G42
W02292

IRRIGATION WATER PUMPING TECHNOLOGIES

A BRIEF OVERVIEW

Pg-8

9-17

P30

48-58

61-69

Missing

August 1982

BEST AVAILABLE COPY

Irrigation Water Pumping Technologies

The following material describes a range of technologies for the pumping of water for irrigation. The technologies have been classified into three general categories: human powered, animal powered, and other energy source driven pumps, such as solar or wind. This material is by no means intended to be a comprehensive study of all such technologies but hopefully what is presented here will enable the reader to assess the feasibility of the various types of pumps for a particular situation. A comparison of the technologies is provided in Table I.

Human powered pumps are, in general, the simplest to fabricate. Many of the designs presented here can be manufactured using materials found in most locations. The simple construction, however, results in a relatively short lifetime for this class of water lifter. The pumping capacity is limited by the low level of power input and, as a result, such pumps must be operated in shifts. By utilizing leg power, however, a somewhat more substantial amount of power can be generated by a human being. A few of the technologies described do lend themselves to the use of leg power and thus can maximize human production of power. Reference 5 briefly discusses this principle.

The other major drawback of these water lifing devices, in particular the force pumps, is that many require that the pump be located directly overhead of the water source. In many circumstances this is not practical.

The only animal-powered technology presented here is the Persian wheel. It can be constructed from locally available materials and has a fairly long lifetime. However, it also must be in part located directly overhead of the water source.

A few of the human powered pumps can, with a little ingenuity, be modified to utilize animal power.

The pumps powered by other sources of energy, namely solar, wind, and biogas, consist of a separate pumping unit connected to a power generating device. The pumping units are fairly sophisticated and cannot be manufactured in most locations. This class of water lifting device is characterized by a long lifetime and low level of maintenance. The exception to this is the biogas digester which requires regular maintenance.

All three of these technologies require a high initial cost which may put them beyond the range of affordable by small landowners. In addition, other preliminary data is required to determine the feasibility and the particular type of system best suited for a particular location.

Outline of Material

1. Manual Pumping of Water for Small-Scale Irrigation, International Reference Center for Community Water Supply and Sanitation

Contents:

- a brief description of handpump technology and various types of handpumps for small scale irrigation.

- pump designs included are:

  a) suction pump (general)
  b) lift pump (general)
  c) rower pump
  d) linked reciprocating piston pump
  e) pendulum pump
  f) diaphragm pump
  g) bellow pump
  h) chain pump
  i) bucket pump
  j) semi-rotary pump

2. Diaphragm Pump, Roegel, RG. Technical Bulletin No. 51016-BK VITA Publication Service, 3706 Rhode Island Avenue, Mt. Ranier, MD 20822

Contents:

- a detailed description of the construction of a diaphragm pump from locally available materials and some words on its applications.

3. Small Scale Irrigation, Stern, P. Intermediate Technology Publications Ltd., International Irrigation Information Center, London, 1979, pp. 115-125.

Contents:

- description of manual water lifting principles

- pump designs included are:

  a) beam and bucket
  b) Archimedean screw
  c) simple hand pump
  d) chain and bucket pump
  e) Persian wheel (animal driven)
  f) water wheel

4. Village Technology Handbook, VITA Publication Service (see reference 2 above), pp. 92-96.

Contents:

- specifications of construction of a chain pump for irrigation

5. Energy for Rural Development - Supplement, Advisory Committee on Technology Innovation, Board on Science and Technology for International Development, Commission on International Relations, National Research Council, Washington, 1981, pp. 12-14, 133, 138-141.

Contents:

- description of solar powered irrigation system in Mali
- fundamentals of pedal power and applications to pumping

6. A Hand Pump for Rural Areas of Developing Countries, PU Report No. RES9, International Bank for Reconstruction and Development, International Development Assn.; Energy, Water and Telecommunications Dept., October 1976, Annex I, pp. 1-7.

Contents:

- description of pendulum pump with information on cost

7. Water Pumping in Developing Countries, prepared by: Systems Consultants Inc., 2828 Pennsylvania Ave., Suite 300, Washington, DC.; for: Solar Energy Research Institute, International Division, 1617 Cole Blvd., Golden, Colorado, October 1980, pp. 9-60, 70-78.

Contents:

- power requirements for pumping
- description of technologies for pumping including:

  a) diesel-powered pumps
  b) human, animal powered pumps
  c) solar powered pumps
  d) wind powered pumps
  e) biogas powered pumps

- comparison of above technologies.

8. Photovoltaic Power in Less-Developed Countries, Smith, DV, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Mass.; prepared for: US Energy Research and Development Administration under contract no. EY-76-C-02-4094, March 1977, pp. xi-xiii, 1-9, 17-47.

Contents:

- case studies of solar powered irrigation projects in Chad, Bangladesh and India

9. Roman and Islamic Waterlifting Wheels by Thorkild Schioler, Odense University Press, Denmark, 1973, pp. 8-41.

Contents:

- description of various types of animal powered water lifting devices used in the Mediterranean world.

REFERENCE NO. 1

MANUAL PUMPING OF WATER

FOR SMALL-SCALE IRRIGATION

BEST AVAILABLE COPY

MANUAL PUMPING OF WATER

CONTENTS

1. INTRODUCTION

2. HANDPUMPS FOR SMALL-SCALE IRRIGATION

3. HANDPUMP TECHNOLOGY

3.1 Hydraulics

3.2 Force Requirements

3.3 Energy (Work) Analysis

4. TYPES OF HANDPUMPS

(Those having potential for small-scale irrigation)

4.1 Reciprocating Pumps

(Handle-lever Pump; Rower Pump; Linked-drive Pump; Diaphragm Pump; Bellow Pump)

4.2 Rotary (positive displacement) Pumps

(Chain Pump; Bucket Pump; Semi-Rotary Pump; Helical Rotor Pump).

5. NON-TECHNICAL ASPECTS

5.1 General

5.2 Organisation

5.3 Maintenance

REFERENCES

1 INTRODUCTION

Water pumping technology has developed in parallel with the sources of power available, and it provides a rich spectrum of techniques and devices.

For small communities, particularly in rural areas, the most readily available source of power often is human and animal power. Under suitable conditons, wind power is of relevance and solar power can have potential. Diesel engines and electric motors are only to be used, if the necessary fuel or electricity supplies are available and secured, together with adequate maintenance and spare parts.

A manual pumping device (thereafter referred to as a "handpump"*) is any simple pumping equipment operated with human power. Where the conditions are suitable, man-powered handpumps may be a valid proposition for small-scale irrigation. Farmers and their families are sometimes the only source of power available. Manual pumping of water for irrigation need not be so ineffective as might appear at first sight. Relatively small amounts of water pumped over a few weeks can save a crop or double the yield of a small farmers' land. In Bangladesh, for instance, handpumps ('MOSTI' - pumps) are widely used for irrigating land to achieve an extra crop.

Using human power for pumping water has features that are important for small farmers irrigating their land:

- The power requirements can be met by the farmers and their families whether in a rural village or farm settlement. The use of a renewable energy resource like human power is very advantageous in view of the sharp rise of fuel costs and the limitations and costs of electric power supplies in rural areas. In these areas, labour typically is in surplus;

---

* This includes devices operated by foot. The term 'handpump' is used because they are the most common human-powered pumping device.

- The capital and operating costs of handpumps are generally low;
- When a group of families or an individual farmer own and operate their own handpump, they are independent of remote authorities, administrative delay, fuel delivery problems, and the common problems associated with large irrigation schemes generally.

Traditional water lifting devices for irrigation purposes usually take water from rivers, streams, canals or other surface water sources. However, in the dry season these sources may run dry for prolonged periods of time.

Handpumps can be used to draw water from open wells or tubewells, if ground water resources are sufficient and at shallow depth. The utilisation of ground water in many instances has great advantages. Withdrawal of water from underground water-bearing strata, can usually continue long after drought conditions have depleted surface water sources.

Deep tubewells have little application for small-scale irrigation purposes. Such tubewells can sometimes provide large quantities of water (2 cubic feet/second or more; sufficient to irrigate 30 - 40 acres of land) but this requires high-capacity pumps, e.g. vertical turbine pumps driven by diesel engines or electric motors. Such high-capacity wells must be shared by a number of farmers, and the common problems of the use of motorized deepwell pumps for irrigation are:

- They are capital intensive;
- Schemes take a long time to organize. Social and political problems are encountered in siting the wells;
- Maintenance and fuel supply are difficult to arrange.

By their simplicity, handpumps will be most attractive to the small farmers who do not currently have access to a reliable means of irrigation. The acceptance and use of handpumps by small farmers depends on many factors, including demonstration of successful use, and the initial costs.

Obviously, the small farmers would prefer to have a motor-powered pump to do the work for them, but until such pumps can be afforded, the people can ensure their land's yield and increase their wealth by hard labour.

One interesting feature of handpump irrigation is that the whole family shares the burden of labour. Men, children and women, take a turn at pumping.

Under the pressure of rising food costs and severe unemployment, it is important to bring out the potential of manual pumping for irrigation purposes. Ingenious mechanical design, coupled with the use of new materials where appropriate, should result in suitable pumping units.

Whilst the technology of manual pumping is important, the successful design and use of these devices depends to a large extent on non-technical factors. The involvement of the users in maintaining their pumping units, and the possibilities of manufacturing the pumps locally are examples. The implications of community water supply and small-scale irrigation in connection with overall irrigation development are of great importance. In fact, they combine and are both essential elements in the overall process of improving the quality of life of the vast rural populations.

2. HANDPUMPS FOR SMALL-SCALE IRRIGATION

There are numerous water lifting devices which can be used for small-scale irrigation. The Archimedes screw; rope and bucket devices such as the mohte, charsa, ramioko, daly, delu, and mota; counterpoise lifts known variously as the shadouf, shaduf, shadoof, chadouf, khetara, kerkaz, kheeraz, guenina, cigonal, bascule, dhenkali, dhenkli, dhingli, picottah, lat, picotas, guimbalete, swape, sweep, et al.; the hinged channel or gutter, doon, baldeo balti, and jantu; paddle wheels; water ladders; and the various chain pumps and wheel pumps.

These are widely used for low-lift irrigation pumping. Many are animal powered. In this chapter only handpumps are considered.

The use of handpumps for small-scale irrigation purposes in fact represents a recent development of traditional irrigation techniques.

The handpumps used are similar to those used in community water supplies, with such adaptations as appropriate.* For instance, in Bangladesh the MOSTI (manually-operated shallow tubewell and pump for irrigation) was evolved on the basis of the New No. 6 pump used by the Department of Public Health Engineering and UNICEF in drinking water supplies. The MOSTI is a standard package consisting of the pump, two 20 foot (6 metres) sections of 1½-inch (40 mm) galvanized steel pipe, and a brass wrapped steel screen 6 feet long. It can be used where the ground water table is not more than 6-7 metres below ground level. This is the case for a large part of Bangladesh. The output of about 30 litres/minute is suitable for irrigating small plots of about 0.25 hectare. Such small fragmented land holdings are common in Bangladesh.

Through irrigation in the dry season, an extra crop can be achieved. The value of the crop depends on market conditions, but should easily gross two times or more the total cost of the MOSTI pump package. It is therefore not surprising that numerous small farmers have spontaneously adopted this method of small-scale irrigation using handpumps. The rapid extension of the use of the MOSTI has been spectacular.**

Manual pumping of water for irrigation purposes can only be effective if there is a balance between the amount of energy expended and the amount of water required for growing the selected crop. For some crops, particularly rice, the water requirements are substantial.

---

* e.g. wooden attachments are sometimes fitted to enable operation by foot. Similarly, a wooden cart-wheel mechanism has been used to increase the pumping speed, and thus the discharge capacity of the pump.

** In 1972, there were 2000 MOSTI's in Bangladesh. By mid-1976 the number had increased to 40 000, and by the end of 1979 to 60 000.

For manual pumping of irrigation water to be worthwhile any wastage of energy must be minimal. If much energy is spent in overcoming friction, or lost altogether when lifted water is allowed to slip back down the well, then such pumping of water is clearly unsatisfactory. It is in this respect that most of the currently available handpumps are unsuitable. They were designed primarily for drinking water supplies, and conservation of the human energy input never was an important consideration.

However, when properly designed, man-powered handpumps can be suitable for small-scale irrigation. They are usually cheap to make, and are small and easily transported. Moreover, in many parts of the world, farmers and their families are the only source of power readily available.

For large-scale irrigation the quantities of water required will rule out manual pumping. Other sources of power will have to be used.

3. TECHNOLOGY OF HANDPUMPS FOR IRRIGATION PURPOSES

3.1 GENERAL

The power available from the human muscle depends on the individual, the environment, and the duration of the task. The power available for work of long duration, for example 8 hours per day, by a healthy man if often estimated at 60 to 75 watts (0.08 to 0.10 horsepower). This value must be reduced for women, children and the aged. It also must be reduced for high temperature, or work environments with high humidity. Where the pump user and the pump are poorly matched - for example, pumping from a stooped position - much of the power input is wasted.

To maximize mechanical advantage and conservation of energy expended in pumping a simply supported pendulum or similar device is advantageous. Fly wheel and bicycle-pedal type of drive can also serve for these purposes. The most effective use of manpower for pumping work of long duration (several hours per day) is through the legs, not

through the arms. Leg muscles are stronger than the muscles in the upper part of the body. A healthy man should be able to develop comfortably about 75 watts (0.10 Horsepower) over long periods, by pedalling. Many low-lift pumping devices employed for small-scale irrigation, use leg power.

When used for irrigation, handpumps are operated very intensively. At 20 strokes (or cycles) per minute, and operated for 10 hours/day, they will do 12,000 cycles/day. For a 100 days irrigation season that means 1.2 million cycles! Very few handpumps will readily stand up to such heavy usage. If the quality of manufacture is poor, rapid wear of the pump is to be expected.

However, in principle, if the smoothness of the cylinder wall, the finish of the plunger cups, the quality of the linkages of pump rod to handle and pump rod to plunger assembly, would be of the same high standard as in a motorcar engine, then a handpump could last for more than 100 years.

Although many manual pumping devices exist, the first type to be considered for small-scale irrigation would be the reciprocating plunger pump.
This type of pump has an ancient history. A study of literature reveals that a certain Ctesibius invented, around 275 B.C., a reciprocating pump. In 17th-century England, reciprocating pumps made of wood or lead and with the plunger packed with leather were in common use. It was not until about the middle of the 19th century that improved means of transport made it economical to manufacture cast iron, and machined metal handpumps for distribution over a wide area.

In the late 19th and early 20th centuries, a very large number of different handpump models were produced. About 3000 manufacturers produced handpumps in the U.S. alone. They were primarily used on farms by single families and their livestock. Later, windmills were increasingly used to drive the pumps.

All these pumps were designed on the basis of the same operating principles, and they differed little from the traditional models. In the period since Ctesibius (some 2250 years) little effort was given to improve the manually operated reciprocating pump. In the industrial countries, interest in this type of pump dwindled when they were less and less used. Over the last ten years however, it has been recognized that manual pumping units have an important role to play in providing adequate supplies of water for domestic use and probably also for small-scale irrigation in rural areas of developing countries.

3.2 HYDRAULICS

While this section focuses on reciprocating plunger pumps, the fundamental principles outlined also apply to other types of pumps, particularly other positive displacement types.

The theoretical discharge capacity of a reciprocating handpump is a function of the cylinder volume swept by the plunger during its upward, pumping stroke, and the number of strokes per unit of time e.g. per minute. This is illustrated in Figure. 1.

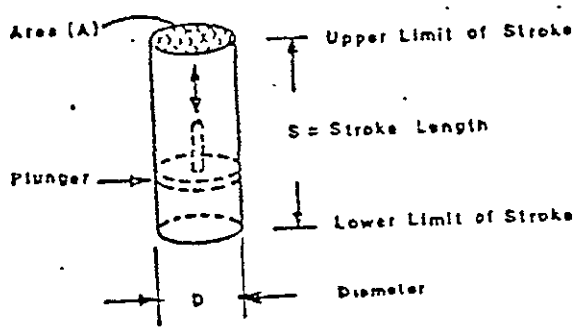
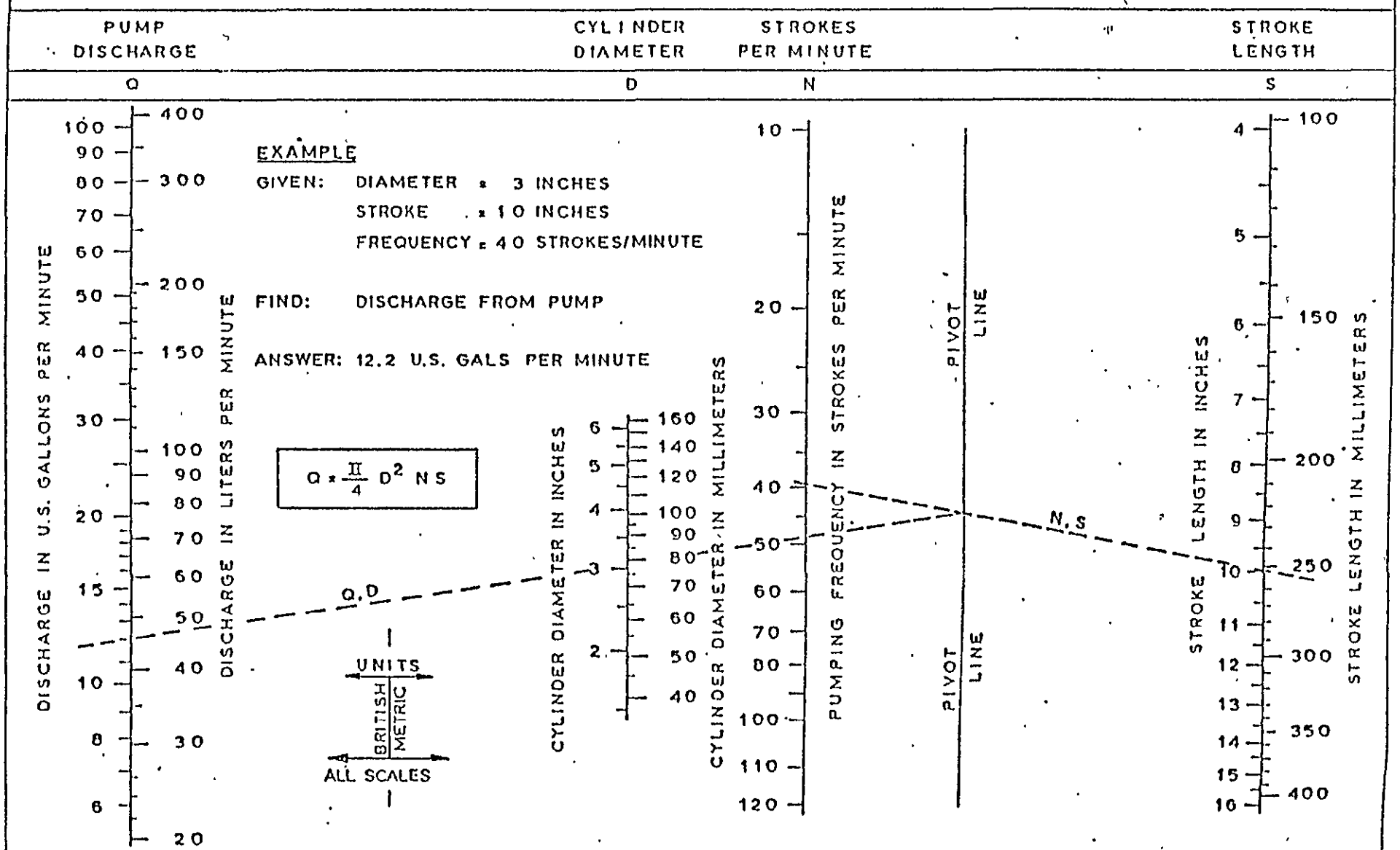


FIG. 1 SWEPT CYLINDER VOLUME

The swept cylinder volume (V) is the product of the (horizontal) cross sectional area (A) and the length of the plunger stroke (S). The cross sectional area (A) can be written in terms of the cylinder diameter (D):

$$A = \frac{\pi}{4} D^2$$

FIGURE 2. NOMOGRAPH FOR HAND PUMP DISCHARGE



EXAMPLE

GIVEN: DIAMETER = 3 INCHES
STROKE = 10 INCHES
FREQUENCY = 40 STROKES/MINUTE

FIND: DISCHARGE FROM PUMP

ANSWER: 12.2 U.S. GALS PER MINUTE

$$Q = \frac{\pi}{4} D^2 N S$$

NOTE: NOMOGRAPH BASED ON 100 PERCENT GEOMETRIC CYLINDER DISPLACEMENT FOR SINGLE ACTION, RECIPROCATING HAND PUMPS (ZERO SLIP)

The discharge capacity (Q) for a given number of pumping strokes per unit of time (N) may thus be calculated with the equation:

$$Q = \frac{\pi}{4} D^2 . S.N.$$

The actual rate of discharge normally varies slightly from the theoretical discharge due to failure of the valves to close instantly when the plunger changes direction, and to leakage between the plunger and the cylinder wall during pumping. This difference is known as slip and is defined as the difference between theoretical discharge (Q_t) and actual discharge (Q_a) as a percentage of the theoretical discharge, that is:

$$\text{Slip} = \frac{Q_t - Q_a}{Q_t} (100) \text{ percent}$$

Slip should not exceed 15 percent, preferably 5 percent, in a well designed and maintained pump. The hydraulic efficiency of a pump is (100 - Slip) percent.

Hydraulic efficiency in terms of swept cylinder volume should not be confused with mechanical efficiency which can never exceed 100 percent.

3.2 FORCE REQUIREMENTS

The force exerted on a pump rod and, through the rod to the pump handle may be as high as 50 kgf (110 lb). However, the muscular force available for continuous pumping by an individual person is generally limited to 10 - 18 kgf (20-40 lb). Through the principle of mechanical advantage, muscle power can be multiplied to successfully operate handpumps to draw water from wells up to even 180 meters (600 feet) in depth.

The principle of mechanical advantage is illustrated in Figure 3.

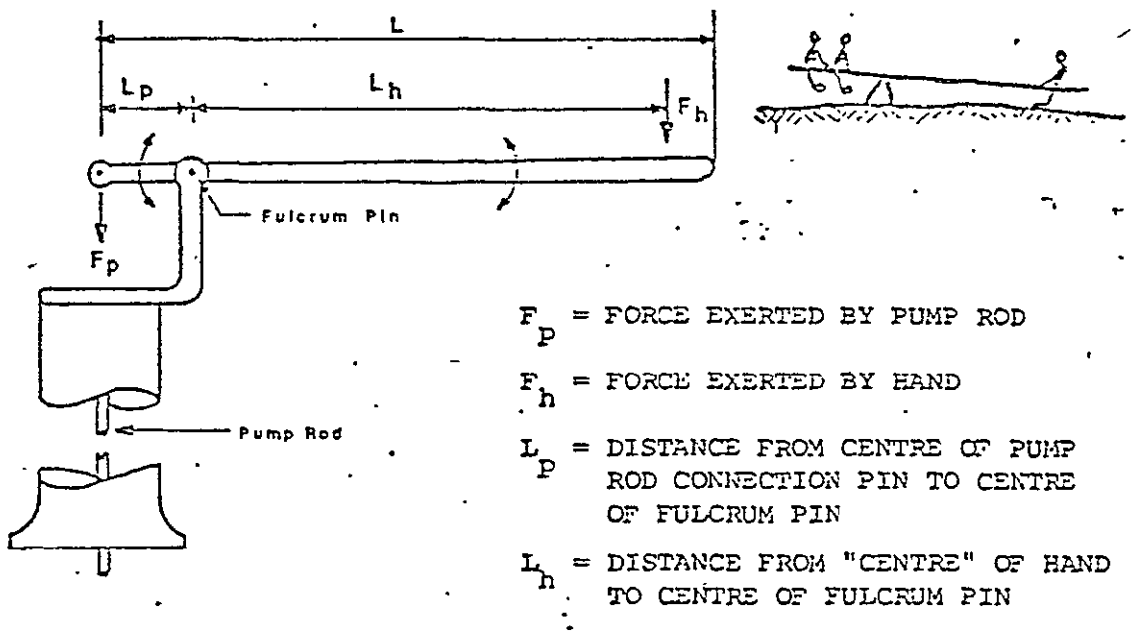


FIGURE 3 MECHANICAL ADVANTAGE OF PUMP HANDLE AS LEVER

A typical mechanical advantage for a shallow well pump is about 4 to 1. This means that the pump rod force is balanced by a handle force about one quarter of it. For deep wells a greater mechanical advantage should be chosen, even up to 10 to 1.

The mechanical advantage cannot be increased without limit. As distance L_h from the fulcrum to the hand is increased, the arc swept by the end of the handle increases. Too large an arc makes the operation of the handle difficult. Decreasing the distance from the pump rod to the fulcrum increases the mechanical advantage but it also decreases the stroke length S of the pump rod and its attached plunger.

Where the required force on the handle for operating the pump is too high, especially for handpumps operated by women and children, improvement may be obtained by extending the handle for greater mechanical advantage or reducing the pump rod force by using a smaller diameter pump cylinder.

3.3 ENERGY (WORK) ANALYSIS

Very few measured data of human energy output for work such as water pumping have been obtained under field conditions. The power available during short work periods is much greater than for long duration effort. Table 1 summarizes modified data from Krenkel (1967).

TABLE 1: MAN GENERATED POWER

Age	Man generated power by duration of effort (in watts)					
Years	5 min	10 min	15 min	30 min	60 min	180 min
20	220	210	200	180	160	90
35	210	200	180	160	135	75
60	180	160	150	130	110	60

The human power available for long duration effort is often estimated at 50 to 75 watts (0.07 to 0.10 horsepower).

The following analysis is illustrative:

- A man works a handpump lifting water for small-scale irrigation purposes at a rate of 50 watts (2200 ft lb/min), 5 hours/day (excluding rest periods). The overall (hydraulic and mechanical) efficiency of the pump is 50 percent. The water is pumped from 3 metres depth.

Energy input effective for

lifting the water: 50% of 50 watts = 25 watts (1100 ft lb/min.)

To lift 1 litres/sec. over 1 metre requires 10 watts, and over 3 metres it takes 30 watts.

Approximate rate of delivery for 25 watts effective energy Input:

$$\frac{25}{30} \times \text{litres/sec} = 0.83 \text{ litres/sec} = 50 \text{ litres/minute}$$

(13.5 gpm)

Assume for a small area of 0.5 hectare ($5.000\ m^2$) a crop irrigation water requirement of 900 mm for the season (say, 120 days), with a peak requirement of 250 mm/month.

The calculated requirement in the peak month would be:

$$\frac{250}{1000} \times 5000 = 1250\ m^3$$

At a rate of 50 litres/minute, pumping would be required for $\frac{1.250}{50} \times 10^3$ = 25.000 minutes = approximately 420 hours.

Over the 120 days season this represents less than 4 hours pumping per day.

4. TYPES OF HANDPUMPS

4.1 GENERAL

Very often the best starting point for the selection or further development of a handpump for irrigation purposes is the observation of available handpump models already in use. The next step is to choose an option which seems most appropriate. Careful evaluation of the different pump components is important, so is experience by

trial and error. More often than not, it takes field testing, redesign, retesting, etc. to develop the design so that it gradually converges around the best solution.

Based on the mechanical princples involved, handpumps for small-scale irrigation, should be subdivided in:

- Reciprocating Piston Pumps;
- Rotary Pumps (positive displacement)

4.2 RECIPROCATING PISTON PUMPS

SUCTION (Shallow Well)

In the suction pump, the plunger and its cylinder are located above the water level - usually within the pump stand itself (Fig. 4).

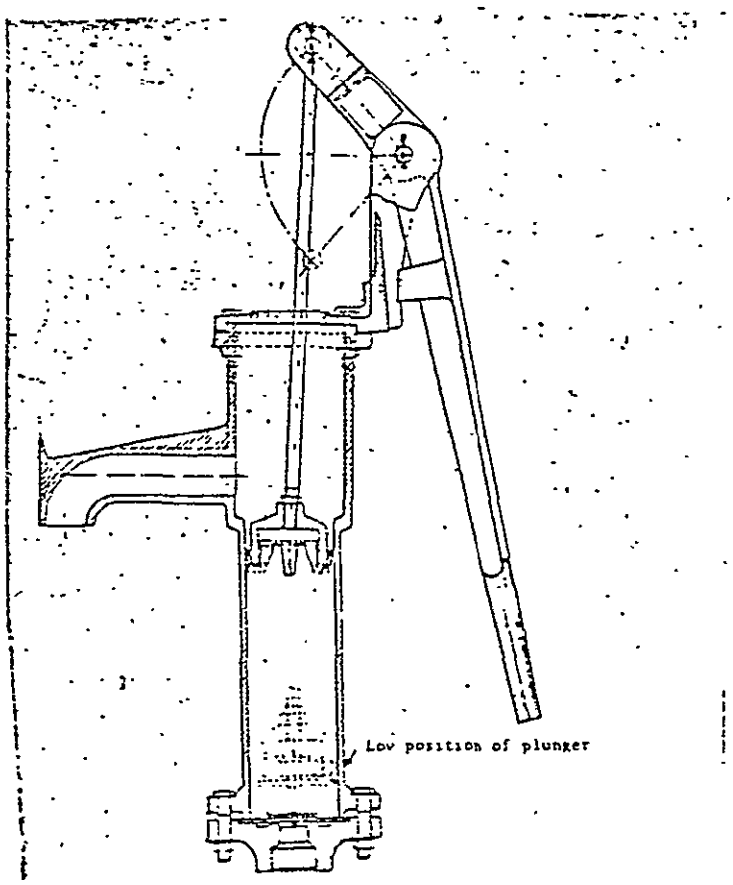


FIG. 4 TYPICAL SUCTION (SHALLOW WELL) PUMP.

The suction pump relies on atmospheric pressure to push the water upwards to the cylinder. Contrary to popular belief, this type of pump does not "lift" the water up from the source.

Rather the pump reduces the atmospheric pressure on the water in the suction pipe and the atmospheric pressure on the water outside of the suction pipe pushes the water up. Because of its reliance on atmospheric pressure, the application of a suction pump is limited to situations where the water table during pumping is within 7 metres of the suction valve. Theoretically, the atmospheric pressure would allow a suction pump to draw water from as deep as 10 metres, but in practice 7 metres is the limit.

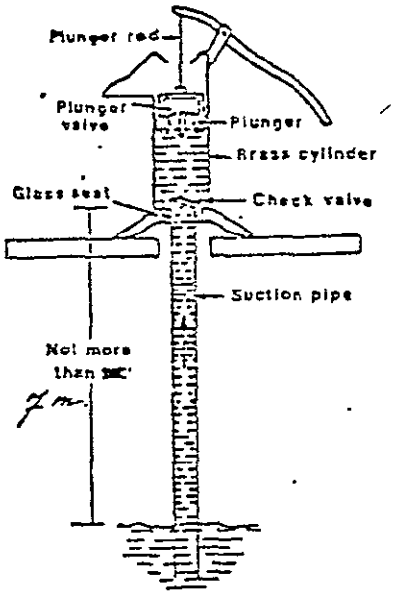


FIG. 5 DIAGRAM OF SUCTION PUMP (SCHEMATIC)

LIFT PUMPS (Deepwell)

In the deepwell pump the cylinder and plunger are located below the water level in the well. This pump can lift water from wells as deep as 180 metres. The forces created by the pumping work increase with the depth to the water table. The problems associated with reaching the cylinder set deep in the well for maintenance and repair are also much more difficult than in shallow well pumps. Thus the design and

costs of pumps for deepwell use are more critical than for suction pumps.

Hand-operated lift pumps are generally not suitable for irrigation purposes, if the water is drawn from a larger depth, as their delivery capacity is limited.

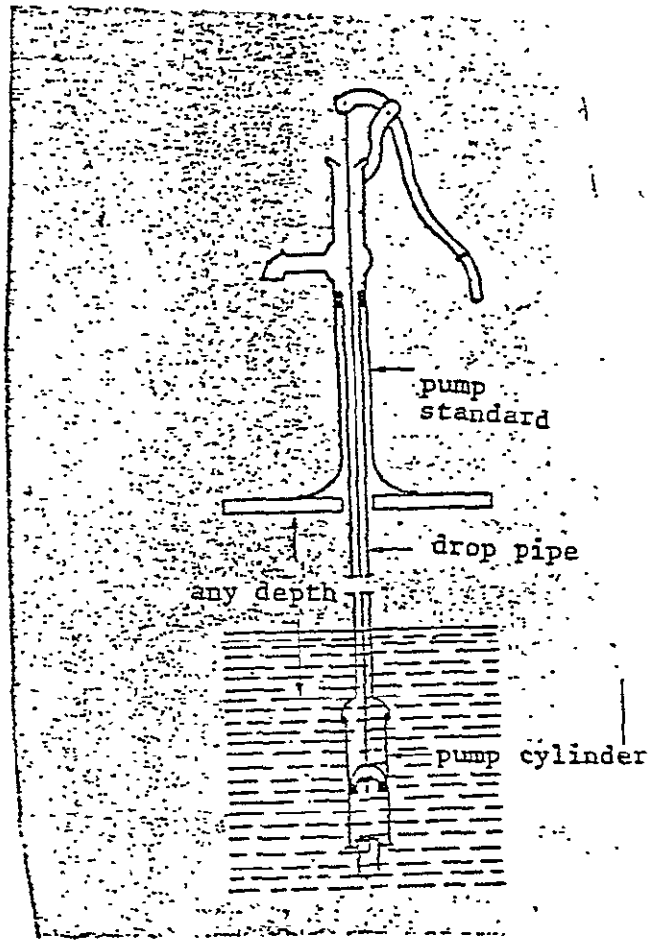
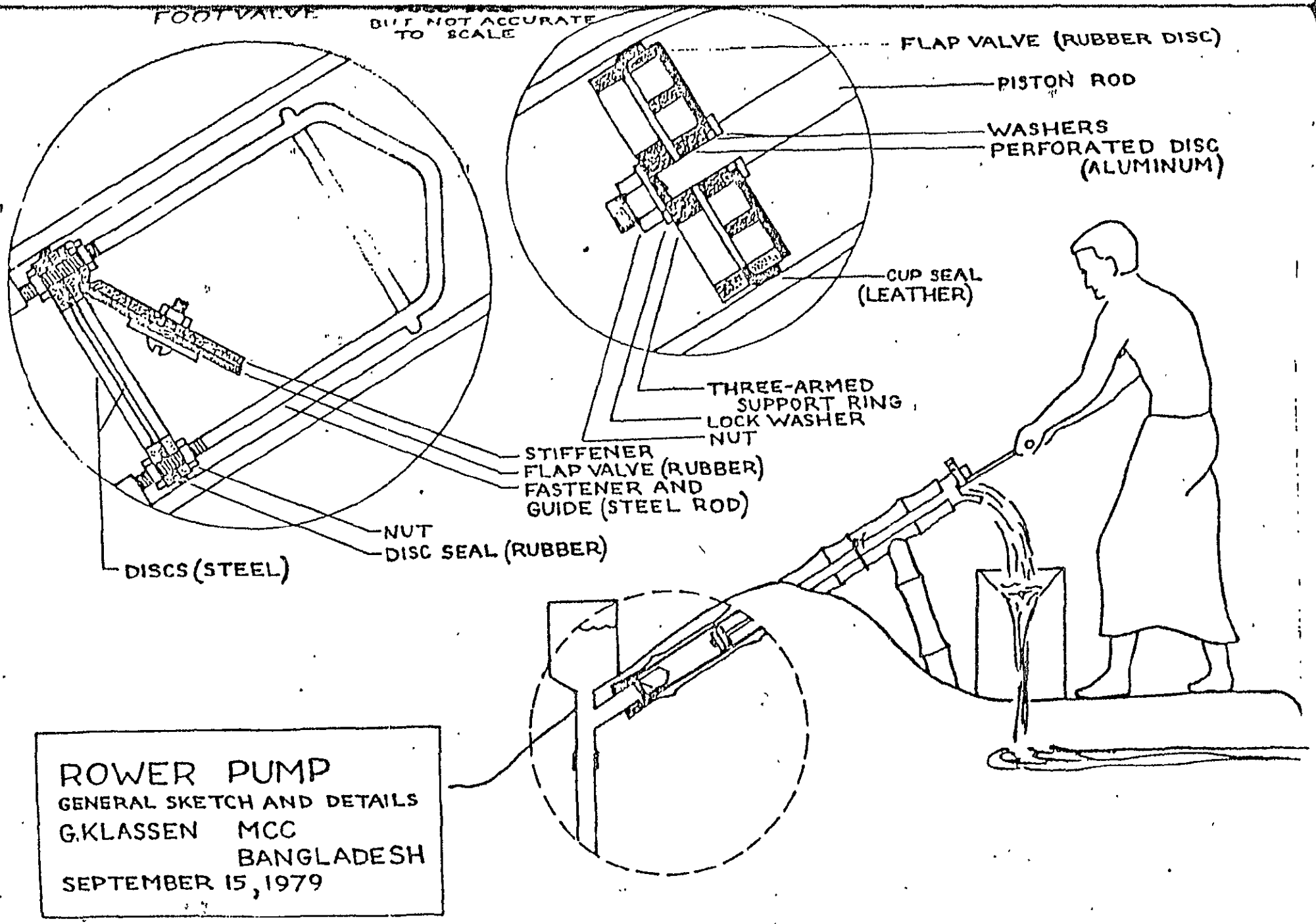


FIG. 6 DIAGRAM OF (DEEPWELL) LIFT PUMP.

ROWER PUMP

The Rower pump is a reciprocating piston pump with a PVC cylinder included at 30° from horizontal (See Fig. 7). The operator pushes and pulls directly on the 'T' - handle at the end of the piston rod. A rowing action is used, hence the name "Rower Pump".



ROWER PUMP
GENERAL SKETCH AND DETAILS
G.KLASSEN MCC
BANGLADESH
SEPTEMBER 15, 1979

The Rower pump has been designed for irrigation in Bangladesh. Other uses and conditions may require quite different pumps. However, it is felt that some of the ideas incorporated in this pump may find usefulness elsewhere, too. They are summarized as follows:

1. The inclined position of the pump eliminates levers and pins in the handle, simplifying and reducing maintenance. The direct action on the piston also allows the use of a light and cheap cylinder and support.

2. The surge chamber significantly improves human water-lifting capacity, especially at higher lifts. It has been used successfully on the conventional cast iron hand pump as well and would appear to be applicable to deep well pumps.

3. The valves are simple and effective, using flexing discs (inner tube rubber) as the moving parts. The piston and foot valve assemblies are simple to remove, repair and replace.

The pump has already been tested for durability. Three pumps have been operated on tubewells for 5 hours daily for four months without significant wear problems.

It is estimated that this pump can be produced for less than 60% of the cost of producing the New No. 6 pumps in Bangladesh.

FIG. 8 OPERATING THE ROWER PUMP (Bangladesh)

FURTHER INFORMATION TO BE
TAKEN FROM "ROWER PUMP"
DOCUMENTATION.

LINKED RECIPROCATING PISTON PUMPS

The reciprocating movement to manually operate a lift pump, can be tiring and reduces the suitability for irrigation purposes.

In Nepal, a design has been developed for a single frame which links two reciprocating pumps and enables a single operator to work the linked pumps using his feet. This is less tiring and, because two pumps are working, gives a greater and continuous flow of water (up to 60 litres per minute). Fig. 9 shows how the pumps are linked. The treadle is centrally pivoted and the suction pipes are connected by a connector pipe.

Two alternative settings are provided for the pump rod connections to the treadle. At the wide setting the pumps work quite well at low lifts but for lifts above 5 metres it is an advantage to set the pumps closer together to make pumping easier, with a reduced output. Output is satisfactory to about 7 metres but then all pipe joints must be airtight.

The frame and the working parts can be made from steel angle (or even wood) with hand tools and the construction should be within the capabilities of a village craftsman. However, as with all mechanical devices, it is the maintenance and care after installation which ultimately decides how useful this machine will be. The users should be trained in simple maintenance (which is in this case only a matter of regular lubrication of the pivots and care of the valves and washers in the pumps).

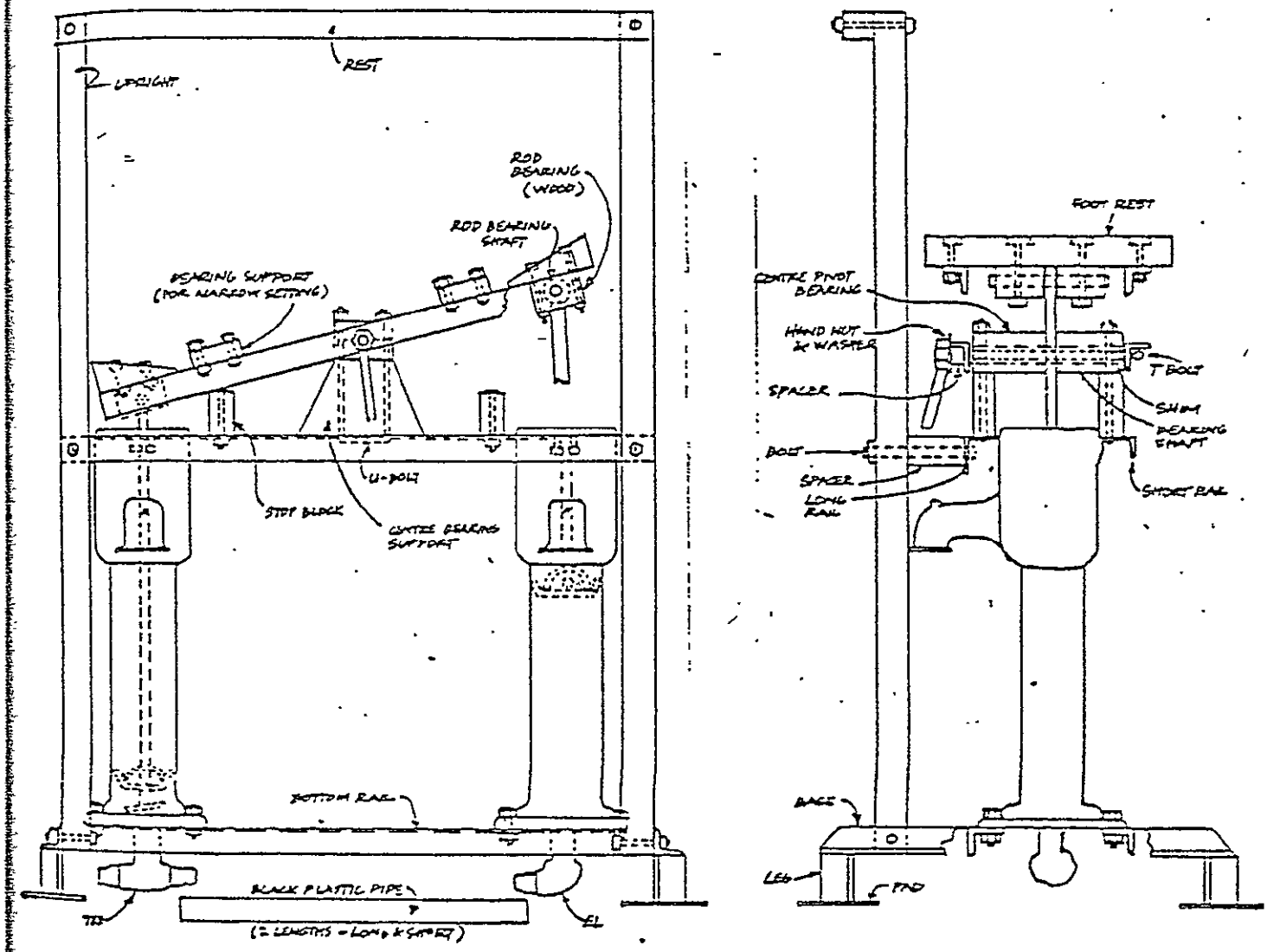
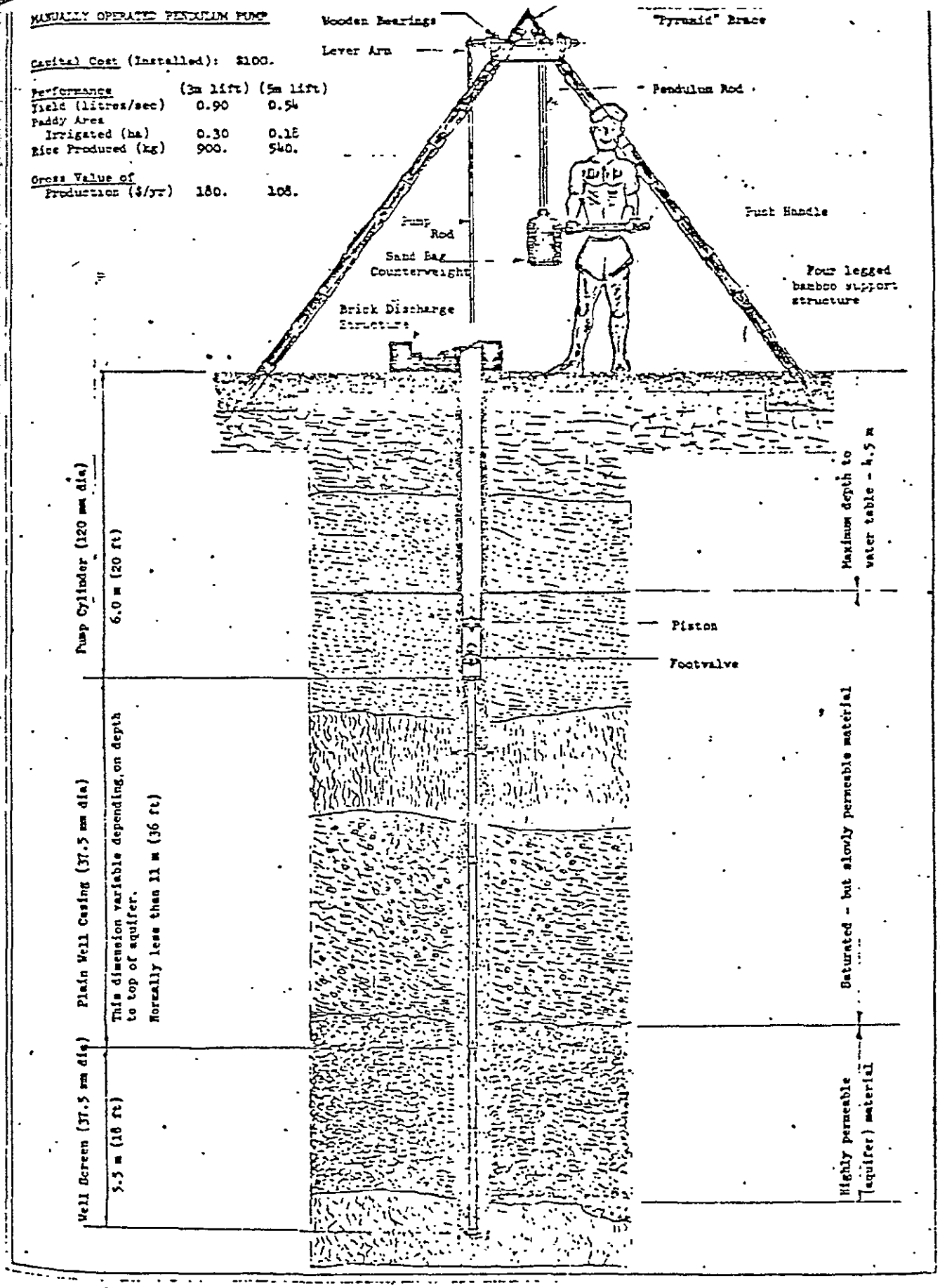


FIG. 9 LINKED RECIPROCATING PUMPS

PENDULUM PUMPS

These pumping devices have been designed for manual operation using energy at a rate which can be easily sustained up to 5 hours a day, under tropical conditions, i.e. about 50 watts (0.7 horsepower). The actual horizontal force which has to be applied to the push handle is between 7 and 10 kgf, when lifting water 3 and 5m respectively (Fig. 10). The counterweighted bailer is a similar pumping device (Fig. 11).



BEST AVAILABLE COPY

FIGURE 10: MANUALLY OPERATED PENDULUM PUMP

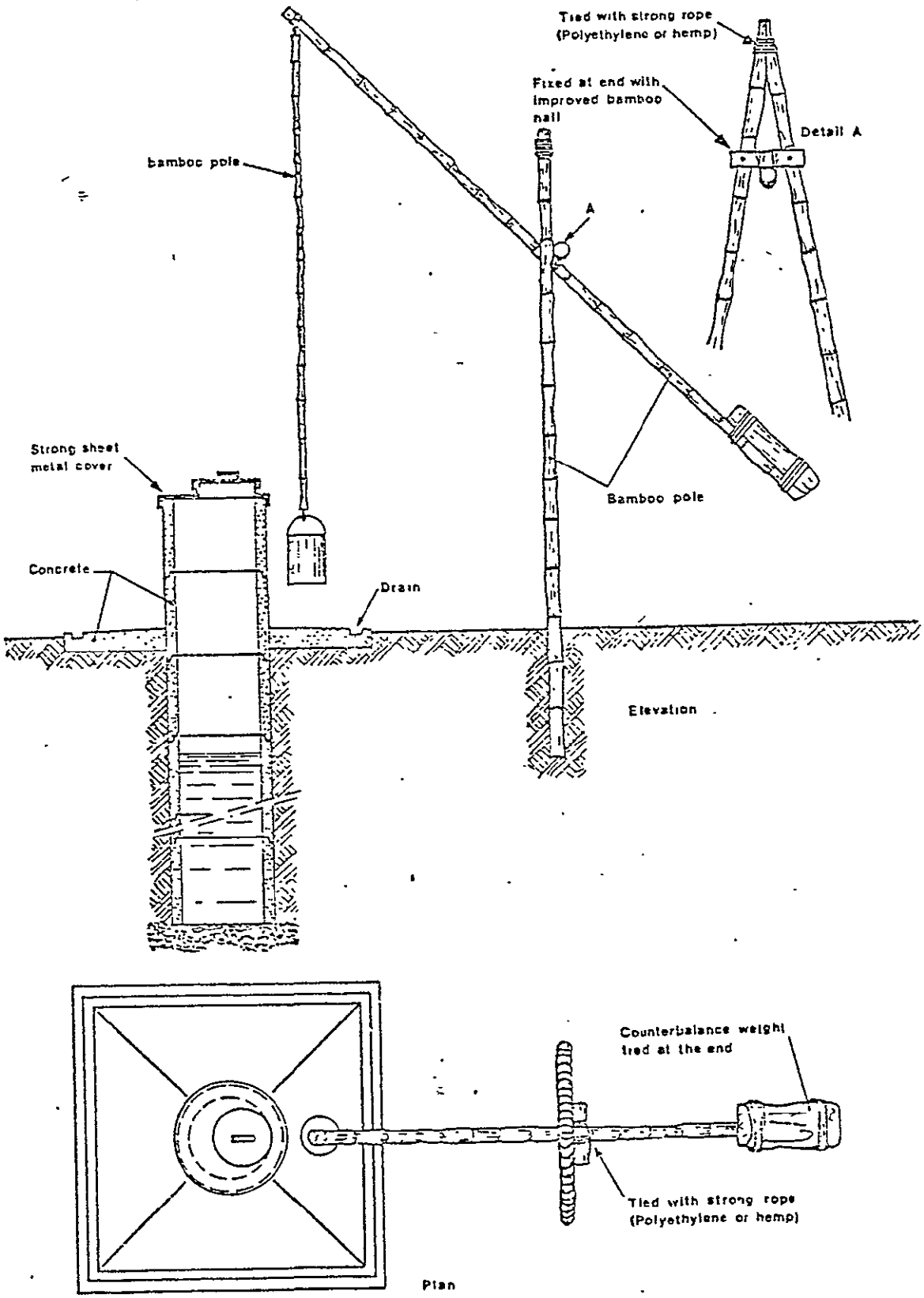


FIG. 11 COUNTERWEIGHTED BAILER USED IN THE PHILIPPINES

DIAPHRAGM PUMP

In this type of pump the reciprocating action is imparted to the water by a flexible metal or rubber diaphragm. Non-return valves are fitted at the inlet and outlet (Fig. 12).

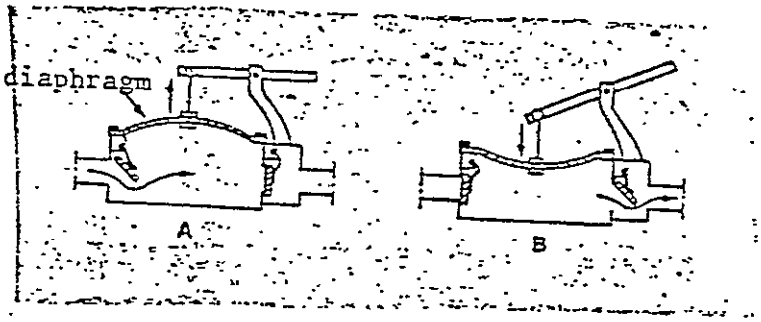


FIG. 12 DIAGRAM OF A DIAPHRAGM PUMP

When the diaphragm is lifted, water is drawn in through the inlet When the diaphragm is pushed down, the water is forced out through the outlet valve.

The diaphragm pumping principle is used in a number of novel handpump designs. These pumps are being tested and developed for use in rural water supplies. (e.g. Hydropompe Vergnet; Petro Pump).

BELLOW PUMP

This is a water lifting device using a pair of flexible bellows as the pumping element. The idea was originally evolved at the International Rice Research Institute (IRRI), Philippines, where a prototype design was developed for use in irrigation. A modified design was developed and tested at the Asian Institute of Technology, Bangkok.

The main components of the bellow pump are:

- pair of flexible bellows
- supporting frame and base plat
- discharge box
- suction lines with check valves, and
- foot rests.

See Fig. 13.

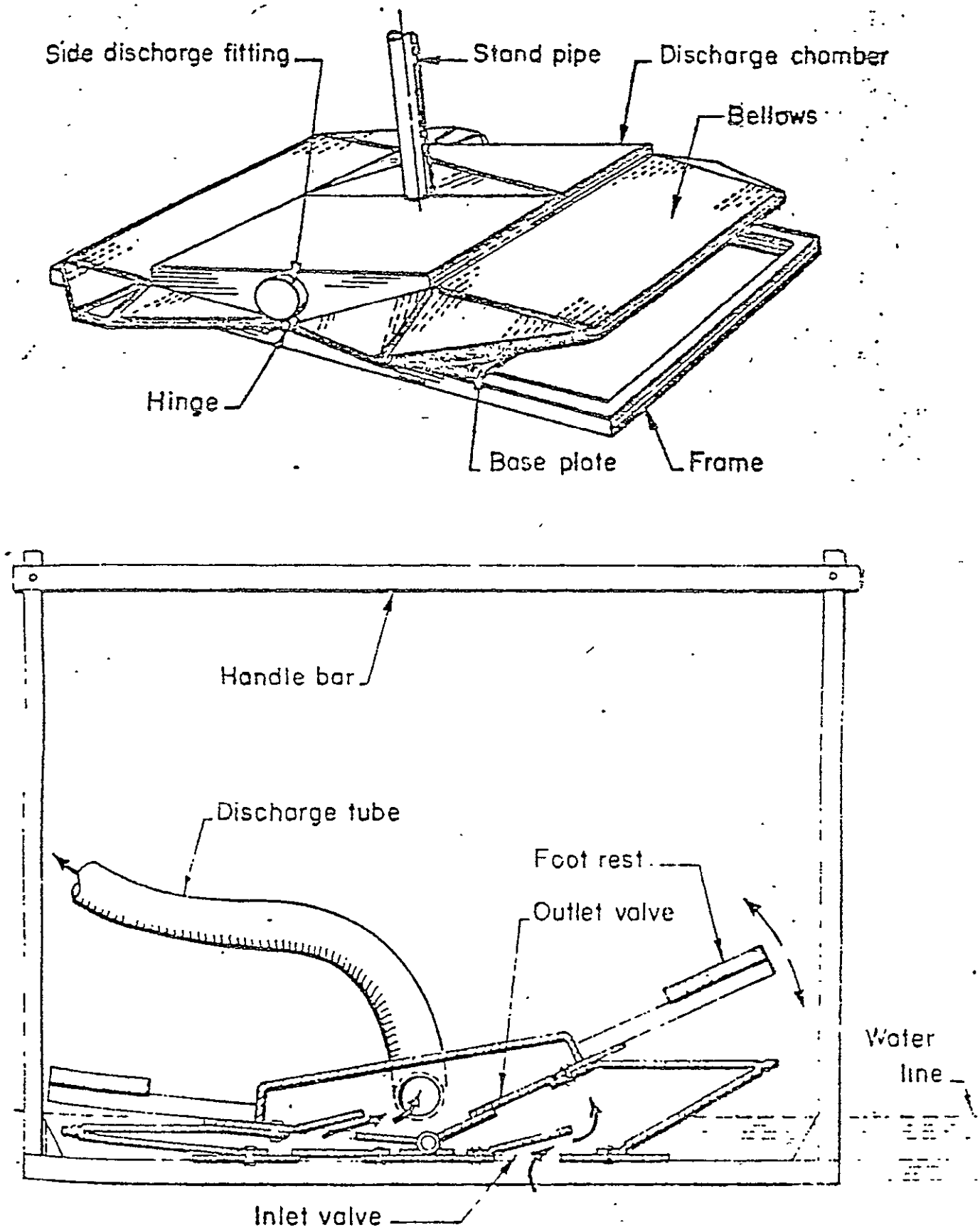


FIG. 13 BELLOW PUMP

The bellows constitute the basic pumping element; they are supported at the bottom by the base plate fixed to the wooden frame. The suction lines deliver the water to the bellows, and these discharge into the discharge box which is connected to the delivery pipe.

The bellow pump is easy to operate. The operator stands on the foot rests and merely shifts his weight from one foot to another thus expanding one bellow while compressing the other. The expanding bellow sucks in water from the source, while water is forced from the compressing bellow out into the discharge box. Operating the pump in a rythmic manner produces a continous flow of water.

4.2 ROTARY (POSITIVE DISPLACEMENT) PUMPS

CHAIN PUMPS

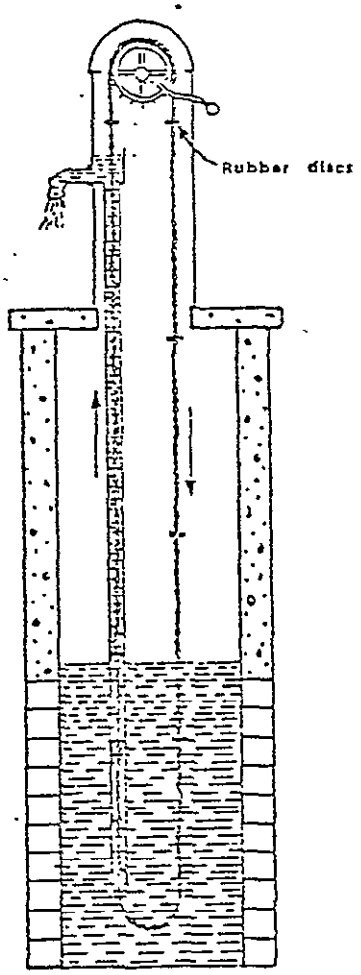


FIG. 14 CHAIN PUMP

In the chain pump, discs of a suitable material (e.g. rubber) attached to an endless chain that runs over a sprocket at the top, are pulled upward through a pipe to lift water mechanically up to the spout. It can only be used on cisterns and shallow dug wells. This type of pump is readily adaptable to manufacture by village artisans. A small chain pump using a pipe of 20 mm diameter, with rubber discs spaced 1 metre can discharge from 5 to 15 litres of water per minute depending on the speed of rotation of the operating wheel (30 to 90 rpm).

Chain pumps using rags and balls instead of discs were commonly used for draining mines in Western Europe in the 16th Century. Animal-powered chain pumps are reported to be widely used in China for irrigation pumping.

BUCKET PUMPS*

Another type of positive displacement, hand-operated pump is the bucket pump. An example is shown in Fig. 15.

