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Design of a Cost Effective Solar Powered Water Pump

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by

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ABSTRACT

The design and performance of a vacuum lift, solar powered water pump is discussed. The basic design consists of an expanding gaseous piston confined inside a chamber which is located in series with, and between an inlet, and an outlet check valve. The gas is generated by volatilizing cyclopentane or hexane. Four variations of this basic design concept were built and evaluated. The various features of each are discussed.

Considerations in the choice of a cost-effective solar collector are also reviewed. Several of the more promising types of solar collectors were built and evaluated for use on the pump.

A 70°C heat source temperature is required to operate the pump if cyclopentane is used as the volatile fluid, 90°C is required if hexane is used. The volatile fluid is not expended in the pumping process.

The pumps constructed on this project have a capacity of approximately 6 liters/minute when pumped to a height of 2 meters. Two square meters of sunshine are sufficient to operate the pump.

ACKNOWLEDGMENTS

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INTRODUCTION

Where topography permits, irrigation water is obtained by diverting river flow to farm land through gravity-flow distribution systems. In many of the world's richer agricultural areas, particularly in the more developed countries, large volumes of irrigation water are pumped for irrigation use. Unfortunately, a very large percentage of the subsistence farmers in the less developed countries live where they cannot obtain even the relatively small amounts of water needed to irrigate their small plots of ground without pumping. Many of these people live in geologically old, flat, low-lying valleys that have fertile soil and ground or river water only a few feet below their fields. They cannot afford sophisticated pumping equipment and rely on animal or even human power to lift the relatively small volume of water required for their little plot to field level (Figure 1).

Because of this widespread situation, a simple mechanism having a low initial cost and not requiring costly fuel would be of great benefit to mankind. Solar powered water pumps offer considerable potential for meeting this need. Specifically, 1) technologically unsophisticated systems can be built from low-cost, locally available materials, 2) both solar energy collection and its use in pumping can be reliable and trouble free, 3) the solar energy itself is free and nonexpendable, 4) solar energy is most readily available in countries where low-lift pumping is most needed, and 5) irrigation water requirements are greatest when sunshine is most readily available. This report describes an attempt to develop a technically feasible solar powered water pump design to meet this need.

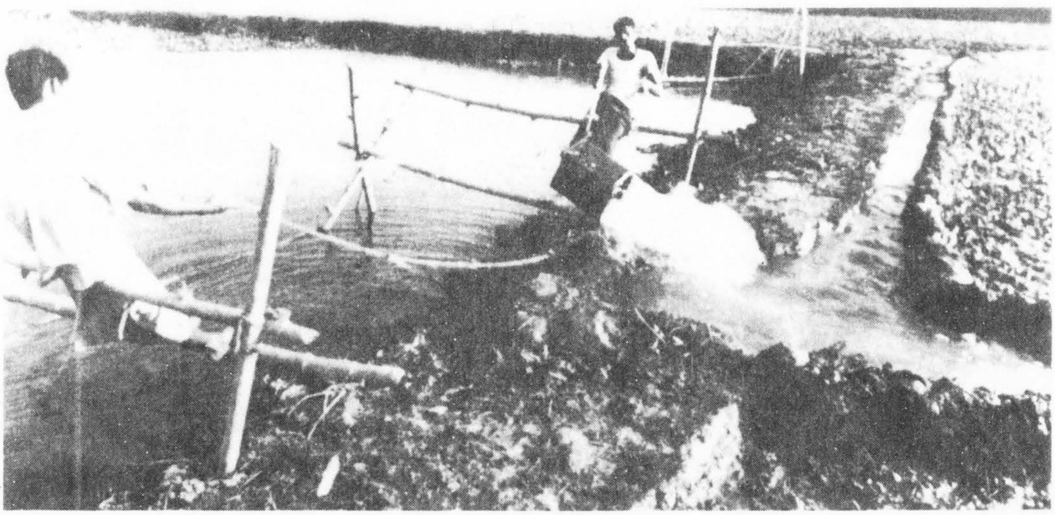

Figure 1. Primitive water pumping methods in Bangladesh. (Courtesy of "Environment.")

BASIC DESIGN CONCEPT

The amount of solar energy impinging on 6 square meters of surface area per day has the heating equivalent to 1 gallon of gasoline. An area of approximately 18 m x 18 m has solar heat energy impinging on it each day equivalent to the energy in a 50 gallon drum of gasoline. Clearly, if a small fraction of this energy could be harnessed to do mechanical work such as pumping water, great benefits could accrue. Low solar energy transfer efficiency obtained in pumping water should not be a great deterrent to the use of a solar powered system, since the energy itself is free. The obvious advantage of greater energy transfer efficiency lies in making a smaller and less costly collector possible. If the total system, the collector and the pump, can be made inexpensive and reliable, solar powered water pumping can supply a very important need.

The energy for the pump would come from solar heat, and heat engines are both very old in concept and very slow in development. The Stirling engine, for example, which operates on heated air was invented in 1816, used in India generations ago, and is still being researched extensively. Ford Motor Company recently received a 100 million dollar grant from the federal government for further research and development of the Stirling heat engine. Likewise, low-lift condensing gas pumps have been known for a long time. None of these designs have succeeded, however, to the point of coming into general use in situations in which low-cost pumping of small volumes of water at low heads is required. Thus research is aimed at overcoming the deficiencies which have limited use of the earlier pump designs and in particular at simplifying and more nearly reducing to practice the utilization of a low-head solar-powered water pump. While the system is not developed here to the point of becoming operationally satisfactory, progress was made towards the design of a practical double-check-valve solar-powered water pump.

The original concept of a double-check-valve condensable-vapor vacuum water-lift pump was patented in 1698 by Thomas Savery of England (Thurston 1891), to pump water out of coal mines. It was never very successful, however. In subsequent years the piston-type Newcomen steam engine, invented in 1712, replaced the Savery engine. The superior efficiency of the Newcomen engines caused the Savery concept to lie virtually forgotten until recent times.

A solar-powered, steam engine-driven water pump of appreciable size was developed by Shuman and Boys in 1911 for installation in Cairo, Egypt. Because of technical difficulties and high system cost, the solar pump could not compete with cheap fossil fuels and the gasoline or diesel engines, which were being rapidly developed at that time. As internal combustion engine development was spurred by automobile engine/transportation research, the enthusiasm for solar-powered water pumps waned, and the subject again was forgotten.

Now, in recent years, interest has been reawakened in solar energy and its potential for pumping water. Several factors have caused this, including the scarcity and cost of other energy sources, and the need to increase agricultural production in less developed countries that have an abundance of water but little gravity flow irrigation potential.

THEORY OF OPERATION

Several forms of the double-check-valve type pump were conceived, built, and evaluated before and during the course of this project. The double-check-valve configuration had been the subject of numerous earlier patents (U.S. Patent 2, 757, 618, etc.). Each of these patents disclosed pumps too complicated and costly for the efficiency they possess. Being aware of these past failures, the effort in this project was expended in trying to design a system that is reliable, simple to operate, and as inexpensive as possible.

The system requires both a solar collector and a pump. Several types of solar energy collectors were built and evaluated. As the search for a suitable solar energy collector proceeded, it became apparent that the cost of the collector system may greatly exceed the cost of the pump itself. A discussion of solar collector problems and recommendations for overcoming them is reported later under the heading of "Solar Collectors."

The theory behind the double-check-valve condensation pump as invented by Savery is illustrated in Figure 2. Steam is generated in boiler A and allowed to flow past valve B into chamber C filled with water. Valve D is closed by pressure of the water column and applied pressure from tank C. Consequently water cannot flow downward through D, but must instead flow past valve E which readily opens under the pressure supplied by the steam. Water is thus free to travel up pipe F where it is discharged through opening G. After C is nearly empty of water, valve B is closed and steam condensation takes place creating a vacuum in C. Atmospheric pressure at H is able to then push water up past check valve D, refilling tank C, whereupon the cycle is completed; the next cycle may be repeated as soon as adequate steam is available, and the condensation is completed.

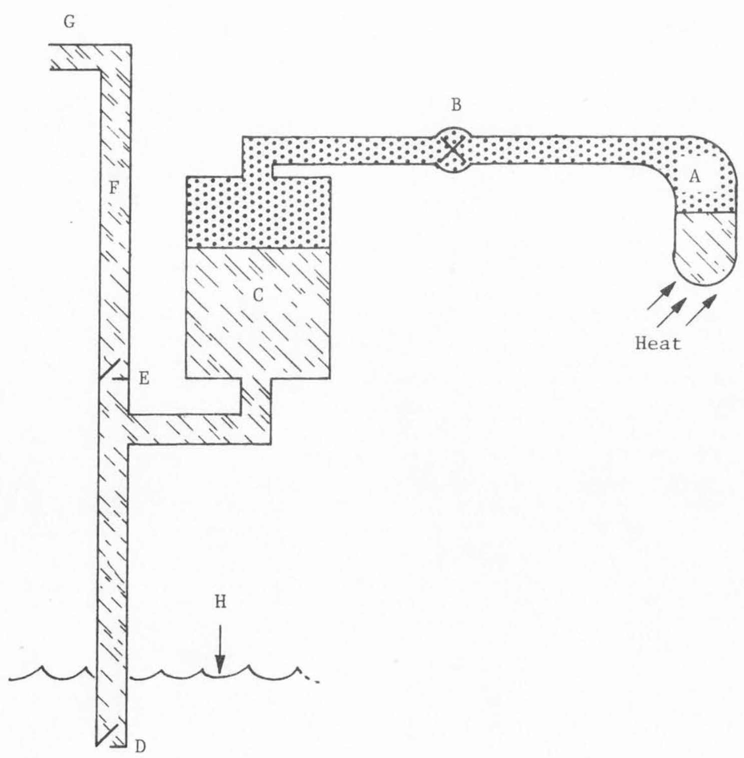

Figure 2. Thomas Savery "fire engine."

The primary disadvantages of the Savery-type pump illustrated in Figure 2 are 1) eventually boiler A will boil dry, 2) no provision is made for the automatic operation of the steam valve B, 3) air released from the water by boiling is trapped in the top of the chamber causing the system to shut down, and 4) steam temperatures of 110° to 150°C are required. This temperature range, while not very high for many types of solar collectors, is beyond the efficient operating limits for low technology, inexpensive flat plate solar collectors.

The maximum output achieved with the Savery engine was about 1.85 x 10^{-5} Joules of energy per kilogram of coal burned. This calculates to be an efficiency of 0.6 percent (Thurston 1891). Considering the relatively high temperatures available in burning coal, 0.6 percent efficiency is very small and far below the theoretical Carnot efficiency. On the other hand, the Savery double-check-valve pump has strength in its basic simplicity. Since solar power is free in that one does not have to worry about escalating fossil fuel cost, the cost of the pump is of greater concern than the cost of fuel. A simple design has a major advantage. Furthermore, new thermodynamic liquids and construction materials are becoming available to improve solar-pumping performance. The feasibility of solar pumping in this changing situation needs to be reevaluated.

Selection of a Volatile Liquid

In many ways, the water-steam cycle is the ideal pumping liquid. Water is readily available at little if any cost and nontoxic. The disadvantage is that the use of solar energy to boil water requires concentrating collectors to deliver the necessary heat for rapid vaporization and that other liquids are intrinsically more efficient in the vaporization-expansion process.

Several factors need to be considered in selecting the volatile liquid to be used for operating the pump. For best efficiency, the liquid should have low heat of vaporization, low molecular weight, and be insoluble in water. It should also be chemically stable, have a boiling point in the range of 50-80°C, achievable with low cost solar collectors, be inexpensive, be readily available worldwide, and be noncorrosive and nontoxic. No one liquid is ideal in all these respects. An extensive search was made, basic properties of several of the more promising thermodynamic liquids are listed in Table 1.

The fluid ultimately judged best for many pumping situations was the hydrocarbon, cyclopentane, C_5H_{10}. Cyclopentane is available in large quantities from oil refineries at nominal cost. It can also be purchased in small quantities from chemical supply houses. As seen from Table 1, hexane may also be considered as a viable choice for higher lift situations where 85°C boiler temperatures are needed to obtain rapid vaporization.

Solar Powered Water Pump--Model I[1]

The first double-check-valve pump developed at USU is illustrated in Figure 3.

[1]The model number designations I, II, III, and IV are given to indicate chronologic development. Correlation of model numbers with performance ranking is not implied.

Table 1. Characteristics of various thermodynamic liquids considered for use in a solar powered pump.[a]

Liquid	Chemical Formula	Boiling Point °C	Heat of Vaporization cal/gm	Solubility in Water	Molecular Weight	Volume @ Std. Pressure cm^3/gm	Cost Per Liter (Approx.)	Comments
Cyclo-pentane	C_5H_{10}	49.3	97	Insoluble	70	375	$0.40	Flammable chemically stable
Hexane	C_6H_{14}	68	79.3	Insoluble	86	340	$0.40	Flammable chemically stable
Water	H_2O	100	539	Soluble	18	1623	0	Harmless chemically stable
2-Methyl butane	C_5H_{12}	27.9	80	Insoluble	72.2	343	$0.40	Too low a B.P. for warm climates or high vacuum lifts

[a]Other well known thermodynamic liquids such as the R113, etc., fluorocarbon series, methyl chloride, carbon tetrachloride, alcohols, carbon disulfide, etc., are unsuited because of boiling point, solubility, corrosive nature, etc.

The pump consists of two closed, outer metal cylinders 1 and 2; an inner closed cylindrical float 3; an inner open ended cylinder 4; interconnecting pipes 5, 6, 7, 8; check valves 9 and 10; and a heating coil 11. Its principle of operation is as follows:

Heat is applied through a copper pipe 11 that is externally coiled around cylindrical tank 2 and warms a thin column of liquid lying between the inside wall of container 2 and an almost submerged cylindrical float 3. As this thin liquid column volatilizes in a matter of 15-20 seconds, float 3 is forced downward by vapor accumulating in the top of container 2. The vapor-liquid interface at 12 drops also since hydrostatically the liquid level in pipe 5 cannot be higher than the liquid in cylinder 2.

As the floating piston 3 moves downward, cyclopentane flows rapidly out of the chamber through pipe 6, up the outer wall between containers 1 and 4 and over the open upper end of container 4, pushing water ahead of it. Since water is more dense, it cannot rise out of the lower portion of cylinder 4. Rather, the water in 4, under pressure due to the expanding gas in 2, as explained above, is forced past check valve 10 and out into pipe 8, and discharged at 13.

Eventually the liquid in container 2 and in pipe 5 drops low enough so that the vapor trapped in pipe 5 can escape upward into the top of chamber 1 blowing the liquid out of region 14 almost instantly. This action ends the expansion portion of the pumping cycle. With pipe 5 now clear of liquid, the vapor trapped in container 2 flows rapidly through pipe 5 and condenses into the cold liquid in container 1. As the vapor condenses, atmospheric pressure on the body of water at 15 forces the water upward past check valve 9 back into chamber 4. The cyclopentane returns to chamber 2 and area 14 of pipe 5, replacing the void caused by the escaping vapor which was condensed in the top of container 1. As float 3 rises, the liquid column lying between it and the cylinder walls of 2 are quickly reheated and the expansion phase of the pumping cycle starts over again.

