'STUDIES INTO THE PERFORMANCE OF SOLAR STILLS"

BY

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MEMORANDUM

This thesis is submitted to the University of Ghana in partial fulfilment of the requirement for the degree of Master of Philosophy. It has not been submitted previously to this University or any other University. It contains an account of the work carried out by the author, unless otherwise specified in the text, at the Department of Physics, between October 1993 and August, 1994 under the supervision of Dr. K.G. Adanu of the University of Ghana, Legon.

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ABSTRACT

This research was aimed at improving on distilled water production in the basin-type solar stills. Four similar stills were built with local materials.Results from this work indicated that for good performance of the basin-type solar still, a depth of 3.0cm should not be exceeded.

The still, when covered throughout the night and put into operation the following day, increases the yield.

Furthermore, sawdust has been found to be a good substitude for the traditional urethane foam as lagging material for the basin.

Finally, purity analysis of the distillate revealed a conductivity range of 3.11 to 3.30us/cm, a pH range of 5.67 to 5.68 for different sources of water at 25°C. Silica content ranged from 0.03 to 0.057mg/i. Oxygen content was 0.4006mg/l. There was no residue present in the distillate.

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CHAPTER ONE

1.0.0 INTRODUCTION

Water is a world-wide traveller and takes many forms as it goes through its hydrological cycle. About 97% of the Earth's water mass lies in its oceans[1]. Of the remaining 3%, five-sixths is brackish, leaving a mere 0.5% as fresh water. As a result, many people do not have access to adequate and inexpensive supplies of potable water. Expansion of the World's population into uninhabited land may be possible in some areas by converting ocean water and brackish water into freshwater where none exists.

Ocean water or brackish water can be purified either mechanically, thermally or chemically. The mechanical processes include sedimentation, coagulation and filtration. Similarly, distillation, deaeration and demineralisation make up the thermal method, while the chemical processes include cold-lime-soda softening, hot lime-soda softening, lime-phosphate softening, ion-exchange process, hot lime-soda and zeolite process and the addition of acid to control alkalinity.

The method applied to purify brackish water depends on the impurities present in the water and also what the final product is to be used for. The main pollutants of water are of four major groups[1]. The first consists of colloids of organic and mineral deposits. The organic impurities originate from the presence and decay of plants and animal parts in water, while the presence of minerals in water is as a result of dissolution of rocks over which the water runs when in transit. The second type is made up of coarsely dispersed substances including sand and clay of varying sizes. One other type consists of molecular dispersed substances of salts and gases that dissolve in the water. The salts present in water normally dissociate to a considerable extent, furnishing the solution with ions among which are Na^+, Ca^{2+}, Mg^{2+}, Cl^-, $SO^{2}_{4}{}^-$, HCO_3^-, NH_4^+ etc. It is the presence of these ions that gives the water its high electrical conductivity value. The fourth is made up of micro-organisms, which are germs of various types. Of all these pollutants, this type is the most harmful and deadly. It is responsible for the numerous water-borne diseases. Because of the presence of these organisms in water, people are advised to purify their water from the streams or rivers before drinking it. One common approach to this issue is by boiling. The source of energy for boiling the water in most cases, is wood. Hence the forest happens to be the immediate victim, causing a lot of environmental degradation. Furthermore, in laboratory works, very pure water is often required. This is obtained from distillation. This process is accomplished using scarce available non-renewable energy resources which could have been used for some other processes. Fortunately for us in Ghana, there is abundant sunshine throughout the year, hence a way of conserving our forest and the other sources of energy could be achieved by resorting to the use of solar energy to distill raw water. The process is called solar distillation.

Cooper[3], in his effort to document the development and use of solar stills, reported that Arabian alchemists were the earliest known people to use solar distillation to produce potable water in the sixteenth century. But the first documented reference for the device was in 1742 by Nicolo Ghazzi of Italy, although it is not known whether he went beyond the conceptual stage and actually built it. The first modern solar still was built in Las Salines, Chile in 1872 by Charles Wilson. It consisted of 64 basins of a total area of 4,459m^2, made of blackened wood with sloping glass covers. The installation supplied 20,000 litres of water per day.

It was only in the 1950s that interest in solar distillation was revived, and in virtually all cases, the objective was to develop large centralised distillation plants. However ten years afterwards, researchers around the world concluded that large solar distillation plants were much too expensive to compete with fuel-fired ones. So research shifted to small solar distillation plants.

Although solar distillation at present cannot compete with oil-fired desalination in large central plants it will surely become a viable technology within the next hundred years when oil supplies will have approached exhaustion [4].

THE SOLAR DISTILLATION PROCESS

Solar distillation is the process by which the heat from the sun is used directly in a simple equipment to purify water. The equipment is commonly called a solar still. It consists primarily of a basin with a transparent cover. The sun heats the water in the basin, causing evaporation. Moisture rises, condenses on the cover, and runs down into a collection trough, leaving behind the salts, minerals and most other impurities including germs.

This process could be a big relief to many people especially those in the developing World in several ways:

1. Solar distillation can be a cost-effective means of providing clean water for drinking, cooking, washing and bathing.
2. It can improve health standards by removing impurities from questionable water supplies.
3. It can help extend the usage of existing fresh water in locations where quality or quantity of supply is deteriorating.
4. Solar stills, operating on sea or brackish water can ensure supplies of water during a time of drought, of late a common

phenomenon in developing countries.

5. Solar distillation generally uses less energy to purify water than other methods [5].
6. It can foster cottage industries, animal husbandry or hydroponics for food production in areas where such activities are now limited by inadequate supplies of pure water.
7. Solar distillation will permit settlement in sparsely populated locations, thus relieving population pressures in urban areas.

In fact the energy from the sun used to distill water is free. However, the cost of building a still makes the cost of solar distilled water rather high, at least for large-scale uses, such as agriculture. Consequently, the solar still is used principally to purify water for drinking, for industry and laboratory. There is however a good chance of reducing the capital cost by using cheaper and durable materials for construction of stills.This is one of the aims of this project.

Although there are many designs for solar stills, four general categories exist, viz:

(i) concentrating collector stills,
(ii) multiple tray tilted stills,
(iii) tilted wick solar stills, and
(iv) basin stills.

Of these, the first three are not suitable for developing countries because of the high cost of construction and maintenance[1]. The basin type is most appropriate for countries such as Ghana.

There are three types of basin stills. These are the wick-type basin still, the deep basin-type and shallow basin-type. Though the wick-type basin still has a high efficiency, its production cost makes the distilled water very expensive[1]. The deep basin-type has a disadvantage of lower efficiency [1]. These two types have no promising future. As regards efficiency and production cost, the shallow basin-type has a very bright future [5]. It is hoped that with further research work, higher values of efficiency and lower production cost could be achieved.This project is aimed at meeting these requirements.

The basic design can take on many variations but the concept is still the same. The greatest changes have involved the use of new building materials which is aimed at lowering the overall cost at the same time providing an acceptable long useful life and better performance.

Like any other basin still, the shallow basin-type has four major components:

(i) a basin (ii) a support structure

(iii) a transparent glazing cover and (iv) a distillate trough. In addition to these, ancillary components are: (1) insulation, (2) sealants (3) piping and valves, (4) facilities for storage and (5) an external cover to protect the other components from the weather.

1.1.0 FACTORS INFLUENCING SOLAR STILL OPERATION PERFORMANCE

A number of factors affect the rate of production of distilled water. These could be climatic or due to the design of the still.

1.1.1 CLIMATIC FACTORS

1. The amount of solar radiation a solar still receives is one important factor affecting its performance. The greater the amount of radiation received, the greater the quantity of water distilled.

The energy from the sun travels a distance of about 150 million kilometers to the earth. Not all this energy reaches the earth's surface due to the presence of some atmospheric constituents in the lower atmosphere. Ozone, atomic oxygen, carbon dioxide and water vapour are atmospheric constituents that absorb some of the solar radiation, while scattering of some of this radiation is carried out by dust particles, gas molecules and droplets of water in the atmosphere. As a result of this process of scattering, some of the solar energy reach the earth's surface as diffuse radiation with the remaining as direct radiation. These two phenomena (absorption and scattering) bring about a reduction of solar radiation at the surface of the earth, hence the variation of the intensity of solar radiation at different parts of the earth depending on the local constituents of the atmosphere.

2. A high air temperature favours a high production rate. A large difference in pressure between water in the basin and the condensing water under the colder roof is very necessary for distillation. Fortunately the vapour pressure–temperature curve for water rises so steeply that a ten degrees difference in temperature gives a much greater pressure difference at high ambient temperatures.

3. Wind speed is one other factor that affects the rate of distillation. Increase in wind speed increases the rate of evaporation and condensation as the glass cover is cooled by the effect of the wind. However, wind of very high speed reduces the energy reaching the still by sweeping the radiation away.

1.1.2 DESIGN AND OPERATING PARAMETERS

The efficiency of a solar still is controlled by a number of factors among which are: the thermo–physical properties of the materials used in its construction, the orientation of the still, inclination of the transparent cover, spacing between the water surface and transparent cover, the number of glazings, insulation of the base and sides, vapour tightness, the depth of water in the basin, and initial water temperature in the basin.

Building materials (especially those for the encasement of the still) of low thermal conductivity tend to limit heat losses and thereby maintain a higher efficiency of the still.

The orientation of the still is one major factor that requires serious attention so as to obtain reasonable efficiencies. The angle at which the transparent cover is set influences the amount of solar radiation entering a solar still. When sunlight strikes the glass straight on at 90° to the surface, about 90% of the light passes through. Any angle less than this gives rise to greater losses by reflection. For instance, at 70° angle of incidence, practically no light passes through [1]. Places at the Equator need a glass cover slope of approximately 1° South or North [5]. The slope of the glass cover does not in fact affect the rate at which the distillate runs down its inner surface to the collection trough [1]. A common misconception was that the glass cover must be given a reasonable tilt to get the water to run off. This may have arisen from the fact that ordinary window glass, as it comes from the factory, has a minute oily film on it. But if the glass is cleaned the water itself will form filmlike condensate on it, and will be able to run off at a very small slope [1]. There are three reasons why it is best to use as low a slope as possible:

i) the higher the slope, the more glass and supporting materials are required to cover a given area of the basin.

ii) the higher slope increases the volume and weight of the still.

iii) setting the glass cover at a higher slope increases the volume of air inside the still. This introduces heat losses and thus lowers the efficiency of the system.

Locations in the Southern hemisphere are made to slope Northwards at an angle equal to their latitudes and vice versa for locations in the Northern hemisphere.

The distance from glass-to-water has a ceiling beyond which the efficiency of the still is lowered, as heat losses due to convection become greater. This distance is 7cm according to McCracken [6].

But for the extra cost added to overall production cost, provision of two or more glazings tends to increase the efficiency of a still. This approach would be pursued only when the cost of the glazing is low enough to bring about the extra efficiency outweighing the extra cost.

Insulating the base and sides of the basin prevents or lowers heat losses in the system. Some insulating materials such as fibreglass, are expensive and increase the overall production cost. One main aim of this project is to come out with some other materials that serve this purpose more effectively and at the same time reasonably cheaper and affordable to beat down the production cost of the still.

The still needs to be airtight so that no vapour is lost to the surrounding. Any of such losses causes a reduction in yield.

Also, an initial high water temperature gives the water in the basin an advantage of starting the processes of evaporation and condensation early in the day.

Finally, the depth of water in the basin is of another serious concern to Scientists. Deep basin stills have lower efficiencies than the shallow ones [1]. The question that arises is "to what depth does a shallow basin-type still cease to operate as a shallow still?" This project is aimed at answering this question as well.

The solar radiation that arrives at the transparent cover may be lost:

(i) by absorption, radiation and reflection by the transparent cover,

(ii) due to incomplete solar absorption by the collector. The black pan should absorb all solar wavelengths falling on it. However, most "black" surfaces are not completely black and even the best velvety blacks are incomplete absorbers. In practice, no object functions as a "black body", absorbing all wavelengths of radiation falling on it and reradiating them later.

(iii) no matter what material and its quantity is used as insulation for the base and sides of the basin, some amount of heat is lost at these sites. When suitable materials are used, the heat loss in question can be reduced to 10% or even less [2].

(iv) the air, saturated with water vapour, circulates around within the still. This movement brings about some losses in energy which even though not excessive amounts to about 4%

of the overall heat losses under average conditions [2].

(v) the temperature of the black pan is higher than that of the condensing surface. Therefore continuous heat exchange takes place which results in some unavoidable heat losses. This could amount to about 10% of the total incident solar energy [2].

(vi) serious losses may be caused by the leakage of water from the collecting channels and basin. Cracks or holes in the mounting of the glazing cover could permit the escape of water vapour as well.

One innovation in solar distillation is the use of an insulating cover to be put over the glazing at night or during extreme cloudy weather. This cuts heat losses, allowing distillation to continue longer, and retain heat overnight, causing production to start earlier the following day. The cost of the insulating cover used in this project will be evaluated vis–a–vis the additional yield.

1.1.3 SUMMARY OF OBJECTIVES

The objectives of this project are:

(1) to determine the optimum depth limit of a still that makes it function effectively as a shallow still, i.e. the threshold depth.

(2) to determine the extent to which the yield is increased and the cost involved when the still is covered at night before

being put into operation the following day.

(3) to identify cheap but effective lagging materials for the basin, and

(4) to determine the purity of the distillate.

1.1.4 STRUCTURE OF REPORT

This report is presented in five chapters.Chapter one is an introduction to the project.In chapter two, the theory in solar distillation is presented.Chapter three deals with construction and experimental procedures adopted in the project.Results of the experiment are presented in chapter four. Chapter five deals with discussion of results obtained in the project. Conclusions drawn from the project are presented in chapter six. The report ends with a list of references and symbols.

CHAPTER 2

2.0.0 THEORY

2.1.1 PROCESS OF DISTILLATION

Radiation from the sun is made up of the entire electromagnetic spectrum. The glass cover is opaque to radiations of long wavelength but transparent to those of short wavelength. On reaching the cover the radiation of short wave-length passes through to the absorber surface. Here the collector absorbs the radiation, raising its atoms to excited states. Its temperature is thus elevated. The collector, at this state, seeks to restore its original state. This it does by re-radiating the extra energy acquired to neighbouring atoms of the water. By this method the temperature is evened out and the excitement of the collector and water in contact becomes uniform. As a result of the redistribution of the energy the emitted radiation is of long wavelength unlike the absorbed radiation which is of short wavelength. Painting the collector black makes it act as a "black body", permitting it to absorb and later radiate energy of infinite number of wavelengths. The still then acts as a heat trap, because the roof is transparent to the incoming short wavelength radiation, but is opaque to the long wavelength infrared radiation from the collector.

A liquid molecule requires a specific amount of kinetic energy to enable it escape from the attraction of its neighbours as vapour. At any given temperature molecules do not all have the same energy at any instant. The mean energy rises with temperature but at any instant there are molecules of more and some with less energy than the mean energy. More of the higher energy molecules escape from the liquid as vapour as the temperature rises. Also some dissolved air in contact with the hot collector is heated and expands, its density is thus reduced relative to that of air above. As a result the hot air rises because it is buoyant while cooler denser air of the top layer moves in to take the place of the hot air that had risen. A convection air current is thus set-up in the water just as another one above the water which is made of rising hot air from the water and water vapour. Whereas the hot air and water vapour rise to the cover, cooler air above the water moves towards the water surface, establishing a second convection current.

Different liquids require different amounts of energy for evaporation and each one exerts its own partial pressure. Only those attaining the saturated vapour pressure have the tendency of returning into the liquid state; a process known as condensation. By this process the glass cover is at a lower temperature at any instant than the rising vapour-air mixture. This rising air current,laden with moisture, cools on contact with the glass cover. Some of this then condenses on the glass cover and runs down into the trough at the edge. The distillate, on condensing on the glass cover releases heat of condensation onto the glass, raising its temperature. Some of the energy acquired by the cover from the condensation process is lost to the surrounding, lowering the higher temperature of the cover.

2.1.2 ENERGY BALANCE IN A STILL

Solar-still performance is rated in terms of the overall efficiency, defined as the ratio of the rate at which heat is used to produce condensate per unit collector area to the incident solar flux. It is mathematically expressed as:

$$\eta_o = \frac{\dot{m}\, h_{fg}}{A I_o} \qquad (2.1)$$

In this expression $\dot{m}$ is the rate of condensate production, h_{fg} is the enthalpy of evaporation, A is the total area of glass surface, and I_o is the incident solar flux.

Another useful measure of efficiency is the internal efficiency defined in terms of solar energy absorbed by the brackish water:

$$\eta_i = \frac{\dot{m}\, h_{fg}}{A(\tau\alpha) I_o} \qquad (2.2)$$

where $\tau\alpha$, which measures the efficiency of capture of solar radiation is η_o/η_i

To maximise the overall efficiency:

(i) the depth of the cover should be as low as possible;

(ii) the depth of the brackish water in the basin should be as shallow as possible to decrease thermal storage effect;

(iii) the basin should be amply insulated along its sides and bottom to prevent heat losses.

The energy transport mechanisms in a basin-type solar still are shown in fig. 2.1.

Two energy flux balances come into the picture here – one for the water basin and the other for the cover glass.

