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A State of the Art Survey of Solar Powered Irrigation Pumps, Solar Cookers, and Wood Burning Stoves for Use in Sub-Saharan Africa

by: J.D. Walton, Jr., A.H. Roy and S.H. Bomar, Jr.

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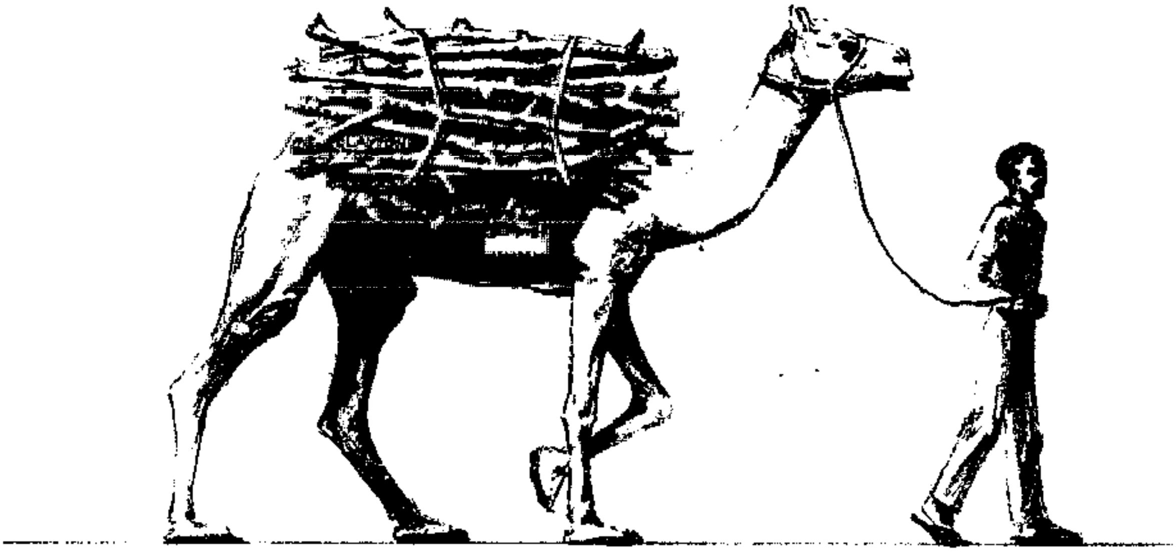
FINAL TECHNICAL REPORT

A STATE OF THE ART SURVEY OF SOLAR POWERED IRRIGATION PUMPS, SOLAR COOKERS, AND WOOD BURNING STOVES FOR USE IN SUB–SAHARA AFRICA

BY J. D. WALTON, JR.
A. H. ROY
S. H. BOMAR, JR.



FOR AL DIR'IYYAH INSTITUTE
OF GENEVA, SWITZERLAND

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OF
SOLAR POWERED IRRIGATION PUMPS, SOLAR COOKERS AND WOOD BURNING STOVES
FOR USE IN
SUB-SAHARA AFRICA

FINAL REPORT

June 1 through November 30, 1977

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For

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of Geneva, Switzerland

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Atlanta, Georgia 30332

Georgia Tech Project A-2004

ABSTRACT

This report presents the results of an in depth survey of solar powered water pumps, solar cookers and wood burning stoves, conducted for the Al Dir'Iyyah Institute of Geneva, Switzerland by the Georgia Institute of Technology, Engineering Experiment Station. The purpose of this survey was to collect, organize and disseminate pertinent information on available energy technology which will benefit the people of the less developed countries of the world.

Although the results are applicable in many areas of the world, the survey concentrated on technologies which can help alleviate the serious problems of deforestation and lack of water in the area just south of the Sahara in Africa, the Sahelian and Sudanese zones. The lower than normal rainfall of the past several years in this area has combined with ever increasing cutting of firewood for cooking and other thermal applications to create an energy and ecological crisis; energy for pumping water for irrigation to reduce dependency on rain and energy for cooking to halt the excessive cutting of firewood. Three technical innovations have been identified as being capable of alleviating this crisis: 1) solar powered water pumps for irrigation and domestic water supply, 2) use of simple, direct heating solar cookers for preparing mid-day meals, and 3) use of simple, efficient wood burning stoves to reduce the amount of wood required for cooking when solar radiation is not available.