Heat is applied to cylinder 2 in the manner illustrated in Figure 4. Cyclopentane is used to fill the s-shaped heating tube which is soldered to a flat, 20-gage piece of

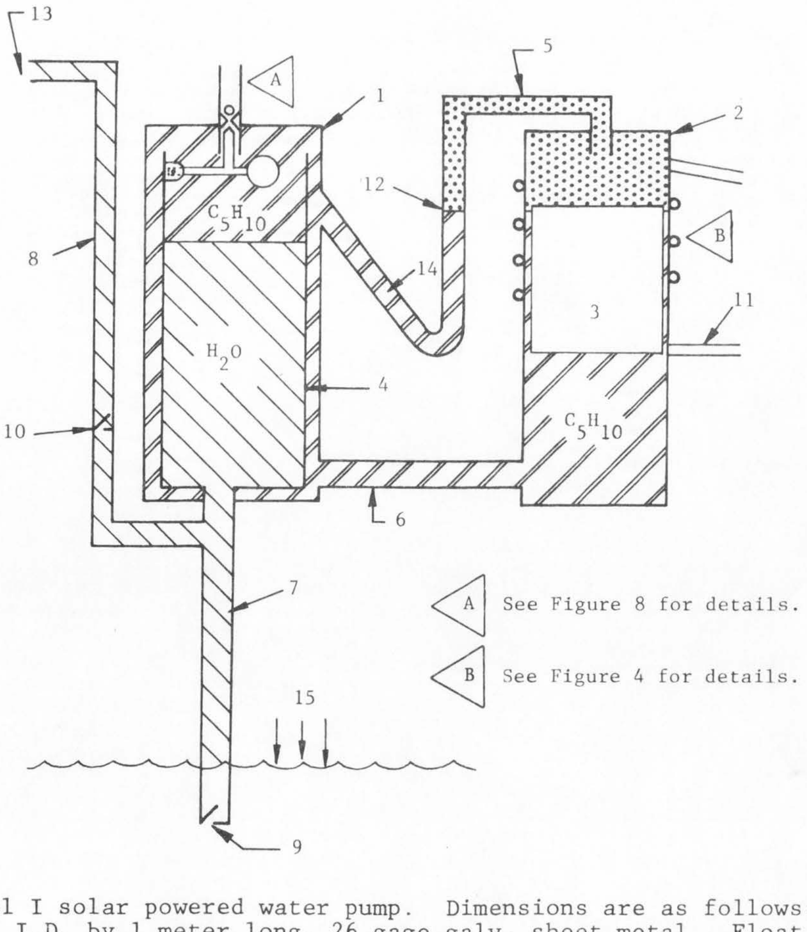

Figure 3. USU Model I solar powered water pump. Dimensions are as follows: Tanks 1, 2 - 20 cm dia. I.D. by 1 meter long, 26 gage galv. sheet metal. Float 3 is 19.5 cm dia. O.D. x 33 cm long, 20 gage galv. sheet metal. Tank 4 is 17 cm dia. x 90 cm long. Pipes 6 and 7, 1¼ in. galv.; Pipe 5, 1 in. galv.

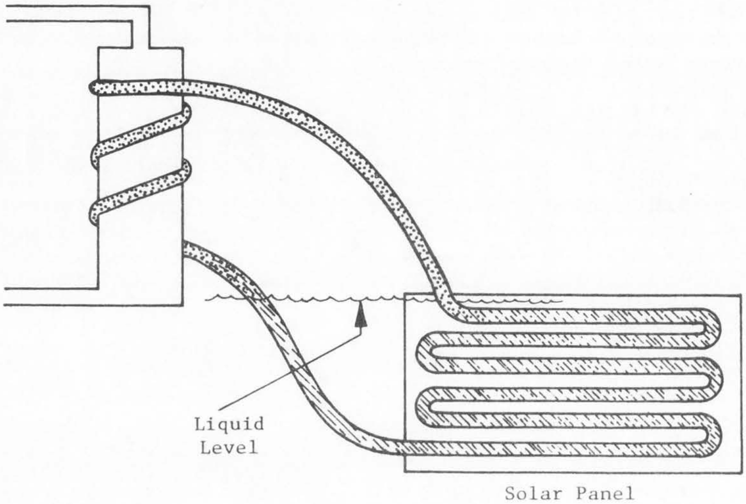

Figure 4. Sketch of a solar panel and heat transfer coil for Model I pump.

sheet metal.[2] The cyclopentane in the solar panel boils readily at achievable flat plate temperatures. As it vaporizes it flows freely to the condensing coil wrapped around the pump. Since the pump is cooler than the heat source, the vapor condenses giving up its latent heat of condensation. This warms cylinder 2 sufficiently (65-70°C) to operate the pump. The condensed liquid can then flow by gravity back to the heating coil via the lower return flow tube where it is heated as it gradually rises in the coil and is again vaporized. Cyclopentane in the solar panel coil can be recycled in this manner indefinitely without the aid of any mechanical pumping mechanism.

The Model I pump just described has the following operating characteristics. The input heat rate is 5 k-calories per minute at a temperature of 62-65°C. The cycle time is approximately 35 seconds and it pumps 7 liters of water each cycle to a test height of 2.1 meters.

From these data the efficiency of the pump can be calculated. The rate of output work is:

$$\left(\frac{7\ \ell}{\text{cycle}}\right)\left(\frac{1\ \text{kg}}{\ell}\right)\left(2.1\ \text{m}\right)\left(\frac{9.807\ \text{Joules}}{\text{m-kg}}\right)$$

$$= 144\ \frac{\text{Joules}}{\text{cycle}} \quad \left(\frac{106\ \text{ft}\ \#}{\text{cycle}}\right)$$

The rate of input work is:

$$\frac{(2917\ \text{g-calories})}{\text{cycle}} \times \frac{(4.186\ \text{Joules})}{\text{g-cal.}} = \frac{12{,}200\ \text{Joules}}{\text{cycle}}$$

The percent efficiency is:

$$\frac{\text{output work}}{\text{input work}} \times 100\% = \frac{144\ \text{Joules/cycle}}{12{,}200\ \text{Joules/cycle}} \times 100$$

$$= 1.18\%$$ [3]

Compared to modern engine efficiencies, a 1 percent efficiency is very low. However, if the low capital and operating costs of the 1 percent efficient engine are considered in comparison with capital costs, pumping efficiencies, and high energy costs for conventional pumping mechanisms, the feasibility of using a solar powered water pump is enhanced. In an 8 hour day, for example, the work accomplished by the small pump amounts to about 120 kilojoules. If it were scaled up in size by a factor of 10, the output would be approximately 60 cubic meters of water raised 2 meters in height.

As part of the pump cycle operates on a vacuum lift principle, the theoretical maximum lift possible due to the vacuum phase of the cycle is of interest. The maximum height that water can be raised by vacuum is limited by the vapor pressure of the volatile pumping liquid used in the pump which varies as a function of temperature in a manner shown in Figure 5. From these vapor pressure data, the maximum heights that water can be raised are calculated, and illustrated in Figure 6, for temperatures ranging between 0 and 100°C.

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[2] Structural details of the flat plate collector are discussed along with alternate forms of collectors later in the report.

[3] This efficiency is calculated using 5000 g-calories/minute delivered to the pump. It does not include the collection efficiency of the solar panel discussed later.

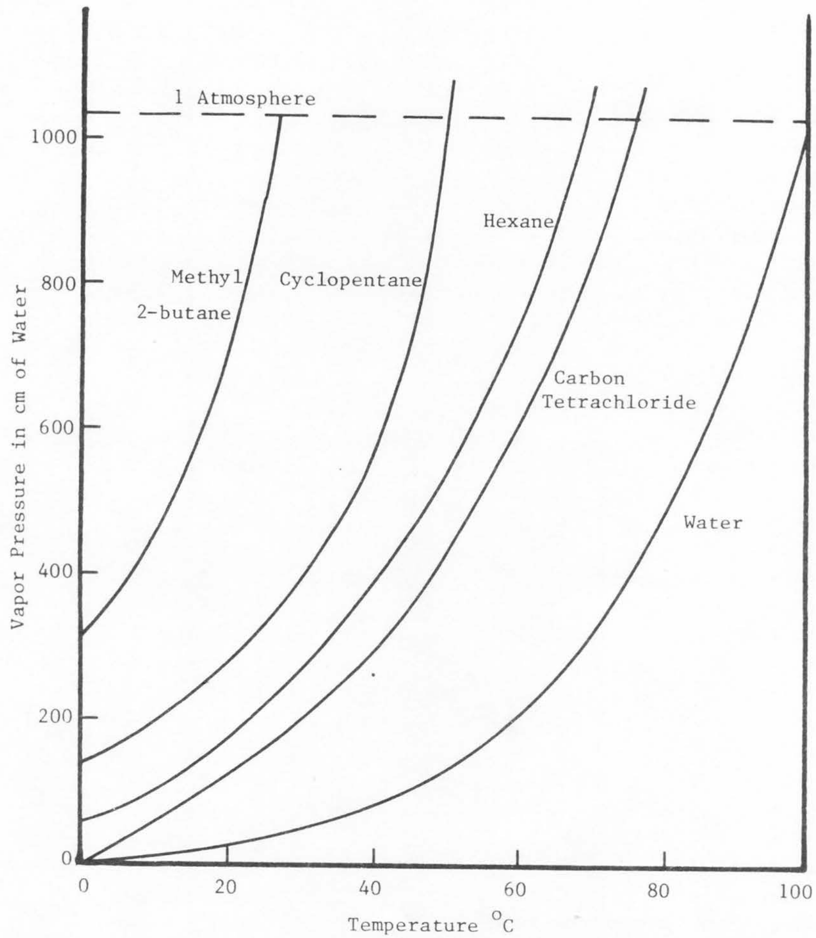


Figure 5. Vaporization curves for various thermodynamic liquids (Shortly and Williams 1961).

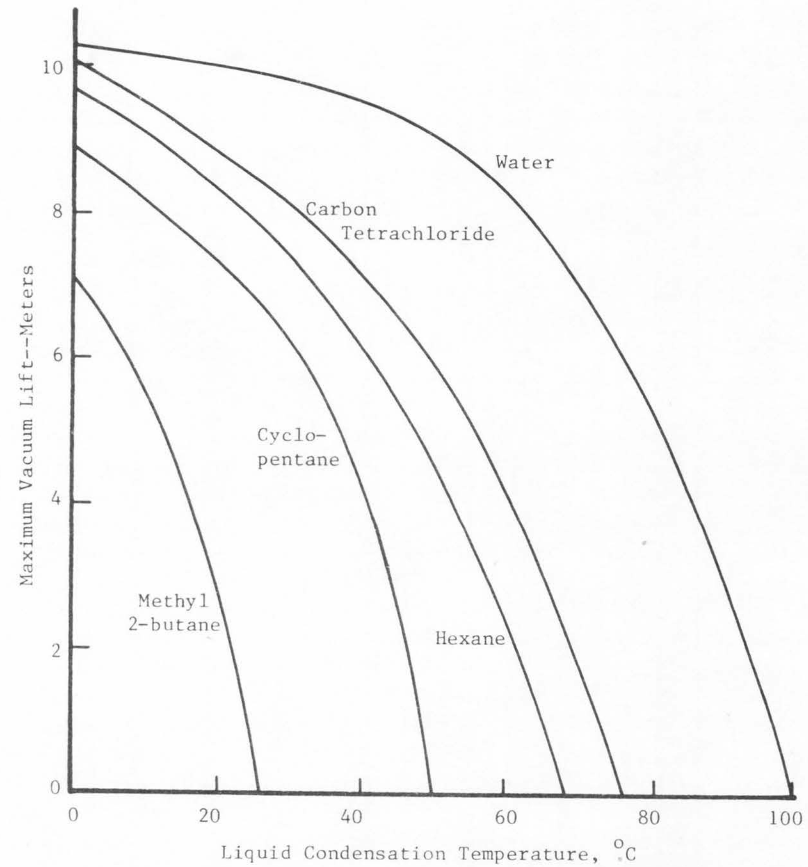


Figure 6. Maximum vacuum lift possible plotted as a function of the liquid condensation temperature.

In addition to the vacuum phase of the lift, the water can be pushed to greater heights by the pressure, or discharge, phase of the pumping cycle. The practical limits to this phase of the pump cycle are determined by the temperature of the boiler. As seen in Figure 7 higher lifts are only made possible by using higher boiler temperatures.

The Model I pump was considered successful in that it reliably pumps water in an unattended manner at an acceptable efficiency using a low temperature energy source. There are several problems, however, that should be discussed. Some of the problems can be solved by building the unit with more precision than was used for the prototype. The tanks and float were made of galvanized sheet iron. All seams were soldered. Soldered seams were determined to be quite unreliable and cracks or pinhole leaks frequently occurred. Another problem concerned the float. The 33 cm long float in cylinder 2 was designed to have only 10 percent of its length above the liquid level. Considerable ballast is required in the float to keep it floating in this almost submerged manner. With this adverse buoyancy to mass ratio, the float would sometimes catch on wall roughness and hang-up. Any such hang-up will abort the pump's normal operation. This tendency to hang-up is aggravated by a chemical reaction that takes place between the zinc plated sheet metal cylinder and float, and the cyclopentane. A white residue (probably zinc oxide) formed on the galvanized surfaces that were in contact with the cyclopentane. This residue builds up until the smooth gliding surfaces between the float and the cylinder walls ultimately stop the float action. An obvious remedy to this problem is to use a teflon coated cylinder wall, or construct the pump from injected plastic or perhaps use an aluminum instead of a galvanized iron cylinder, etc.

Another problem this pump has is its tendency to vapor lock. If too much heat is applied to the system, it ceases operation. This is caused when the heat transfer into the thin liquid column is too great, and too much vapor is generated before the floating piston can return to its top-most position. This tends to shorten the pumping cycle and thereby reduce the amount of water pumped. If the heat supply is increased still further, the piston will not rise at all. The

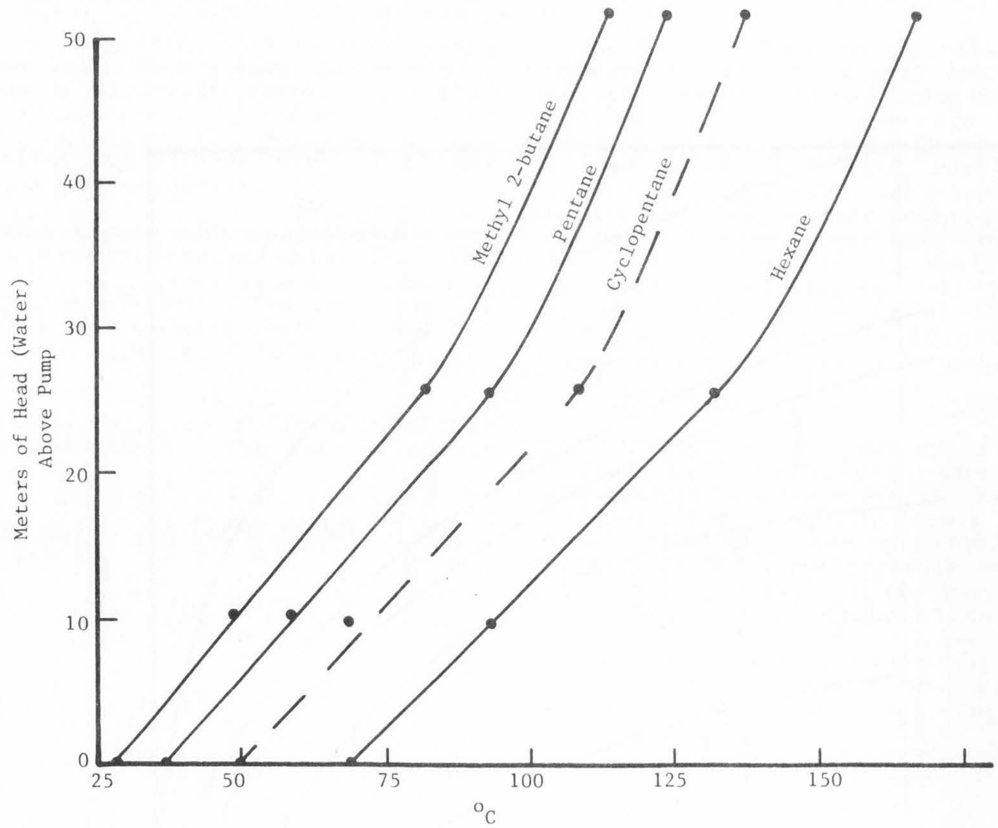


Figure 7. Relationship of pumping head plotted as a function of vapor temperature. These data illustrate the ability of the pump to lift water above the pump. (Data taken from Handbook of Chem. & Physics.)

system will generate a steady-state vapor at the condensation rate and cause the cyclic operation to cease.

During the operation of the pump it was noted that small quantities of air accumulated at the top of the condensation chamber in cylinder 1. This is probably due to air leaks in the cylinder, and a slight out gasing of dissolved air in the water. The gradual accumulation of air is detrimental to the pump's performance so a check valve was connected in series with an air release valve at the top of cyclinder 1, as shown in Figure 8. Air can escape on the pressure or discharge portion of the cycle when the float buoyancy is lost due to an air bubble which allows the float valve to open. Air can pass through the open float valve forcing the check valve to open. On the vacuum phase of the cycle, the check valve in series with the float valve, blocks any return air flow. This venting technique works well but it adds some to the system complexity and cost.