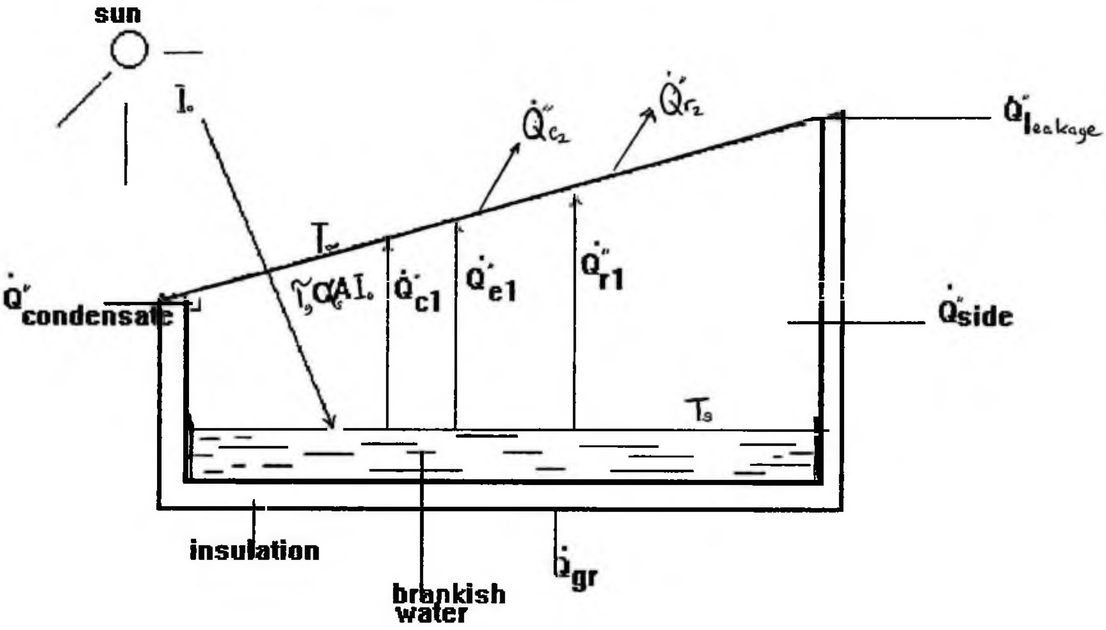
The primary energy exchange for the brackish water in the basin consists of absorption of the solar energy transmitted through the cover and the losses to the cover by convection, evaporation and radiation. The instantaneous-energy balance on the water yields:

$$(\tau\alpha)I_o = \dot{Q}''_{c1} + \dot{Q}''_{e1} + \dot{Q}''_{r1} + \frac{mc}{A}\frac{dT}{dt} + \frac{Ki\ Ai}{Xi\ As}(Ts - T_\infty) \qquad (2.3)$$

where $(\tau\alpha)I_o$ is the input to the basin which is solar energy transmitted by the glass and absorbed, $\dot{Q}''_{c1}$ is the energy loss due to convection to the inner cover surface, $\dot{Q}''_{e1}$ the energy loss due to evaporation to the inner cover surface, $\dot{Q}''_{r1}$ the energy loss due to radiation to the inner cover surface, $\frac{mc}{A}\frac{dT}{dt}$ is the thermal storage of the water in the basin, and the last term being conduction through the still walls and bottom.

This result assumes the surface area of the brackish water is the same as that of the cover, which is reasonable for small-cover slope(normally about 10°). For the situation under study, where the depth is less than 10cm, the fourth term on the right hand side of equation 2.3 may be neglected(since the quantity of water is small)

FIG.2.1.Major energy transport mechanisms in basin-type solar still



just as the last term,if the sides and bottom walls of the still are well insulated.

Dunkle[8] suggested the brackish water to cover heat fluxes are given by :

$$\dot{Q}''_{c1} = 8.8 \times 10^{-4}\left[T - T_{c1} + \left[\frac{Ps(T1) - Ps\ (Tc1}{268.9 \times 10^3 - P_s(T)}\ )\ T\right]^{1/3}\right.(T-T_{c1})$$

$$\dot{Q}''_{e1} = 16.276\ \dot{Q}''_{c1}\left[\frac{Ps(T) - Ps(Tc1)}{T - Tc1}\right] = \frac{\dot{m}}{A} h_{fg} \tag{2.5}$$

and

$$\dot{Q}''_{r1} = 0.9\sigma\ (T^4 - T_{c1}^4) \tag{2.6}$$

In these expressions, T is the water temperature in kelvin, T_{c1} is the temperature of the inner cover surface in kelvin, Ps(T) is the saturation pressure at temperature T in Pa.

For the glass, energy is received from the basin, and some solar energy is absorbed directly. The glass sheds its energy to the surrounding through convection and radiation. Again, assuming equal area for the basin and cover glass, the energy balance on the cover gives

$$\dot{Q}''_{c1} + \dot{Q}''_{e1} + \dot{Q}''_{r1} + \alpha_g I_o = \dot{Q}''_{c2} + \dot{Q}''_{r2} \tag{2.7}$$

The heat loss from the outer cover surface to the ambient air is:

$$\dot{Q}''_{c2} = h_{\infty}(T_{c2} - T_{\infty}) \tag{2.8}$$

Where T_{c2} is the temperature of the outer cover surface, T the ambient temperature h_{∞} is ambient convection coefficient ($Wm^{-2}K^{-1}$).

The outer cover radiative loss is given by

$$\dot{Q}''_{r2} = \quad {}_g\ \sigma\ (T_{c2}^4 - T_{sky}^4) \tag{2.9}$$

Where α_g is the glass absorptivity(solar), T_{sky} is the apparent sky temperature for long wavelength radiative exchange.

Considering only the conduction through the cover plate we obtain

$$T_{c1}-T_{c2} = t/k\,(\dot{Q}''_{c1} + \dot{Q}''_{e1} + \dot{Q}''_{r1}) \qquad (2.10)$$

where t and k are respectively the thickness and thermal conductivity of the cover. For a thin cover $T_{c2} = T_{c1}$.

According to Dunkle [5], at typical solar irradiation levels, the production rate is a linear function of the expression:

$$\dot{m}/A = 3.125 \times 10^{-4}\, I_o - 3.438 \times 10^{-5} \qquad (2.11)$$

for determining the maximum production rate. In this equation I_o is in kWm^{-2} and $\dot{m}/A$ is in $kgm^{-2}s^{-1}$.

Overall daily efficincy of a still is calculated with

$$\eta_o = h_{fg}\int_{t_{sr}}^{t_{ss}} m(t)/A\, dt \,/ \int_{t_{sr}}^{t_{ss}} I_o\, dt \qquad (2.12)$$

Upon substituting equation 2.11, this reduces to

$$\eta_o = h_{fg}\,(3.125 \times 10^{-4} - 3.438\; \frac{t_{ss} - t_{sr})}{H} \qquad (2.13)$$

where t_{ss} and t_{sr} are times at sunset and sunrise respectively

$$H = \int_{t_{sr}}^{t_{ss}} I_o\, dt$$

According to Clark [7], Malik developed the mathematics of a solar still under forced convection,steady flow state to come out with the forms:

$$\dot{Q}''_{c1} = h'_c\,(T_s - T_g) \qquad (2.14)$$

$$\dot{Q}''_{e1} = 0.70h'_c\,(P_{ws} - P_{wg})\, h_{fg} \qquad (2.15)$$

and

$$\dot{Q}''_{r1} = \frac{\sigma\left[T_s^4 - T_{c1}^4\right]}{\frac{1}{\epsilon_s} + \frac{1}{\epsilon_g} - 1} \qquad (2.16)$$

so that the energy flux balance for the basin is

$$I_o \tau_g \alpha_s = \frac{\sigma\left[T_s^4 - T_{c1}^4\right]}{\frac{1}{\epsilon_s} + \frac{1}{\epsilon_g} - 1} + h'_c (T_s - T_g) + 0.70 h'_c (P_{ws} - P_{wg}) h_{fg}$$

$$+ \frac{Ki\ Ai}{Xi\ As} (T_s - T_{sky}) \qquad (2.17)$$

where

I_o = solar flux (W/m^2)
τ_g = glass transmissivity (solar)
α_s = basin absorptivity (solar)
T_s = basin temperature (K)
T_g = glass temperature (K)
ϵ_s = basin emissivity (infrared)
ϵ_g = glass emissivity (infrared)
h'_c = modified convection coefficient (W/m^2 K)
σ = Boltzman constant
P_{ws} = basin water saturation pressure (atm)
P_{wg} = condensate saturation pressure (atm)
h_{fg} = heat of vaporization (kJ/kg)
K_i = insulation conductivity (W/mk)
A_i/A_s = insulation area normalized by basin area
X_i = insulation thickness (m)

T_∞ = ambient temperature (K)

0.7 = mass transfer–heat transfer proportionality constant

(kg K/atm KJ)

The energy flux to and from the glass is

$$\frac{\sigma[T_g^4 - T_g^4]}{\frac{1}{\epsilon_s}+\frac{1}{\epsilon_g}-1} + h'_c(T_s - T_g) + 0.70h'_c(P_{ws} - P_{wg}) + a_g I_o \qquad (2.18)$$

$$= E_g \sigma (T_g^4 - T_\infty^4) + h_\infty (T_g - T_{sky})$$

where

a_g = glass absorptivity (solar)

h_∞ = ambient convection coefficient (W/m^2K)

However, in 1990, Jim A. Clark[7] conducted further research on the performance of solar stills and came out with results that required modification of the equation for the energy flux by replacing the mass transfer–heat transfer proportionality constant with 0.35. Hence the equations 2.17 and 2.18 were modified:

$$I_o \tau_g \alpha_s = \sigma\frac{[T_s^4 - T_g^4]}{\frac{1}{\epsilon_s}+\frac{1}{\epsilon_g}-1} + h'_c(T_s - T_g) + 0.35h'_c(P_{ws} - P_{wg})h_{fg} + \frac{K_i}{x_i}\frac{A_i}{A_s}(T_s - T_{sky}) \qquad (2.1$$

and

$$\sigma\frac{[T^4 - T_g^4]}{\frac{1}{\epsilon_s}+\frac{1}{\epsilon_g}-1} + h'_c(T_s - T_g) + 0.35h'_c(P_{ws} - P_{wg}) + \alpha_g I_o = \epsilon_g\sigma[T_g^4 - T_\infty^4] + h_\infty(T_g - T_{sky}) \qquad (2.2$$

These two energy balances are two equations with the two unknowns T_s and T_g. A simultaneous solution yields the basin and glass temperatures, following which the still steady-state efficiency can be calculated as evaporation heat flux divided by incoming solar flux.

CHAPTER THREE

3.0.0 DESIGN. CONSTRUCTION AND EXPERIMENTAL PROCEDURE

3.1.0 MATERIAL REQUIREMENTS OF BASIN STILLS

Materials used for all types of stills should have the following characteristics:

(i) Materials should have a long life under exposed conditions and be inexpensive enough to be replaced upon degradation.

(ii) They should be sturdy enough to resist wind damage and slight earth movements.

(iii) They should be nontoxic and not emit vapour or introduce an unpleasant taste to the water under elevated temperature.

(iv) They should be able to resist corrosion from saline water and distilled water.

(v) They should be of a size and weight that can be conveniently packaged and carried by local transportation.

(vi) They should be easy to handle in the field.

3.2.0 BASIC COMPONENTS

3.2.1 THE BASIN

The basin holds the saline or brackish water that is to undergo distillation. By virtue of this role, it must be waterproof. Selecting a suitable material for basin construction is the biggest problem in the solar still industry [4]. No one construction material is appropriate for all circumstances or locations. Table 1 lists the various materials and rates them according to properties desirable for this application [1]. The column for local availability has been modified to suit the Ghanaian situation.

TABLE 1: A COMPARISON OF VARIOUS MATERIALS USED IN SOLAR BASIN CONSTRUCTION[1].

TYPE OF MATERIAL	DURABILITY	COST	LOCAL AVAILABILITY	SKILL NEEDED	CLEANING	WT OR PORTABILITY	TOXICITY
Enameled Steel	high	high	low	low	high	medium	low
EPDM rubber	high	high	low	low	high	high	low
Butyl rubber	high	high	low	low	high	high	low
Asbestos cement	high	medium	high	medium	medium	medium	high
Black polyethylene	medium	low	low	low	medium	high	low
Wood	low	low	high	medium	medium	low	low
foamed fibre glass	medium	medium	nil	low	high	medium	low
Copper	high	medium	nil	low	high	low	low
Aluminum	medium	medium	high	low	high	low	high

Wood, aluminium and copper are competitive materials from the table above, based on their properties. Wood was not selected because of its low durability and non-suitability for investigating for the best lagging material . Aluminium would have been preferable but for the fact that it is highly toxic; corrosion condition at the water line can be severe that basin made of the metal – even those coated with anti-corrosive materials tends to corrode in a few months, unlike copper which is worn out in a few years [1]. Based on this, copper was selected as the material for the basin.

Each basin was constructed from a sheet of copper .A pair of hand shears was used to cut the sheet according to some measurements. The cut sheet was then folded up into a basin. All joints of the basin were then welded to enable it contain water. The height of the basin was 6.0cm while the base was 86cm by 17.8cm . Seven holes were drilled on one face at depths of 1.0cm, 1.5cm, 2.0cm, 2.5cm, 3.0cm, 3.5cm and 4.0cm. With araldite, each of these holes was given an extension with glass tubes, of length 10cm and internal diameter 6mm. These tubes served as outlets for the basin and determined the depth of water in the still. The inside of the basin was painted with anti-rust black paint to perform two functions:

(i) to prevent corrosion

(ii) to increase the absorptance of the metal.

The appearance of the basin is as shown in figure 2.2.

3.2.2 THE GLAZING COVER

After the basin, the glazing cover is the most critical component of any solar still[7].It is mounted above the basin and must be able to transmit a lot of light in the visible spectrum yet keep the heat generated by that light from escaping out of the still. Exposure to ultra violet radiation requires a material that can withstand the degradation effects or that is inexpensive enough to be replaced periodically. Since it may encounter temperatures approaching 90°C, it must also be able to support its weight at those temperatures and not undergo excessive expansion, which could destroy the airtight seals.

Ideally, the glazing material should be strong enough to resist high winds, rain, hail and small earth movements, and prevent intrusion of insects. Other factors that determine the suitability of glazing materials include the cost of the materials, its weight, life expectancy, local availability, maximum temperature tolerance and impact resistance. Table 2 compares the various glazing materials based on these factors [8], the last column has been modified to suit the Ghanaian situation.

FIG.2.2: THE BASIN

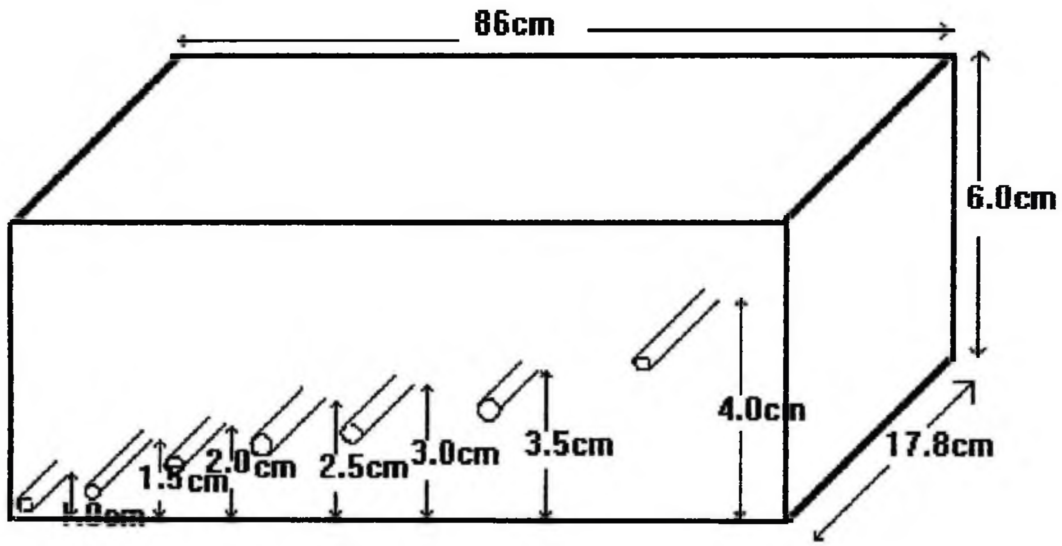


TABLE 2: A COMPARISON OF VARIOUS GLAZING MATERIALS USED IN BUILDING SOLAR STILLS[1]

TYPE OF MATERIAL	RELAT-IVE COST	WEIGHT kg/m2	LIFE EXPECTANCY (YRS)	MAX TEMP /°C	SOLAR TRANSMITTANCE (%)	INFRARED LIGHT TRANSMITTANCE (%)	IMPACT RESISTANCE	WETTABILITY	LOCAL AVAILABILITY
Tempered glass	highest	8.5-13.3	50$^+$	204-316	91	less than 2	low	excellent	No
ordinary window glass	medium	6.54	50	204	86	2	low	excellent	Yes
tedlar	low	0.154	5-10	107	90	58	low	treatable	YES
acrylic	high	4.15	25$^+$	93	89	6	medium	treatable	YES
polycarbonate	high	4.15	10-15	127	86	6	medium	treatable	YES
fibre glass	medium	1.33	8-12	93	72-87	2-12	medium	treatable	YES
polyethylene	low	0.122	0.67	71	90	80	low	treatable	YES

Of the materials listed in table 2, ordinary window glass is the best choice in the Ghanaian environment. It is comparatively cheap two thousand cedis per 1800 cm^2 and thickness of 2.9mm, with a weight of 1.395 kg. The life expectancy is fifty years, maximum temperature of 204°C, solar transmittance of 86%, allowing through it only 2% of infrared radiation. It is locally available due to the establishment of a glass factory in Accra.Ordinary window glass does not require any treatment to improve on its wettability.