This report documents previous technical developments in the three areas identified and describes findings obtained during visits to four countries of the sub-Sahara: Sudan, Niger, Mali and Senegal. Although programs to develop solar cookers have been actively pursued for over 100 years, they have never found acceptance at the village level. This study suggests that the lack of acceptance may be due more to insufficient attention to developing an adequate program of village instruction than to technical or social/cultural problems per se. Solar powered irrigation systems have been used in these areas for over ten years and are accepted as the only solution to providing water by pumping. Simple wood burning stoves made from local materials, primarily clays, could dramatically reduce the amount of wood used for cooking which is now usually done on open fires.

The conclusions of this report are used to recommend four areas for further development: 1) more efficient, higher temperature solar powered water pump systems, 2) a program to introduce low-cost, locally fabricated parabolic dish type solar cookers for village use, 3) a simple, locally manufactured, essentially ceramic wood burning cookstove, and 4) an African workshop to better disseminate technical, social and cultural information between the various sub-Sahara countries and between those countries and the developed countries which possess the needed energy technology.

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I. INTRODUCTION

Since the oil embargo of 1973 world attention has turned to the problem of diminishing fossil fuel supplies and to the search for alternative energy resources. Among the renewable energy resources which are being considered one of the most popular and perhaps the most promising is solar energy. The almost explosive growth of this technology since 1973 is evidenced by the fact the Federal (NSF-ERDA-DOE) budget for solar energy research and development increased from $6 million in Fiscal Year 1973 to almost $400 million for FY-1978 1/. Essentially all of these monies are directed toward solving solar energy problems associated with developed nations and are based generally on a high level of technology, and a high standard of living.

Long before 1973 it was becoming apparent that the less developed countries (LDC's) would be facing energy problems quite different from those which would be faced by the developed countries in the 1970's. With a low technological base and immature economic development, the LDC's depend heavily upon man or animal power for mechanical energy and upon forest and agricultural products for thermal energy. Therefore, as these countries began the process of developing, and as their population and standard of living began to increase serious energy shortages developed. During this period a number of concerned organizations and individuals began to consider the problem of increased energy requirements for these countries and started experimenting with the use of solar energy as a means of supplying their energy needs. These efforts generally have not been successful on a significant scale because of technical, economic, social or political reasons. However, they have served to identify and prioritize the most serious energy problems facing the LDC's. It is generally agreed that high among these is the combined energy/environmental problem of deforestation. Nowhere is this problem more serious than in the Sahelian and Sudanese zones of Africa (sub-Sahara Africa). Since wood is rural Africa's primary source of thermal energy, development leads to a vicious cycle of over population/overconsumption of available firewood/deforestation/siltation/flooding and reduced productivity. This makes meeting even the existing fuel needs of the villages of sub-Sahara Africa a monumental task. The environmental problem of naturally low rainfall in the sub-Sahara has become even more serious during this decade because of below normal rainfall. Therefore, the combined tasks of reducing the requirement for firewood and at the same time providing the water needed to reverse the process of deforestation are indeed overwhelming and have been considered by some to be the most profound ecological challenge of the late 20th century 2/. However, during the past 15 years it has been amply demonstrated that solar energy can provide both the thermal energy required for cooking and the mechanical energy necessary to pump the water needed for irrigation. Further, because of the distributed nature of solar energy, it is readily available to the widely dispersed village population of sub-Sahara Africa.

References are identified by numbers in this format: 1/.

II. PURPOSE

The purpose of this program is to carry out an in depth state of the art survey of solar powered irrigation pumps, solar cookers and wood burning stoves. The irrigation survey emphasizes shallow well irrigation pumps that lift water 6 to 8 meters (20 to 25 feet). However, a brief summary of current activities on deep well pumps utilizing solar power is included. The solar cooking survey considers primarily cooking systems that are capable of transferring the heat from a collector into a shelter and which provide some amount of storage. The wood burning stove survey emphasizes very simple devices, capable of being manufactured locally and which would significantly increase the thermal efficiency of wood burning for cooking. These cooking and solar irrigation systems are being considered for use in the Sahelian and Sudanese zones of Africa in order to reduce the use of wood and to aid in reclaiming productive land lost through deforestation and drought.