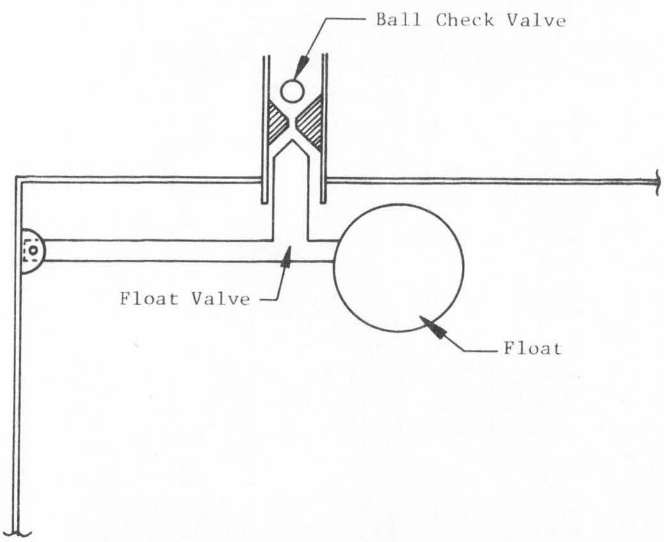


Figure 8. Air release valve in series with a ball check valve used for venting unwanted air accumulation.

Model II Solar Powered Water Pump

In an effort to overcome some of the complexities associated with the Model I pump just described, a second configuration was designed which would trade operating efficiency for simplicity of construction and reliability of operation. This design is illustrated in Figures 9 and 10. The operation of the pump is described as follows.

Distilled water or a volatile liquid is heated via solar energy in boiler 1. The resulting steam or other gaseous vapor builds up the pressure in the boiler until it suddenly blows a pressure release valve open, 2, that is connected to the boiler by pipe 3. This sudden opening of the valve is enhanced by a positive feedback arrangement which gives a snap action to the opening of valve 2. A more detailed explanation of valve 2 is discussed in Appendix A. When the valve opens, steam escapes up through pipes 4 and 5 into an inflatable bladder 6. As this bladder rapidly expands due to the sudden inflow of steam, it displaces the water in container 7. The only place the displaced water can go is up through check valve 8 into chamber 9 where it can then flow out through pipe 10. After bladder 6 is extended, the steam pressure in the boiler drops to about 6.89 kPa (1) psi as the heat in the boiler becomes expended. This pressure is not sufficient to maintain valve 2 open and the valve closes cutting off any further steam flow.

Condensation in flexible bladder 6 occurs by a heat transfer process across the bladder walls from the steam to the cool water surrounding it. As this process continues the pressure in tank 7 is greatly reduced below ambient atmospheric pressure drawing check valve 8 tightly shut. At this point atmospheric pressure is sufficient to force check valve 11 open and cause water to enter inlet pipe 12 to replace the water displaced from chamber 7. This action completes the pumping cycle.

Condensation from the bladder is drained off through pipe 13 where it collects in a vertical column. The condensate is unable to return into the boiler because check valve 14 is held closed by steam pressure from the boiler. When the column height is sufficient, however, e.g., about 1 meter, enough static pressure is built up to open check valve 14 and the condensate can then drain back into the boiler. This return flow occurs at the end of each pumping cycle when the pressure in the boiler reaches its lowest point of about 1 psi. Thus the boiler liquid is completely recyclable and can run indefinitely without being expended.

Pumping efficiencies of the Model II pump are not as good as those in the Model I pump. This is due to the requirement that the same place had to be heated and cooled. The Model I pump had a cold place and a separate warm place which is intrinsically a more efficient design. There are some nice features to the Model II pump, however. The inherent simplicity of the Model II pump is an improvement over the more complex arrangement of the earlier pump configuration which required 3 cylinders instead of one. The system is not troubled by air locks. Any air drawn in through the inlet valve or leaks within the main tank causes very little problem since the system will discharge any air that accumulates up through the check valve into the atmosphere each cycle. Thus no gradual air accumulation occurs so no float valve-check valve combination is

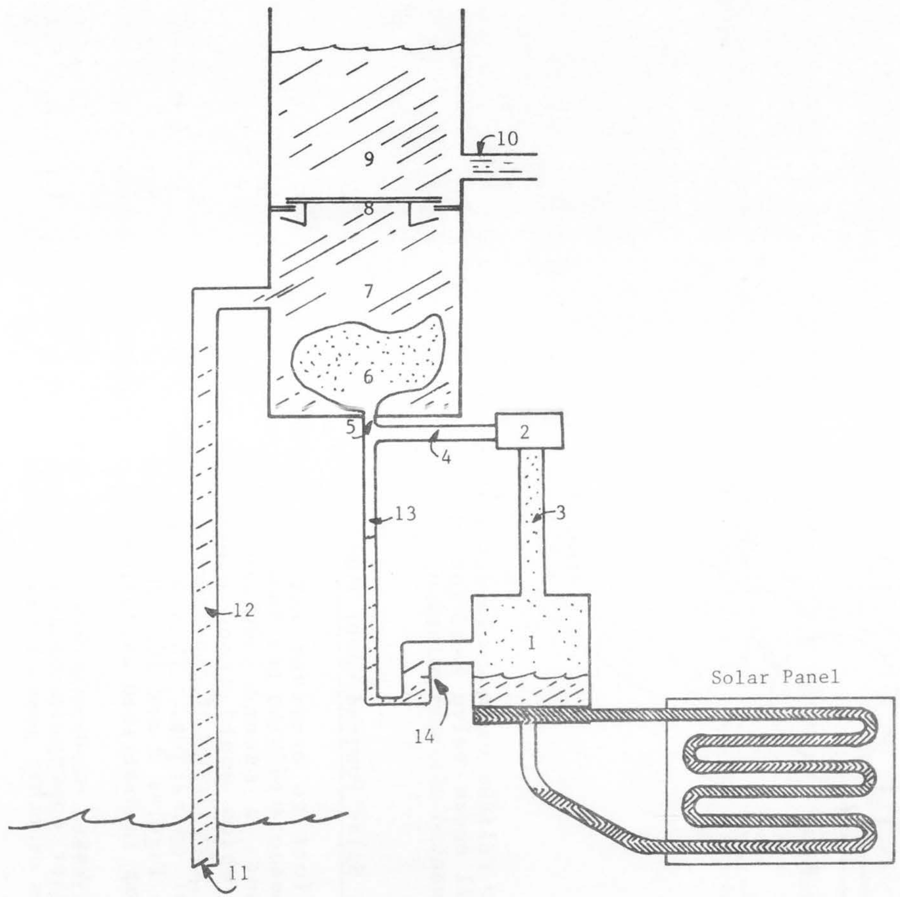


Figure 9. Diagram of Model II solar powered water pump.

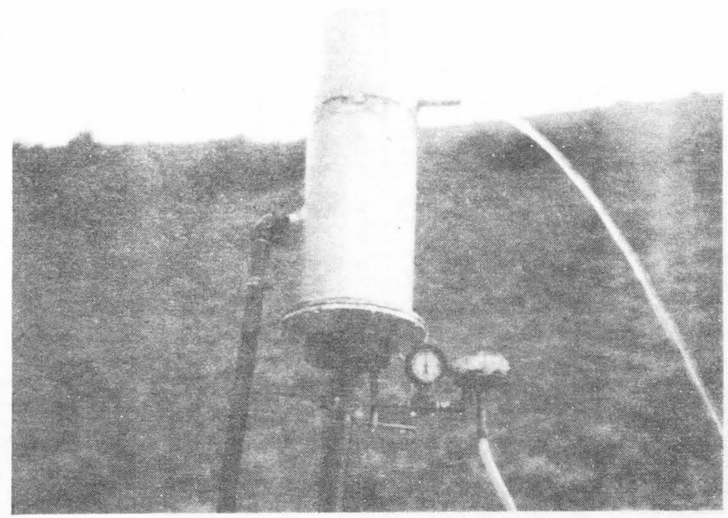


Figure 10. Picture of the Model II pump.

required. Also the system is not bothered by overheating and no vapor locks occur. Whenever sufficient thermal energy is accumulated the valve opens and the pumping cycle is initiated. In this manner it can pace itself according to the heat available. The only requirement on cycle time is that the condensation cycle should be completed before the expansion cycle begins. This is assured by adjusting the available heat to be commensurate with the condensation time. Condensation time is a function of the latent heat of condensation of the vapor, the thermal conductivity of the diaphram, and the water temperature in the container.

The pump illustrated in Figures 9 and 10 was constructed from a piece of 20 cm diameter x 76 cm long aluminum pipe. Considerable difficulty was encountered in finding a suitable expandable bladder. Hydrocarbons have a deleterious effect on virtually all natural and synthetic elastomers. The notable exceptions were TFE and FEP teflon in the plastic family and viton in the elastomers. Teflon is not easy to form or bond and viton is quite expensive, i.e., $74 per square meter. For testing purposes two special bladders were purchased which cost more than the projected cost of the entire pump. These bladders proved to be faulty in construction, and as a consequence a suitable bladder was improvised, from three butyl rubber punching bag bladders. The bladders were placed one inside the other in order to get the necessary thickness to give a condensation rate that would permit 2-3 cycles per minute. Since butyl rubber absorbs cyclopentane, hexane, etc., water was substituted for the volatile liquid. The total cost of the three bladders direct from the manufacturers was $3. They were used on an intermittent basis using steam as the condensing liquid for a period of several months without failure or sign of aging.

The notable disadvantage of the system as described and tested was that flat plate collectors are not efficient for heating water to 110°C which is a requirement if water is to be used as the volatile liquid and the pump is to be operated at sea level. This problem can be overcome, however, if a nonfocusing east-west oriented compound trapezoidal trough or parabolic concentrator (CPC) is used. The trapezoidal trough is discussed later in this report. Other types of concentrating collector configurations which may also be used are also discussed in the section on Solar Collectors.

Two problems in the Model II pump that were observed should be noted: 1) The condensate must build up a static head of about 1 meter before it can overcome the internal boiler pressure at its lowest point in the pressure cycle. This requires that the pump be located about 1.2 meters higher than the heat source. In some situations this is of little consequence; in other conceivable situations it is a disadvantage. 2) The valve which turns the steam on and off was not commercially available. As a result, an attempt was made to design and build a special valve for the pump. It worked with limited success. The configuration illustrated in Appendix A functioned well in the turn-on phase. The turn-off portion of the cycle was unsatisfactory. It functioned well on the bench when no appreciable back pressure was applied to the discharge side but when connected in the system it tended to be erratic in the shut-down mode.

Several techniques were explored to correct the steam valve function. Shut-off problems were aggravated by the fact that the spring has the weakest restoring force where the spring is fully extended at the crucial shut-off position. Obviously a more secure shut-off could be effected using a magnet which would aid the shut-off process, having an ever increasing magnitude in pulling force as the magnet face, and shut-off position, is approached. Another alternative is to use a negator-type spring which has linear restoring force regardless of the spring position. One form of the magnet approach was used with some success. Instead of placing the magnet near the valve shut-off point, however, a magnet was placed in such a position that it would latch the valve open. Using the magnet in this fashion retarded the shut-off pressure beyond the normal shut-off time. The shut-off didn't occur until the restoring spring was able to not only override the back pressure but the magnetic pull as well. Once the magnetic pull was overcome it had sufficient extra spring force to force the valve shut. This approach, though not as effective as a magnet at the close-off point, improved the valve's performance, but its operation was still not considered adequately reliable. Although the problem was annoying, it is tractable and there is no basic reason why it cannot be solved in the manner outlined, provided more care is taken in construction and closer tolerances are maintained in the machining of the valve components.

Problems encountered in the pressure relief valve, although not serious, prompted another configuration which terminated further work on the Model II pump.

Model III Solar Powered Water Pump

The Model III pump configuration was designed to eliminate the pressure valve. The embodiment of the concept is illustrated in Figure 11. The operation of the pump can be described as follows.

A gaseous vapor exists in gas chamber 1 which is interconnected with chamber 2 by an interconnecting pipe 3. The condensating temperature of the gas is at a considerably higher temperature than is the water which is above the diaphram 4 in the area labeled 5. Because of the cool water in 5, heat will flow through the diaphram into the water causing the vapor below the diaphram to

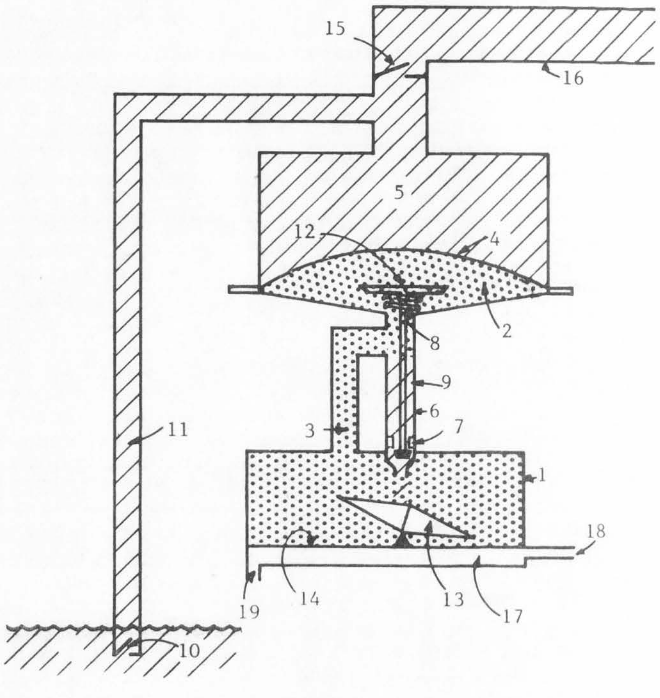


Figure 11. Cross-sectional view of Model III solar powered water pump.

condense. As condensation occurs, the condensate will form in droplets and run down the inclined plane and collect in column 6. It cannot escape through the bottom of the column since the pipe is closed at the end by valve 7 which is held shut due to an upward force exerted by spring 8 through an interconnecting rod, 9.

As condensation takes place the pressure in chamber 1 drops well below the atmospheric pressure. This low pressure area thus created, permits atmospheric pressure to push water past check valve 10, up through inlet pipe 11 and into chamber 5 and diaphram 4 moves downward. As the diaphram drops it comes in contact with the pressure plate 12, and due to the differential pressure between chambers 5 and 2, a force is applied to the pressure plate causing valve 7 to open. At this point, the condensate which accumulates in 6 suddenly flows down into the tipping bucket 13. When about 40 cc have flowed into the bucket the center of gravity of the bucket has moved far enough to the left to cause the bucket to tip, discharging its contents suddenly on the hot evaporation plate 14. The volatile liquid suddenly dumped on the hot surface 14 is evaporated in 3 to 4 seconds time. The resulting hot gas rushes up tube 3 into chamber 2 extending the diaphram upward which pushes accumulated water in tank 5 past check valve 15 and out the discharge pipe 16. As the diaphram is lifted upward, spring 8 restores valve 7 to the closed position and condensate in 6 again begins to collect, thus the cycle is completed.

The advantage of this configuration is that when a measured amount of liquid is completely vaporized the vapor source is automatically expended. Thus no potentially troublesome vapor pressure shut-off valve is required.

A prototype Model III pump was built and is shown in Figure 12. Both cyclopentane and hexane were used as the volatile pumping liquid. The capacity of the tipping bucket is 40 cc per side which theoretically corresponds to a 12 liter vapor displacement at atmospheric pressure. Heat is supplied by condensing either steam or a volatile hydrocarbon in chamber 17 (Figure 11). As the flash boiler is connected at all times through an open pipe to the condensation chamber, no check valve is required in the vapor supply system. This fact eliminates the requirement for a 1 meter static head in the condensate line which is otherwise necessary to override boiler pressure and return the condensate to its source as was necessary in the Model II pump.