Four sheets, each of dimension 90cm by 20cm, were purchased from a shop and framed with wawa boards. The "wettability" of each was improved by washing the surface of each sheet with a detergent dissolved in water. The property of "wettability" allows the condensing vapour to form as sheets of water on the underside of the glazing cover rather than as water droplets. If the water does form as droplets, it will reduce the performance of the still for the following reasons:

(i) water droplets restrict the amount of light entering the still because they act as small mirrors and reflect light back out.

(ii) a percentage of the distilled water that forms as droplets on the underside will fall back into the basin rather than flow down the glazing cover into the collection trough.

3.2.3 THE TROUGH

The trough, located at the base of the tilted glazing, serves to collect the condensed water and carry it to storage. A wide range of materials are suitable for this purpose; however, in all cases, conditions outlined in the case of the basin materials are also pre-requisites for the trough. Besides, the materials must not react with distilled water. All metals, except aluminium, would react with distilled water until after sometime before the reaction ceases[8]. Aluminium was therefore chosen as material for the trough. With a pair of hand shears, a piece of dimensions 86cm by 2.5cm was cut out from a sheet of aluminum of thickness 2mm and given a V-shape. The edges were folded in such a way as to form a collecting structure. The small size was chosen as to avoid shading the basin. Four of these were constructed, one for each still.

3.2.4 ANCILIARY COMPONENTS

These include insulation, sealants, piping valves, fixtures, feed and storage facilities.

Locally available materials were used, with particular attention to those that could be easily replaced in the event of breakages or deterioration.

The fixture, which in fact, is the encasement in the still, was made out of wawa boards. In all four boxes were built, each of interior dimensions 86cm by 18cm as base and a height of 14.5cm at the front, while that at the rear was 17.0cm. The difference in height at the front and rear accorded the end-product a slope of eight degrees, to enable the distilled water run down into the trough, at the same time exposing the glazing cover to maximum solar radiation. Accra lies on latitude 6.5°N, hence the still could have been given a slope of 6.5°, but from previous work carried out by Felli[9] of the Department of Physics, of the University of Ghana from March to May in 1986, a slope of 8° gave the maximum yield, hence the reason for the present choice of the angle of slope. In fact this value fell within McCraken's[6] proposed range. According to him the angle of slope lies within the range θ to $\theta+5°$, where θ is the number of degrees of the latitude of the place of experimentation.

Holes of diameter 1.1cm were drilled at the front side of the encasement to accommodate the outlet pipes fixed to the basin.

The materials chosen for lagging were of four types, namely: coconut fibre, spent cotton, urethane foam and sawdust. Linseed oil putty was initially chosen as sealant, but substitutes had to be sought for, upon realising that the cost of the putty was rather high. As a substitute, powdery sawdust was mixed with a quantity of water and white carpenter's glue. Coconut fibre wrapped in pieces of polythene later served as a better substitute.

For piping and storage facilities, glass tubes and conical flasks were respectively chosen.

The feed is simply a container from which raw water is fed into the still. For the case in point, a single feed was constructed to serve all four stills. An empty milo tin of diameter 9.2cm and height 16.5cm was used for this purpose. A hole of diameter 1.1cm was drilled at the center of the bottom of the tin. A glass tube of external diameter 1.0cm and length 10.0cm was affixed in the hole and sealed to the tin using super glue.

The inside of the container was painted with black anti-rust paint to eliminate corrosion when in contact with air and water. The protruding glass tube was then connected to a rubber tubing of comparable diameter. This served as a link between the feed and the still.

3.2.5 ASSEMBLING OF COMPONENTS

Assembling of the components into single units was carried out at the roof-top of G2 laboratory, at the Department of Physics, University of Ghana. This site was chosen for assembling the stills because measurements were going to be taken there. Each of the stills, when assembled appeared bulky and delicate to handle; bulky because the building materials were quite substantial and each unit reasonably heavy, and delicate to handle because of the breakable parts – i.e. the glazing glass cover and the glass tubes serving as outlets. For this reason, it was preferable to assemble the stills at the experimental site. It became necessary to choose the roof-top as experimental site because up there, there was little or virtually no human interruption. Furthermore, destruction of the wooden parts of the still by termites and shading by trees and other bodies were eliminated up at the roof-top.

For a start, the base and all sides except the front one, were screwed together. In stills A and B, the said sides and base were lined with urethane foam previously measured and cut out according to the inner dimensions of the stills. A second lining of pieces of wawa board of thickness 0.6cm was put in place and the basin then sat in the parts so far assembled. The front of the basin was lined with a piece of wawa board of thickness 0.6cm and followed by urethane foam of thickness 2.5cm. The outer front-wawa board was then screwed onto the parent structure. The two front lining comprising of the thin wall of wawa boards, and urethane foam together with the front thick wawa board were all perforated at points to allow the emergence of the glass tubes glued to the basin. The thin wawa boards forming the innermost lining of the still were coated with white oil paint before being assembled. The coating served as a preventive material against rot, as the wood would be in constant touch with water vapour, and also a reflective surface, redirecting the sunlight falling on them onto the basin.

The glass frame, which had earlier been fixed to an aluminum trough, was placed as a cover over the top of the still, and screwed onto the outer wooden structure. Air-tightness was ensured initially using linseed oil putty. In its finished form, the putty is a paste-like matter with some oil at the top which had to be worked on until it became pliable. A thin layer was put at every external joint, plastered up, and allowed to dry. The drying process took as much as a week.

The open end of the storage was sealed with a piece of white polythene material to prevent any interference of the atmosphere with the distillate: atmospheric carbon dioxide could dissolve and alter the ionic concentration of the product; so could evaporation of the distillate take place if not covered. A small hole was bored into the polythene material to accommodate a tube coming from the still.

On exposure to sunlight, some rays of light passed through the glass into the still and ended up by heating water that was earlier fed into the still via the feed. Some water got evaporated, rose to the glass cover where it was cooled and condensed, the condensed vapour run down the glazing cover and then into the trough where it was led into the storage via a rubber tube.

After operating stills A and B for three days it was realised that the yield for the two stills was irregular. This called for opening up still B whose yield was far below that of A even though they were both exposed to the same conditions. Nothing unusual was detected, so the cover was replaced with more putty being used, for a possible air leakage could cause the lower yield in B. Upon operation the situation had not changed. The still had to be opened several times in attempt to identify the problem. This meant more and more of the putty had to be used. However, the substance was expensive and continuous reliance on it could increase the production cost of the still. In a search for an alternative means, powdery sawdust mixed with some water and some carpenter's glue worked perfectly well until it rained and the substance began to break apart. Further investigation unfolded another break-through. Coconut fibre wrapped in a piece of polythene, when pushed into the spacing between the framed cover and the lower structure formed an excellent sealant. This sealant was very cheap, easily accessible and quite durable.

This discovery was the outcome of some constructional error in the still. The length of the trough was 86cm to match the exposed area of the glass cover instead of the entire length of 90cm. Some of the distillate was lost as a result of the shorter trough which could not collect some distillate which run down beyond the exposed area of the cover, and trickled back into the basin. This was detected only after several attempts of opening and sealing the still. An extension of the trough was made using a piece of polythene material glued onto the aluminium trough and the wooden frame.

Photograph of the basin-type solar still built for this research. The Milo feed is lowered after feeding the still in order to avoid shading the still by the Milo feed.

3.2.6 EXPERIMENTAL PROCEDURE

After rectifying all errors, the stills A and B were first calibrated. In doing so both stills were fed with tap water to a depth of 1.0cm. This was done by closing all the outlet tubes except the one at a depth of 1.0cm, and pouring water into the feed which was led into the basin. Excess water flowed out through the open outlet before it was closed. Both stills were placed side by side facing South and left to operate after sunrise. Hourly yield, ambient temperature, basin water temperature and remarks on the weather were noted and recorded from sunrise to sunset. The process was repeated on the second and third days with water depths of 2.0cm and 3.0cm respectively.

Temperatures were measured with mercury-in-glass thermometers.A hole was drilled into a piece of urethane foam and fitted to the exposed part of the thermometer for measuring the basin temperature .This was an attempt to reduce the effect of radiant heat on the basin temperature. The hourly values of the distillate were measured with a measuring cylinder.

Upon ascertaining that the yield in both stills were comparably close in each case, the threshold depth was then investigated. This was done by maintaining the depth in A at 1.0cm and varying that in B day after day and then comparing the yield in both stills. The lower yield in B is attributed to the fact that B contained more water than A. The experiment was repeated, this time keeping the depth in B at 1.0cm throughout while varying the depth in A day after day. The average yield of the two experiments was calculated from which the effect of increasing the depth in the stills was revealed.

Four stills labelled A,B,C,D were used in the project. The errors in A and B were taken care of in C and D. But for the insulating material, which was sawdust in C and D, all four stills were identical. Calibration of these stills was carried out just as in the case of A and B. They were then used to determine the threshold depth, following the same procedure as in the case of A and B.

Stills C and D were employed to determine the effect of covering the glass cover the previous night before being put into operation. Maintaining equal depths in both stills at all times, the glass cover of D was covered each night while that of C was not. Both stills were left to operate the following day in each case. Hourly variation in yield, ambient temperature, basin water temperature and remarks on weather were noted and recorded. All this time still A was being rehabilitated from a leakage as a result of breakage of one of the outlet tubes.

In order to determine a better lagging material for solar stills, C and A were dismantled so that their lagging materials could be changed. The basin in A was lagged with coconut fibre while that in C was lagged with spent cotton. The new labelling was such that A, B, C and D were respectively lagged with coconut fibre, sawdust, spent cotton and urethane foam.The mean distance from water to glass cover was 7.0cm in each still.

All the four stills were arranged in line close together facing Southward, with the same parameters except the lagging materials. For a start, all stills were fed to a depth of 1.0cm and allowed to operate under the same atmospheric conditions. The hourly variation in yield, ambient temperature, basin water temperature and remarks on weather were noted and recorded right from the start to the end of distillation. The process was repeated for depths of 1.5cm, 2.0cm, 2.5cm, 3.0cm and 3.5cm for different days.

3.2.7 DETERMINATION OF PURITY OF DISTILLATE

The purity analysis of all samples was carried out in a laboratory at Water Resources Research Institute, Accra.

3.2.8 CONDUCTIVITY MEASUREMENT

A conductometer is the instrument used to determine the electrical conductivity of each sample. Before each determination the temperature of each sample was brought to 25°C and transferred into a thermostat. The conductometer cell was then thorougly rinsed with a portion of the sample and completely immersed in the sample, ensuring that no air bubbles adhered to the electrodes.

The electrical conductivity was then indicated on the screen of the instrument.

3.2.9 pH MEASUREMENT

A pH meter is the instrument used for measuring the pH of each sample. Before the instrument was used to determine the pH of each sample, it was first standardized. By this the probe of the meter was immersed in an electrolyte of pH 7.0 and the meter was adjusted to indicate 7.0 on its screen. The process was repeated with a second electrolyte with a pH of 4.0. After this, the meter was said to be standardized. The probe was then rinsed with deionized water and immersed in each sample. A reading indicated on the screen kept on varying until after a minute it became constant. This value was then read as the pH of the sample.

3.2.10 RESIDUE CONTENT

Each sample was collected in a hard-glass bottle. This was a precaution against contamination of samples by solvent action of water on the container, which is unlikely in the case of a hard-glass bottle. In each sample analysis, an empty clean dish was dried in an oven at 105°C. The dish was allowed to cool for sometime. It was transferred into a desiccator while still warm. After two hours the dish was removed and weighed. 25ml of well-mixed sample was measured out with a pipette and poured into the dish on a steam-bath. After complete evaporation of the water the dish was transfered into an oven, to prevent particles in the atmosphere from settling on it to alter its weight while it was cooling. It was reweighed after cooling. The total residue was calculated from the formula:

$$\text{Total residue(mg/l)} = \frac{100 \times G}{V}$$

where G = increase in weight over the empty dish (mg)

V = volume of the sample(ml)

3.2.11 SILICA CONTENT

In each sample analysis two sample cells were filled with 25ml of the sample. 0.5ml of molybate 3 Reagent was added to each sample cell. After swirling to mix, the samples were allowed a reaction period of 4 minutes. Contents of a citric Acid Reagent Powder Pillow were added to each sample ceil and mixed up by swirling. After one minute reaction period for destruction of possible phosphate interference, one Amino Acid F Reagent Powder Pillow was added to each one of the sample cells, and mixed by swirling. This served as the prepared sample while the other one stood in for the blank. The silica content of the latter followed by the former, were determined using a spectrophotometer.

3.2.12 OXIDIZABLE MATTER-OXYGEN CONTENT

The method employed for the determination of oxidizable matter or oxygen content is the iodemetric method.

Each sample was collected into a bottle with a stopper without causing any change in the concentration of dissolved oxygen. Contact with air or agitation was avoided. The samples were protected from sunlight. 2ml of Manganous sulphate solution and 2ml of alkaline iodine solution were added in succession to each sample right after sampling. The stopper was carefully replaced to avoid inclusion of air bubbles and the content was thoroughly mixed by vigorously inverting and rotating the bottle several times. A brown precipitate was formed in each case which settled leaving a clear supernatant liquid. In the case of sea water the precipitate settled with great difficulty; settlement was however improved by rotating the bottle carefully before vigorous shaking.

Each sample was then transferred from sampling site to the laboratory for analysis. 4ml of 0.0125N sulphuric acid was measured out and added to each sample and the stopper replaced immediately. The content of the bottle was thoroughly mixed by rotating it. The precipitate dissolved easily in each case except that of sea water where a repeated mixing and shaking had to be carried out 100ml of each solution was measured in a conical flask and immediately titrated with standard thiosulphate solution using 2ml of starch solution as an indicator towards the end-point when the pink colour began to change to clear. The starch solution changed the nearly clear solution to black-blue. Upon further titration the colour of the solution changed to colourless at the end-point. The volume of thiosulphate solution used was noted and recorded. The dissolved oxygen content was then obtained from the formular:

$$\text{Dissolved Oxygen Content(mg/l)} = \frac{\text{Volume of 0.0125N thiosulphate (ml)} \times 101.6}{\text{volume of sample(ml)}}$$

3.2.13 CHLORIDE CONTENT

Chloride is determined in a neutral or slightly alkaline solution by titration with standard silver nitrate, using potassium chromate as indicator. Silver chloride quantitatively precipitated before reddish chromate is formed.

PROCEDURE

100ml of each sample was measured out into a conical flask on a white surface. The pH in each case was found to be between 7.0 - 9.5, a prerequisite condition for the reaction. 1ml of potassium chromate solution was added to each sample and then titrated with silver nitrate solution, with constant stirring until a perceptible reddish colouration persisted. This was taken as the end-point of the titration. In the case of sea water, 1.0ml of a sample was diluted with 99ml of distilled water before titrating with silver nitrate. In each case a blank test was conducted, using distilled water in place of the sample.

The chloride content was then calculated from the equation:

$$\text{Chloride as } Cl^- = \frac{(V_1 - V_2) \times 100}{\text{Volume of sample(ml)}} \text{mg/l}$$

Where V_1 = Volume of silver nitrate solution required by sample

V_2 = Volume of silver nitrate solution required by blank

3.2.14 SODIUM CONTENT

The method used to determine sodium content of each sample is called Atomic absorption spectrophotometry.

Atoms of all elements can absorb radiation at very narrow wavelength bands when the element is chemically bound in the free atomic state and preferably in the ground or zero energy state. For most elements, this requirement necessitates vaporization of the sample containing the element in some manner. The most common procedure is to aspirate a liquid sample into a flame so that light absorbed by the ground atoms in the flame is measured.

The atomic absorption spectrophotometer consists of four basic components; a light source, atomizer-burner assembly, a cylinder of gas and a computer system.

Before making spectrophometric measurements, the spectrophotometer was set in accordance with a set of instructions and lighted by an electrical means. Four standard solutions of sodium, of different concentrations, were each aspirated into a flame, in the atomizer-burner. The solution aspirated into the flame vaporized and the atoms at their ground state absorbed some amount of the characteristic line spectrum emitted by the source of light made of a hollow cathode constructed with sodium. A graph of concentration against absorbance was automatically plotted on the screen of the computer. A straight line graph was obtained. Hence the instrument was standardized as such.

50ml of each sample was then acidified with 1.5m nitric acid and transfered to a 100ml graduated flask. 50ml of distilled water was added to the content of the flask. 20ml of the solution was poured out into a test tube and aspirated into the burner flame to atomize. The degree of absorbance of the line spectrum depended on the concentration of sodium in each solution.

The concentration of each solution was indicated on the screen of the computer. The experiment was repeated for acidified distilled water as a blank test.