III. BACKGROUND

A. The Energy Problem

On a world wide basis, wood is considered the fourth most important source of energy after oil, coal and natural gas. In developing countries, wood accounts for 28 percent of energy use, and in Africa south of the Sahara the figure is 75 percent. For the world as a whole, 50 percent of the wood consumed as fuel is used for cooking and 30 percent for domestic heating; the remaining 20 percent is used for other household purposes, for processing agricultural products, and for industry.

Many less developed countries depend upon wood as their major source of fuel. In rural areas of the third world where wood is readily available, nearly 95 percent of households use it as a primary source of energy and it has been referred to as the poor man's oil 3/. In 1974, according to statistics provided to the United Nations, about 52 percent of the total world round timber production was used as firewood or as charcoal 4/ (see Table I). Since the greater part of firewood production and usage takes place outside commercial channels and therefore goes largely unrecorded, it is safe to assume that over half the world's wood crop is being burned as fuel. In developing regions, the proportion is much higher; according to Food and Agriculture Organization (FAO) of the United Nations statistics, 93 percent of wood cut in Africa south of the Sahara is used as fuel, and 86 percent is used over all the developing world 5/.

The magnitude of firewood consumption in the world, especially in the developing countries, as well as its significance in the everyday life of more than two billion people, was not realized until recently. The energy crisis which started in 1973, together with the increasing attention now being given to rural economies in general, and rural energy requirements in particular, have attracted new interest to the problems of firewood.

With the catastrophic drought and famine of early 70's south of the Sahara, little known countries such as Chad, Upper Volta, Mauritania, Senegal, Mali and Niger suddenly appeared in front-page newspaper stories. As the stories of misery and dislocation facing millions of Africans began to unfold, so did the realization that desert-like conditions were being created by indiscriminate cutting of trees to serve as firewood 6/. The U. S. Agency for International Development estimates that over the past fifty years 650,000 square km of land suitable for some form of agriculture have been forfeited to the Sahara along its southern edge. Various analysts dispute the rate of encroachment but all of them are in agreement that the productivity of sub-Sahara Africa is being severely damaged by intensive cutting.

Firewood is a scarce and expensive item throughout sub-Sahara Africa, all the way from Senegal to Ethiopia. The scarcity of firewood imposes a particular economic and social burden on the poor. A family in Niamey

TABLE I

ESTIMATED FUEL WOOD AND CHARCOAL CONSUMPTION 1971

	Population Millions	Wood Fuel Consumption		
		Total Million m^3	m^3/capita	As a Percentage of Total Round Wood Consumption
World	3,683	1,381	0.37	52
Developed Economies a/	1,125	161	0.14	13
Developing Economies	2,558	1,220	0.48	86
South-East Asia and Oceania	306	278	0.91	88
South Asia	711	267	0.38	95
China and rest of Asia	839	148	0.18	75
Near East North Africa	194	68	0.35	88
West and Central Africa	119	110	0.92	93
East and South Africa	103	117	1.14	93
Central America and Caribbean	92	33	0.36	75
South America	194	199	1.03	83

a/ Australia, Canada, Europe, Israel, Japan, South Africa, USA, USSR.

Sources: IBRD Atlas 1973; FAO Yearbook of Forest Production 1973 Table 4.

must now spend about 1/10 of its income on fuel for cooking. The caravans that bring this precious resource into the towns are contributing to the creation of desert-like conditions in a wide band along the desert's edge. Virtually all the trees within 70 kilometers of Ouagadougou in Upper Volta have been consumed as fuel by the city's inhabitants, and the circle of land stripped bare for firewood is continually expanding 2/.

The collection and transport of wood in rural areas is mainly by human and animal labor, so it is normally gathered from areas within walking distance of the village, a distance which in hard-pressed firewood areas such as the Sahelian region may be as much as 50 kilometers. The Acacia tree, useful for firewood, was common around Khartoum, Sudan as recently as 1955; by 1972, the nearest such trees were 90 kilometers south of the city. It is estimated that the overall southward progression of vegetational belts in Sudan has proceeded by 150 kilometers in 20 years 6/. The inhabitants of rural villages in the developing world - usally the women - must walk increasing distances to secure domestic fuel. In terms both of labor and money, half the world's population finds the price of firewood too high to pay.