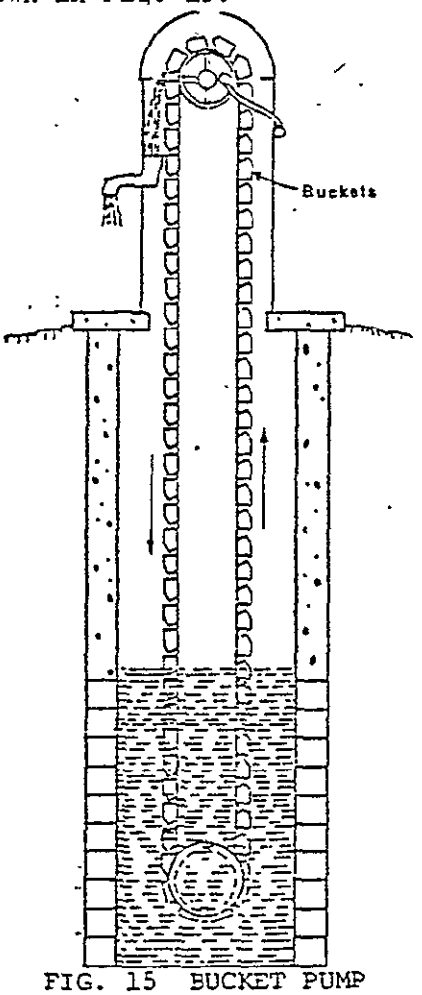


FIG. 15 BUCKET PUMP

* Not to be confused with the name "bucket pump" sometimes given reciprocating well pumps whose plunger to cylinder seals are sometimes called "buckets".

Small buckets attached to an endless chain are rotated over sprockets as shown so that each bucket dips water from the source at the bottom, carries it to the top, and empties it into the spout as it passes over the top sprocket. At least one manufacturer makes a pump using a sponge-like belt in lieu of the buckets with a squeegee at the top to remove the lifted water. Another handmade version uses a rope driven by a bicycle wheel with a sharp bend at the top to discharge the water by centrifugal force. These pumps are used mostly on cisterns and shallow dug wells.

SEMI-ROTARY PUMP

The "Semi-rotary" Pump (Fig. 16) is occasionally used.

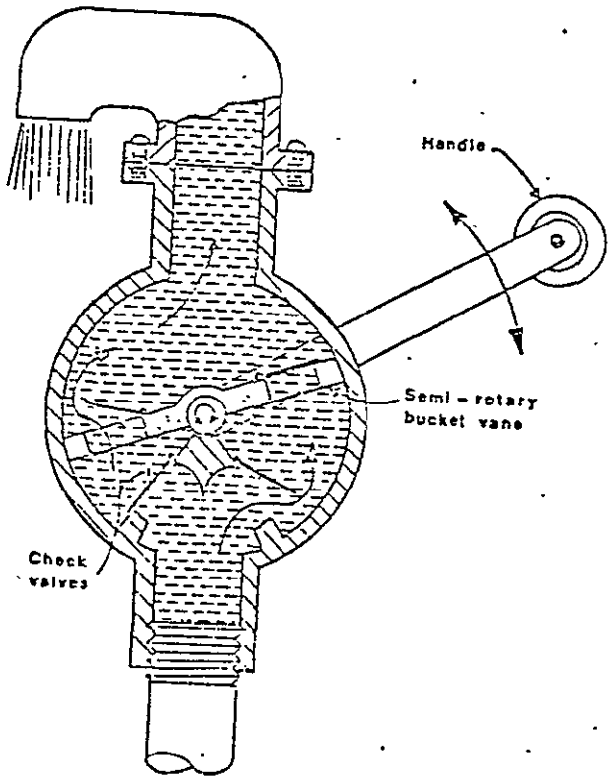


FIG. 16 SEMI-ROTARY PUMP

5 NON-TECHNICAL ASPECTS

5.1 GENERAL

A manual water pumping unit for small-scale irrigation is a small technical device in a complex economic and socio-cultural system. Such factors may be difficult to define, but they are inherent in every installation programme of manual pumping devices, and become especially manifest in the operation and maintenance of the pumps. Many pump installations in rural areas have failed, or have been abandoned by their users, either because they did not have the skill and resources to keep them going, or because of mistrust in the agencies providing the pumping devices.

In practice, the reliability and durability of a manual pumping device interact with the social environment in which the pump operates. In this respect, it is necessary to follow an approach involving the local people, to the maximum extent possible, in the design and installation of the pump. The social factors influencing the acceptance of the pump by its users, should be recognized in order to avoid frustration, sabotage and pilferage.

It is the obvious failure of pumping equipment, particularly in rural areas, that is forcing engineers and economists to consider more carefully the available manual pumping devices. Gaining the confidence of the users, training local people and organizing maintenance must be an integral part of any irrigation development scheme.

5.2 ORGANISATION

An effective pump installation programme is a conglomerate of technology, institutions and people - individuals who must plan, design, manufacture, finance, purchase, install, operate, maintain, supervise and use the pumps. In addition to the central agency, some organizational structure should be developed at the local level in the form of a committee or some other entity that is usual in the country. The importance of a local committee is that it represents the users, directly involves the community in the day to day operation and administration of the pumping devices and hopefully, helps motivate the users of the pumps.

The great number of small units in a pump installation programme usually requires a central organization for planning, funding, engineering, purchasing, construction, training, supervision and control. Such an organization can obtain the benefits of economies of scale, bulk purchasing, standardization and qualified staff. The central organization may also be responsible for administering the pump installation programme; sets the technical standards and controls the execution of the programme; is responsible for promoting community involvement; and insuring information and training of the committees and the users.

The central organization should provide the necessary assistance to the committee and users. It should have central and regional stores of spare parts, and materials, tools, as well as heavy equipment for use in special repairs. Support could include technical assistance, and the provision of training at the local level. Financial support could include funds, spare parts, tools, transport and the administration of a revolving fund. The fund could be incremented by revenues from charges for use of the pumping units.

5.3 MAINTENANCE

When selecting or developing a pumping device for use in small-scale irrigation, it should be carefully considered whether the expected involvement of the users in the maintenance of their pump is realistic. The envisaged division of responsibility for maintenance tasks should be clearly stated.

Without adequate information, the users cannot be expected to be co-operative in ensuring the proper maintenance of their pumps. Without support, ie. supply of spare parts, it will be impossible for them to contribute their part to the servicing of the pump. Certain requirements are simply beyond the local capacity, at least under present conditions.

The high rate of abondoned or defective manual pumping units is not simply a reflection of poor quality pumps but also of inadequate maintenance and repair. Many authorities contend that maintenance is the critical element of pump installation programmes. The possible causes of poor maintenance may provide some insight into possible improvements. They are:

(1) Poor quality of pump design and manufacture. To a considerable extent this condition is also the result of many years of trimming weight, bearing sizes, etc., in seeking low bids (tenders) in the absence of strict specifications. Much pump procurement has an inherent bias towards low initial capital cost and ignores the total costs over the life-span of a pump.

(2) The usual technology makes frequent lubrication mandatory. Iron and steel journals and bearing, poor fits and large clearances, lack of lubricant stocks, and exposure to weather.

(3) Large variety of pumps in use with accompanying need for many different spares. Limited interchangeability of spare parts, sometimes even between different pump models of the same manufacturer.

(4) Little feedback from maintenance to design, engineering, and procurement personnel. Little analysis, for example, of the most common failures. Record keeping is often inadequate.

(5) Poor maintenance skills, lack of training, inadequate tools (for example, few village maintenance men have a clevis for pumling up pump rod, drop pipe, and cylinder), lack of transport, and lack of supervision are characteristic of many programmes.

Most pump maintenance systems can be characterized as a one or two level system. The one level system is one where all maintenance is the responsibility of the central organization. In the two level organization, maintenance is shared with local communities or individual smaller farmers.

In both systems the central organization usually installs the pump. The well may be the task of another central agency. For dug wells the village may provide labour under central agency supervision. The central agency usually handles major repairs or replacement of the pumps

in both systems. It maintains stores of parts and lubricants and provides transport, warehousing, and training. When the central agency provides routine maintenance, it often employs a roving maintenance man or team with a vehicle and who services from 20 to 200 pumps on a repetitive basis.

In the two level system, the local community or a farmer employed by the central organization assumes responsibility for all lubrication and minor repairs, for example, replacement of cup seals ("leathers"). Where villagers deal only with the basic maintenance tasks requiring frequent attention, the backup service could visit the pump at regular intervals (e.g. every three months) for a thorough servicing. This system is found in parts of India.

In some programmes certain users may be given a thorough training in pump maintenance and virtually all responsibility left in their hands. These approaches are being tried, for instance, in Kenya and Tanzania. Each village is required to nominate a person before the well is sunk who will go to the district office for two weeks to learn about well construction and particularly for maintenance of the pump. He will then be responsible for the well once it is sunk, and will keep a small stock of leather components and other spare parts in his house. If a major breakdown occurs he will call upon the district office and either get the parts needed to carry out the repairs himself, or he will get the district's mechanics to do the job.

Some people have argued that if a pump could be designed capable of being made by a village craftsman using simple tools and off-the-shelf local materials, then the maker of the pump would always be on hand to repair it when necessary.

This argument is supported by the observations that many low-lift irrigation pumps of "traditional" design are built and maintained by village craftsmen. Such pumps have been designed, built, and used in small-scale irrigation. However, most have been unsuccessful in intensive use.

REFERENCES

BENAMOUR, A.
Les Moyens d'Exhaure en Milieu Rural
Comité Interafricain d'Etudes Hydrauliques (C.I.E.H.), Ouagadougou, March 1979.

EWBANK, T.
A Descriptive and Historical Account of Hydraulic and Other Machines for Raising Water
Tult and Bogue, London, 1842. Reprint Edition, The Arno Press, New York. 582 pp. 1972.

JOURNEY, W.K.
A Hand Pump for Rural Areas of Developing Countries
P.U. Report No. RES 9. Research Working Paper Series, International Bank for Reconstruction and Development, Washington, D.C. 9 pp. + Annexes and figures, October 1976.

Manual de Operacion y Mantenimiento de Installaciones y Equipos en un Acueducto.
Panamerican Health Organization, Washington, D.C. 1970.

McJUNKIN, F.E.
Hand Pumps (also translated into Spanish and French)
Technical Paper No. 10. WHO International Reference Centre for Community Water Supply, The Hague, 230 pp. 1977.

McJUNKIN, F.E. HOFKES, E.H.A.
Handpump Technology for the Development of Groundwater Resources
Paper presented at the Symposium on Engineering Science and Medicine in the Prevention of Tropical Water-related Diseases, London, 11-14 December 1978.

MOLENAAR, A.
Water Lifting Devices for Irrigation
FAO Agricultural Development Paper No. 60, Food and Agricultural Organization of the United Nations, Rome, 76 pp. 1956.

ROMERO, J.A.C.

Manual de Pozos Rasos

Panamerican Health Organization, Washington, D.C. November 1977.

SHAWCROSS, J.F.

Handpump Maintenance

Draft Report, WHO International Reference Centre for Community Water Supply, The Hague, February 1978.

SHAWCROSS, J.F.

Handpump Tubewells for Irrigation Purposes

Internal Memorandum, UNICEF, Dacca, 1975.

STERN, P.H.

Hand Pump Irrigation in Bangladesh

Waterlines Vol. 1, No. 1.March 1979.

WATT, S.B.

Approaches to Water Pumping in West Africa

Paper presented at FAO/DANIDA Seminar on Small-scale Water Resources Development in West Africa, Ouagadougou, Upper Volta, 29 September - 6 October 1975.

VITA TECHNICAL BULLETIN

REFERENCE NO. 2

Diaphragm Pump

DR. RICHARD G. KOEGEL

The hand operated pump presented here was first used in Vietnam; it is made entirely of wood, rubber, common pipe fittings, and metal fasteners, washers, and bushings. It consists of a watertight wooden box fitted at intake and outlet openings with two rubber flap valves. The rubber diaphragm, made from old auto inner tube material, forms the working piston of the device. The pump handle is attached to the diaphragm. Movement of the handle increases or decreases the volume within the box and this change of volume activitates the intake and outlet valves to allow water to be pumped through the mechanism. Two to three liters per strcke can be pumped to a height of three to four meters. The pump can be operated by one or two men, and can be easily adapted for use with animal or wind power.

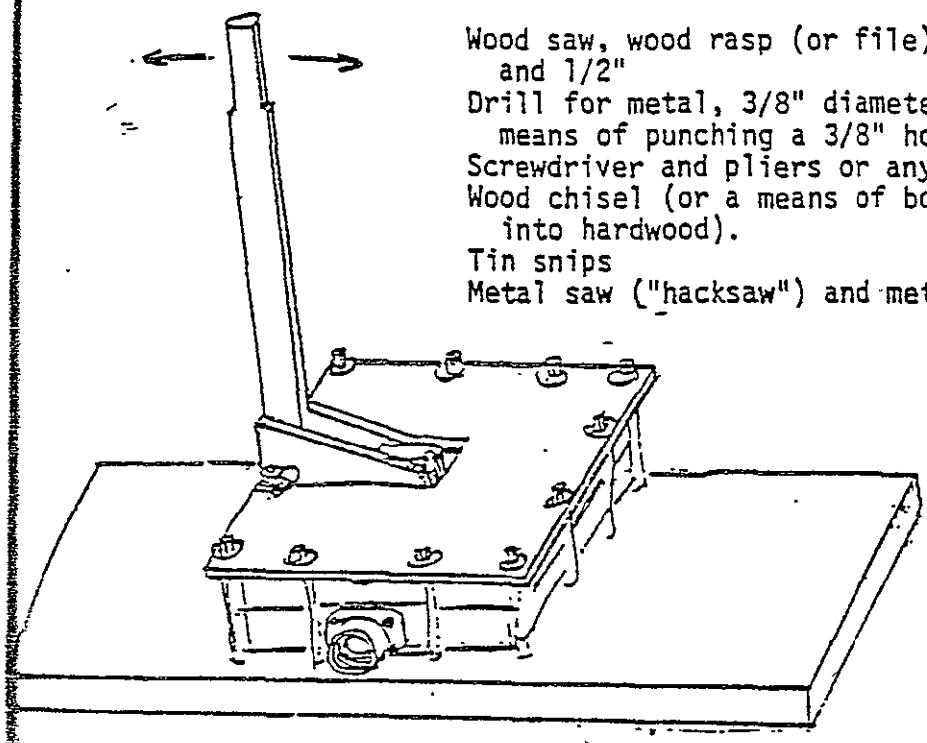
Dr. Richard G. Koegel, the primary author of this plan, is with the University of Wisconsin at Madison's Department of Mechanical Engineering. A VITA Volunteer for almost 12 years, Koegel previously spent eight years in Asia and Africa where he designed, built and tested a number of the technologies now disseminated by VITA.

Please send testing results, comments, suggestions and requests for further information to:

Technical Bulletins
VITA Publications Service
3706 Rhode Island Avenue
Mt. Rainier, MD 20822 USA

Tools

Wood saw, wood rasp (or file); wood drills 1/4", 3/8" and 1/2"
Drill for metal, 3/8" diameter--can substitute with a means of punching a 3/8" hole in sheet metal
Screwdriver and pliers or any type of adjustable wrench
Wood chisel (or a means of boring a hole 2" in diameter into hardwood).
Tin snips
Metal saw ("hacksaw") and metal file



DIAPHRAGM PUMP

Materials

(Note that planks of 12 x 14" widths can be substituted by an assemblage of smaller width boards which are adequately cross-braced.)

Qty.	Size	Description & Part No. ()
1	2" x 2" x 36" (hardwood)	handle, (1)
1	1" x 6" x 8 1/2" (hardwood)	handle arm, (1a)
1	1" x 14" x 14" (hardwood)	top plate, (2)
4	1" x 4" x 12" (hardwood)	top and bottom frame, (3) & (5)
4	1" x 4" x 10" (hardwood)	top and bottom frame, (3) & (5)
1	2" x 4" x 6" (hardwood)	diaphragm support arm, (4c)
2	1" x 7" x 7" (hardwood)	diaphragm supports, (4a)
1	2" x 14" x 48" (hardwood)	baseboard, (9)
1	2" x 4" x 6" (hardwood)	spacer block (6e)
2	±1/16" x 12" x 12" (inner tube rubber)*	diaphragm (4) and bottom gasket (8)
2	±1/16" x 2 1/2" x 2 3/4" (inner tube rubber)	outlet check valve (6) and inlet check valve (7)
3	±1/16" x 4" x 6" (inner tube rubber)	outlet and inlet valve gaskets (6d), (6e) & (7d)
6	3/8" dia. x 4" (machine bolts, nuts and flat washers)	arm to pump handle bolts (1b)
1	3/8" dia. x 5" (machine bolts, nuts and flat washers)	diaphragm support arm connector (4d)

Qty.	Size	Description & Part No. ()
4	3/8" dia. x 1/1/2" (machine bolts, nuts and flat washers)	inlet valve assembly bolts (7f)
2	1/4" dia. x 1" (machine bolts, nuts and flat washers)	outlet and inlet valve reinforcements (6b) & (7b)
12	3/8" dia. x 12" (machine bolts, nuts and flat washers)	unit assembly bolts--requires 24 flat washers (10)
24	±1/4" x 2" (lag bolts or wood screws)	top and bottom frame fastening screws (3a) & (5a)
9	±3/16" x 2" (lag bolts or wood screws)	aphragm support fastening screws (4b)
2	±1/4" x 3 1/2" (lag bolts or wood screws)	diaphragm support arm fastening screws (4b)
6	3/4" length (flat head nails)	outlet and inlet check valve fasteners (6c) & (7c)
2	±1/16" x 2 1/2" dia. (sheet metal disks)	outlet and inlet check valve reinforcement (6a) & (7a)
2	±1/16" x 1" x 4" (sheet metal band)	pivot rod mounting clamps (1d)
1	1/2" dia. x 8" (steel rod)	pivot rod for handle (1c)
2	2" inner dia. (pipe flange)**	outlet (6g) and inlet (7e)
1	±2 oz. (waterproof glue, gum, or pitch)	for sealing the joints in the pump chamber against water and air leaks

* More thickness of rubber for the diaphragm may be required when pumping to greater heights (or heavier weight inner tube material).

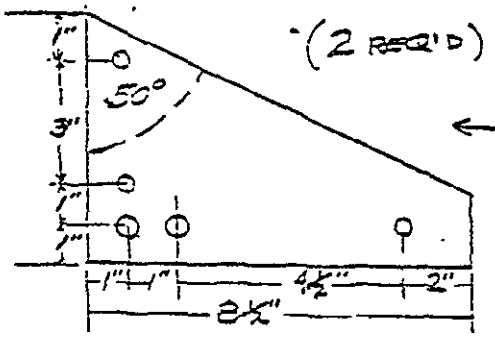
** Obtain the metal pipe flanges first. The size of these flanges will greatly affect the subsequent assembly of both the inlet and outlet check valves, the location of the inlet and outlet holes, as well as the alignment of the mounting bolts for same. A substitute for the pipe flange could be made by welding a 2" pipe coupling to a 1/4" thick steel plate which would function as the face plate of the flange, the inside of the steel plate being cut out to form a 2" diameter hole.

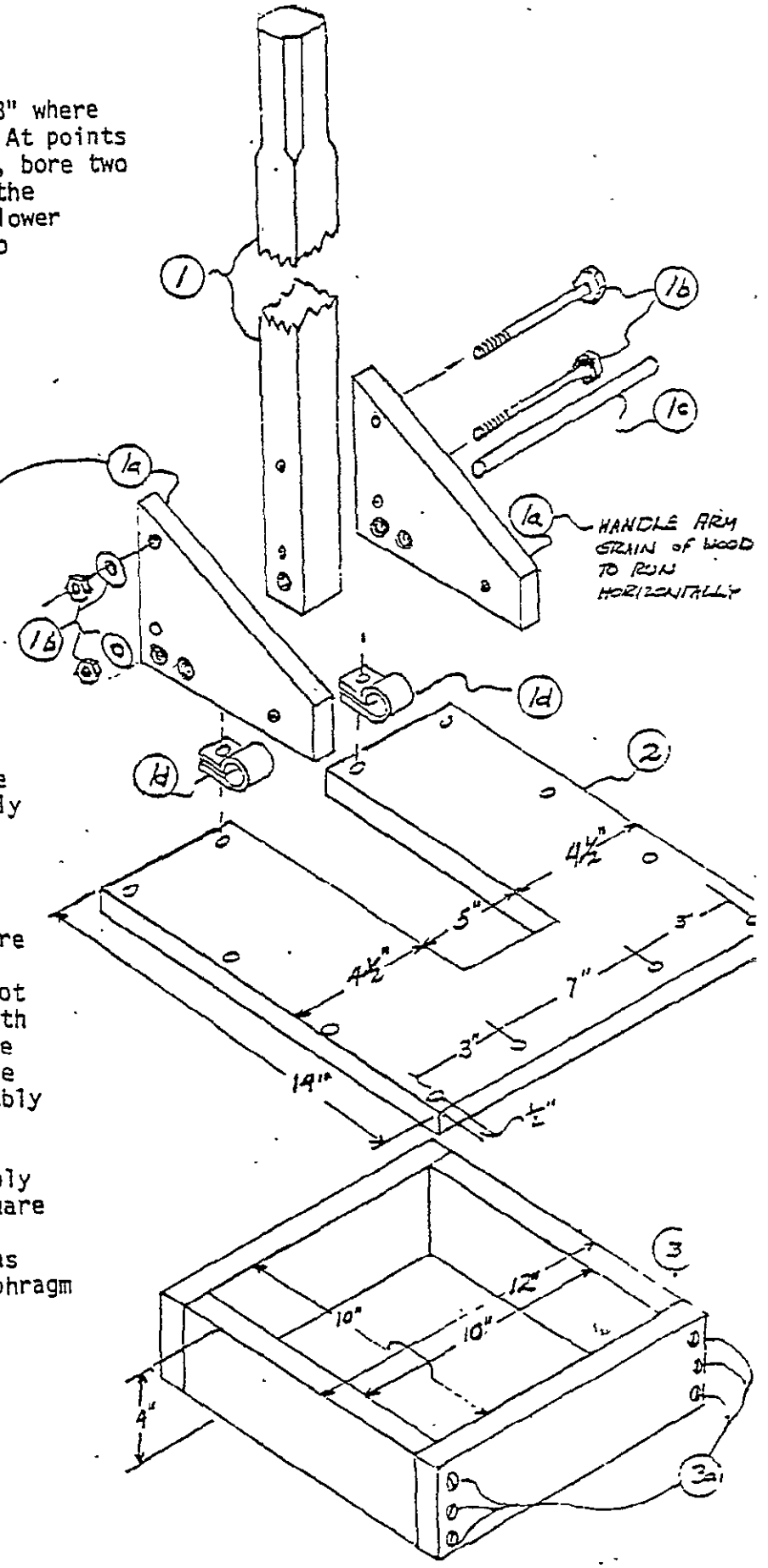
PUMP HANDLE AND TOP HOUSING

Assembly

Handle is smoothed along top 6-8" where it will eventually be grasped. At points 2" and 5" up from the lower end, bore two 3/8" holes through the side of the handle. At a point 1" up from lower end bore a 1/2" hole parallel to 3/8" holes.

Handle arm is cut as follows:





The holes at the larger end are 3/8", 3/8" and 1/2" respectively top to bottom. A second 1/2" hole should be drilled for future adjustments.

The two mounting clamps (1d) are pieces of 16 gauge sheet metal which are wrapped over the pivot rod. They are then drilled with a 3/8" drill. These clamps are eventually mounted to the frame via two of the pump unit assembly bolts (part 10).

In making the top frame assembly make the frame as flat and square as possible with particular emphasis on the bottom face, as this face will secure the diaphragm in place.

BEST AVAILABLE COPY

DIAPHRAGM

Assembly

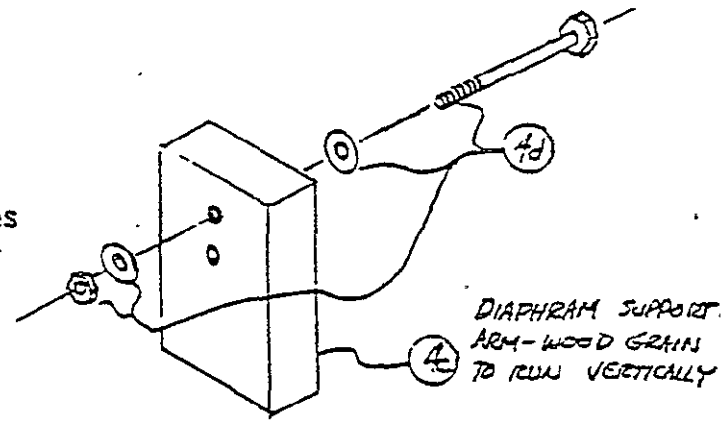
Diaphragm (4) is cut from inner tube. Holes in rubber section should be made after diaphragm supports are aligned. Supports clamp over the diaphragm and are fastened together with wood screws or equivalent. NOTE: Smooth the edges and round the corners of the diaphragm supports around which the diaphragm will eventually be bending.

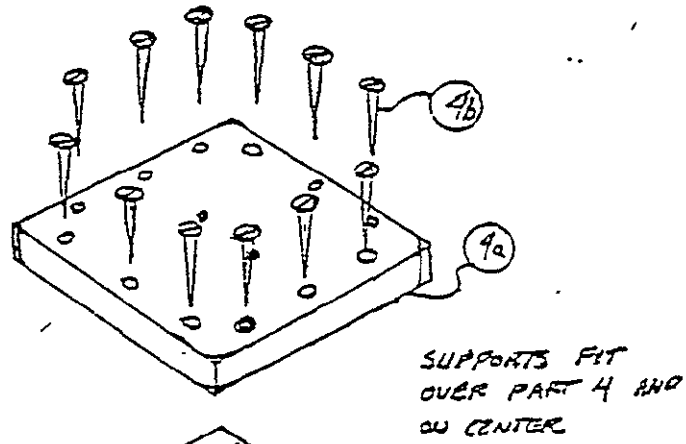
Support arm is fastened to both upper and lower support by means of wood screws or lag screws. Use hardwood for support arm. Bore two 3/8" diameter holes at points 1" and 2" down from top of support arm and in the center with respect to the vertical side of the block. The additional hole is provided for eventual adjustment.

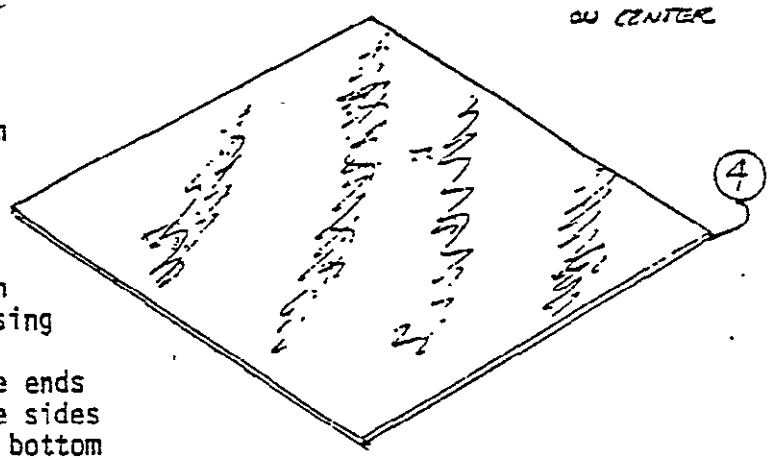
This pump has actually been built according to the specifications provided here; that is, with the diaphragm supports and support arm fastened together with screws. It has been suggested that bolts might be stronger than screws, and would ease the task of replacing a worn diaphragm. In an earlier design; the bottom housing pieces were held together by long threaded rods through holes in the ends which extended slightly beyond the sides of the housing. This allowed the bottom housing to be tightened easily if leakage developed.

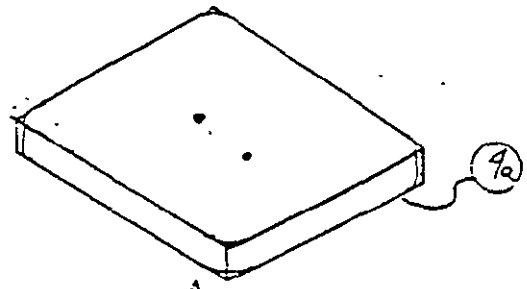
Part (4d) fastens the support arm to the handle arm, which converts the back and forth motion of the handle into the up and down motion of the diaphragm.

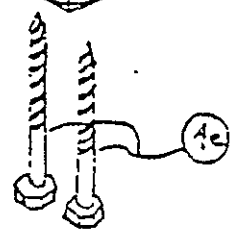
The grain in the upper diaphragm support should run horizontally and at 90° to the grain of the lower support (parts 4a).





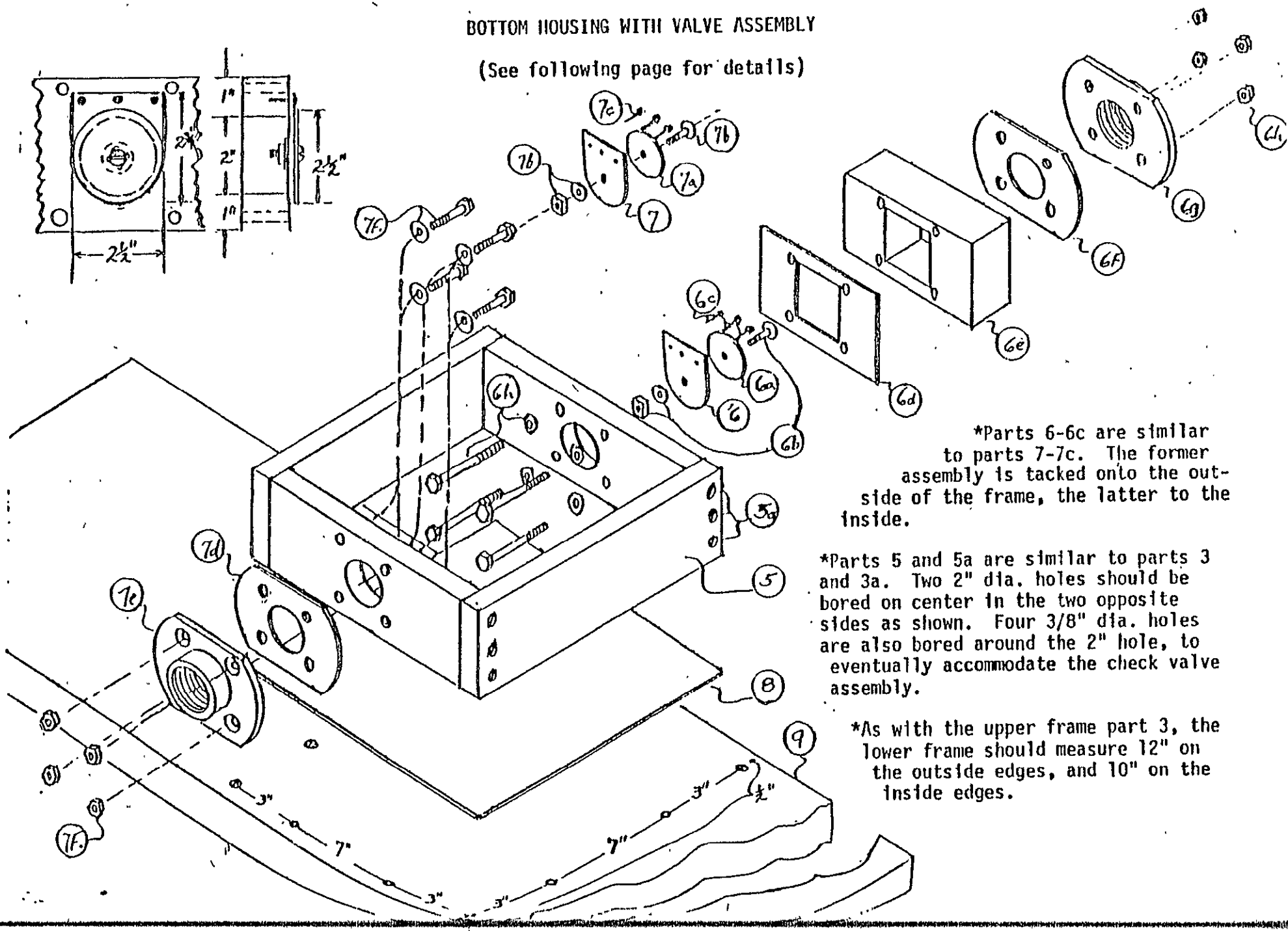






BOTTOM HOUSING WITH VALVE ASSEMBLY

(See following page for details)



*Parts 6-6c are similar to parts 7-7c. The former assembly is tacked onto the outside of the frame, the latter to the inside.

*Parts 5 and 5a are similar to parts 3 and 3a. Two 2" dia. holes should be bored on center in the two opposite sides as shown. Four 3/8" dia. holes are also bored around the 2" hole, to eventually accommodate the check valve assembly.

*As with the upper frame part 3, the lower frame should measure 12" on the outside edges, and 10" on the inside edges.

All joints shown in the previous diagram should be made airtight by sealing with the waterproof glue, gum or pitch. Make all joints as close fitting as possible to aid in waterproofing.

Note the following areas for possible discrepancy due to variations of materials used in construction:

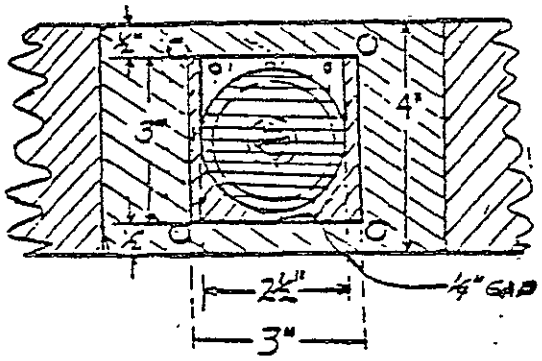
(1) The pipe flanges, parts 6g and 7e should not touch the baseboard, or overlap the upper frame as this will affect the watertightness of the joints. Cut the flat face of the flange to the necessary size in order to avoid this problem.

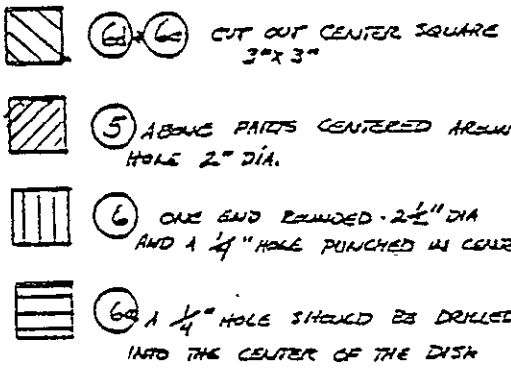
Where the handle arm mounts to the diaphragm support arm, make sure that the connecting bolt (4d) does not rub the slot in the top plate while the handle is moved back and forth. If it does, cut the bolt shorter or cut an appropriate notch in the top plate.

The unit assembly bolts, although not shown, are inserted from the bottom of the pump through the top face plate. Flat washers should be placed on both the bottom and top. Take care to align the top face plate and baseboard for accurate location of holes for the unit assembly bolts.

In bolting the upper and lower units to the baseboard, tighten all of the bolts with gradual even pressure, alternating from one side of the frame to the other.

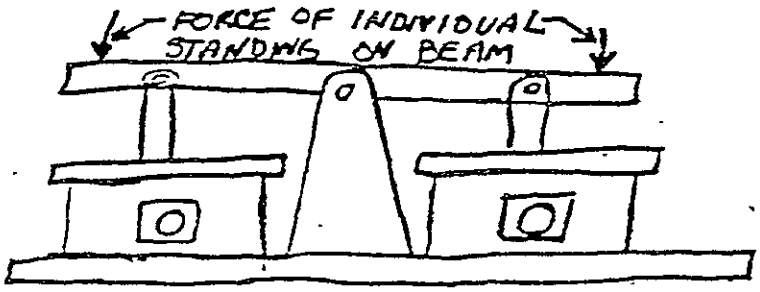
OUTLET VALVE ASSEMBLY
PIPE FLANGE NOT SHOWN.



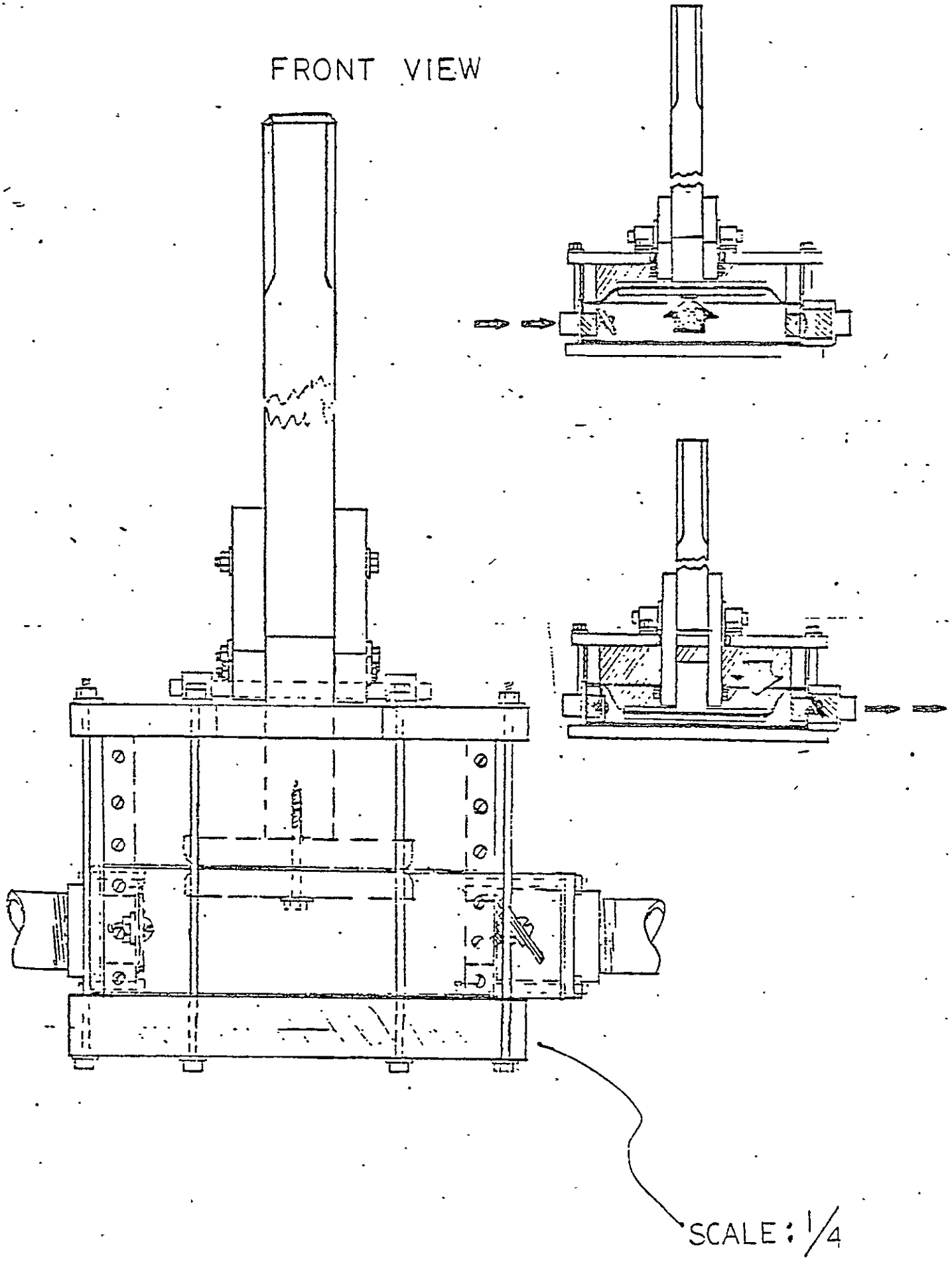


Operation

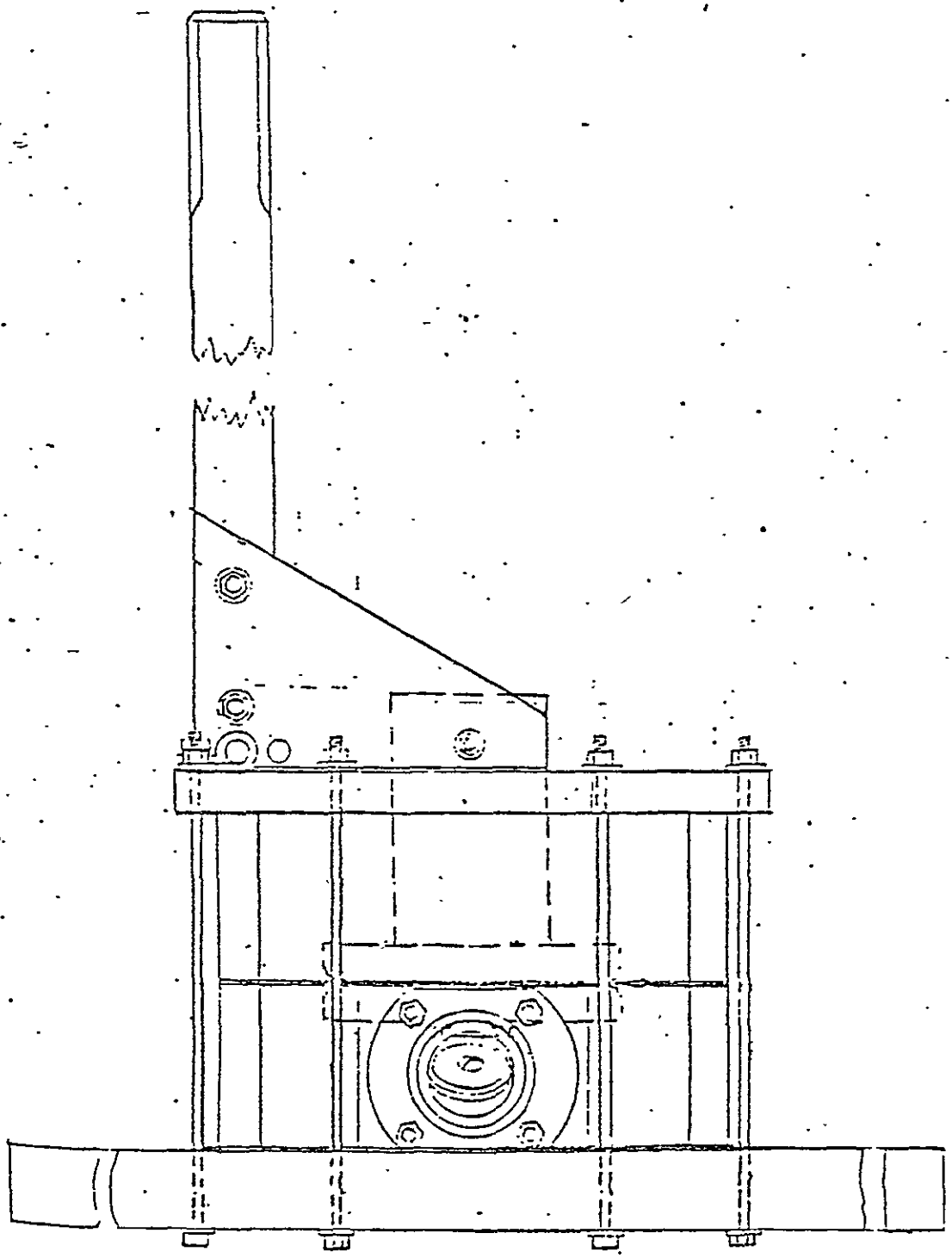
Operation involves priming the pump at the beginning of its initial application. To do this, simply fill the pump up, pivoting the pump on its inlet side and fill the diaphragm chamber with water through the outlet. With the pump in this position and with the inlet hose inserted into the water source, crank the pump while pouring more water into the chamber. The pump will soon become energized. The time and effort required to prime the pump will depend on the depth and/or length of the inlet pipe. In general, five or ten strokes of the pump handle should be sufficient.



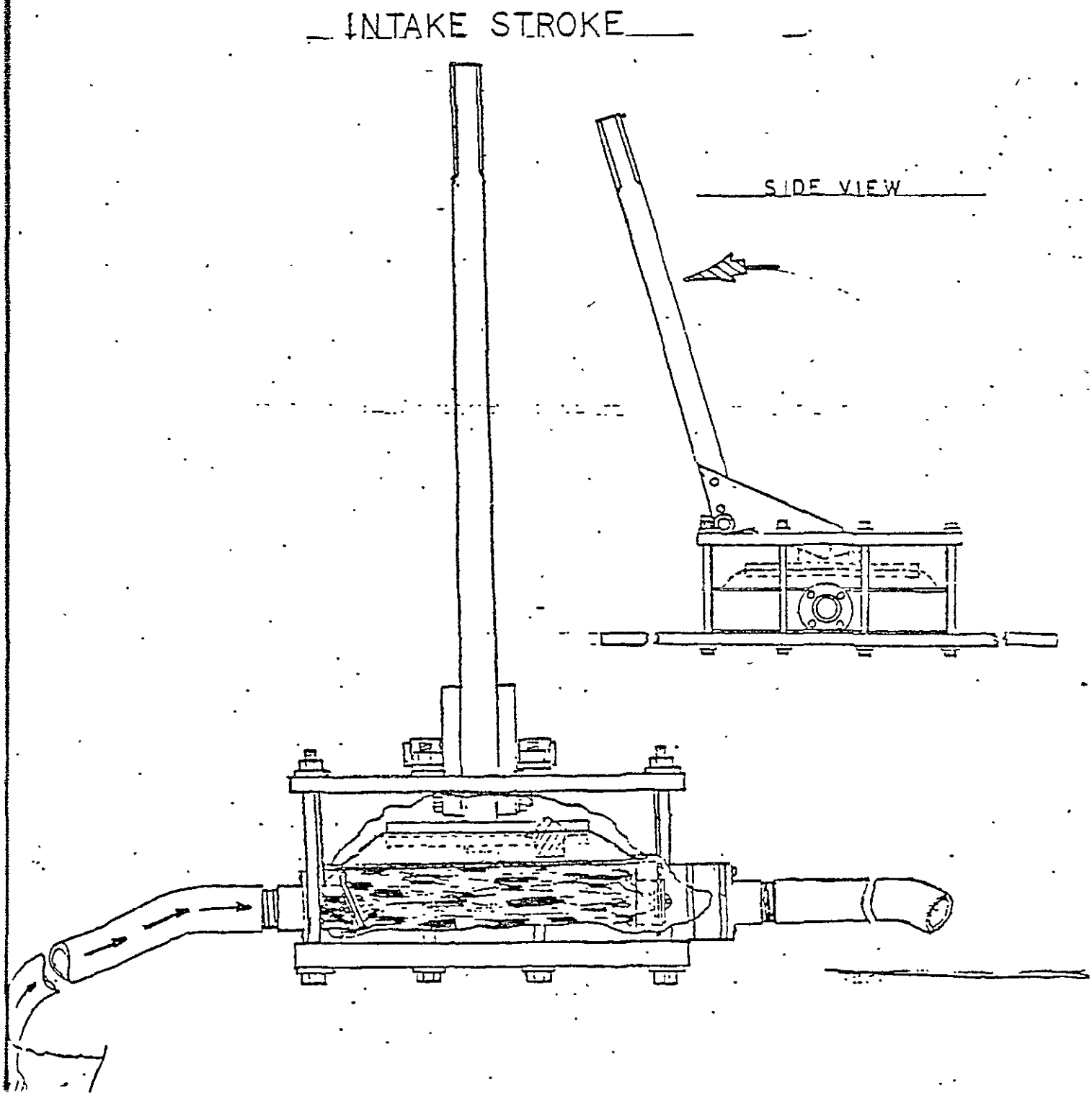
Two pumps arranged as shown and actuated by a person shifting his weight from side to side (from one leg to the other, bicycle fashion) would make efficient use of human effort.


FRONT VIEW
SCALE: 1/4

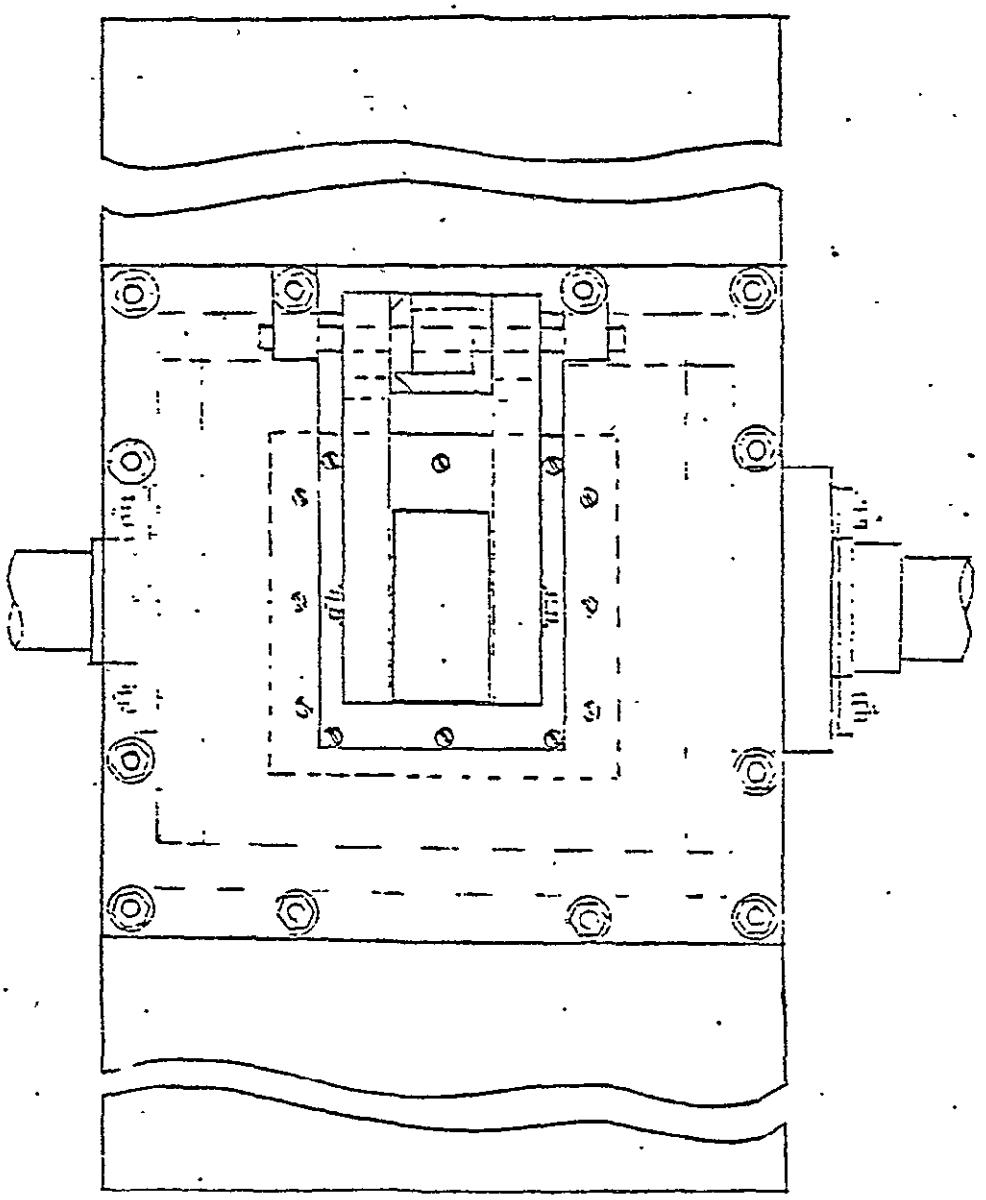
SIDE VIEW



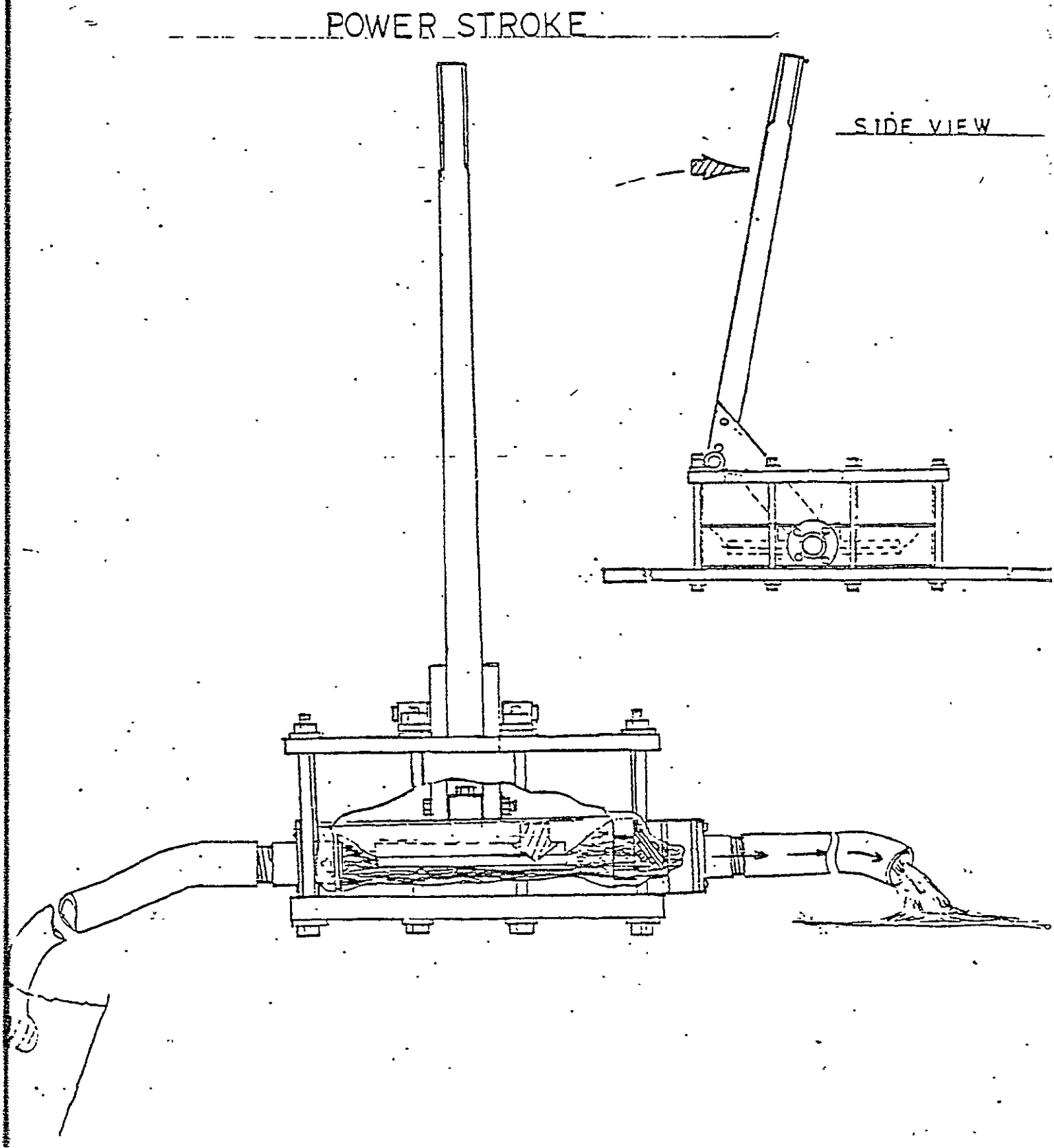
SCALE: 1/4


INTAKE STROKE
SIDE VIEW

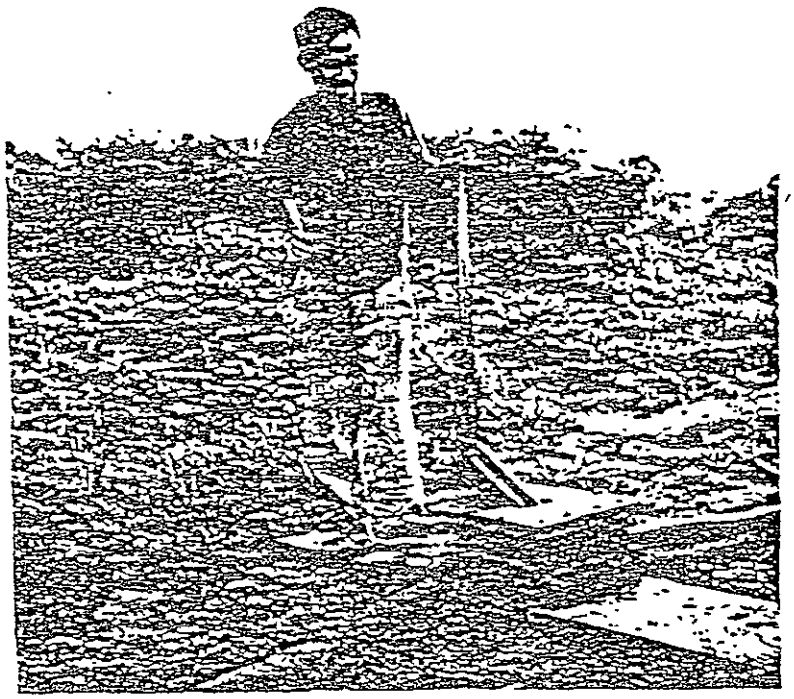
TOP VIEW



SCALE 1/4


POWER STROKE
SIDE VIEW

IRRIGATION PUMP



This hand operated pump is made entirely of wood and rubber with the exception of metal fasteners, washers, and bushings at two wear points. It consists of a water-tight wooden box fitted with two rubber flap valves. A rubber diaphragm made from old inner tube material forms the top of this box. The center of this diaphragm is attached to a vertical pump handle. Movement of this handle increases or decreases the volume within the box, and this change of volume working in connection with the rubber inlet and outlet valve allows water to be pumped. With this pump, two to three liters per stroke can be pumped to a height of three to four meters. By changing the dimensions of the pump, a smaller volume could be pumped to a higher elevation, or a larger volume could be pumped to a lower elevation. The pump can be operated by one or two men, and can be easily adapted for use with animal or wind power. But use of cheap bamboo piping, water could be pumped for considerable distances economically. Two or more pumps can be joined in series or paralleled to give the desired pumping characteristics.

This pump has the following advantages over various other arrangements:

- Extreme simplicity; no close fitting or machined parts. It can be built or repaired with skills and materials found in the average village.

- As opposed to hand irrigation from buckets, the operator remains stationary while only the water moves. In using pole and buckets, he must raise his entire body weight plus that of the pole and buckets, totaling one and one-half to two times that of the water he carries to the same height as he raises the water. In addition, he must make the return trip empty which expends energy without moving any water. Needless to say, the pole and bucket system wastes a great deal of human energy.

- The irrigator is independent of motors, the breakdown of which, or the lack of fuel for which could mean a crop failure.

Maintenance

The frequency with which the pump's rubber valves must be replaced will vary widely with the type and purity of water being pumped as well as the quality of rubber available and the amount of hours used. It is estimated that all parts should last about 9-12 months under normal usage (2-3 hours per day) prior to replacement of the diaphragm rubber.

Any failure of this pump to deliver water will, in 9/10ths of the cases, be due to air leaks caused either by faulty construction and alignment of valves or by a worn valve or diaphragm rubber.

A small quantity of grease should be applied to the two pivot points as needed.

Adjustment

In circumstances where greater leverage is required, a second 1/2" diameter hole is provided in the handle arm. The pivot rod (part 1c) could be relocated through this hole. A different means of fastening the pivot rod at this new location would have to be devised but this matter would hardly tax the ingenuity and therefore bears no further consideration here.

Further and finally, with the pivot rod in the new location, the handle and handle arm would have to be rounded at the bottom outside edge to permit unobstructed movement.

Chapter 15

Water Lifting

While the earliest irrigation schemes in history probably depended only on the gravity flow of water, it was not long before man became aware of the need to lift water for irrigation, and many devices were developed for this purpose in different parts of the world using man or animal power. The advent of mechanical power and modern machinery revolutionised the technology of water lifting, enabling water to be raised to heights and in quantities enormously greater than had hitherto been possible. Cheap oil fuel and hydro-electric power where available contributed to the popularity of power driven pumping, and pump schemes for irrigation were developed wherever they were found to be financially and economically viable.

The success of the mechanical pumping system has, however, been marred by the very high incidence of failure where it has been applied inappropriately to agricultural communities which cannot manage installations which are too dependent on imported equipment and spare parts and on skilled labour which is in very short supply. Because of this, and because of the increasing costs of oil fuels and other sources of power, research and development resources are now being developed on quite a large scale, to re-discovering the use of man, animal and wind power for water lifting, and to improving traditional technology with the aid of modern knowledge and materials

In this chapter we summarise briefly the different types of water-lifting devices available for irrigation, without entering into great detail Useful references to these subjects will be found at the end of this chapter.