The concentration of the metal in each sample is given by the formular:

$$\frac{(\rho_t - \rho_b) \times 100}{V}$$

Where ρ_t is the concentration of the metal in mg/l corresponding to the absorbance of the sample.

ρ_b is the concentration of the metal in mg/l corresponding to the absorbance of the blank;

V is the volume, in ml of the acidified sample taken for analysis.

CHAPTER FOUR

EXPERIMENTAL RESULTS

4.1 DETERMINATION OF THRESHOLD DEPTH

TABLE 3: HOURLY VARIATION OF YIELD IN STILLS A AND B
DATE: 17/3/94
Depth in A = 1.0cm
Depth in B = 1.0cm

TIME IN HRS GMT	AMBIENT TEMP±0.1/ °C	BASIN WATER TEMP±0.1/ °C		VOL. OF DISTIL.±0.5/ML		YIELD±0.002/ LM^{-2}HR^{-1}		REMARK ON WEATHER
		A	B	A	B	A	B	
06.00	26.0	26.0	26.0	0.0	0.0	0.000	0.000	clear
07.00	27.0	29.5	29.5	0.0	0.0	0.000	0.000	"
08.00	27.8	36.4	35.5	2.0	1.5	0.014	0.010	"
09.00	30.9	41.0	40.5	9.0	8.5	0.062	0.058	sunny
10.00	33.5	53.2	51.2	24.0	23.5	0.164	0.161	"
11.00	34.6	56.5	54.0	35.0	34.0	0.239	0.233	"
12.00	35.8	61.0	59.0	51.0	50.0	0.349	0.342	"
13.00	37.5	66.5	64.1	61.5	61.0	0.421	0.417	"

14.00	37.6	63.4	61.2	74.0	73.5	0.506	0.503	"
15.00	36.2	60.1	57.0	60.0	60.0	0.414	0.410	"
16.00	32.8	52.0	49.5	45.0	44.5	0.308	0.304	"
17.00	30.5	41.5	40.0	24.0	23.5	0.164	0.160	"
18.00	28.8	32.0	32.0	10.0	11.0	0.068	0.075	dull
19.00	28.5	29.5	30.0	8.5	9.5	0.058	0.065	dark + cool
20.00	28.2	29.3	29.8	6.5	7.5	0.044	0.051	"
21.00	27.9	29.0	29.6	5.0	5.5	0.034	0.038	"
22.00	27.5	28.8	29.4	4.0	5.5	0.027	0.031	"
23.00	27.1	28.3	29.3	2.5	3.0	0.017	0.021	"
00.00	26.8	28.0	28.1	0.0	0.0	0.000	0.000	"
TOTAL				422.5	421.0	2.890	2.880	

Percentage fall in yield in B =

$$\frac{[\text{Daily yield in A} - \text{Daily yield in B}]}{\text{Daily yield in A}} \times 100\%$$

$$= \frac{[2.890 - 2.784]}{2.890} \times 100\%$$

$$= \underline{0.35\%}$$

Calculation of yield

Transmitting area of glass = 86cm x 17cm
= $1462 cm^2$

Area of glass shaded by trough = 86cm x 1cm
If volume of distillate = 2ml = 2×10^{-3} L
=> $1462 cm^2$ produced 2×10^{-3} L
$1 m^2 = 10^4 cm^2$ will produce : $\frac{10^4}{1462} \times 2 \times 10^{-3}$ L

= $\underline{0.014 \text{ L}}$

Hence the yield = $\underline{0.014\ Lm^{-2}\ hr^{-1}}$

TABLE 4 : HOURLY VARIATION OF YIELD IN STILLS A AND B
DATE: 25/3/94
Depth in A = 1.0cm
Depth in B = 2.5cm

TIME IN HRS GMT	AMBIENT TEMP ±0.1/°C	BASIN WATER TEMP±0.1/°C		VOL. OF DISTIL.±0.5/ML		YIELD±0.002/ LM^{-2}HR^{-1}		REMARK ON WEATHER
		A	B	A	B	A	B	
06.00	26.2	25.1	25.1	0.0	0.0	0.000	0.000	Clear
07.00	27.2	25.3	25.4	0.0	0.0	0.000	0.000	"
08.00	28.0	25.5	25.5	3.0	1.0	0.021	0.007	"
09.00	30.2	37.0	31.5	5.0	4.0	0.034	0.027	sunny
10.00	32.3	42.0	37.0	21.5	9.0	0.147	0.062	"
11.00	34.5	53.0	41.0	34.5	22.5	0.236	0.154	"
12.00	34.2	54.0	42.5	53.5	35.5	0.366	0.243	partially cloudy
13.00	36.2	53.5	46.0	50.0	42.5	0.342	0.291	sunny
14.00	36.5	60.0	48.0	64.0	51.5	0.438	0.352	"
15.00	35.6	51.0	46.0	69.0	59.5	0.472	0.407	"

16.00	34.1	50.0	41.0	50.0	50.0	0.342	0.342	"
17.00	31.4	42.0	38.0	31.0	38.0	0.212	0.260	"
18.00	29.3	35.5	33.0	14.0	22.0	0.096	0.150	dull
19.00	28.1	34.1	32.9	12.5	15.5	0.085	0.106	dark + cool
20.00	27.8	33.2	32.5	10.5	13.0	0.072	0.089	"
21.00	27.6	32.8	32.1	8.5	9.5	0.058	0.065	"
22.00	27.4	32.4	31.8	7.0	7.5	0.048	0.051	"
23.00	27.1	31.6	31.7	5.5	6.0	0.038	0.041	dark + cold
00.00	26.9	30.7	30.9	2.0	4.5	0.014	0.031	"
01.00	26.7	28.9	29.0	1.5	3.5	0.010	0.024	"
TOTAL				4.43	395.0	3.030	2.702	

Percentage fall in yield in B = 10.8%

TABLE 5: HOURLY VARIATION OF YIELD IN STILLS A AND B
DATE: 27/3/94
Depth in A = 1.0cm
Depth in B = 3.5cm

TIME IN HRS GMT	AMBIENT TEMP±0.1 /°C	BASIN WATER TEMP±0.1/°C		VOL. OF DISTIL.±0.5 /ML		YIELD±0.002/ $LM^{-2}HR^{-1}$		REMARK ON WEATHER
		A	B	A	B	A	B	
06.00	26.8	27.1	27.1	0.0	0.0	0.000	0.000	clear
07.00	27.1	28.2	29.1	0.0	0.0	0.000	0.000	"
08.00	28.2	30.1	30.0	3.0	0.5	0.021	0.003	sunny
09.00	31.2	37.0	33.0	5.0	1.5	0.034	0.010	"
10.00	33.2	45.0	39.0	14.0	2.5	0.096	0.017	"
11.00	36.3	52.5	47.0	29.5	15.0	0.202	0.103	hot
12.00	34.8	58.0	49.0	48.5	18.0	0.332	0.123	partially cloudy
13.00	36.6	64.0	59.0	65.0	22.0	0.445	0.150	sunny
14.00	37.2	65.0	62.0	95.0	35.0	0.650	0.240	hot
15.00	35.5	60.0	60.5	74.0	37.0	0.506	0.253	"
16.00	34.6	51.5	56.0	58.5	35.5	0.400	0.243	"

17.00	31.8	42.5	49.0	38.5	25.0	0.263	0.171	"
18.00	29.2	35.5	45.0	17.0	21.0	0.116	0.144	dull
19.00	28.1	35.0	43.5	14.5	18.5	0.099	0.127	dark + warm
20.00	27.8	34.7	41.9	12.5	15.0	0.085	0.103	"
21.00	27.6	33.9	39.5	9.5	12.5	0.065	0.085	"
22.00	27.4	33.1	38.6	7.5	9.0	0.051	0.062	dark + cool
23.00	27.1	32.5	37.1	5.0	7.0	0.048	0.048	dark + cold
00.00	26.8	31.2	36.2	4.5	5.5	0.038	0.038	"
01.00	26.5	29.5	34.1	3.0	4.0	0.021	0.027	"
TOTAL				304.0	284.5	3.451	1.946	

Percentage fall in yield in B = 43.6%

TABLE 6 : RESULTS ON DETERMINATION OF THRESHOLD DEPTH USING STILLS A AND B

	DEPTH±0.1/CM		VOL.OF DISTIL.±0.5/ML		PERCENTAGE DECREASE
DATE	A	B	A	B	IN PRODUCTION
17/3/94	1.0	1.0	422.0	407.0	0.4
22/3/94	1.0	1.5	516.0	502.5	2.60
24/3/94	1.0	2.0	495.5	473.0	4.5
25/3/94	1.0	2.5	443.0	395.0	10.8
26/3/94	1.0	3.0	544.0	473.0	13.1
27/3/94	1.0	3.5	504.5	284.5	43.6
28/3/94	1.0	1.0	436.0	430.5	-1.3
29/3/94	1.5	1.0	346.5	339.5	-2.1
30/3/94	2.0	1.0	410.0	413.0	0.7

1/4/94	2.5	1.0	459.0	481.5	4.7
2/4/94	3.0	1.0	509.0	536.0	5.0
3/4/94	3.5	1.0	397.0	432.5	8.2

TABLE 7: THE RELATIONSHIP BETWEEN DEPTH IN STILLS AND PERCENTAGE DECREASE IN PRODUCTION

DEPTH±0.5/CM		% FALL IN PRODUCTION		
		EXPT 1	EXPT 2	AVERAGE
1.0	1.0	0.4	-1.3	-0.45
1.0	1.5	2.6	-2.1	0.25
1.0	2.0	4.5	0.7	2.60
1.0	2.5	10.8	4.7	7.90
1.0	3.0	13.1	5.0	9.05
1.0	3.5	43.6	8.2	25.90

4.2 VERIFICATION OF THE EFFECT OF COVERING THE STILL THE PREVIOUS NIGHT BEFORE PUT INTO OPERATION

TABLE 8 : HOURLY VARIATION OF YIELD IN STILLS WHEN D WAS COVERED THE PREVIOUS NIGHT WHILE C WAS NOT

DATE: 5/5/94

DEPTH IN C = DEPTH IN D - 1.0CM

TIME IN HRS GMT	AMBIENT TEMP±0.1/°C	BASIN WATER TEMP±0.1°C		VOL. OF DISTIL±0.5/ ML		YIELD±0.002/ $LM^{-2}HR^{-1}$		REMARK ON WEATHER
		C	D	C	D	C	D	
06.00	26.5	26.6	26.9	0.0	0.0	0.000	0.000	clear
07.00	26.6	26.6	27.5	0.0	0.0	0.000	0.000	"
08.00	28.7	29.0	30.0	1.5	2.5	0.010	0.017	"
09.00	29.4	36.2	38.0	3.0	3.5	0.021	0.024	sunny
10.00	30.8	44.5	46.1	10.0	11.5	0.068	0.079	partially cloudy
11.00	31.7	49.5	51.5	22.5	24.5	0.154	0.168	sunny
12.00	34.4	50.2	60.0	42.5	44.0	0.291	0.300	"
13.00	33.7	60.0	64.5	61.5	66.5	0.421	0.455	"
14.00	33.0	59.0	61.0	78.0	80.0	0.534	0.547	warm
15.00	34.6	61.0	63.9	85.5	88.0	0.585	0.602	"

16.00	33.0	56.0	58.0	69.5	71.5	0.475	0.485	"
17.00	32.1	49.0	51.5	47.0	49.0	0.321	0.335	"
18.00	28.3	42.5	44.0	32.5	33.5	0.222	0.229	"
19.00	27.2	34.0	38.8	21.0	22.0	0.144	0.150	dull
20.00	27.0	33.0	34.5	13.5	14.0	0.092	0.096	dark + warm
21.00	26.7	29.0	31.6	8.5	10.0	0.058	0.068	"
22.00	26.3	28.5	29.5	5.5	7.0	0.038	0.048	dark + cool
23.00	26.1	27.9	27.9	4.5	5.0	0.031	0.026	"
00.00	25.9	27.5	27.7	2.5	3.5	0.017	0.024	"
TOTAL				509.0	536.4	3.482	3.666	"

$$\text{Percentage increase in yield in D} = \frac{[\text{Daily yield in D} - \text{Daily yield in C}]}{\text{Daily yield in C}} \times 100\%$$

$$= \frac{[3.666 - 3.482]}{3.482} \times 100\%$$

$$= \underline{5.3\%}$$

TABLE 9 : HOURLY VARIATION OF YIELD IN STILLS WHEN BOTH STILLS WERE UNCOVERED THE PREVIOUS NIGHT

DATE: 6/5/94

DEPTH IN C = DEPTH IN D = 3.5CM

TIME IN HRS GMT	AMBIENT TEMP±0.1/°C	BASIN WATER TEMP±0.1/°C		VOL OF DISTIL±0.5/ML		YIELD/LM^{-2}HR^{-1}		REMARK ON WEATHER
		C	D	C	D	C	D	
06.00	26.5	26.6	26.6	0.0	0.0	0.000	0.000	clear
07.00	26.7	28.2	28.4	0.0	0.0	0.000	0.000	"
08.00	27.3	30.5	30.9	0.0	0.0	0.000	0.000	sunny
09.00	29.7	32.4	33.0	1.5	1.5	0.010	0.010	"
10.00	29.7	35.2	36.1	4.5	5.0	0.031	0.026	"
11.00	32.4	40.5	42.0	11.5	12.0	0.079	0.082	"
12.00	35.2	45.6	47.3	16.5	17.5	0.113	0.120	hot
13.00	34.2	47.2	50.1	35.5	35.5	0.243	0.243	"
14.00	35.2	56.7	59.2	47.5	48.0	0.325	0.328	"
15.00	32.8	55.1	57.1	65.0	65.5	0.445	0.448	"
16.00	31.3	50.2	51.2	57.5	58.0	0.393	0.400	partially cloudy

17.00	32.2	45.7	46.3	50.0	50.0	0.342	0.342	sunny
18.00	29.9	40.2	41.5	45.0	45.5	0.308	0.311	dull
19.00	28.3	39.5	40.9	40.5	40.0	0.277	0.274	dark + cool
20.00	27.3	38.2	39.5	32.5	32.5	0.222	0.222	"
21.00	27.1	37.1	38.2	25.5	25.0	0.174	0.171	"
22.00	26.8	36.9	37.9	15.5	16.00	0.106	0.109	"
23.00	26.3	36.7	37.5	9.5	9.5	0.065	0.065	"
00.00	25.4	36.5	36.7	7.0	7.5	0.048	0.051	dark + cold
TOTAL				465.0	469.0	3.181	3.208	

Percentage increase in yield in D = 0.9%

TABLE 10: HOURLY VARIATION OF YIELD IN STILLS WHEN D WAS COVERED THE PREVIOUS NIGHT WHILE C WAS NOT

DATE: 7/5/94

DEPTH IN C = DEPTH IN D = 3.5CM

TIME IN HRS GMT	AMBIENT TEMP±0.1/°C	BASIN WATER TEMP±0.1/oC		VOL OF DISTIL±0.5 /ML		YIELD±0.002/ LM^{-2}HR^{-1}		REMARK ON WEATHER
		C	D	C	D	C	D	
06.00	27.2	27.2	28.0	0.0	0.0	0.000	0.000	clear
07.00	27.4	27.4	28.4	0.0	0.0	0.000	0.000	"
08.00	28.0	28.9	29.2	0.0	1.5	0.000	0.010	"
09.00	30.4	31.1	31.9	2.0	4.5	0.014	0.031	sunny
10.00	32.4	34.2	35.8	5.5	8.5	0.038	0.058	"
11.00	33.5	35.5	38.1	12.5	15.5	0.085	0.106	"
12.00	34.1	40.2	41.2	18.5	21.5	0.127	0.147	"
13.00	35.2	45.5	49.5	37.5	40.5	0.256	0.277	hot
14.00	36.1	49.6	52.1	52.5	67.0	0.359	0.458	"
15.00	35.8	59.5	62.5	64.5	78.0	0.441	0.534	"
16.00	33.0	58.1	60.9	57.5	63.5	0.393	0.434	"

17.00	29.0	55.2	57.9	49.0	57.0	0.335	0.390	"
18.00	28.8	50.0	56.5	42.0	51.0	0.287	0.349	dull
19.00	27.5	48.5	53.4	35.5	45.0	0.243	0.308	dark + warm
20.00	27.3	47.2	52.2	25.0	33.5	0.174	0.229	"
21.00	27.1	46.1	51.7	17.5	26.0	0.120	0.178	"
22.00	26.9	43.2	49.5	15.0	21.0	0.103	0.144	"
23.00	26.8	40.9	48.1	11.5	17.0	0.079	0.116	dark + cool
00.00	26.6	40.1	47.0	9.5	11.5	0.065	0.079	"
TOTAL				455.	562.5	3.116	3.841	

Percentage increase in yield in D = 19.5%

TABLE 11: HOURLY VARIATION OF YIELD IN STILLS WHEN NONE WAS COVERED THE PREVIOUS NIGHT
DATE: 14/5/94
DEPTH IN C = DEPTH IN D = 2.0CM