In order to operate the pump, the vapor chamber is initially evacuated and 100 cc of cyclopentane is placed in reservoir 6. Initial pumping tests were disappointing. A

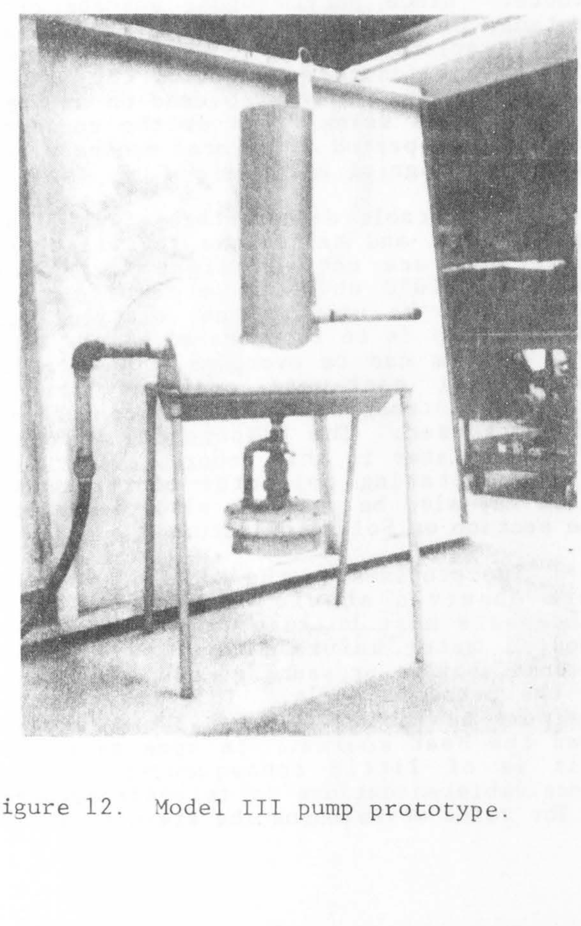


Figure 12. Model III pump prototype.

study of the pump's operation revealed several problems. Perhaps the biggest problem is to maintain complete air tight integrity in chamber 3 along with the interconnecting pipes and the flash boiler system. The sealed unit which holds the volatile liquid and its expansion chamber experiences a moderate vacuum on each condensation phase of the pump cycle. Because cyclopentane was used as the volatile liquid, ordinary sealants used to bond the viton diaphram to the metal parts quickly softened and weakened. The small amount of pumping fluid located inside of the flash boiler rapidly disappeared. A new type of special viton sealer was procured, and it was an improvement, but the airtight integrity was still not fully maintained. Any air leaks whatsoever cannot be tolerated if the pump is to work trouble free.

Each time air leaks into the Model III pump configuration, the cycle time, which is normally 2-3 times per minute, slows down. The maximum lift capability is reduced and the system gradually losses the 100 cc of C_5H_{10} used as the pumping fluid. Once the fluid is lost new pumping fluid must be put into the system and a vacuum must be reestablished. The problem of leaking air or vapor is not considered insurmountable but it is serious enough to justify redesign.

One other troublesome design defect of the Model III pump concerns the condensate holding column 6. It was originally designed to be in thermal contact with the heat source to preheat the accumulating condensate. Maintaining careful control of the temperature in this region of the pump proved to be difficult, however. If the reservoir walls become too hot the liquid overheats and tends to boil. This can cause the vapor to recycle in a continuous mode and the pump ceases to operate. The temperature of the liquid in the reservoir is a function of the flash boiler temperature and the condensation temperature which is a function of both the height of pumping and the cycle time which is also a function of water temperature. The greater the pumping height, the cooler chamber 3 must be in order for the vapor to condense. This situation is illustrated with the aid of Figure 6 which shows the relationship between absolute pressure and the condensation temperature.

Because of the problems enumerated above no quantitative data were obtained; instead, new design concepts were considered in order to circumvent the problems encountered.

Model IV Pump

Due to problems with the design of the Model III pump a new design concept was sought that would capitalize on the good points of the previous designs and overcome trouble spots in the earlier concepts. The final pump design is illustrated in Figure 13. This pump has the same basic inlet and outlet check valves but has some features that are superior to concepts of the Model III pump. The operation of the pump is best described with the aid of Figure 13.

Consider a condition where closed tank 1 is divided into two parts by a partition 2. In the top part of the right hand side of the partition is a gaseous vapor, cyclopentane, which is gradually condensing because of the heat that is being absorbed through the partition and by the surface of the unvolatilized cyclopentane 3, that floats on top of the column of water 4. As the vapor condenses the pressure drops in area 5 such that atmospheric pressure acting on the water supply 6 pushes open check valve 7 and causes water to flow up through inlet pipe 8, into the pumping tank 1. Outlet check valve 9 is closed during this portion of the pumping cycle. As water flows into the tank the liquid cyclopentane level rises until it reaches an open pipe, 10. The liquid cyclopentane flows into this pipe and rapidly fills a small cup, 11, which contains a small syphon tube. When the liquid reaches the top of the inverted U-shaped syphon tube it starts to syphon itself empty, discharging its contents into a preheated flash boiler, 12. In a matter of 3-4 seconds the volatile cyclopentane is vaporized creating considerable pressure in the boiler and in region 5. This sudden increase in pressure forces the liquid column downward and the water flows under the bottom of the partition and up past check valve 9 which is forced open during this portion of the cycle. Check valve 7 automatically closes during this part of the cycle. Water is thus displaced into the surge tank 13 and out the discharge pipe 14. This completes one pumping cycle, whereupon the next cycle begins.

The flash boiler is heated in a manner similar to the boiler previously described in the Model III pump. Solar heated cyclopentane vaporizes and creates about 20 lbs of pressure in the tubing within the solar panel (Figure 13). The vapor flows rapidly to the flash boiler through pipe 16 where it condenses on a thick aluminum plate, 15. The condensate falls to the bottom of the boiler where it is collected and returned by pipe 17 to the boiler. Again, no mechanical pump of any kind is needed for the heating fluid to circulate, as it is driven by the thermal gradients that exist between the flash boiler and the solar panel.

Two configurations of the Model IV pump were constructed and evaluated. (See Figures 14 and 15.) Attention is given to simplicity of construction using readily available materials in the design of the pump. One configuration (Figure 14) incorporated the use of a 44 liter barrel (Figure 16) with a removable end that was held in place by a ring clamp. A thin film of silicone RTV rubber used on the neoprene rubber lid gasket made an effective air tight seal. The second pump housing was constructed from a section of 20 cm (8 inch) diameter aluminum irrigation pipe. The disadvantage of working with

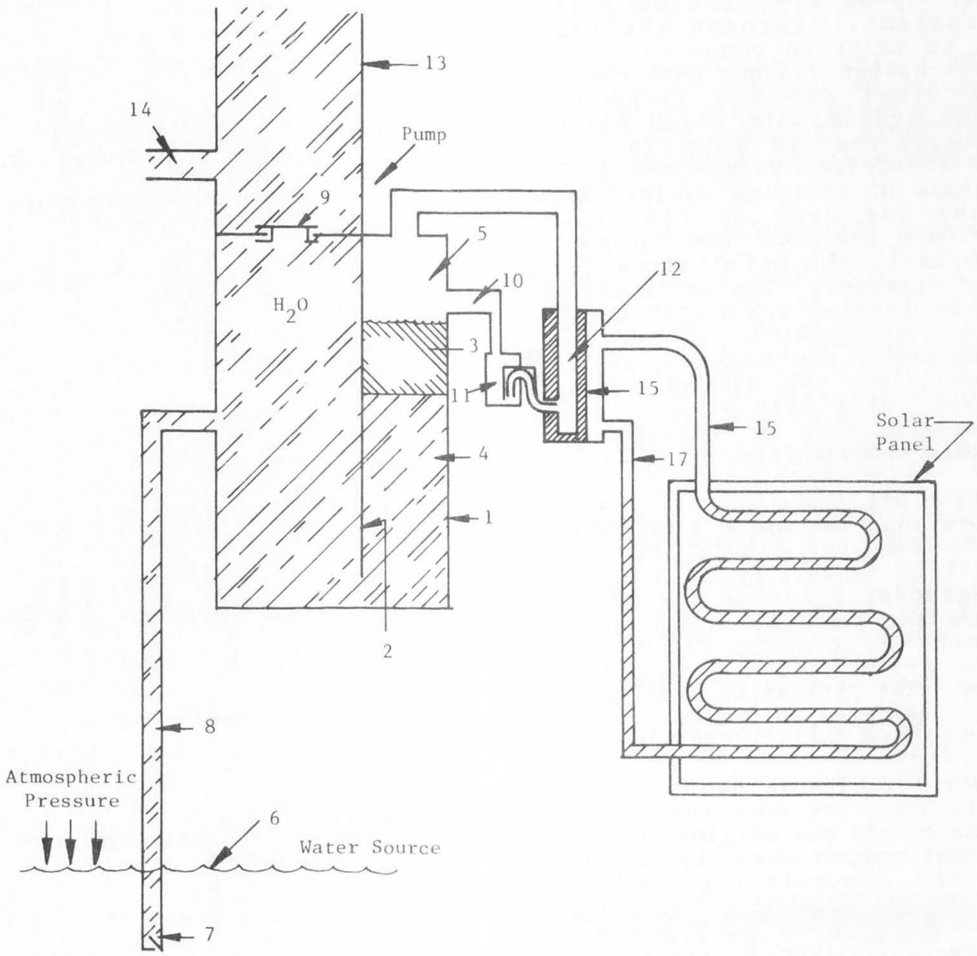


Figure 13. Model IV pump using the syphon cup principle.

aluminum is that end plates, flanges, etc., must be added to the pipe. They must be either brazed or welded in an inert atmosphere, e.g. using helium or argon gas, etc. The advantage of the aluminum pipe over the steel barrel is its resistance to corrosion, the steel barrel by reason of its size has the largest pumping capacity.

Use of a pumping tank that is too large may create structural problems. A barrel with a 33 cm end plate diameter for example, made of 20 gage mild steel, tends to deflect in "oil can" fashion on the vacuum versus pressure parts of the cycle. This displacement cuts down on pumping capacity in direct proportion to the volume equivalent of the displacement of the ends. If a larger, e.g. 210 liter (55 gallon), drum is used without reenforcement, the ends are not strong enough to withstand the pressures that are generated during the pumping cycle. The force on the large drum end area is approximately three times that of the force on the smaller barrel ends discussed above, whose end plate strength is considered marginal for a 3 meter high lift. The aluminum pipe housing of Figure 15 is strong enough for any physically realizable vacuum or pressures that may be encountered, e.g. 344 kPa.

The most important dimension that determines the pumping capacity of the pump is the size of the internal cylinder. Obviously if too much volume in the inner cylinder is displaced with vapor, the liquid level will drop so low that cyclopentane can escape underneath the cylinder wall in which it is normally trapped. Loss of this fluid will quickly cause pump operation to cease. The amount of vapor generated is determined by the syphon cup size and the flash boiler efficiency in conversion of liquid into vapor quickly, i.e. 3-4 seconds. Provided the heat supply, flash boiler, and inner cylinder size are adequate, the larger the syphon cup the more water pumped.

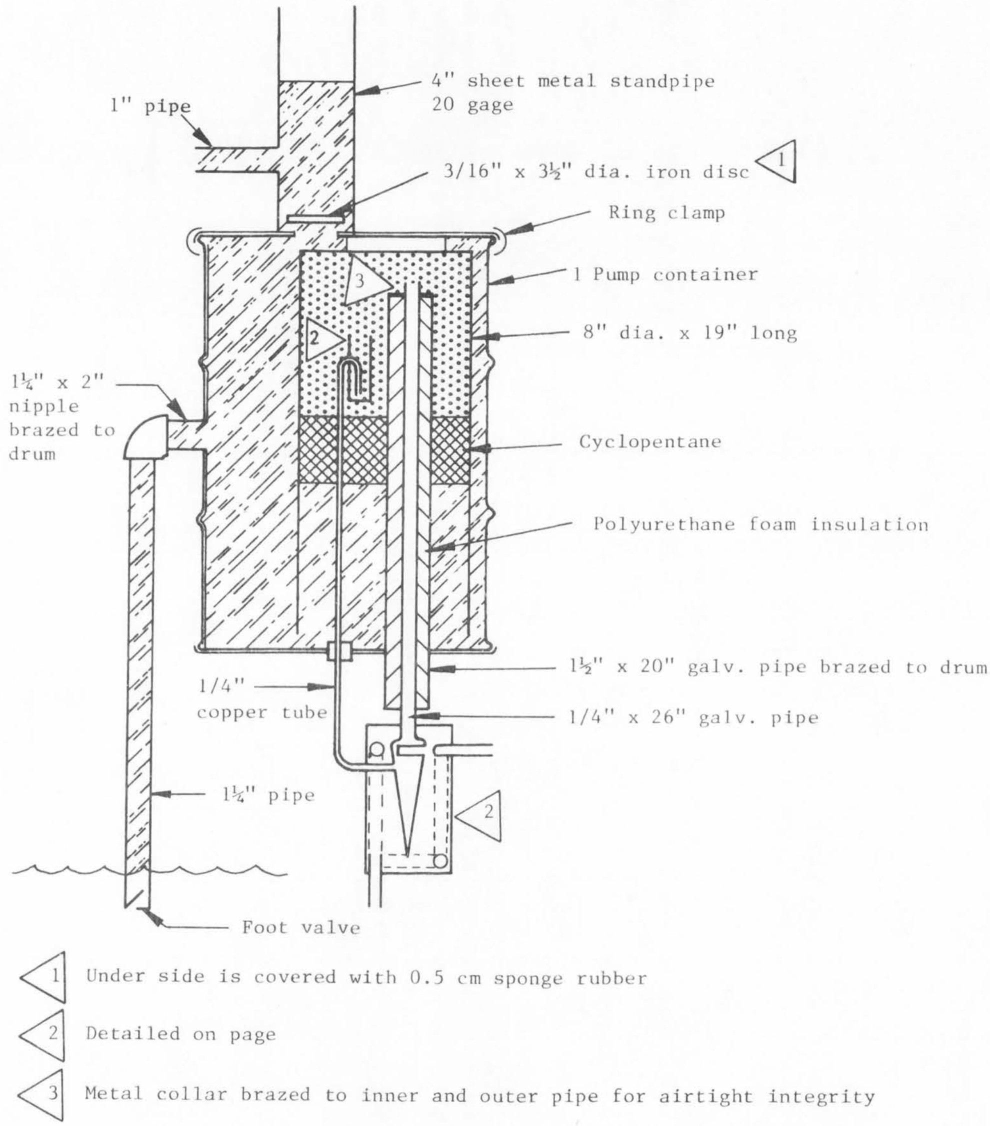


Figure 14. Model IV A pump. Outer container is a 44 liter barrel. This unit pumps 8 liters/ minute at a height of 2½ meters.

Determination of the appropriate size of the inner tank is important to achieve the best operating efficiency. If the inner tank diameter is too large, or too small, in either case the condensing surface area becomes larger than necessary for a given water displacement. The optimum diameter can be approximated by arbitrarily selecting a displacement amount and then determining the optimum diameter dimension that has a minimum area for condensation at the point of greatest liquid displacement. This point is chosen because it is where equilibrium is reached with respect to the rate of vapor generated versus the rate of vapor condensed; no greater displacement is therefore possible and the maximum capacity of the pump is reached under this condition.