Manual Water Lifting

The simplest form of manual device is the water container which is filled and carried to the plants to be irrigated. In the Central Valleys of Oaxaca, Mexico, where the water table is 1 to 10 m below ground surface farmers open wells in the fields at intervals of 20 to 40 m A 10 to 14 litre clay or

metal vessel is used to draw water from these wells. It has been estimated that a farmer can water up to 400 square metres in an 8-hour working day in this way. The watering can (Figure 20) is another vessel used in this way. Water can be raised by scooping, and a device for doing this is shown in Figure 40.

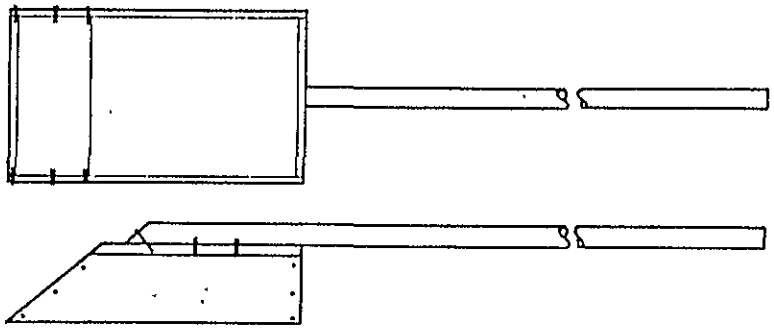


Fig.40 Irrigation by scoop

Man-powered Systems

A system commonly seen throughout the Middle and Far East uses the principle of the lever to raise a bucket from a well or irrigation channel (Figure 41), known by its Arabic name as the 'shadouf'. The Indian 'dall' or 'auge' (Figure 42) uses the lever in a similar way.

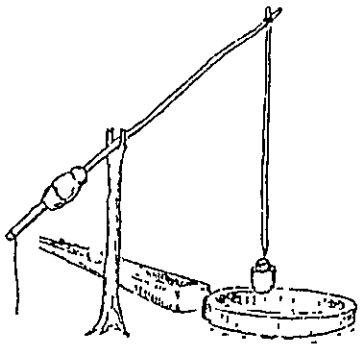


Fig.41 The beam and bucket

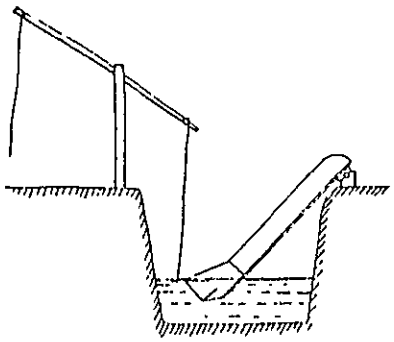


Fig.42 The Indian 'Dall'

The Archimedian Screw, said to have been invented by Archimedes about 200 B.C is shown in Figures 43 and 44. It is still used in Egypt and India, for low lifts of between 0.25 m and 1.30 m. Limited to working between fairly constant operating levels, it is one of the more efficient water lifting machines in terms of output for energy input.

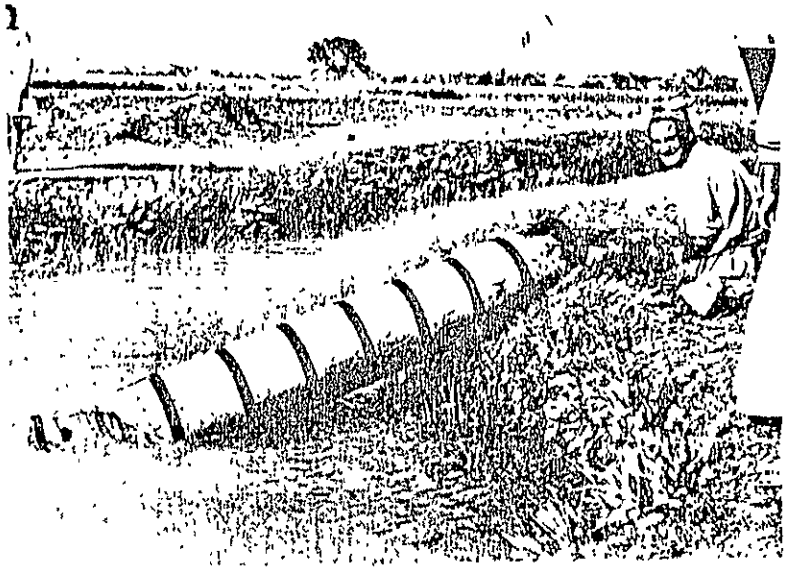


Fig.43 Archimedean screw (Photo: Douglas Dickens)

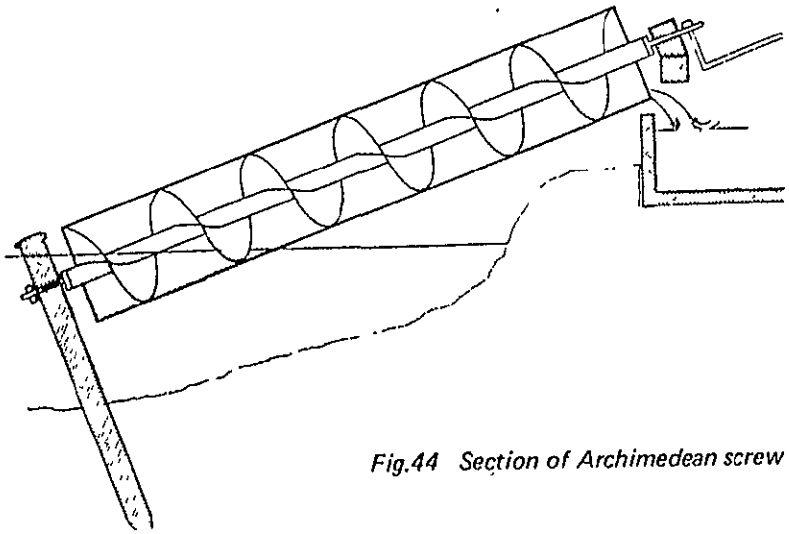


Fig.44 Section of Archimedean screw

Hand operated chain and bucket pumps are shown in Figures 45 and 46. They both consist of continuous chains suspended and rotated vertically. In the former case discs or washers are attached to the chain, which passes through a vertical tube in its upward movement; in the latter case

buckets are attached to the chain. The chain pump was used extensively in mines in Europe in the 16th Century More recently it has been developed in China

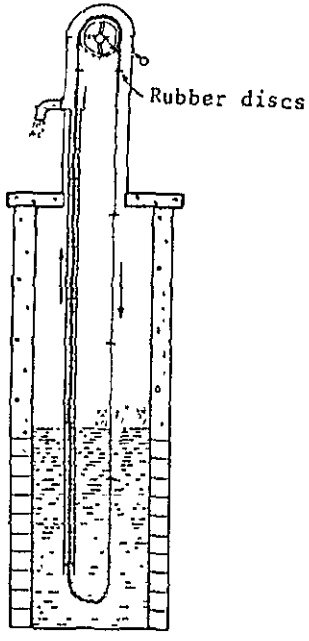


Fig.45 Chain pump

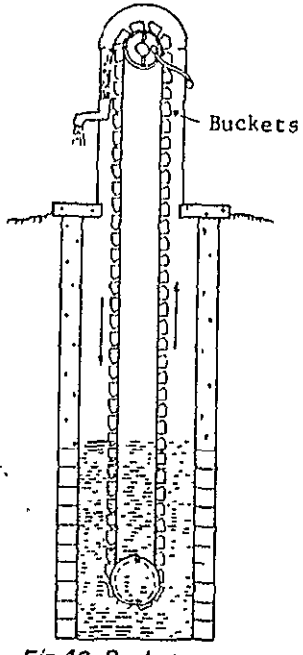


Fig.46 Bucket pump

The reciprocating pump is the type of hand pump most widely used, primarily for community water supply, but also for irrigation. The origins of the reciprocating pump are believed to date from about 275 B.C. A wooden reciprocating pump was used as a ship's pump in the early Greek and Roman navies, and archeological remains of reciprocating pumps from late Roman times have been found in Europe. Wooden reciprocating pumps were in common use in Europe throughout the 16th and 17th centuries and in the 19th and early 20th centuries metal hand pumps were manufactured on a large scale in the United States and Europe.

The main parts of a reciprocating hand pump are shown in Figure 47. The handle, connected to the pump rod, moves the plunger up and down inside the pump cylinder. As the plunger rises, water is drawn through a non-return valve at the bottom of the cylinder, into the cylinder. On the downward stroke, the bottom valve closes and the water passes

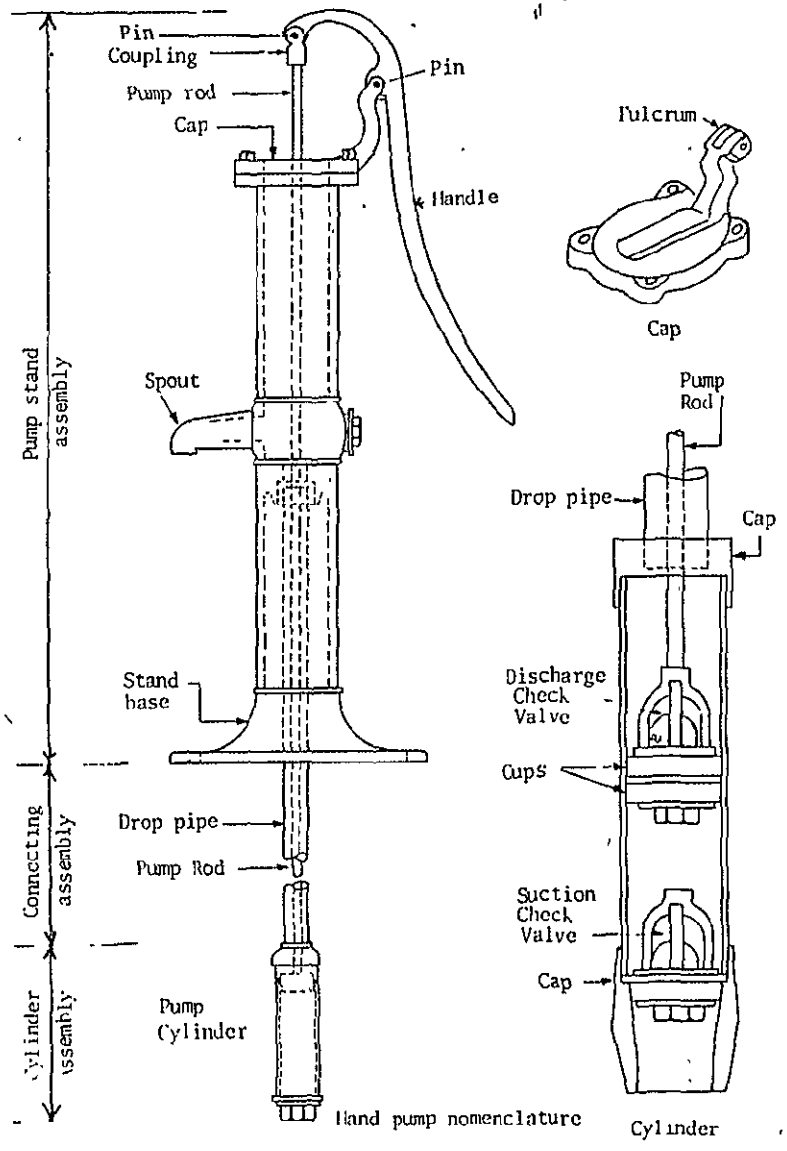


Fig.47 Reciprocating hand pump

BEST AVAILABLE COPY

through a second non-return valve in the plunger, to the upper side of the plunger. On the next upward stroke, this water is forced up the drop pipe (or rising pipe), while a second intake of water is drawn in through the bottom of the cylinder. Water is thus raised to the pump head and discharged through the spout.

The pump cylinder may be placed below the pump stand or within it, depending on the depth of the water surface below ground level. Where this depth is less than about 6 m, the cylinder can be in the pump stand, connected to a rising pipe and foot valve in the water. Where the depth to the water surface is greater than 6 m, the cylinder must be placed below the pump stand, either in the water or not more than 6 m above it, and connected to the pump stand by a drop pipe.

If it is required to raise water to a point above the pump stand, a version of this pump known as the lift and force pump is used, in which the spout is replaced by a delivery pipe. For this version a water seal is needed at the top of the pump stand, and a linkage arrangement for the handle which keeps the pump rod moving vertically without lateral movement.

The output of a hand pump is directly related to the energy capacity of its operator. While a human being can generate quite considerable energy in short bursts, the average output for prolonged work is 0.1 to 0.08 horsepower, and 0.08 horsepower is usually taken as the operator input for a hand pump. Energy is lost in working against friction in the pump and the ratio of available power to input power is known as the efficiency of the pump, often expressed as a percentage. A usual efficiency for handpumps is 60%, so that the available power is about 0 05 horsepower.

The power used in lifting water is given by the equation -

$$\text{Horsepower} = \frac{(\text{Flow in l/s}) \times (\text{Lift in m})}{76\ 1}$$

Thus for a hand pump with 0.05 available horse power, Flow x Lift = 3 8, approximately For a lift of 1 m, delivery would be 3 8 l/s, for a lift of 20 m, delivery would be 0.2 l/s.

Despite its relatively simple mechanism, the hand-operated reciprocating pump has had a poor record of performance in a number of developing countries Bangladesh is one country

BEST AVAILABLE COPY

which has successfully adopted the reciprocating hand pump for small-scale irrigation With assistance from UNICEF, a hand pump programme for shallow groundwater, known as MOSTI (Manually Operated Shallow Tubewell for Irrigation) was evolved, which included a simple borehole which could be driven by manual labour and a hand pump for irrigating an average of 0.2 ha of rice or 0.25 ha of dryland crops. The MOSTI system was introduced in the late 1950s and by 1976 there were 60,000 units in use. The cost of the installation in 1976 was US$70. The pump finally adopted for this programme, known as the 'New No.6' (Figure 48) is a cross between the USAID 'Batelle' pump and an earlier locally manufactured pump

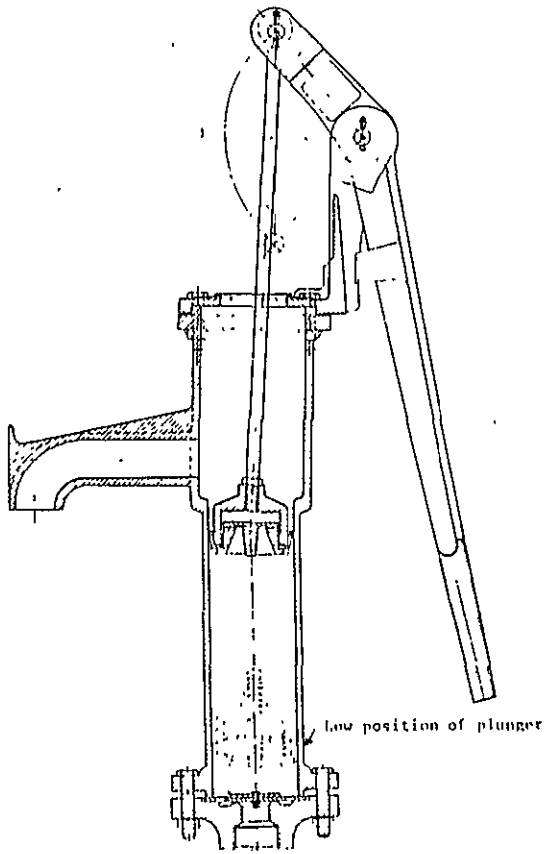


Fig.48 New No.6 hand pump (Bangladesh)

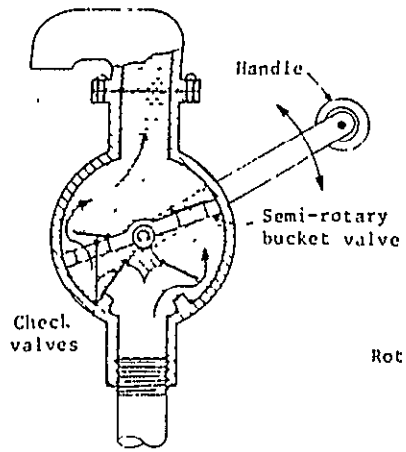


Fig.49 Cross-section of a semi-rotary pump

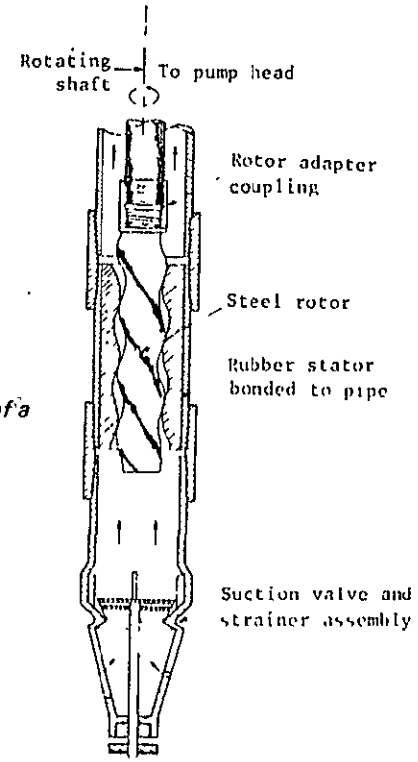


Fig.50 Cross-section of a helical rotor pump

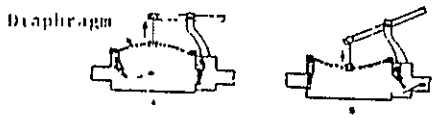


Fig.51 Cross-section of a diaphragm pump

BEST AVAILABLE COPY

Other types of hand pump which are available include the semi-rotary and helical rotor pumps (Figures 49, 50) and the diaphragm pump (Figure 51).

Animal-powered Systems

Animal power has been used for water lifting in parts of the world for many centuries. One of the most common methods is the Persian Wheel or Saqia, which takes different forms, but they all comprise a water wheel or a chain of buckets, operated by an animal harnessed to a beam which rotates in a horizontal circle to provide the motive power (Figures 52, 53) Another use of animal power which originated in India (sometimes called the Mot) is illustrated in Figures 54 and 55. It is usually assumed that an animal working on a circular track can exert a force of one tenth of its weight at a speed of 0.7 metres per second. For an ox weighing 400 kg this is equivalent to an output of 0.4 horse-power.

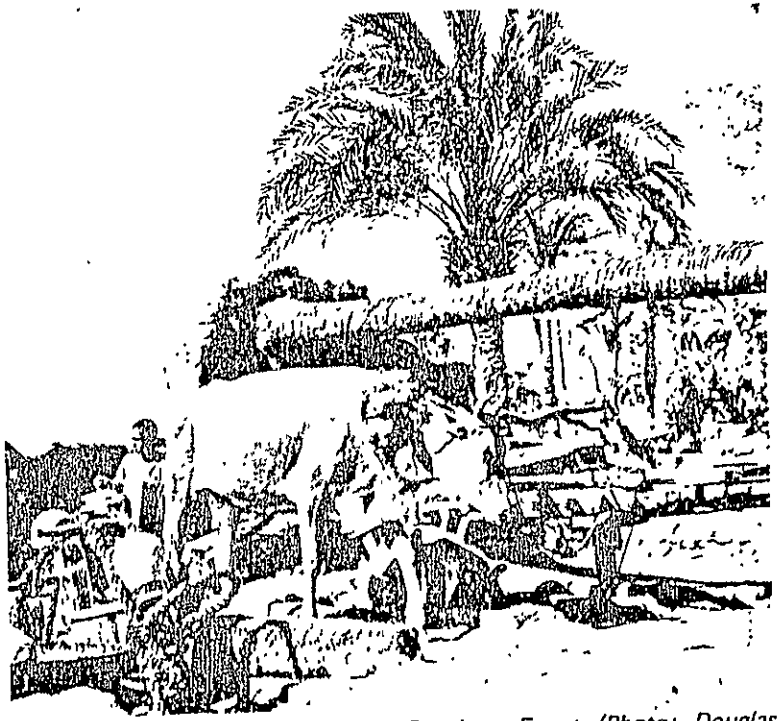


Fig.52 Persian wheel ('saqia') at Dendera, Egypt (Photo: Douglas Dickins)

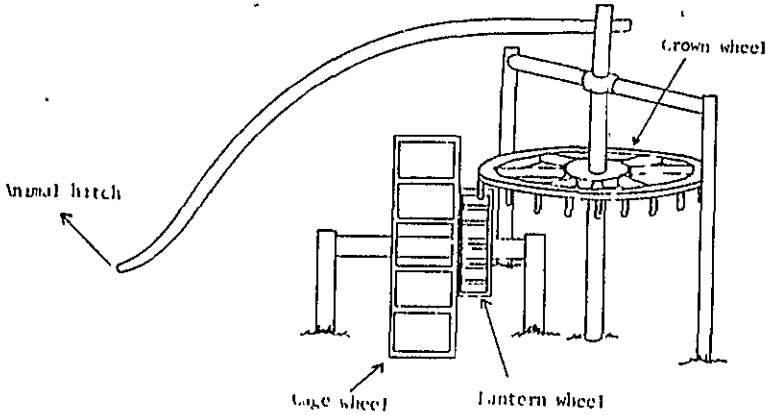


Fig.53 Details of Persian wheel (Illustration: James Goodman)

Fig.54 Indian 'mot' at Isle of Djerba, Tunisia (Photo: Douglas Dickins)

Water Power

The energy of flowing water is used for raising water, as in the water wheel (Figure 56) and the hydraulic ram or hydram (Figures 57, 58). Water wheels are common in countries in the Far East, and can be used where there is a fairly constant flow in a river or large canal. The hydraulic ram is a self-acting pump in which a stream of water falling through a small height

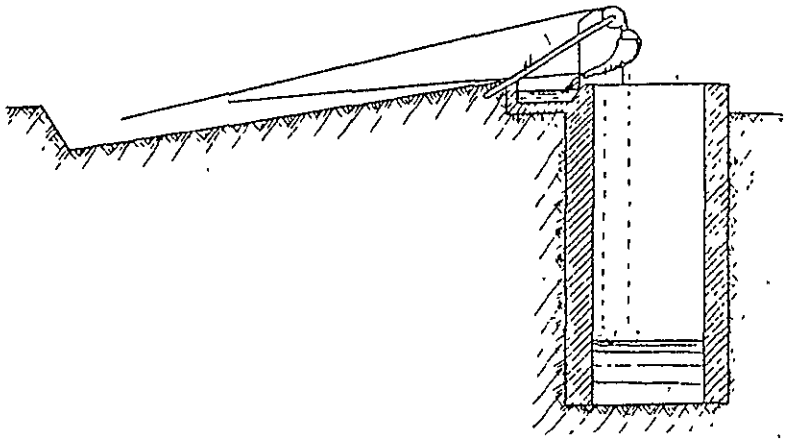


Fig.55 Details of Indian môt

raises a portion of the water to a greater height. The rate of delivery will depend upon the supply available, the working head and the height to be lifted. If a supply of 20 l/s were used with a fall of 5 metres, a delivery of 1 l/s could be raised to a height of 60 metres.

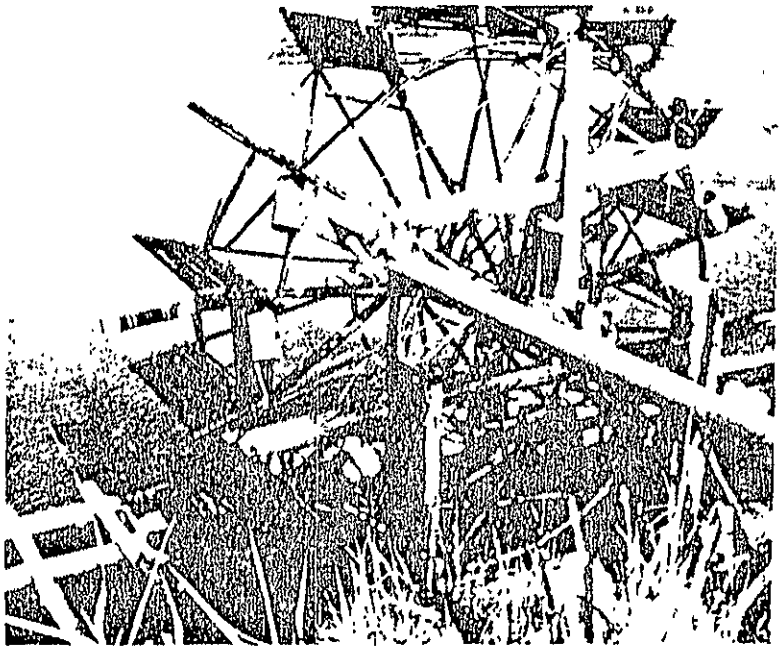


Fig.56 Water wheel on the Nile near Juba, Sudan

CHAIN PUMP FOR IRRIGATION

The chain pump, which can be powered by man or animal, is primarily a shallow-well pump to lift water for irrigation (see Figure 1). It works best when the lift is less than 6 meters (20'). The water source must have a depth of about 5 chain links.

Both the pump capacity and the power requirement for any lift are proportional to the square of the diameter of the tube. Figure 2 shows what can be expected from a 10cm (4") diameter tube operated by four men working in two shifts.

The pump is intended for use as an irrigation pump because it is difficult to seal for use as a sanitary pump.

Tools and Materials

Welding or brazing equipment

Metal-cutting equipment

Woodworking tools

Pipe: 10cm (4") outside diameter, length as needed

5cm (2") outside diameter, length as needed

Chain with links about 8mm (5/16") in diameter, length as needed

Sheet steel, 3mm (1/8") thick

Sheet steel, 6mm (1/4") thick

Steel rod, 8mm (5/16") in diameter

Steel rod, 12.7mm (1/2") in diameter

Leather or rubber for washers

The entire chain pump is shown in Figure 3. Details of this pump can be changed to fit materials available and structure of the well.

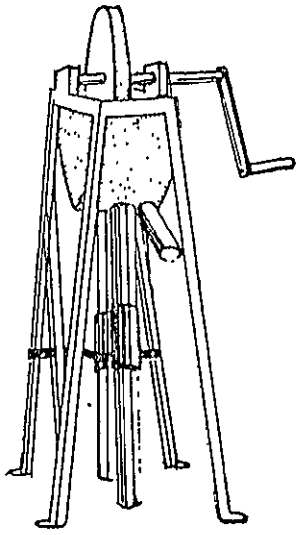


FIGURE 1

The piston links (see Figures 4, 5, 6 and 7) are made from three parts:

1. a leather or rubber washer (see Figure 4) with an outside diameter about two thicknesses of a washer larger than the inside diameter of the pipe.
2. a piston disc (see Figure 5).
3. a retaining plate (see Figure 6).

The piston link is made as shown in Figure 7. Center all three parts, clamp them together temporarily, drill a hole about 6mm (1/4") in diameter through all three parts and fasten them together with a bolt or rivet.

The winch is built as shown in Figure 3. Two steel discs 6mm (1/4") thick are welded to the pipe shaft.

FIGURE 2

LIFT	QUANTITY
6 METERS (18 FEET)	11 CUBIC METERS/HOUR (2906 GALLONS/HOUR)
3 METERS (9 FEET)	20 CUBIC METERS/HOUR (5284 GALLONS/HOUR
1.5 TO 2 METERS (4.5 TO 6 FEET)	25-30 CUBIC METERS/HOUR (6605 TO 7926 GALLONS/HOUR

Twelve steel rods, 12.7mm (1/2") thick, are spaced at equal distances, at or near the outside diameter and are welded in place. The rods may be laid on the outside of the discs, if desired.

A crank and handle of wood or metal is then welded or bolted to the winch shaft.

The supports for the winch shaft (see Figure 3) can be V-notched to hold the shaft, which will gradually wear its own groove. A strap or block can be added across the top, if necessary, to hold the shaft in place.

The pipe can be supported by threading or welding a flange to its upper end (see Figure 8). The flange should be 8mm to 10mm (5/16" to 3/8") thick. The pipe passes through a hole in the bottom of the trough and hangs from the trough into the well.

Sources:

Robert G. Young, VITA Volunteer, New Holland, Pennsylvania, Chapter

Water Lifting Devices for Irrigation, by Aldert Molenaar, Rome: Food and Agriculture Organization of the United Nations, 1956.

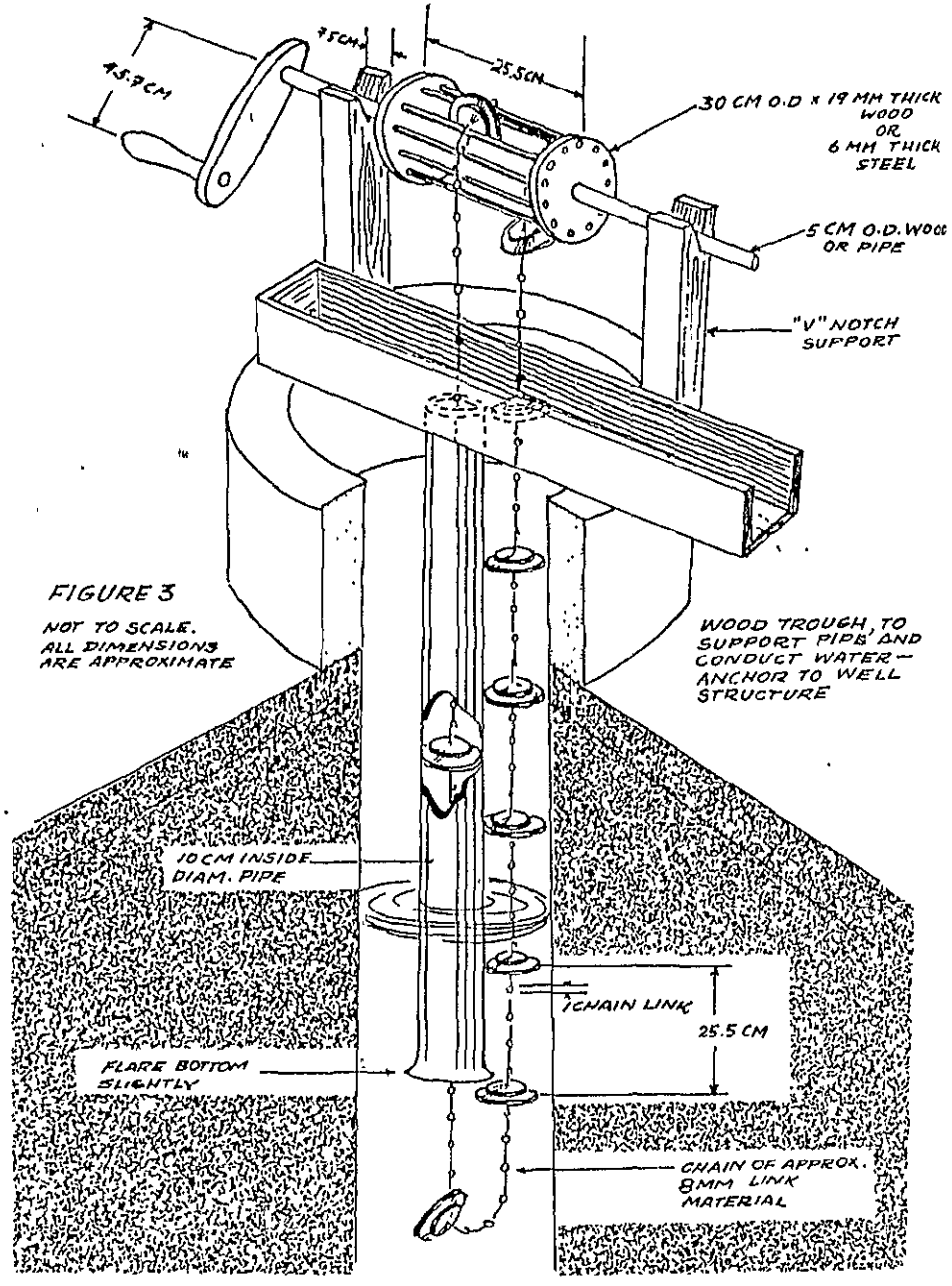
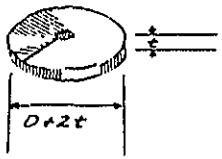


FIGURE 3

NOT TO SCALE. ALL DIMENSIONS ARE APPROXIMATE

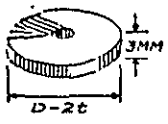
FIGURE 4
LEATHER WASHER



PIPE DIAMETER PLUS TWICE t

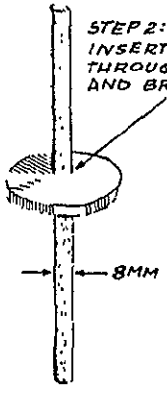
FIGURE 5

STEP 1: CUT CIRCULAR DISK AND DRILL HOLE IN CENTER



PIPE DIAMETER LESS TWICE THE THICKNESS OF LEATHER WASHER

STEP 2: INSERT ROD THROUGH HOLE AND BRAZE



STEP 3: BEND ROD ENDS TO LINK WITH CHAIN

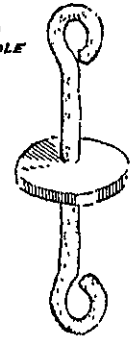


FIGURE 6
RETAINING PLATE

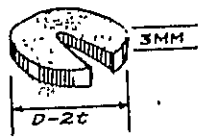


FIGURE 7
PISTON LINK
ASSEMBLED

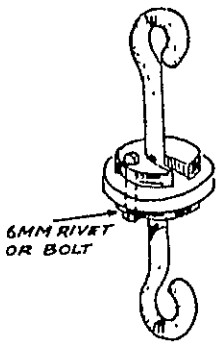
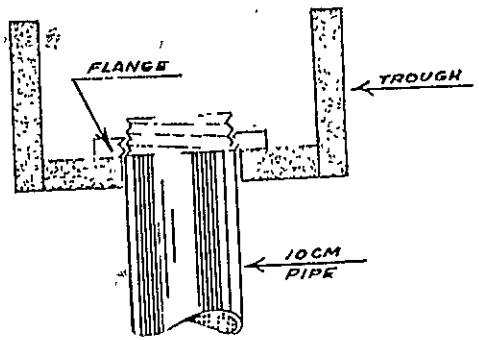


FIGURE 8 PIPE SUPPORT



INERTIA HAND PUMP

The inertia hand pump described here is a very efficient pump for lifting water short distances. It lifts water 4 meters (13') at the rate of 75 to 114 liters (20 to 30 U.S. gallons) per minute. It lifts water 1 meter (3.3') at the rate of 227 to 284 liters (60 to 75 gallons) per minute. Delivery depends on the number of persons pumping and their strength.

The pump is easily built by a tinsmith. Its three moving parts require almost no maintenance. The pump has been built in three different sizes for different water levels.

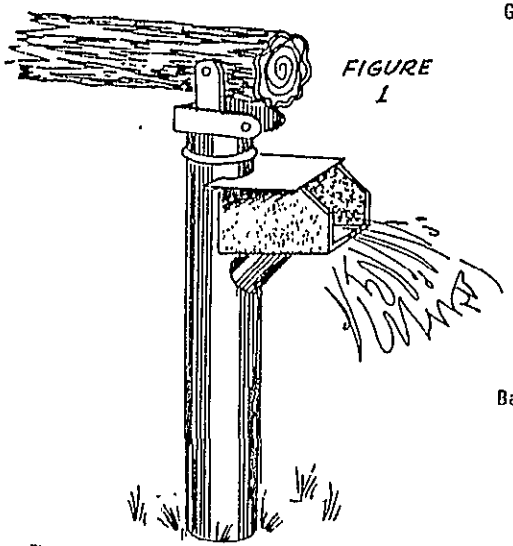


FIGURE 1

The pump is made from galvanized sheet metal of the heaviest weight obtainable which can be easily worked by a tinsmith (24 to 28-gage sheets have been used successfully). The pipe is formed and made air tight by soldering all joints and seams. The valve is made from the metal of discarded barrels and a piece of truck inner tube rubber. The bracket for attaching the handle is also made from barrel metal.

Tools

Soldering equipment

Drill and bits or punch

Hammer

Saws

Tinsnips

Anvil (railroad rail or iron pipe)

Materials for 1-meter (3.3') pump:

Galvanized iron (24 to 28 gage):

Shield: 61cm x 32cm, 1 piece (2' x 12 5/8")

Shield cover: 21cm x 22cm, 1 piece (8 1/4" x 8 5/8")

Pipe: 140cm x 49cm, 1 piece (55 1/8" x 19 1/4")

Top of pipe: 15cm x 15cm, 1 piece (6" x 6")

"Y" pipe: 49cm x 30cm, 1 piece (19 1/4" x 12")

Barrel metal:

Bracket: 15cm x 45cm, 1 piece (6" x 21 1/4")

Valve-bottom: 12cm (4 3/4") in diameter, 1 piece

Valve-top: 18cm (7 1/8") in diameter, 1 piece

Wire:

Hinge: 4mm (5/32") in diameter, 32cm (12 5/8") long

This pump can also be made from plastic pipe or bamboo.

conditioners, and storage. Work is being done to develop new low-cost support structures, increase efficiencies of power converters, and lower the costs of storage, as well as to examine new storage techniques. As these programs advance, the prices of complete systems could drop and system reliability will be improved. Present lifetime expectations are 20 years for modules, 10-12 years for power converters, and 8-10 years for storage (if batteries are used). It is hoped that costs of complete systems without storage will reach approximately $2/Wp by 1986.

Information on photovoltaic devices has become increasingly available over the last several years, but information on the needs of people in developing countries has only recently begun to flow to manufacturers. (See Appendix C for listing of recent publications on photovoltaics.)

RECENT APPLICATIONS OF PHOTOVOLTAICS IN RURAL AREAS

Telecommunications

In 1975, over 4,000 photovoltaic-powered educational television sets (ETVs) were installed in Niger and the Ivory Coast (Weiss 1976). The success of this system in education in rural villages has been demonstrated, and expansion is anticipated. An Ivory Coast firm projecting the production of more than 13,000 photovoltaic-powered sets in the next decade (Sloop and Watt 1979). Weiss and Pak (1976) estimate a worldwide demand of 10 MW for ETVs by the early 1980s and conclude that photovoltaic-powered sets presently have an economic advantage over alternative systems.

Another remote telecommunications application, operated since 1977 by the Mexican government, utilizes 36 W of photovoltaic power, operates a rural telephone station, and is unique in that all components of the system were designed and produced in Mexican laboratories. It is anticipated that 70 more stations will be installed in rural areas and a solar cell pilot production line is being set up to produce 20 kW/yr (Perez, *et al.* 1978).

Irrigation

In Mead, Nebraska, a 25-kWp irrigation system, larger than most rural applications, has provided important base-line information on silicon module reliability and system design (Figure 1). This project, sponsored by DOE, has shown a module failure rate of 2 percent in 2 years (Forman 1979) and has provided important statistical information on such aspects as soiling and cleaning (Forman 1978). In the 2 years that it has been in operation, the system has provided power with less down time than the local utility. Fur-

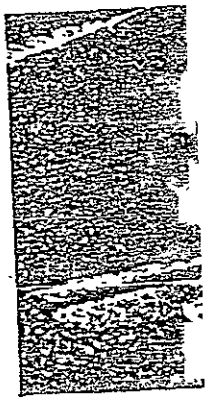


FIGURE 1 A 25
sponsored by DOE.

ther U.S. applicat
identified and ana
A study pertin
Aeronautics and
states that under
5-7 mi (8-11 km
blum, *et al.* 1978
pumping applicati
as systems becom
lead time is nece
systems will be pa
Several other s
in pumping applic
Campana, *et al.* 19
The Republic
tems (W. Mackie,
At least five syst
are used primaril
shows a 16-kWp
vide power for w
and cooling for th
Under a progr
ment (AID) and
more water pum
photovoltaic arr
ft³) of water st

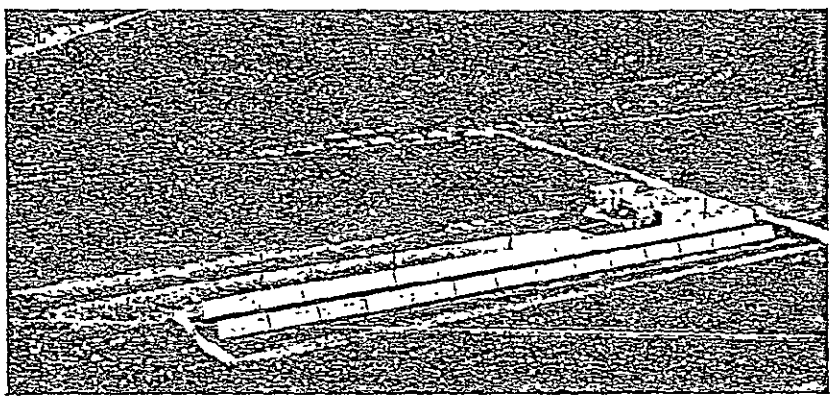


FIGURE 1 A 25-kWp photovoltaic-powered irrigation system at Mead, Nebraska, sponsored by DOE.

ther U.S. applications of photovoltaic devices to irrigation systems have been identified and analyzed (see Twersky and Fischbach 1978).

A study pertinent to irrigation systems conducted by the U.S. National Aeronautics and Space Administration (NASA) at its Lewis Research Center states that under present cost goals, a utility grid extension of greater than 5-7 mi (8-11 km) makes the use of photovoltaic systems attractive (Rosenblum, *et al.* 1978b). The study also projects a 6-GWp market in foreign water pumping applications, and a significant market penetration in 1981 or 1982 as systems become economically feasible. But the study cautions that a 4-year lead time is necessary to evaluate and test planned systems, and that those systems will be paced by costs, government attitudes, and sources of funding.

Several other sources have also presented prospects for photovoltaic power in pumping applications in rural areas (see Agarwal 1978; Sangal, *et al.* 1978; Campana, *et al.* 1976).

The Republic of Mali has had extensive experience with photovoltaic systems (W. Mackie, SERI, Golden, Colorado, personal communication 1979). At least five systems have been installed, most with French assistance, and are used primarily for pumping water in rural areas (Figure 2) Figure 3 shows a 16-kWp system being installed at a hospital. This system will provide power for water pumping, refrigeration for pharmaceuticals, and lighting and cooling for the operating rooms.

Under a program financed by the U.S. Agency for International Development (AID) and administered by the Solar Energy Research Institute, four more water pumping stations will be installed in four regions. The 2-kW photovoltaic array-powered stations will also feature 20-30 m^3 (706-1,059 ft^3) of water storage, and are a part of a completely packaged pumping

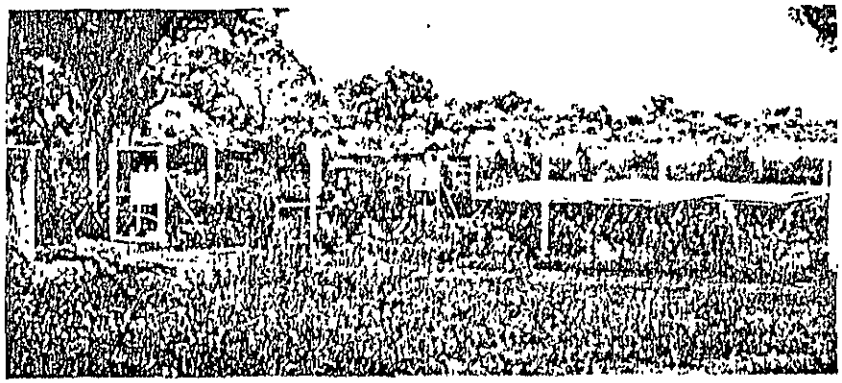


FIGURE 2 Remote photovoltaic-powered water pump in Mali. (Photograph courtesy of W. Mackie, SERI, Golden, Colorado)

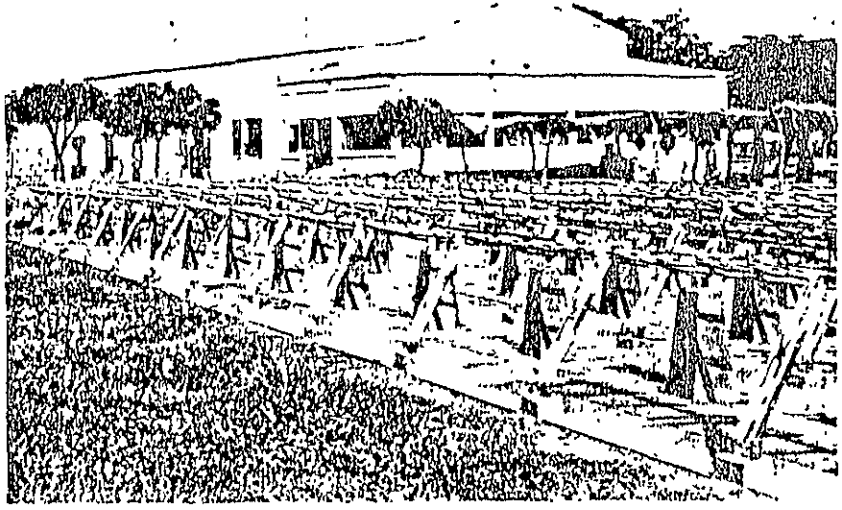


FIGURE 3 A 16-kWp photovoltaic array being installed at the Djiola Hospital in Mali. (Photograph courtesy of W. Mackie, SERI, Golden, Colorado)

system offered by Pompes Guinard of France. No electrical storage is planned for the systems, which will be installed by Peace Corps Volunteers.

Total Village Power Needs

Photovoltaic systems that meet the major electrical power needs of a village are also being implemented. It has been estimated that a 10-kWp system is

necessary to meet
Upper Volta or
demands would in
lighting, milling, re
tions.

One study of
countries conclude
cost of $1.60-$2
reduced to $.25-$
vantages of the m
lem of initial high

Two further st
village power syste
for foreign marke
24 Wp per person
DOE price goals a
second study an
diesel and utility
4 and 5, photov

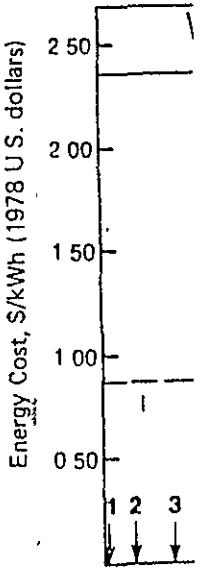


FIGURE 4 Photo
et al. 1979)

Pedal Power

INTRODUCTION

One of the most efficient mechanical devices developed by man is the bicycle, and pedaling is the key to the most efficient use of leg power. The thigh muscle (the quadricep) is the largest and most powerful muscle in the human body. Through pedaling, this muscle can be used to perform a variety of useful tasks.

Pedaling enhances the power of the legs, which are then relieved of the effort of standing or supporting the body. The usual pedaling speed, 60-80 rpm, uses leg muscles at their maximum efficiency. Studies have shown that this speed yields somewhat less than 0.1 hp (74.6 W). In some cases, professional cyclists have produced up to 1 hp for short periods of time.

Pedal power is particularly appropriate when small amounts of power are needed at irregular intervals, or when a mobile power source is desirable. Because many pedal power devices are lightweight, they can be carried easily to a worksite to power such devices as winnowers, threshers, and water pumps.

Pedal power units are sometimes referred to as "dynapods" (Greek for power and foot), and usually consist of a stationary bicycle frame, seat, handlebars, and pedals which drive a series of chains or belts. The number of revolutions per minute (rpm) can be changed by adding or subtracting pulleys or gears. Usually a flywheel is necessary to smooth out the high and low power output of a person's natural pedaling rhythm. The use of the flywheel assures constant speed and power to the device being driven by the dynapod (see Weir 1979).

During the past 5 years, new pedal power technologies have evolved that can be used in the transportation, agricultural, and domestic sectors of

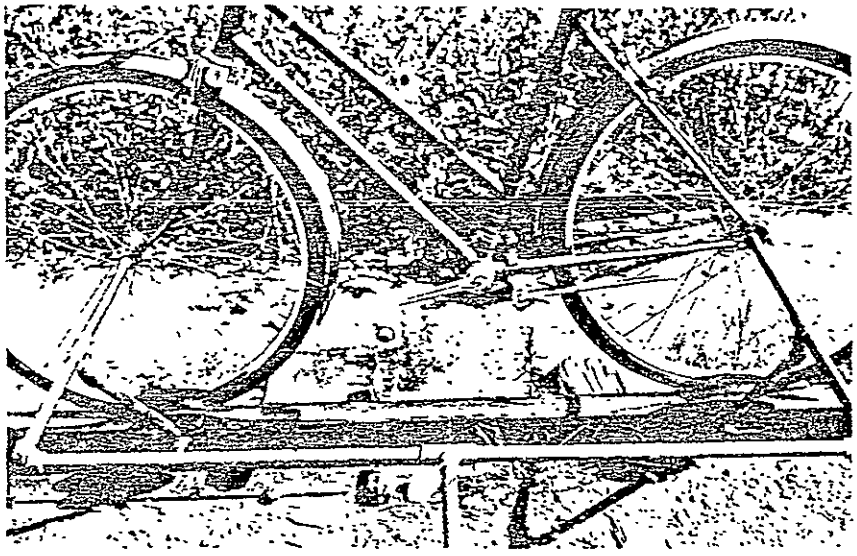


FIGURE 65 Details of railbike attachments. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

A U.S. inventor, Mark Hansen, of Onamia, Minnesota, has enlarged the concept of the railbike by building a vehicle that will support 2–3 people or 700 lb (315 kg) (see Hansen 1976).

AGRICULTURE

Pumping

Probably one of the oldest applications of pedal power is pumping water. Wood is an excellent material for constructing water pumps. In low salt-flat areas, corrosion of metal pumps would cause maintenance problems. In Taiwan, foot pumps made in the ancient Chinese way use few if any metal parts (see Figure 66). The water being pumped acts as a lubricant, making such a pump quite easy to operate. In large, flat, marshy areas, the water usually needs to be lifted about 2 ft (0.6 m) and the depth of the evaporation ponds is only a few inches. Two people work together to operate the pump as the power rotor has two sets of pedals.

At the International Rice Research Institute (IRRI) at Los Baños, Laguna, the Philippines, engineers have developed a small, lightweight, inexpensive foot-powered pump that will lift large quantities of water several feet, using only moderate amounts of human power. The operator simply stands on two footrests at either end of the pump and rocks back and forth (see Figure 67).

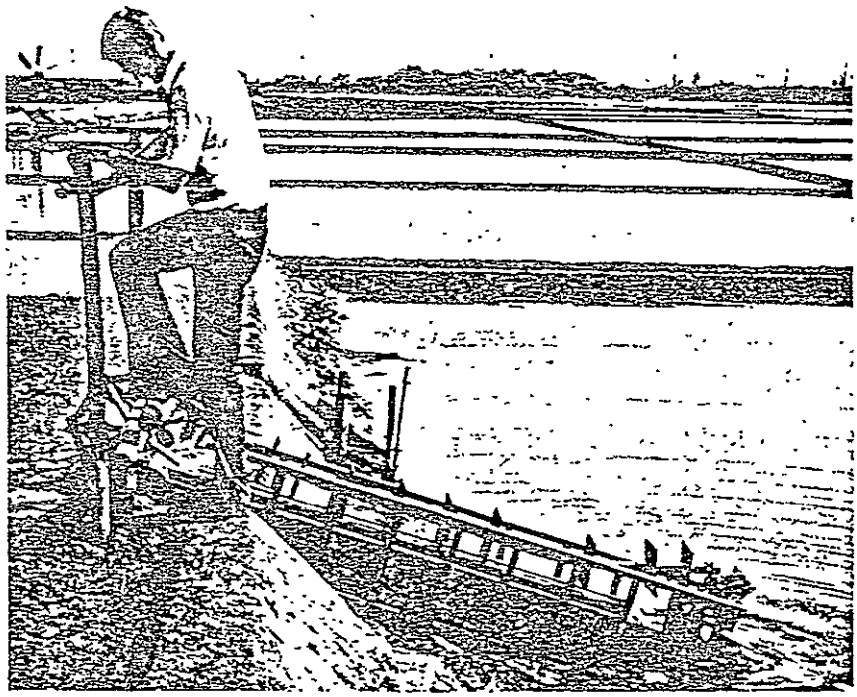


FIGURE 66 Old-style wooden water pumps used in Taiwan for raising sea water into salt-evaporation beds at a coastal town. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

This effort compresses a diaphragm, which forces water from the outlet valve. By operating the pump in a rhythmic manner, a continuous flow of water is pumped. It is estimated that the foot pump will cost only $25–$30 to manufacture. IRRI gives designs for its machines at no charge to fabricators throughout Asia.*

Pedal power can also be applied to existing hand pumps. Figure 68 depicts a pitcher pump; an activator rod from a reciprocating pedal power device can supply the up and down motion to pump water.

A simple, inexpensive (less than $5) centrifugal pump can also be attached to a pedal-driven device (Figure 69). These devices can pump 3,500 gal/hr (13,248 l/hr), sending water streaming out 30 ft (9 m) through a hose nozzle.

*More information on this technology is available from the International Rice Research Institute, Agriculture Engineering Department, Post Office Box 933, Manila, Philippines, and from Volunteers in Technical Assistance, 3706 Rhode Island Avenue, Mt. Rainier, Maryland 20822, USA.

FIGURE 67 Pedal pump designed by the International Rice Research Institute, Los Baños, Laguna, the Phillippines. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

Plowing, Cultivating, and Harrowing

The research and development laboratories of Rodale Press, Inc. (Emmaus, Pennsylvania (USA) have developed a pedal power farming system, the Mechanical Mule™ (see Figure 70). This two-person operation consists of a pedal power winch that is used to reel in a steel cable attached to a mobile tool carrier. The tool carrier can be equipped with a plow, harrow, cultivator, or other tools, all quickly interchangeable.

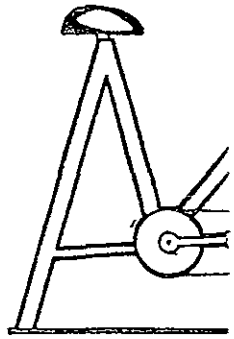


FIGURE 68 Pitcher p

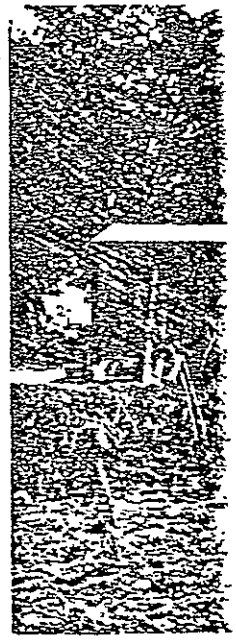


FIGURE 69 Pumpin
printed from *Pedal Po*
PA 18049)

Seated in the pec
den row (spade blad
cable attached to th
rier, equipped with

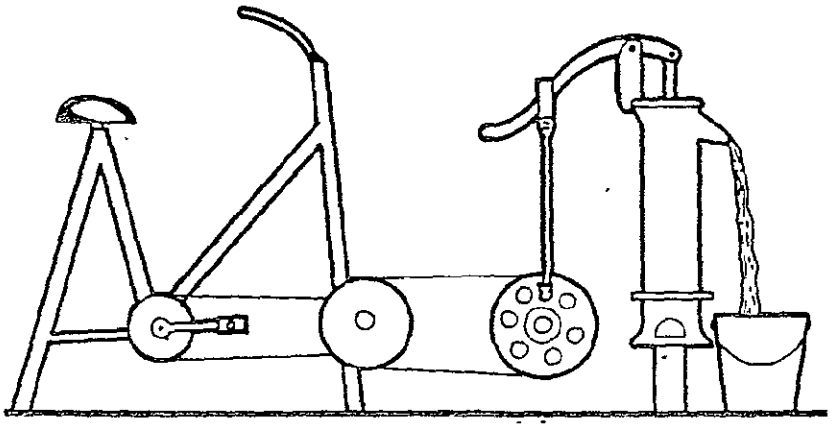


FIGURE 68 Pitcher pump (prototype).

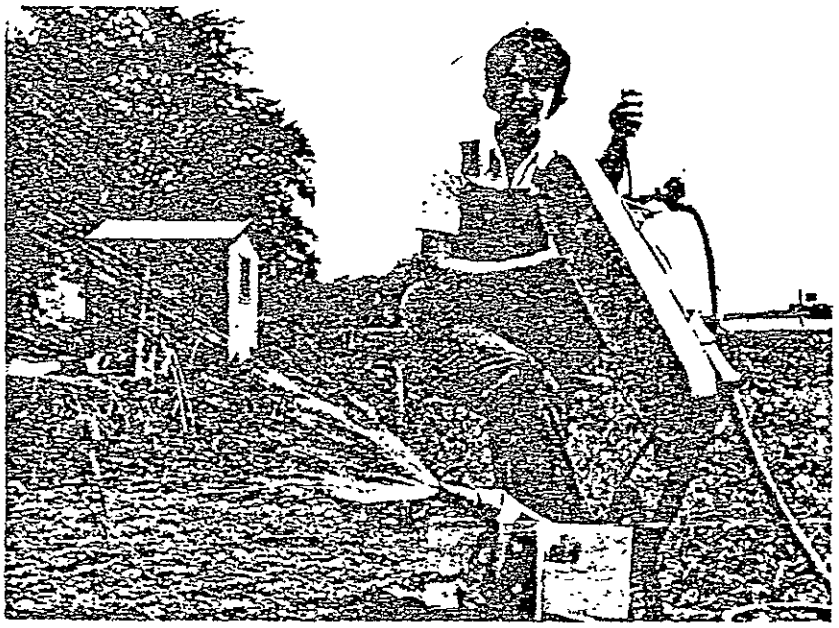


FIGURE 69 Pumping water using a centrifugal pump and a pedal-driven device. (Reprinted from *Pedal Power* © 1977. Permission granted by Rodale Press, Inc., Emmaus, PA 18049)

Seated in the pedal power unit which is positioned at the head of the garden row (spade blades keep it in position), the operator pedals to reel in the cable attached to the tool carrier, which is guided by a helper. The tool carrier, equipped with the right tool for the desired operation (say, a plow), is

FIGURE 70 Plowing operation using the Mechanical Mule™.

positioned at the foot of the same row. When the tool carrier reaches the head of the row, the operator stops pedaling and pushes a lever that slips the reel into "free-reeling" position. The helper then wheels the tool carrier to the foot of the next row, thus unreeling the cable. Simultaneously, the operator moves the pedal power unit to the head of the next row. This sequence is followed until the entire plot of ground is cultivated or plowed.

The pedal power unit or winch (Figure 71) is designed with a three-speed sprocket-and-chain drive (Figure 72) which permits over 1,000 lb (453 kg) of pull with normal pedaling effort. "Low gear" is used for jobs requiring a slow, powerful pull, such as plowing through heavy turf. "Second" or "high" gears are used for easier jobs, such as harrowing or cultivating. The pedal power is much faster than hand spading and raking. Because the unit's design is simple, repairs or adjustments can be handled using simple tools. The unit can be built for less than $150 in quantities of 25 units.

DOMESTIC APPLICATIONS

Most domestic chores require a stationary power source. The use of pedal power in such a capacity necessitates overcoming a number of problems, in-

PENDULUM PUMP

What is it?

A manually operated pump
- incorporating a new principle (the pendulum) to conserve energy, and a new material (PVC) to minimise friction, corrosion and deterioration.

Why do we need it?

As a minimum cost, minimum maintenance, solution to the problem of lifting irrigation water from wells, and to avoid the social/organizational problems associated with shared irrigation supplies.

Where will it work best?

Where high population densities and high water tables coincide, i.e., Northeastern India and Bangladesh, possibly the Nile Delta, and some places in Indonesia.

Who will it work for?

The smallest farmers, who with even the limited cash and energy resources available to them, can use it to produce enough to feed themselves and their families.

What will it cost?

Less than $100 (installed), with much of this being in labor and local materials contributed by the farmer, the rest locally manufactured.

How hard is it to work?

One man with this pump can lift 18 gpm, more or less steadily, from a depth of 12 feet. (Visualize carrying a gallon jug in each hand up a flight of stairs every 7 seconds!). There is no way to make this easy, regardless of the ingenuity of the machine employed, but if the alternative is going without food, that is not exactly easy either. In the course of a 120-day season, he may work, on the average, 5 hours per day, for a total of 600 hours.

What will he get for this effort?

From a half-acre of land he should get about 1200 lbs of rice, i.e., for each hour of work he gets about 2 lbs, or two days' food for a member of his family.

The Need for Improved Technology in Manual Pumping of Irrigation Water

by S. V. Allison[1/]

Background and Statement of Problem

1. Over an area exceeding 40 million ha in monsoon Asia, intensive crop production is possible only with irrigation. Soils are good and temperatures are sufficient for year round cultivation. Because of high annual rainfall, water resources are generally adequate. The principal problem is the difficulty of getting the water from wherever it is (underground, or in streams and ponds) onto the land, where it is needed to support cropping activities.