TIME IN HRS GMT	AMBIENT TEMP±0.1 /oC	BASIN WATER TEMP±0.1/oC		VOL OF DISTIL±0.002/ML		YIELD±0.002LM^{-2} HR^{-1}		REMARK ON WEATHER
		C	D	C	D	C	D	
06.00	25.1	25.6	25.6	0.0	0.0	0.000	0.000	dull
07.00	25.2	25.8	25.8	0.0	0.0	0.000	0.000	"
08.00	28.8	30.2	30.9	1.0	2.0	0.007	0.014	sunny
09.00	29.8	38.0	37.8	4.0	3.0	0.027	0.021	"
10.00	30.7	45.5	45.2	12.5	11.5	0.085	0.079	"
11.00	30.7	47.5	47.0	20.5	19.5	0.140	0.133	partially cloudy
12.00	34.2	54.4	54.8	26.5	27.0	0.181	0.185	sunny
13.00	30.9	49.5	50.0	34.5	36.0	0.236	0.246	partially cloudy
14.00	32.5	53.0	53.6	31.5	33.5	0.215	0.229	"
15.00	33.6	56.0	56.8	44.5	48.0	0.304	0.328	"
16.00	29.6	48.0	49.0	44.0	50.5	0.301	0.345	"

17.00	28.8	43.0	44.0	36.0	30.0	0.246	0.205	dull
18.00	27.8	38.5	40.0	25.0	18.5	0.171	0.127	dark
19.00	27.6	30.0	31.0	12.0	13.5	0.085	0.092	dark + cool
20.00	27.4	29.4	29.0	9.0	10.0	0.065	0.068	"
21.00	27.1	28.7	28.9	6.5	7.0	0.044	0.048	"
22.00	26.9	28.0	28.5	5.0	5.0	0.031	0.031	dark + cold
23.00	26.7	27.2	28.3	3.0	3.5	0.021	0.024	"
00.00	26.4	27.0	28.1	2.0	2.0	0.010	0.014	"
TOTAL				317.5	320.5	2.172	2.192	

Percentage increase in yield in D = 0.9%

TABLE 12 : HOURLY VARIATION OF YIELD IN STILLS WHEN D WAS COVERED THE PREVIOUS NIGHT WHILE C WAS NOT

DATE: 16/5/94

DEPTH IN C = DEPTH IN D = 2.0CM

TIME IN HRS GMT	AMBIENT TEMP±0.1oC	BASIN WATER TEMP±0.1oC		VOL OF DISTIL±0.5/ML		YIELD±0.002 $LM^{-2}HR^{-1}$		REMARK ON WEATHER
		C	D	C	D	C	D	
06.00	25.6	25.8	27.5	0.0	0.0	0.000	0.000	partially cloudy
07.00	25.7	25.8	27.5	0.0	0.0	0.000	0.000	"
08.00	29.3	29.5	32.5	2.0	3.0	0.014	0.021	sunny
09.00	32.3	37.4	40.5	3.0	4.0	0.021	0.027	"
10.00	31.4	44.0	46.5	17.5	18.5	0.120	0.127	partially cloudy
11.00	33.5	47.5	49.5	25.5	27.0	0.174	0.185	sunny
12.00	34.2	50.0	52.5	31.0	32.0	0.212	0.219	"
13.00	35.0	62.5	65.0	60.0	65.0	0.424	0.445	"
14.00	33.1	59.2	63.0	49.0	50.0	0.335	0.342	"
15.00	32.2	57.5	59.5	31.5	32.0	0.215	0.219	"
16.00	30.1	49.2	51.0	25.0	25.5	0.171	0.174	"

17.00	29.5	42.1	43.5	19.5	20.0	0.133	0.137	"
18.00	27.2	35.2	36.0	12.0	13.0	0.082	0.089	dull
19.00	26.6	35.0	35.8	9.5	10.0	0.065	0.068	dark + cold
20.00	26.4	34.8	35.2	7.0	7.5	0.048	0.051	"
21.00	26.1	34.5	35.0	4.5	5.0	0.031	0.034	"
22.00	25.9	34.0	34.2	3.0	3.0	0.021	0.021	"
23.00	25.7	33.8	33.9	2.0	2.5	0.014	0.017	"
00.00	25.4	30.5	30.8	1.5	2.0	0.010	0.014	"
TOTAL				305.5	320.0	2.076	2.189	

Percentage increase in yield in D = 5.2%

TABLE 13 : RESULTS FOR DETERMINING THE EFFECT OF COVERING THE STILL THE PREVIOUS NIGHT BEFORE PUT INTO OPERATION

	DEPTH IN		VOL. OF DISTIL±0.5/ ML		PERCENTAGE DIFFERENCE	STATE OF D THE PREVIOUS NIGHT
DATE	C±0.5 /cm	D±0.5/ cm	C	D	IN YIELD	[IN ALL CASES C WAS UNCOVERED]
16/4/94	1.0	1.0	439.5	447.5	1.8	uncovered
5/5/94	1.0	1.0	509.5	536.0	5.3	covered
10/5/94	1.5	1.5	526.0	531.0	1.0	uncovered
12/5/94	1.5	1.5	467.5	488.5	4.50	covered
14/5/94	2.0	2.0	317.5	320.5	0.9	uncovered
16/5/94	2.0	2.0	303.5	320.0	5.4	covered
18/5/94	2.5	2.5	425.5	429.0	0.8	uncovered
20/5/94	2.5	2.5	350.5	414.5	18.3	covered

21/5/94	3.0	3.0	310.0	313.0	1.0	uncovered
22/5/94	3.0	3.0	410.5	488.0	18.9	covered
6/5/94	3.5	3.5	465.0	469.0	0.9	uncovered
7/5/94	3.5	3.5	455.5	562.5	23.5	covered

TABLE 14: THE EFFECT ON YIELD AS A RESULT OF COVERING A STILL THE PREVIOUS NIGHT AS AGAINST DEPTH IN WATER IN STILL BASIN

DEPTH/CM	% INCREASE IN YIELD
1.0	3.5
1.5	3.5
2.0	4.5
2.5	17.5
3.0	17.9
3.5	22.6

21/5/94	3.0	3.0	310.0	313.0	1.0	uncovered
22/5/94	3.0	3.0	410.5	488.0	18.9	covered
6/5/94	3.5	3.5	465.0	469.0	0.9	uncovered
7/5/94	3.5	3.5	455.5	562.5	23.5	covered

TABLE 14 : THE EFFECT ON YIELD AS A RESULT OF COVERING A STILL THE PREVIOUS NIGHT AS AGAINST DEPTH IN WATER IN STILL BASIN

DEPTH/CM	% INCREASE IN YIELD
1.0	3.5
1.5	3.5
2.0	4.5
2.5	17.5
3.0	17.9
3.5	22.6

RESULTS OF THE DETERMINATION OF BEST LAGGING MATERIAL (S)

TABLE 15 HOURLY VARIATION OF YIELD IN STILLS
DATE: 23/5/94
DEPTH IN ALL FOUR(4) STILLS = 1.0CM

Time In Hrs. GMT	Ambient Temp /°C	Basin Water Temp./°C				Volume of Distillate/ML				Yield/ LM^{-2}HR^{-1}				Remark on Weather
		A	B	C	D	A	B	C	D	A	B	C	D	
06.00	25.7	26.5	26.5	26.5	26.5	0.0	0.0	0.0	0.0	0	0	0	0	dull
07.00	25.8	26.5	26.5	26.5	26.5	1.5	2.0	1.5	1.5	0.010	0.014	0.010	0.010	clear
08.00	27.6	38.4	39.0	38.0	38.2	4.0	5.05.0	3.0	3.5	0.027	0.021	0.021	0.024	"
09.00	28.0	43.5	44.2	43.0	43.0	10.0	13.0	9.0	9.5	0.068	0.062	0.061	0.085	partially cloudy
10.00	32.7	50.9	53.0	50.0	50.2	24.0	30.0	16.5	19.0	0.164	0.021	0.113	0.130	sunny
11.00	31.1	49.0	51.0	48.5	48.9	30.0	34.5	19.5	22.0	0.205	0.236	0.133	0.150	partially cloudy
12.00	32.2	58.5	61.0	57.9	58.0	42.5	58.0	32.0	37.5	0.291	0.399	0.219	0.258	sunny
13.00	32.5	60.9	63.0	60.0	60.5	49.5	59.0	35.0	38.5	0.339	0.404	0.235	0.263	"
14.00	30.8	59.5	61.9	58.9	59.0	52.5	73.0	41.0	43.0	0.335	0.495	0.280	0.294	"
15.00	30.4	50.0	52.0	49.5	49.8	42.5	54.0	34.0	35.5	0.291	0.365	0.233	0.243	"
16.00	30.3	46.9	48.0	45.8	46.0	31.5	40.0	26.0	27.0	0.215	0.274	0.178	0.185	"
17.00	28.4	36.0	38.6	35.8	35.9	20.0	26.5	18.5	20.5	0.139	0.181	0.129	0.140	'
18.00	27.8	32.5	34.5	31.6	32.0	8.5	9.0	7.0	8.0	0.005	0.061	0.048	0.055	dull

19.00	27.6	31.0	33.0	30.5	31.0	7.0	7.5	6.5	7.5	0.048	0.052	0.044	0.055	dark + cool
20.00	27.3	30.5	32.1	30.0	30.4	5.5	6.0	5.0	6.0	0.038	0.041	0.034	0.041	"
21.00	27.1	30.0	31.5	29.1	29.7	3.5	5.0	3.0	4.0	0.024	0.034	0.021	0.027	"
22.00	26.9	29.1	30.6	28.4	28.6	3.0	3.5	2.5	3.5	0.021	0.024	0.017	0.024	"
23.00	26.3	28.5	29.6	27.5	27.9	2.5	3.0	1.5	2.5	0.017	0.021	0.010	0.017	"
24.00	26.1	27.4	29.0	27.0	27.5	1.5	2.0	0.5	1.5	0.010	0.014	0.003	0.010	"

TOTAL 340.5 431.0 263.0 288.0 2.325 2.948 1.799 1.966

RATIO OF YIELD = 0.79 : 1 : 0.61 : 0.67

TABLE 16 : PURITY ANALYSIS

Sample	pH	Conductivity in us/cm	Oxygen Content in mg/l	Sodium Content in mg/l	Residue in mg/l	Silica Content in mg/l	Chloride content in mg/l
sea water	7.92	57×10^3	6.11	49.80	508.0	0.167	3.09×10^4
distilled sea water	5.68	3.30	0.40	0.32	0	0.057	0.50
pond water	8.86	178.7	6.01	4.50	744.0	0.102	6.50
distilled pond water	5.67	3.20	0.04	0.31	0	0.051	0.42
tap water	6.87	53.7	5.97	3.74	60.0	0.081	5.80
distilled tap water	5.68	3.11	0.40	0.31	0	0.030	0.41
lab distilled water	5.50	3.00	6.21	0.29	0	0.02	0.40

CHAPTER FIVE

5.1.0 DISCUSSION OF RESULTS

5.1.1 CALIBRATION OF STILLS

In the case under study, two stills; A and B constructed with the same dimensions and other parameters, were employed in the process of calibration. Strictly speaking, each of these should have been calibrated with an auxiliary equipment that has been calibrated earlier. However, this was not the case in this particular situation, because the two stills were simply to operate side-by-side. In which case the manner or extent to which one operates with respect to the other is what is of prime importance.

In calibration, both stills were mounted side by side on the roof-top, fed to the same depth each day and the yield and temperatures were read and recorded hourly. The depth in the stills was varied from day to day, making sure that on every occasion equal depths were adhered to. In all cases, the daily yields agreed with one another with a precision of less than 1%. This precision value indicated that, despite some slight differences or errors in construction, the two equipments could be used for the purpose for which they were made without any hesitation. The same procedure was followed in the calibration of the other pair – C and D, which in fact had different lagging materials.

5.2.0 THRESHOLD DEPTH

Figures 3, 4 and 5 depict the graphical representation of the results in tables 3, 4 and 5 respectively indicating the hourly variation of distilled water produced during the day. They are a few typical results of the experiment. Each one of them gives a smooth curve, rising gradually from 07.00 GMT to 09.00 GMT, steeply from 10.00GMT and reaching a maximum between 13.00GMT and 15.00GMT and falling steeply from the time of the maximum yield to 18.00GMT. The curve then falls gradually from 18.00GMT to hours between 23.00GMT and 01.00GMT.

5.2.1 THE FIRST PHASE OF DISTILLATION IN STILLS

At 06.00GMT, when the sun is just rising, no distillation is observed in all days. The process is actuated by radiation from the sun. At the early hours of the day, the intensity of solar radiation is so low that little energy is supplied to water molecules in the basin of the stills to start evaporation, hence no distillation at the time in question.

With the lapse of time, the solar elevation changes such that the intensity of solar radiation increases. Also, the direct solar radiation reaching the glass cover begins to pass through the latter as the glazing angle increases beyond 20°; the minimum glazing angle at which transmission of light is possible for glass[1].

The result of these two effects is marked by the gradual rise in temperature of the basin water and subsequent commencement of the distillation process between 07.00GMT and 08.00GMT. The commencement is followed by a gradual rise in yield between 8.00GMT and 10.00GMT.

5.2.2. THE SECOND PHASE OF DISTILLATION IN STILLS

After 15.00GMT the yield rose sharply until between 13.00GMT and 14.00GMT when a maximum was reached. During these hours the whole bulk of the water in the basin absorbed enough energy, and more and more molecules escaped from the surface to condense later on the glass cover. This process is brought about as a result of further increase in the transmittance of the glass cover to direct solar radiation as the sun approached overhead position, thereby increasing the glazing angle.

5.2.3. THE THIRD PHASE OF DISTILLATION IN STILLS

The opposite of what was seen during the second phase of distillation is what happened during this phase. Between the hours of 13.00GMT or 15.00GMT and 18.00GMT when the sun was going down, the yield decreased sharply as the intensity of solar radiation and the glazing angle of the direct solar radiation falling on the glass cover decreased.

5.2.4 THE FOURTH PHASE OF DISTILLATION IN STILLS

The decrease in yield from 18.00GMT to 0.00GMT is extremely gradual. The energy available for distillation during these hours was mainly in the form of stored energy in the still and a small amount from emission of radiation from the earth and the atmosphere.

5.2.5 VARIATION OF AMBIENT TEMPERATURE

As the sun rose at 06.00GMT the ambient temperature read between 24°C and 27°C each day, increased gradually from 06.00GMT to 08.00GMT. It further rose to a maximum between 13.00GMT and 14.00GMT in a gradual manner. It then fell gradually between the time of maximum ambient temperature and 18.00GMT. Between 06.00GMT and 18.00GMT, there were however some instances of fluctuations in temperature as a result of the appearance of clouds in the sky. The ambient temperature, after 18.00GMT, fell very gradually until the rate of change of temperature reached −0.2°C per hour.

5.2.6 VARIATION OF TEMPERATURE IN STILLS

The basin water temperature behaved the same way as the ambient temperature except in some cases when a cloud disappeared shortly after forming. Such cloudy conditions caused a fall in the ambient temperature which was not reflected in the basin temperature as a result of energy made available from the stored energy.

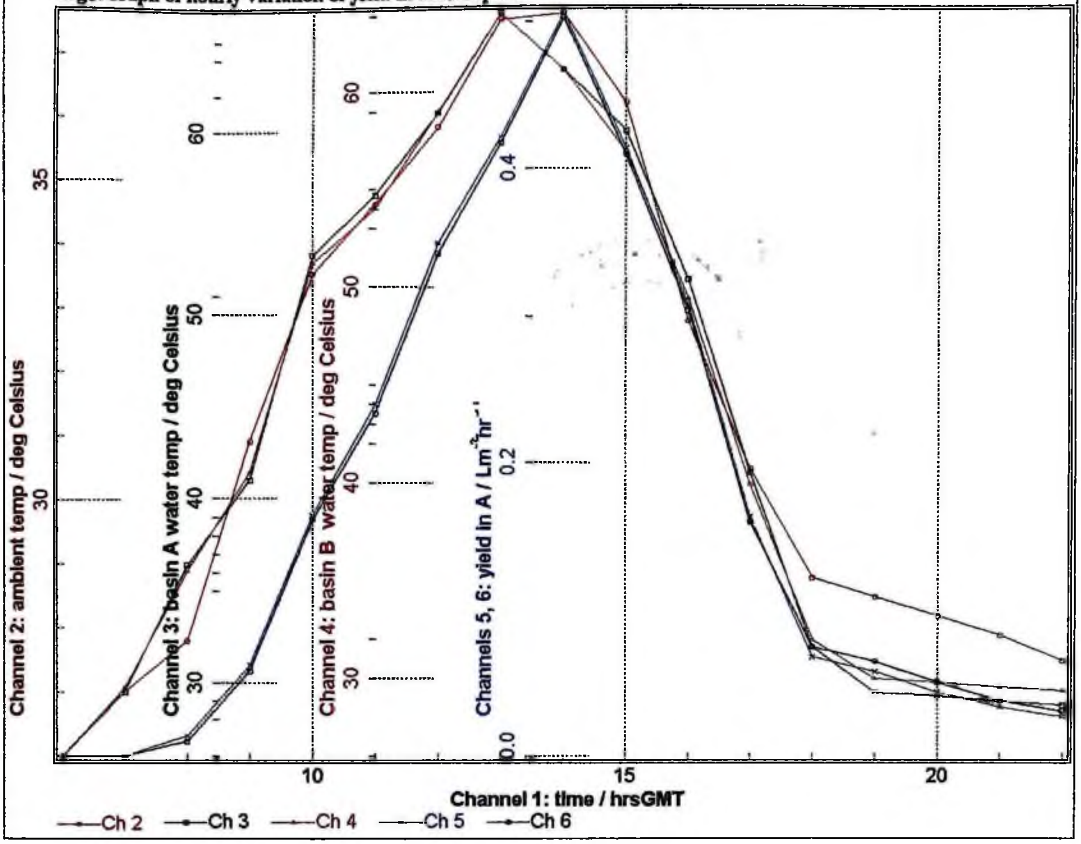
The rise in basin water temperature from 06.00GMT to 14.00GMT and its subsequent fall is generally in response to the ambient temperature, which is a result of the nearness of the sun to a particular point on the earth. The sun is farthest during sunrise at 06.00GMT (approximately) and sunset at approximately 18.00GMT and closest between 12.00GMT and 14.00GMT.