The equations which determine optimum conditions are

$$\text{total condensing area} = 2(\pi r^2) + 2\pi rh \quad . \quad . \quad (1)$$

and

$$\text{total displacement volume} = \pi r^2 h \quad . \quad . \quad . \quad (2)$$

The first term of Equation 1 represents the surface areas of the liquid exposed to the vapor and the closed top end of the container, where r is the radius of the inner

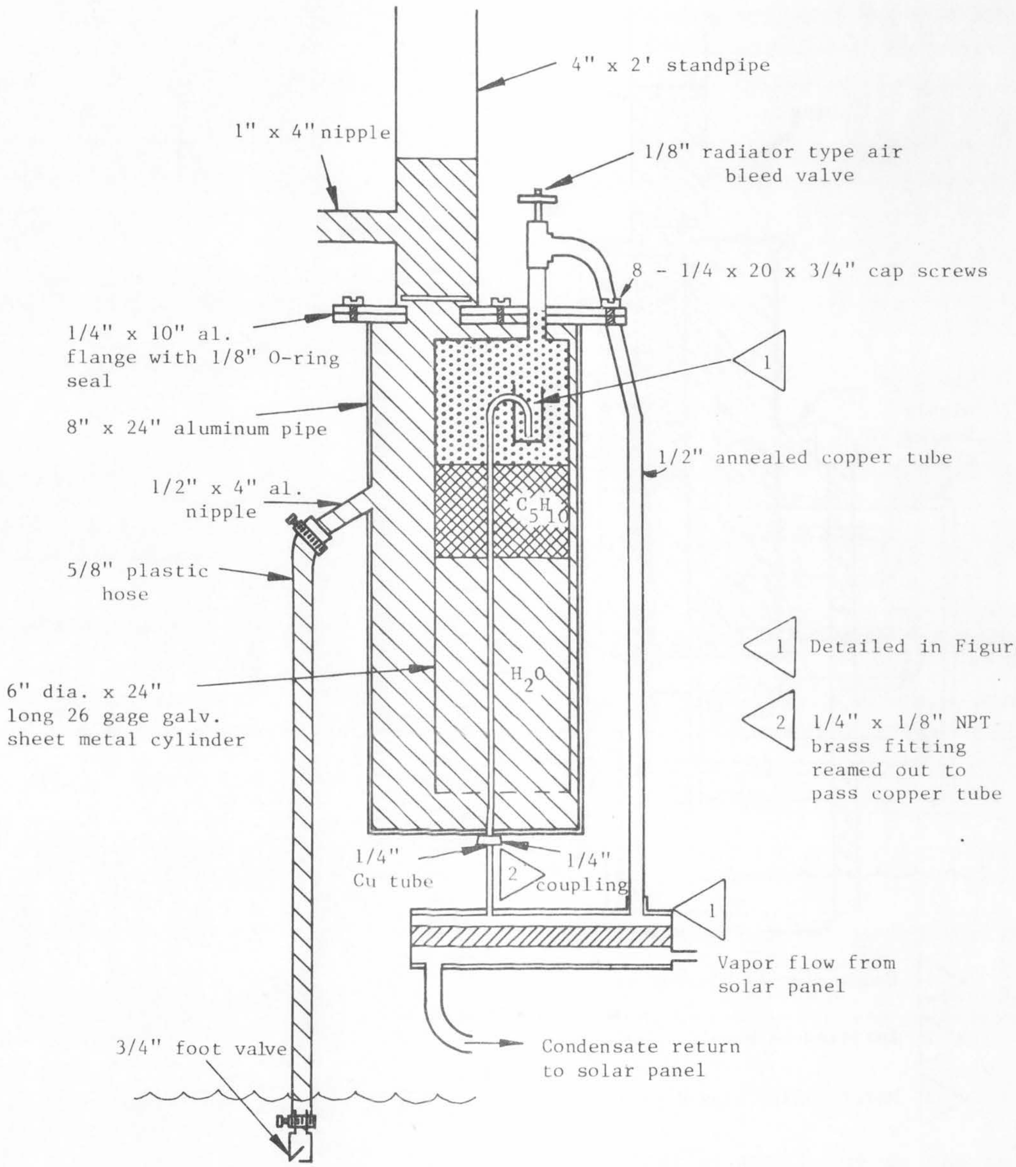


Figure 15. Model IV B pump. Outer container is a 20 cm dia. aluminum irrigation pump. Note that the flash boiler is only heated from the bottom side making it less efficient than the boiler used on Model IV A.

tank. The second term represents the area of the inner cylinder walls, where h is the height of the vapor column.

The optimum cylinder diameter can be determined by setting Equation 2 equal to the displacement volume, selecting various values of h and solving for the radius r. The value for the radius can then be substituted in Equation 1 to solve for the condensation area. The results of this procedure are plotted in Figure 17. This figure illustrates for example, that the radius can vary over a 7.5 cm to 15 cm radius range for only a 10 percent change in condensation area using the 8 liter pump cycle curve. This wide operating range is fortuitous and indicates no serious sacrifice in efficiency if the size of inner tank radius is not optimum.

Pumping Rate Comparisons

The pumping rate of the Model IV pump is similar to rates achieved with the other pumps described in this report. At the outset it should be emphasized that all pumps are of modest size and no attempt was made to build a particularly large pump. The Model II, III, and IV pumps have the physical capacity to pump up to 10 liters per cycle. With the flash boilers and size of syphon cups used, the pump configurations of Figures

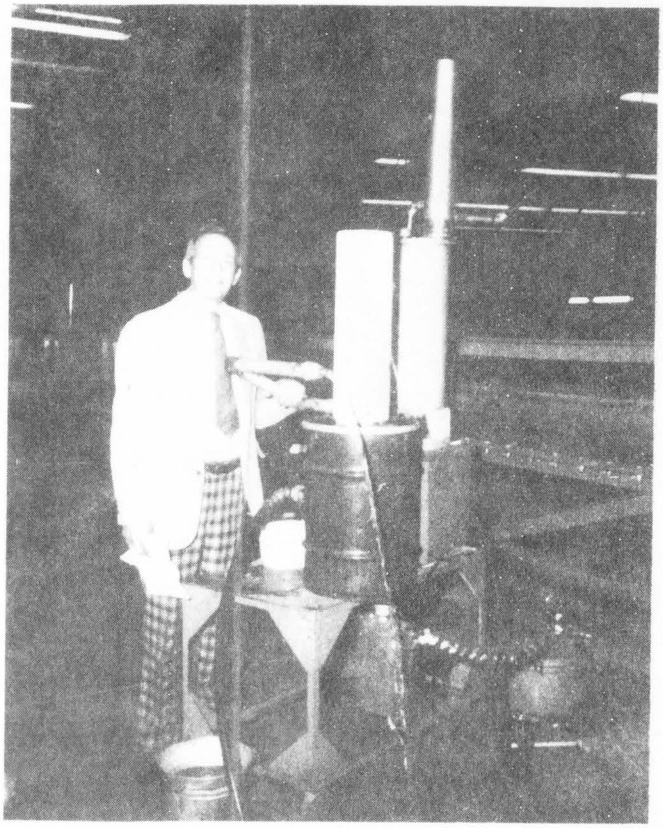


Figure 16. Model IV pump in operation with a propane hot plate and pressure cooker used in lieu of solar energy. In background is the Model IVB configuration.

14 and 15 had a pump capacity of 3 liters and 1 1/2 liters per cycle respectively. The Model I pump was designed to pump 7 liters per cycle. It pumps 7 liters per cycle since the length of the pumping stroke and therefore its displacement capacity is fixed in its design.

The time for each cycle varies in accordance with the type of volatile liquid used, the temperature of the water being pumped, and on the height of lift as previously discussed. Typical cycle times for 10°C intake water from the Logan River using cyclopentane are plotted as a function of height in Figure 18. The Model IV pump used on the Logan River and powered by a solar panel is illustrated in Figure 19. If hexane is used instead of cyclopentane, higher vaporizing temperatures are required, i.e. 85°C as opposed to 65°C, for cyclopentane but the cycle time can be reduced since there is a greater condensation rate possible.

The two Model IV pumps of Figures 14 and 15 give surprisingly different pumping rates. The pump of Figure 14 can pump approximately two times more water per cycle than does the pump in Figure 15 as noted above. Interchanging flash boilers while still using the same heat source, increases the pumping capacity of the smaller pump by a factor of two and accordingly decreases the output of pump of Figure 14 by the same factor. This experiment illustrates the importance of efficient flash boiler design. Design details of these boilers are given in the next section.

<u>Flash Boiler</u>

The Model I pump receives heat in a continuous mode through a simple condensation coil surrounding the vaporization tank discussed earlier (Figure 4). For the Model II pump heat is generated in a conventional boiler that has a predetermined steam capacity which is determined by the bladder size. The Model III and IV pumps use a flash boiler that creates special design problems and added expense which is in part offset by a simpler pump mechanism made possible by their existence.

Three flash-type boilers were designed. Two of them are shown in Figures 20 and 21. A detailed sketch of the boiler used in the tipping bucket type configuration of Model III (Figure 11) is not given but it is similar in heat transfer design to the boiler of Figure 21. The major difference between them is the way in which the hot liquid is dispersed over the hot plate.

As discussed previously, the boiler of Figure 20 is twice as effective in operation as the more simply constructed boiler of Figure 21. The chief reason is that heat can be applied from both sides of the boiler in Figure 20 and from only one side in Figure 21. The result is that the boiler of Figure 20 vaporizes more liquid and raises it to a higher initial temperature.

Much of the heat that is used in the pump is lost in bringing the liquid and cylinder end surfaces of the expansion chamber inside the pump up to the temperature that will sustain the induced vapor. Once that condition is met a relatively small amount of vapor actually displaces the pumped water. For example in the Model IV pump 40 cc are discharged into the boiler. If 4 liters are displaced this accounts for only 12 cc of the total 40 cc injected into the boiler, the remainder is either not vaporized or condensed in the priming process of bringing the chamber back up to vapor sustaining temperatures. Obviously if the syphon cup capacity and the flash boiler capacity is increased the pumping efficiency should increase in a disproportionate and advantageous manner.

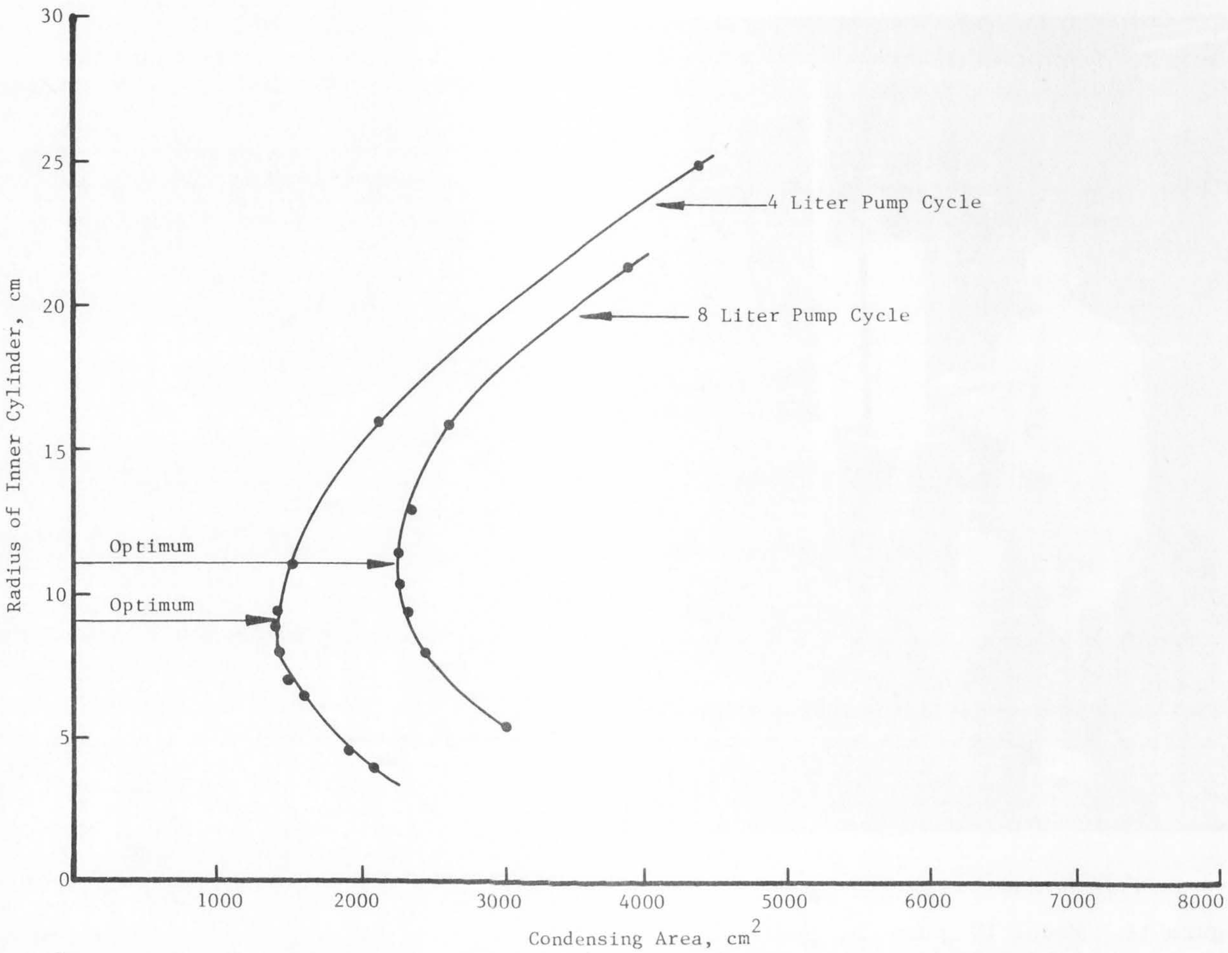


Figure 17. Graph showing the most favorable inner tank diameter per given pump displacement. Operating with the condensing area at a minimum maximizes efficiency.

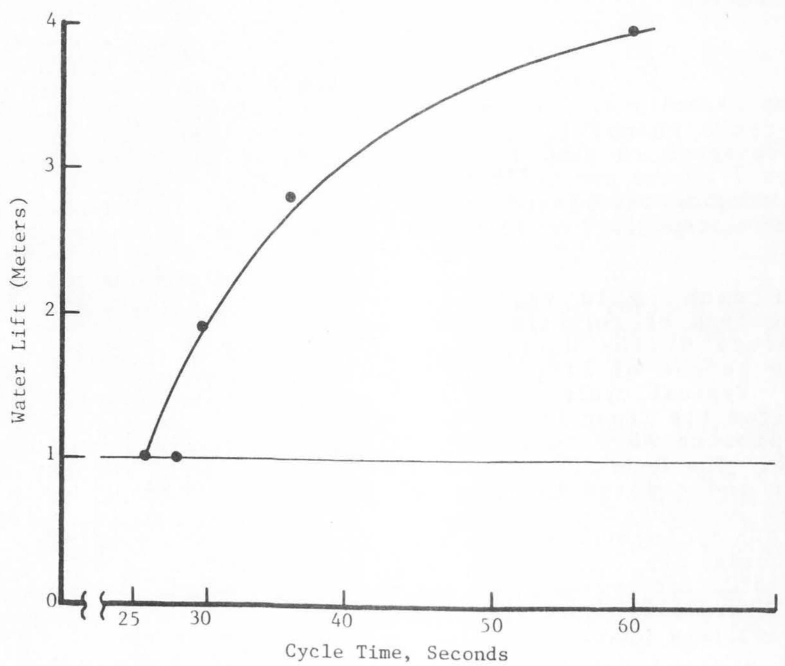


Figure 18. Plot of cycle time versus height of water lift.

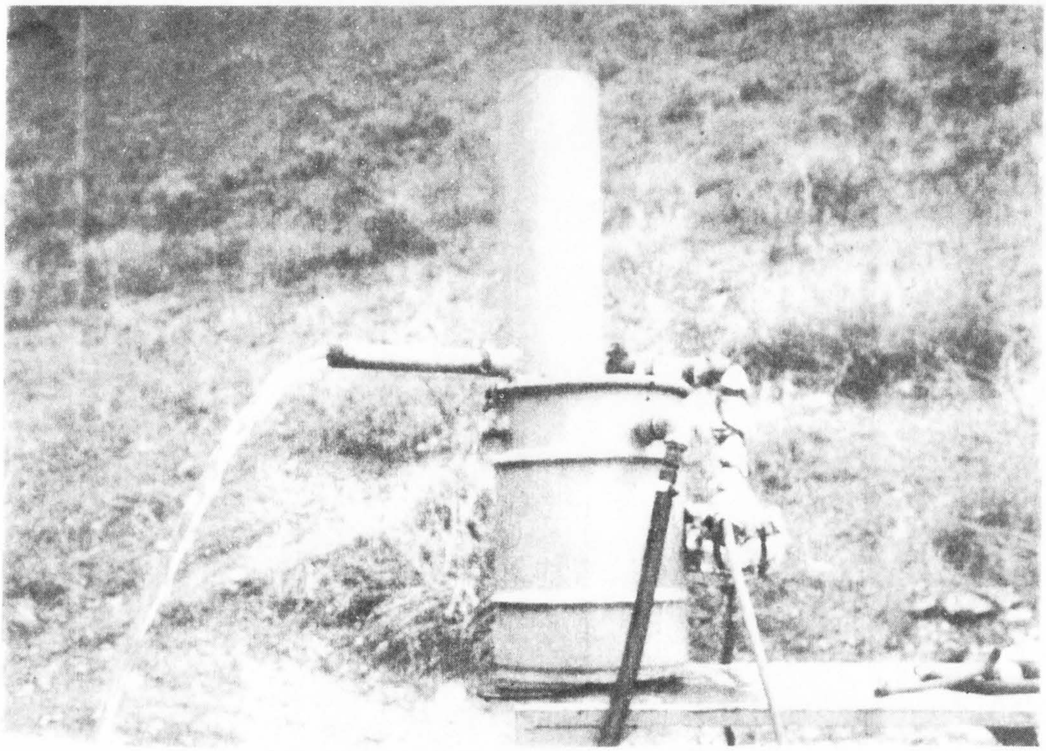


Figure 19. Model IV pump, pumping out of Logan River, operating from a single flat plate solar collector.