2. This situation, of course, provided the justification for innumerable irrigation works which have been built over the centuries. A wide variety of constraints are now operating however to prevent the rate of construction of new facilities from equalling the rate of increase of demand for food. Additional solutions are thus required.

3. Manual pumping shows promise for this purpose because:

a) these are typically labor surplus regions;

b) the costs of other energy sources continue to rise sharply and there is a continuing shortage of fuel;

c) the capital costs of individually operated manual pumping units are sufficiently low to permit their purchase by even the smallest farmers;

d) the energy requirements for pumping can be provided from within the smallest farm family;

e) the water output of manual pumping units can meet the entire irrigation needs of the small blocks of land typically owned; and

f) because of the happy match between resources and requirements, these units can be installed and operated without the need for cooperation between farmers, which has proved to be a major stumbling block for most other types of irrigation facility.

4. Manual lifting of irrigation water has, of course, been practised in Asia for centuries. Except where lifts were very low (less than 1 m) it has however been found too costly in countries which had the possibility

---

1/ October 1975 (Internal World Bank memorandum).

of one major rainfed crop per year; the economics of rainfed cropping kept food prices below the opportunity cost of the labor needed to produce more food by manual pumping. In more arid areas, where all cropping depended on irrigation, man/land ratios were lower and much irrigation was done by animal powered pumps. Where semi-arid conditions and high population densities coincide, as in China, manual pumping became and still is common.

5. The principal factor which has created the current need for manual pumping in South Asia in the course of the last few years is then the population increase, which has:

a) pushed the demand for food up faster than the supply, with the expected effect on food prices, and

b) made more human labor available at costs which are lower relative to the cost of food.

6. One of the most important limitations of the manual pumping approach is the balance between the amount of energy available in a (not very well nourished) human body, and the large quantities of water required in the irrigation of any crop, particularly rice. The critical nature of this balance means that, for manual pumping to pay, absolutely minimal quantities of energy must be wasted overcoming friction or lifting water which is then permitted to slip back down the well. It is in this respect that most currently available handpumps are unsatisfactory. They were designed primarily for drinking water purposes and conservation of the human energy input was never an important consideration.

Description of Improved Technology

7. Under the pressure of rising food costs and severe unemployment attention is again being focussed on this problem. There is now reason to believe that ingenious mechanical design, coupled with the use of new materials, can minimize energy losses to make manual pumping for irrigation purposes a feasible and attractive proposition.

8. One such design is illustrated in Fig. 1. The distinctive features here are:

a) elimination of the standard cast iron pump body, by expanding the upper 6 m of well casing to become the pump cylinder;

b) setting of a simple piston below the water table in such a position that water will be lifted directly rather than by suction, and the piston gasket (pump leather) will remain moist at all times instead of passing through the wetting and drying cycles which cause deterioration of gaskets in surface mounted pumps which have their pistons above the water table;

c) use of low cost PVC pipe with very smooth interior surfaces for all downwell components, eliminating the possibility of corrosion and minimizing energy losses due to friction. This pipe is easy

to transport and may be installed without difficulty by local artisans;

d) use of a ribbed and fine slotted PVC well screen, in which the ribs act to facilitate the development of a natural granular filter around the screen, and the slots are sized to pass the required fraction of fines -- and not more -- of the material from the surrounding aquifer;

e) use of a simply supported pendulum above the well, to maximize mechanical advantage and conservation of the energy expended in pumping.

9. The pump has been designed to use energy at a rate which can be sustained up to 5 hours a day, by a small man working under tropical conditions (i.e. about 0.067 HP). The actual horizontal force which has to be applied to the push handle is between 7 and 10 kg, for lifts of 3 and 5 m respectively.

10. With this energy input, the pump will perform as summarised on Fig. 1. Hydraulic performance has been tested successfully under laboratory conditions but not, to date, in the field.

11. A pump of this design will cost about $100 installed, as detailed in Annex 1.

Cost/Benefit Analysis

12. To obtain perspective on the economic merits of this design it may be compared with two principal alternatives: power-pumped shallow tubewells, and manually operated units using pump of designs currently in use. As all alternatives show economic returns well in excess of the opportunity cost of capital and range upwards, depending on the assumptions used, to well over 100%, a more relevant criterion for comparative purposes is the contribution of irrigation to the cost of the rice produced. The important variables and assumptions in this analysis are presented in Annex 1, and the results are summarised in Fig. 2.

13. Several conclusions can be drawn from Fig. 2. It appears that, except at very near zero wage rates, power pumping is substantially more attractive than manual pumping. This is certainly true from the engineering and economic viewpoints, but it is valid only within bounds defined by social and organizational constraints too complex to be neatly quantified. For a start the process of comparison implies that we have a choice, or must choose, between these technologies. The fact is that the power pumped wells are being installed throughout the region at a high rate and in fact about as fast as financial and organizational constraints permit. Under these circumstances what we would recommend is not that manual pumping installations should be supported instead of power pumps, but in addition to them.

14. Secondly, electricity is simply not available in some areas, so power pumping implies the use of an internal combustion engine. For the necessary degree of reliability this means diesel engines and these are not made smaller than about 4.5 HP. If one is used it means either:

a) producing enough water for 5 to 15 farmers, with associated requirements for organization or cooperation, or

b) leaving a costly piece of equipment unused for between 50 and 90% of the time it could be working.

15. Finally, it has to be emphasized that, with the minimum cost of a power pump installation being about $1,300, only the larger farmers have the cash, or the influence necessary to get credit instead of cash. The manual pumping alternative, by contrast, is biased toward the smaller farmer because, from the farmers' perspective, this approach is considerably more attractive financially when labor internal to the farm family is used for pumping. A farmer with more than 3 ha of land would be incapable of having a family large enough to irrigate it all by manual pumping.

Potential for Development

16. It is clear that manual pumping, by any means, is a practical proposition for irrigation only when the static lift is less than 5 m. There are substantial areas (probably 4 to 5 million gross ha) in the most densely populated parts of the Indo-Gangetic plain, where the water table rises to near or above the surface during the rainy season and then falls to 4 m or less before the onset of the next monsoon. This condition is typically reached only in April or May, while the winter rice crop matures in March and may even benefit from drying out in April. During the important irrigation months, December to February, the average lift will thus be less than 3 m.

17. Irrigation from wells of any type will hasten the depletion of the water table as shown in the following table:

Fraction of Area Irrigated (%)	Additional Depth of Water Table (m)	
	End December	End March
10	0.26	0.85
25	0.66	2.12
50	1.32	4.24

18. This suggests that, in 4 million ha, manual wells should not be installed to serve more than about a million ha. This would still require 3 million wells -- scope enough for a major investment program.

Next Steps

19. What is needed next is a series of tests, to ensure that the new pump functions as well in the field as it does in the workshop. Performance in terms of areas irrigated under different conditions, and the reactions of the farmers to the pendulum operating principle, need to be closely monitored through an entire irrigation season.

20. Only when this phase, which should, ideally, include 30 to 50 installations in differing areas, is complete will the concept be sufficiently proven to include in large quantities and major projects. At the present time we have several projects in the pipeline which may include manual pumping. Unless the pendulum principle is proven first, however, pumps of traditional design will be used, and project benefits will be significantly lower than if the human energy input was expended more efficiently.

TABLE I: Comparison of Pump Technologies

TECHNOLOGY	REF. NOS.	TYPE OF PUMP	MAXIMUM HEAD (METERS)	FLOW AT 5 METERS HEAD (LITERS/SEC)	NUMBER REQUIRED[b]	MANPOWER REQUIRED PER UNIT	FABRICATION
A. Human Powered							
1) Simple Hand Pump	1,3	suction/force	5-7/180	0.7 - 0.8	4 - 5	2[d]	Prefabricated materials required. Cannot be easily made locally.
2) Pendulum Pump	1,6	force	50 - 150	0.5 - 0.6	6 - 7	1	Prefabricated materials required. Cannot be easily made locally.
3) Rower Pump	1	suction	5 - 7	0.7 - 0.8	4 - 5	2[d]	Mostly local materials, but some materials may not be available.
4) Diaphragm Pump	1, 2	suction	5 - 7	0.7 - 0.8	4 - 5	1	Can be manufactured locally.
5) Bellows Pump	1	suction	5 - 7	0.7 - 0.8	4 - 5	1	Can be manufactured locally.
6) Archimedean Screw	3,7	force	0.5-1.5.	1.2 - 1.5	6 - 9[c]	2[d]	Can be manufactured locally.
7) Water Ladder	5,7	force	0.5-1.5	0.7 - 0.9	12 - 15[c]	2[d]	Can be manufactured locally.
8) Chain/Bucket Pump	3,4	force	20 - 50	0.8 - 1.5	2 - 3	2[d]	Can be manufactured locally.
B. Animal Powered							
1) Persian Wheel (Noria)	3,7,9	force	3 - 5	2 - 10	0.5 - 1.5	1 man plus 1,2 bullocks	Can be manufactured locally.
C. Other Energy Sources							
1) Wind Powered	7	suction	(250)[a]	variable[a]	a	-	Wind mill can be made locally; pump cannot.
2) Solar Powered	5,7,8	suction	(250)[a]	variable[a]	a	-	Cannot be made locally.
3) Biogas Powered	7	suction	(250)[a]	variable[a]	a	-	Digester can be made locally; pump cannot.

NOTES: [a]Dependent upon local conditions, size of pump, etc. See reference 7.

[b]Number required to pump 100 m^3 water, 5 meters of head, in 8 hour day.

[c]To lift 5 meters, 3 units in series are required

[d]Two men working in shifts.

TECHNOLOGY	RELATIVE COST	LIFETIME	COMMENTS
A. Human Powered			
1) Simple Hand Pump	L-M	4-8 years	Requires frequent maintenance; must be located directly above source.
2) Pendulum Pump	L-M	4-8 years	Requires frequent maintenance; must be located directly above source
3) Rower Pump	L	2-5 years	Some maintenance required
4) Diaphragm Pump	L	≅800 hours	Some maintenance required; short lifetime
5) Bellows Pump	L	≅800 hours	Some maintenance required; short lifetime
6) Archimedean Screw	L	8-10 years	Appropriate for very low lifts (up to 1.5 m) but can possibly be made to lift higher; little maintenance required.
7) Water Ladder	L	4-8 years	Appropriate for very low lifts (up to 1.5 m) but can possibly be made to lift higher; little maintenance required.
8) Chain/Bucket Pump	L	8-10 years	Must be located directly above source.
B. Animal Powered			
1) Persian Wheel	L	10-15 years	Simple construction; long lifetime must be partially located directly overhead of source.
C. Other Energy Sources			
1) Wind Powered	H	15-20 years	High initial cost; long lifetime; windspeed data required; not suitable for locations with little wind; little maintenance
2) Solar Powered	H	15-20 years	Very high initial cost; long lifetime; relatively maintenance fre
3) Biogas Powered	H	15-20 years	Requires constant input of organic material for digester; long lifetime; frequent maintenance required

NOTES: L = Low M = Moderate H = High

A. Detailed Cost Estimate

Item	Quantity	Cost ($) Local	Foreign	Total
Upper well casing (120 mm dia.)	6 m	-	18.00	18.00
Lower well casing (37.5 mm dia.)	11 m	-	22.00	22.00
Well screen (37.5 mm dia.)	5.5 m	-	11.00	11.00
Pump		12.00	12.00	24.00
Installation		15.00	-	15.00
		27.00	63.00	90.00
Contingencies		3.00	7.00	10.00
		30.00	70.00	100.00

B. Variables and Assumptions in Cost/Benefit Analysis

	Power Pumped Shallow Well	Manually Pumped Present Design	Manually Pumped New Design
Capital Cost ($)	1,300	70.00	100.00
Area Irrigated (ha)	6	0.13	0.25
Incremental Rice Production (tons/crop)	15	0.45	0.825
GVP at $200/ton	3,000	90.00	165.00
GVP/Capital Investment	2.3	1.28	1.65
Pumping Energy Use			
Power (gals diesel)	134	-	
Manual (kg rice)	-	30.00	
Value of Energy Consumed			
Diesel price range (0.40 - 1.00/gal)	53.60 to 134.00		
Rice price (.20 cts./kg.)	-	6.00	
Operating Labor Requirements (man/day/crop)	12	120	
Labor Costs ($/crop) (Range $0.10-1.00/day)	1.20 to 12.00	12.00 to 120.00	

2.4 Power Requirements

The power requirements for an irrigation pump are basically determined by the amount of water to be lifted per unit time--the discharge rate--and the total height or head it must be lifted. The total head consists of the suction head--the vertical distance from the water surface in the well to the pump mechanism--and the discharge head--the height the water must be pushed beyond the pump. In addition, allowance must be made for pump efficiency and for losses in the pipes and distribution system.

Pumps are classified as high and low lift. A low lift pump is surface mounted and used wherever the water table is high enough that the water is within suction distance of the pipe. In theory, suction distance is 34 feet, but friction, leakage and efficiency considerations limit it to no more than 30 feet; 24 feet or under is preferred. A high lift (deep well) pump is used for low water tables; it is placed within the well casing so that it is within suction distance of the water. In some instances, the pump is submerged in the water. Discharge head is not limited by atmospheric pressure as is the suction head, theoretically it is limited only by pump power and friction within the discharge piping, however, insufficient discharge head or excessive flow can cause cavitation. In U.S. designs, the maximum lift, or discharge head, per stage for centrifugal pumps is usually 250 feet.

The power required to pump water at a rate of V m^3/hour through a total head of y meters is given by the relation $P = \frac{V(m^3/h) \times y(m)}{272 \times E}$ where P is in h.p. and E is the pump efficiency.

Given a particular lift and volume requirement, an electric or diesel motor and pump can be matched to the need. The many small holdings in developing countries make practical pump sizing for the individual farmer difficult. The majority of farms are less than 2 hectares (5 acres), which for most crops means a water requirement of about 4-18 m^3/h or an average of about 12 m^3/h (539 GPM).[12] While the water table varies, it is within the range of low lift pumps in many regions (in some delta areas the water sources is a stream). Usually a short discharge pipe empties into a ditch, with little discharge head; in fact, pump cavitation may be a problem due to lack of water in the discharge pipe. Generally, only a small pump and prime mover at dispersed locations is required. In those few areas which are electrified, this means a high cost for the power distribution network. Diesel pumps are available, but the smaller sizes cost more per output horsepower and require more maintenance. Also, because the market in smaller size pumps is more volatile, spare parts, even at the manufacturers level, can be a problem. Thus, larger pumps--sometimes larger than necessary--are used where possible, usually hooked into systems covering several farms or wheel mounted and relocated, resulting in a complex irrigation system. Sometimes this is done by cooperative groups and sometimes the government provides operations and maintenance personnel.

Using the pumping conditions described above--12m^3/h with a total head of seven meters--works out to a theoretical horsepower delivered to the water of about 400 watts to meet the average requirement, assuming a pump

efficiency of about 60 percent. To meet peak requirements would require twice this amount. Allowing for losses, this means a pump of about 1/2 kW to 1 kW size is needed.

For the purposes of this study, we can distinguish the following four types of pumping systems applications:

- Low head, low volume rate pumping: This is the case for the majority of small farmers with farm sizes below 2 ha. Power requirements range from about 400 watts to 1 kW.

- Low head, high volume rate pumping: This is the requirement for farmers operating farms in excess of, about 5 ha. Their power requirements would normally be in the range of 2 to 5 kW.

- High head, low volume rate: This application is suited for drinking water supplies to small rural communities in arid areas and for watering livestock. For a community of 500 persons drawing water from a deep well with a head of about 30 m, the power requirement would be about 500-600 w.

- High head, high volume rate: This would be the case for large farms in arid areas with deep water tables. Power requirements would be in excess of 10 kW to as much as 30 kW (e.g., the Bakel project in Senegal or the Arizona, Nebraska and New Mexico solar pumping projects).

SECTION III
CONVENTIONAL TECHNOLOGIES

3.1 Diesel-Powered Pumps

Diesel engines are one of the two primary sources (besides humans and animals) for irrigation pumping. They are manufactured in many countries and are available throughout the world. The advantage of diesel power relative to electricity, the primary alternative, is that a diesel engine can be operated anywhere and its fuel can be transported. For this reason, it is the primary mechanical power source in rural regions. A diesel engine has three disadvantages, however: its weight and size, which make it difficult for small farmers to transport; the need for a trained operator/mechanic; and its fuel costs.

Transport is a problem because roads to many farm areas are essentially dirt tracks and the vehicles used are carts or light trucks. Since a diesel engine with attachments would weigh about 250 pounds, the farmer has a difficult task. For this reason alone, most pump installations require outside aid.

The engine requires lubrication, cleaning and adjustment to maintain it. Untrained operators and difficulties in getting parts delivered, result in higher operating cost and more service outlays than would be expected from review of manufacturers data.

The major drawback to diesel is the difficulty of obtaining clean fuel and the cost of that fuel if it can be obtained. Reports indicate that diesel pump engines break down three times more often than electric motors.[13] The most frequent repair problem cited was "replacement of nozzles and plungers" which are part of the fuel injection system and are damaged by dirty fuel.

The primary diesel engines used for water pumping range in size from about 3 to 20 horsepower at 1500 to 1800 RPM. While higher speed engines with more horsepower per unit weight are available, the slower speed engines normally have a longer life and fewer maintenance problems.

Price Ranges and Energy Cost

The deciding factor between diesel, solar or any other energy form will probably be its cost per unit of energy output. The hourly cost per horsepower for a diesel engine is the sum of its capital recovery, maintenance and fuel costs. These are computed in the following paragraphs for estimated 1985 costs.

For an engine rated at a maximum hp Pr by the manufacturer, usable hp (P) is somewhat lower depending on ambient conditions and the kind of operation the engine is used for. It can be determined from the relation [14]

$$P = P_r X \text{ (rating factor)}$$

where rating factor = {100 -(% altitude correction + % temp. correction = % reserve correction) } / 100.[14]

Altitude and temperature corrections are specified by the manufacturer, heating value corrections are related to the ratio of the higher heating val (HHV) to the lower heating value (LHV) of the fuel used, and reserve correction is a safety factor allowance to permit design output under variou operating conditions depending on application (for irrigation pumping, recommended % reserve correction is 20%).

For purposes of evaluating energy generation costs, the net effect of a rating factor different from unity is to increase capital costs of engines over manufacturers' list prices, as a lower rating factor implies th a larger capacity engine is needed to deliver the same usable power. Since are interested in applications to irrigation, we assume a rating factor of 0 (taking % reserve correction as 20% and 10% for other corrections which are site-specific).

Cost Analysis

Recent price checks indicate that the 1980 price of a U.S. manufactured 3.3 HP, 1800 RPM engine with clutch is $2,100.00.[15] A 20 HP, 1500 RPM engine with clutch is $7,300.00. Both prices are for delivery f.o.b Baltimore. Comparison with 1975 prices for the same engine indicates that cost escalation has averaged 15 percent per year over the past five years. (that basis, the 1985 price of a 3.3 HP engine would be $3,400.00. Subsequent checks showed that engines were being manufactured and sold in India for abou the same as the U.S. price.[16]

The useful life of the diesel engine we are discussing is estimate to be eight years at about 1200 hours of use per year. This assumes that irrigation service is seasonal and that the interval between seasons is used for repairs. The estimated life, which may be optimistic, is based upon literature review and observation of actual examples. For an engine of 3.3 delivered for $3,400.00 in 1985, the yearly capital charges are computed from

$$R = C \frac{i(1 + i)^N}{(1 + i)^N - 1}$$

where C = initial cost of $3400.00
i = interest charges assumed as 12%
N = life of asset, taken as eight years

or:

$$R = 3400 \frac{.12(1.12)^8}{(1.12)^8 - 1}$$

$$= \$685.00 \text{ per year}$$

On the basis of 1200 hours use per year, the capital recovery cost is $0.57/HR.

BEST AVAILABLE COPY

Cost for maintenance and operations exclusive of fuel are reported as ranging from about 3.5¢/HR to 5¢/HR in India in 1975, in Bangladesh 5¢/HR in 1976.[17 18] These figures include the price of parts, lubricants, and labor. Using 3.5¢/HR. for the 3.3 HP engine and an escalation rate of six percent a year, on the assumption that local labor costs will escalate slowly, results in a 1985 maintenance cost of approximately 8¢/HR.

Fuel is becoming the single biggest cost item. The U.S. manufacturer of the engine being considered lists its fuel consumption as .231 kg/HP-HR. This equates to 0.09 gal/HP-HR. Studies show that under field conditions, fuel consumption is closer to 0.3 kg/HP-HR. Thus, at an output of 3 HP, the engine would use .27 gal of diesel fuel per hour. The delivered price of fuel in the less developed countries varies with supply and with the degree of government subsidy. A recent survey indicates that the price of diesel varied from $.65/gal in India, where it is subsidized, to $1.00/gal in Singapore.[19] The average for the countries in the survey is $.86 per gallon. The cost to transport the fuel to its place of use can be considerable, and has been reported to be as much as the price.[20] On that basis, a 1985 price of $1.50 per gallon is assumed as a conservative figure, amounting to a yearly escalation in fuel and delivery costs of about 7.5 percent. At a fuel use of .27 gal per hour for 3 HP output, the fuel cost then will be approximately $.41/HR.

In summary, the hourly cost of operation of a 3.3 horsepower diesel pump used 1200 hours per year will be:

	$ Per Hour
Capital Recovery	$ 0.57
Maintenance	.08
Operations	.41
Fuel	
Total Hourly Cost	$ 1.06
Cost per HP/HR (3 HP effective output) =	$ .35

For a given engine life and interest charges on capital, current and projected fuel costs imply that operational components of the cost, largely fuel, dominate when the number of hours of operation increases above a certain amount. Improved maintenance and scheduling to prolong engine life are the best course to reduce overall cost, given the fact that fuel costs are beyond the farmers control.

Estimated Engine Life

The estimated life of the diesel engine will be assumed to be eight years for the purposes of calculating the annual charges on capital investment. Manufacturers indicate that, on the average, 20,000 hours of running time will be achieved before a major overhaul or replacement is required. Experience in India and Bangladesh suggests that life in the field is about half this based on an average use of 1200 hours per year.[21 22]

Operational/Maintenance Experience

Internal combustion engines require more frequent maintenance, in general, than electric motors. In LDCs, the lower cost of labor (repairmen etc.) may frequently be balanced by the higher costs of obtaining spare parts. U.S. experience suggests that 1.5 percent of the capital cost be ta as the annual cost of maintenance of a diesel powered irrigation pump.[23] D gathered in India indicate the same cost to be about 5¢ per operating hour. Perhaps 3¢ of this could be attributed to engine repair and maintenance alo

3.2 Electrically-Powered Pumps

Electric motors are manufactured in many countries in a complete range of sizes from fractional horsepower to thousands of horsepower for us with alternating or direct current and at variable or constant speed. Thus is fairly easy to select a motor to match pumping requirements and power needs.

In addition to widespread availabililty, electric motors have oth advantages. Compared to internal combustion or Rankine cycle engines, they are lighter per horsepower, are simpler to operate, and require minimal operator training and less maintenance.

All of the advantages of electric engines can be offset in the absence of an electric power grid. In many developing countries single tran mission lines do not cover any significant area. In addition to the small area, single line coverage can cause reliability problems. For this reason, farmers in Punjab and West Uttar Pradesh in India who have the financial resources maintain a diesel pump as a backup.[26]

In all instances where power is available, the electric motor is cheaper, smaller and simpler to operate than the diesel. Economic compariso between electric and any other system is complicated by varying rate structures which do not always reflect the true cost of the electricity.[24,25] Nevertheless, due to its ease of operation and its apparent low energy cost, the electric motor will likely remain the preferred power source where electricity is available.

Price Ranges and Energy Cost

Operating cost for an electric motor, as with diesel, consists of the capital, maintenance, and fuel or electric power costs. The capital cost of an electric motor varies radically with motor type, housing, voltage, and type insulation. At current prices for delivery in the Washington area, a General Electric, 3 HP 1800 RPM, 230/460 V pump motor retails for $250.[27] Based on 15 percent per year escalation the 1985 cost would be $500.00. Life expectancy of electric motors is longer than that of internal combustion engines--frequently over 20 years in an enclosed space with proper maintenance--though smaller motors tend to have a shorter life span. In addition, the literature indicates that service life in developing countries is in the range of ten years. This, plus consideration of the damp and dusty working environment which usually exists, leads to the conclusion that ten years is a conservative estimate for the capital recovery time. On that

basis, annual capital recovery costs for a $500.00 motor using an annual interest of 12 percent and a ten-year life is $88.49. On the basis of 1200 hours of operation a year, the capital recovery charges would be $.073 per hour.

Maintenance costs for electric motors in the U.S. are very low, but costs per hour are $.03 in India and was $.02 to $.025 in Bangladesh.[28 29] Escalating the $.03/HR amount at six percent a year results in a 1985 cost of approximately $.04/hour. Operating cost for an electric motor depends on the tariff established by the company or government monopoly which delivers the power. In some instances the delivered rate does not reflect the true cost of power, because the government desires to stimulate power use. Thus, there is considerable debate about "true" power cost. The actual price to the farmer in 1978 varied from a low of $.03/kWh in India to a high of $.049/kWh in Malaysia.[30 31 32] Taking $.04 as an average figure and assuming escalation of 7.5 percent per year (as with diesel fuel) yields a 1985 price of $.066/kW. The efficiency of electric motors varies with size, i.e., larger motors are more efficient. Manufacturers information indicates that small engines have an efficiency of 80-85 percent. At 80 percent efficiency, a 3 HP engine uses about 2.8 kWh/HR which comes to $.186 per hour.

In summary, the typical energy costs per horsepower hour for a 3 HP engine which operates 1200 hours a year for 10 years are:

			$/HR
Capital Recovery			.073
Operations	Maintenance	.04	.226
	Electricity	.186	
Cost per hour.			.299
Cost per horsepower hour			.099

electricity accounts for = 60%

The above price to the farmer is a subsidized cost; while apparently inexpensive, the use of electric motors is restricted to the relatively small areas which have access to electricity.

3.3 Traditional Water Pumping Systems

The other power sources used for pumping in the developing countries are human and animal power coupled to relatively simple systems of levers, wheels, counterweights and buckets. They are the predominant systems today, particularly for shallow wells. In this instance, a shallow well is defined as one where the water table is less than 30 feet below the top of the well.

Human-Powered Pumping Systems

Human powered devices for raising water have existed since the first need to distribute water on a field or to raise it for drinking. In general, they can be classified as hand- or foot-powered, and divided within those groupings into those devices which do and do not amplify muscle power. There are many versions of these devices which vary by detail and names from country to country.

Hand-operated devices start with simple scoops or buckets and progress to the counterpoise lift. The counterpoise, which has various loc names, is constructed by hanging a bucket from one end of a pivoted pole an attaching a rock or mud counterweight to the opposite end. The counterweig permits lifting a larger bucket with less effort. The depth of the well an height of the lift is controlled by the length of the pole and of the rope from which the bucket hangs. Another hand powered water lifter uses the cr and windlass systems to lift buckets or scoops of water to the top of the well. In addition, the United Nations and the Agency for International Development both have had programs for development of a simple hand pump adaptation of the lever handled reciprocating farm pumps for village wells.

A unique type of hand pump is the enclosed helix, said to have be invented by Archimedes and still called the Archimedean Screw.[35] One end o the device, which ranges up to about eight feet long, is inserted in an irrigation ditch and the other end is propped over the bank. As a crank attached to the central shaft is turned, water is scooped into the bottom of the tube, the rotation forces it up the internal helix, and it is dumped out of the upper end.

Foot-powered devices which use leg muscles and body weight result more power and/or can be operated for a longer time than hand-powered pumps. The "Plcottah," a foot-powered counterpoise, is used for wells. A bucket is suspended from the end of a beam which is much larger than in the hand-operated version. In this instance, the counterweight is provided by one or two men who walk back and forth on footholds in the top of the beam. In the Far East, farmers use foot-powered paddle wheels. The shaft or axle of the wheel is extended on each side and foot treadles are fastened to it. In so instances, the bottom of the paddles are box-shaped. What might be consider a variant of the paddle wheel is the water ladder, in which wooden paddles mounted on an continuous chain are enclosed in a trough. At each end, the chain runs over a sprocket; the ladder is powered by foot treadles mounted c the shaft which supports the upper sprocket.

Animal powered devices are variants of those described above but with walking animals providing the power source. In some instances, the animal merely walks away pulling a rope over a windlass, thereby raising a bucket. Another version has the animal attached to a pivoted sweep with the lift chain attached to the opposite end. As the animal walks in a circle, t rotary motion of the sweep transmitted over pulleys alternately raises and lowers a bucket.

One of the most widespread animal powered devices is the many variations of the "Persian wheel". In its basic form, this is a large vertical wheel with buckets mounted on the periphery; the shaft of the wheel is extended and a cogwheel or gear is mounted on its end. This gear meshes with a larger horizontal gear pivoted on a vertical shaft. The shaft in turn supports a lever which the draft animal rotates by walking in a circle. In some models, the vertical wheel acts as a sprocket for a chain of buckets which descend into a well.

BEST AVAILABLE COPY

Cost

The cost of lifting or pumping water by human or animal power varies from country to country and even seasonally with the cost of labor and the cost of owning and feeding the animals. The one constant factor is the number of personnel and draft animals used and the time they are used to lift a specified quantity of water. This information can be computed from data in the literature. Tables 5 and 6 give the time in hours and the type labor involved to lift one hectare-centimeter (water needed to cover one hectare to a depth of one centimeter--about 26,240 gallons) a distance of five feet. During the irrigation season, a one hectare field would need that much water every one to three days, depending on the crops and the region.

Pros and Cons

Obviously, human- and animal-powered pumps are much slower than diesel- or electric-powered ones. Their advantage is that they are made of low cost local material with indigenous labor. Furthermore they are familiar items requiring simple maintenance. If labor is cheap and, available and the required water output is low, human- and animal-powered pumps can be used, but, the low output would restrict them to small farms or to areas which need relatively little irrigation. Use on a small farm implies operation by the owner-farmer; in this context, the time required to pump water becomes significant because it is time not available for other tasks to increse food output. Also, the humans and animals which provide the pump power are, themselves, consumers of the scarce food produced.

TABLE 5

ELAPSED TIME TO LIFT 1 HA/CM OF WATER 5 FEET (1.5 METERS)[36]

METHOD	TIME (HOURS)	WORKERS
Persian Wheel	4.5	Pair of bullocks & 1 boy
Counterpoise Lift	14.3	2 men in shifts
2 Archimedean Screws*	6.7	4 men in shifts
2 Water Ladders*	11.1	4 men in shifts

*2 devices operating in series.

TABLE 6

ELAPSED TIME TO LIFT 1 HA/CM OF WATER 30 FEET (9 METERS) FROM WELL[36]

METHOD	TIME (HOURS)	WORKERS
Persian Wheel	11.0	Pair of bullocks and 1 bo
Self Emptying Bucket	14.3	Pair of bullocks & 1 man
Rope & Bucket	6.0	2 Pairs of bullocks & 3 m

Current cost: $8/peak watt i.e. $8000/peak kW

SECTION IV
SOLAR WATER PUMPING SOURCES

Depending. At 15% discount rate & projected diesel fuel cost of 35US¢/liter photovoltaic powered pumping is competitive with the least-cost fossil fuel alternative

4.1 General

The potential for using solar power in water pumping applications has been recognized for some time. This section covers the state-of-the-art of various solar technologies along with cost analyses and a look at existing installations around the world.

Cabort $1300 per peak kW

4.2 Photovoltaic Pumping Systems

Photovoltaic (PV) arrays convert sunlight directly into electricity (DC) through the photovoltaic effect. The basic element of the array is a solar cell consisting of suitable n-type and p-type semi-conducting materials joined together at a junction. The incidence of a quantum of light creates positive and negative charge carriers ("holes" and "electrons") which drift across the junction setting up a voltage. By attaching positive and negative contacts on the p- and n-type layers, current can be caused to flow in an external circuit.

Semi-conducted materials used for constructing arrays include mono-crystalline silicon, polycrystalline silicon, cadmium sulfide, gallium arsenide and others. To date the most operating experience has been with mono-crystalline silicon. Almost all commercially available solar cells are manufactured with silicon, although one manufacturer claims near commercialization potential for a thin film CdS/CuS cell.[37]

PV arrays were originally used to provide power for space applications. With a cost decline from around $300/peak watt to the current $7-10/peak watt, PV arrays have become cost effective for use in remote terrestrial applications such as powering navigation buoys, telecommunication equipment, anti-corrosion pipeline equipment, railroad signals, etc.

Numerous practical designs for PV water pumping systems have been proposed. The simplest PV water pumping system, illustrated in Figure 1, consists of a solar array without battery storage providing power to a DC motor which drives a centrifugal pump through a mechanical (shaft) transmission. More than 60 such systems have been installed and operated by Pompes Guinard in Africa and the Mediterranean area. The inclusion of a power conditioner or an electronic tracker which maximizes the output of power from the array under differing insolation conditions is claimed to offer considerably improved performance in matching pump output to the array output. Other systems which use battery storage to improve system performance or which use an AC motor are illustrated in Figure 2. The use of AC motors can simplify the choice of motor-pump combination since AC induction motors are available very cheaply in almost all sizes relevant to water pumping needs. On the other hand, use of an AC motor necessitates a DC/AC inverter and batteries which add considerably to the cost of the system.

FIGURE 1

PHOTOVOLTAIC WATER PUMPING SYSTEM WITHOUT STORAGE

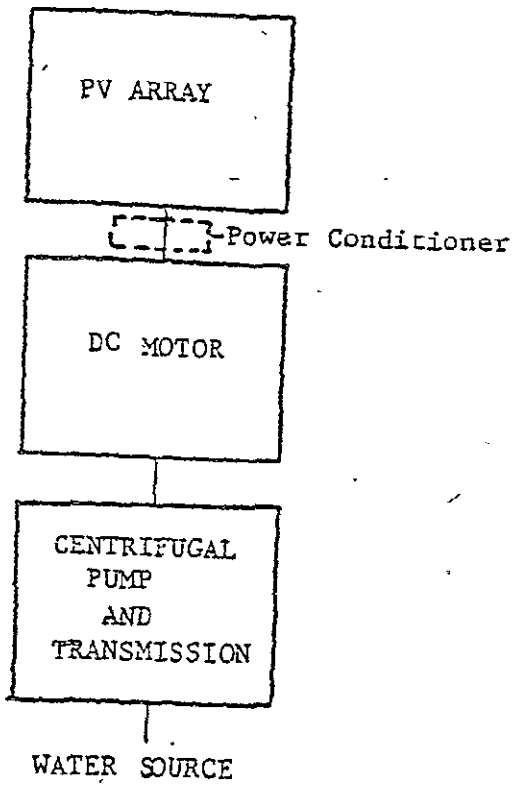
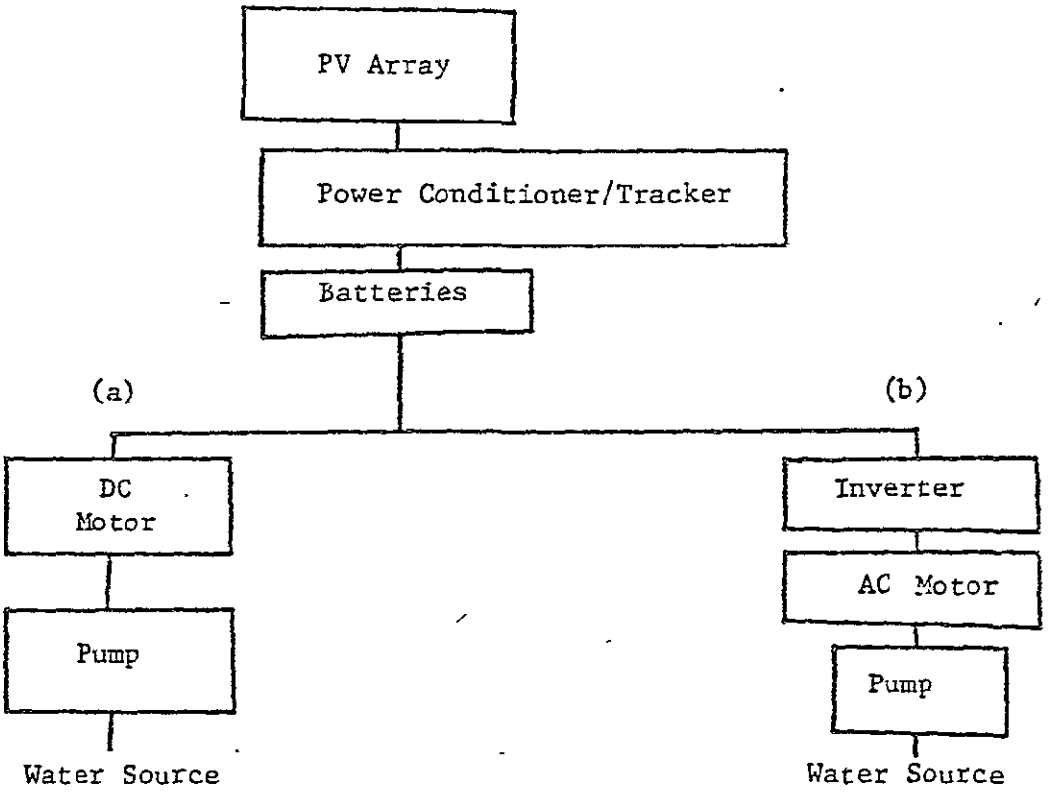


FIGURE 2

PHOTOVOLTAIC WATER PUMPING SYSTEM WITH STORAGE



(a) DC Motor
(b) AC Motor

The power output of the PV array is proportional to the irradiance. It is possible to increase the output of a given array through optical concentrators (mirrors or lens) and, since the PV array is the most expensive component of the system, this is generally cheaper than building a larger array. Since concentrators use direct radiation, however, they require tracking of the sun and this is an extra complication and expense. Moreover, concentrating sunlight would also increase the temperature of the array. This requires a cooling system to avoid loss of power (and possible damage) since cell voltage decreases by about one percent for every 2°C. rise in temperature. For a small water pumping system, concentration--with its additional need for a heat sink--would not significantly decrease cost. On the other hand, manual tracking of a flat array (east-west), as offered by one manufacturer, seems to be a simple solution for increasing output of small systems relative to a fixed array. For larger systems, especially where the heat removed by the cooling system can be put to other use, concentrators/ trackers may well prove to be more economical.

Existing PV Installations

Table 7 shows existing PV water pumping installations.[38] Most experience has come from the flat plate arrays installed by the French company Pompes Guinard.

Design Trends in Photovoltaics

Design trends in PV arrays applied to generating power for applications such as water pumping are generally related to increasing cell efficiencies and decreasing costs of array manufacturing. R&D is underway on potentially cheaper or more efficient solar cells than those made of single crystal silicon. Materials being used include polycrystalline silicon or amorphous silicon, cadmium sulfide and gallium arsenide. GaAs cells in the laboratory have achieved efficiencies of over 20 percent as compared with 10-14 percent for mono-crystalline Si cells. Automated manufacturing processes can also play a significant role in cost reduction. Furthermore, R&D on concentrators used to increase radiant intensity and so reduce the cell area required for a given power output has been mentioned. Tracking equipment is also used to orient the array to the sun and increase output from a given area.

In addition, R&D on ancillary equipment such as cheaper batteries to reduce storage costs, power conditioning equipment and DC motors is expected to play a significant role in increasing the techno-economic feasibility of PV arrays for water pumping.

Cost Analysis

The system envisaged for cost analysis is 1 kW peak solar cell array with battery storage powering a DC electric motor driving a centrifugal pump. (To use a conventional AC motor which runs on utility current requires an inverter which adds significantly to the cost of the system). During the day the solar array charges the batteries which are used to operate the pump at night. Alternatively, the pump may be operated during the day with the batteries providing power stability in intermittently cloudy periods. Water pumping is not ordinarily an operation requiring energy on demand. The demand

TABLE 7

Existing Photovoltaic Pumping Installations [1]

LOCATION	YEAR INSTALLED	PHOTOVOLTAIC POWER W	DAILY OUTPUT m^3	HEAD m	APPLICATION	MANUFACTURER/ SUPPLIER
ABU DHABI Al Ain		600	40	15	livestock	PG
ALGERIA Bou Saada		600	46	15	Agricultural Institute	PG
ECUADOR		600	50	10		PG
FRANCE						
Corsica	1975	600	16	25	irrigation	PG
Corsica		600	16	25	irrigation	PG
Tours	1974	400	15	20	demonstration	Briau
Montpellier	1979	27KW			irrigation	PG
INDIA						
Orissa (3 units)	1979	240	~ $5m^3/h$	~ 5	irrigation	SEI
Hyderabad	1979	240	~ $5m^3/h$	~ 5	demonstration	SEI
Delhi	1979	240	~ $5m^3/h$	~ 5	demonstration	SEI
Sahibabad	1979		~ $2m^3/h$		demonstration	CEL
IRAN						
Tehran	1976	800	10-12	43		Briau
Tehran	1976	800	10	39		Briau
IVORY COAST Yamoussokro		900	19	35	college	PG
LIBYA						
Tripoli		1300	34	30	) farm	PG
Tripoli		1800	42	40	) equipment	PG
Tripoli		1300	34	30	) supplier	PG
Benghazi	1973	800	15	18		
MALI						
Koni	1977	900	40	18	irrigation	PG
Mopti		2600	24	30		
Wabasso	1977	900	30	24	village	PG
San	1979	1800	25	30	hospital	PG
Tominian	1977	1300	70	25	village	PG
Yamgasso	1979	1300	56	25	village	PG
MAURITANIA						
Gayak		3900	600	7	) food	PG
N'takat		900	58	15	) co-operative	PG
MEXICO						
-		1800	29	50		PG
-		1800	29	50		PG
-		600	29	12	irrigation	PG
Guerrero		600	25	18		PG
-		120				PG
-		120	$3m^3/h$	1	university	PG
-		120	$3m^3/h$	1	demonstration	PG
NIGERIA Kano		600	24	20	irrigation	PG
OMAN Muscat		320	10	15		Briau
PAKISTAN Islamabad	1979	240	$5m^3/h$	5	demonstration	SEI

TABLE 7

Existing Photovoltaic Pumping Installations [18]

(Sheet 2 of 2)

LOCATION	YEAR INSTALLED	PHOTOVOLTAIC POWER W	DAILY OUTPUT m^3	HEAD m	APPLICATION	MANU SU
RWANDA						
-		600	120	5	village	
SENEGAL						
Babak		1300	65	20	village	
Basbey	-	900	100	10	irrigation	
Dakar	1975	400	10-15	20	university	
Dakar	1975	360	12-18	15-20	university	
UPPER VOLTA						
Kamboinse	1977	760	15	27		
Karbo	1977	840	10	40		
Mogtedo	1977	600	10	28		
Ougacougou		600	24	20	engineering village	
Tangaye	1979	1800	water pumping and other applications	water pumping and other applications	village	NASA
SAUDI ARABIA						
-		600	18	25	village	
UNITED STATES						
El Monte Ca		2400			fountain	Arco
Isletta Pueblo, NM	1976	375 (pump)			livestock	Arco
Navajo, Az		1500 (pump)	39	122		Arco S
Mead, NB	1977	25kW			irrigation	MIT Lin
Schuchuli, Az	1978	3500 1500W (pump)	$4.3m^3/h$		village	NASA-L
VENEZUELA						
Caracas	1976	120	15	12		3r

PG = Pompes Guinard (France)
SEI = Solar Electric International (USA)
CEL = Central Electronics Limited (India)

BEST AVAILABLE COPY

for irrigation is spread out over a few months and a storage reservoir should be able to handle small fluctuations in the pumping rate. However, water storage may be difficult on small farms which are likely to use a 1 kW system and, for certain crops, peak period water requirements may exceed system capacity.

The cost of supplying electricity from a solar cell array with one day's battery storage is calculated as a function of cell panel cost and the average solar insolation per day; storage costs are assumed to be $50/kWh of battery storage.

If average solar insolation is I kWh/day/peak kW of installed cell capacity, the average number of sunny days per year is 300, and battery efficiency is 85 percent, the total energy available on demand per year

$$= I \times 300 \times 0.85 = 250I \text{ kWh/pk kW}$$

The solar panel life is assumed to be 20 years, battery life to be 7 years, and the cost of the solar panel to be $M/pk kW. One day of battery storage costs $50I/pk kW of cell capacity. The interest rate on capital is assumed to be 10 percent. The total annual cost per pk kW of capacity

$$= R\ (10,20)\ M + R\ (10,7) \times 50I$$

where R is the capital recovery factor.

The energy (on demand) cost is then given by

$$E_d = \frac{R\ (10,20)\ M + R\ (10,7) \times 50I}{250I} \quad \$/\text{kWh}$$

$$= \frac{0.118M}{250I} + 0.041 \ \$/\text{kWh}$$

Figure 3 shows the energy costs as a function of I for various values of M. Unless the costs of secondary batteries decrease substantially, it is clear that even with solar panels at $500/pk kW (projected by DOE-78 for 1985) the cost of delivered electricity will remain at 8¢/kWh or above even in areas of high insolation. In the absence of any battery storage, energy cost will be about 4¢/kWh with solar panels at $500/pk kW in high insolation areas.

Table 8 presents some figures on the availability of solar energy in electrical units (kWh/pk kW of installed capacity) in various countries at different times of the year. These figures have been deduced from the solar radiation data presented in Table 9.

Operational/Maintenance Experience

The PV array is encapsulated in material to protect the cells from mechanical damage and the environment. In many designs, an element of redundancy is introduced so that a bad connection does not cause module failure. The module has to be rugged, capable of withstanding wide temperature variations, moisture, dust and other hazards. In irrigation systems in developing country environments, the array has to be designed and

Figure 3

ELECTRICITY COST FROM SOLAR CELLS [39]

(ONE DAY ENERGY STORAGE)

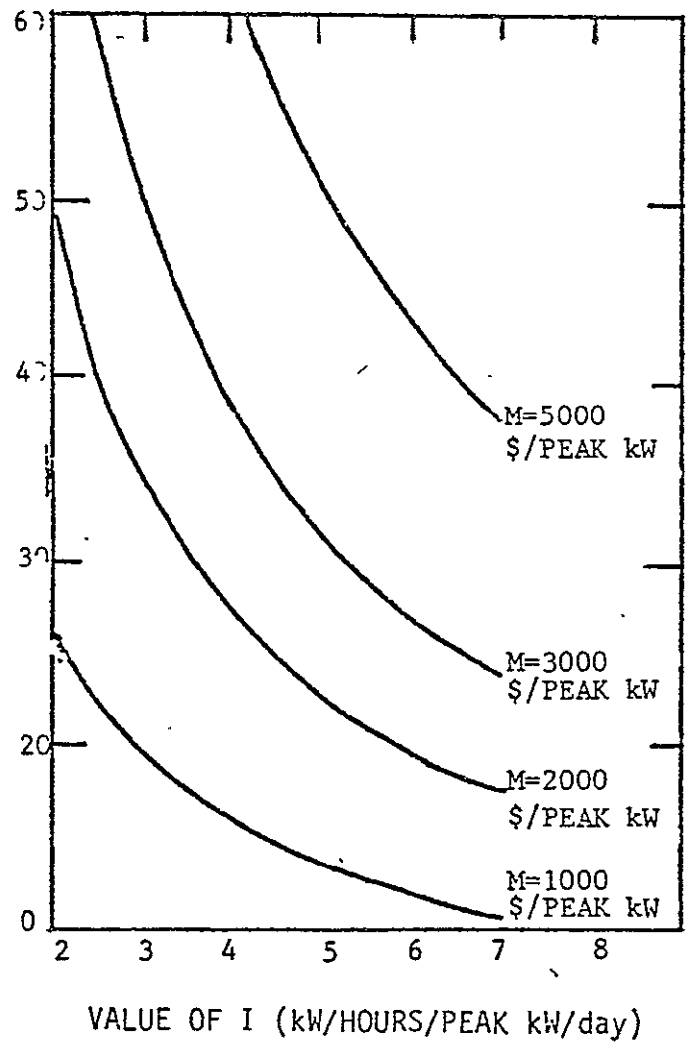


Table 8

SOLAR-CELL ELECTRIC ENERGY PRODUCED DAILY

(kWh/PEAK kW)

IN VARIOUS COUNTRIES *

Area	Energy Produced Daily (kWh/peak kW)				
	March	June	Sept.	Dec.	Av.
USA (Washington, DC)	4.1	6.4	4.7	1.8	4.2
Brazil (Brasilia)	5.2	3.5	5.3	5.3	4.8
Indonesia	5.3	4.7	5.3	4.7	5.0
India (Central)	6.4	6.4	5.8	4.7	6.3
Mali, Niger, Chad	7.0	7.6	6.4	4.1	6.3
Zambia	5.2	5.2	6.4	5.8	5.7
Korea	4.1	5.8	4.1	1.8	3.9

*Approximate data obtained by using Worldwide Solar Radiation Maps in the paper "World Distribution of Solar Radiation" by G. Lof, J. Duffie, and C. Smith, presented at the Solar Energy Society Conference in Phoenix, Arizona, March 1965.

BEST AVAILABLE COPY

Table 9

SOLAR RADIATION DATA FOR VARIOUS COUNTRIES*

Area	Daily Means of Total Solar Radiation (On Horizontal Surface) (In GM CAL./CM^2/DAY)				
	March	June	Sept.	Dec.	Annual & Averag-
(Washington, DC) Latitude 40°N)	350	550	400	150	362
zil (Brasilia) (Latitude 16°S)	450	300	450	450	412
onesia (Latitude 0°)	450	400	450	400	425
dia (Central) (Latitude 25°N)	550	550	500	400	500
ali, Niger, Chad (Latitude 20°N)	600	650	550	350	538
mbia (Latitude 18°N)	450	450	550	500	488
orea (Latitude 40°N)	350	500	350	150	338

*Approximate data obtained by using Worldwide Solar Radiation Maps in the paper "World Distribution of Solar Radiation" by G. Lof, J. Duffie, and C. Smith, presented at the Solar Energy Society Conference in Phoenix, Arizona, March 1965.

BEST AVAILABLE COPY

erated to withstand rough handling and damage from animals and birds. Protection from vandalism is also necessary. No special maintenance is necessary for the arrays apart from occasional cleaning of the array surface to remove dust and, possibly, bird droppings. Where batteries are used along with the array, a routine check of the electrolyte level is essential to prevent battery failure.

Considerable operational experience has been gained in PV systems used to power educational TV sets in Niger for over nine years. In general, the arrays have functioned satisfactorily and 20 year life appears a reasonable goal. Accelerated aging tests in laboratories appear to confirm this.

4.3 Solar Thermal Powered Pumps

A solar thermal powered pump collects solar heat, converts it to mechanical energy and uses that energy to drive a pump. In conventional terminology, this might be likened to a boiler which absorbs fossil-based heat to produce steam that, in turn, drives a turbine and pump. The relatively low temperatures achieved by solar collectors, however, require design of new systems components and sometimes the use of working fluids other than water.

Solar Thermal Pumping Systems

Many different kinds of solar thermal engines have been reviewed in the literature since the first solar steam engine was demonstrated in the 19th century. The basic principle in all these devices is to transfer the collected thermal radiation through a working fluid to operate a heat engine which can drive a pump. Figure 4 shows a schematic version of a basic solar thermal pumping system.

Early solar engines used concentrators and steam as a working fluid. Modern engines in the small sizes use flat plate collectors and organic liquids, such as freon, with low boiling points. Most of the small solar thermal pumping systems have been built and installed by the French company SOFRETES, which employs a flat plate collector and an engine with freon as the working fluid delivering about 1 kW of mechanical power.

The efficiency of a heat engine is limited by the Carnot efficiency

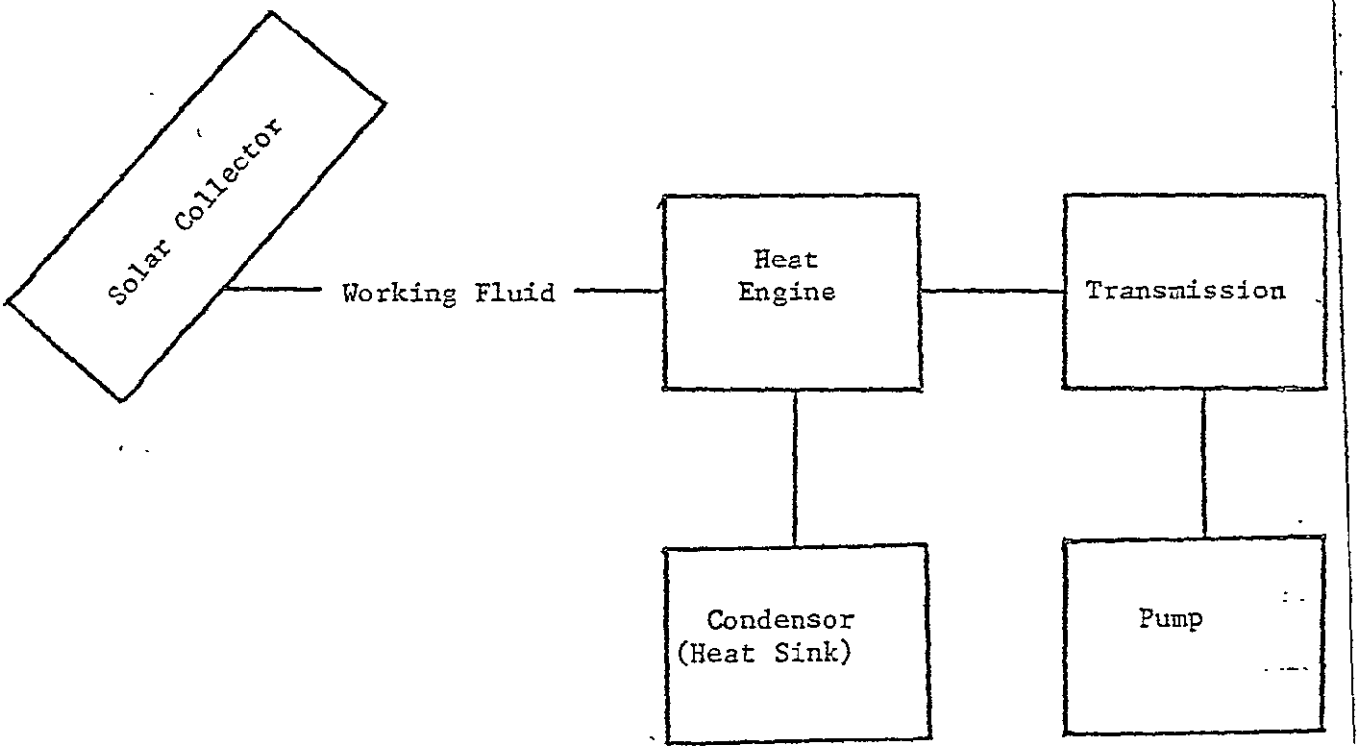
$$\eta = 1 - \frac{T_2}{T_1}$$

where T_2 is the (absolute) temperature of the heat sink and T_1, of the heat source. There is a trade-off between increasing the efficiency of the engine--which requires as large a temperature difference as possible between the source and the sink (ambient air or water)--and increasing the efficiency of the collector--which decreases with increasing temperature difference between itself and the ambient surroundings. In practice, the SOFRETES engines achieve an overall efficiency of about one percent.

BEST AVAILABLE COPY

FIGURE 4

SCHEMATIC OF A SOLAR THERMAL PUMPING SYSTEM



Existing Installations

SOFRETES has installed nearly 70 percent of the solar thermal powered pumping stations now in existence (see Table 10). In addition, there are numerous experimental installations, some of which consist of large concentrating arrays intended to produce relatively large amounts of power. These include the 25 kilowatt system in Willard, New Mexico, which started operating in 1977, and the world's largest, located southwest of Phoenix, Arizona. This latter system uses 5500 square feet (512.25M^2) of concentrating collectors to provide power to a 50 horsepower (37.3 kW) pump. The ground area required, the system complexity and the power output make this large type solar energy system unsuitable for the small farms in the LDCs. The smaller systems installed by SOFRETES have a collector area of about 100 square meters, which can be mounted on a farm building. Table 10 is a listing of several existing and proposed installations showing their characteristics.

There is a wide array of pump sizes to which the solar engine can be coupled. In some instances, reciprocating pumps are used since they are already widespread in agriculture. Because these can require a large starting torque, which may not be available, most pumps are of the rotary type. In each instance, pump characteristics must be matched to the motor and to the pumping environment. The connection between the motor and the pump may be mechanical or hydraulic, or the solar engine may drive a generator which powers an electric pump.

Design Trends in Solar Thermal Flat Plate Collectors

Flat plate collectors are shallow glass-covered boxes which contain tubes or troughs through which water is pumped. (There also is a thermal syphon system, but its output is too low for most pumping.) The collectors are oriented toward the sun which enters the glass and heats the water. To increase efficiency, the box is insulated and, in some models, the water tubes and backing are made from the same sheet of copper to increase heat collection. Similarly, the use of double glazing, in lieu of a single sheet of glass, reduces heat loss and increases the water temperature.

Concentrating Collectors

A concentrating collector focuses the sun's energy on a central absorber which contains the working fluid. Most are long parabolic curved troughs with an absorber tube along the focus of the trough. In some instances, a parabolic dish resembling a television or microvave radio antenna is used to concentrate the sun's rays at a single point and, thereby, achieve a higher temperature. One source estimates that use of a parabolic dish of 20m^2 (5m diameter) can produce the output of 200m^2 of flat plates.[41] With both types of arrays, the glass or reflective concentrator becomes dusty, scratched or discolored due to ultra violet radiation, rain, general dirt and airborne dust. Concentrating collectors, particularly the parabolic dish, are easier to keep clean becuase of their smaller size.