Moumouni surveyed the energy needs and problems in the Sahelian and Sudanese zones and how they might be provided by solar energy 7/. The countries of concern were Senegal, Mauritania, Guinea, Mali, Upper Volta, the Ivory Coast, Togo, Dahomey, Niger, Nigeria, Cameroon, Chad, Sudan, Ethiopia, Uganda and Kenya, (Figure 1). As he pointed out, the consumption of wood, with the attendant environmental consequences (deforestation, erosion, changes in rainfall, etc.) is one of the most worrisome energy policy trends in African countries of the Sahelian zone. The average per capita consumption of wood for cooking is estimated at one half ton per year. This amounts to 50-60 million tons of wood per year for cooking in the Sahel (Chad, Mali, Mauritania, Niger, Senegal and Upper Volta).

Another serious problem in sub-Sahara Africa is the shortage of natural rainfall. This characteristic of the climate is directly responsible for the meager firewood resources in the area as well as great personal and economic hardship for the inhabitants. The starvation of human beings, the destruction of cattle and the degradation of the environment have acquired proportions that are scarcely conceivable, basically because of unresolved problems of energy needs for the pumping of water (for irrigation, drinking and cattle raising) from existing rivers, wells or artifical lakes and ponds 7/.

Clearly, developing energy sources to replace wood for cooking and for the pumping of water for irrigation would solve two of the most serious energy/environment problems of sub-Sahara Africa.

Because of the broad scope of existing solar energy expertise and capability at Georgia Tech and because of the potential of this resource to help in solving the human/energy/ecological problems of the countries bordering