5.2.7 DISCUSSION OF SPECIFIC GRAPHS

Figure 3 is a graphical representation of yield in stills A and B when both were fed to the same depth of 1.0cm. The ambient temperature at 06.00GMT was 26°C. It rose gradually, reaching a maximum of 37.6°C at 14.00GMT and afterward fell just as it rose, from 14.00GMT to 18.00GMT. The fall in ambient temperature as from 18.00GMT was more gradual than the previous hours.

The basin water temperature of both stills rose and fell in response to the ambient temperature, with A leading B from 07.00GMT till 18.00GMT when B then led A. The temperature of the basin water of A rose to a maximum of 66.5°C at 13.00GMT while B attained 64.1°C. Unlike the ambient temperature, the temperature in both stills rose and fell sharply except during the night when

Fig3:Graph of hourly variation of yield in stills.depth in both stills=1.0cm



GRAPH OF CUMULATIVE YIELD IN A AND B VRS TIME

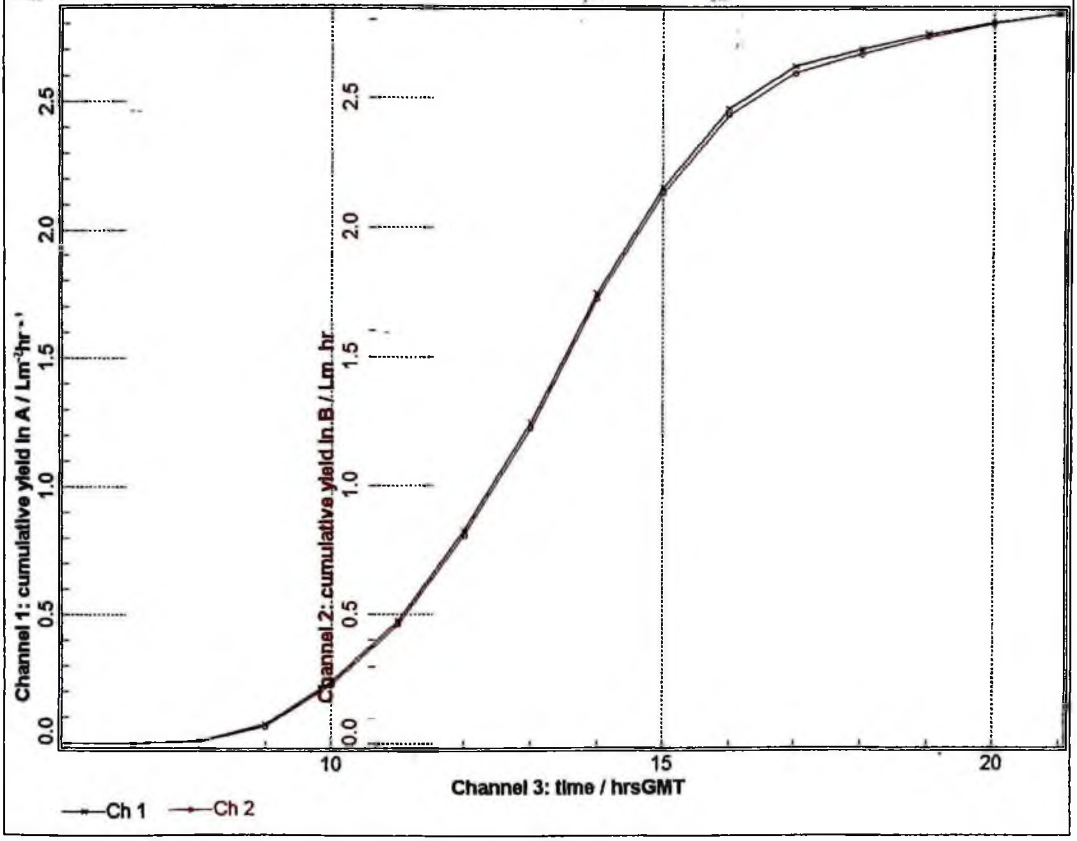
Channel 1: cumulative yield in A / $Lm^{2}hr^{-1}$

Channel 2: cumulative yield in B / $Lm^{-2}hr^{-1}$

Channel 3: time / hrsGMT

Data information:

Fig. 4 GRAPH OF CUMULATIVE YIELD IN A AND B VRS TIME



the fall was gradual.

The distillation started after 07.00GMT, increased gradually until after 09.00GMT the yield curves rose sharply to a maximum of 0.506 litre per square metre of glass surface per hour for A while that in B was 0.503l m^{-2} hr^{-1} at 14.00GMT. The yield in both stills fell sharply in response to their respective basin water temperatures until after 18.00GMT when the fall took a gradual trend. Both stills attained a steady state right after 19.00GMT; with a fall of less than 0.5°C per hour.

The sharp rise in yield between 09.00GMT and 13.00GMT is a result of more and more water molecules obtaining enough energy from the basin to evaporate and subsequently condense on the glass cover. Conversely, the sharp decrease is a result of less and less molecules receiving energy from the sun which was moving farther and farther away from the overhead position. As stated earlier, the yield after 18.00GMT was a consequence of the stored energy in the stills. Though both stills operated at the same depth, the yield in A was more than in B. This is due to better constructional and lagging measures in A than in B. Such errors are inevitable in real life situation. The error in B with respect to A was 0.4 percent.

5.2.8 THE EFFECT OF CLOUD ON YIELD

Figure 5 is a graphical representation of hourly variation in

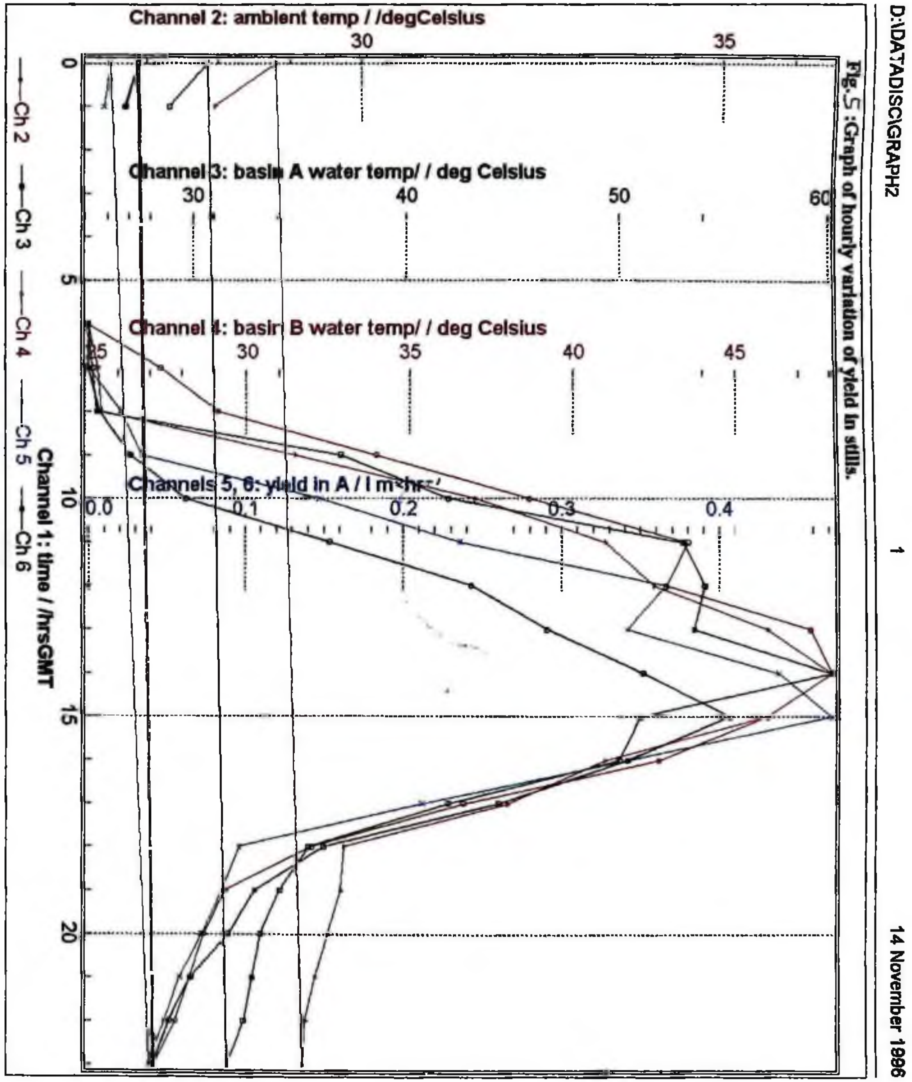


Fig.5 :Graph of hourly variation of yield in stills.

yield recorded in table 5.. The depth in A was maintained at 1.0cm while that in B was increased to 2.5cm. The only remarkable occurrence was at the time between 11.00GMT and 12.00GMT when the ambient temperature fell as a result of the formation of a partial cloud. 'A', which had less water in it, responded at a later time to the fall in ambient temperature by a fall in yield and basin water temperature while B hardly did. The conclusion that could be drawn from this, is that the shallower the basin water, the more the still responded to the effect of reduced solar radiation due to cloudiness.

As shown in figure 5, there was a sudden drop in ambient temperature at 12.00GMT followed by a sharp rise at 13.00GMT. From table 5 it is seen that a cloud formed partially at 12.00GMT. This cloud disappeared within so short a time that the effect was not felt by either of the stills, temperaturewise or by way of yield. Under extreme cloudy conditions, the transient term of equation 2.3 decreases in value[5]. This is accompanied by a corresponding decrease in yield.

5.2.9 SUMMARY ON THE DETERMINATION OF THRESHOLD DEPTH

The efficiency of a still is proportional to the mass of distillate produced during any period, hence the change in percentage of production is equal to the change in efficiency. The effect of decrease in percentage of production or efficiency, as a result of increasing the depth of water in the still is represented in Figure 6. The gradients of the lines AB, BC, CD ,DE, and EF are 1.4, 4.7, 10.6 , 2.3 and 33.7 respectively. The sudden rise in gradient from 2.3 to 33.7 for the line EF represents a remarkable decrease in efficiency of the stills from a depth of 3.0cm to 3.5cm. A depth of 3.0cm is hence seen as the threshold depth as compared to 2.5cm reported by McCracken and Gordes [1].

Figures 7 and 8 show the graphs of total daily yield as a function of daily mean ambient temperature and daily mean basin temperature respectively. The graphs show that an increase in daily mean ambient temperature results in an increase in daily mean basin temperature and total daily yield.

5.3.0 RESULTS AND DISCUSSION OF COVERING THE STILL THE PREVIOUS NIGHT

Figure 9 shows the variation of yield in stills C and D when D was covered with a polythene bag filled with sawdust the previous night while C was not. Both stills started distilling after 07.00hrsGMT. Distillation was very slow in both stills between 08.00hrsGMT and 09.00hrsGMT ,increased sharply from 09.00hrsGMT and reached their maximum concurrently at15.00hrsGMT,that of D being higher than that of C. The process slowed down sharply from 15.00hrsGMT to 19.00hrsGMT after which the production rate fell gradually till 01.00hrsGMT when the process ceased. D led throughout in production by 5.3 percent.

Fig6:Graph of percentage fall in yield vrs depth of water in still.