Concentrating collectors use less area, an advantage in less developed areas where farm plots are some distance from the village and a sturdy nearby roof for mounting collectors may be difficult to find. The major disadvantage of the concentrators is that a tracking system is needed

Small-scale SOFRETES Solar Thermal Pumping Installations

LOCATION	YEAR INSTALLED	COLLECTOR AREA m^2	DELIVERY FLOWRATE m^3/h	WATER HEAD m	OPERATING HOURS h	APPLICATION
ABU DHABI	1976	90	4	35	5-6	Small irrigation system
ALGERIA						
ANNABA	1977	77	9	10	5	Demonstration and teaching
BRAZIL						
ICO LIMA CAMPOS (Ceara)	1977	75	5	20	5-6	Drinking water supply
CAMEROON						
MAKARY	1976	70	3	20	6	Livestock watering
LOGONE BIRNI	1979					Irrigation
CAPE VERDE ISLANDS						
SAN DOMINGOS	1979	70	3	35	5-6	Village water supply
CHAD						
KARAL	1976	70	3	20	5	Livestock watering
ATI	1977	70	3	28	5	Livestock watering
N'GOURI	1977	70	3	35	6	Village water supply
N'DJAMENA	1978	180	20	32	6	Water supply + power + refrigeration
IRAN						
SHIRAZ	1977	77	4	35	5-6	Village water supply
KENYA						
WAJIR	1978	77	5	30	5	Village water supply
MADAGASCAR	1977	77	7-8	15	5	Village water supply
MALI						
DIOILA	1975	80	3	30	6	Village water supply
KATIBOUGOU	1977	105	6-7	15	5	Irrigation
MAURITANIA						
CHINGUETTI	1973	72	5	23	5-7	Village and livestock water
MEXICO						
CABORCA (Sonora)	1974	90	3	45	5-6	Village water supply
CEBALLOS (Durango)	1974	90	4	40	5-6	Village water supply
CEDRAL (San Luis Potosi)	1975	80	4	20	5-6	Small irrigation syst
MEXICALI (Baja California)	1975	80	7	20	5-6	Water supply
LA CRUZ (Chihuahua)	1975	80	4	30	5-6	Village water supply

BEST AVAILABLE COPY

Small-scale SOFRETES Solar Thermal Pumping Installations

(sheet 2 of 3)

LOCATION	YEAR INSTALLED	COLLECTOR AREA m^2	DELIVERY FLOWRATE m^3/h	WATER HEAD m	OPERATING HOURS h	APPLICATION
MEXICO (Continued)						
NUEVO PROGRESSO (Campeche)	1975	70	4	25	5-6	Village water supply
MARGOS (Chihuahua)	1976	90	4	30	5-6	Village water supply
DOS SANTOS (Baja California)	1976	90	4	30	5-6	Village water supply
LOSA (Zacatecas)	1976	90	4	30	5-6	Village water supply
LLA DE COSS (Zacatecas)	1976	90	4	30	5-6	Village and livestock water
VID GUSTAVO (Quintanarro)	1976	90	4	50	5-6	Village water supply
HUITLAN (Oaxaca)	1976	90	4	22	5-6	Irrigation
ACUIXTLA (Tlaxcala)	1976	90	4	30	5-6	Small irrigation scheme
NGREJOS (Jalisco)	1976	90	4	50	5-6	Village and livestock water
EMAVE (Tamaulipas)	1976	90	4	13	5-6	Village and livestock water
ASO GUAYABAL (Mexico)	1977	90	4	35	5-6	Village water supply
NIGER						
LAMEY - BOSSEY BANGOU (ONERSOL, National Solar Energy Agency)	1973	100	8-10	12	5-6	Village and livestock water
PHILIPPINES	1976	77	9	10	5	Demonstration pump
SENEGAL						
DAKAR (Meteorological Physics Institute)	1968	88	6	25	5-6	Pilot station
DAKAR (UNO Industrial Development Project at the University)	1975	72	4	30	6	Assessment project
MEDINA - DAKAR	1976	70	3	40	5	Village water supply
TAKHENE	1976	70	3	40	5	Village water supply
MOUANE	1977	70	3	40	5	Village water supply
DAKAR (Technology Institute, at the University)	1977	70	3	40	5	Demonstration and information
TAGLE	1977	70	3	40	5	Small irrigation system

BEST AVAILABLE COPY

Table 25

Small-scale SOFRETES Solar Thermal Pumping Installations [40]

(sheet 3 of 3)

LOCATION	YEAR INSTALLED	COLLECTOR AREA m^2	DELIVERY FLOWRATE m^3/h	WATER HEAD m	[illegible] m	APPLICATION
SUDAN						
SOBA	1977	112	5-7	25	5-7	Village water suppl
HAMAD	1977	112	3	55	5-7	Village water suppl
UPPER VOLTA						
OUAGADOUGOU(Inter-state Rural Engineering College)	1971	30	2	20	5-6	Demonstration and Teaching
KOUPELA	1975	75	5	20	5-6	Refrigeration
DJIBO	1976	70	5	20	5	Village water supp
KASSOUM	1978	77	5	30	5-6	Village water supp
THIOU	1978	77	5	30	5-6	Village water supp
TAPARKO	1978	77	5	30	5-6	Livestock waterin
DEMNOUO	1978	77	5	30	5-6	Livestock watering
GANGAOL	1978	77	5	30	5-6	Livestock waterin
KIEMBARA	1979	77	5	30	5-6	Village water supp
DJIBASSO	1979	77	5	30	5-6	Village water supp
KONGOUSSI	1979	100	7	30	5-6	Village water supp
BARSALOGHO	1979	100	7	30	5-6	Village water supp
GOROM-GOROM	1979	77	5	30	5-6	
MARKOYE	1979	77	5	30	5-6	
PUYTENGA	1979	77	5	30	5-6	Livestock waterin
PO	1979	77	5	30	5-6	

BEST AVAILABLE COPY

for precise focusing on the sun. The tracking system itself uses power and may introduce more complexity than the user can handle. Using a tracking collector is advantageous, however, because in theory a collector continually focused on the sun receives $\frac{\pi}{2}$ times as much solar radiation as one that remains fixed. In practice, an even greater gain is experienced.[42] This may be because the reflection due to the sun's changing angle on the fixed collector plate is decreased.

Some have suggested that the collectors be mounted on gimbals and moved manually at periodic intervals or that a system of weights and pulleys be used, which could be reset daily.[43] There are also solar cooker designs which increase the size of the concentrator and necessitate less accurate tracking. None of these ideas have yet been demonstrated.

Rankine Cycle

Some version of the Rankine cycle is used in practically all of the solar thermal-powered pumps in existence or under development. Development efforts primarily seek to: (1) increase operating temperature; (2) increase the difference between the high and low temperature sides of the system; and (3) alter the working fluid to get lower vaporization temperatures or higher density vapor.

The simplest Rankine cycle is a flat plate collector which heats a working fluid to vaporization and runs it through a turbine which drives a pump. The exhaust steam is then condensed in a condenser which is cooled by the pumped water. In most of its installations SOFRETES changes from single cycle to double cycle operation by adding a heat exchanger in which hot water from the collectors heats a working fluid which in turn drives an expansion engine or a turbine.[44] This permits use of water in the collectors, where leaks are harder to control, and confines a lower boiling point fluid to an "interior" or motor circuit.

In smaller systems of 1 kW, the power from an expansion motor drives a hydraulic motor which in turn drives a pump. In larger systems, a turbine drives an alternator and an electric motor. The SOFRETES system and many others use fluor-carbon (Freon) type working fluids. Hydro-carbons such as butane are also used, but these are flammable and could produce serious hazards during handling or in the event of a leak.[45] In an Italian-made pump driven by a Rankine vapor cycle, sulfur dioxide is vaporized in a flat plate collector.[46]

The engines mentioned above usually operate with collector outlet temperatures of about 150°C (302°F). Higher temperatures can be achieved by increasing collector area and using concentrating arrays. For instance, a system installed by ACUREX near Coolidge, Arizona uses 48,960 square feet (4500m^2) of concentrating collector to reach a temperature of 288°C (550°F). In this case the discharge goes to a 30,000 gallon (113,580ℓ) storage tank or to a heat exchanger to vaporize toluene which in turn drives an organic Rankine cycle turbine that powers a generator.[47] The resultant electricity drives well pumps.

Stirling Cycle

Stirling engines can be generically described as gas-driven piston engines. There are both free and connected piston models. The piston is driven by the expansion of an externally heated gas--air, hydrogen or helium. In theory, the gas receives heat but maintains a constant temperature; the internal energy caused by the heat absorption is used to push the piston. Th heat absorbed by this cycle goes to a regenerator which is used to reheat the working gas.

The free-piston model was developed to eliminate the excess frictic losses caused by the original crank driven Stirling engines. Using a gas in the Stirling cycle requires very high temperatures--between 300°C and 1000°C which necessitates the use of concentrating collectors.[48,49]

No Stirling engine pumps are now being produced. The "Beale" free piston pump manufactured by Sunpower, Inc. U.S.A. and the "Fluidyne" pump manufactured by Metal Box Ltd. (India) are reported to be close to production.[50]

Other Hardware

Most solar thermal system descriptions concentrate on the collector and the heat engines, but because most solar energy systems work at relativel low temperatures or with low boiling point liquids, the design of all components and their proper construction is equally important. Construction without leaks and the ability to repair leaks and recharge the sytem is particularly essential, as is insulation to prevent heat loss.

Because insolation may be intermittent, many systems include heat storage--generally a tank containing water or the working fluid. In some instances, the tank contains rock or gravel to increase heat retention.

Cost Analysis

As with all solar energy systems, the primary component of solar thermal system cost is the capital investment. There is no fuel cost and operation and annual maintenance is usually a small percentage of initial outlay. Except for research and development units, few solar thermal pumps are in service; therefore, reliable cost information is sketchy, and comparison is difficult. One source indicates that the first cost of a SOFRETES 1 kW system operating at about 50°-75°C was about $13,000 (1978).[51] A unit installed in Africa and operating 1800 hours a year, pumping from a 3(meter depth, is estimated to pump water at $.60/m^3.[52] For a 1 kW engine at 8 percent efficiency, the lift would indicate a volume of about 10^3/hour or a total charge of $6.00 per hour. In the first instance, a capital cost of $13,000 and a life of 15 years operating 1800 hours per year with an interes charge of 12 percent per year works out to be a capital recovery charge of $1.06 per hour. The higher figure, probably more correct, comes to about $5.60 per hp/hr, more than conventional pumps. The same approximations exis for smaller engines. Table 11 gives estimated costs for the systems listed. Table 11A gives probable cost ranges for 150 watt power sources, a size whic could be used on small farms.

Note that figures ($0.25/hp-hr diesel & $0.10 for electric) are for water only

BEST AVAILABLE COPY

TABLE 11

SURVEY OF SOLAR POWERED IRRIGATION PUMPS[51]

Parameter	SOFRETES (Typical)	SOFRETES (Khartoum)	FRDA (Willard)	Battelle (Ella Bond)	Sunpower (Proposed)	Helio (Proposed)	Kinetics (Proposed)	Birla Inst. (Lab Model)
				-COLLECTORS-				
Collector Type	Flat Plate	Flat Plate	Parabolic Tracking	Parabolic Tracking	Parabolic Tracking	Parabolic Tracking	Parabolic Tracking	Flat Plate
Effective Solar Collection Area, m^2	70	100	624	510	360	1727	140	100
Fluid Circulation	Thermosiphon or Circulator	Thermosiphon	Circulator	Circulator	Circulator	Not Reported	Circulator	Thermosiphon
				-ENGINE CIRCUIT AND PUMPS-				
Evaporator/ Condenser	Tubular Elements	Tubular Elements	Tubular Elements	Tubular Elements	Tubular Elements	Not Reported	Tubular Elements	Coil and Tank
Working Fluid	Butane or Freon	Freon	Freon	Freon	Steam	Not Reported	Freon	Pentane
Expansion Engine	Two Cyclinder	Two Cylinder	Turbine	Turbine	Double Act. Piston	Not Reported	Rotary Expander	Direct on Water
Rotation Speed, rpm	200	200	36,000	Not Reported	600	Not Reported	1800	Not Appl.
Water Pump	Hydraulic Transmission	Hydraulic	Rotary	Rotary	Rotary Pump Stage Lift	Not Reported	Hydraulic Transmission	Work Fluid on Water
				-OPERATING CONDITIONS-				
Mean Solar Incident Radiation, W/m^2	700	700	800-900	800-900	800-900	800-900	800-900	Varies
Pumped Water Temperature, ^oC	20-30	20-30	20-30	20-30	20-30	20-30	20-30	20-30
Operating Time, hr/day	5-7	5-7	5-7	5-7	5-7	5-7	5-7	6
Daily output, m^3	30	40	1200	14,000	5500	1240	280	105
Manometric Height, m	20	38	25	4.3	50	50	20-30	30
Effective Pumping Power, kW	1	1	20	40	30	67	10	1
Approximate Cost, $US	48,900	50,000	500,000	2,500,000	100,000	Not Reported	75,000	6,750

BEST AVAILABLE COPY

TABLE 13A

COST OF VAPORS POWER SOURCES

	SOLAR THERMAL <80°C Rankine	SOLAR THERMAL 120°C Rankine	SOLAR THERMAL > 200°C Rankine	SOLAR THERMAL >300°C Stirling
1 Solar collector:				
(a) type	flat-plate	line focus	line focus	point focus
(b) efficiency range	30-60%	30-60%	30-60%	40-70%
2 Thermal storage and/or heat exchanger (th) and battery storage (PV) efficiency range	70-100%[2]	70-100%[2]	70-100%[2]	70-100%[2]
3 Heat engine (th) or electric motor (PV)	2-7%	4-12%	8-16%	12-28%
4 Transmission and ancillary losses[1]	50-100%[2]	50-90%	50-80%	50-80%
5 Pumping efficiency	30-90%	30-90%	30-90%	30-90%
6 Overall system efficiency:				
(a) range (worst - best)	0.1-3.5%	0.5-6%	1-7%	2-14%
(b) typical good design	1%	2%	3%	8%
7 Collector area or peak array output per 150W peak pumped water output at 900W/m² insolation[3]				
(a) range (worst - best)	170-5m²	33-3m²	17-2.4m²	8-1.2m²
(b) typical good design	17m²	8m²	5.5m²	2m²
8 Likely unit collector cost:				
(a) range (today)	30-150$/m²	100-300$/m²	150-400$/m²	300-1,800$/m²
(b) typical (today)	80$/m²	150$/m²	200$/m²	800$/m²
(c) possible if mass produced (future)[5]	40$/m²	60$/m²	100$/m²	300$/m²
9 System collector cost:				
(a) range (today)	$750-5,000	$900-1,300	$1,000-2,550	$2,000-2,400
(b) good design (today)	$1,400	$1,200	$1,100	$1,600
(c) possible (future)	$700	$500	$550	$600
10 Engine/transmission/pump costs:				
(a) today	$2,000-4,000	$2,000-4,000	$2,000-4,000	$2,000-4,000
(b) future	$500-1,000	$500-1,000	$300-1,000	$200-1,000
11 Control system and energy storage costs (today and future)	$0-1,000	$0-1,000	$0-1,000	$0-1,000
12 Total system costs (per 150W peak output):[3]				
(a) range (today)	$2,750-10,000	$2,900-8,360[6]	$3,000-7,550[6]	$4,000-7,400[6]
(b) mean (today)	$6,375	$5,600	$5,275	$5,700
(c) possible range (future)	$1,200-2,700	$1,000-2,500	$850-2,550	$800-2,600

Notes: 1 Ancillary losses include tracking unit, drive power, control system, pumps, etc.
2 Items marked thus are not used in all systems, therefore efficiency is nationally 100% in systems where they are not included.

BEST AVAILABLE COPY

System Operation and Maintenance

The operation and maintenance of the solar Rankine cycle power plant or any solar device are the most important and most often neglected factors in developing countries. Experience shows that many technically sound and economically competitive machines have failed in a location due to the lack of skilled technician or the availability of spare parts. In selecting any system for a given application in developing countries, operation and maintenance must be given top priority. Engineering designs and economic calculations must take this into account.

4.4 Wind-Powered Pumps

Wind has been a power source for irrigation for centuries. Wind turbines, or windmills, which convert the force of wind to mechanical energy can be divided into (1) those with horizontal and vertical axles; (2) those with rigid or cloth blades; and (3) those in which the blades are of the drag or lift types. The lift type blades are airfoil shaped and, therefore, extract additional power from the suction which their shape creates in the wind. Because they operate best at high speeds and have low torque at low speeds, they are generally unsuitable for water pumping unless they first power a generator which drives an electric pump.

The power of the wind machine is dependent on blade area and wind speed. The general formula is:[54]

$$P = \frac{EAV^3}{2}$$

in metric units the formula becomes:

$$P = .01319EAV^3$$

for average conditions where:

P = Power in watts
A = Useful blade area in square meters
V = Wind velocity in kilometers per hour
E = Efficiency

Horizontal axis machines have the greatest efficiency, generally are self starting and have better low speed torque. The horiziontal rotor must face the wind and is aimed by a rudder vane similar to that on a weather vane. When the wind direction is variable, as may happen in light air situations, the need to track the wind may reduce power output. Vertical axis machines are omnidirectional.

All wind machines have a particular wind "rated speed," at which they deliver rated horsepower, and a lower "cut-in speed," at which the machine is engaged and starts producing power. The multi-bladed farm windmill usually has a cut-in speed of about 7 mph (11 km/hr). The National Aeronautical Laboratory of India has developed a cloth-bladed rotor which will cut in at 6 km/hr (4mph).[55]

Wind Powered Mechanical Systems

In mechanical systems, the rotor is connected to a pump mechanism through a gear box. Mechanical systems are simple, less complicated to operate and cost less. Their disadvantage is that the wind machine must be directly over the well and the wind in that location must deliver the needed torque over a sufficient time interval. Since wind speed is influenced by topography and obstructions, this is not always possible. For example, instructions for installing the "Aeromotor" windmill once popular on U.S. farms indicate it must be 10 ft. above and 300 ft. from all wind obstructions.[56]

Mechanical windmills can be divided into "modern" and "local" or indigenous types. The "modern" variety are manufactured at a central location, involve engineered designs, have a long life, can handle very high heads, and usually have a high first cost. The "local" type uses the available local material and manufacturing abilities, may or may not involve engineering, work at lower heads and have a shorter life. Frequently, they use wood or bamboo spars and cloth sails. While cloth sails have a short life, the fact that they tear in high winds may save the rest of the machine from damage. "Local" machines can be repaired with available talent and material.

Following is a brief description of some mechanical type windpowered pumps.

U.S. Farm" Type - This is the "windmill" invented in 1854 and popular on U.S. farms until supplanted by electricity in the 1930s. The top of the machine consists of a vertical multi-bladed rotor with rigid blades mounted on a horizontal shaft connected to a gear box. The gears achieve speed reduction and connect to a vertical shaft. On the opposite side of the gear box from the rotor is a large tail vane which keeps the entire assembly headed into the wind. The gear box imparts a reciprocal motion to the vertical shaft which is attached to the piston of a reciprocating pump. Usually, the vertical shaft contains a wooden section which functions as a weak link and will break in the event of excess strain to prevent damage to more expensive parts. The tail vane is connected to the gear box with a spring mechanism that folds the vane parallel to the rotor in excessive winds.[57] This points the entire mechanism into the wind and effectively stops it to prevent gear damage. The pump and rotor size are matched for the power requirements. The overall design has evolved over many years and reliably pumps water at wind speeds in excess of about 7 miles per hour.

Greek Sail Type Rotor - This horizontal rotor, also referred to as Cretan type, has been adapted for use in Ethiopia, Thailand, Malaysia, Sri Lanka, and China, and has been further developed in India by the National Aeronautical Laboratory.[58,59] It has a high starting torque, low starting speed, light weight and low cost and can be adjusted for changes in wind velocities. It consists of six to 12 wood spars connected to a hub with their outer ends connected to a circumferential wire or rope. Triangular cloth sails are connected to each spar along the sail's longest edge, the inner corner of the sail is fastened to the hub, and the outer corner, which is

furthest from the spar, is connected either to the circumferential wire or to the next spar. Sails can be wrapped around the spar in strong winds to reduce their area. This type of rotor, as evidenced by its wide adaptation, is well suited to local manufacture in lesser developed countries.

Princeton Sail Wing - Each blade of this two-bladed rotor has a rigid front spar, tip and root chords, which are three times the tip. The blade is a double thickness of sail cloth fastened at the leading edge to the spar and to the rigid root and tip chords; the trailing edge of the sail is a catenary supported by a cable which runs between the ends of the tip and root chords. The blade is comparable in performance to a rigid rotor but at less cost. It could probably be made by indigenous labor after some instruction.

Netherlands Rotor - The traditional Dutch windmill consists of four spar-supported cloth-covered wooden lattices. It operates at a low rotational speed but at high torque. It requires skilled carpenters and is rarely used.

Another rotor used in the Netherlands, Denmark and some French salt works consists of four rectangular one-piece steel blades. The blades are cambered by being twisted so that the pitch decreases from root to tip. Work to optimize the design has been done by the Technical University Eindhoven, the Netherlands.[60]

National Aeronautical Laboratory, India - This wind machine is a larger adaptation of the Cretan sail windmill. It has six cloth sails on a steel rotor 10m (32.28 ft.) in diameter which is mounted on a 12m tower. The rotor is coupled to a rotary pump. One such machine can irrigate one hectare of wheat in an area where average wind velocity is 10km/hr (6 mph) for ten hours a day.

Madurai Windmill - This adaptation of the Cretan windmill built by M. Sherman in Madurai, India was intended to use cheap locally available wood and cloth. The rotor, 7.5m (25 ft.) in diameter mounted on a wood pole tower about 5.5m (18 ft.) high, was constructed of a one meter diameter cartwheel to which three 18-foot bamboo poles were lashed to the hub with the ends overlapping. Each pole formed the leading edge of a sail and a nylon cord from the outer tip to the rim of the cart wheel formed the trailing edge. A two-layer triangular cloth sock was drawn over the bamboo frame to form the blade surface. The wheel hub was fastened to an automobile axle which rotated in two sets of ball bearings mounted on pillow blocks. The version described by Sherman had three blades and was mounted directly over an open well in which it operated a chain pump.[61] The machine is supposed to be capable of lifting 40,000 gal/day from a well 20 ft. deep with a 10 mph wind. Other versions of the same design have six blades, are 10m in diameter, and are connected to a variable stroke reciprocating pump.[62]

Jib Sail Rotor - A vertical axis rotor which has been suggested for possible direct adaptation to the Persian Wheel is the "jib sail" rotor which has been used in the Turks and Caicos islands for filling salt ponds.[63] It consists of six triangular sails mounted on vertical poles so that they resemble jib sails. Each vertical sail is mounted on supports which radiate from a vertical shaft.

Savonius - The Savonius is a vertical axis rotor made of two half cylinders which overlap the axis. It has been made from the two halves of an oil drum cut vertically. It has high starting torque but low efficiency and has not been very successful. Occasionally, it has been combined on the same shaft with a Darrieus rotor which develops high speed but has low starting torque.

Wind-Powered Electrical Systems

As previously noted, it is not always possible or convenient to place the machine directly over the well. In these instances, the solution is to use wind power to drive a generator and then power electric pumps. (Most of the newer, larger machines are being developed exclusively to supply electric power.) A major problem, however, is that most electric motors require constant voltage and frequency and use alternating current, while the output of a wind machine varies with wind speed and is direct current. Most manufacturers of small wind generators use the wind machine to charge batteries which in turn furnish alternating current through an inverter, but batteries are expensive. Another approach is to remove batteries from the circuit and permit power from the direct current wind generator to go directly to the inverter. Thus, the wind machine supplements the existing system which provides all power during periods of calm. Such an approach reduces energy cost but duplicates first cost and does not solve the problem of the rural farmer who is not near a grid.

Horizontal axis electricity generating wind machines can all be classified as high speed propeller type, usually of two or three blades. The U.S. Department of Energy is testing small commercial wind systems (40 kW or less) at its Rocky Flat Systems Test and Development Center to assess their performance and provide information to assist small machine manufacturers. There are three projects aimed at low maintenance 1 kW engines, four to develop 8 kW engines and two to develop 40 kW systems.

Existing Installations

Many existing small-scale installations have been mentioned in the preceeding sections. Windmills were used throughout the U.S. until the mid-1930s and many still exist. There are thousands of cloth bladed "sail" machines on the island of Crete and this type has been adapted elsewhere. Windmills also have had a long history in the lowlands of northeastern Europe. Though the use of windmills is widely dispersed, there are still many areas where the technology can be applied through introduction of simple models.

The Department of Energy is funding two medium-scale systems: Mod 0 and Mod 0A series high speed propellers. The Mod 0, which has a 125-foot diameter and is rated at 100 kW in an 18 mph wind, is installed near Sandusky, Ohio. Mod 0A wind turbines have been installed at Block Island, R.I., Clayton, N.M., and Culebra, P.R. This model also is 125 ft. in diameter but is rated at 200 kW at 18 mph. Wind machines increase in size to the 300-foot diameter turbine under design by Boeing Aircraft, which is intended to produce 2.5 MW at 20 mph wind speed.

Also under test at Sandia, N.M. is the Darrieus rotor, a vertical axis lift type machine with three constant chord blades bent in a catenary curve which are fastened to the vertical axis shaft at top and bottom. Compared to other vertical axis machines, the Darrieus sweeps a large area in proportion to its weight, requires less support structure and is more efficient. Though it is less efficient than a high speed propeller, it needs no wind tracking systems, since vertical axis rotors are omnidirectional.

Cost Analysis

As with all solar energy systems, wind machines have a high first cost and relatively low follow-on expenditures. Therefore, escalating oil costs make them more desirable. Wind machines can be divided into three groups which roughly coincide with their first cost, manufacturing and maintenance technology requirements and type of applications: High Speed Propeller, U.S. Farm and Indigenous. The comparison in Table 12 shows that the Indigenous machines are more suitable for small farms in remote rural areas.[64] Cost per unit output depends on hours of use, wind strength and the cost of the machine itself. Average costs of some U.S. Farm type multi-bladed windmills with accessories are given in Table 13.[65]

Based on this information, the 1980 U.S. price for a 16-foot diameter rotor on a 35-foot tower would be about $7300. To estimate the annual volume of water pumped at a given site, the following expression can be used:

$$V = C \left(\frac{h_1 + h_2}{2}\right)$$

Where: V = Gallons pumped per year
C = Gallons pumped per hour at rated capacity
h_1 = Hours when wind is above cut in speed
h_2 = Hours when wind is above rated speed

Table 14 lists approximate 1980 costs per gallon and per hectare/cm for areas where wind speeds are available.

Figures in the same detail are not available for the indigenous wind machine. It hs been reported, however, that the sail rotor, developed by the National Aeronautical Laboratory of India, pumps water at costs equal to about $7.20 per ha-cm (1978).[67] In another case, the "Polomo" windmill (an adaptation of the Cretan Sail Machine) used in Ethiopia was reported to cost $798.00 U.S. (1978) and $965.00 (1980) and to have a capacity of 1440 gallons per hour at 15 miles per hour.[68] On the assumption that this machine cuts in at least the same speed as the solid bladed U.S. Farm type, and taking 1440 gallons per hour as its rated output, it would pump about 3219 thousand gallons per year in Nairobi, Kenya. Assuming a ten-year life, a 12 percent loan for that period and an average maintenance cost of two percent of the original price, the cost would be approximately $.06 per 1000 gallons or $1.56 per hectare centimeters.

TABLE 12

WIND MACHINES MANUFACTURED IN THE U.S.

FEATURE	HIGH SPEED PROPELLOR	U.S. FARM (AEROMOTOR)	INDIGENOUS (HYBRID)
First Cost	Very High	High ($2000-$6000)	Low ($150 - 600)
Useful Life	Unknown	30 Years	5 - 15 Years
Technology; Design	Very Sophisticated Developmental	Proven Engineering	Trial & Error Design
Manufacture	High Technology	Requires Steel Fabrication Facilities	Uses Available Capabilities
Maintenance	Indeterminate	Low-May Require Shop Facilities	High But Uses Local Facilities
Application	Electricity Feed to Grid	(1) Direct Water Pumping (2) Decentralized Electricity	Water Pumping
Capability	N.A.	High Heads Up to 1000' Relatively Low Volume Compared to Diesel	Low Heads 9M Low Volume
Availability	N.A.	On International Market	Locally Where Built
Application (2)	None	Small Farms or Cooperatives	Individual Farms

(1) Hybrid - Refers to Aerodynamic Improvement of Machine to Increase Low Wind Output While Retaining Indigenous Character
(2) For Irrigation in L.D.C.s.

TABLE 13

AVERAGE COSTS OF U.S. MULTIBLADED WINDMILLS, TOWERS AND PISTON PUMPS

Blade Diameter	Capacity* (gallons per hour)	Windmill Cost (US$)	Tower Cost (US$)	Pump Cost (US$)
6'	137	659	968	146
8'	275	922	968	146
10'	430	1545	1035	146
12'	654	2475	1316	146
14'	878	4290	1359	146
16'	1700	5812	1359	146

*At 100 ft. dynamic head, and rated windspeed quoted by the manufacturer (usually in the range 15-20 mph).

Total Cost 16' Rotor on 35' Tower = $7317.

Table 14

COST OF MECHANICAL WATER PUMPING AT SELECTED SITES[69a]

Location	V_m (mph)	h_1 (hours)	h_2 (hours)	$\frac{h_1 + h_2}{2}$	V_a (1000 cals.)	$ /1000 gal	$ /ha cm
New Delhi, India	5.7	400	3700	2050	3485	.22	5.81
Bangalore, India	5.9	330	3000	1675	2848	.27	7.02
Hreiba, Israel	10.9	955	8045	4500	7650	.098	2.62
Bhopal, India	8.0	800	5000	2900	4930	.15	4.05
Nairobi, Kenya	6.6	529	3942	2235	3782	.20	5.29
Mandera, Kenya	8.2	747	4555	2651	4486	.17	4.46

Assumptions - Wind Machine Life = 20 Years
(U.S. Average = 30 Years)
Purchased on 10-Year Loan @ 12% Annual Interest
Yearly Maintenance Over 20 Years Averages 1.5% of Purchase Cost

NOTE: Because well costs are so variable by type well and by construction method, they are not included in the above figures.

The above costs are approximate estimates using available data for comparative purposes. They do not reflect actual local labor conditions and do not take into consideration the distribution of the wind relative to the periods of the irrigation season when water is needed. Site specific studies would be needed for exact estimates.

One deficiency of the windmill directly used for water pumping is that it must be located above the well or water source, which may not be the optimal location for wind availability. In such cases, a wind-electric generator coupled to an electric pumpset offers greater flexibility.

Small propeller-type wind-electric generators were used extensively in the United States in the 1930s and 1940s by rural households without central station electric power. Extension of the low-cost central power grid to rural areas by the early 1950s nearly eliminated the country's wind generator industry. Today, there are probably only 50 to 100 wind generators sold each year, primarily in the 1 to 6 kW range. Nevertheless, many models of wind-electric generators, varying in capacity from a few hundred watts to about 10 kW are still commercially available.

The annual energy generation cost in ¢/kWh for a given wind-electric generator can be calculated as follows:

$$\frac{\text{Annual cost}}{\text{kWhr}} = \frac{\text{capital cost}}{\text{rated kW}} \times \frac{\text{rated kW}}{\text{average kW}} \times \frac{\text{amortization}}{\text{factor}}$$

The rated kW per average kW is the reciprocal of the capacity factor which is a function of the average wind speed at the location of the generator. Figure 5 shows the cost of generating power, for various capacity factors, as a function of capital cost per installed kW of the generation. The assumption modes are: 20 years life of the wind generator, 10 percent interest rate. At an assumed capital cost of $1300/rated kW, the cost of generation varies from 4.5 to 17.5 ¢/kWh for capacity factors lying between 0.4 and 0.1*. Table 15 uses the results of a study done by Georgia Institute of Technology to estimate the range of generation costs of wind generators for a given location with a known mean annual wind speed. The G.I.T. study analyzed the dependence of wind turbine performance (measured in capacity factor and recovery factor) on cut-in speed and rated speed for various mean wind speed and wind variance regimes (assuming wind speed distributions to be Weibull distribution). For the purpose of our study, the mean variance case and a wind turbine (5 kW) with 10 mph cut-in speed and 25 mph rated speed are used.

Based on Table 15, irrigation costs can be evaluated when such a wind turbine is coupled to a 4.5 hp electric centrifugal pumpset. Figure 6 shows this cost as a function of mean wind speed at hub heights of 33 ft and 100 ft. Irrigation costs range from $3 to $5 per acre-in at 9 mph mean wind speed and decrease to about $2 per acre-in at 18 mph mean wind speed.

* Estimates by the U.S. Dept. of Energy put generation cost from wind generators at between 5 to 10¢/kWhr for a capital cost of $1300/kW. The $1300 per kW capital cost projected based on a mature market, is significantly lower than the current market price.

FIGURE 5

ELECTRICITY GENERATION COSTS FOR WIND ENERGY SYSTEMS [69]

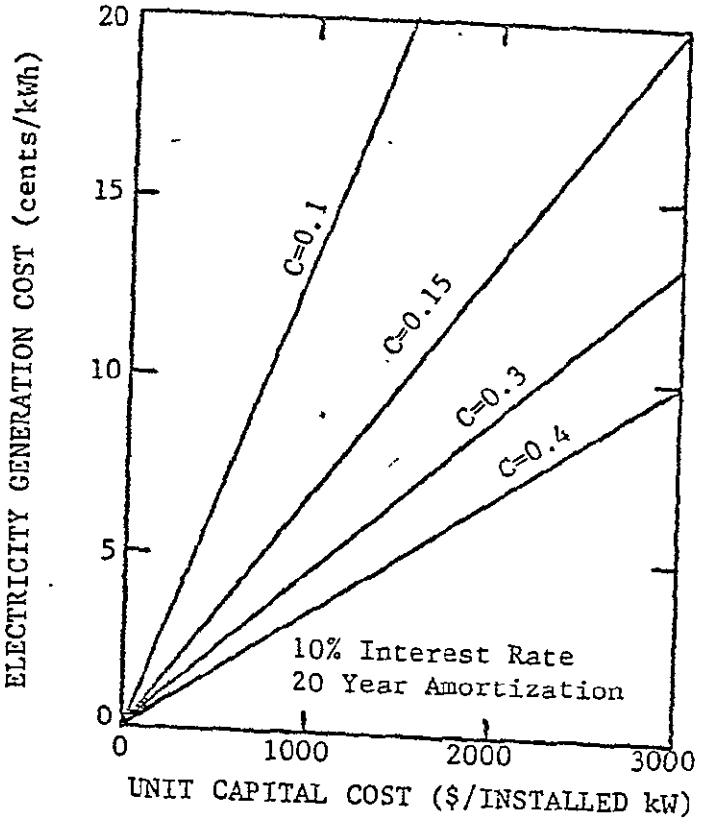


TABLE 15

ENERGY GENERATION COST OF WIND ELECTRIC GENERATORS[70]

$\overline{V}$ (10 m) mph	Cost (c/kWh) 10 m	30 m
9	24.0	10.9
12	12.5	6.5
14	7.5	4.4
16	5.2	3.4
18	3.9	2.9

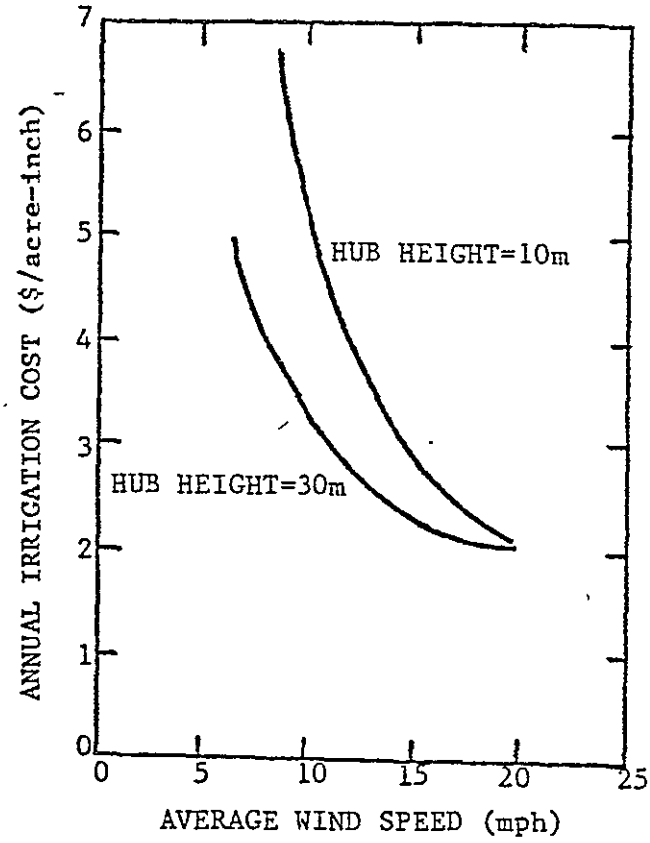
Rated Speed = 25 mph

Cut-in Speed = 10 mph

Average Variance

FIGURE 6

ANNUAL IRRIGATION COSTS OF WIND-ELECTRIC SYSTEMS[70]



Assuming Weibull Distribution for wind speed distribution with mean variance, Table 16 shows the irrigation cost using wind turbine coupled to an electric centrifugal pumpset for a few selected locations. A comparison of Table 15 and Table 16 shows that the irrigation cost of wind-electric pump systems is a little higher than wind-mechanical pumps at an optimistic estimate of $1300/kW of capital cost for wind electric generators.

Operational/Maintenance Experience

Except for the high speed propeller wind machines and the high speed Darrieus rotors used for electricity generation, all of the wind machines discussed have been in operation for many years. As with any machine, they must be maintained and protected from over stress (extreme winds). Probably the critical element is the connection to the pump and wear within the pump. This requires operator training and the provision of tools and replacement parts. With proper operator training, lubrication and mechanical supports, the machines have a record of reliable low-cost service.

4.5 Biogas-Powered Pumps

Biogas is a medium-Btu gas, approximately 550-600 Btu/cu. ft. (20,000 joules/m^3), produced from the anaerobic fermentation of organic materials such as animal dung and agricultural residues. The major components of biogas are methane (CH_4), 55-60 percent by volume and CO_2 with small traces of H_2S, H_2 and N_2. Although the technology of anaerobic digestion has been utilized in urban sewage treatment plants for many years, its use for producing energy (and fertilizer) at the village or farm level is relatively new. Reviews of the technical, economic and social aspects of biogas technology as applied in developing countries have recently appeared in the literature.[71,72,73] China and India are two developing countries where the technology is most advanced in the rural areas, with almost 7 million digestors in China and about 70,000 operating in India.

Figure 7 is a schematic of a biogas plant. The digestor consists of a large tank in which a mixture of wastes mixed with water are placed. The digestion process proceeds in two steps (Figure 8): an "acidogenic" phase in which acid-forming bacteria break the complex organic waste into (mainly) organic acids and CO_2, followed by a "methanogenic" phase in which methane-forming bacteria break the organic acid into CH_4.

Although a number of different digestor designs have been proposed and are in operation, two major designs--the Chinese and Indian--have seen the most application. The Chinese design (Figure 9) is referred to as a water presssure digestor. It consists of a sealed, rigid wall tank with an effluent chamber designed to act as a pressure regulator. The Indian design (Figure 10) is a rigid wall digestor with a floating cover made of steel which captures the gas and floats on the slurry in the tank. The main advantages of the Chinese design is that it has no moving parts and can be constructed very cheaply from locally available materials. Though the Indian design costs more because it is made of steel, it produces a more even gas pressure.

BEST AVAILABLE COPY

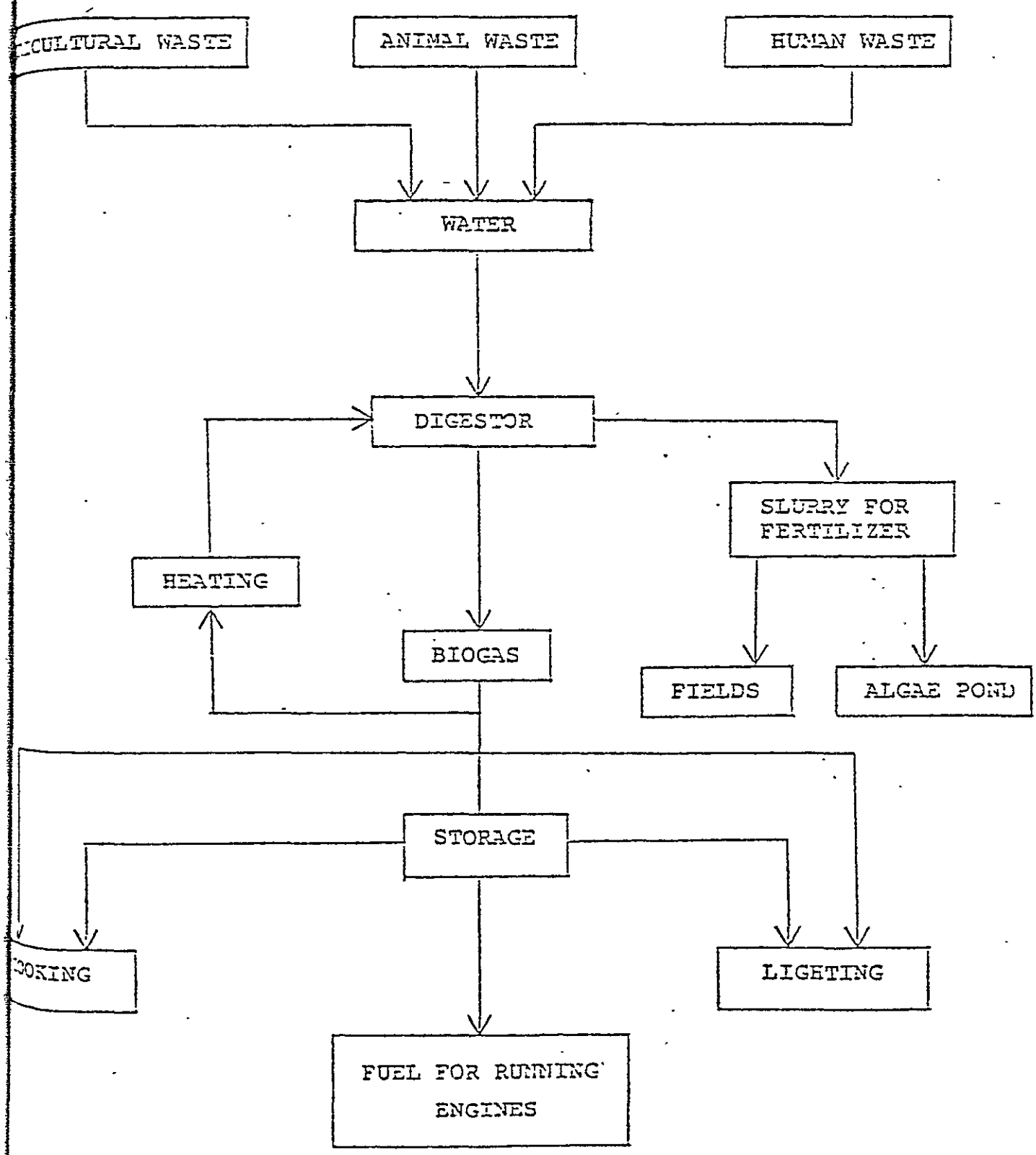
TABLE 16

IRRIGATION COSTS OF WIND-ELECTRIC TURBINE AT SELECTED SITES[70]

Location	Vm (mph)	Irrigation Costs ($/acre-i
Lindi, Tanzania	13.4	2.50 - 3.20
Nairobi, Kenya	7.6	4.30 - over 8.00
Bangalore, India	5.7	6.00 - over 10.00
Hreiba, Israel	10.9	3.00 - 4.30
Amarillo, Texas	12.6	2.70 - 3.60

FIGURE 7

FLOW CHART OF BIOGAS MODEL PLANT[74]



PHOTOVOLTAIC POWER IN LESS DEVELOPED COUNTRIES

I. PHOTOVOLTAIC POWER

This report concerns the economic and technical viability of using solar cells to power irrigation pumps and other village power-consuming needs in the less developed regions of the world. Attention is focused on likely costs of such cells (fabricated into solar arrays) by 1986 according to ERDA projections. Attention is restricted to installations exceeding two kilowatts (kw) (peak electric).

Solar cells are thin wafers of a semiconductor material, such as silicon, "doped" with p- and n-type substances selected to enhance the photovoltaic effect. This effect, long known to physicists, is the creation of charge carriers within a material by the absorption of energy from incident ionizing radiation, e.g., light. Light meters for photography have long exploited this effect to advantage, but it has only been the space program with its need for spacecraft power at any cost that has developed solar cells of "interesting" efficiencies from 3 to 25 percent.

Recent advances in the technology of solar cell manufacture have succeeded in dramatically lowering costs, compared with the space program, at conversion efficiencies of around 10 percent. It is the possibility of continued cost decreases coupled with certain inherently attractive features of solar cells that make them of interest for application on earth. These features include:

a. Reliability with low maintenance requirements

b. No fuel costs

c. Quiet, pollution-free operation

d. Modularity (even if part of the system goes out, the rest continues to function).

Solar cells convert incident solar energy directly into DC electricity at about 0.5 volt. Derived voltages and currents are achieved by connection of

cells into series-parallel configurations called solar arrays or panels. Because solar cell output is proportional to incident illumination (and a function of the received spectral pattern of radiation) there is often a need for battery storage of electricity. This is to even out the supply of power to the device of interest (for example, a pump motor) and to make power available during periods of low illumination intensity (rainstorm or at night). Because output of cells and batteries is DC, inverters are necessary to produce AC, or use of DC equipment is mandatory. Thus energy storage and power conditioning are essential elements in design of any photovoltaic system.

Photovoltaic generation of electricity is currently used in many countries for communications purposes in remote installations where supply is difficult. Developing country applications have been limited but Niger runs several dozen educational television sets with solar cells and a few water pumping installations exist in Africa, Sicily, and the Persian Gulf. Interest, however, is high and a number of countries that have or will have pilot systems in operation over the next few years include India, Iran, Pakistan, Senegal, Brazil, Kuwait, Abu Dhabi, and Thailand.

Irrigation and Village Electrification

Several writers have recently begun stressing the role of energy in the development process (Revelle; Makhijani; Makhijani and Poole.) They argue that:

1. Large amounts of human and animal labor and noncommercial fuels are currently used in the rural areas of the poor countries
2. These energy inputs and much smaller quantities of commercial fuels and fertilizers are used inefficiently so that useful energy inputs are often pitifully small compared with gross energy inputs
3. Human and animal labor in these areas is hard and even unproductive and burning of fuels such as wood and dung can be ecologically harmful

4. In many regions where crop yields are low because of low useful energy inputs, less than one-tenth of one percent of incident solar energy is captured

5. Up to a point, net energy output of agricultural products increases much faster than the energy inputs needed for higher yielding agriculture: irrigation, fertilization,* and multiple cropping

6. Development of the rural, poor areas of the world will require an infusion of more energy used more efficiently.

One of the most important ways in which this increased energy will be applied is irrigation. This is especially true where the greatest development challenges lie: the African Sahel and the Indo-Gangatic Plain of India, Bangladesh, and Nepal. Other significant consumers of energy in the rural third world will be fertilization, power for land preparation and harvesting, and agricultural processing. Furthermore, a key element in any scheme to improve rural health must be improvement in water supply. This most often means replacement of presently contaminated water sources by tubewell water pumped by hand, animal, or motor.

The challenge, then, is to develop energy technologies that meet these needs while satisfying criteria relevant to developing countries. These criteria might be:

1. Ease of maintenance and operation

2. Low use of nonrenewable resources

3. Minimal environmental impact

4. High reliability

5. Low ratio of cost-of-energy input to value-of-energy output

6. Low capital and foreign exchange requirements.

---

* This is especially true if organic fertilization is used to the extent possible.

Photovoltaic power systems admirably fulfill the first four of these criteria. The fifth criterion is the subject of this report, and the last criterion is the major drawback to the use of solar power cells. It is a matter subject to considerable research both in the U. S. and overseas at the present time.*

Of the five principal energy needs of the rural third world: irrigation, fertilization, motive power, agricultural processing, and potable water pumping, photovoltaic systems appear most suited to pumping water for irrigation and water supply and to driving motors of stationary agricultural machinery. By case studies, reports are made of two energy areas: (a) irrigation water pumping, and (b) village power supply for potable water pumping, driving agricultural processing machinery, lighting on a modest scale, and operating an educational TV.

The Case Studies

This report does not attempt to estimate the total market for photovoltaic systems in the LDCs but to investigate their economic and technical viability in selected applications. This will demonstrate a methodology for evaluation of photovoltaic systems, show their potential in actual situations, and provide a conceptual basis for a full-fledged marketing study.

The irrigation case study is an irrigation project in West Africa on the shores of Lake Chad in the Republic of Chad. Pumping is from shallow wells along the lake shore and, as a consequence, low-head, high-discharge pumps can be used. Captial investment in power and pump is thus much less per volume-unit of water lifted than in high-head situations. Fuel requirements, of course, are also less. The area for study has a high rate of solar radiation and a low fluctuation over the year, evapotranspiration is high while rainfall is low, diesel fuel is expensive and unreliable, and diesel engine maintenance facilities are lacking. For these reasons the area appears favorable for use

*Research is under way in some LDCs to develop local solar energy equipment manufacturing capabilities: fabrication of concentrating collectors used with solar cells, wiring together of solar cells, installing and maintaining systems, and training personnel. Manufacture of cells will take place in the rich countries for some time [deWinter & deWinter; Furber].

of solar cells. The author is familiar with the project area, having visited the site on a USAID-sponsored appraisal mission in 1975. Because of the analysis made by Dr. Richard Tabors at that time, excellent cost estimates of alternative water-lifting technologies are available.

To supplement the Chad case study and elucidate several issues that arise in different types of irrigation pumping situations, additional cases were analyzed in Asia: Bangladesh, India, and Pakistan. The Bangladesh case compares a photovoltaic system with current low-lift pumping practice: one crop irrigation of rice or wheat during the winter by diesel/pump water-lifting from a river. Again, this is a situation familiar to the author from work in that country in 1970-71 on the Bangladesh Land and Water Study and in 1975 on the Bangladesh Energy Study. To show the impact of pump use for part of a second rice crop (before the Brahmaputra floods) this Bangladesh analysis is extended to Assam. Assam was selected because the World Bank is currently interested in groundwater development in that state and has performed comparisons of water-lifting costs using different technologies, including hand pumping

Finally, the lifting of water from tubewells is considered in the last case of the Pakistan Punjab. In this region, irrigation by canals fed from the Indus and its tributaries has been ongoing for many years. Water scarcity and waterlogging caused by canal seepage have combined to make tubewell irrigation a profitable proposition for Punjab farmers who install tubewells on their own initiative and drive them with diesel engines or, if electricity is available, with electric motors. In this case, the impacts of higher head, lower fuel costs, and better maintenance facilities can be seen.

For a village electrification case study a village of 600 persons in northern India was chosen. The village lies 16 km from the nearest 11-kv transmission line and has no motors at present. It is postulated that better health of the village depends on an assured, protected water supply, that agricultural progress depends on irrigation, that overall development depends on establishment of agricultural processing and cottage industries, and that educational progress will be hastened with electric lights and educational television. All of these activities are powered by solar cells installed in a modular fashion

over time. Costs of such a photovoltaic system are compared with costs of the cheapest, motorized means of accomplishing the tasks. No attempts are made in any of the case studies to compare photovoltaic systems with human labor, animal power, wind, biogas or other solar alternatives.

Methodology

The basic procedure to evaluate solar cells applied to irrigation water lifting in LDCs is to compare their cost, including power conditioning equipment, with the cost of the least-cost alternative using conventional technology. This is accomplished by making fairly detailed assumptions about operating procedures for the two technologies being compared. When the products of the two technologies are the same (in terms of cubic meters of water pumped in a year) then comparison is made on cost per horsepower-hour (hp-hr) to drive the pump. When the products of the two technologies are dissimilar, as when the diesel pump can cover more hectares of land, then comparison is made on cost per thousand cubic meters of water pumped.

The following important assumptions have been made:

1. The lowest discount rate appropriate for evaluation of public sector projects in the countries considered (Chad, Bangladesh, India, and Pakistan) is 10 percent. This is the rate used in International Bank for Reconstruction and Development (IBRD) evaluation of rural electrification projects (Anderson) and of solar cells for ETV (Weiss and Pak).* Sensitivity of photovoltaic electricity costs to discount rate is demonstrated for higher rates of 15 and 20 percent.

* Weiss and Pak use discount rates of 10, 14, and 25 percent. This rate can be assumed approximately equal to the lowest internal rate of return a government project is expected to earn. For the IBRD this is between 10 and 15 percent (Pak and Taylor).

2. No adjustment is made for the shadow price of foreign exchange which can be expected to lie somewhat above the official rates of exchange (Meta: Bangladesh Energy; IBRD: Bangladesh Development). This assumption is warranted for Chad because 100 percent of the cost of solar cells is foreign exchange and all cost computations are done in U.S. dollars. This assumption biases results slightly against diesel, however, because local costs given in francs (Chad) and converted to dollars at the 1974 official rate of 237 francs per U.S. dollars would be less converted at an IBRD shadow rate of CFAF 270 per U.S. dollar (IBRD: Chad: Polders, p.vi).

3. No transport costs of solar arrays, engines, or motors from the U.S. (where f.o.b. prices are used) to the country of use are included.

4. No estimate is made of the following photovoltaic costs:

   a. labor and materials for installation, or
   b. on-site structures for housing storage batteries.

   It is assumed ERDA solar array prices include structural elements sufficient for the unit to support its own weight.

5. Cost of land is not included in any of the costs. This is appropriate in Chad where land is not a development constraint, but inappropriate in Bangladesh where land is exceedingly scarce. (A solar array to power a 5-hp, low-lift pump would occupy approximately 55 m^2 of land; that is, 600 square feet, 1.4 percent of an acre, or a 25 by 25 foot rice paddy, which could yield 13 pounds of rice in Bangladesh or enough to feed one adult for two weeks.

6. Benefits in terms of crop value are assumed identical across energy technologies so only costs need to be compared. It is assumed that if a project is economically sound given one set of costs (say with diesel pumps) and if photovoltaic costs are less, then the project remains sound.

7. Costs are compared on the basis of equivalent annual costs at mid-1976 prices. This is a totally static analysis that assumes no changes in cost, benefit streams, or load factors over time.

8. No alternatives that include water storage above ground are considered.

9. Equipment lifetimes are assumed as follows:

   a. solar arrays, 20 years with sensitivity analysis for 10 years
   b. DC motors, 12 years
   c. batteries, 7 years
   d. diesel engines, 8 years
   e. pumps and wells, 8 years

10. Two thousand-cycle, deep-discharge, lead-acid batteries are used with an estimated cost of $ 50 per kwh (Bechtel). This is, in fact, a cost goal, and not a current cost.

11. Efficiencies of equipment are:

   a. DC motors 5 hp and above, 80%
   b. DC motors, below 5 hp, 75%
   c. pumps, 60%
   d. batteries, 85%

12. Solar radiation received during the peak irrigation pumping month of June at Bol, Chad, is 550 cal/cm^2/day (mean). This is 2300 joules/cm^2/day or 6.4 kwh/m^2/day.

Other assumptions are discussed as they arise.

Methodology for the village study is similar. Cost of a photovoltaic system to accomplish a specified task is compared with cost of the least-cost alternative, which might be a gasoline engine, diesel engine, diesel generator for lights and TV only, diesel generator for village, or grid electrification. Again, the analysis is static, but because there are no economies of scale in photovoltaic systems (excluding power conditioning) and solar arrays are only fielded when the demand has developed,* this static assumption does not bias the results as it would if autogeneration were being compared with grid electrification (Anderson).

* The solar arrays used as village power sources are assumed to be nearly fully utilized for productive purposes, except for a lighting load factor of 60 percent. This is not, however, the case with irrigation applications.

III. IRRIGATION WATER PUMPING WITH PHOTOVOLTAIC POWER

Lake Chad Polders Project

The major irrigation case study discussed in this report is an analysis of alternative techniques of water lifting, with emphasis on photovoltaics and diesel engines for a specific area in the middle of Africa. As far as is known, the descriptive information presented about this area is factual; it is based on a field visit by the author to the area and on extensive interviews with knowledgeable individuals in Chad, France, Italy (the United Nations Food and Agriculture Organization, Rome [FAO]), and the U. S. A.

The Lake Chad Polders Project lies to the northeast of Lake Chad in the Republic of Chad at latitude approximately 13°N (Fig. 1). The lake is shallow and as a consequence relatively small changes in level make a large difference in the location of lake boundaries. Therefore, after a period of years of average-to-high rainfall and a high lake level, the lake expands to an area of 30,000 km^2. More recently, during the drought, the lake shrank to an area of less than 5,000 km^2.

The lake itself is divided into a basin that is sometimes separated into northern and southern basins when the lake is very low. Astride and to the northeast of both basins is the archipelago area which is made up of a large number of long, narrow islands, oriented northeast to south. These islands are the remnants of ancient sand dunes and are partly inundated depending on lake level.

The low areas between the dunes or islands are comprised of exceptionally fertile clay or clay-loam soils on the surface, underlain by a thin sandy or calcareous layer which, in turn, is underlain by a thick layer of fissured, heavy clay. Because of the fertility of these interdunal areas, their direct access to lake water is often cut off by man-made dams built between the dunes. When this is done the interdunal areas are called "polders." Because polders lie below or near the level of the excluded lake, they feature high water tables so that a shallow well can be dug and water lifted by shadoof (human-powered, counterpoise lift) from less than one meter.

-7-2916

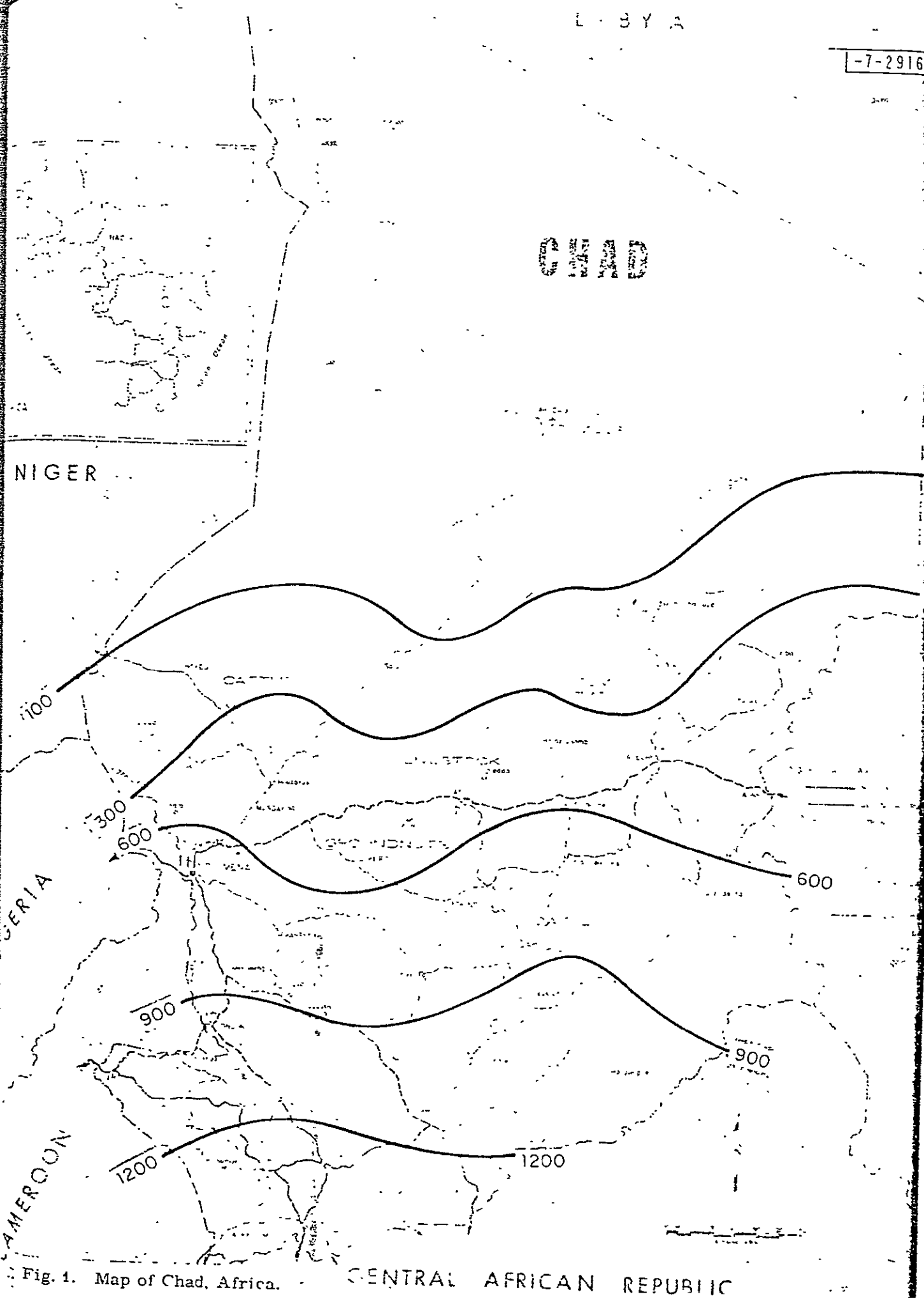


Fig. 1. Map of Chad, Africa.

BEST AVAILABLE COPY

The water in the lake itself is amazingly low in salinity considering the lake's lack of surface outlet. Nevertheless, salinity problems develop over time in the polders because of underwatering in shadoof irrigation. (The water contains some salt that is never leached away by heavy rain or heavy irrigation applications, and thus, it builds up in the root zone.) Eventually, it is often a matter of only a few years, the polder is abandoned and a new one is built.

Focusing on the town (prefecture headquarters) of Bol on the shore of the lake and near several polders, including Guini, Berim, and Djiboulboul, and the proposed polder of Mamdi: Bol is accessible by barge from the Chari River and across the lake, but only from November to March during years of sufficiently high water level. There is a small airstrip at Bol, but primary access is by road from N'Djamena – a distance of 305 km most of which is desert track passable only to four-wheel drive vehicles (with good drivers).

Bol is sunny, hot, and dry. April daytime temperatures average 38.5°C (101.3°F). Average rainfall is 285 mm (11 inches) which is just enough to produce the lowest yielding crop of millet. Evapotranspiration, on the other hand, is high: 2140 mm per year. Solar radiation averages nearly 540 cal/cm^2/day and never drops below a mean daily figure of 470 cal/cm^2/day. (About 70 percent of the rains occur in July and August.)

The town of Bol has some importance as headquarters of the Prefecture du Lac and as a regional office of SODELAC (Societe du Developpement du Lac) which is a small government corporation responsible for development of the Lake Chad region. The town itself has several thousand inhabitants but no industry aside from cottage-level blacksmithing, basket-making, leather working, and pottery making. SODELAC has a workshop and diesel storage depot and there is a government rest house (with water supply occasionally provided by a Peace Corps-installed Dempster windmill). There is not much wind in Bol, however. Population of Bol and neighboring villages is a little over 7,000 people. Population density along the archipelago region of the lake is about 30/km^2.