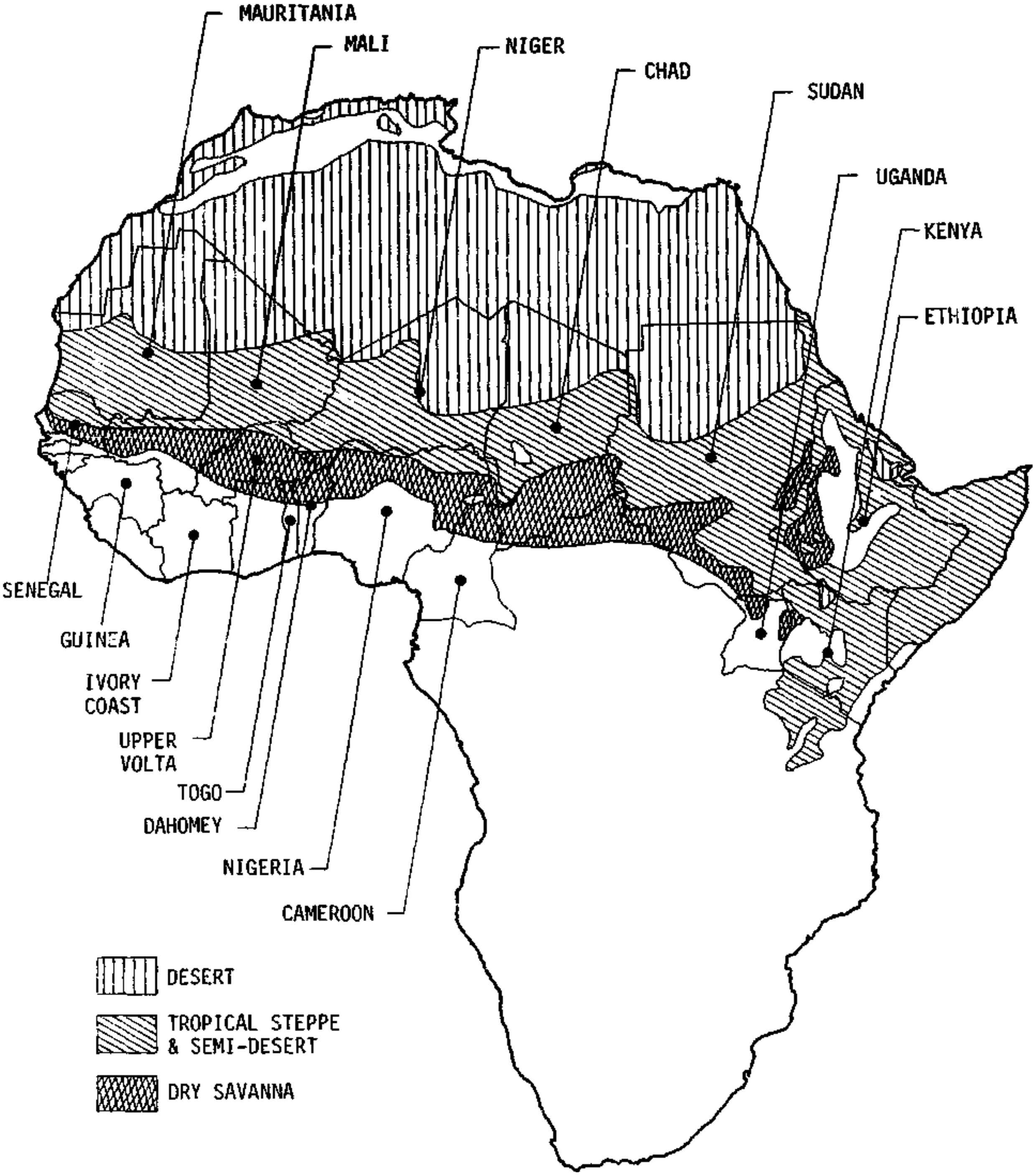


Figure 1. Map Showing Countries of Sahelian and Sudanese Zones of Africa and Areas Occupied by Desert, Semi-Desert and Dry Savanna.

the Sahara, Georgia Tech provided funds for the author to personally visit seven of these countries to see first hand the energy/ecological problems and to obtain available information concerning the results of efforts to apply solar energy to solve these problems. The countries visited were Algeria, Tunisia, Egypt, Sudan, Niger, Mali and Senegal. Sudan was visited in July and the other countries in October 1977. In all countries researchers involved in the solar energy programs were visited and the state of development of each country's program reviewed. In addition, critical energy problem areas were identified and efforts to apply solar energy discussed. In all cases the problems of deforestation and lack of water previously described in this section were confirmed.

B. The Solar Solution

As pointed out in the previous section there is a growing awareness of the special nature and seriousness of the energy problems of the less developed countries. Also, it is becoming increasingly clear that in the United States and in the developing countries themselves solar energy technology is being developed which is capable of solving those problems. By surveying the state of solar energy technology relevant to the most critical needs of the LDC's and keeping in mind the need to protect their social, cultural, political and religious values it should be possible to identify and/or conceptualize solar systems with the greatest potential for supplying a significant portion of their energy needs.

It has been previously noted that energy for water pumping and cooking represent two of the most critical energy and ecological problems of sub-Sahara Africa.

Water pumping requirements of developing nations generally are for raising water from depths of less than 10 meters (about 30 feet). A number of solar pumping systems have been developed and currently are in operation in various parts of the world. Generally these utilize low temperature flat plate collectors to heat an organic working fluid which drives a heat engine to power a mechanical pump 8/. Because of the low temperature of the working fluid, the overall efficiencies are of the order of one to two percent and consequently these systems are not yet economical for most applications. In the United States there are experimental solar powered water pumps using parabolic trough collectors with efficiencies of the order of 10 percent 9/. Georgia Tech recently participated in an ERDA program to develop a 150 kW solar electric central receiver power system for deep well irrigation 10/. Because of the very high temperature provided, the overall efficiency of this system should be of the order of 20 percent. The economics of these systems are not yet established and each will have advantages and disadvantages with respect to suitability for less developed countries. Several other systems using different types and sizes of collectors and various working fluids are being developed and each one must be evaluated in light of the needs of the particular country for which it is being considered.

At this time solar units for cooking food are not seriously being developed in the United States. Those which currently are in use in other parts of the world and which are being developed in other countries usually provide heat for cooking only when the sun is shining. Typically this is from about 9 a.m. until 3 or 4 p.m. As pointed out in the previous section, obtaining wood for cooking is becoming increasingly difficult in many areas of sub-Sahara Africa and a major portion of the day is required for collection. The growing seriousness of the problem can be seen when it is realized that in a typical village in Senegal about 80 percent of the total energy demand is for cooking 11/. Therefore it is urgent that a substitute be found to replace wood for the cooking of food. Based on most reported efforts to use solar cookers at the village level, they should not be expected to replace a significant quantity of wood unless they can provide for the cooking to be done in the shade. Also it would be desirable if cooking could be done at times other than just when the sun is shining. This requires that some type of thermal storage system be incorporated into the cooker. However, in Khartoum it was reported that 80 percent of the wood used for cooking was consumed in the middle of the day 12/. Except for some systems which used circulating hot oil and were proposed many years ago, storage and subsequent transfer of the collected heat represent new requirements for solar cookers. A review of the state of technology of solar cookers must therefore incorporate a review of the state of technology of thermal storage and heat transfer systems in order to be complete.