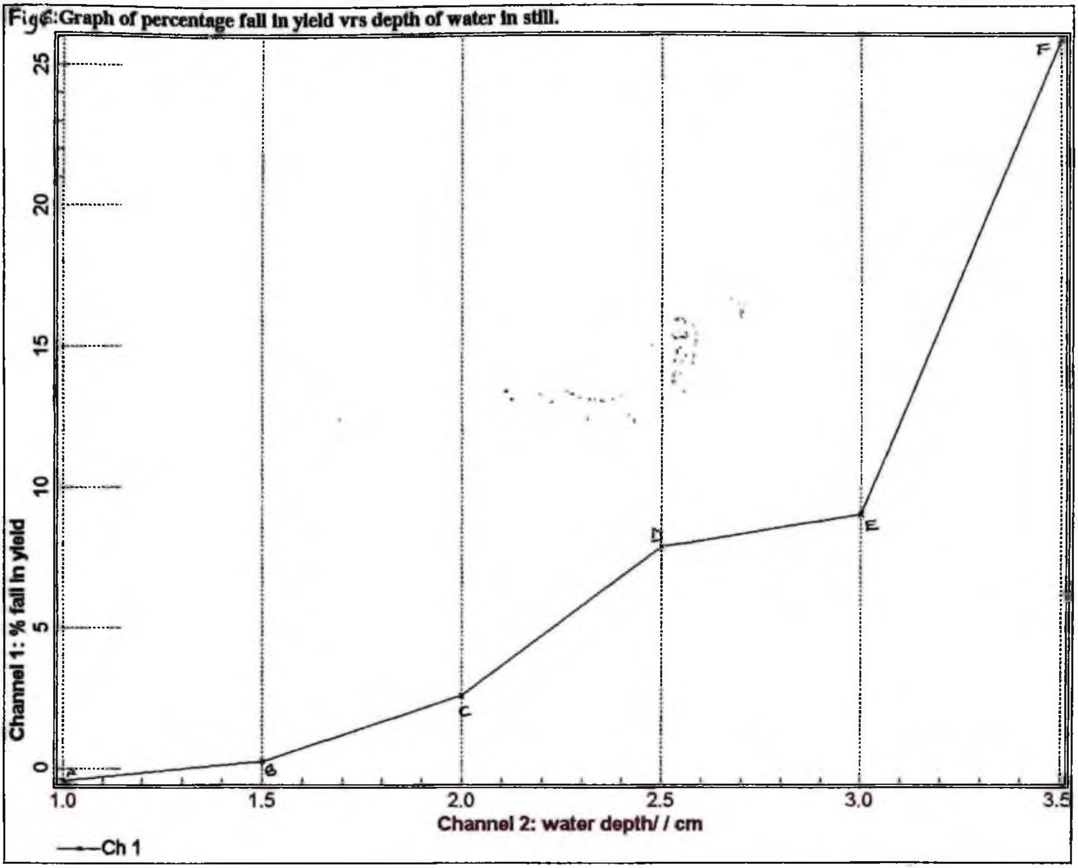


Fig.7 :Graph of total daily yield vrs mean ambient temperature

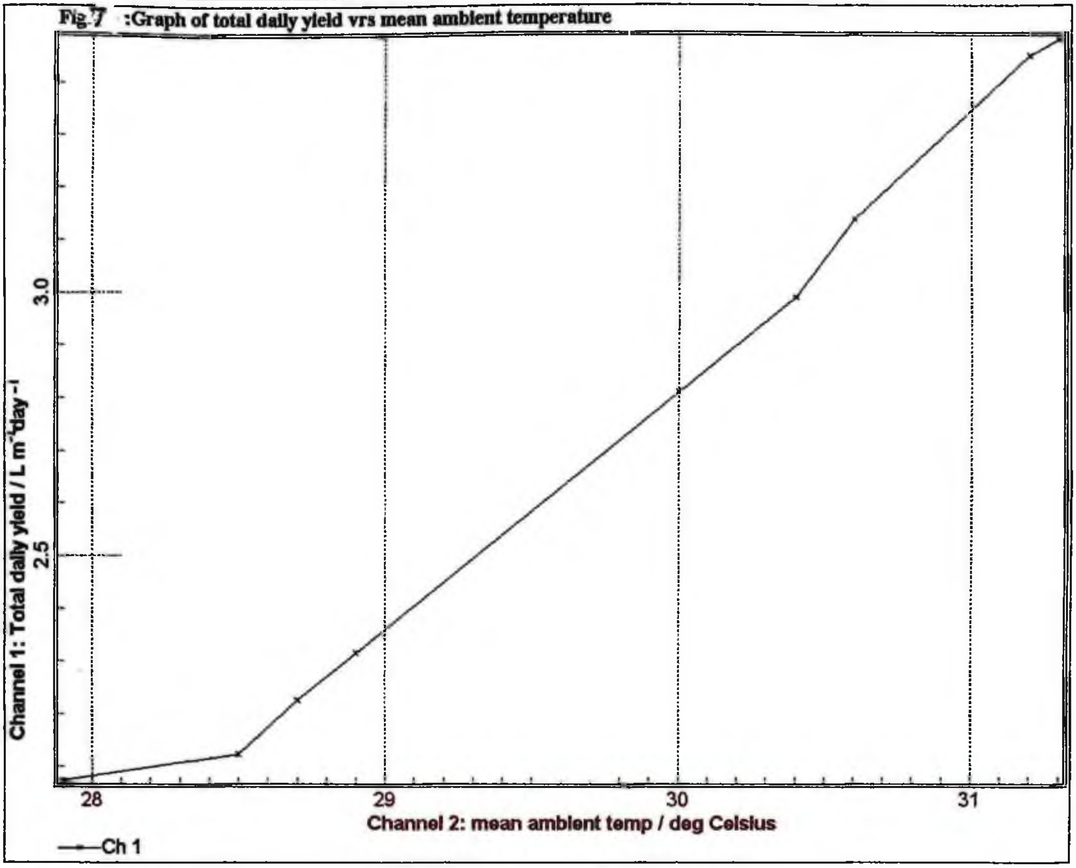


Fig. 8 :Graph of total daily yield vrs mean basin(A) temperature

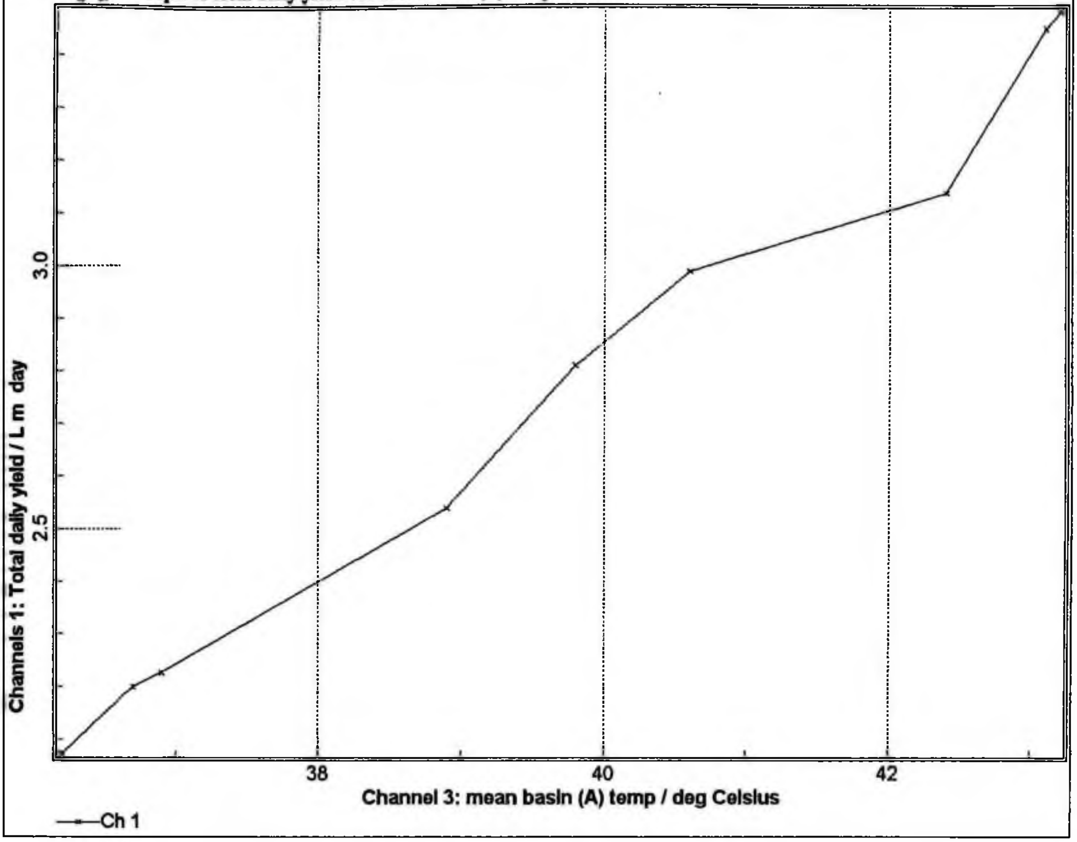
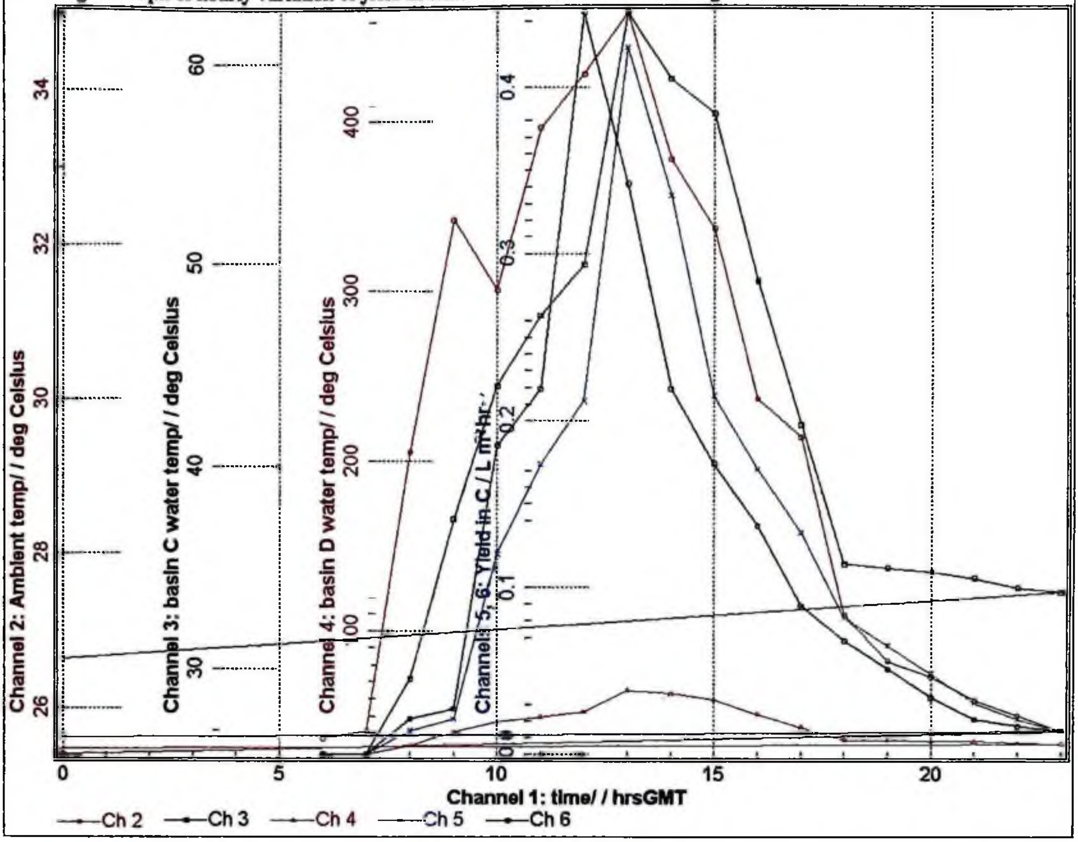


Fig.9: Graph of hourly variation of yield in stills when D was covered overnight



On 16th April, when both stills operated under the same conditions, D led C in production by 1.8 percent, hence, of the 5.3 percent, 3.5 percent of the yield was the effect of covering the glass cover the previous night with an operating depth of 1.0cm.

Results of the variation in yield in stills as recorded on 6th May, is graphically shown in figure 10. This was the case when both stills operated without covering any of the stills the previous night. Both stills operated at a depth of 3.5cm. There is nothing perculiar about this graph as compared to the case when they both operated at 1.0cm under the same conditions. D distilled more than C by 0.8 percent.

The following day, the depths in both stills were maintained at 3.5cm but D was covered the previous night.The production curves are shown in fig 11. By 08.00GMT D had started distilling while C was warming up. By 09.00GMT C had started producing too. The production rate was quite gradual in both stills until after 12.00GMT when a sharp rise in production rate was chalked by both stills. This continued till 15.00GMT when the maximum was reached in both stills. Production then slowed down gradually throughout the rest of the day.D distilled more than C by 23.5%. 22.6 percent of this was due to the cover over D the previous night,since D produced 0.9% more than C when both stills operated under the same conditions.

Figure 12 depicts the curves for yield in the stills on the 14th

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Fig. 10: Graph of hourly variation of yield in C and D

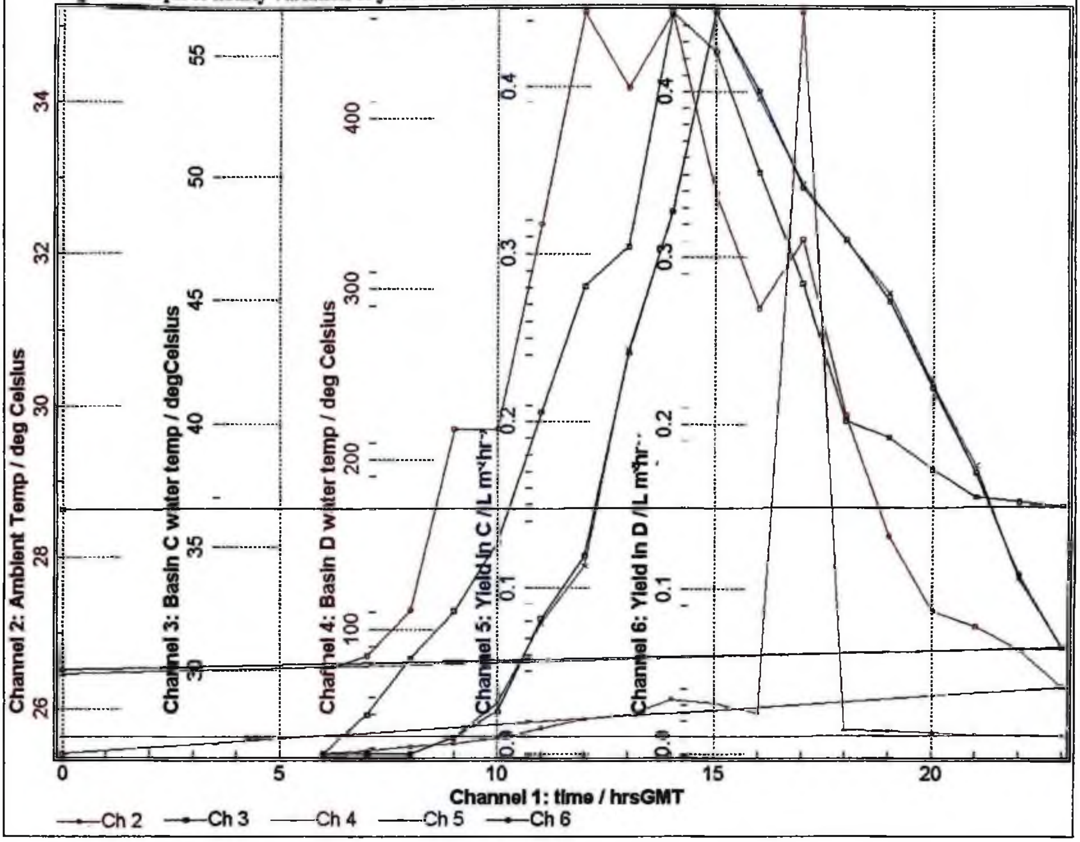


Fig.11: Graph of hourly variation in yield in C and D.

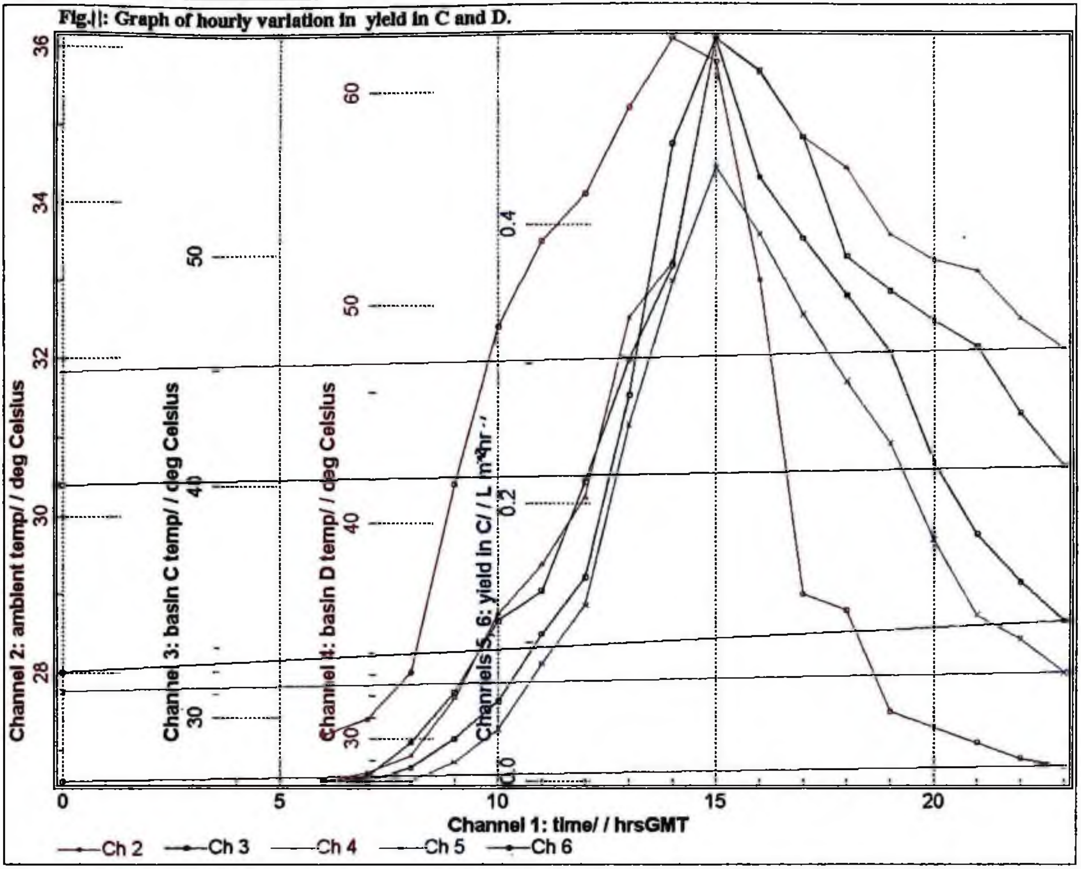
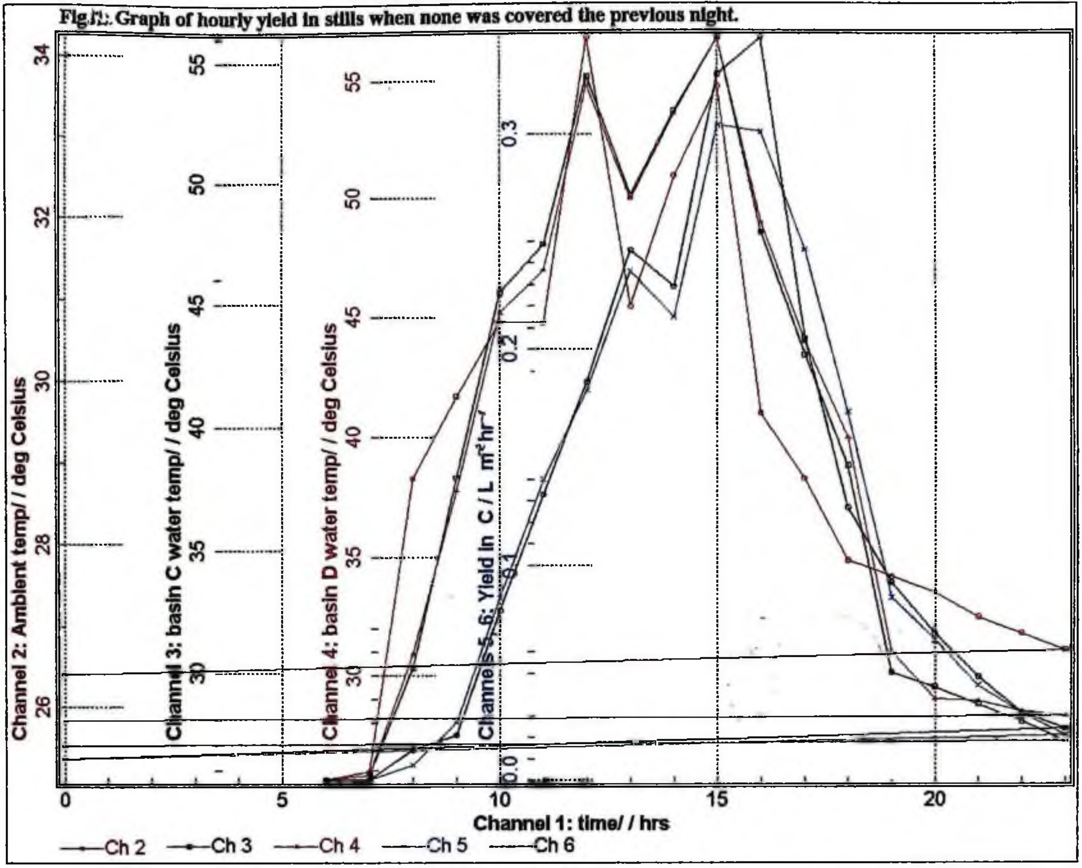


Fig.11: Graph of hourly yield in stills when none was covered the previous night.



of April when they were operated at a depth of 2.0cm under the same conditions. Both stills, by 08.00GMT had started distilling. Distillation in both stills was very gradual till after 09.00GMT when it increased slightly in both systems, concurrently reaching a maximum at about 15.30GMT after a sudden fall between 13.00GMT and 14.00GMT as a result of some cloud formation during that period. Incidentally C led D in production from 08.00GMT only to be overtaken at 12.00GMT by D. 'D' then led C till 16.36GMT when C took over from D. Production in D fell sharply from 15.30GMT to 19.00GMT while the fall in C was gradual till 19.00GMT. The rest of the day was characterised by a very gradual fall in production in both stills, coming to a stop just after 00.00GMT. On that day, D produced more than C by 0.9 percent.