Local people (Badumas, fishermen and pirates originally from the islands, and Kanembous, cattle people from the mainland) live a seminomadic life with

fishing and cattle raising important to all. Cultivation is traditionally not a preferred activity and consists of rainy-season millet on the dunes. Maize, wheat, and onions are grown in wet areas of the polders near the lake edge. Maize is for local consumption, but wheat and onions are profitable to export to Nigeria or southern Chad. Irrigation of wheat and onions is by shadoof. Small motor pumps have been tried, but lack of maintenance or fuel has prevented their success.

Both Guini and Berim polders are located within 5 km of Bol. They were empoldered in 1951 and 1954, respectively, and some shadoof irrigation still goes on in parts of these polders. [During the height of the drought (1972-1975) this ceased, however.] Guini polder was partly developed as a gravity, surface irrigation project between 1969 and 1972. The development included water intake, irrigation canals, drainage channels, draining pumping station, service roads, and an agricultural research station (Matafo). As a result of a certain amount of success with this pilot project the IBRD is proposing to fund extension of the system to all of Guini and Berim polders (IBRD: Chad).

In 1973, on a visit to the area for USAID, Roger Revelle suggested use of the low-lift motor pumps to lift water from shallow, hand-dug wells. These pumps could replace the traditional shadoof irrigation, and would overcome salinity problems if used properly. It was anticipated that such a scheme would demand less capital than the costly IBRD project outlined above and that it would alleviate the need for pumped drainage. Extensive studies were subsequently conducted on salinity dynamics, economics of alternative water-lifting technologies, and other aspects of the proposed scheme and it was found feasible for Djiboulboul polder pending soil and water testing by ORSTOM (Meta Systems: Chad). USAID is currently sponsoring the necessary testing as well as supporting a research staff to complement the Lake Chad Polders Project activities. This research will include examination of low-lift pump alternatives and problems with use of shallow wells.

One of the most useful products of the Meta Systems study was an in-depth comparison of water-lifting costs including shadoofs, persian wheels, gasoline engines, high- and low-speed diesel engines, windmills, electrification of a project area and use of electric pumpsets, and two different types of centrifugal

pumps, one especially adapted to low-lift applications. The study also examined alternative pump capacities. The existence of this study and personal knowledge of the project area on the part of the author were compelling reasons for choosing the Lake Chad polders area for a photovoltaic pumping case study. There are other reasons as well:

1. Solar radiation is high with 550 cal/cm^2 per day mean for the peak irrigation pumping month of June. In no month is the mean radiation below 470 cal/cm^2 per day. There are over 3000 hours of sunshine per year. The high radiation output and low fluctuation of energy receipt state make the Lake Chad region well suited to utilization of solar energy devices (Terjung).

2. Chad produces no fossil fuels, and as a consequence, all fuel must be imported and carried over a long and expensive motor road from the coast to N'Djamena. Furthermore, access to Bol is extremely difficult because there is no road—only a desert track—and the lake is often not navigable to Bol. As a consequence fuel is expensive and its availability is unreliable.

3. Maintenance of engines has been a major problem facing attempts to irrigate in the polders region of Lake Chad.

4. Extension of a grid to Bol based on hydroelectric developments in southern Chad is far in the future.

Each of these characteristics of the project makes it of interest for utilization of low maintenance, fuel-free solar pumping.

Irrigation Water Requirements and Solar Radiation

Table 1 displays data relating to both irrigation water requirements and solar radiation for a wheat/cotton system at Bol. Irrigation water requirements are from two feasibility studies of polder projects (Meta Systems: Chad;

TABLE 1:

IRRIGATION WATER REQUIREMENTS AND SOLAR RADIATION - LAKE CHAD POLDERS PROJECT - COTTON/WHEAT CROPPING PATTERN

	NOV	DEC	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	TOTAL
Evapotranspiration ETP mm	179	146	144	142	208	228	227	185	181	148	151	199	2138
Average rainfall mm							8	9	69	142	43	9	280
Effective rainfall ER mm									35	71	22		128
Crop	|---|	Wheat			|---|	|---|	Cotton					|----|	
Crop coefficient ETR/ETP	0.6	0.6-1.0	1.0	0.75		0.6	0.6	1.0	0.0	0.9			
Water requirements ETR-ER mm	72	110	144	71		45	136	185	146	62			971
From groundwater mm									73	31			104
Net irrigation requirements mm	72	110	144	71		45	136	185	73	31			867
Gross irrigation requirements mm	120	183	240	118		75	227	310	122	52			1447
m^3/ha	1200	1830	2400	1180		750	2270	3100	1200	520			14470
Cal/cm^2/day - mean	520	480	480	550	600	630	590	550	530	470	500	550	
kwh/m^2/day - K	6.1	5.6	5.6	6.4	7.0	7.3	6.9	6.4	6.2	5.5	5.8	6.4	
Liter.second/hectare (for K hours)	1.8	2.9	3.8	1.8	---	1.0	2.9	4.5	1.2	0.8	---	---	
"Surplus power" (Peak KW)	3.3	2.0	0.9	3.3	5.5	4.3	2.0	0	4.0	4.5	5.5	5.5	
"Available panels" (Peak KW)*	2.6	1.6	0	2.6	5.5	3.4	1.6	0	2.7**	3.1**	5.5	5.5	

*80 percent of "surplus power" except during months of no pumping or months of some effective rainfall.

**Depends on actual rainfall but this is minimum available assuming zero rainfall.

IBRD; Chad). Solar radiation data are from (Löf; FAO).* Figure 2 schematizes the configuration suggested for photovoltaic pumping in Chad.

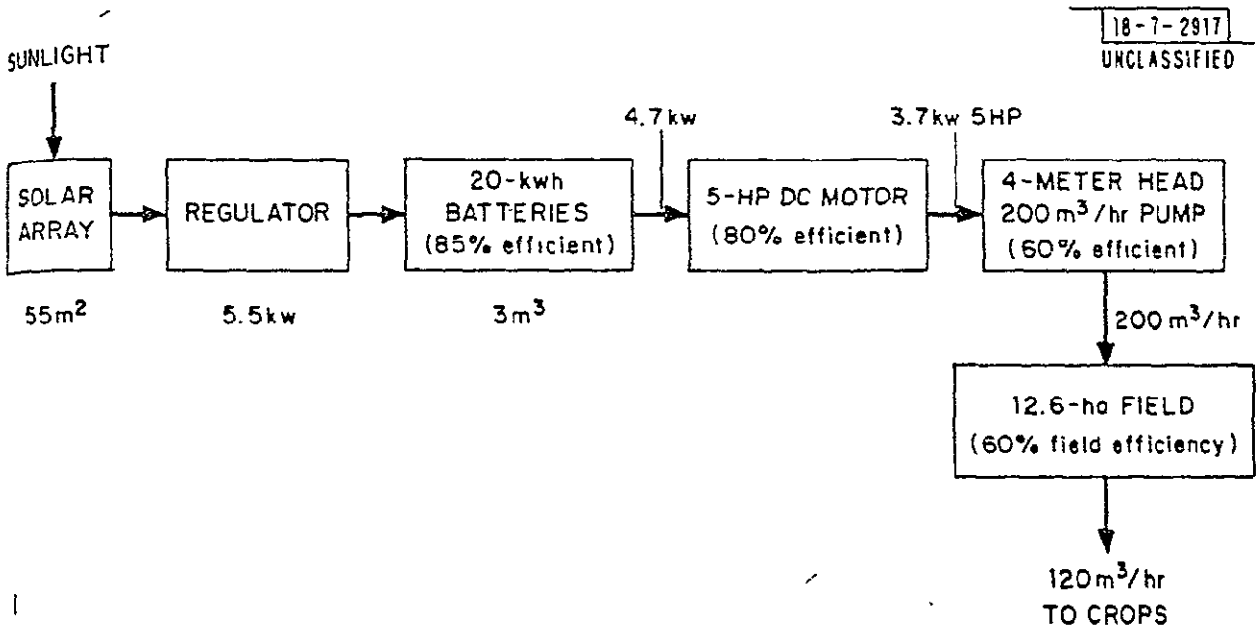


Fig. 2. Irrigation pumping configuration for Chad Polders Project.

The peak month for irrigation requirements is June (Table 1). In sizing of the solar array/motor pump system, however, it is necessary to relate daily irrigation needs to daily solar radiation to develop required pumping capacity. Conceptually, this is done by assuming one day's storage and pumping at night. Pumping for 6.4 hours at full power is possible during June; 5.6 hours during December (Table 1). Consequently, for the same amount of water pumped, 14 percent more capacity is needed during December ($\frac{6.4}{5.6} - 1.0$) than during June. Water quantities pumped are not the same, however, so the required monthly pumping rate must be computed as a function of the monthly water requirements and the number of hours at full-power pumping (Table 1,

* The Löf data have been adjusted downward using data reported in the FAO study.

line 13). In practice, of course, all pumping is not done at night, but the answers are unaltered.

It is asssumed, based on institutional and water management grounds, that 204 m^3/hour (2-cusec) pumps are used. For a dynamic pumping head of 4 meters and an efficiency of 60 percent, 5 hp is required.* Assuming a motor efficiency of 80 percent (standard assumption for 5-hp motors) and a battery storage efficiency of 85 percent (Bechtel), the peak panel requirement is:

$$\frac{5 \text{ hp} \times 0.746 \text{ kw/hp}}{0.8 \times 0.85} = 5.5 \text{ peak kw}$$

Several hours of battery storage might be included to buffer the motor (DC motor) from the fluctuations of array output and to provide pumping capacity during short periods of cloud cover during the onset of the monsoon when irrigation water is still required and during particularly dusty periods when solar insolation is reduced temporarily. Twenty kwh of battery storage is suggested to cover 3.6 hours of storage per 5-hp pumpset. This is the least amount of battery storage that is available with 2,000-cycle batteries. (It is not anticipated, however, that the batteries are often fully discharged.) Inclusion of battery storage in the system implies that proper battery maintenance must be available on a regular basis to check electrolyte levels and electrical connections.

Costs of Solar Pump

The cost, in cents per kwh, of providing solar power to the irrigation pumping system depends on the cost of solar arrays, S, (in U. S. dollars per peak kw) and the interest rate chosen. It also depends on assumed solar array lifetimes and insolation. In the following analysis for Chad a 20-year life for solar arrays and an average insolation equivalent to 6.2 kwh per peak kw per

---

$$* \text{hp} = \frac{204 \text{ m}^3\text{/hour} \times 4\text{m}}{272 \times 0.6} = 5.0 \text{ hp at motor shaft.}$$

day is assumed. Furthermore, the cost depends critically on the number of hours of use, which for the cotton/wheat system studied here is 920 hours.*

Storage cost is assumed as $50/kwh with a life of 7 years (Bechtel). For 20-kwh storage capacity the capital cost of batteries is $1,000. Total annual cost of the solar array with battery storage is:

$$R(i,20) \times 5.5S + R(i,7) \times 1000$$

where R(i,t) is the annual capital charge factor for an interest rate, i, and lifetime of t years.

Cost in cents per kwh delivered to the motor is:

$$\frac{R(i,20) \times 5.5S + R(i,7) \times 1000}{5.5 \times 920 \times 0.85 \times 0.01}$$

Setting i as 10 percent, this becomes:

$$E\,(\text{cents/kwh}) = 0.015S + 4.77.$$

Note that this expression has a solar array cost term and a battery cost term and that both vary inversely with the number of hours of use (in this case 920 hours).

Variation of energy cost with S is given in Table 1a.

TABLE 1a

VARIATION OF ENERGY COSTS (E) WITH SOLAR ARRAY
(Costs for Chad pumping case: 920 hours of pumping)

S $/peak kw	E Cents/kwh
300	9
500	12
1,000	20
2,000	35
10,000	154
14,000	214

* This total hourly requirement is calculated as follows:

$$920 = \frac{6.4 \text{ hr/day} \times 30 \text{ June days}}{0.21}$$

where 0.21 is the fraction of the annual irrigation water requirement falling during the peak month of June.

TABLE 2

VARIATION OF SOLAR ELECTRICITY COST WITH COST OF ARRAYS, INTEREST RATE, LIFE OF ARRAYS, AND HOURS OF USE FOR CHAD IRRIGATION CASE

S $/Peak kw	i Interest Rate	t_a Solar Array Life in Years	h Hours of Use	E Cents/kwh
500	10	20	920	12
		20	1,800	6
		10	920	15
		10	1,800	8
	15	20	920	16
		20	1,800	8
		10	920	18
		10	1,800	9
	20	20	920	20
		20	1,800	10
		10	920	22
		10	1,800	11
1,000	10	20	920	20
			1,800	10
	15		920	26
			1,800	13
	20		920	33
			1,800	17
2,000	10		920	35
			1,800	18
	15		920	47
			1,800	24
10,000	10		920	154
	15			210
14,000	10			214
	15			292

Table 2 expands on Table 1a to display variation of E with S, i, life of arrays (t_a), and number of hours that electricity is used at full power (h).

Table 2 is useful in comparing solar array costs with alternative electricity costs, but in villages and on farms around Bol, Chad there is no alternative electricity source requiring the addition of an electric motor to the solar system. The resulting cost is then compared with a configuration using a diesel engine.

Capital cost of a 5-hp DC motor is assumed as $1100 (Reliance Electric Co.) plus $100 for spares. Life is 12 years; maintenance is assumed at $15 per year (Meta Systems, p. 85).

Annual cost = R(i,12) × 1200 + 15. Cost per hp-hr (H_s) as a function of solar array cost (S) is given in Table 2a.*

It is of interest to examine the components of H_s. This energy cost is comprised of the solar array cost plus the power conditioning cost. Storage batteries and a regulator are needed to provide a buffer between array output and motor. Furthermore, a DC motor is used to eliminate inverter losses if an AC motor was usd. The DC motor is at least five times more expensive than the equivalent (for this application) AC motor, however.

By separating components of H_s, it may be shown that:

$$H_s = 4.16 + 4.44 + 0.014S$$

where the first term is motor cost in cents per hp-hr (920 hours), the second term is battery cost, and the final term is the solar array cost. Thus the motor and battery cost 8.6 cents per hp-hr irrespective of solar array costs. Variation of the solar array component of costs with unit cost of the arrays is shown in Table 2b.

---

* To compute cost per hp-hr:

$$H_s = \text{cents/hp-hr} = \frac{100[R(i,12) \times 1200 + 15]}{5 \times 920}$$

$$+ \frac{0.746}{0.8} \left[\frac{R(i,t_a) \times 5.5S + R(i,7) \times 1000}{5.5 \times 920 \times 0.85}\right] \times 100$$

where 0.8 is the motor efficiency and 0.746 is the theoretical kw/hp.

TABLE 2a

VARIATION OF COST PER HORSEPOWER-HOUR WITH SOLAR ARRAY COST

S ($/Peak kw)	H_s (cents/hp-hr) = 4.16 + 0.93E
300	13
500	16
1,000	23
2,000	36
10,000	148
14,000	204

TABLE 2b

VARIATION OF SOLAR ARRAY COMPONENT OF COSTS WITH SOLAR ARRAY COST FOR 920 HOURS PUMPING

S ($/Peak kw)	0.14S
300	4.2
500	7.0
615	8.6
1,000	14.0
2,000	28.0

For any values of S below $615 per peak kw the motor plus battery costs predominate. This has several implications:

1. There is a floor of about nine cents per hp-hr below which cost cannot drop no matter how cheap solar arrays become.

2. There are definite economies of scale in DC motor costs which translate into moderate scale economies (in the fractional-to-25 hp range) for the solar system in spite of the lack of such scale economies with the solar arrays alone.

3. There are clearly strong reasons for reducing costs of battery storage and of appropriate DC motors. Alternatively, as the power conditioning costs begin to predominate, the emphasis on reducing solar array costs becomes less important relative to research and development directed at reducing power conditioning costs.

4. A field test should be initiated immediately to determine the feasibility and consequences of operating a DC motor/water pump directly from solar arrays with no battery storage.* The pump would not necessarily have to be a centrifugal pump, but could be a positive displacement pump, even an electrified (and upgraded) persian wheel.

Costs of Diesel Pump

Capital cost of a 5-hp diesel engine is taken as $1250 (Mubayi). This is, in fact, the cost of a 6-hp engine de-rated because of high working temperatures and dust to 5 hp. This is a somewhat smaller engine than would ordinarily be recommended for such an application and depends on the low lift and use of a "sewage" pump (Meta Systems, p. 95). Spares add another $150 or 12 percent (Meta Systems, p. 84). Maintenance, lubricants, and oil/fuel filters come to about $0.41 per operating hour or $377 per year for 920 hours (Meta Systems, p. 85). An eight-year life is assumed. Fuel consumption is taken as 0.31 liters per hp-hr (Mubayi) or 0.41 U. S. gallons per hour for a 5-hp engine.†

Table 2c illustrates the variation of the cost of diesel pumping with fuel costs.

---

* This is alleged for a few installations fielded in Sicily and the Persian Gulf by Pompes Guinard of Paris.

† Cost per hp-hr becomes:

$$H_d = \frac{100[R(i,8)] \times 1400 + 377}{5 \times 920} + 0.31\ C_d \quad ,$$

where C_d is cost of diesel fuel in cents per liter.

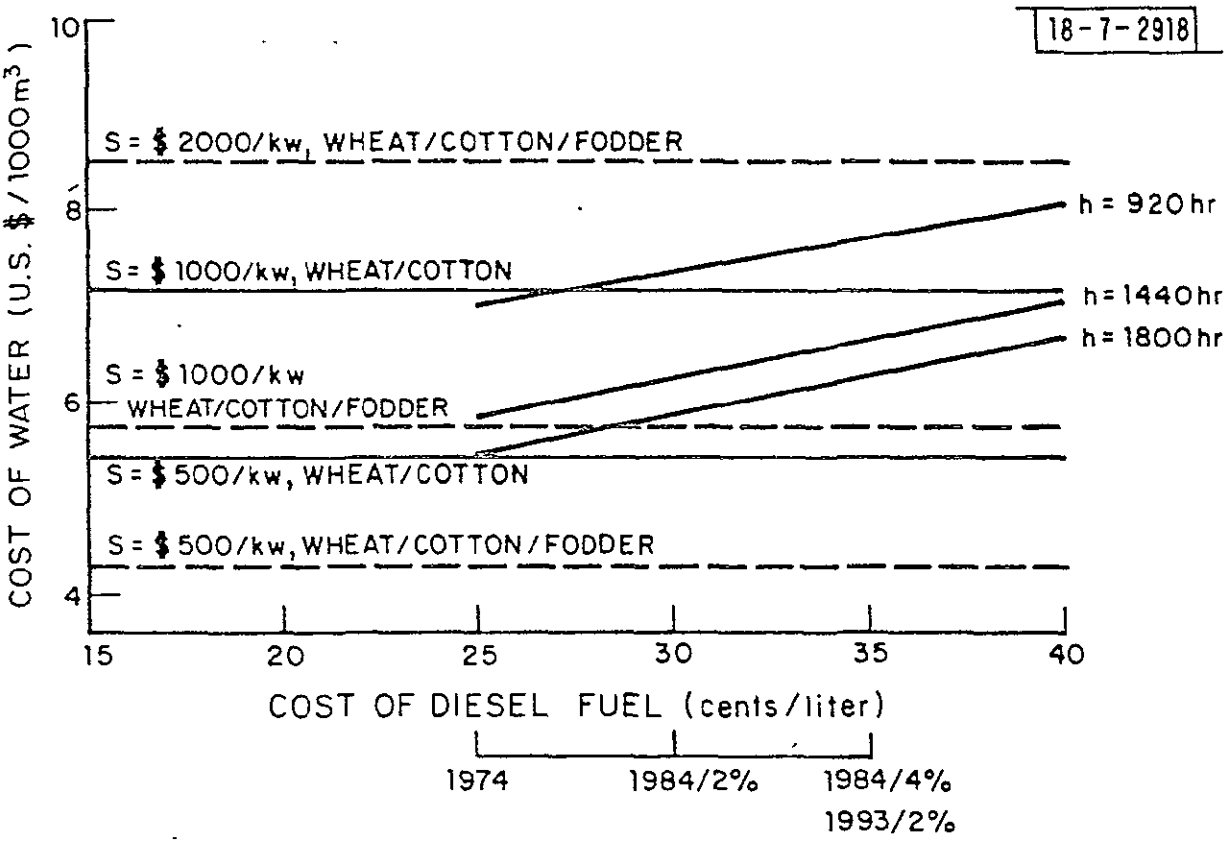


Fig. 3. Variation of water costs for Chad Polders Project: Pumping by diesel and photovoltaic power.

Appendix B explores the implications of use of a pump with less than a capacity of 204 m^3/hour (2 cusec). It is demonstrated that because of the high cost of diesel engine maintenance that is relatively unchanged by the rated power of the engine, such engines become less attractive at smaller pump sizes relative to solar array pumping. Similar results could be expected in a comparison of solar and gasoline engines although such a comparison was not made in this report.

Appendix C assesses the impact on the two pumping alternatives (photovoltaic and diesel power) of increased pumping head. This Appendix also

PREVIOUS PAGE BLANK

TABLE 2d

SOLAR RADIATION CLIMATES OF CHAD, BANGLADESH, AND PAKISTAN

Country	Location	Average Annual Hours of Sunshine	Mean Solar Radiation ($cal/cm^2/day$)	Monthly Radiation ($cal/cm^2/day$) Maximum	Minimum
Chad	Bol, 13°N	3200	540	630 (April)	470 (Aug.)
Bangladesh	Bogra, 25°N	2800	400	500 (May)	300 (Sept.)
Pakistan	Lyallpur, 32°N	3200	470	650 (June)	250 (Dec.)

Sources: (Mani and Chacko, Löf, FAO)

complements Appendices A and B by continuing analysis of the components of pumping costs.

This Chad, low-lift irrigation, pumping study has been done for an irrigation system considered favorable to solar energy utilization because of high rates of solar radiation, low solar radiation variability, and high fuel costs. It is interesting to examine several other irrigation pumping situations to illustrate the effects of:

1. Lower and more variable solar radiation
2. Cropping pattern changes
3. Pump capacity changes
4. High-head pumping.

For this exercise the analysis shifts to the Indian subcontinent, but first, a glance at Table 2d illustrates the new solar radiation climates to be discussed.

Low-lift Pumping in Bangladesh and Assam (India)

Irrigation in Chad is entirely different from irrigation in Bangladesh (and Assam) (Table 2e).

TABLE 2e

COMPARISON OF BANGLADESH AND CHAD

	Bangladesh	Chad
Population density (persons/km^2)	550	3
Mean annual rainfall (mm)	1,560*	285†
Approx. no. low-lift irrigation pumps	40,000	100
Approx. no. tubewells for irrigation	3,000	–
Major food crop	rice	millet/sorghum
Major export crop	jute	cotton
GDP‡ per capita (U. S. $)	75	75

* Bogra, northwest Bangladesh.

† Bol, northeast shore of Lake Chad.

‡ Gross domestic product.

BEST AVAILABLE COPY

The last line of Table 2e emphasizes the major similarity of the two countries; they are both about as poor as a nation can be and still have statistics.

In spite of the considerable mean rainfall over all of Bangladesh (nowhere is it less than 1250 mm) and the ubiquitous problem of floods (over one-half the land area is subject to flooding) irrigation is considered by most experts to be a prerequisite for significant agricultural development. This is because of the November-March season with no rainfall and the frequent drought periods during the remainder of the year when crops can be damaged by lack of water. This is especially critical during the jute/rice planting month of April when a late monsoon can throw off the rest of the year's crop calendar.

Irrigation in most cases has been directly from a river. That accounts for the relatively large number of low-lift pumps in Bangladesh (nearly all diesel or gasoline fueled) and it is these pumps whose operation is analyzed in this study.

Before proceeding to that analysis, however, a few more notes about rural Bangladesh are required. Although in the lake region of Chad, land ownership does not reside with individuals or families, in Bangladesh private ownership of land is well established.* A typical farmer will own, however, less than six-tenths of a hectare and this modest farm will be split into ten or more plots scattered over several kilometers radius from the home. A scrawny cow might be owned, and if so, it would be used for ploughing, unlike in Chad where cattle are not used as beasts of burden.

Over a quarter of the villagers of Bangladesh are landless or near-landless. They work as field hands or laborers for subsistence wages. Very few are wealthy in any village but each village has its local influential men who exercise power over nearly all aspects of the lives of the others. Four hectares constitutes a large farm.

There are about 65,000 villages in Bangladesh with populations ranging from 200 to 2,000. Almost none of these are electrified unless they happen to lie right in the route of a transmission line linking a power station with a city,

* Technically, all land is owned by the government, but this is not pertinent to this discussion.

BEST AVAILABLE COPY

and even then, it is doubtful if a transformer and distribution system would be present. Cottage industries tend to use noncommercial fuels: wood, bagasse, vegetable wastes, and dung, although small rice mills (there are 7500, but mainly in the bigger towns) use diesel engines. Most villages have no power machinery: water is pumped and hauled by hand, cloth is woven by hand, pots are baked with wood, sugarcane is crushed by animals, lights are dim and normally nonexistent except in the wealthiest homes. If there is a power machine it is most likely an irrigation pump.

To examine the influence or attractiveness of photovoltaic power on an irrigation regime different from that in Chad, Tables 3, 4, and 5 have been prepared for the following cases (where the cotton/wheat cropping pattern for Lake Chad is Case I):

II. Wheat in northwest Bangladesh followed by an unirrigated rice crop

III. Winter (boro) rice in northwest Bangladesh followed by an unirrigated jute crop and/or aman rice crop.

IV. Wheat and early rice in Assam (northeast India) with irrigation only necessary through May and with an unirrigated rice crop also being grown.

These three cases have been selected because they have been extensively studied, because they are familiar to the author,* and because they provide a contrast to the Chad case in the following respects:

1. At Bol, Chad, the solar radiation during the peak pumping month is 550 calories per cm^2 per day. In northwest Bangladesh it is 450 for rice (March is the peak month) and 330 for wheat (January is the peak month). In Assam it is also 450 during March. These lower levels of solar radiation arise because irrigation in Bangladesh and Assam

* Bangladesh water requirements were first developed by the author and M. Maasland in 1968.

TABLE 3

IRRIGATION WATER REQUIREMENTS AND SOLAR RADIATION
NORTH BENGAL (BANGLADESH) WHEAT

Requirements	OCT	NOV	DEC	JAN	FEB	MAR	Total
Evapotranspiration, mm	103	78	66	77	83	140	547
Crop coefficient	.21	.49	.70	1.06	1.15	.42	
Water requirements							
crop, mm	22	38	46	82	95	59	342
land preparation, mm	57	19					76
Total, mm	79	57	46	82	95	59	418
Effective rainfall, mm	90	4	1	6	9	24	207
From groundwater, mm					38	14	76
Net irrigation requirements, mm	0	53	45	76	48	21	243
Gross irrigation requirements, mm	0	88	75	127	80	35	405
m^3/ha	–	880	750	1270	800	350	4050
Cal/cm^2/day, mean	360	350	310	330	400	450	
kwh/m^2/day, K hr	4.2	4.1	3.6	3.8	4.7	5.2	
Liter/second/hectare, K hr				3.0			

Source: Center for Population Studies, "Progress Report: Ganges – Brahmaputra Basin Studies," Harvard University, September 1968, Table IIb-7 and Table IId-1. 60 percent irrigation efficiency is assumed. Solar radiation estimates from (Mani and Chacko).

TABLE 4

IRRIGATION WATER REQUIREMENTS AND SOLAR RADIATION
NORTH BENGAL (BANGLADESH) BORO RICE

Requirements	NOV	DEC	JAN	FEB	MAR	Total
Evapotranspiration, mm	89	61	61	86	132	429
Crop coefficient, mm		1.2	1.35	1.45	1.50	
Water requirements						
Crop, mm		74	84	124	198	480
Land preparation, mm	127					
Deep percolation, mm		76	76	76	76	304
Total, mm	127	150	160	200	274	911
Effective rainfall, mm	10	3	13	13	25	64
Net irrigation requirements, mm	117	147	147	187	249	847
Gross irrigation requirements, mm	138	173	173	220	293	997
m^3/ha	1380	1730	1730	2200	2930	9970
Cal/cm^2/day, mean	350	310	330	400	450	
kwh/m^2/day, K hr	4.1	3.6	3.8	4.7	5.2	
Liter/second/hectare, K hr		4.3		4.6	5.0	

Source: Center for Population Studies, "Progress Report: Ganges – Brahmaputra Basin Studies," Harvard University, September 1968, Table IId-4; 85-percent field channel efficiency is assumed plus deep percolation from fields of 2.5 mm per day. Solar radiation estimates from (Mani and Chacko).

TABLE 5

IRRIGATION WATER REQUIREMENTS AND SOLAR RADIATION
ASSAM, INDIA - WHEAT AND EARLY RICE

Requirements	NOV	DEC	JAN	FEB	MAR	APRIL	MAY
Evapotranspiration, mm	72	62	62	92	134	150	155
Crop	Wheat				Early Paddy		
Crop coefficient, mm	.9	.15	.4	.7	.8	1.0	1.21
Water requirements							
Crop, mm	65	9	25	64	107	150	188
Land preparation, mm					50		
Deep percolation, mm						60	60
Total, mm	65	9	25	64	157	210	248
Average rainfall, mm	9	7	17	9	73	136	276
Effective rainfall, mm	0	0	0	0	54	120	195
Net irrigation requirements, mm	–	9	25	64	103	90	53
Gross irrigation requirements, mm	–	15	42	107	172	150	88
m^3/ha		150	420	1070	1720	1500	880
Cal/cm^2/day, mean*	320	300	320	450	450	470	470
kwh/m^2/day, K hr	3.7	3.5	3.7	5.2	5.2	5.5	5.5
Liter/second/hectare, K hr					3.0		

5740.

* Shillong

Source: Solar radiation estimates from (Mani and Chacko). 60-percent irrigation efficiency is assumed. Water requirements data from (IBRD Allison).

is primarily needed during the dry winter* and because the latitude is between 25° and 27° North.

2. The wheat/cotton cropping pattern in Chad required 920 hours of pumping. Wheat in Bangladesh requires 380 hours, boro rice in Bangladesh requires 550 hours, and wheat/early rice in Assam requires 540 hours. Both Bangladesh and Assam receive plentiful rainfall most years from May to September, while in Chad, irrigation water is applied even in the "high" rainfall month of August.

3. Because irrigation requirements arise during the winter in Bangladesh and Assam the potential evapotranspiration is relatively low (as is the solar radiation (see 1) and discharge capacity per hectare is lower (except for boro rice) than in Chad, even with fewer pumping hours per day. As a consequence, more land can be commanded with precisely the same solar array/pump configuration.

To illustrate the revised economics for these cases, Table 3 (Bangladesh wheat irrigation) is compared with the Chad example.

Assuming a 204 m^3/hour (2-cusec) pump† with a 4-meter lift from a river or shallow well, required horsepower, therefore, remains 5 hp and required solar array peak power output remains 5.5 kw. The major difference is in hours of use, which, for wheat alone is 380 hours.‡ Batteries, solar array,

---

* Northwest Bangladesh, at least, has a need for supplementary irrigation during some years of sparse or erratic monsoons. Pumps in place for winter irrigation can also pump during the rest of the year, but they rarely do so, partly because of extensive flooding.

† This is a considerably more controversial assumption for Bangladesh, but in fact, most low-lift pumps in that nation are rated at 2 cusec.

‡ Hours of pumping = 380 = $\frac{3.8 \text{ hours/day} \times 31 \text{ January days}}{0.31}$,

where 0.31 is the fraction of the total irrigation requirement falling during the peak month of January.

diesel engines, and motor are assumed to cost the same in Bangladesh as in Chad.* As a consequence, solar system energy costs differ from those in Chad by a factor of $\frac{920}{380} = 2.4$ when related as cents per kw-hr. The same is true of H_s: cents per hp-hr.

Thus, for varying values of S, solar pumping costs are found in cents/hp-hr (Table 5a).

TABLE 5a

VARIATION OF PUMPING COSTS WITH SOLAR ARRAY COST
(for solar array-powered pumps – 380 hours)

S $1 Peak kw	H_s Cents/hp-hr
300	31
500	38
1000	55
2000	86

Analogous costs for diesel pumping are presented in Table 5b.

TABLE 5b

VARIATION OF DIESEL PUMPING COSTS WITH FUEL COSTS
(for diesel-powered pumps – 380 hours – where it is necessary to use the expression for H_d in terms of h)

C_d Cents/Liter	H_d Cents/hp-hr
25	30
30	31
35	33
40	34

Solar arrays are not competitive with diesel if both systems are used for only 380 hours. That should come as no surprise from the form of the expressions for H_s and H_d. Furthermore, it is recognized that diesel pumps will be used more than 380 hours.

* To do this analysis properly for Bangladesh, it is necessary to revise these costs slightly (especially maintenance), but it is comparability with Chad that is desired.

First, it can be argued that both systems can and should be used more than 380 hours because of extension of the irrigation season beyond the October-March period assumed for wheat. This implies irrigation of aus rice or jute in April/May (as in Assam, Table 5) and possibly supplemental irrigation during a bad monsoon.

Second, it can be argued that the diesel system alone could cover more land area. The system, as described above, implies command of 18.9 hectares.* This is about 23 acres per cusec, which is not much of a coverage according to irrigation handbooks. It is close to actual coverage of 2-cusec, low-lift pumps in Bangladesh, however, because of institutional constraints on increasing command area (B. Ahmed, p. 4). For example, in Bogra district, for which the data in Table 3 relate, during 1971-72, 16 acres were irrigated per cusec and 450 hours were worked per year per 2-cusec pump (M. Alam, p.38).

This is not the place to go into all the reasons for these low rates of use, but the reasons include lack of fuel, large numbers of farmers that need to cooperate when plot sizes are as small as in Bangladesh, lack of spares, breakdowns, poorly trained and motivated drivers, problems with government distributing pumpsets, and lack of water. It is interesting to note that some of these difficulties would be absent or lessened considerably with photovoltaics.

It is concluded, therefore, that under the institutional conditions existing in Bangladesh, solar water pumping could be competitive with diesel pumpsets even with a greatly restricted use.† The challenge is to use the solar arrays for other productive purposes when not pumping water. Since this is not done now with the diesel engines, the challenge will not be easy to meet. But if it can be met it will be solar arrays that, once purchased, give "free" energy for the cost of the wiring and power conditioning.

---

* $\frac{204\ m^3/hr \times 1000\ liters/m^3}{3.0\ l/sec/ha \times 3600\ sec/hr} = 18.9$ hectares.

† Note that Table 5 demonstrates photovoltaics are even more competitive in Assam in the sense that they would work 540 hours to pump a total of 5740 m^3/ha. Size of the system would be the same as Table 3.

TABLE 6

IRRIGATION WATER REQUIREMENTS AND SOLAR RADIATION - PAKISTAN PUNJAB - WHEAT/COTTON - NO CANAL WATER

	NOV	DEC	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	TOTAL
Evapotranspiration* mm	75	49	49	64	113	162	208	220	192	169	154	123	1578
Crop	----------Wheat----------						----------Cotton----------						
Crop coefficient (weighted - 3 plantings)	.42	.61	.87	1.19	1.12	.41	.45	.65	1.15	1.35	1.15	.65	
Water requirements† mm	32	30	43	76	127	66	94	143	221	228	177	80	1317
Effective rainfall mm	--	--	9	--	12	9	6	18	82	94	21	--	251
Net irrigation requirements mm	32	30	34	76	115	57	88	125	139	134	156	80	1066
Gross irrigation requirements mm‡	51	48	54	121	183	90	140	198	221	213	248	127	1694
m^3/ha	510	480	540	1210	1830	900	1400	1980	2210	2130	2480	1270	16,940
cal/cm^2 - mean	350	330	320	400	450	560	600	600	450	450	450	450	
kwh/m^2/day - K	4.1	3.8	3.7	4.7	5.2	6.5	7.0	7.0	5.2	5.2	5.2	5.2	
Liter/second/ha (for K hr)											4.4		

Source: International Bank for Reconstruction and Development, "Programme for the Development of Irrigation and Agriculture in West Pakistan", Comprehensive Report, Vol. 7, Annexure 9 - Agriculture, 1966, pp. 56-63, Fig. 9.4.

*Lower Chenab Canal Command data applied to uncommanded area

†Consumptive use

‡Field irrigation efficiency 70 percent, watercourse losses 10 percent

Tubewell Irrigation in Pakistan Punjab

Table 6 presents the irrigation requirements/solar radiation situation for an area northwest of Lahore, Pakistan, that is without canal water, but has abundant groundwater of suitable quality at a depth of 4.5 meters (Johnson; IBRD: Pakistan; Indus). With a 3.5-meter drawdown to be expected pumping at a rate of 100 m^3/hour—the total lift is about 8 meters or twice the lift required in the Chad case. Consequently, the same 5-hp, 5.5-peak-kw unit designed for the Chad case will pump half as much water in the Pakistan case with other assumptions (regarding pump efficiency, although the pump itself will change) held constant. It is, therefore, assumed that the 5.5-peak-kw solar array will suffice for one cusec in this Pakistan case. Battery, motor, and diesel engine costs are assumed the same for comparative purposes. In fact, because motors, engines, and batteries* can be produced in Pakistan, the economics are altered not only because of different prices, but also because of different shadow costs of foreign exchange. This factor is not considered here.

Major differences, therefore, between the Chad and Pakistan examples arise from less solar radiation in Pakistan during September—month of peak period pumping—than in Chad during its peak month of June,† and from the increased pumping lift in Pakistan. Maximum water delivery rates for solar pumping are nearly the same (4.4 – 4.5 liter/second/hectare) so areal coverage in the two cases is just a function of pump discharge (i.e., the Chad 2-cusec pump commands twice the area of the Pakistan 1-cusec pump). Pumping in the Pakistan case averages 1040 hours per year.

It is assumed that the diesel-powered pump works an average of 1950 hours per year (Johnson, p. 18). Cost per thousand cubic meters of water pumped by the two systems works out as follows.

---

*It is not certain batteries of requisite quality are available in Pakistan, however. Also, the motor and diesel engine are undersized for the Pakistan application, but the comparative effect is small.

†There is more solar radiation in the Pakistan Punjab in June than in Chad near Bol. Peak irrigation requirements in Pakistan come in September when clouds restrict solar radiation.

Cost of a 5-inch private tubewell in Pakistan is Rs. 9590 including pump (Johnson, p. 14), which is $983 (U.S.). Life is assumed at 8 years so that annualized cost is R(i, 8) × 981 = $184 at 10 percent.

U.S. dollars per thousand cubic meters (excluding pump operator costs) become* for solar pumping 1040 hours:

$11.25 for S = $1000/peak kw
$ 8.30 for S = $ 500/peak kw
$ 7.12 for S = $ 300/peak kw.†

U.S. dollars per thousand cubic meters (excluding pump operator costs)‡ for diesel-powered pumping 1950 hours:

$ 9.84 for C_d = 25 cents/liter
$10.58 for C_d = 30 cents/liter
$11.33 for C_d = 35 cents/liter
$12.07 for C_d = 40 cents/liter.

In fact, fuel was costing about 10 cents/liter in Pakistan in summer 1975 (Johnson, p. 8; 4.5 Rs/imperial gallon). At this price the water cost becomes $7.61. Actual fuel consumption in the SCARP II area§ appears to exceed the assumption of 0.31 liters per hp-hr and to average about 0.37. On the other hand, actual maintenance costs (averaged over 1960-1975) for 5-inch private tubewells in SCARP II were $116, which is considerably below the diesel-engine maintenance cost estimate for Chad of $800. The truth presumably

---

* $10 \left[\frac{39560 + 64S + 18400}{16940 \times 6.4}\right] = \$5.35 + \frac{.590S}{100}$ is the expression for cost.

† Note that of this $7.12, $5.35 or 75% is cost of batteries, DC motor, and tubewell/pump and is invariant with S. Only increased hours of operation can reduce this cost. The possibilities of doing this have been analyzed in the Chad case.

‡ $10 \left[\frac{26180 + (41)(1950) + (1.55)(1950)\,C_d + 18400}{16940 \times 6.4 \times (\frac{1950}{1040})}\right]$ is the expression for cost.

§ SCARP II area is a well-documented irrigation pumping area in the Punjab. SCARP stands for Salinity Reclamation And Control Project.

lies in between for 1977: closer to $800 for Chad and perhaps closer to $116 for Pakistan. If a maintenance cost of $400 is assumed, the water cost is 10 cents per liter, but 0.37 liters per hp-hr becomes $5.93/10^{3}m^3 or $7.32 per acre-foot. This is above Johnson's reported costs of $3.20 for the following reasons:

1. Actual installations were pumping 1.33 cusec on average, not 1.0 cusec as assumed here. (Their engines were also somewhat larger than assumed here, however.)
2. Assumed maintenance costs in this study are still much higher than reported from Pakistan, even with the above reduction.
3. This study assumes an 8-year diesel engine life (in Chad). Johnson uses 13 years. This study also assumes shorter lifetimes of pump and tubewell.

Use of Johnson's assumptions yields his reported cost of $3.20 per acre-foot. The photovoltaic systems cannot compete with this cost at any solar array price.* It is only when fuel costs and maintenance expenses increase and engine lifetimes decrease that photovoltaic systems look competitive.

These examples illustrate one of the major difficulties with photovoltaic power. Power is available, if and when the sun is shining, otherwise, there is no power in the absence of expensive storage. Because sufficient capacity must be available to supply peak-period water requirements, a solar array may be fully utilized in the peak month (or 20-day period) for fewer than seven hours even in that month and for much less than seven hours in other months of less water demand. As a consequence, there is considerable incentive to "peak-shave" or "fuel-save" in the use of solar arrays. Either approach evens out pumping demands on the solar pumping system.

* Because of power conditioning costs (batteries and DC motor), fewer hours that a solar system can pump, and because fuel supply and diesel engine maintenance are relatively satisfactory in Pakistan compared to Chad.

"Peak-shave" means application of a series of agricultural techniques to reduce the peak-period water applications relative to those in other periods. Some of these techniques are acceptable to agronomic experts: adjustment of crop calendar, multiple planting dates, and varietal shifts. Other techniques are anathema to experts, but widely practiced by successful farmers: over-watering followed by underwatering, underwatering followed by overwatering (to leach salts), and simple acceptance of lower yields by varietal change coupled with underwatering (IBRD: Pakistan).

Farmers can also improve their water application efficiencies during peak periods. If gross irrigation requirements were decreased 10 percent during June for the Chad example, areal coverage would increase 10 percent over the entire crop year. Operating hours would increase to nearly 1000 hours per year as compared with 920 hours with no peak shaving. Cost per thousand cubic meters of delivered water would decrease 8 percent.

"Fuel-save" means use of photovoltaics in conjunction with diesel or gasoline engines (or even human-power shadoof or animal-power persian wheels). There are, in fact, two variations on the fuel-saver theme: either use another source of power to relieve photovoltaics during peak periods or use photovoltaics during slack periods to relieve other sources of power (such as diesel generators in town). Clearly, the second application is the more attractive because it reduces needed capital investment (in more engines/pumps) and maintenance worries. Again, however, as long as the expensive power conditioning features that have been included in this study are needed, the choice is one dear only to Hobson.*

Conclusions

1. In the Lake Chad, low-lift pump, case study, photovoltaic power for irrigation pumping is competitive with diesel pumping at solar array costs of $1000 per peak kw at current diesel fuel prices.

2. At a diesel fuel price of 35 cents per liter (1984 price at 4-percent annual escalation over 1974, or 1993 price at 2 percent) photovoltaic power is competitive at solar array costs of $1300 per peak kw.

* Hobson, J. E., "Economics of Solar Energy."

3. These projections assume some use of solar pumping for a fodder crop and use of diesel pumps for approximately 1500 hours per year.

4. Bangladesh, India, and Pakistan case studies show that photovoltaic power for irrigation pumping is less competitive than in Chad because of fewer pumping hours under supplementary irrigation in Bangladesh and Assam, less solar radiation, lower fuel costs, and higher heads in Pakistan.

5. Photovoltaic power costs depend to a considerable extent on requirements for battery storage and DC motors. If battery storage can be eliminated by proper selection of a motor-pump combination, the competitiveness of photovoltaic power increases significantly so that at current diesel prices a solar array cost of $1300 per peak kw is competitive.

6. To test the feasibility of operation without battery storage, the advantages of operating with battery storage, and the practical problems of the mode of irrigation outlined in this report, it is essential that field trials be initiated as soon as possible.

FIGURE 8

ANAEROBIC FERMENTATION PROCESS

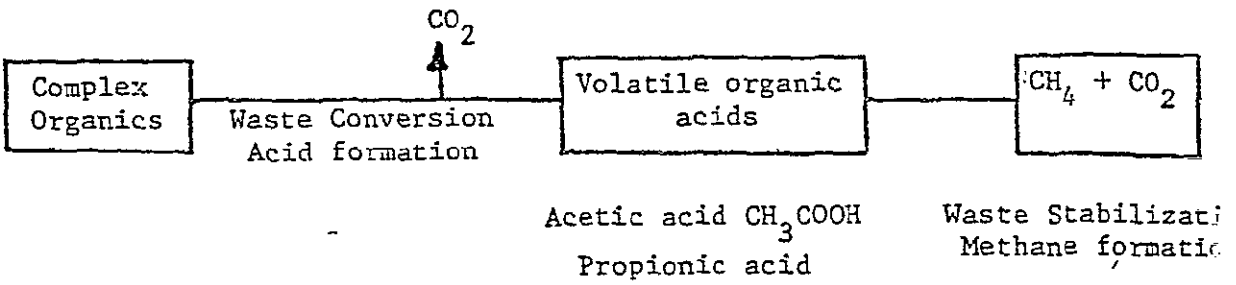


FIGURE 9 WATER PRESSURE BIOGAS PLANT SECTION (CHINA)[73]

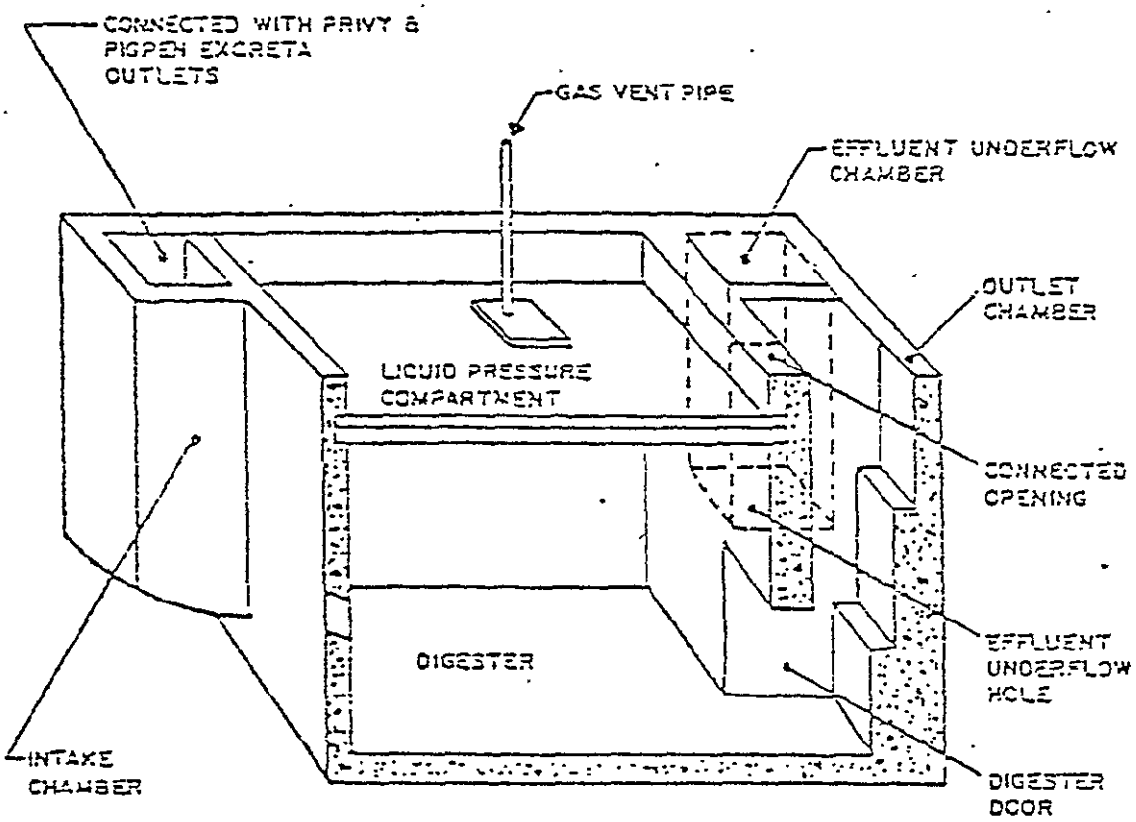
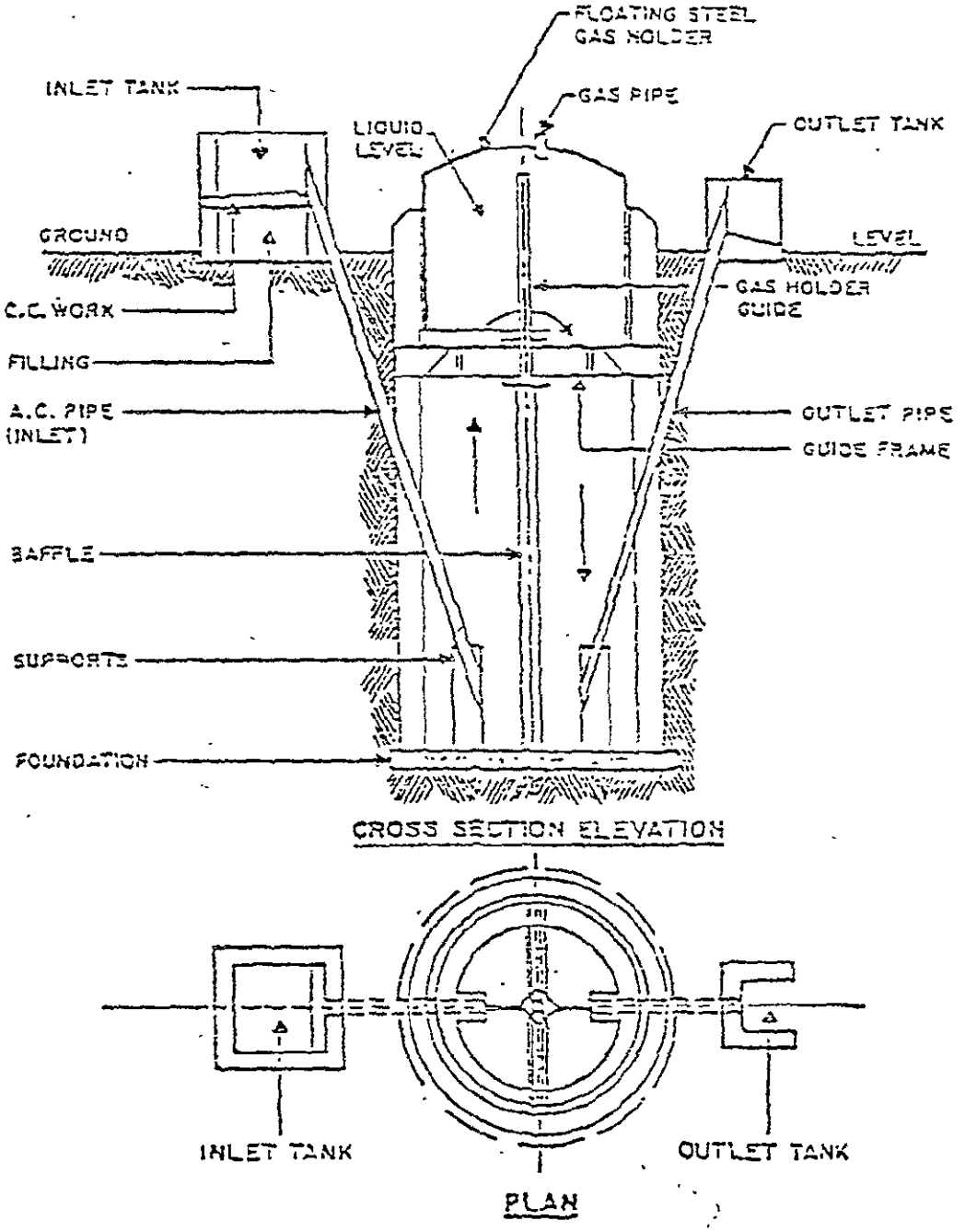


FIGURE 10

STANDARD INDIAN DESIGN BIOGAS PLANT

WITH FLOATING STEEL GAS HOLDER[75]



Most biogas plants have been designed to produce gas for household domestic uses such as cooking and lighting; in a number of instances, however, the gas has been used as a fuel for operating engines. Most of the experience has been gained with dual fuel types of diesel engines in which diesel injection is used to initiate combustion. With modified carburetion, biogas can also be used directly in standard internal combustion engines.

Biogas-Powered Irrigation Pumps

In a recent installation of a community size (90 m^3/day) biogas digestor in India, the biogas is being used for cooking, electricity and water pumping for irrigation and to supply clean drinking water to the village community.[73] Electricity is used only for lighting and is generated through a 3.5 kVA generator running on a 6 hp dual fuel engine consuming an 80 percent gas - 20 percent diesel mixture. Water pumping is done by a 4 hp pump driven by a 7 hp engine through a counter shaft which also consumes a 80 percent gas - 20 percent diesel mixture.

Internal combustion engines operating on methane have been in use for several years, particularly in sewage treatment plants where the 'sludge' gas has a methane content of 70-75 percent. Biogas produced from the anaerobic digestion of animal and agricultural wastes has a lower methane content (50-60%), which sometimes varies from day-to-day operation of the digestor, plus a varying admixture of corrosive gases like H_2S. Sathianathan provides a detailed account of attempts made in India to modify small gasoline and diesel engines to enable them to operate successfully on biogas.[75] These engines have been used to operate irrigation pumps and supply power to small agro-industries such as chaff-cutters and grain grinders. According to the report, however, "extensive use of biogas for stationary engines will depend greatly on research and development which alone can overcome many of the problems now being faced in using (low-Btu) methane as fuel."[75]

Cost Analysis

Small hp engines designed to operate specifically on biogas are not commercially manufactured, so no cost data is available. Since most of the experimental work to date has been on modifications to conventional diesel engines to operate on the dual fuel principle, the cost of a diesel engine can be used as a starting point for the cost of a biogas engine. One estimate of fuel consumption is based on Sathianathan's account of experiments done on conventional diesel engines by engineers of the Khadi Village Industries Commission in India. They modified a single cylinder, horizontal, four-stroke cycle engine run on diesel to operate on the dual-fuel principle with diesel injection to initiate combustion. An engine of about 4 hp capacity consumed about 15 ft^3 of biogas per hp-hour.* Diesel consumption (at 10 percent gas calorific value) was about 0.005 gallons per hp-hour. In the community biogas plant in India referred to above, gas consumption in the 4 hp dual fuel engine powering a water pump is about 16 cu. ft. per hp-hr of output. Diesel consumption (at 20% gas calorific value) is 0.01 gallons/hp-hr.

* A FAO/UNDP Study reports that diesel engines have also been adapted to use biogas in China and the fuel consumption rate was estimated at 17 ft^3 per hp-hr for a 1 hp engine.

The cost of producing biogas from a community-size plant (of about 5000-8000 ft^3 per day capacity) is estimated to be in the range of $1-$2 per Mcft.[76] For use as a fuel for engines, the gas may have to be scrubbed, stored or distributed, and, possibly, compressed. Conservatively, this may double the generating cost. Thus the fuel is estimated to range from $2.00 $4.00 per Mcf.**

For our cost analysis, we can assume the engine cost and life to b the same as the 3.3 hp diesel engine analyzed in Section 3.2. The capital recovery charges will be identical to those calculated earlier, the only difference being in the operating and maintenance costs. Assuming fuel consumption as 16 cu. ft. of biogas per hp-hr and 0.01 gallons of diesel per hp-hr, the fuel cost will be 0.016 Cg + 0.01 C_f ($/hp-hr) where Cg is the co of gas in $/Mcf and Cf the price of diesel ($/gallon). Maintenance cost we can assume conservatively to be double the maintenance cost taken for the diesel engine, i.e., 16 per hour for 3 hp output. Taking biogas costs to b in the range of $2-$4/Mcf and diesel as $1.50/gallon, the total cost works o to be (on a hp-hr basis):

Capital recovery	:	$0.19
Fuel (Gas)	:	0.03-0.06
Fuel (Diesel)	:	0.015
Maintenance	:	0.05
Total	:	0.28-0.31

For generating mechanical energy, biogas at $2/Mcf is approximately equivalent to diesel fuel at 10¢/liter (about half the current U.S. price of 88¢/gallon assuming that the capital cost of the engine is the same in both cases). Hence, considered as a small-scale, decentralized energy source, biogas from a community-size digester is already cheaper than convention l petroleum fuels. This assumes, of course, that the numerous technical as wel as social problems involved in the implementation of a biogas program are successfully solved.[78,79]

With biogas at $2/Mcf equivalent to fuel at 10¢/liter, the cost of irrigation from a 5 hp biogas-powered centrifugal pump can approximately be $3/acre-in for 800 hours of operation/year.

Typical Cost of Biogas Generation from Community-Size Plants

The biogas generation cost ($/Mcf) derived here is based on preliminary cost data obtained from a pilot project designed to investigate the advantages of large-size community biogas plants over individual family plants in a typical Indian village.[80] Under the project, two plants with a combined production capacity of 3 Mcf/day were installed for study. Table 17 shows major cost components of these plants.

BEST AVAILABLE COPY

** Estimates on the costs of biogas generation from a village level plant in India shows that biogas can be generated and distributed at a unit cost of about $1.70 per Mcf.

TABLE 17

ESTIMATED COSTS OF COMMUNITY SIZE BIOGAS PLANTS (INDIA)

Investment Costs	1976 U.S. $
A. Plants	
Digesters	5000
Holder	2250
Misc	1350
	8600
B. Distribution	
25 mm G.I. pipe (2000 meters at $2/m)	4000
Compressor	600
	4600
C. Operating and Maintenance Costs per Annum	
Purchase of dung (220 kg at $6/ton per day)	480
Plant maintenance (25¢/100 liters/day of capacity)	210
Maintenance of distribution system (3% of distribution system cost)	260
	950

Assuming the life span of the plant and distribution system to be 20 years, 10 percent interest rate, the energy generation cost (delivered to irrigation pumps) is around $2.3/Mcf. This cost could be reduced to about $1.7/Mcf if we include the revenue that could be generated by selling the nitrogen fertilizer which is a main by-product of biogas plants.*

* It is estimated that about 1.2 tons/year of fertilizer can be obtained from a biogas plant of 3 Mcf/day production capacity. This would generate about $500 in revenue at a price of $400/ton for fertilizer.

Technology/Resource Typology

The technologies proposed for providing power to the prime mover are direct solar (thermal and photovoltaic), wind (mechanical and electric) and biomass conversion (gasification through pyrolysis or anaerobic digestion). Demonstrations have to take account of the resource availability in the area where they are held. To do this, it is useful to consider a geographical typology of different agroclimatic zones so that resource availability can be matched both to the type of system selected and to the application for which it is required. One possible typology is described in Table 18.

System Application and System Size

System applications--crop irrigation or water for human consumption--determine the system size and its economic feasibility among other alternatives in a given area. System size, as shown earlier, depends on the depth of the water table, i.e., the height through which water has to be lifted, and the water requirements (both peak and average in case of irrigation) as determined by type of crop and the area to be irrigated. Referring to the typology, arid zones generally have deep water tables exceeding 25 meters in depth. In tropical zones, water tables are usually higher, often as little as 5m to 10m in river valleys and deltaic plains. We can distinguish four types of applications.

- Low head, low volume pumping (LL). The majority of applications will fall into this category if water needs (rather than economic demands for water) are the main criteria. Most of the subsistence farmers operating holdings of less than 1 ha.--the large majority of operational holdings--are in this category. System power needs range from about 300W to less than 1 kW. This is also the area where renewable technologies, especially photovoltaics, are likely to be most cost effective.

- Low head, high volume pumping (LH). This category has the most potential for commercial application since those farmers who can potentially afford to pay for the technologies are commercial farmers with farms in excess of 5 - 10 ha. These farmers, only a minority, generally have diesel or electric pumps. System power requirements in most cases will range from 1 kW to about 5 - 7 kW.

- High head, low volume pumping (HL). This would be the requirement for providing water for human/livestock consumption in arid zones and, perhaps, for traditional crops grown in such areas (e.g., sorghum, millet) with low water requirements. System power requirements would be on the order of 1 kW.

