();*/
gotoxy(20,10);
printf(" No of iteration is = %d \n", i);
}

}
```

□