On the 15th of May, D was covered throughout the night while C was not. The production curve for the two stills the following day, 16th May, is shown in figure 13. By 08.00GMT both stills had produced some quantity of distilled water, with D starting before C. Distillation was quite slow in both stills from the time of commencement of operation till 10.00GMT when both still stepped-up their production rates with D leading. They both attained their maximum yields at 13.00GMT, slowed down in the process almost at the same rate from that time to 19.00GMT, assumed a very gradual rate only to cease operation after 00.00GMT. That day, D distilled more than C by 5.4 percent, as compared to the 0.9 percent

Fig.13: Graph of hourly variation of yield in stills when D was covered overnigh

Channel 1: time/ hrsGMT

Channel 2: Ambient temp/ deg Celsius

Channel 3: basin C water temp/ deg Celsius

Channel 4: basin D water temp/ deg Celsius

Channel 5: Yield in C / L m^{-2}hr^{-1}

Channel 6: Yield in D/ L m^{-2} hr^{-1}

Data information:

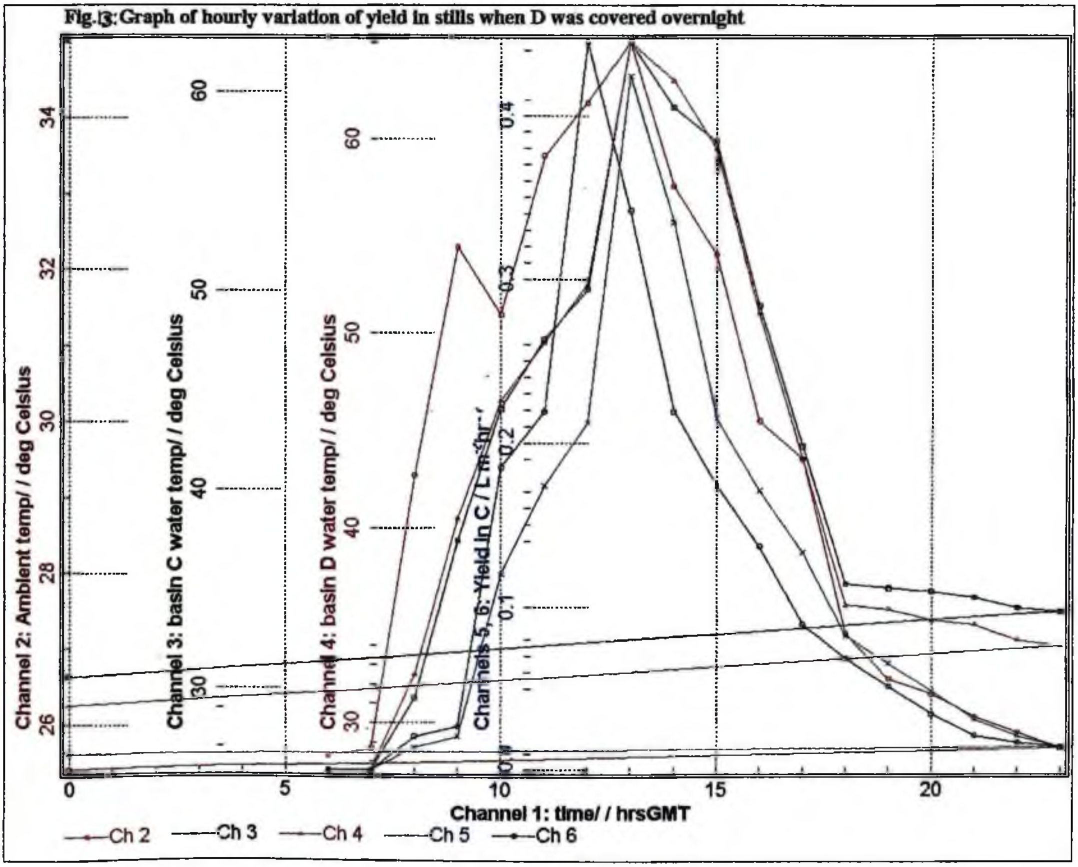


Fig.13:Graph of hourly variation of yield in stills when D was covered overnight

production when the two operated under the same conditions two days before. A net percentage increase of 4.5 is thus a result of covering D the previous night.

Figure 14 showed the relationship between the effect of covering a still as against the depth of water in the still. The gradient of each straight line, AB, BC, CD, DE and EF stands at 0.0, 2.0, 26.0, 0.8, and 9.4 respectively. A very remarkable increase in gradient in seen to exist for the path CD, revealing a remarkable increase in yield from a depth of 2.0cm upward as a result of covering the glass cover of the still the previous night before its operation.

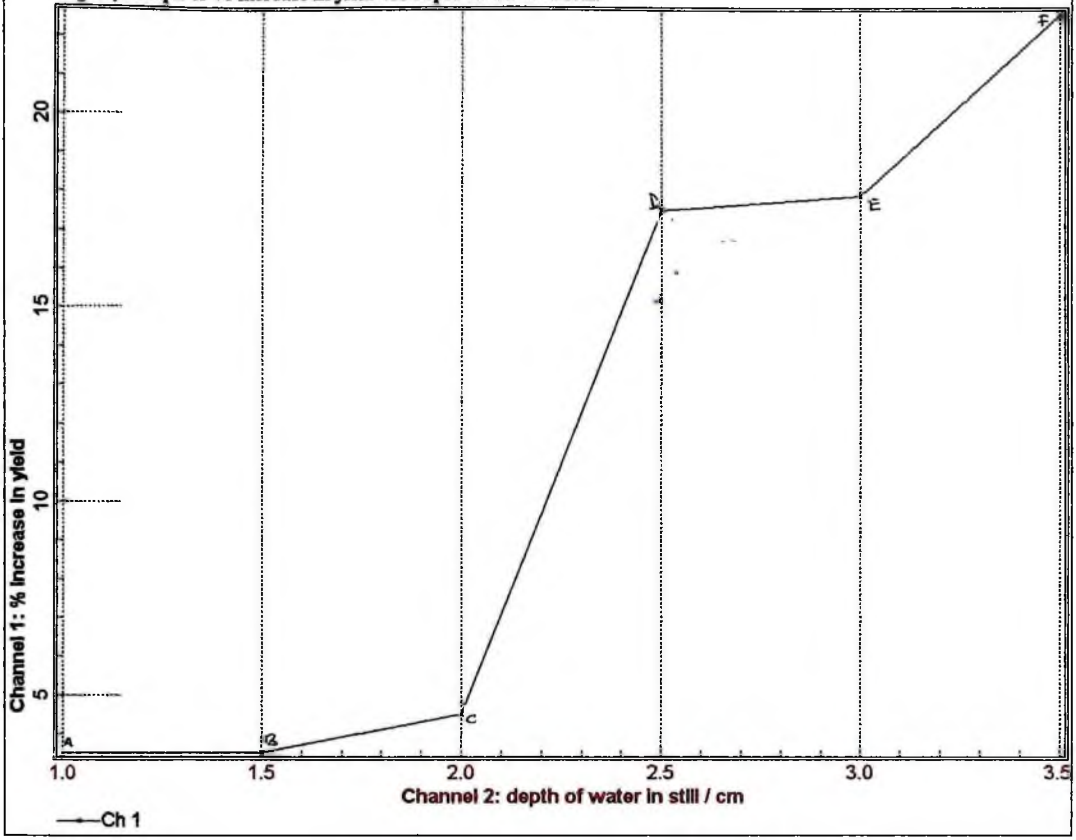
5.4.0 LAGGING MATERIALS

Table 15 depicted a typical case of the variation in yield in the stills with different lagging materials. The lagging materials for A, B, C and D were respectively coconut fibre, sawdust, spent cotton and urethane foam. In all cases B proved the best, hence using it as a standard, 'A' followed with an average yield of 85.8%. Next was D, with an average yield of 67.2% and last came C with an average yield of 62.2%.

5.5.0 PURITY ANALYSIS

Table 16 shows the purity analysis of the distillate. Columns 1 and 2 show the pH and electrical conductivity values of the

Fig .14:Graph of % increase in yield vrs depth of water in still.



various water samples.

Electrical conductivity depends on the ionic strength of the water. It is related to the nature of the various dissolved substances, their actual and relative concentrations, and the temperature at which the measurement is made.

Solutions of most inorganic salts, acids and bases are good conductors. Conversely, the dissolution of most organic compounds is very small in comparison with that of inorganic ones, or they do not dissociate and they therefore conduct an electrical current very poorly, if at all.

The determination of electrical conductivity provides a rapid and convenient means of estimating the concentration of electrolytes. One application of electrical conductivity is the purity of distilled or deionized water.

From the table the electrical conductivity of sea water is as high as 57.0×10^3 µs/cm at 25°C. This value is reduced to 3.3 µs/cm after distillation. The implication of these values revealed the effectiveness of the solar stills. The raw sea water remaining in the basin was found to be highly concentrated with an electrical conductivity of 80.0×10^3µs at 25°C. This system could serve two purposes when fed with saline water. First a distillate is collected, and the remaining water in the basin could be emptied into an open container and left out in the sun to evaporate further so that common salt (NaCl) could be collected. This would however need further purification due to the presence of other unwanted components of sea water.

The value of 53.7 µs/cm for tap water at 25ºC was also brought down to 3.11 µs/cm at that same temperature after distillation using the equipment. Unlike sea water, which contains a wide range of chemical elements, in the case of tap water the main element, as was tested for was chloride ions, which was added to the water to kill bacteria.

The salty taste of sea water is attributed to the presence of an appreciable amount of sodium chloride which dissociates into Na^+ and Cl^-. Tap water lacks a similar salty taste due to the low concentrations of Na^+ and Cl^-.

The electrical conductivity of water in the pond in front of Balme Library was found to be 178µs/cm at 25ºC but showed 3.20µs/cm at that temperature when distilled using the solar still. Once again the equipment can be said to be effective not only for tap water and sea water but also for water from ponds. In the case of the latter, a thick colloidal solution was left in the basin after the distillation process. This called for adding a large quantity of fresh water into the basin to flush out the muddy water which could reduce the efficiency of the still by preventing the direct solar rays from reaching the basin for onward conversion into infrared radiation.

5.5.1 pH VALUES

Every aqueous solution contains both hydrogen ions (H^+) and hydroxyl ions (OH^-). The concentrations of these ions are normally expressed in powers of 10. In every aqueous solution the concentration of these ions are so small that the said powers are always negative. The pH of a solution is the negative logarithm to base 10 of the concentration of the hydrogen ions. Hence the pH is one simple and convenient way of expressing the hydrogen ion concentration and hence the acidic or basic nature of a solution. Its values range from 0 to 14, with 7 as the value for a neutral solution, while values between 0 and 7 are acidic, and those between 7 and 14 are basic.

From table 16 raw sea water has a pH of 7.92 showing the extent to which it is basic. After distillation, the distillate showed a pH of 5.68, hence slightly acidic. Raw tap water indicated a pH value of 6.87, demonstrating the presence of more hydrogen ions than hydroxyl ions, and hence slightly acidic. Its distillate showed a further acidic property. The pond water behaved similar to sea water. In its raw form, its pH stood at 8.86, while its distillate depicted a value of 5.67. Hence in its raw form it is basic but acidic when distilled.

From the pH values indicated in the table, it has come to light that solutions become acidic when distilled, or putting it another way, upon distillation of a solution, more hydrogen ions get evaporated out and condense later than hydroxyl ions.

5.5.2. OXYGEN CONTENT

Most laboratory experiments involve oxidation reactions. If oxidizable matter is present in the distilled water used for preparing the solutions, this can affect the results to a large extent. Hence there is the need to know the extent to which the matter is present in the distilled water so as to be in a position to tell whether or not the distillate could be used for laboratory work.

From table 16, sea water has the highest oxygen content (a representation of oxidizable matter) of 6.1097 mg/l, followed by pond water with 6.0096 mg/l and lastly tap water with 5.99 mg/l. After distillation the values reduced to 0.4006 mg/l for all the three water specimens at 27°C.

5.5.3 RESIDUE CONTENT

Residue is the amount of matter left in a dish after evaporation of a sample of water and its subsequent drying in an oven at a definite temperature. In the case of distillation the residue content determines the effectiveness of the equipment employed in the process. The pond water depicted the highest residue content of 744 mg/l, followed by sea water with 508 mg/l while tap water indicated only 60 mg/l. Upon distillation, all samples showed the absence of residue, implying a high degree of residue elimination by the solar stills.

5.5.4 SILICA CONTENT

Silica is one of the commonest chemical compounds present in natural water. It is likely that most of the dissolved silica in water originate from the chemical breakdown of silicates (another chemical compound mostly found in the earth's crust) in the processes of metamorphism or weathering [9]. It is quite reactive and would stick to most surfaces such as metals and glass surfaces. In taps and boilers, silica can build up as scale and eventually cause a blockage which could lead to an explosion in pipelines and lower efficiency in boilers. The formation of scales in laboratory equipment is undesirable. The silica itself, reactive as it is, interferes in chemical reactions, hence undesirable in distilled water.

The silica content of each of the samples is shown in table 16, raw tap water has a value of 0.081 mg/l, raw pond water has 0.102 mg/l and sea water has the highest of 0.167 mg/l. After distillation the values for tap water, pond water and sea water came down to 0.030, 0.057 and 0.057 mg/l respectively as against 0.029 mg/l for laboratory distilled water.

CHAPTER SIX

CONCLUSIONS

6.1 THE THRESHOLD DEPTH

This research has brought to light the depth to which a still could be stocked with water without lowering its efficiency. This depth is what is referred to as the threshold depth which is 3.0cm. Observations from this study indicate that on very sunny days, a depth of 0.5cm of water evaporated from the basin. Hence 1.0 to 3.0cm is a recommended depth range in the basin of solar stills.

6.2 THE EFFECT OF COVERING THE STILL AT NIGHT

Another measure taken to increase production in solar stills has been the provision of a lagging material over the glazing cover at night before putting them into operation the following day. Results from this research have shown that there is an increase in yield in the stills at all depths of water in the basin, but more so when the depth exceeds 2.0cm. It can therefore be concluded that this measure is very necessary for higher production in the deep basin-type solar stills. The materials used for the covering are cheap and durable: just sawdust and a piece of polythene which costed only fifty cedis; hence the high cost-effectiveness of the measure.

6.3 LAGGING MATERIALS

Heat losses need to be minimized in solar stills, so as to improve upon the output of the equipment. Lagging the basin with a suitable material has been a major approach to the problem. Urethane foam has been the material for this purpose. This research has revealed that sawdust does the job best.

6.4 PURITY OF DISTILLATE

Purity analysis of water is quite extensive and very expensive. The source of the water and what it is to be used for, determines the parameters that would have to be investigated. The expectation of this work is that the distillate would meet the distilled water needs in school laboratories, hence the analysis was focussed on conductivity, pH, residue, sodium, silica and chloride contents. Using distilled water from the laboratory as a reference sample, values for these parameters of distillate from the solar stills came close to those of the reference sample as shown in table 16, hence the suitability of distillate from the stills for laboratory work.

6.5 PROBLEM(S) ENCOUNTERED

One shortcoming of this study is the absence of the calculated value of efficiencies of the stills. This is so because of the non-availability of a pyranometer to measure the daily solar radiation during the period of experimentation. The nearest meteorological station, when contacted, was of no help either. The availability of the average solar radiation for each day would have made possible the determination of efficiencies of the stills using equation 2.1.

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LIST OF SYMBOLS

A_i = insulation area
A_s = basin area
ϵ_g = glass emissivity
ϵ_s = basin emissivity
h'_c = modified convection coefficient
h_{fg} = enthalpy of evaporation
h_∞ = ambient convection coefficient
I_o = solar flux
K_i = insulation conductivity
$\dot{m}$ = rate of condensate production
P_{ws} = basin water saturation pressure
$P_s(T)$ = saturation pressure at temperature T
P_{wg} = condensate saturation pressure
$\dot{Q}''c_1$ = energy loss due to convection to inner cover surface of still
$\dot{Q}c_2$ = energy loss due to convection at the outer cover surface of still
$\dot{Q}''e_1$ = energy loss due to evaporation to the inner cover surface of still
$\dot{Q}r_1$ = energy loss due to radiation to the inner cover surface of still
$\dot{Q}r_2$ = energy loss due to radiation at the outer cover surface of still
t_{ss} = time at sunset
t_{sr} = time of sunrise
T_s = basin temperature
T_∞ = ambient temperature
T_{c1} = temperature of inner cover surface of still
T_{c2} = temperature of outer cover surface of still
T_{sky} = apparent sky temperature
τ_g = glass transmissivity

α_s = basin absorptivity

σ = Stefan–Boltzmann constant

η_i = internal efficiency of still

η_o =overall efficiency of still