- High head, high volume pumping (HH). This would be required for crop irrigation in arid areas needing substantial quantities of water or where large areas of land have to be irrigated. Demonstrations in Gila Bend, Arizona; Willard, N.M. and Mead, Nebraska are examples. System power requirements would be in excess of 10 kW. This application would not be applicable to

TABLE 18

RESOURCE AVAILABILITY

Zone	Solar	Wind	Biomass	Water Table
Arid	High(H)	Variable(V)	Low(L)	Deep(D)
Tropical	Medium(M) - H	V	H	Shallow(S)
Mountain	L - M	M - H	L - M	S - D*
Island	M - H	H	M - H	S - D

*Surface stream usually abundant.

less developed countries where farm sizes are generally much smaller, except in areas of Latin and South America (e.g., Northern Mexico or Southern Brazil).

Considering the water table and water requirements, the above applications can be related to the various agro-climatic zones as shown in Table 19.

Proposed Systems

The systems proposed for demonstration are:

A. Solar Thermal - These would consist of a collector field (flat plate or parabolic trough) and a Rankine cycle heat engine coupled to a recriprocating or centrifugal pump. The smaller SOFRETES engine, with a peak power output of 1 kW, has been extensively demonstrated in Africa. The results, generally, have not been very encouraging and SOFRETES itself no longer manufactures these small engines. Although different designs may perform better technically, it is perhaps more advisable to confine the solar thermal demonstration to larger system sizes similar for example, to the Bakel project in Senegal used for high lift pumping in arid areas.

B. Photovoltaic Systems - Since PV arrays are modular, this system could be used for application of different power levels. The simplest system would consist of a cell array with a power conditioner feeding a permanent magnet DC motor coupled to a centrifugal pump. It is proposed that half the systems demonstrated should be without any battery storage; the other half could incorporate one or two equivalent days of storage capacity. Since storage adds significantly to the system cost, it is important to obtain technical performance data on systems without storage to test field performance. Different pump and motor combinations could be tested-for example, an AC induction motor driving a vertical turbine pump in the case of high lift pumping. The additional cost of adding an inverter has to be considered,however. Since AC induction motors are cheaply available and are manufactured in some developing countries, this could be a factor in favor of considering them for some demonstrations.

C. Wind Pumps - Mechanical wind pumps have long been a commercial technology and no special demonstrations are necessary to prove their technical and economical viability. Most of the demonstrations for wind machines should focus on wind-electric systems coupled to an AC induction motor driving a centrifugal pump. One or two demonstrations could concentrate on innovative wind mechanical pump designs meant to work at low starting wind speeds.

D. Biomass Conversion Systems - Pumping systems running on either medium-BTU gas produced from an anaerobic digester or low-BTU gas from pyrolysis generally use a dual fuel engine (with 10-15% diesel injection). The advantage is that the prime mover and pump can be conventional equipment; however, the demonstration has to be tied to

TABLE 19

Pumping Applications in Various Zones

Zone	HH	HL	LH	LL
Arid	*	*		
Tropical			*	*
Mountain				*
Island				*

an existing or specially constructed biomass conversion unit (digester or pyrolysis unit). Since this is linked to the availability of the input material (animal/agricultural residues), required for production of gas, the demonstrations must be on the site of existing or planned biogas production units.

Table 20 shows the technologies applicable to the various applications.

6.3 Program Strategy

The objective of this program is to accelerate the widespread use of solar water pumping systems in developing countries. This will be done by aggressive demonstrations of applicable water pumping systems for the agricultural sector based on specific requirements and solar technology applicability. The strategy will be to maintain maximum direct contact between suppliers and purchasers of solar water pumping technologies. The program will provide a single focus for coordinating assistance to manufacturers to facilitate private sector involvement. A key element is the pursuit of development needs in developing countries as well as efforts to foster expansion of U.S. manufacturers/suppliers.

6.4 Program Elements

A proposed program for development of water pumping in developing countries will have the following elements:

- Research and Development - A major effort should be undertaken to develop solar water pump technologies which are relevant to the needs of developing countries. In some cases, relatively small changes in research programs or modest extensions of those programs can yield useful products with international marketing potential. A detailed evaluation of DOE's Solar RD&D Program should be conducted to determine areas with the greatest potential for application in LDC environments. A parallel effort should evaluate research and development in the private sector. In addition to identifying developments of relevance to developing countries, the study should evaluate ways in which potential marketing information can be gathered, analyzed and disseminated to private firms.

- Demonstrations - A number of assistance programs should be established to erect and field test a range of solar water pump technologies in a variety of developing country conditions, with an emphasis on the need to transfer the results to other economic and geographical conditions. Field tests should employ a standardized evaluation procedure addressing system reliability and maintainability, system economics, and other factors. It is important to provide not only the actual test results, but also information which allows other countries to interpret the results for their own conditions.

TABLE 20

Applications of Solar Technology for Pumping

	HH	HL	LH	LL
Solar Thermal	*	*	*	
Photovoltaic	*	*	*	*
Wind Energy		*		*
Biomass			*	*

- Commercialization - The involvement of the private sector, both in the developing country and in the United States, should be maximized in program implementation. The private sector is ofte unaware of the market potential for various energy-related products. Studies should be conducted to identify potential markets for solar water pumping technologies. Private sector participation can be increased through investment guarantees and other financial incentives such as using the U.S. Overseas Private Investment Corporation (OPIC) investment assurance arrangements and encouraging international financial institutions to be more responsive to funding of solar water pumping projects. AID could arrange for initial purchases of a minimum number of units from U.S. corporations which have developed a product particularly applicable to developing country requirements. A network should be established to provide up-to-date information to the private sector.

- Training - The potential for solar water pumping systems abroad is affected by the degree to which local resources are available for the installation, maintenance or repair of the equipment. Some markets may require assembly or complete production of systems overseas, involving trained technical and managerial manpower. Training programs must be provided on a number of levels, ranging from village extension workers to university programs and middle level government officials.

- International Collaboration - International cooperative activities provide access to information from other countries about new or alternative directions of possible significance to our own R&D program without bearing the entire cost of a broad yet advanced research program within each technology. This element will promote regional and international cooperation in exchanging information on the development, adaptation and transfer of solar water pumping technologies.

6.5 Country Selection

A number of demonstrations are to be established to field test a range of solar water pumping technologies in a variety of developing country conditions. Three sets of countries representing various climatic zones have been selected. The selected countries are shown in Table 21. The technology and application to be demonstrated in each country will be derived from Tables 19 and 20.

6.6 Funding Level

Three funding levels are proposed. The minimum program includes countries in SET I only. A basic program will include countries in SET I plus countries in SET II, while an enhanced program will include all selected countries. An estimate of the funding levels is made by considering three demonstrations per country for SET I, five demonstrations per country for SET

BEST AVAILABLE COPY

TABLE 21

COUNTRY SELECTION MATRIX

ZONE	SET I (Minimum)	SET II (Basic)	SET III (Enhanced)
ARID	Egypt Senegal Sudan India	Egypt Senegal Sudan India Jordan Tunisia	Egypt Senegal Sudan India Jordan Tunisia Botswana
TROPICAL	Thailand Malaysia Guyana Jamaica	Thailand Malaysia Guyana Jamaica	Thailand Malaysia Guyana Jamaica Kenya Niger
ISLAND	Micronesia Indonesia	Micronesia Indonesia Philippines	Micronesia Indonesia Philippines Dominican Republic
MOUNTAIN	Colombia Nepal	Colombia Nepal Peru	Colombia Nepal Peru

II, and seven demonstrations per country for SET III at a cost of $225,000 per system. An additional 10 percent of system cost is included to accommodate manpower training.

Minimum Program - $8.91 million

Basic Program - $19.8 million

Enhanced Program - $34.65 million

CHAPTER 1

Waterwheels: Classification and Technology

A review of past and present waterwheels in the Mediterranean world

To facilitate the student's approach to the subject it is necessary to have a classification, and this has the added advantage of solving the constantly recurring problem of terminology, since it permits the use of typological designations instead of names. On the other hand, it is difficult to remember twenty different labels, so to aid the memory, each designation includes the name of a geographical locality and a drawing.
The classification is based on the construction principle used. This is the system applied in Jorge Dias: *Aparelhos de elevar a água de rega.* Porto, Portugal 1953, p. 60, and, somewhat later, in Julio Caro Baroja: *Norias, azudas, aceñas.* [Revista de dialectología y tradiciones populares, Vol. *X* (Madrid 1954), pp. 29–160], and, in the next volume of the same periodical, Julio Caro Baroja: *Sobre la historia de la noria de tiro.* [Revista de dialectología y tradiciones populares, Vol. *XI* (Madrid 1955), pp. 15–79].

Waterwheels can be classified into two main groups:

I. Machines with a gear.
II. Machines without a gear.

Group *I* can be defined as machines in which the traction power of a draught animal is transmitted to a potgarland by means of a right-angle gear.

Group *II* may be defined as water-driven wheels or treadwheels, the rims of which are provided with a number of containers for lifting the water.

Group *I*

Group *I* can further be sub-divided according to the type of horizontal shaft:

A. Machines with a short shaft.
B. Machines with a long shaft.
C. Machines with an elevated shaft.

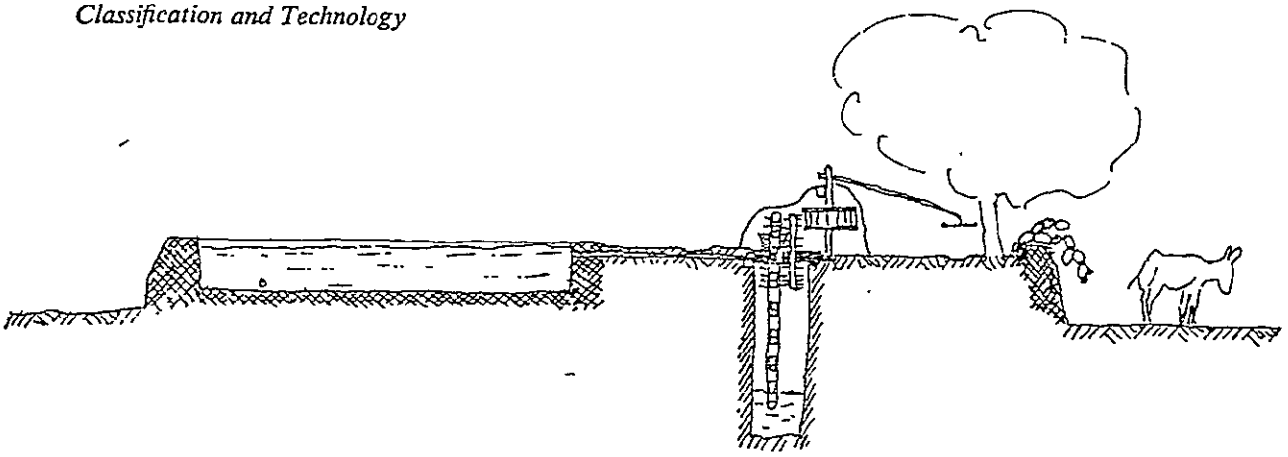


Fig. 2. Type IA, noria with short shaft.

These three types are shown in Figs. 2, 3 and 4. In principle, the cogs of a right-angle gear can be arranged in two ways, viz:

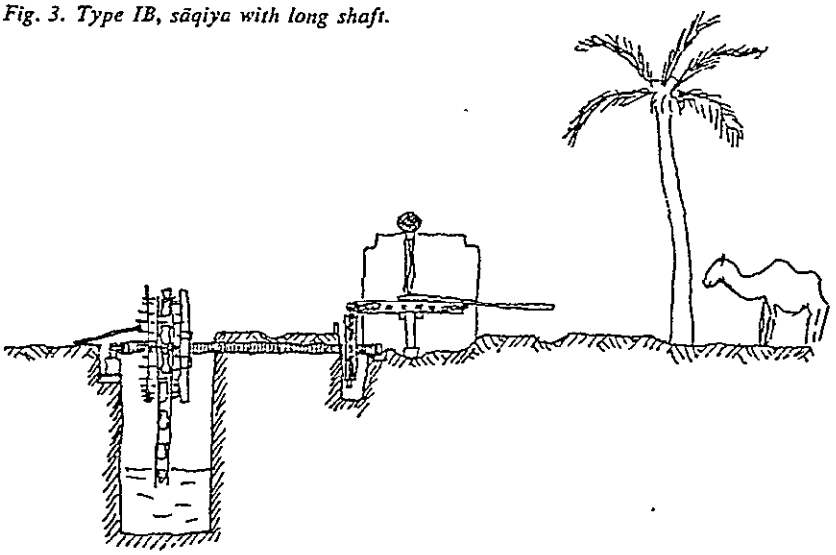
1. Radially projecting cogs.
2. Cogs arranged parallel to the shaft.

We thus have six different types.
Turning to the paternoster chain, we find two different systems:

a. Earthernware pots or tins, firmly lashed to two endless ropes.
b. Rectangular buckets fastened to a ladder-like iron chain.

This last sub-division increases the number of types from six to twelve.

Fig. 3. Type IB, sāqiya with long shaft.



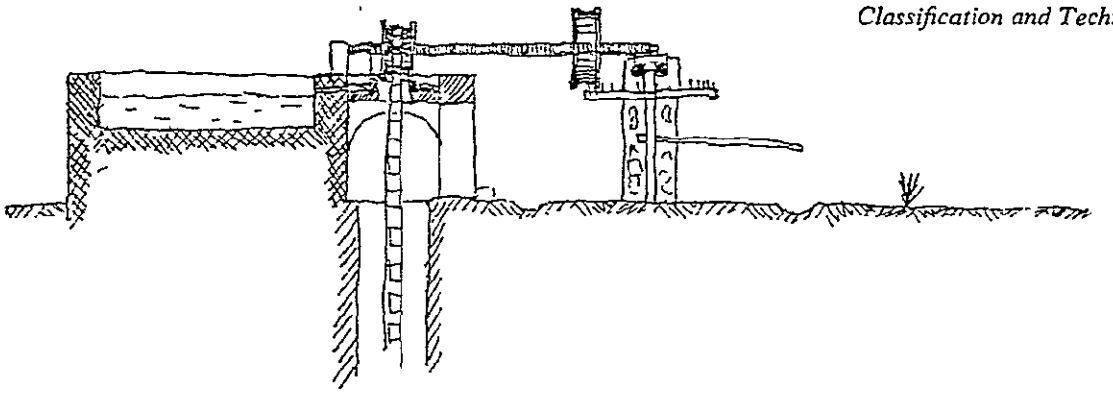


Fig. 4. Type IC, sāqiya with long, elevated shaft.

At the beginning of this chapter, the geared machines were given a rather narrow definition, which means that the classification is representative. If we were to broaden the definition, the classification would become exhaustive, but then not representative. It has therefore been found best to abide by the definition given and to describe variations simply as "other geared machines". Only two types of machines are included in this category:

1. Geared machines powered by a draught animal, but with the paternoster chain replaced by a wheel with a compartmented rim. See Fig. 29.
2. Geared machines powered by a draught animal, but with the paternoster chain replaced by a paddle-wheel, the blades of which follow a spiral course. See Figs. 54a and 54b.

We thus have a total of 14 different types of machines in group *I*. The first 12 of these are arranged systematically, while the last two do not quite fit in, which is unfortunate since they are both very common in Egypt.

Group *II*

Group *II*, which is only of secondary interest here, comprises water-wheels without a gear. The definition of this class of wheels on page 11 includes the basic sub-division, the following designations being used:

A. Water-driven wheel.
B. Treadwheel.

The term water-driven wheel indicates a paddle-wheel turned by the current of a river. See Figs. 1 and 32. A treadwheel is a large wheel turned by the tread of one or two labourers. See Fig. 100.

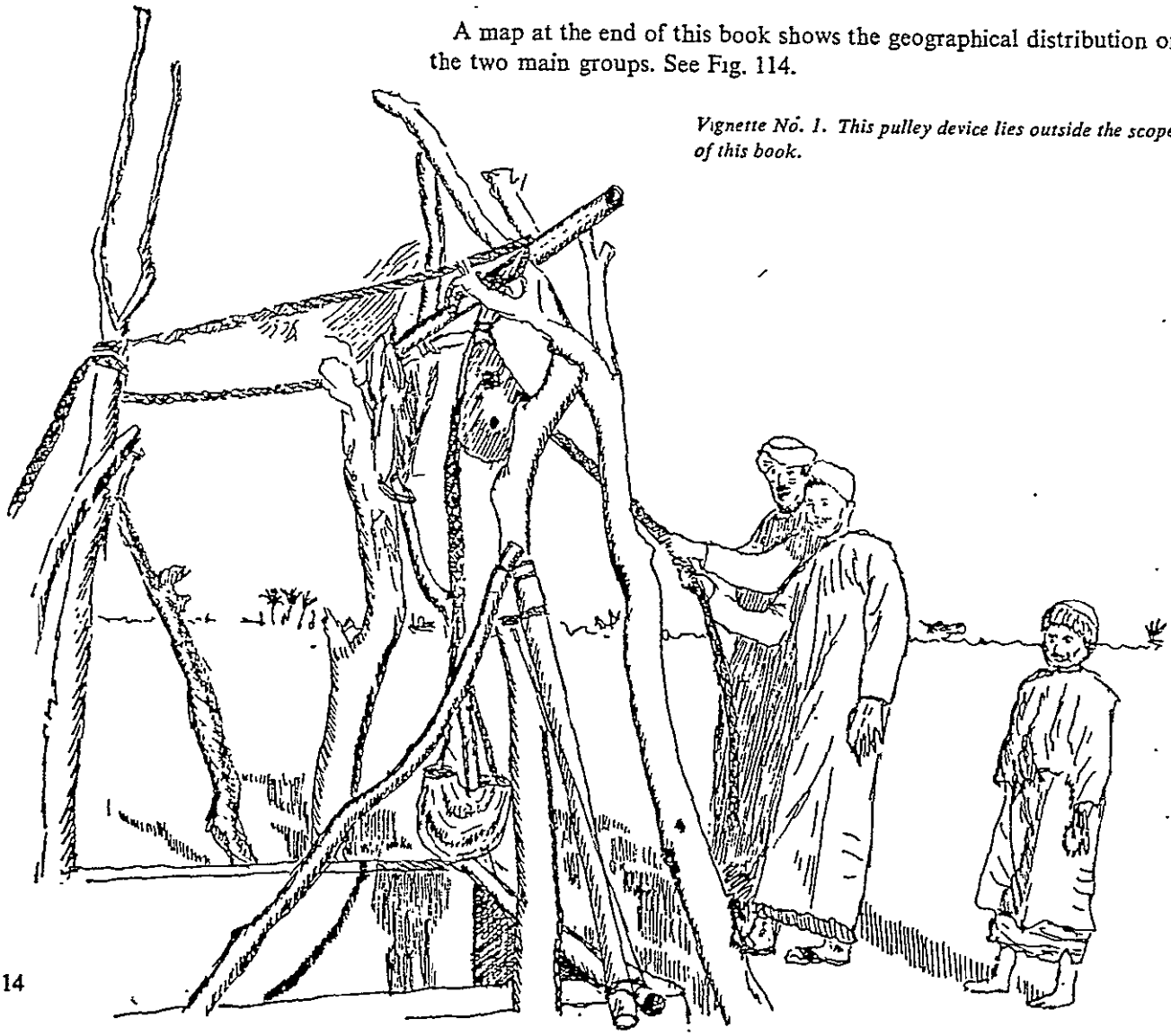
Two types of containers are used:

1. Slender pots or hollow bamboo canes lashed to the rim of the wheel.
2. Partly closed compartments forming the actual rim of the wheel. See Fig. 34. In this case, the structure is known as a compartmented wheel.

Two types of machines remain, which do not fit into the classification, but which are a hybrid of the two groups. These we will call "other machines":

1. A treadwheel and a potgarland sharing the same shaft. See Fig. 95.
2. A composite hand- and treadwheel designed to carry a potgarland. See Figs. 56 and 57.

A map at the end of this book shows the geographical distribution of the two main groups. See Fig. 114.



Vignette No. 1. This pulley device lies outside the scope of this book.

Classification of Waterwheels

I Machines with gear

A. Short shaft (noria)

1 Parallel cogs	*a* Potgarland	Ibiza
	b Bucket chain	Ma'arrat
2 Radial cogs	*a* Potgarland	Salḥin
	b Bucket chain	Aleppo

B. Long shaft (sāqiya)

1 Parallel cogs	*a* Potgarland	Hala
	b Bucket chain	Ḥaswa
2 Radial cogs	*a* Potgarland	Mi'timdiyyá
	b Bucket chain	Fayyūm

C. Elevated shaft (sāqiya)

1 Parallel cogs	*a* Potgarland	Formia
	b Bucket chain	Palestine
2 Radial cogs	*a* Potgarland	India
	b Bucket chain	Syria

II Machines without gear

A. Water–driven wheel (hydraulic noria)

1 Pots	Hīt
2 Compartmented rim	Ḥamā

B. Treadwheel

1 Pots	Riotinto
2 Compartmented rim	Ostia

Classification and Technology

We will now discuss the individual types of machines. In order to avoid repetition only the noria-type from Ibiza and the sāqiya-type are dealt with in detail.

Group *I.* Machines with gear

Short shaft

Type *IA1a* *Ibiza*

This type of noria is native to Spain, Portugal and Morocco, and is characterized by its short shaft. See Figs. 5, 6, 7, 55, 69, and 113.

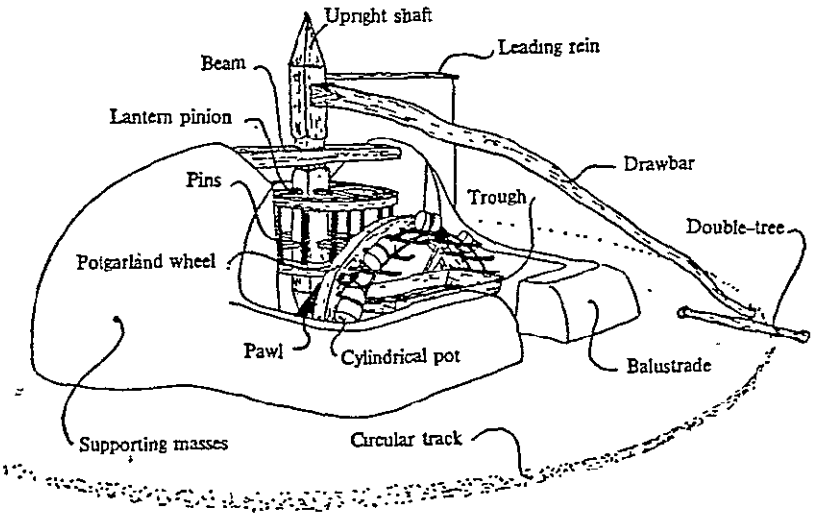
La Mancha

South of Madrid, norias were still numerous in 1960, and in the famous province of La Mancha, as many as 19,000 were counted in 1918. Otto Jessen: *La Mancha.* [Mitteilungen der Geographischen Gesellschaft in Hamburg, Vol. 41 (Hamburg 1930), pp. 180–184]. In about 1900 there were no less than 4,000 norias in operation on Majorca, but only a few of these remain today (1963). As far as Portugal is concerned, this subject has been dealt with in detail by Jorge Dias (cf. p. 11), and it appears that almost all types of water-lifting machines are represented there. It is a pity that similar books are not available for the other Mediterranean countries.

Ibiza

In the neighbourhood of the town of Ibiza there are many norias (1955), sometimes only a hundred metres or so apart, corresponding to one for each farm. In these norias, both the machine and its water tank are raised one or two metres above ground level, which means that the tank also acts as an elevated cistern from which water can be led all over the farm.

Fig. 5. Noria type IA1a, Ibiza. The lantern pinion engages with the paternoster wheel. The pots empty the water into the trough standing inside the wheel.



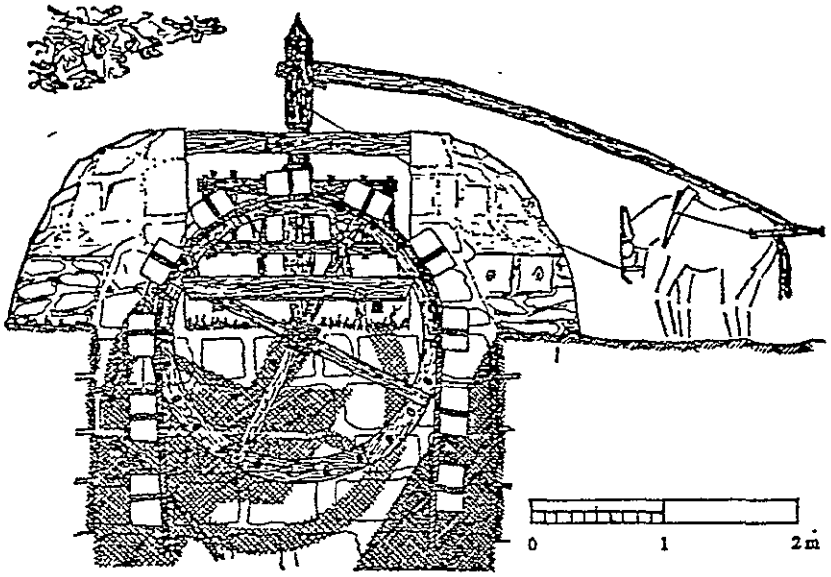


Fig. 6. Noria Ibiza, Balearic Islands. Scale drawing by the author, 1955. From the wooden trough the water runs through a pipe leading under the circular mule-track to a large water tank.

The total area of a farm seldom exceeds one hectare and of this the tank occupies about 100 square metres and the machine a further 100 square metres. The well, which is rectangular, has a depth of approximately 4 metres and is lined with stone. The edge of the well is provided with a balustrade, which curves elegantly into the two supporting masses. The building material used is rough-hewn volcanic rock, a smooth surface being achieved by means of mortar and plaster. In June of each year, the womenfolk whitewash the masonry. The water tank is built in the same way, except that the interior surface is given a cement rendering. The internal dimensions of the water tank are 10 × 10 × 1 metres, giving a capacity of 100 cubic metres or 1 cm-ha, a unit preferred by irrigation engineers. At one corner of the water tank, steps lead down to the water, and here the women wash the newly shorn wool. Drinking water is taken directly from the machine. The water raised by the wheel flows into the water tank through a pipe laid under the circular mule-track. Every evening, the tank is opened and the water is led out to the fields through a large number of walled channels.

In Salvator's two-volume work on the Balearic Islands this scene is depicted in some very fine engravings, which are also remarkable for their exactitude. Ludwig Salvator: *Die Balearen, geschildert in Wort und Bild.* Würzburg und Leipzig 1897, Vol. *I*, p. 7 and p. 229.

Figs. 6 and 7 show a scale drawing of a noria which was still in use in 1955, but which I found in ruins just a few years later.

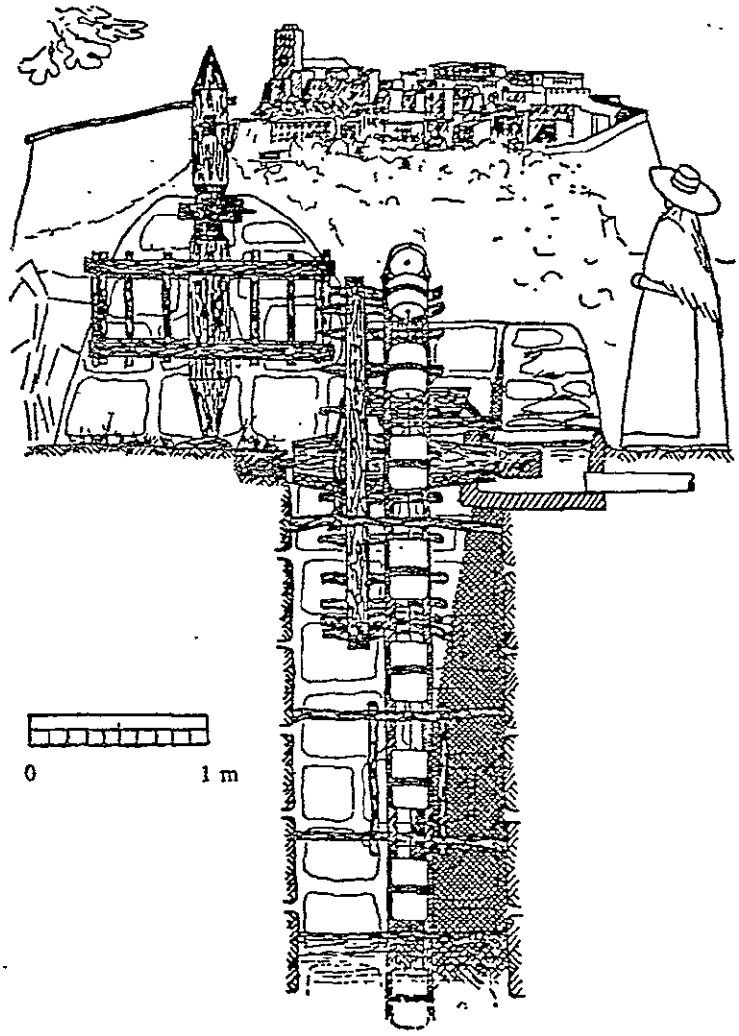


Fig. 7. Noria Ibiza Scale drawing by the author. The same machine as in Fig. 6, but seen from the other side.

The crux of these machines is the gear, which has a single function – that of altering the motion from horizontal to vertical. The gear itself consists of a lantern pinion and a large cog-wheel. In the following, the latter will be referred to as the potgarland wheel, since it also operates the paternoster chain.

The most convenient way of describing such a machine is to follow the power transfer through the machine, starting with the draught animal and ending where the water leaves the machine. The draught animal is usually a mule or a donkey wearing on its shoulders and neck a collar harness that transmits the power through two traces to a double-tree fastened to the drawbar. The drawbar passes through a hole in the upright

shaft. The leading rein, which is attached to a second bar protruding from the shaft, forces the animal to follow the circular track, although it cannot see this because its eyes are blinkered.

The lantern pinion is fixed to the upright shaft by means of two sets of spokes, one for the upper rim and one for the lower. The spokes are made in one piece from bars equal in length to the outer diameter of the rims and countersunk inside the shaft so that they bisect each other in the same plane. To achieve this, the hole through which one bar passes through the shaft is made twice the height of the hole for the other bar. When the spokes are in place, the larger hole is wedged to keep the spokes locked in position.

Both wheel-rims of the lantern pinion are made by the carpenter from six or seven pieces of wood, cut to a template. The pieces are joined together by double-lipped and notched table scarves. See Fig. 8. The scarf joint method of assembly is efficient as long as the wood is sound but is valueless when it dries out. It is therefore quite common to see peasants stiffening such joints by means of wooden scarves. The pins of the lantern pinion are slightly conical in shape and are of a soft wood because they are easy to make and the peasant puts in new pins approximately every other year. The cogs with which the pins mesh are difficult to make so a hard wood is used that will last for many years.

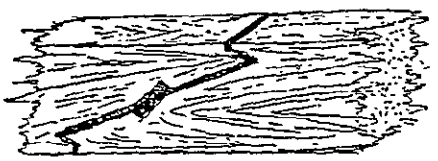
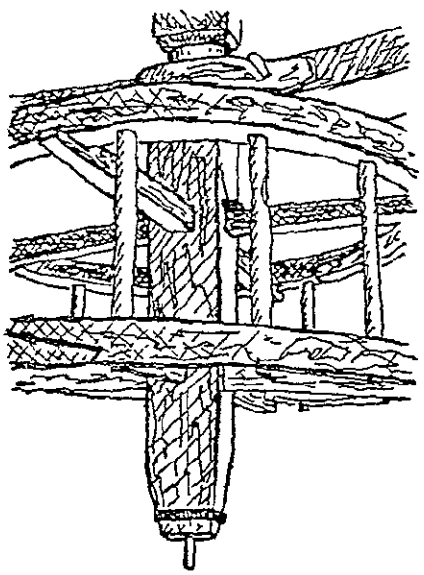


Fig. 8. Double-lipped and notched table scarf. An iron wedge keeps the two parts of the rim firmly together.

Before we leave the lantern pinion there are a few other details concerning the upright shaft that are of interest. At its base, the shaft ends in an iron gudgeon, which is bedded in a stone. The end of the shaft is provided with an iron ring to prevent it from splitting. See Fig. 9. The

Fig. 9. Lantern pinion, with pins, rim with spokes, and upright shaft with iron ring and gudgeon.



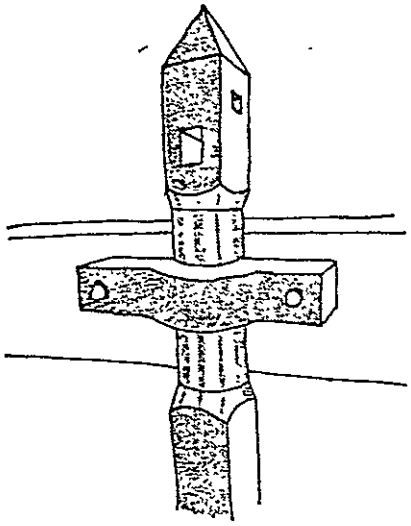
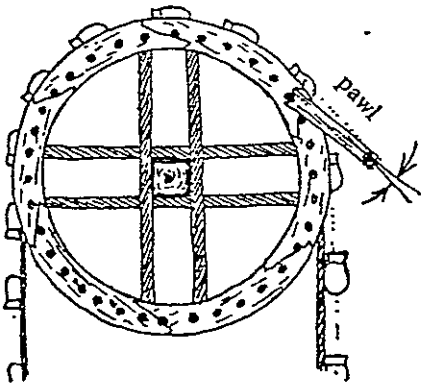


Fig. 10. The top bearing consists of a horizontal beam and a bearing lining.

Fig. 11. Paternoster wheel with pawl and potgarland. Majorca.



upper bearing for the shaft is located about 20 centimetres above the lantern pinion and consists of a beam with a yoke or liner fixed in position by two wooden spikes. The arrangement is supported on the two characteristic supporting masses mentioned earlier. See Fig. 10.

The potgarland wheel has two functions: it is primarily a cogwheel, but it also forms the drum that carries the potgarland. Each cog and carrying peg are made in one, as shown in Fig. 7. The potgarland wheel of the Spanish noria has only one rim, which is made from six pieces, and four spokes made from two continuous bars equal in length to the diameter of the wheel. The short shaft is very thick and is provided with a gudgeon at each end, turning in wooden blocks.

In order to prevent the wheel from going into reverse, the machine is provided with a pawl mechanism, which acts on the cogs of the potgarland wheel. See Fig. 11. To appreciate the vital function of this pawl it is only necessary to remember that the draught animal is subjected to a constant pull both when moving and when standing still. This pull is exerted by the part of the potgarland carrying the full pots. The pawl is activated in two cases – when the animal is to be unharnessed and in the event of the harness or traces breaking. Without the pawl the machine would turn backwards at great speed and, after one revolution, the drawbar would hit the draught animal on the head. At the same time, many of the pins of the lantern pinion would break and the pots smash. A local carpenter once told me that several conscientious donkeys had been killed because of defective pawls. However, although most of the norias I saw in Ibiza were more or less defective, their pawls were always in order. In this connexion, it should be noted that not all waterwheels are provided with a pawl mechanism. In places where the lift is less than 2 metres, there is practically no risk of a serious accident because the drawbar would move too slowly to kill the donkey. The draught animals are completely familiar with the operation of the pawl. If we watch one, we will see it turn its ears in the direction of the tick-tock of the pawl when it wants to stop. When it hears the sound the animal halts and takes a step backwards, at which point the pawl mechanism takes over the pull exerted by the full pots. If the animal did not await the sound of the pawl, it would have to move back 1.5 metres, which is against its nature. Now let us turn to the potgarland, which consists of two endless ropes spaced according to the diameter of the cylindrical pots. Besides serving as pot-carrier, the ropes act as a buffer between the pots and the carrier-pegs of the wheel, *i.e.* the pots are carried on the ropes, not between them. If the pots were carried in the latter manner, the edge of a pot might catch on a carrier-peg and break.

The pots have a small vent at the bottom to permit air to escape when the pot hits the water bottom up. Unfortunately, this vent gradually becomes clogged with leaves, and when that happens the pot floats on

the water, the next pot hits it and they both break. The vent appears to be a disadvantage because some of the water runs out of it. However, there is really very little loss because most of the water just runs down into the next pot. Rather more water is lost as the pots discharge their contents at the top of the wheel, because some of it hits the carrier-pegs and splashes down outside the trough.

A discussion of the *modus operandi* of the potgarland must include a description of the two guide-rods which keep the potgarland on the right course up to the potgarland wheel. These two rods are placed on either side of the potgarland and at an angle of about 45° to it. Without the rods, the potgarland would slide out along the carrier-pegs and finally fall off them. The constant bumping of the pots against the guide-rods results in deep wear marks on either side of the pots (cf. p. 102).

"Inside" the potgarland wheel there is a large wooden trough supported by two brackets embedded in the balustrade of the well.

Efficiency

The efficiency of a machine is defined as the ratio between the output power and the input power. This ratio gives only the efficiency of the machine itself; to obtain an idea of the total efficiency it would also be necessary to take into account the efficiency of the draught animal. However, for the sake of simplicity, the efficiency of the machine alone will be considered in the following.

In the case investigated, the tractive force exerted on the drawbar varied between 50 and 250 newtons, *i.e.* between 5 and 25 kilograms force. The mean value was found to be 120 newtons. The large variations were caused by the fact that three or four pots were missing from the potgarland.

Calculation

The input power is now determined as the force multiplied by the velocity or, to be correct, as the torque multiplied by the angular velocity. As the force is not exerted at right-angles to the drawbar, we have to multiply the tractive force by the cosine of the angle between the traces and the drawbar:

$$P = T \times \omega = F \times v \cos\alpha$$

$$P = F\frac{2\pi n}{60} R \cos\alpha = 120\frac{2 \times \pi \times 1.7}{60} 3.65 \times 0.95 = 75 \text{ watts}$$

where $n = 1.7$ rpm, $\cos\alpha = 0.95$, and the radius of the circular mule track $R = 3.65$ m; the remaining notation is as follows:

P = power, F = force, v = velocity, T = torque, ω = angular velocity.

For the output power we have to measure the rise in water level in the water tank within a certain period and determine the water-head. The flow was found to be 67 l/min, corresponding to 670 newtons/min, and

the head was estimated to be 4 m. The output power is then calculated as the flow multiplied by the head: $670 \times 4/60 = 44$ watts.

The efficiency of the machine is then:

$$\eta = \frac{44}{75} = 0.6$$

This value is significant in that it bears comparison with the efficiency of modern pumps. As a rule of thumb, the flow from a defective, mule-drawn noria will be 4 m^3/h for a head of water of 4 m. If the head is doubled, the flow must be halved.

As we watch the potgarland and its wheel, the following question arises: why does the potgarland not slip on the wheel when the pull exerted by the full pots greatly exceeds that exerted by the empty pots? We shall find the answer by investigating whether the following inequality is fulfilled:

$$\frac{S_1}{S_2} < e^{\mu\alpha}$$

where S_1 is the pull exerted by the full pots, and S_2 is that exerted by the empty pots. According to the engineering manuals, the coefficient of friction is of the order of magnitude of 0.4 to 0.5. The potgarland circumscribes an angle α of slightly more than π or 180°. The value e is the base of natural logarithms. By substituting on the right-hand side of the inequality, we obtain values from 3.5 to 5. In the noria discussed above, the ratio between the pull exerted in the two directions was $800/300 = 2.7$, *i.e.*, less than the permissible value, which means that the rope does not slip. On the other hand, while I was in Egypt I noticed a potgarland in which the pots had been replaced by buckets, and here the rope did tend to slip. The ratio in this case between the pull in one direction and that in the other was $350/100 \doteq 3.5$, *i.e.* in the vicinity of the permissible value.

Type *IA1b*
Ma'arrat al Nu'mān

This type, which is found in Syria (1969), is very similar to the Spanish noria, except that a bucket chain and bucket wheel are used.

On the road from Ḥamā to Aleppo there is a small town called Ma'arrat al Nu'mān, which once had a large number of norias. Unfortunately, they are now no longer in use and are therefore in ruins, but I did manage to find one in a sufficiently good state of repair to allow me to make a scale drawing of it. See Figs. 12 and 13.

The bucket wheel consists of 10 compartments, each with an outlet. The wheel itself is held together by two hoops and a large number of long bolts and fittings. Far less water is wasted with this construction than with the former. In the village of Tall Minnis, 5 kilometres east of the town, I saw this type of wheel in operation. It stood in the middle of the market place, raising drinking water for the villagers.

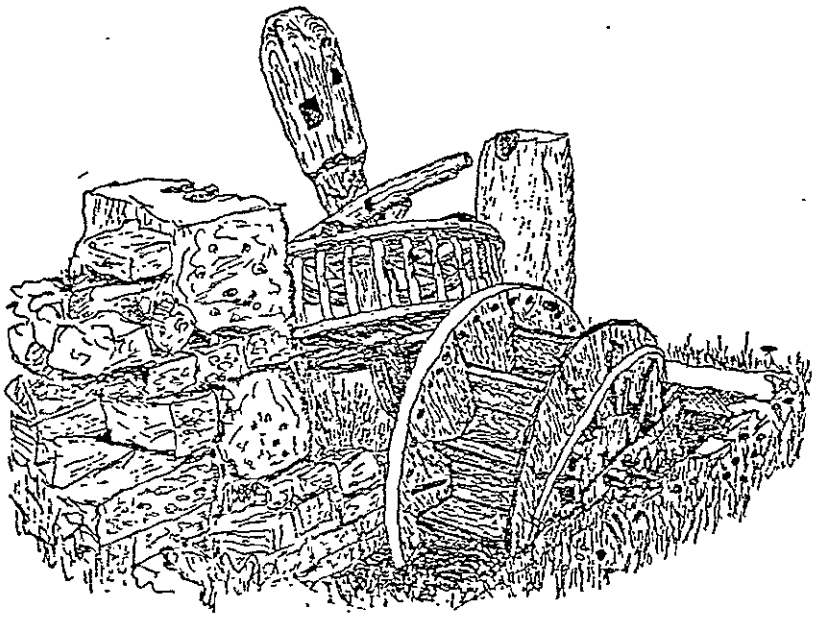
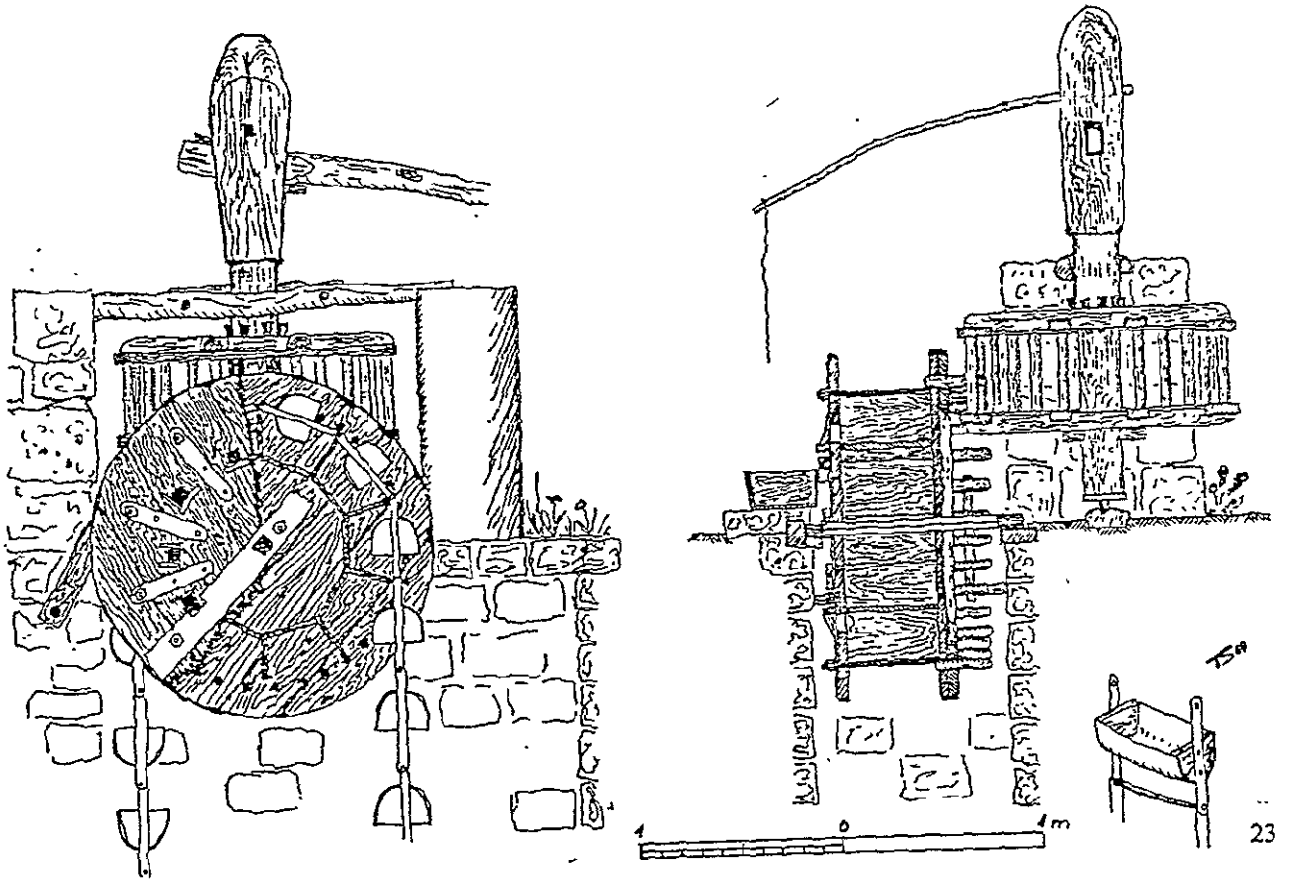


Fig. 12. Defective noria at Ma'arrat al Nu'mān; on the road from Ḥamā to Aleppo [Ḥalab]. The wheel is provided with open compartments into which the buckets empty their water. The bucket chain has gone, and the front "hoop" has fallen off. The stone on the right is what remains of a Roman column.

Fig. 13. Reconstruction of the defective noria on the road from Ḥamā to Aleppo. The left-hand drawing shows a partial section of the bucket-chain wheel, and the right-hand drawing shows a section of the bucket-chain wheel and the lantern pinion.



Classification and Technology

Type *IA2a*
Salḥin

About 4 kilometres south of the Citadel of Aleppo lies a district called Salḥin, where there were still many norias of this type when I visited the area in 1969. See Fig. 14. The brickwork surrounding the well and the water tank is built along the same lines as in the norias of Ibiza, but the wooden machinery differs considerably from the Spanish version. The upright shaft, which is very long and very heavy, rotates in a bedding stone. The cogwheel itself is a simple construction, consisting of four heavy beams fixed in position by means of wedges and diagonals. See Fig. 15. The upper bearing consists of two long beams and two small crossbars, which together form a square gap through which the shaft passes. Two heavy blocks of stone are used to weigh down the beams and keep them in position. See Fig. 16.

Fig. 15. The upright shaft and cog-wheel. The bedding stone at the bottom must be subjected to a load of more than half a ton.

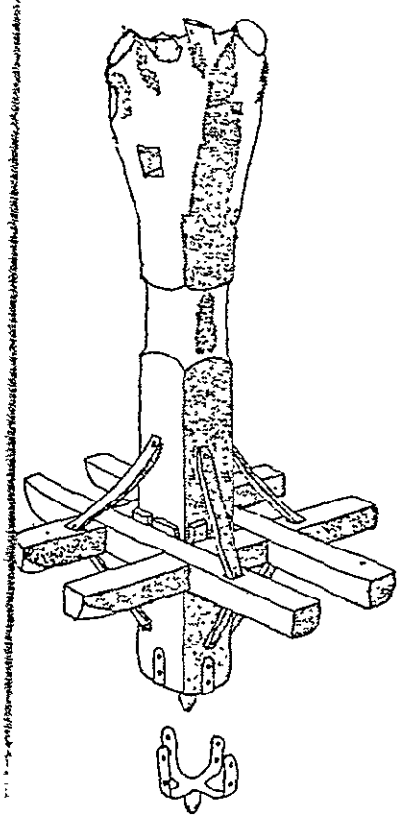
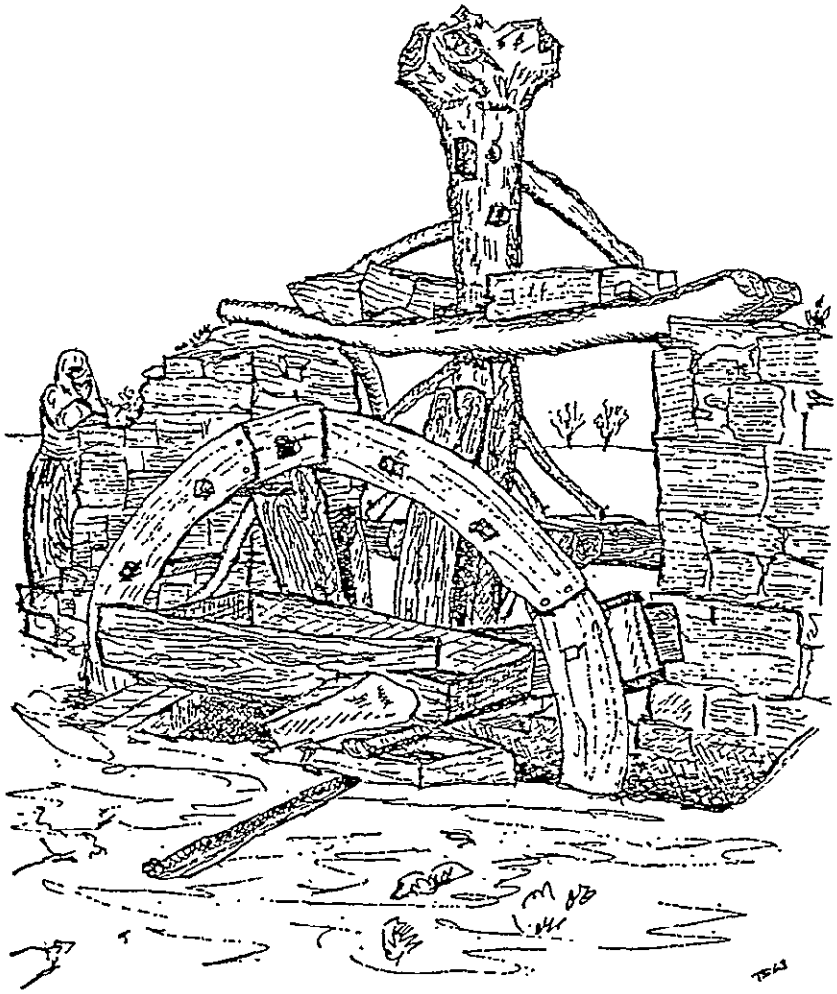


Fig. 14. Noria at Salḥin outside Aleppo. The upright shaft has a height of almost 3 metres.



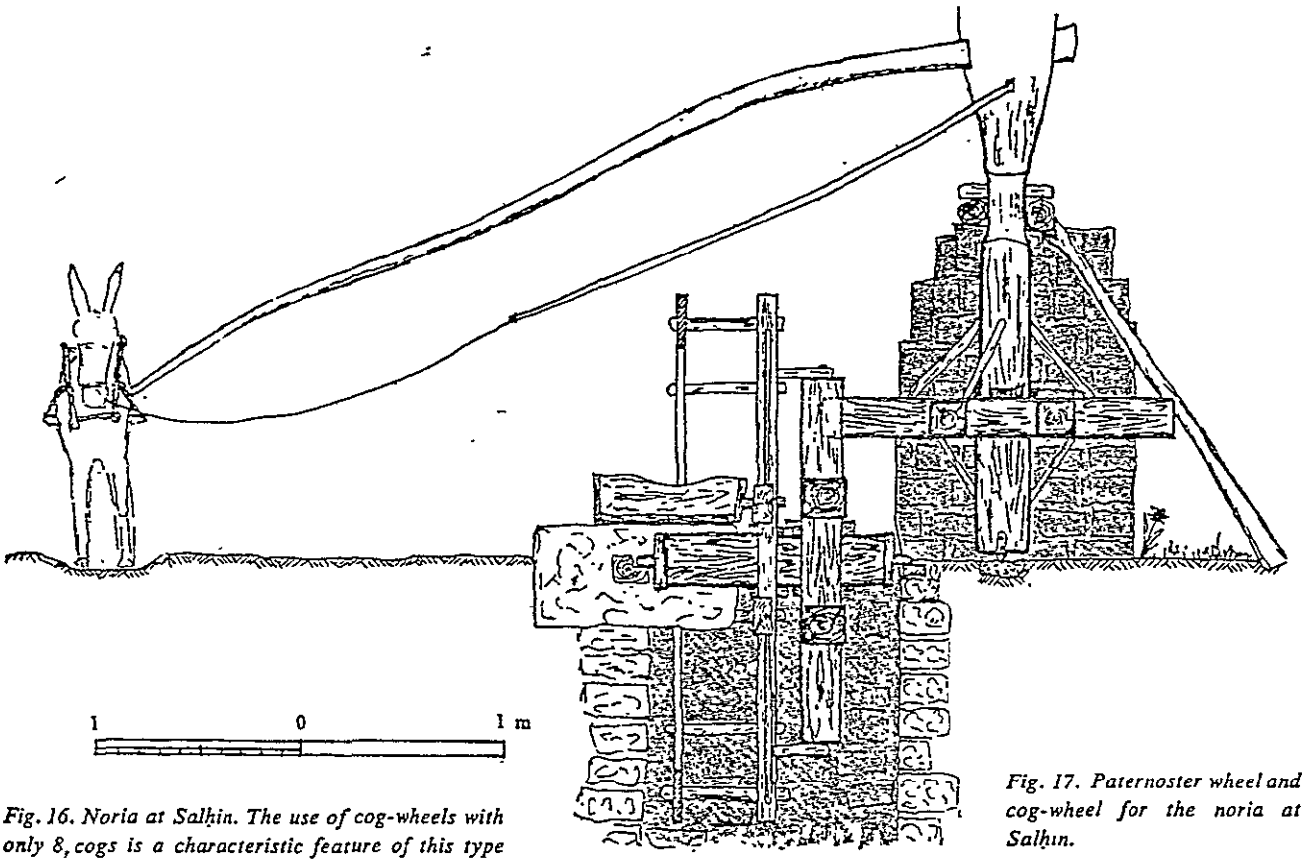
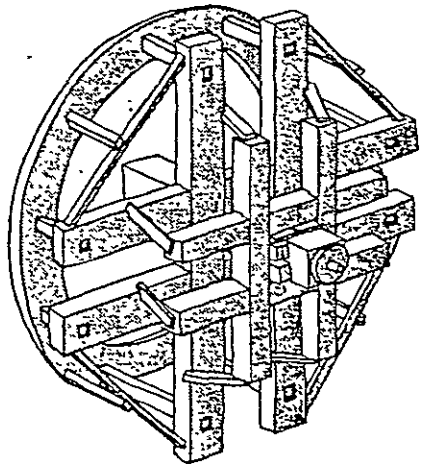


Fig. 16. Noria at Salḥin. The use of cog-wheels with only 8, cogs is a characteristic feature of this type of waterwheel. Forty years ago, potgarlands were still in use, but these have now been replaced by chains and tin buckets. These have been omitted from the drawing.

Fig. 17. Paternoster wheel and cog-wheel for the noria at Salḥin.



The horizontal shaft carries two wheels, see Fig. 17, one of which acts as cogwheel, and the other as potgarland wheel. The latter will be described later as it is identical with the drum in the Egyptian sāqiya, type *IB2a, Al Mi'timdiyya.*

The potgarland originally consisted of hemp ropes and earthenware pots, but nowadays iron chains and buckets are used instead.

This noria had no pawl because there were no cogs on which it could play, and no guide-rods were used. All in all, it was very primitive and had to be supervised by two women.

The machine was in operation while I measured it – a rather hazardous occupation – but I made good use of the opportunity offered by stoppages caused by a couple of buckets getting caught up in the potgarland wheel.

Type *IA2b*
Aleppo

This type has the same gear construction as the previous type, but the potgarland wheel is replaced by a bucket wheel and bucket chain. According to Moussly, this machine is called a ḥallāf. Nazim Moussly: *Le problème de l'eau en Syrie.* Lyon 1951, p. 144.

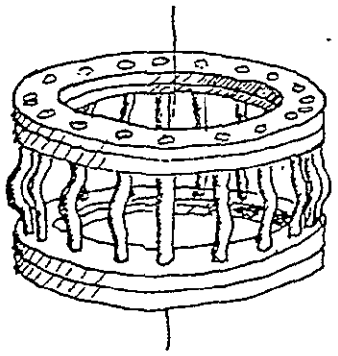


Fig. 18b. The lantern pinion.

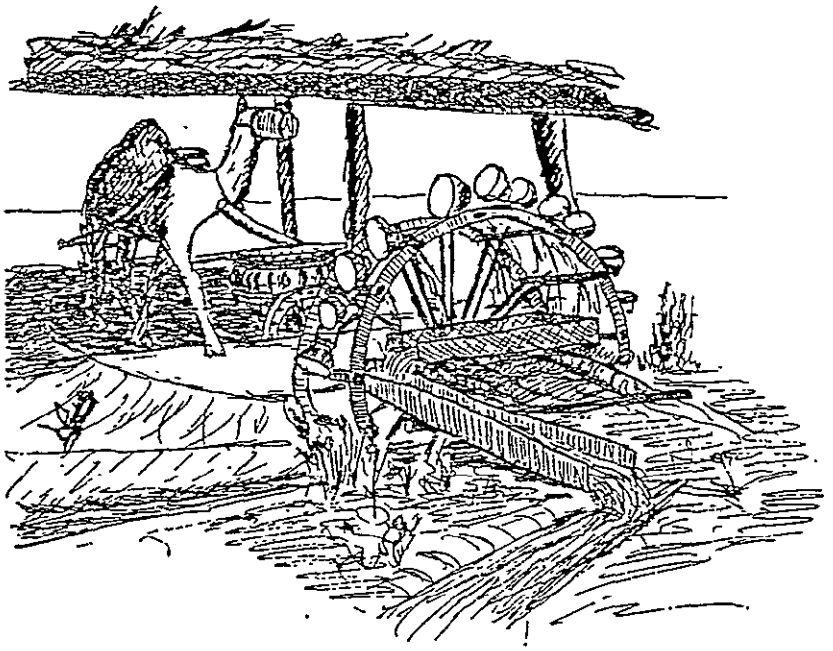


Fig. 18a. Sāqiya with long shaft. Note the lantern gear construction. West Pakistan.

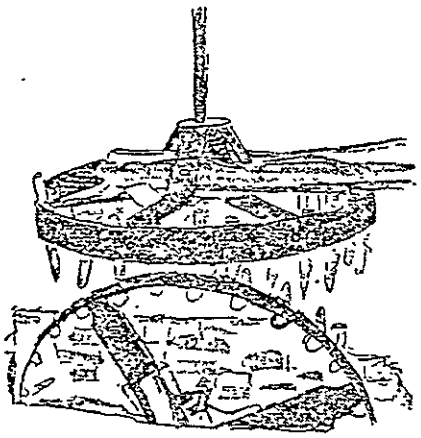
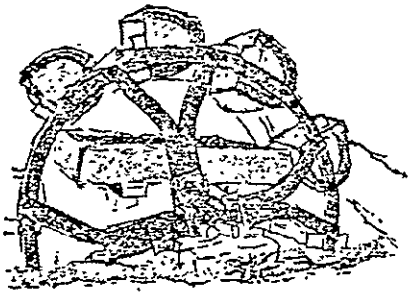
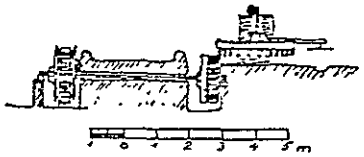


Fig. 19. Iron sāqiya. Iraq, 1969.





Long horizontal shaft

We now come to the types with a long horizontal shaft. Owing to the method of classification adopted, we have to deal with a rare type of wheel before the Egyptian sāqiya.