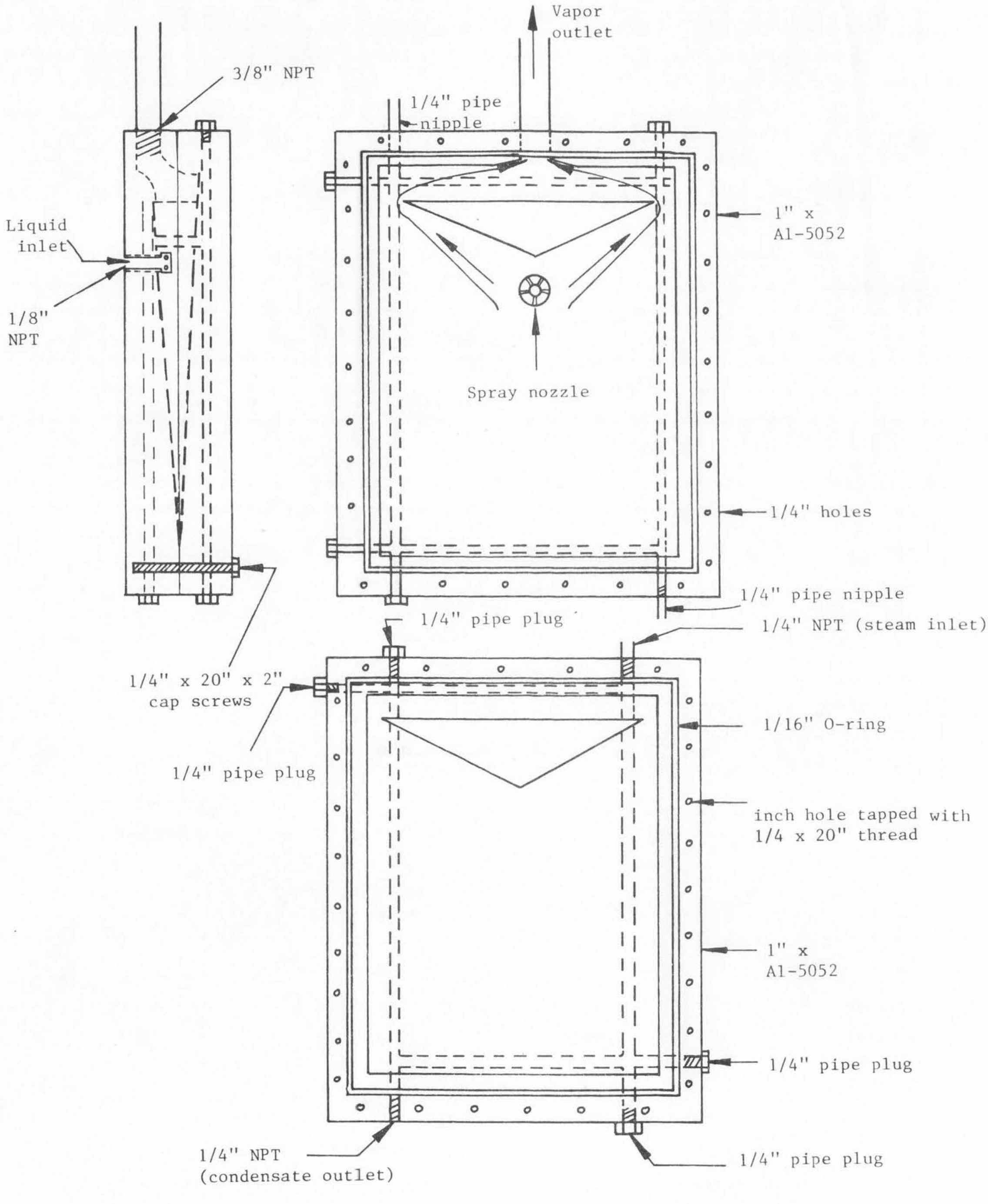


Figure 20. Flash boiler having highest efficiency. Heat is applied by condensing hot vapors conducted through the 1/4" bore holes in aluminum blocks.

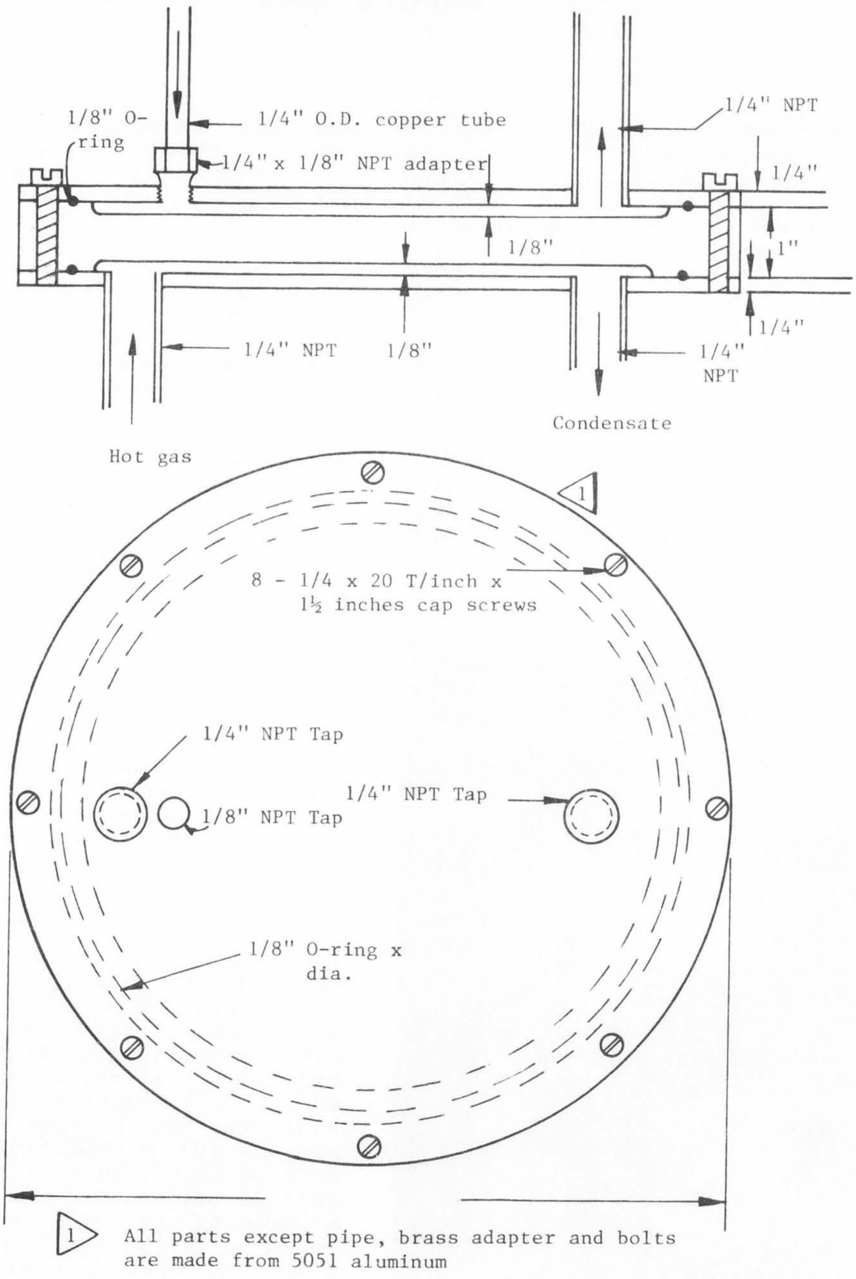


Figure 21. Flash boiler. Heat is applied to under side by condensing vapor. Vaporizing fuel flows in through 1/4" O.D. copper tube, is vaporized and the vapor escapes through the outlet pipe.

SOLAR COLLECTORS

In many solar-powered systems the cost of the solar collectors that supply the heat energy to the engine greatly exceeds the cost of the engine. The best designed pumping mechanism operating on solar energy may prove to be totally impractical when the cost of the collector system is considered. Consequently, considerable time was spent studying and evaluating various solar energy collector techniques. The various type of collectors that were experimentally evaluated are illustrated in Figures 22, 23, 24, 25, and 26. The common types of collectors that were not experimentally evaluated are the parabolic trough and the parabolic dish. Instead, a right angle cone reflector-concentrator and a trapezoidal trough concentrator were evaluated which have similar although slightly inferior characteristics to parabolas. These two linear configurations are more economical to build in limited quantity than their parabolic counterparts since they can be fabricated without special dyes, molds or stamping equipment, etc.

The following discussion of the various solar collectors is not detailed in a comprehensive analysis. General observations are reported on each type tested and the basis for the ultimate selection of the collector type chosen is given.

Cone Collector

The cone shaped solar concentrator is of considerable interest because of its simplicity of construction and ability to achieve reasonably high concentration ratios and correspondingly high temperatures (NASA 1976). The cone configuration is illustrated in cross-sectional view in Figure 27. If the internal angle on the apex of the cone is a right angle, and if the rays of the sun are parallel to the center line of the cone, then rays coming from the sun are reflected from their incoming angle, passing through a center line along the longitudinal axis of the cone. The cone is thus seen to have a line focus along the center line axis. The concentration ratio varies in accordance with the diameter of the cone and the diameter of the solar receiver, or pipe located along the center line. At the base of the cone little or no concentration is achieved, towards the outer extremity of the cone concentration of 10 or more may be obtained.

Since the greatest amount of solar energy is focused near the top of the receiver or "boiler," the outermost boiler extremity is the hottest region in the system. This is fortuitous since surface boiling is most desirable and the steam or hydrocarbon vapor can readily exit through the pipe running axially along the center line of the boiler without carrying large quantities of liquid along with the vapor. After the vapor condenses in the flask boiler of the water pump it flows by gravity back to the solar receiver and enters the receiver near the apex of the cone, as illustrated in Figure 27.

The construction of the cone is basically simple. It is formed from a circular, flat, sheet of metal much like a conical paper cup is formed from a three-quarter

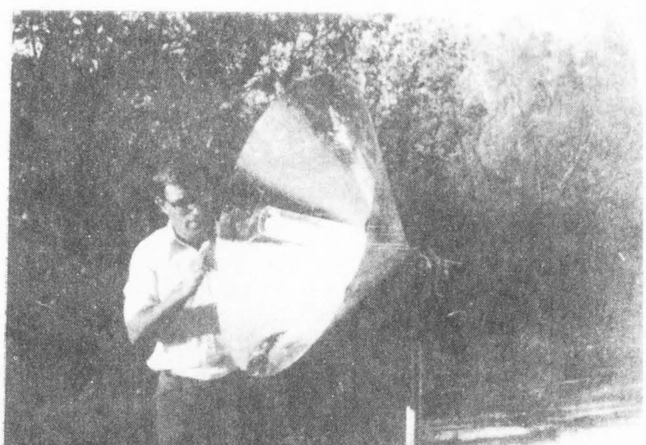


Figure 22. A sheet metal cone-type solar collector/concentrator. Three such units are required to power an 8 liter/minute pump.

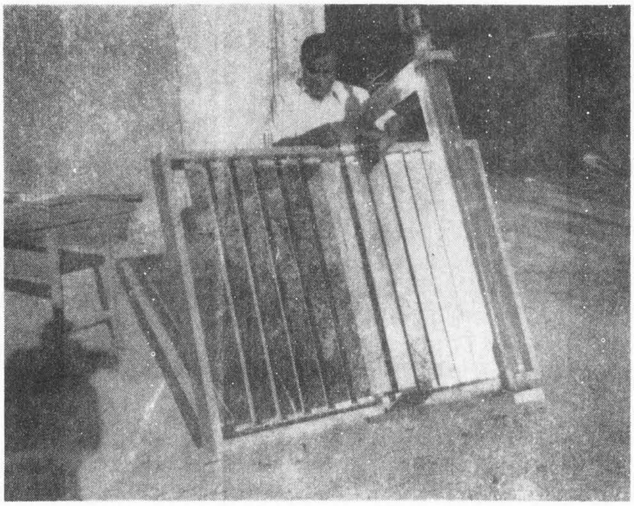


Figure 23. Fresnel type lens movable reflector made from silvered glass segments. A unit this size will power an 8 liter/minute pump.

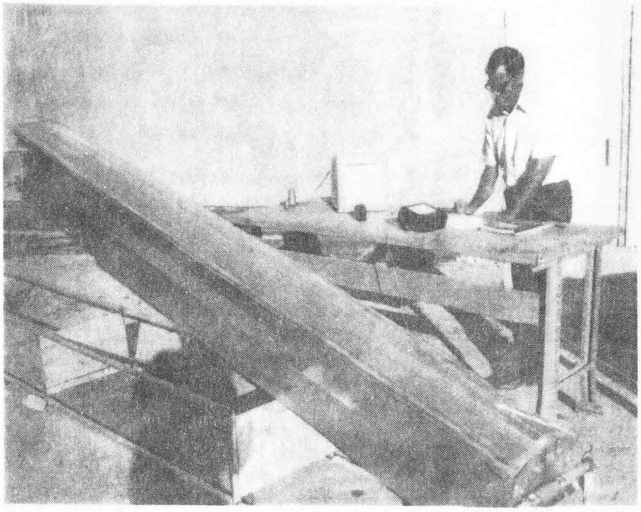


Figure 24. Fresnel lens solar collector. On the table in the background is a pyroheliometer and chart recorder used for measuring insolation.

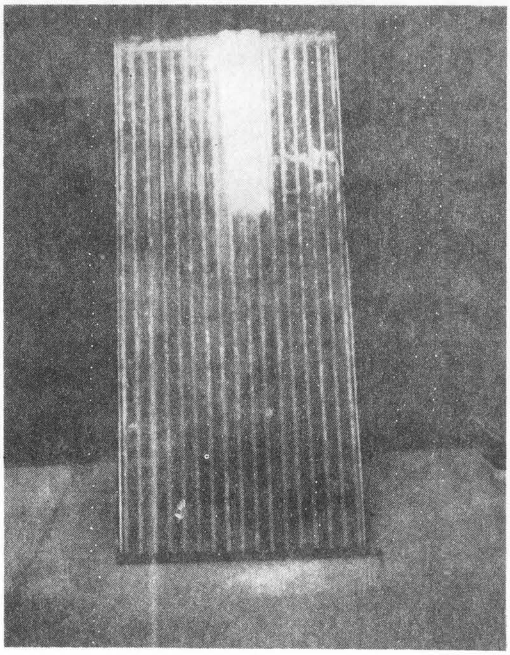


Figure 25. Flat plate collector.

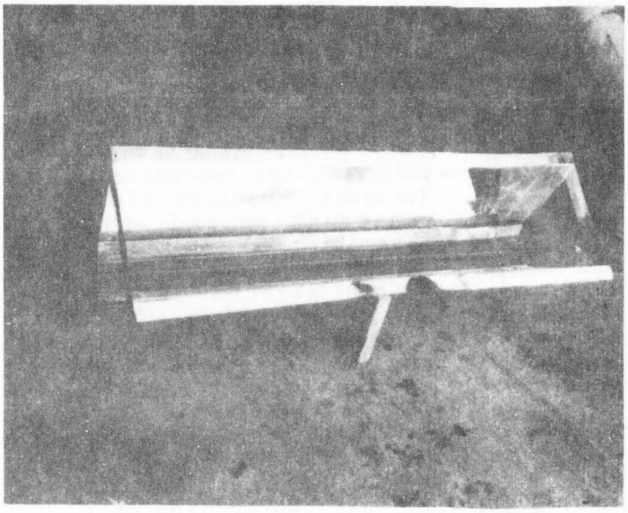
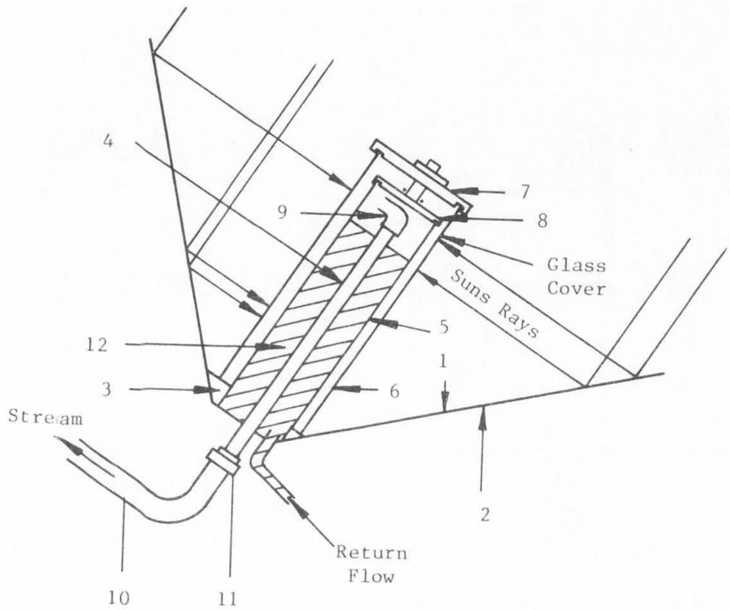


Figure 26. Trapezoidal trough type solar collector. Three troughs this size, 30 cm aperature by 131 cm long, will power any of the pumps discussed in this report. The longitudinal axis of the pump is oriented east and west.