The fascinating point about this machine is its use of a right-angle gear, which represents an advanced level of joinery. See Figs. 18a and 18b. The rims are constructed of laminated wood and the pegs are curved, both details that make the construction rigid and compact. Type *IB1a, Hala.*

As norias are still being built in many countries, attention should be drawn to this joinery method and, in the case of wells with a depth of more than 4 metres, the Spanish design should be borne in mind. The fact that many countries prefer norias made of iron is undoubtedly due to the poor quality of the joinery in earlier norias. In the next example we shall examine a machine made of iron. This is type *IB1b, Ḥaswa.*

Although machines made of iron really lie outside the scope of this book, there is good reason to include this example because it is a true copy of its predecessor, which was made of wood. The drawing in Fig. 19 has been made on the basis of my survey of a dawlāb (sāqiya) near Ḥaswa, between Baghdad and Babylon. In this region there are hundreds of machines, but they are all made of iron; for the wooden version we have to go to Northern Iraq. There is a photograph of such a machine in an illustrated work dating from 1968. According to the caption, the picture is from Palestine, but this must be an error because there is no

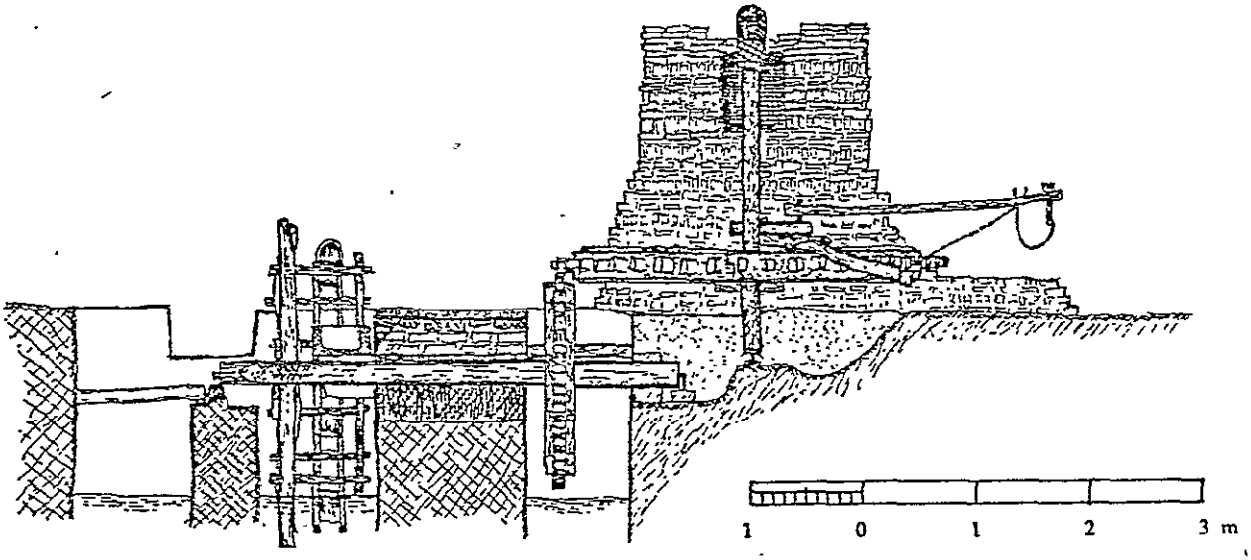


Fig. 20. Cross-section of the sāqiya at Mi'timdiyya near Cairo. Drawn by the author in 1964. For details see Figs. 21, 22, 23 and 24.

doubt at all that it actually comes from Northern Iraq. D. et J. Sourdel: *La civilisation de l'Islam classique*. Paris 1968, fig. 96. It is interesting to note that this construction uses a lantern pinion with one wheel rim instead of two. See also Vignette No. 2 on p. 41.

Type *IB2a*
Al Mi'timdiyya

The best known of all water-lifting machines is the Egyptian sāqiya. The monotonous creaking of the cog-wheels can be heard all the way from the shores of the Mediterranean to deep in the Sudan, where:

> In 1943, the number of waterwheels in the Northern Province was 9,456 ... the figure has declined less than might have been expected.

K. M. Barbour: *The Republic of the Sudan*, London 1961, p. 141 and fig. 41.

Let us now return to Egypt, to the town of Al Mi'timdiyya, which lies outside Cairo, about 5 kilometres west of Cairo Tower, for here there was an old sāqiya of great interest. See Fig. 20. The well, which is only 2 metres deep, is divided into two sections, so there is actually room for two sāqiyas. See Fig. 21. Not far away lie the ruins of another well, in which three sāqiyas once worked. In both cases, the wells are made of burnt red brick, while the surrounding walls consist of mud bricks.

Turning now to the machine itself, we shall follow the power input, from the ox, through the gear, to the potgarland. The sāqiya in question is drawn by an ox moving extremely slowly and bearing on its shoulders a neck-bar, the other end of which is pinned to a small beam cantilevered

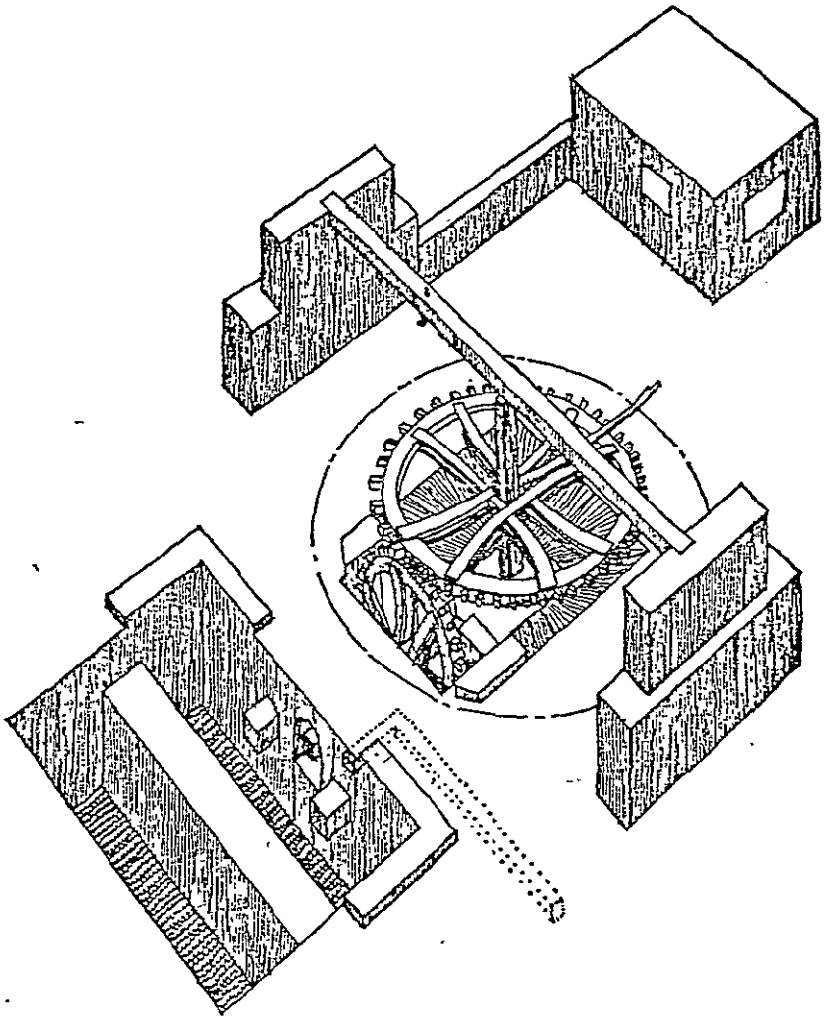


Fig. 21. Perspective of the sāqiya. The bucket-chain wheel has been removed. Mi'timdiyya.

out from the upright shaft. See Fig. 22. If the sāqiya were drawn by two oxen, the neck-bar would be replaced by a yoke. See Fig. 109.

In order to keep the ox on the circular track, the outer end of the neck-bar is provided with a wedge and rope arrangement, forming a halter. The pull of the ox is transmitted by a chain to the drawbar, which is fixed to the cogwheel a quarter turn behind the neck-bar. As stated earlier, the cogwheel is in turn fixed to the upright shaft, the upper end of which has a gudgeon turning in a long palm beam. The lower end rotates in a bedding stone or wooden block, as shown in Fig. 88. The rim of the cogwheel is fixed between an upper and a lower set of spokes. The rim itself consists of six pieces, joined together in a manner that prevents radial displacement. Forty-eight holes are then made in the rim, corresponding

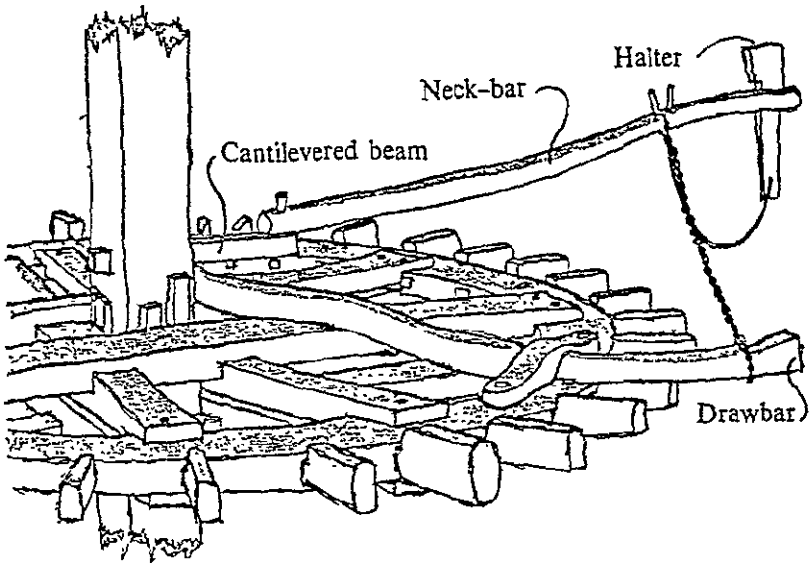
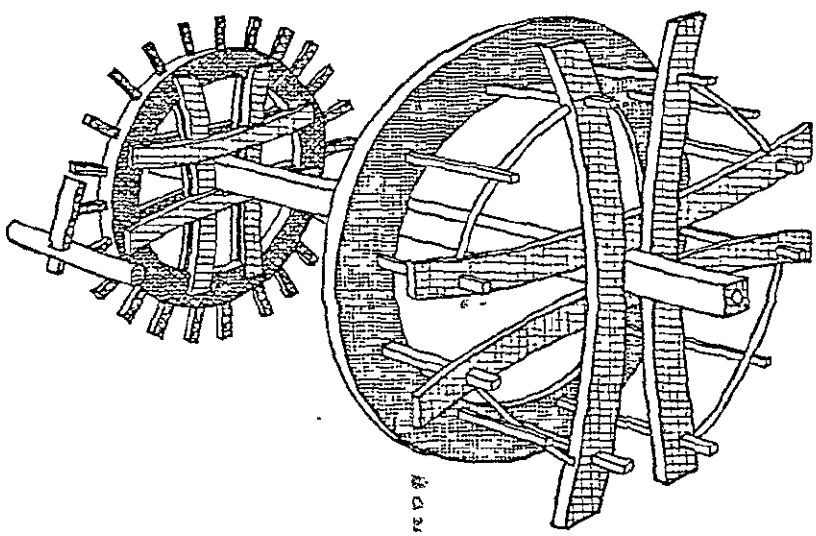


Fig. 22. The large cog-wheel, including the long neck-bar with the chain that transmits the pull to the cog-wheel.

to the number of cogs. Some of the holes coincide with the rim joints, which are therefore spoiled. However, the real assembly mechanism for the rim is provided by the spokes, which act as scarves. The entire weight of the the gear-wheel is supported by a 60 centimetre long transverse rod, and the wheel is centred by means of wedges between the spokes and the upright shaft.

Fig. 23. The horizontal shaft with small cog-wheel and potgarland wheel.



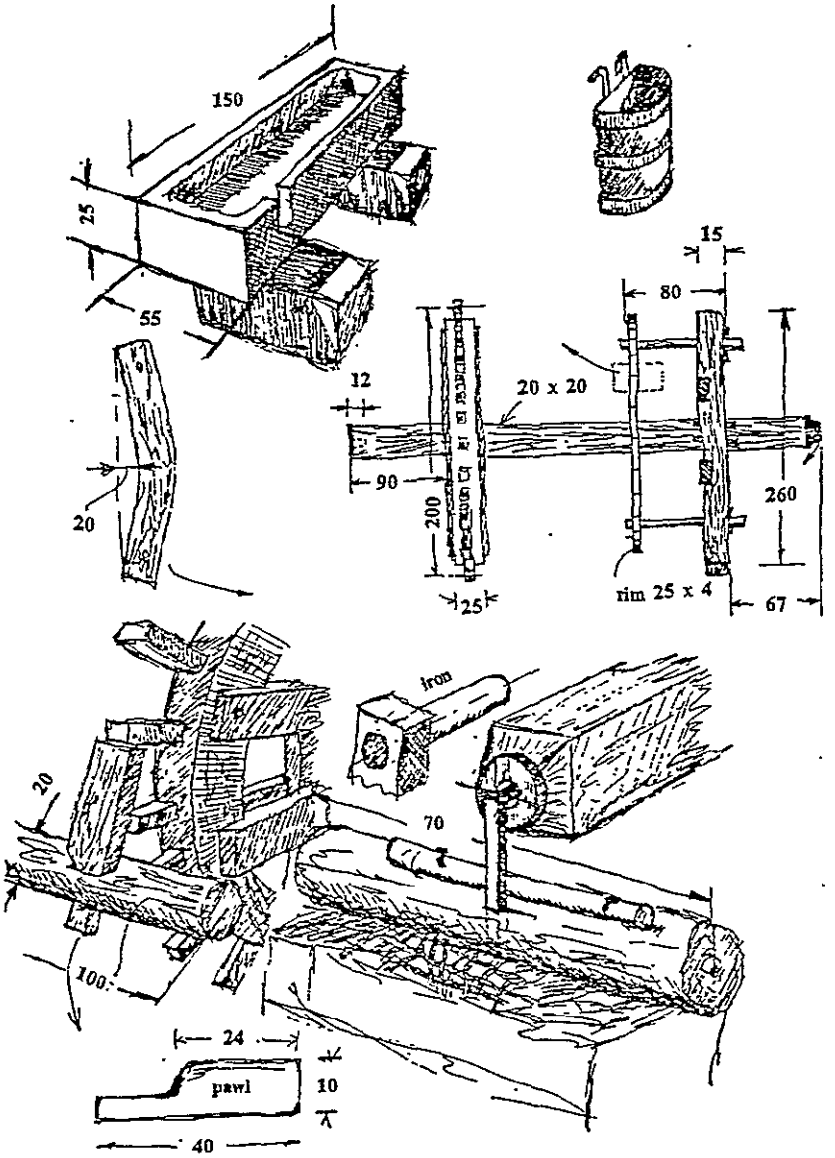


Fig. 24. Details of parts of the sāqiya at Mi'timdiyya. Stone trough. Bucket for bucket-chain wheel. Pawl mechanism. Bearing for the horizontal shaft. Drawn in Egypt 1964.

Passing now to the horizontal shaft, we reach the little cogwheel, which is a copy of the large wheel, so a detailed description is unnecessary. This brings us to the potgarland wheel itself, which consists of more than 25 components. To understand this complicated wheel, the reader is advised to study Fig. 23, on p. 29.

The rim facing us has no spokes so it appears to be suspended in space. In fact, the trough inside the wheel is supported by two small cantilever beams. There is thus no room for spokes in the wheel as they would

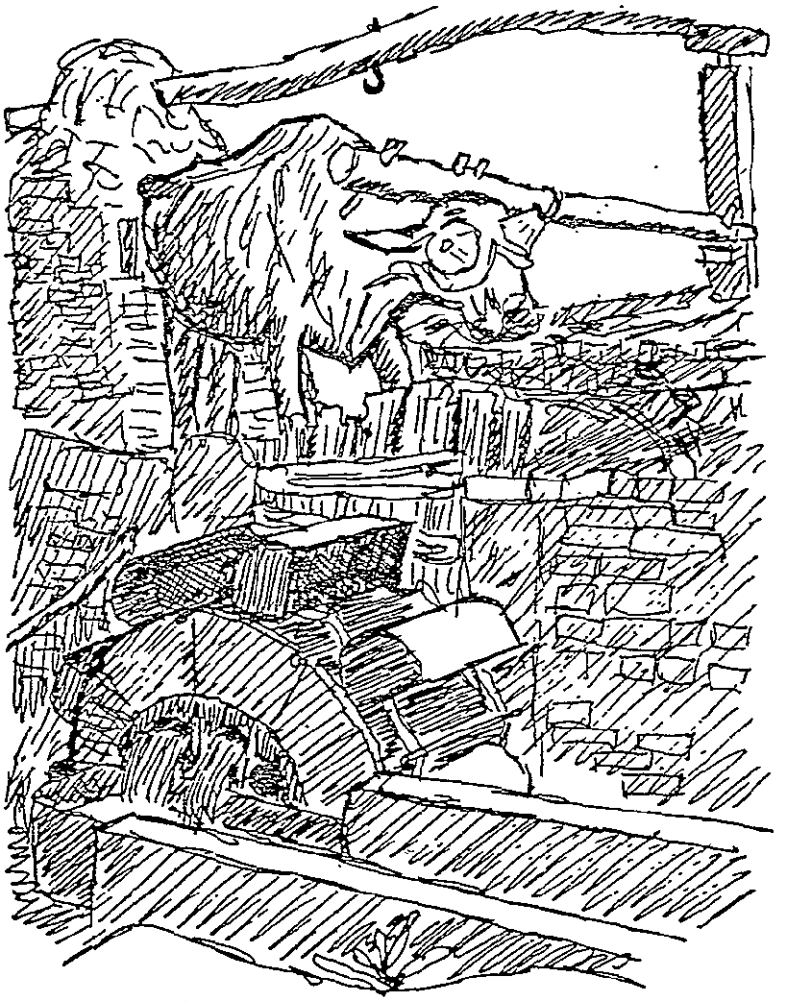
traverse the trough supports. In this wheel, too, the earthenware pots have been replaced by the buckets shown in Fig. 24. The buckets are tied to two small pegs lashed to the potgarland rope.

The trough is made of concrete and its outlet is placed a little way up so there is always a certain depth of water in the trough, thereby minimizing splashing. From the trough the water flows out to the fields through an underground pipe.

The pawl

On this journey through the Egyptian sāqiya we must not forget the pawl. See Fig. 24. This important device was described in the section on the Spanish noria, and it will be remembered that a defective pawl may result in the draught animal being killed. In the Egyptian sāqiya, there is the

Fig. 25. Sāqiya with bucket-chain wheel. Common in the Fayyūm, Egypt.



added danger that the guide-boy who sits on the big wheel may get knocked off it if the wheel suddenly reverses. There is a Coptic story about a little boy who was pushed off the wheel and into the well by the Devil. W. Spiegelberg has translated the story as follows (cf. p. 111):

> .... ein Knabe war auf ein Wasserrad [no, this must be the horizontal cog-wheel] gestiegen, indem er das Vieh des Klosters antrieb. ... Da stieß der Teufel den Knaben in den Brunnen, und er ertrank in dem Wasser.

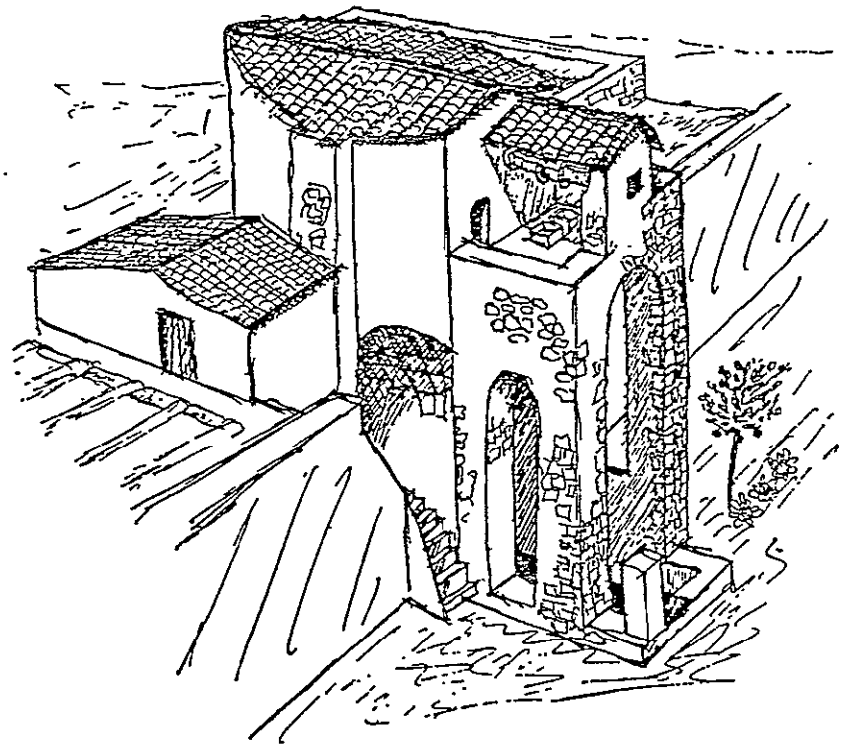
I assume that the Devil must have removed the pawl, which would be quite simple as this is loosely placed in a square hole.

Lastly, let us take a look at the iron hook on the long palm beam, which has no technical purpose, but which is, all the same, a very important piece of equipment. The guide-boy's bread-bag is hung from this hook, well out of the reach of hungry dogs. See Figs. 21 and 25.

Type *IB2b* *Fayyūm*

This is the most effective type of wheel for small lifts, and it is very common in the Fayyūm district of Egypt. See Fig. 25, on p. 31.

Fig. 26a. Noria at Formia between Rome and Naples in 1971.



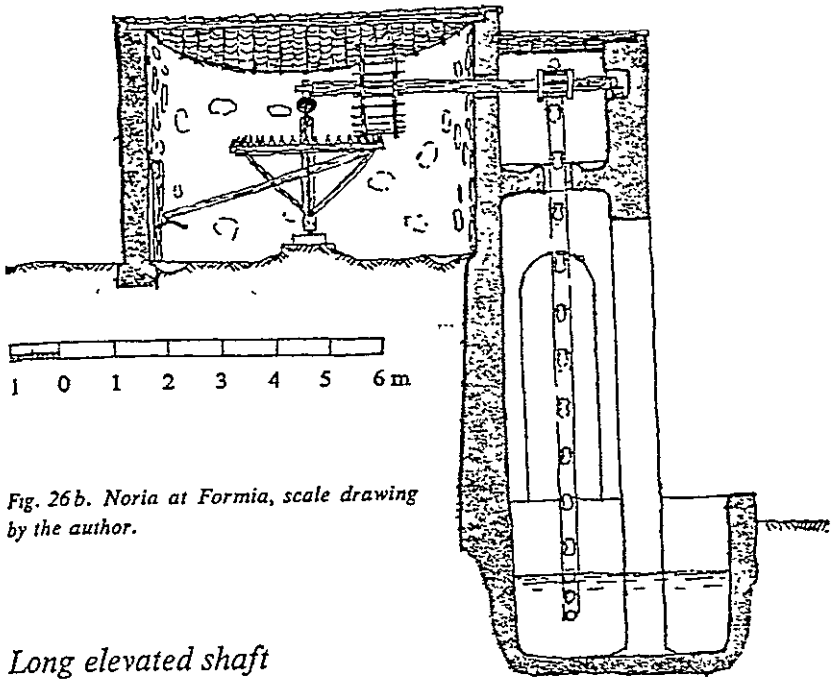


Fig. 26b. Noria at Formia, scale drawing by the author.

Long elevated shaft

The next four types belong to the category with an elevated shaft. They are now a rarity in the field of irrigation, but were not unknown a hundred years ago.

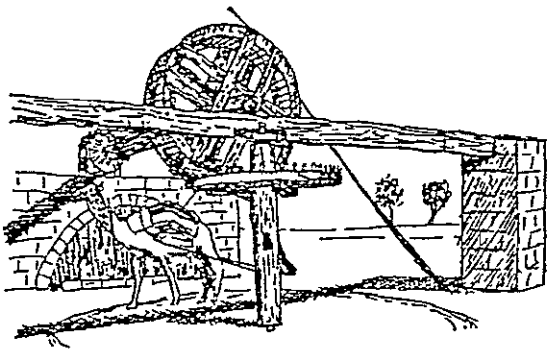
Type *IC1a*
Formia, Italy

During a visit to Italy in 1971, I found, quite unexpectedly, a sāqiya of the elevated shaft type in the town of Formia, between Rome and Naples. Although the machinery had obviously not been used for some years, it was in good condition, except that the potgarland was missing. See Figs. 26a and 26b.

Type *IC1b*
Palestine

This type was once common in Palestine but has now (1969) completely disappeared. As will be seen from Fig. 27, the lantern pinion is carried by

Fig. 27. Sāqiya with elevated shaft. This construction was once common in the Palestine. The long diagonal bar forms part of the pawl mechanism.



the horizontal shaft, and this arrangement is also shown in a rather poor photograph in a German work on Palestine, Gustaf Dalman: *Arbeit und Sitte in Palästina*, Vol. *II, Der Ackerbau*. (Schriften des Deutschen Palästina-Instituts, Vol. 5, (Gütersloh 1932)), fig. 47 and pp. 225–226).

Type *IC2a*
India

We have many pictures of sāqiyas from India, most of which are iron constructions, with a long horizontal shaft, but Fig. 28 shows the main outlines of a wooden sāqiya. The peculiar structure on the right of the men is a cog-wheel with 12 cogs. The potgarland wheel has a number of details that are reminiscent of the wheel from West Pakistan. See Fig. 18a.

Type *IC2b*
Syria

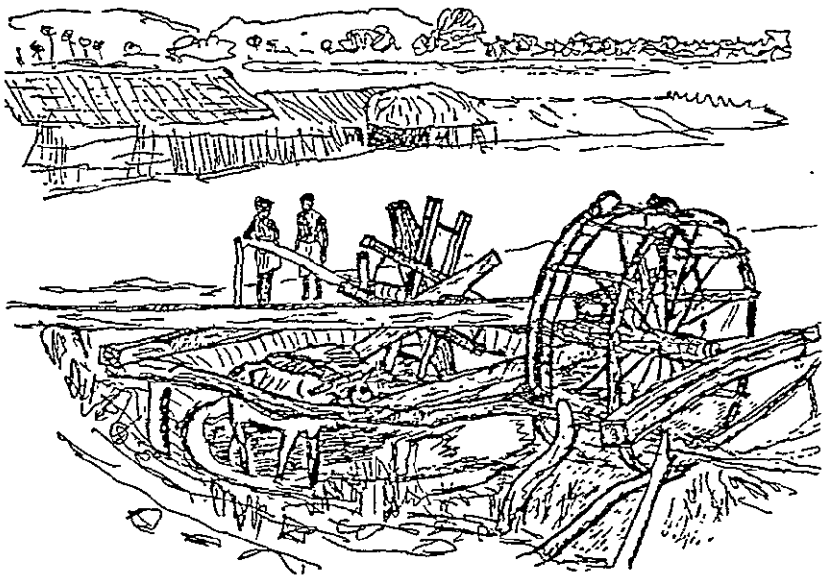
This Syrian type of wheel, which has an elevated shaft and radial cogs, in combination with a bucket wheel, I know only from sketches in a French work, Jacques Weulersse: *Le pays des Alaouites*. (Institut français de Damas). Tours 1940, fig. 82, and from a photograph, A. J. Jaussen et R. Savignac: *Mission archéologique en Arabie. I.* Texte et atlas. (Publications de la Société des fouilles archéologiques). Paris 1909, fig. 31, p. 32.

The last part of this section, group *I*, is devoted to a number of types that do not fit the classification.

Type with hollow rim
Ismailia

For lifts of at the most one metre, it is sometimes found advantageous to use a large wheel with a compartmented rim instead of a potgarland. A sketch of such a wheel, which I found in ruins at Salḥin near Aleppo,

Fig. 28. Sketch of sāqiya with elevated shaft and cog-wheel. The cog-wheel has only 12 cogs. The circular ox-track is below ground level. A long iron-plate chute leads the water to the field. This gutter is placed over the circular track. India about 1950.



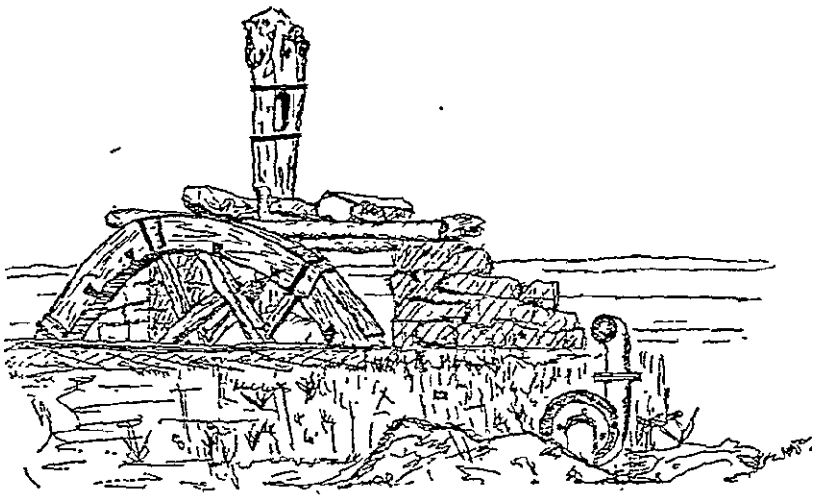
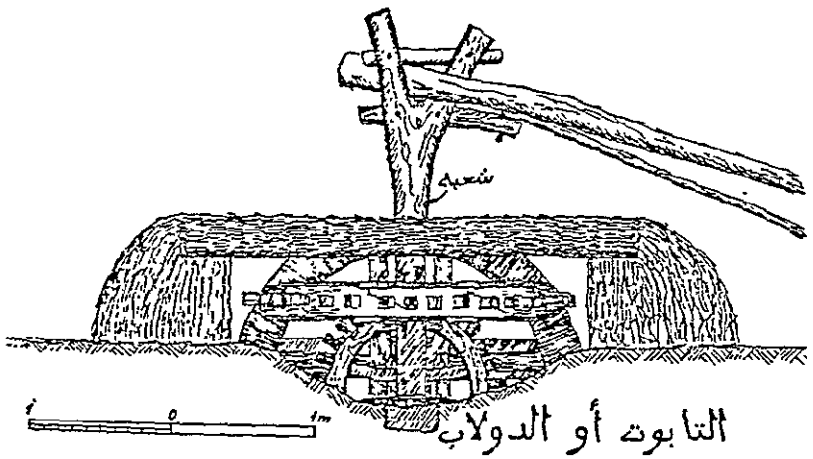


Fig. 29. Defective noria at Aleppo. The waterwheel has hollow rim, with about 16 compartments. The upright shaft is held in position by two beams, weighted by a couple of large stones, to hold them against the piles of stone on which they rest. The centrifugal pump in the foreground was intended to replace the noria, but this, too, is out of order.

is shown in Fig. 29, and there is a photograph of one in a book on water problems in Syria, Nazim Moussly: *Le problème de l'eau en Syrie*. Lyon 1951, plate *III* C.

The best known of the machines based on this principle are to be found in the Nile Delta. The design, which is shown in Figs. 30 and 31, differs in many ways from that of the ordinary sāqiya. The well is located within the circular ox-track, and instead of the long beam, a short pole is used.

Fig. 30. Sāqiya with compartmented rim. The correct term is tābūt. Survey carried out in Ismailia in Egypt 1964.



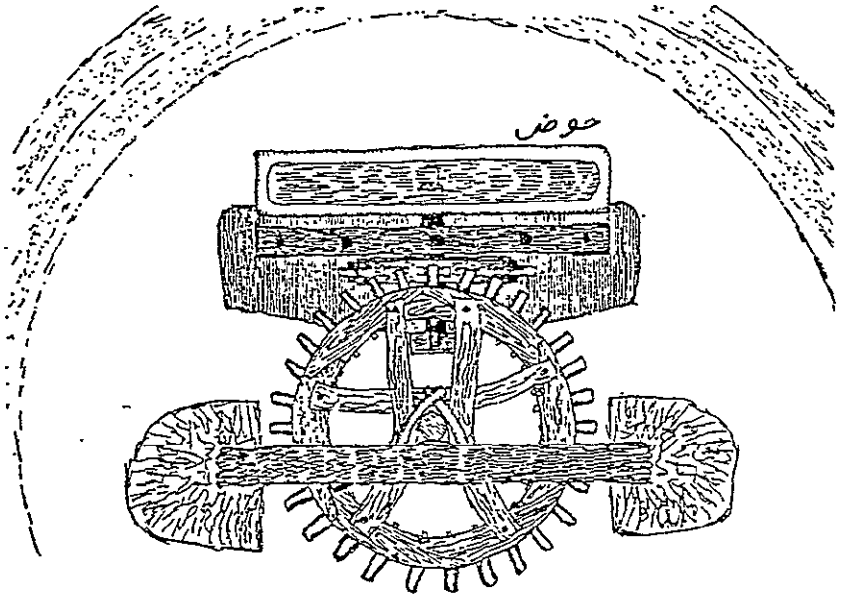


Fig. 31. The same tābūt as Fig. 30, but seen from above. This type of machine is very popular in the Nile Delta and must be the successor of the Roman invention depicted in the wall painting in Alexandria. See Fig. 108 on p. 152.

The compartmented wheel is arranged in direct connexion with the cogwheel. The rim itself consists of 16 compartments, each with two apertures. There are literally thousands of this type of machine in the region north of Cairo. Some Egyptians call it a sāqiya, but its real name is tābūt. I have found illustrations of a similar construction from Italy in K. Jaberg und J. Jud: *Sprach- und Sachatlas Italiens und der Südschweiz.* Illustrationsband, von Paul Scheuermeier: *Bauernwerk in Italien und der rätoromanischen Schweiz.* Erlenbach-Zürich 1945, p. 240.

Type with paddlewheel *Nile Delta*

Another machine common in the Nile Delta operates with a paddlewheel, in which the longitudinal section of the blades resembles a spiral. The paddlewheel, which is always made of iron nowadays, is referred to and illustrated in an F.A.O. publication F.A.O. Agricultural Development Paper No. 90, *Water-Lifting Devices for Irrigation,* prepared by A. Molenaar, Rome 1956. The design principle is a very old one, as is illustrated by a miniature from the 12th century. See Figs. 54a and 54b.

Group *II.* Machines without gear

As indicated in the foregoing, these wheels can be classified in four groups: (A) water-driven wheels, (B) treadwheels, sub-divided into (1) pot-wheels and (2) compartmented wheels.

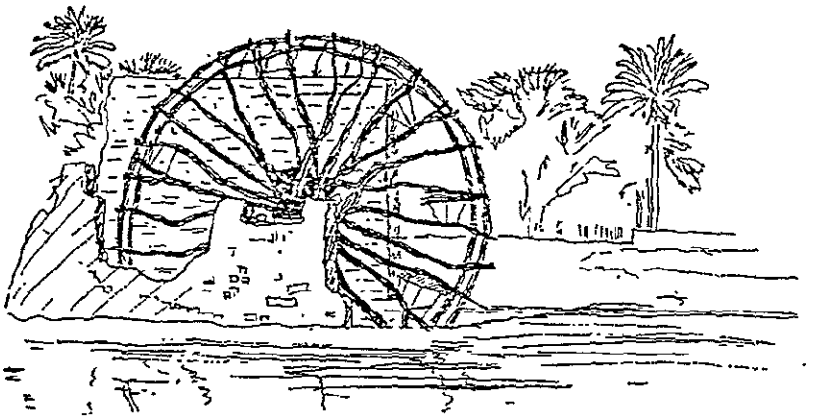


Fig. 32. Hydraulic noria from Hīt on the Euphrates. The wheel is provided with a number of mats that act as paddles in a waterwheel. An endless row of slender pots is fastened to the rim. See also Fig. 71. The drawing shows only one wheel, although there were actually five more behind it.

A. Water-Driven Wheels

Type *IIA1*
Hīt, Iraq

Fig. 32 shows a type of wheel that is still (1969) in use at Hīt on the Euphrates in Iraq. The construction actually has five wheels working on one shaft, but for purposes of clarity, the rear four wheels have been omitted from my drawing.

A large number of pots are lashed to the outer rim. The pots begin to empty as they reach the highest point of the wheel but are not completely drained until they are well on the way down again.

Type *IIA2*
Ḥamā, Syria

The famous wheels of Ḥamā are of the compartmented type. The rims of the largest wheels consist of 120 compartments. These wheels, nine of which were still in operation in 1969, although mostly as a tourist attraction, provide a fascinating spectacle, and the experience is enhanced by the "organ music" produced by their wooden bearings. This music is a mixture of noise and true notes, the deepest of which lie in the frequency band 120–170 Hz, or nearly two octaves below concert pitch.

The largest of the wheels was surveyed in 1935 by Ejnar Fugmann, a Danish architect. Today (1969), this wheel lies partly in ruins. The drawing in Fig. 1 was made by Fugmann on the basis of his extremely complicated survey, which necessitated more than 275 different measurements. Shortly before he died in 1965, Ejnar Fugmann requested me to publish this survey.

The extreme complexity of the design is apparent from Fig. 33 and the construction is as follows: first, four continuous beams constituting the four double spokes are mounted on either side of a frame wedged tightly in position round the hub. Next, the inner rim is constructed and, at the same time, the fan-shaped spokes are nailed in place. The wheel has to be turned at intervals during assembly in order to avoid possible wobbling.

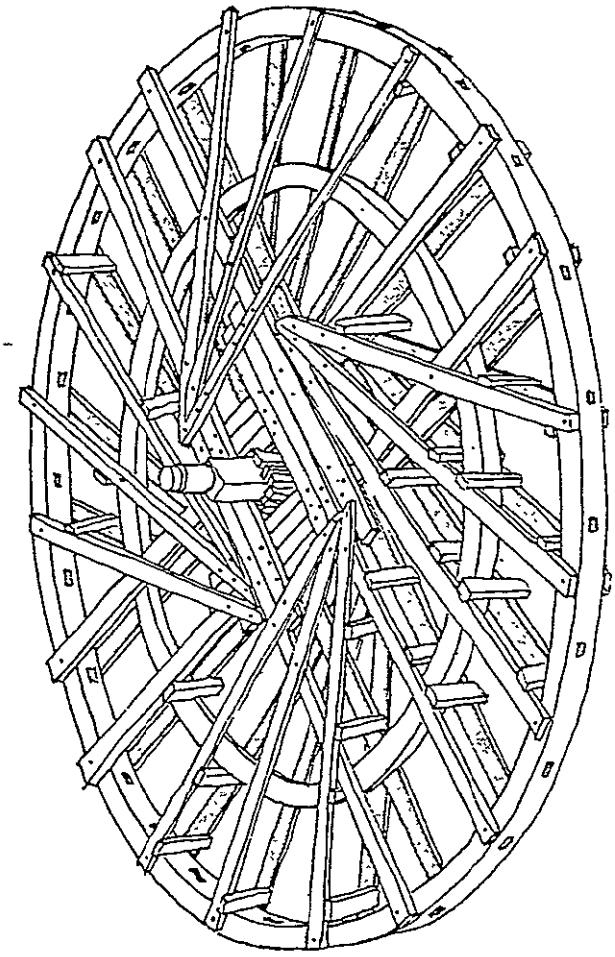
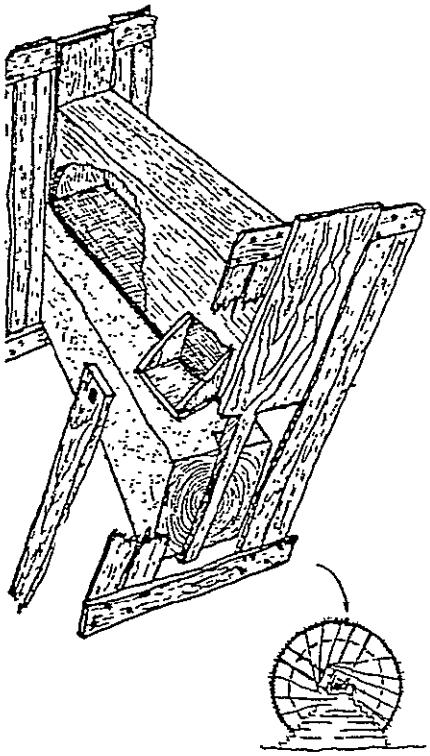


Fig. 33. Model of a Ḥamā wheel. The outer compartmented rim has been omitted. The drawing is not a true representation, the scale of the timbers being out of proportion to the overall size of the wheel. See Fig. 1 on p. 8.

Fig. 34. Ḥamā wheel. The rim consists of 120 compartments, end to end. The paddles are fixed between the compartments.



Finally, the outer rim for the compartments is mounted. The design of the compartments is shown in Fig. 34.

Before leaving these wheels, there are a few points with which I think the reader should be acquainted.

A great many authors have confused these wheels with the geared noria, presumably because both types lift water and both are called a noria. Therefore, in order to differentiate clearly between them, the Ḥamā-type of noria will be termed a water-driven or hydraulic noria, and the other type, an angle-gear or animal-powered noria. Julio Caro Baroja has avoided the pitfall of ambiguity by devoting a separate paper to each type, classified above as groups *I* and *II* (cf. p. 11).

Unfortunately, there are a number of intermediate forms, classified here as "other geared machines", and this has necessitated treatment of all the various types of wheels. The great wheels at Ḥamā have therefore been included in this book even though, in principle, they belong to a group that falls outside its scope. Had the intermediate types been of recent date, it would have been possible to omit the hydraulic noria altogether, but the very oldest picture we have of a sāqiya shows a type combining a gear, oxen, and a waterwheel of the Ḥamā-type.

B. Treadwheels

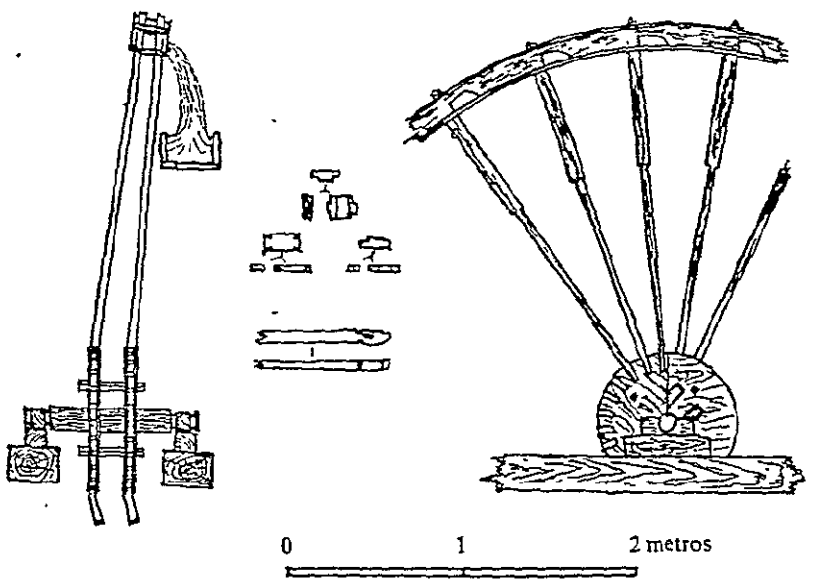
Type *IIB1*
Riotinto

I have not succeeded in finding a specimen of a treadwheel with pots, and although such undoubtedly exist, they must be exceedingly rare. In the Riotinto mines in Spain there were probably such wheels. See G. C. Boon and C. Williams, p. 124, note 25 (cf. p. 160).

Type *IIB2*
Ostia Antica

There are both recent and ancient examples of the treadwheel-compartmented type, the design of which is shown in Fig. 35. In connexion with the treadwheel, we encounter the serious problem of stability, or the ability of the treadwheel operators to control the movement of the wheel. There are two types of treadwheels, one in which men turn the wheel by treading on steps inside the wheel, and one in which the men tread the wheel from above. Since antiquity, treadwheels in which the men work

Fig. 35. Roman treadwheel with compartmented rim from Santo Domingo in Portugal. The remains of wheels of this type are to be found in the British Museum, Musée de Conservatoire national arts et métiers in Paris, and in el Museo de Riotinto in Spain.



inside the wheel have been used to operate winches. In a comment to this, F. R. Forbes Taylor writes:

> With the men inside, it was almost impossible for them to lose control, even without the use of brake or pawl ....

F. R. Forbes Taylor: *The Winch from Well-head to Goliath Crane*. [The Chartered Mechanical Engineer (April 1962), p. 203].

The treadwheel operated by men treading at the top is regarded as an unstable system, although bearing friction improves the stability. Moreover if the wheel is provided with a pawl, I should think that the men have sufficient control over it for water-lifting purposes.

At the end of this section on machines in group *II* we now come to "other types of machines without gear."

Types of wheel turned by hands and feet

The treadwheel can also be coupled to a paternoster wheel. An example of such a combination is shown in Fig. 95. Finally, there is another type of treadwheel, which is turned by means of both hands and feet, and which is also designed to carry a potgarland. See Figs. 56 and 57.

Terminology

The problem of the terminology of waterwheels is practically insoluble. In a geographical region in which a number of different types of machine are used, as in Northern Egypt, the people use a generic term to cover them all. Dictionaries are sometimes of help, but the translations are not always reliable.

In the following a number of the most common terms in use today will be discussed.

In Spain, the term noria is used both for water-driven wheels and animal-powered wheels. To avoid misunderstandings, Caro Baroja uses two terms, *la rueda de corriente* and *la noria de sangre*. In Ibiza, the term, *sèni*, which is of Arabic origin, is used.

In Syria, the people seem to be more consistent. Only the great wheels at Ḥamā are termed norias or, more correctly, the classical form, nāʿūra. This term, on the other hand, is unknown in Egypt, although Europeans use the Spanish form, noria, when referring to the Egyptian sāqiya. In the vicinity of Aleppo, the old Persian word, dawlāb, which is well known in Egypt, the Sudan and Iraq, is used. The term does not refer to a particular type, but is simply a general expression for wheel, possibly a waterwheel.

In Syria, the term ġarrāf is used for the geared noria, whereas the word madār simply means mill or circular track.

In addition to the terms commented on above, there are other terms, such as ṭanbūša, ṭabliyya and ṭulunba. They can hardly be translated as anything but water-lifting wheels.

Bibliography

Each of the works referred to below devotes a few pages to the terminology of the various machines:

Caro Baroja, Julio. *Norias, azudas, aceñas.* [Revista de dialectología y tradiciones populares, Vol. *X* (Madrid 1954), pp. 29–160].

– *Sobre la historia de la noria de tiro.* [Revista de dialectología y tradiciones populares, Vol. *XI* (Madrid 1955), pp. 15–79].

Colin, G. S. *La noria marocaine et les machines hydrauliques dans le monde arabe.* [Hespéris, Vol. *XIV.* (Paris 1932), pp. 22–60].

Dalman, Gustaf. *Arbeit und Sitte in Palästina.* Vol. *II Der Ackerbau* (Schriften des Deutschen Palästina-Instituts, Vol. 5 (Gütersloh 1932), pp. 225–228).

Dias, Jorge y Fernando Galhano. *Aparelhos de elevar a água de rega,* Porto 1953.

Littmann, Enno. *Die Sāqiya.* [Zeitschrift für ägyptische Sprache und Altertumskunde. Vol. 76 (Leipzig 1940), pp. 45–54].

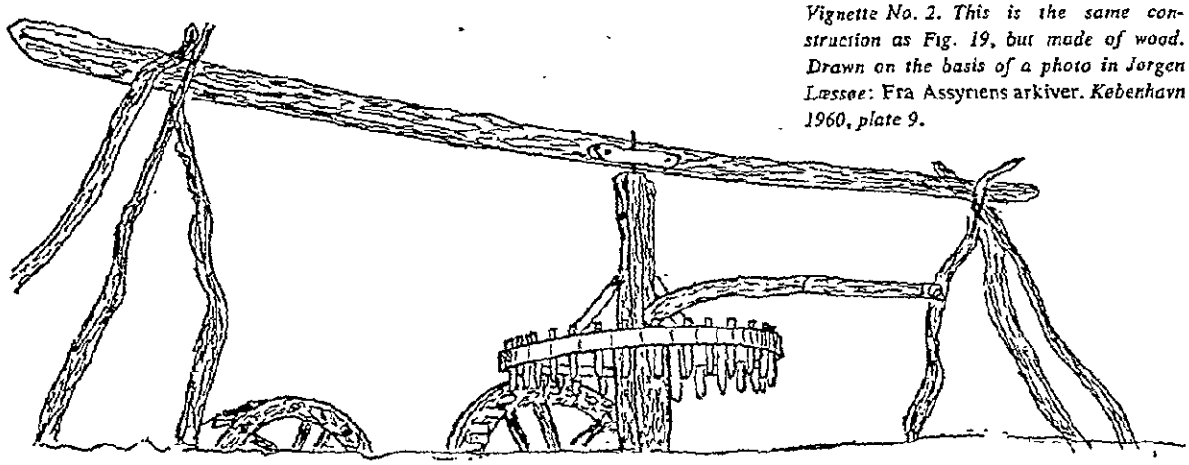
Mitwally, M. *Native Methods of working a Sakia in the Northern Province of the Egyptian Sudan.* [Bulletin of the Faculty of Arts, Vol. 13, part *II* (Cairo 1951), pp. 61–66].

Nicholls, W. *The Sakia in Dongola Province.* [Sudan Notes and Records, Vol. 1 (Khartoum 1918), p. 23].

Nicholson, H. A. *Saqia Terminology in Dongola.* [Sudan Notes and Records, Vol. 18, part 2 (Khartoum 1935), p. 314 ff].

Schäfer, Heinrich. *Nubische Texte im Dialekte der Kunūzi.* [Abhandlungen der Königliche Preußischen Akademie der Wissenschaften, Philologisch-historische Klasse nr. 5 (Berlin 1917), p. 107 ff].

Schiøler, Th. *Las norias ibicencas.* [Revista de dialectología y tradiciones populares, Vol. *XVIII* (Madrid 1962), pp. 480–486].



Vignette No. 2. This is the same construction as Fig. 19, but made of wood. Drawn on the basis of a photo in Jørgen Læssøe: Fra Assyriens arkiver. *København 1960, plate 9.*

REFERENCE NO. 8

SUMMARY AND CONCLUSIONS

Photovoltaic power possesses certain attractive features that suggest an important role in meeting the energy needs of less developed countries (LDCs). Such power is fuel-free, reliable, practically maintenance-free, clean, and quiet. Other investigators have examined use of solar cells in communications applications. This report focuses on the most important energy requirements of the rural third world: irrigation, potable water supply, and agricultural processing.

A survey is made of existing and ongoing studies of national energy systems, power sectors, and rural electrification in the LDCs. It is concluded that although much useful data are contained in these studies, the analyses themselves are of limited utility to assessment of the role of photovoltaic systems because of concentration on centralized systems of electricity, oil, gas, or coal supply and distribution. The demand side of the energy equation receives little attention in most cases; the Bangladesh Energy Study is an exception. As a partial consequence, the energy needs of the rural sectors are neglected.

In order to demonstrate the potential of solar cells in an important application, an irrigation project on the shores of Lake Chad that uses low-lift pumps has been selected as a favorable location for use of photovoltaic power; it is sunny, remote, and lacks good mechanical repair facilities. The analysis of the use of solar cells to replace diesel engines (or gasoline engines) builds on several previous studies of the project area, and therefore, contains the minimal amount of speculation about important irrigation parameters.

Solar arrays are sized to meet maximum pumping demand during the peak month of June in a cotton/wheat cropping system. "Surplus" panels pump water for a fodder crop and suggestions are made for other uses of these panels. Nevertheless, it is recognized that diesel pumps do have the capability of commanding a larger crop area than solar pumps because of their ability to run longer hours, which is taken into account in the comparisons.

The case study found that at the appropriate discount rate of 10 percent and at projected high diesel fuel cost of 35 U. S. cents per liter ($1.34/gallon U. S.) photovoltaic-powered pumping is competitive with the least-cost fossil-fuel alternative at a solar array cost of about $1300 per peak kilowatt (kw). This calculation does not attempt, however, to assess the value of the greater reliability or environmental neutrality of these solar devices. It furthermore does not include value of "surplus" solar arrays used during some months for agricultural processing, but does include pumping for additional fodder crops.

It is assumed in the case study that a minimal amount of battery storage is needed as a buffer between the array output and motor pump. DC motors are used. If batteries are not needed, and it is probable that this question can only be answered by field testing, the economics of photovoltaic power will improve considerably. (They would be competitive today at $1300 per peak kw exclusive of costs for transport and installation and inclusive of costs for support structures and wiring.)

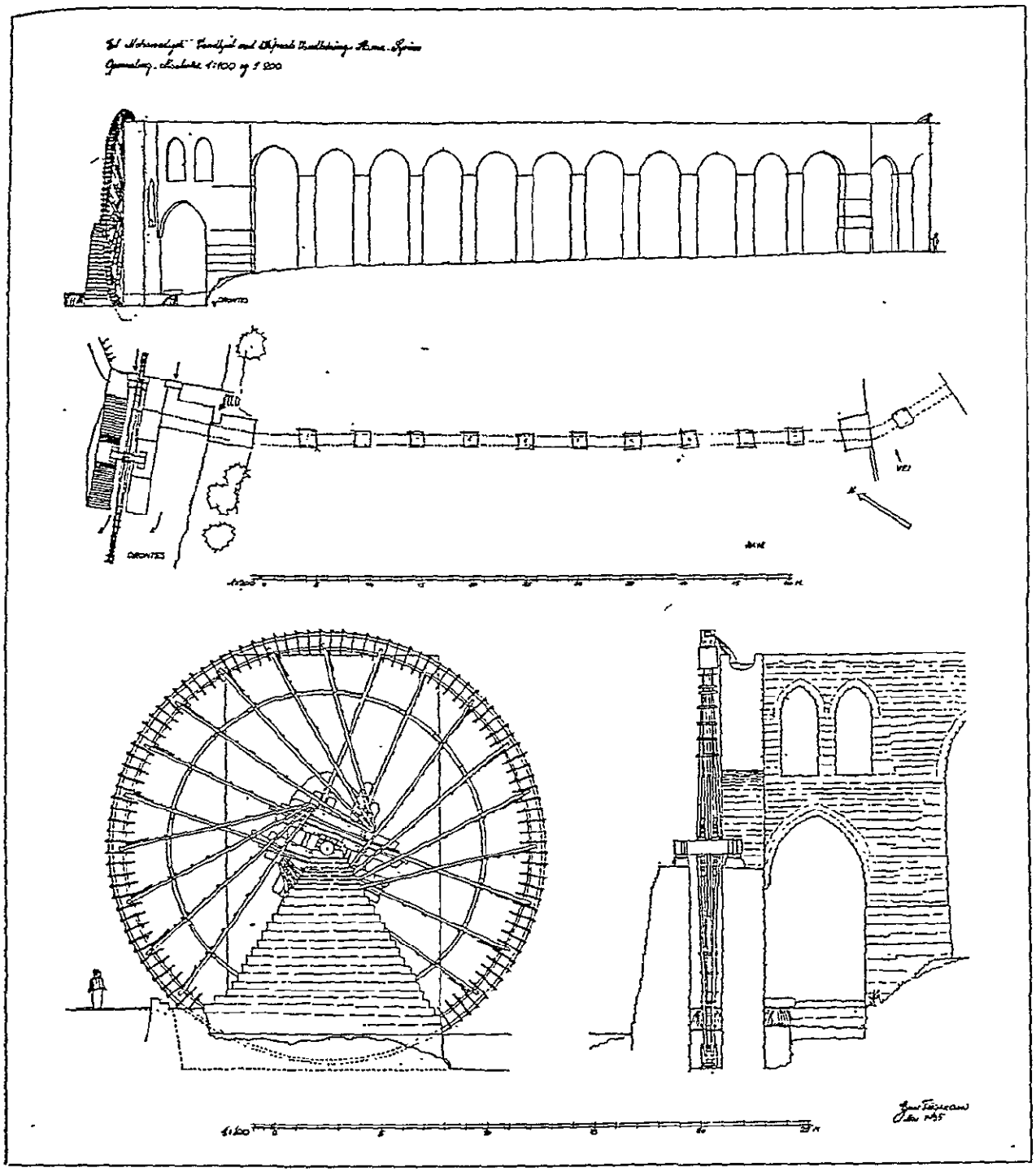
Several other irrigation cases were also examined in Bangladesh, India, and Pakistan. Each of these illustrated some of the factors affecting the relative attractiveness of photovoltaic power for irrigation pumping. The collection of case studies is believed to have laid the groundwork for a marketing study that would sum potential applications of each irrigation type over the LDCs of the world.

The irrigation case studies are followed by analyses of the economics of a photovoltaic-powered village in northern India. It is assumed that solar arrays are supplied in modules to fit growth in demand. Potable water supply, agricultural processing (illustrated by a 5-horsepower rice hulling machine), educational television, and a modest amount of village lighting are considered. In each case, and in cumulation, the costs of a photovoltaic system are compared with the costs of the least-cost alternative, which might be diesel or gasoline engine, diesel autogeneration, and connection to the grid.

In general, it is found that conclusions regarding photovoltaic power in an Indian village differ from conclusions regarding that same power in a Chad irrigation project, primarily because of the different diesel fuel prices that

are 30 percent lower in India. Again, the importance to the economics of photovoltaic power of power conditioning, including storage batteries, is highlighted.

REFERENCE NO. 9



8 *Fig. 1. One of the Great Wheels of Ḥamā in Syria. Scale drawing by Einar Fugmann 1935. The wheel is now (1969) in ruins.*

Introduction

1. Definition of the subject

The subject of this book is water-lifting machines built of wood, clay, stone and rope, in which one wheel, or more, forms a principal component of the structure. Despite the narrowness of the field, the subject is both vast and complex, and other limitations have proved necessary. For example, the type of wheel to which "The Great Wheels of Ḥamā" belong is only touched upon in brief. See Fig. 1.

2. Two problems

Two main problems are encountered in a study of the literature: firstly, there are hardly any good technical drawings of the various types of structures, and secondly, a historical research is made difficult by the high degree of uncertainty regarding the origin of the machines. These problems are very closely related, since a solution of the former is necessary for solution of the latter. The fact is that the terminology used in the historical sources is largely incomprehensible to us, and only an intimate knowledge of the structures themselves can help us to interpret the texts.

3. Sources

In order to attain the necessary intimate knowledge of these machines, we have to study them in the field, and this provides the opportunity of contacting the local carpenter – the only man who really knows the machine and the relevant terminology.

Unfortunately, many of the old water-lifting machines have either disappeared altogether or have been replaced by modern pumps, and in such cases, our studies have to be based on old engravings or photographs. These are usually a poor substitute because the pictorial quality is often so poor that one can hardly even determine the type of machine depicted. A picture in which it is impossible to distinguish between a bolthead and a knot in the wood is worthless to a serious student of the subject. The engravings in earlier literature are very beautiful, but the artists can hardly be accused of having paid too much attention to precision, so these works have to be approached with great caution.

For the recent history of these machines our best sources are travel books and topographical works. Our knowledge of mediaeval machinery is usually derived from illuminated manuscripts and books that have to

be regarded in the light of their author's purpose, which was to sketch new ideas rather than existing machinery. When we turn to Islamic manuscripts, the situation becomes even worse because the authors here were especially fascinated by the concept of perpetual motion and by the idea of a machine with a hidden mechanism. Fortunately, however, there are other sources that provide a more sober picture of the applications of such machines.

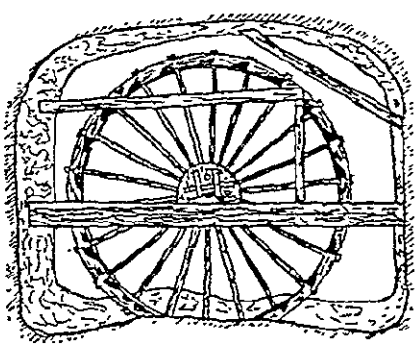
One extremely important source is the Greek papyri, which cover the period from *B.C.* 300 to *A.D.* 600. The greatest difficulty here is the interpretation of the terminology used, but a study of contemporary finds will doubtless help in the solution of this problem.

In the Roman and Islamic Empires there were a number of buildings where water-lifting machines formed part of the complex. From the few preserved for posterity it is possible to form a picture of the original structures from a study of the foundations.

The investigation of such ruins is greatly facilitated by bearing in mind the chapters in Vitruvius that deal with water-lifting contrivances, but it must be remembered that neither in Vitruvius nor elsewhere in the classical literature are there descriptions of a geared water-lifting machine.

Another extensive archaeological material is provided by the characteristic pots formerly used in paternóster wheels.

On the whole, our most valuable and reliable source of information is provided by classical archaeology. Thus, in Alexandria, there is a wonderful painting of a machine, which throws light not only on the history of water-lifting contrivances, but also on the history of technology itself.



See p. 39, Fig. 35.