1 Chrome plated mylar
2 26 gage galvanized sheet metal
3 2" wooden mounting block
4 1/2" O.D. copper steam escape tube
5 2" O.D. copper heat receiver tube
6 10 cm barosilicate glass tube
7 Metal end cap bolted to 5
8 End cap silver soldered to pipe
9 1/2" elbow
10 Radiator hose
11 Hose clamp
12 Heated liquid

Figure 27. Cone type tracking solar collector.

pie-shaped piece of paper. As the radial edges are drawn together the cone shape is formed automatically. If the metal used to form the cone does not have a highly reflective surface it must be covered with a reflective surface such as chrome plated mylar cemented to the surface. Other types of flexible reflecting sheets are available which are preglued such as Kel-F. No effort was made to determine which type is superior. Since the good optical properties of chrome plated mylar are well known and was most readily available, and it costs only 20 cents per square foot in full roll quantities, it was selected for use on this project.

Tests were conducted on a cone whose diameter measured 86 cm and whose depth was 43 cm. The cone operated at an efficiency of 40 percent at a temperature of 100°C with an ambient temperature of 20°C. The receiver used in the cone is an unpainted 5 cm diameter copper tube with single glazing.

The attractive features of a cone collector are its ease of construction and relatively low cost. The ratio of material required to build the right angle cone, to aperature area obtained by the cone is 39 percent. In comparison, a short focal length parabola has a higher material utilization factor, and therefore ultimately, if manufactured in large quantities would be more cost effective.

The disadvantage to either the cone or the parabola is that they both require a tracking mechanism. Since wind loads in either case can be appreciable, the tracking mechanism must be strong. Tracking in one plane only may be possible provided it can be periodically manually adjusted in the vertical plane. The degree of misalignment that can be tolerated depends on the diameter of the boiler tube used. The diameter of the boiler tube also depends on the precision with which the cone is constructed and held to its proper shape. Using 26 gage galvanized steel cone material with a diameter of 86 cm, a 5 cm diameter collector tube was successfully used in the cone illustrated in Figure 22. The collector tube was glazed with a 10 cm diameter borosilicate glass tube to reduce convective losses. Borosilicate glass was used because of its high resistance to thermal shock. A cheaper quality thermal glass such as flint glass would also work well to provide a dead air space around the solar receiver to limit heat loss by conduction.

As can be seen from Figure 22, the copper receiver in the center of the cone was not blackened in any way and considerable light reflection from the target was present. Further sophistication of the construction was not justified in light of the fact that the decision was made not to use this type of collector since another type of collector appears more cost-effective.

Venetian-Blind-Type Fresnel Lens Concentrating Collector

A line focusing concentrator built and evaluated on this project is shown in Figure

23. It can be classified as a segmented fresnel lens. A sketch of it in cross section is illustrated in Figure 28. The unit was built to explore its potential as an inexpensive means of concentrating solar energy by a factor of about 10 times. The movable mirrors are linked together with fixed angle offset so that all 14 mirrors reflect sunlight at all times on the receiver located 1 meter in front of the mirror plane. The glass strips were inexpensively obtained by cutting them out of a plain glass household door mirror. The mirror segments all move together as they are linked to a simple $3 dc motor[4] powered by two small photocells to track the sun. (The electronic circuitry used to track the sun and operate the tracking motor is discussed in Appendix B.)

The collector area as seen in Figure 23 is 1 square meter. The receiver consists of a single glazed 5 cm diameter steel pipe, 1.2 meters in length. No selective coating such as black chrome was used on the receiver. Efficiencies, therefore, were not as high as they could be. Tests demonstrated that the system could produce approximately 5000 cal/min at 82°C with a measured solar influx of 1.4 cal/cm^2/min., and an output of 3500 cal/min at a discharge temperature of 100°C. The ambient temperature during these tests was 21°C. The above data show an efficiency of 36 percent at an ambient to discharge temperature differential of 61°C.

[4]Such as the Hankscraft Model powered by two IR-SM5 photocells.

The chief disadvantages of the louvered mirror lens besides the tracking system required are that it proved to be quite labor intensive to build, and somewhat fragile. Another disadvantage first observed during tests is that the top most part of the boiler is quite high in the air for spring and fall days at latitudes of 30-40 degrees or more, as illustrated in Figure 23. Since the solar powered water pump must be located above the boiler for vapor-phase heat transfer and gravity return flow to take place it increases the amount of pump lift required which wastes energy.

Fresnel Lens Collector

For purposes of comparison with economical collectors built with comparatively low technology reported herein, a commercial Fresnel lens concentrating collector was also tested. Its effective area is approximately 30 cm wide by 3 meters long. (See Figure 24.) For similar solar inputs and ambient temperatures reported above, the measured output available at 100°C was 5280 cal/min. The solar influx was 13,000 cal/min; this gives an efficiency of

$$\text{Efficiency} = \frac{5,280}{13,000} \times 100\% = 40.6\%$$

These results are better than the louvered mirror concentrator discussed in the previous section. A better alignment of the mirrors on the louvered mirror concentrator, and with a black chrome selective coating on the receiver of the unit in Figure 24, the

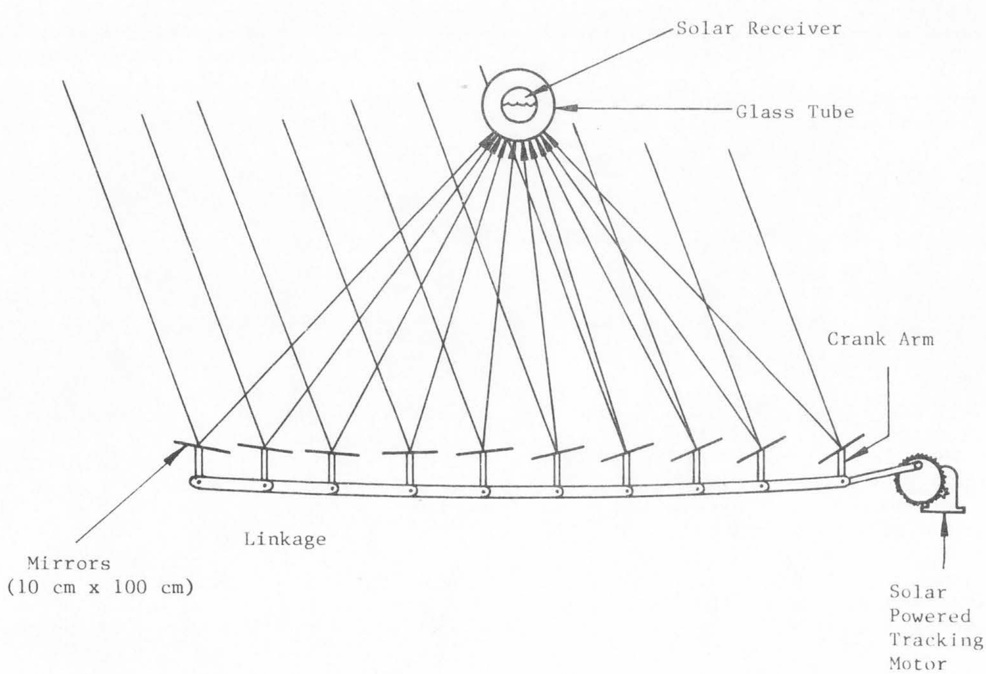


Figure 28. Cross sectional view of linked mirrors which maintain constant focus on the receiver.

results of the two configurations would be comparable. The purchase cost of the Fresnel lens collector is approximately four times the parts cost of the louvered mirror system including the tracking mechanism. The commercial Fresnel lens system had no tracker attached to it. Due to its massive structure, the extremely simple tracking motor powered by two photo cells used in the previous system had inadequate power to operate the tracking mechanism of the heavier commercial Fresnel lens unit.

To perform most efficiently, the longitudinal axis of the lens should be elevated such that its axis is perpendicular to the sun. Accordingly, at 40 degrees latitude it protrudes in the air about 2.5 meters during the vernal equinox, somewhat lower than that during summer months, and higher than 2.5 meters in late fall, winter, and early spring. There is an additional problem with the Fresnel lens collector. In order for the solar panel to operate by gravity flow the solar collector must be located at a slightly lower elevation than the pump. Using such a collector causes the solar powered pump to be located 3 meters in the air, unless an electric pump is used to return the condensate to the panel. While such a system may be feasible for complicated expensive systems, it is not considered practical for the simple, inexpensive system outlined in this research.

Flat Plate Collector

Some of the details of the flat plate collector and how it can be used to power a solar powered water pump have already been presented in connection with Figure 3. Much also can be found in the literature regarding flat plate collectors and they are readily available commercially. The flat plate collector constructed for this project as shown in Figure 29 consists of a 1.2 m x 2.4 m wooden frame, a thin plywood backing with an overlay of a 2.5 cm fiberglass bat which reduces heat loss from the back side of the collector. On top of the fiberglass bat is a 1.2 m x 2.4 m x 26 gage galvanized iron sheet. Approximately 12 meters of 1 cm copper pipe was soldered to the front side of the metal plate to conduct the heating fluid to and from the panel. The top surface of the collector consisted of a 2.5 cm dead air space and a flat sheet of transparent greenhouse quality fiber glass (see Figure 29).

The 1.2 m x 2.4 m panel just described, was adequate to operate a Model IV pump which could lift 6 liters of water per minute with a 2.5 m lift. The solar angle was required to be within ± 3 hours of its optimum position with respect to the panel, however, to run it at its rated output.

The inefficiency of the fixed position panel during morning and late afternoon is a serious disadvantage to the flat plate fixed position collector. Also the cost and overall bulk of the panel were negative factors pertaining to its use. Search for a better solution to the expense and inconvenience of collecting solar energy prompted the evaluation of a little known configuration called a trapezoidal trough collector discussed in the following section.

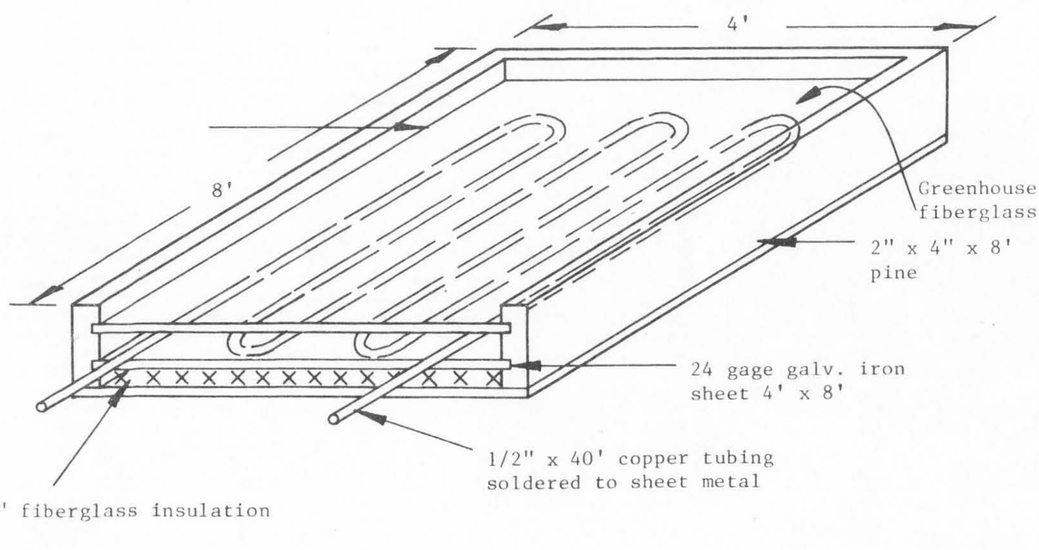


Figure 29. Sketch showing view of a flat plate, nonfocusing, solar collector with the end cover removed so that inner construction can be seen.

Trapezoidal Trough Collector

A trapezoidal trough functions similarly to a compound parabolic concentrator reported by Winston (1974). The trapezoidal trough was mathematically analyzed by Villanueva and Troung in 1977 (Villanueva 1977). In Figure 30. There are variations possible in dimensions and configurations which are too detailed to present in this report. The dimensions shown in Figure 30 are judged to be a compromise between the aperature to material ratio, concentration ratio, and tolerance to misalignment of the sun, etc. The trough, or series of troughs are oriented with their longitudinal axis in an East-West direction, and tilted so that the solar path is perpendicular to the vertical axis of the trough. This tilt angle is not very critical and only needs adjustment once or twice a month.

With the dimensions shown, the aperature to reflectance ratio is 33 percent. The solar concentration factor is approximately 3 to 1.

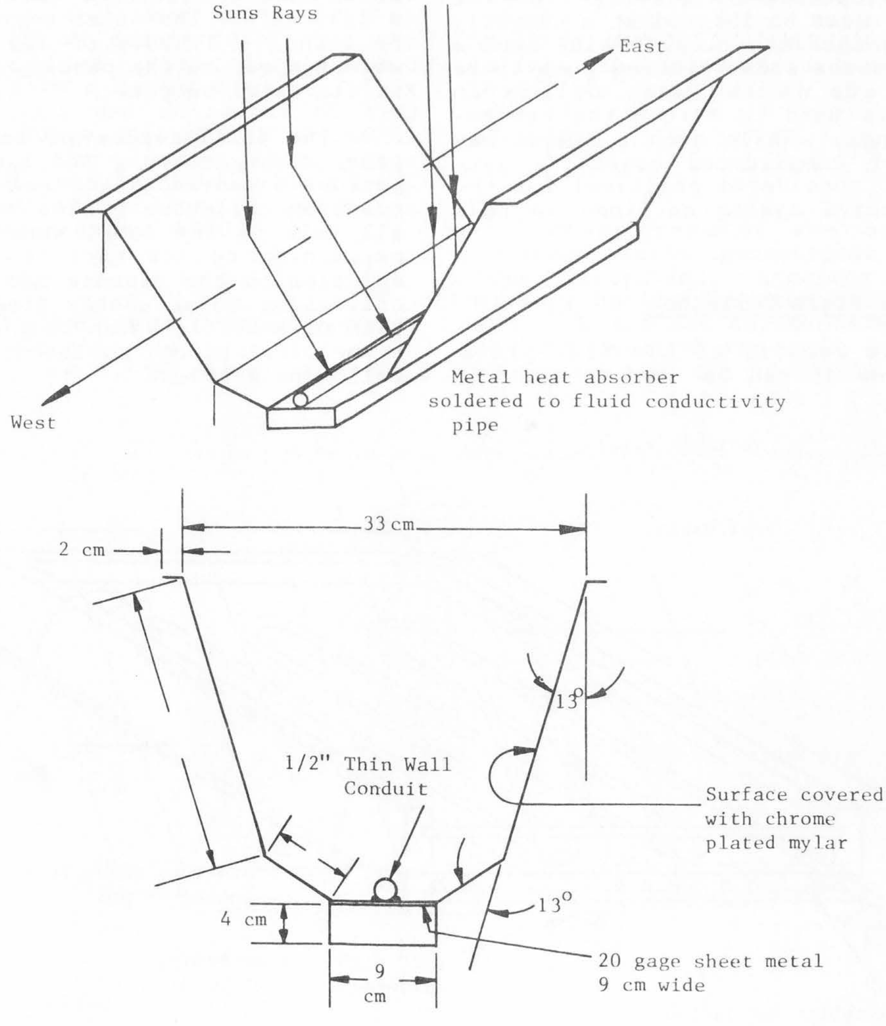


Figure 30. Trapezoidal trough solar collector which gives a concentration of 2-3 and tolerates ± 10° north-south fluctuation of the sun path. Dimensional details are given in Appendix A.

The desirable features of this system are that it is extremely simple to build. Each trough can be made any desirable length, and sections can be easily added or removed. The collector profile is low so that wind problems are minimal. It is basically rugged and can be made without any special equipment except a sheet metal brake, metal shears, and a soldering iron. Since it has a low profile it also does not require that the pump be elevated more than about one-half meter above the ground. Another attractive feature is that no expensive glazing is required and only a single soldered tube is used as opposed to six or eight times that amount of soldering required in a flat plate collector. As a result of these features, the unit is the lowest in cost of any of the collectors discussed and tested on this project. The cost of the trapezoidal trough is estimated to be about $30 per square meter or about one-third of the cost of an equivalent flat plate collector. Because of the concentrations available it is also able to operate at higher temperatures and at higher efficiencies than is the flat plate collector.

The efficiency of the trough varies according to the solar angle, and condition of the reflective surfaces, etc. Efficiency tests run in late October demonstrated its potential as a relatively efficient collector when operated at 100°C. The data taken from these tests are plotted in the graph in Figure 31, and compared to typical flat plate collector efficiency data. These data are for both collector performing at an optimum angle relative to the sun. At angles other than optimum the efficiency falls off as the cosine function of the angle with respect to the sun.

In order for the system to thermally syphon, the outflow end must be slightly, e.g. 5-10 cm, higher than the inflow end. If two or more troughs are nested together care must be taken to assure that they are approximately situated so that a temperature versus elevation gradient is maintained.

<u>Solar Collector Summary Statement</u>

Salient features of the various solar collectors that have been discussed are summarized in Table 2. The types of collectors that were considered are chiefly ones that could be built with low-technology know-how and without special tools. The exception to this is the longitudinal plastic Fresnel lens which requires special dies for lens construction.

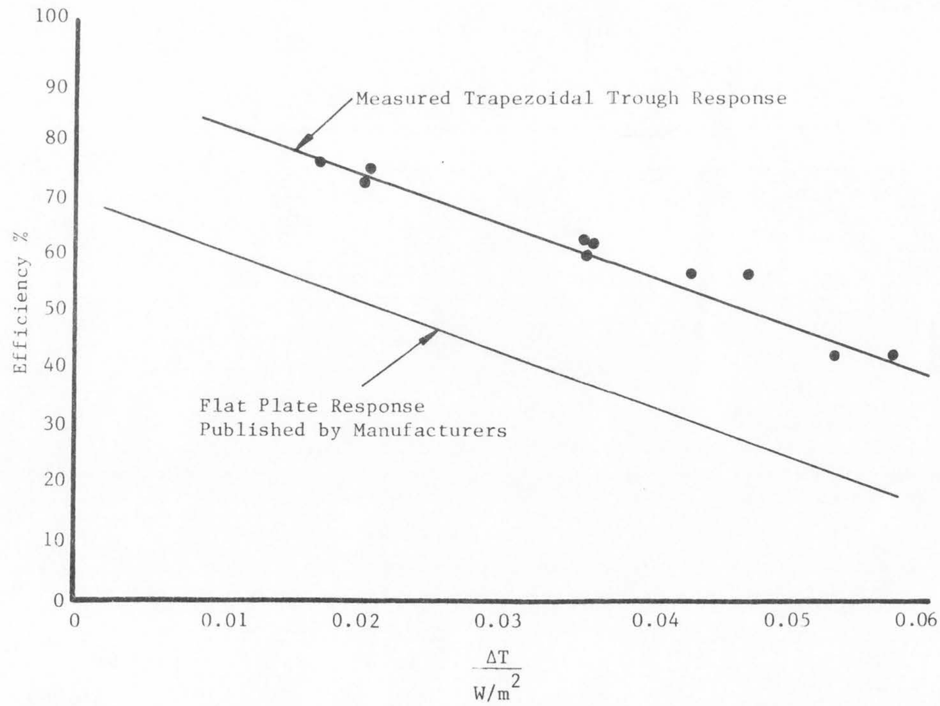


Figure 31. Plot showing measured efficiency of trapezoidal trough compared to a manufacturers published efficiency of a glazed flat plate collector. ΔT is the difference in temperature between ambient in-flowing water temperature and the discharge temperature of the water. W/m^2 is the insolation at Logan, Utah. On the day of the test it was 970 watts/m^2.

The most cost effective, convenient-to-use, and easiest to build collector evaluated was found to be the compound trapezoidal trough collector. It has the unusual combinational advantages of:

1. Lowest cost
2. Nontracking
3. High efficiency at moderately high temperatures
4. Easiest to build
5. Requires no special dies, molds, etc.
6. Lowest elevation outlet pipe
7. Most rugged

The above attractive features, all found in the compound trapezoidal trough, are a fortuitous combination which makes it clearly superior to any other type tested. The trapezoidal trough collector is therefore the collector recommended for use on the solar pump. When two or more collector lengths are required they can be interconnected in such a way that the outlet of each unit is always higher in elevation than its inlet.

Table 2. Comparison of various features of several types of solar collectors.

	Concentrating Factor	Requires Solar Tracking	Surface-to-Aperature Area Ratio	Labor Required to Build	Special Dies, Stamps, Molds or Presses	Pump Height above Ground-Requirement-Meters	Est. Relative Cost/m^2 (Including Tracking Mech.)	Approximate Efficiency at $T_{out}-T_{amb}$ = 50°C	Comments
Cone	5-10 X	Yes	5/2	Med.	No	1-1½	$130	50%	May be subject to damage from high wind loads unless steering mechanism is rugged.
Flat Plate	None	No	1/1	Med.	No	1/2	$100	25%	Subject to glass damage.
Trapezoidal Trough	2-3 X	No	3/1	Low	No	1/2	$30	50%	Solar collector at ground level, low wind profile- rugged, good efficient and temperature range.
Fresnel Lens	3X	Yes	4/1	High	Yes	2-3	$250	50%	Plastic lens--subject to longitudinal cracking--high profile, subject to wind loads.
Louvered Mirrors	10X	Yes	1/1	High	No	1½-2	$100	50%	Fragile--technical construction receiver is 1½ meters above ground level.

SUMMARY

Several low-lift water pumps operating on a low grade solar heat source were built and evaluated according to their practicality for use in low-head, small water volume pumping, a particular need of developing countries. In addition, several promising solar collector configurations were constructed and tested. The goal was to design a system that would give long life, be relatively trouble free, and be cost effective.

The solar collector judged best had a trapezoidal collector configuration which gives 70 percent efficiency at the pump-operating temperature. Cost of this type of collector is estimated at $30 per square meter. For operating the pumps described in this report, 3 square meters of collector area are adequate.

For all four pump models tested, pump construction is simple, requiring little technical skill other than brazing or soldering. A 15-40 liter barrel or other closed container, an 8-12 liter sheet metal cylinder, a flash boiler, two check valves and a minimum of interconnecting plumbing are all that is required to construct the pump. Material cost for the Model IV pump excluding the flash boiler, is estimated at $35. The flash boiler is made of 10-15 lbs of aluminum and its construction cost is estimated at $50. As there are virtually no moving parts, the life of the system is limited mainly by metal-water corrosion rates which can be slowed or stopped by use of corrosion resistant metals or paints.

The Model IV pump uses approximately 6 liters of volatile liquid, C_5H_{10}, which is normally not expended except by small vapor losses that may occasionally occur when accumulated air is allowed to bleed from the system. If purchased in 210 liter drum quantities, the cost is approximately 50 cents per liter.

Because cyclopentane interfaces with the water being pumped federal regulatory agencies would probably not consider the water potable. In the unexpected event that some of the volatile liquid should escape into the pumped effluent, it will float on the surface of the water and rapidly evaporate. Also, according to the Merck index cyclopentane is not considered carcinogenic. The physical size of the pump can vary in accordance with the amount of water required, the heat available, and the practical size limitation imposed by the materials used.

The Model I pump lifts 12 liters per minute to a height of 3 meters, with a heat input of 5000 calories per minute. This gives an efficiency of about 1.2 percent. The estimated materials cost of this pump together with its solar collector is $250.

The Model II and Model IV pumps lift 6 liters per minute to a height of 3 meters for a materials cost for pump and solar collector of approximately $150. The Model III pump did not work well due to thermal barrier problems and air leaks. If a performing prototype were developed, its performance/cost ratio should be similar to the Model II and Model IV pumps.

The Model IV pump, while simplest in configuration does require occasional air bleeding by manual intervention. The Model I and Model II pumps do not require manual intervention. All pumps described in this report are self starting. When initially installed, they require priming.

The vacuum phase of the lift was tested up to a height of 4 meters. At this height, the increased length of the cycle time is a serious problem. If a 4 meter lift is desired a liquid other than cyclopentane should be used to achieve the necessary lower vapor pressure. Hexane with a boiling point of 70°C would be a logical choice for the higher lift situations.

RECOMMENDATIONS

The major effort of the research concentrated on developing a pump that would work at temperatures below 80°C. This concept was based on the premise that higher temperatures could not be economically achieved without using tracking collectors that were considered too costly and complex for the goals of the research, viz., the design of a simple, inexpensive, solar powered water pump.

Towards the latter part of the research, a fixed position trapezoidal trough collector was tested which demonstrated that boiling water temperatures could be economically achieved. The higher temperatures made available by use of the trough can make the design of a cost effective pump possible which does not require the use of a low boiling liquid. Steam could be used instead of cyclopentane. This simplification is attractive and should be investigated further.

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Thurston, Robert Henry. 1891. A history of the growth of the steam engine. Appleton and Co. 1884. (2nd rev. edition).

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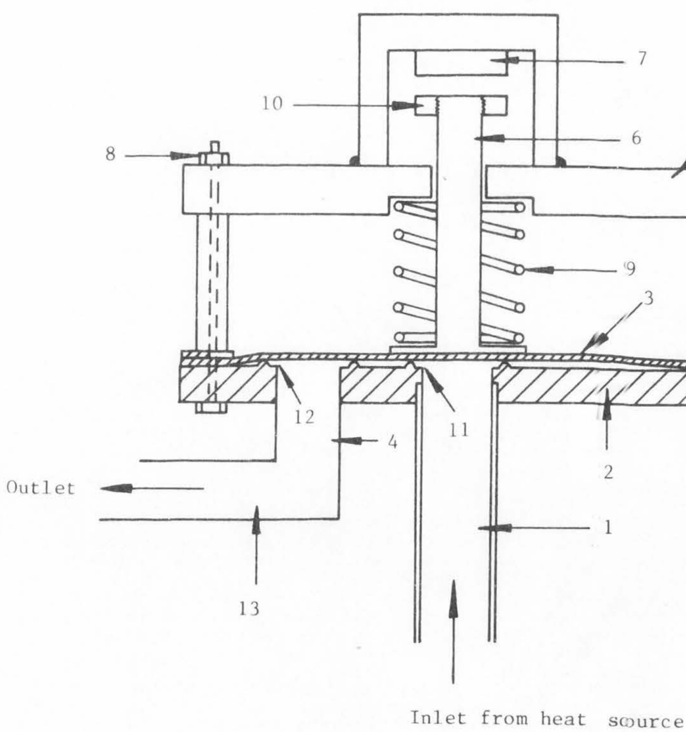
Appendix A

Pressure Operated Valve for Model II Pump

The design of the pressure actuated valve is illustrated in Figure 32. The valve is normally closed by piston 6 being spring loaded against a viton or butyl rubber diaphram, 3, which lies against valve seat, 11. As pressure builds up in pipe 1 to about 50 kPa, the spring is overridden by the applied pressure and steam, or other gases, starts to leak past the valve seat. Pressure is then quickly distributed over a large area greatly increasing the applied upward force. This action opens the valve completely in a few milliseconds; in so doing valve seat 12 is also uncovered and steam can escape through outlet 13 into the pump chamber. As steam escapes, the pressure will drop under the diaphram, but magnet 7 has latched the valve open in the initial opening process by its attraction to the ferrite material of 10 and so despite the dropping pressure, the valve stays open. When pressure drops to about 14 kPa, the magnetic attraction of magnet 7 to the iron plate 6, combined with the upward force of the 14 kPa steam is insufficient to override the downward force of the spring and so the magnet releases its load and the valve snaps shut.



1 1/4" pipe inlet tube
2 1/4" x 2½" diameter brass stock
3 1/16" x 2½" butyl rubber diaphram
4 1/2" copper pipe outlet pipe
5 1/4" x 2½" diameter brass plate
6 1/4" x 1½" brass rod with 3/4" x 1/16" flange on lower end
7 Magnet from magnetic cupboard latch
8 8-32 x 1 3/4" screws (8 total)
9 1/2" dia. x 1" spring
10 Soft iron threaded washer
11 Valve seat, 3/8" dia.
12 Valve seat, 1/2" dia.
13 1/2" rigid copper pipe
14 1/4" spacers 1" long (8 total)

Figure 32. Sketch of pressure sensing trip valve.

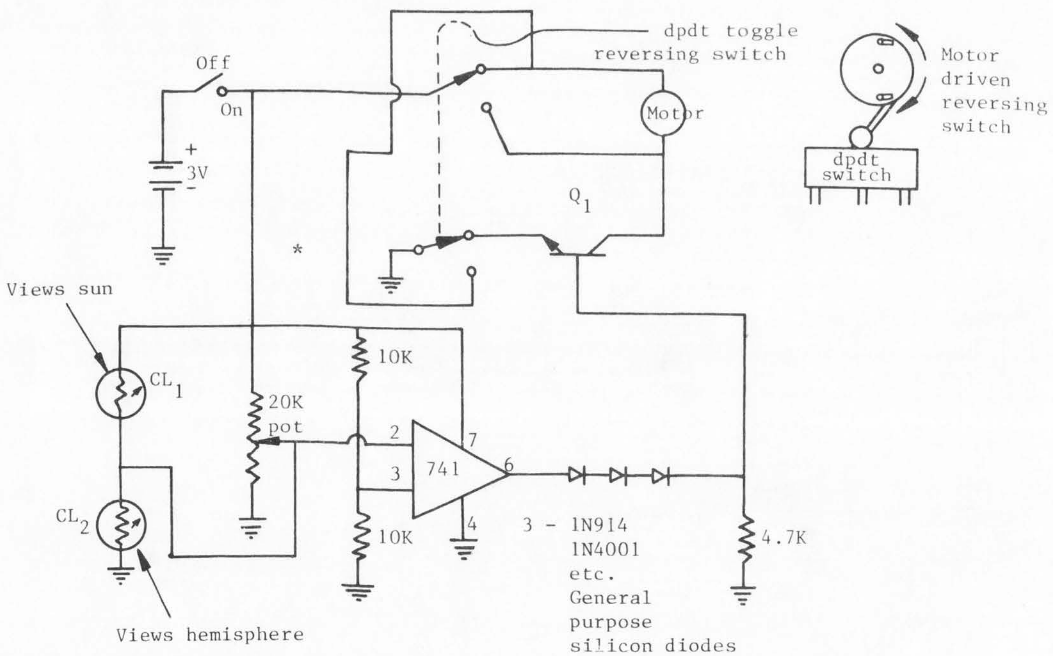
Appendix B

Solar Tracking System

The solar tracking circuit of Figure 33 was used to keep the segmented mirrors properly oriented to focus the sun on the receiver.

This circuit operates on two flashlight batteries. Since the power drain is very small, in the order of 10 ma., solar cells can be economically used in lieu of batteries.

When CL_1 is illuminated by reflected light from one of the mirrors from the sun, its resistance is lower than the resistance of CL_2 and the input to the 741 amplifier is positive. The output of the amplifier is negative in this condition and the 1N914 diodes block drive current to the switching transistor Q_1. The motor does not operate in this situation. This condition prevails as long as the mirrors are properly aligned. If Cl_1 is not illuminated, the voltage on pin 2 of the amplifier drops below the bias voltage of pin 3 and the result is a positive voltage at the output, pin 6. This voltage is applied to Q_1 switching it on, thus turning on the tracking motor. The motor will run until the mirrors are properly aligned, at which time the motor stops. The dpdt switch is motor actuated to automatically return the Fresnel lens toward the East, its normal starting point, when the sun sets in the West. If solar cells are used, the system is self-stopping and self-starting at evening and morning, respectively. If batteries are used, an evening detection shut down circuit must be added to conserve battery power.



*This may work on 3V also.

Motor is Hankscraft Model 3440 - 1/2 Rev/minute
Part # 8600-710-000
From: Hankscraft Motors
P.O. Box 120
Reedsburg, Wisconsin 53959
Cost: ≈ $10
741 is general purpose operational amplifier.
CL_1, CL_2 - Clairex CL 903L cadmium sulfide photo cell. Many other types will do.
Q_1 is NPN general purpose transistor 2N3904, 2N1302, etc.

Figure 33. Electronic solar tracking system.