In carrying out such a state of the art survey it also is important that consideration be given to such other factors as village size and other methods which might be used to conserve or augment present energy sources, particularly wood. Therefore, multiple or hybrid energy sources should be considered. For example, when introducing solar cookers into a village it might be appropriate also to introduce a simple wood burning stove that would more efficiently use wood at times when the solar cooker could not be used. The presently inefficient use of wood for cooking is to a large extent responsible for the excessive use of wood. A simple wood stove alone could reduce the consumption of wood by at least 50 percent. In sub-Sahara Africa with its 200 million people, this could represent a potential saving of more than 50 million tons of wood per year. Therefore, a section of this report will review the state-of-technology of wood burning stoves. Another example of multiple energy use might involve agricultural products; for example, in areas where peanuts are a major crop, peanut oil might serve as an available heat transfer fluid for a solar cooking-storage system. The combustible waste products from the peanut processing could be employed as a fuel, either directly or as charcoal for a steam engine which could also be powered by solar energy. The steam engine could be used to produce electricity for pumping water and also to provide lighting. The hybrid operation of the steam generator would allow it to utilize solar power during the day and combustible waste product as fuel in the evening. A steam engine using peanut waste has been successfully operated in Koulikoro, Mali 13/. Finally, to maximize the utilization of available energy, surplus heat from the steam engine could be used to augment the solar heat for the storage system in the cooking unit.

IV. SURVEY OF SOLAR POWERED WATER PUMPS, SOLAR COOKERS AND WOOD BURNING STOVES

All of the pertinent background material relevant to this survey was collected to form a comprehensive review and is included as a Bibliography in the Appendix. Most of the solar energy material was obtained from such sources as Solar Engineering, Solar Age, Solar Energy, Sun World, Journal of Scientific and Industrial Research, Proceedings of the United Nations Conference on New Sources of Energy and Heliotechnique and Development. The most promising concepts and results obtained from these sources are presented in the following sections as they suggest ways and means that might lead to the successful introduction of solar water pumps, solar cookers and wood burning stoves into the rural areas of sub-Sahara Africa.

A. Survey of Solar Powered Irrigation Pumps

Toward the end of the last century, work to develop solar steam boilers and power plants assumed technical significance under the investigations of Mouchot and Pifre 14/. Mouchot's boilers, protected by two glass cupolas, were arranged on the focal line of a conical mirror. In order to increase the concentration of solar rays on the heating surface of the boiler, Pifre used an approximate paraboloid, composed of strips of truncated cones. These machines were used to prepare food, to distill sulfuric acid, to prepare benzoic acid, and to purify linseed oil. They also produced steam at 3 to 9 atmospheres pressure which was used to drive steam engines, for water-lifters and for producing ice. A picture of one of Mouchot's solar steam power systems used to run a printing press is shown in Figure 2. In spite of their sensational success, these machines did not withstand the competition of cheaper and more reliable coal-fired steam boilers and thus never found wide use.

The next most significant development was by F. Shuman in 1910-1913 in Tacony near Philadelphia and in Midi near Cairo 14/. The boiler system of the latter of these stations was constructed of five parallel-connected boilers heated by concentrated solar energy reflected from a faceted parabolic-cylindrical mirror 61 m long and 3.9 m wide. These mirrors, which consisted of 16 flat strips,provided only a relatively low concentration so that the efficiency of the system was only about 4 percent. Due to its complexity, the relatively high cost of custom manufacture, and the limitation of working only during hours of sunshine, this machine could not withstand the competition of combustion equipment and was scrapped after a few years of operation.

With the growing abundance of cheap fuel and the development of highly efficient internal combustion engines and gas turbines, solar powered mechanical devices were reduced to the role of curiosities during the decades of the 1920's through the 1950's. During the 1960's however, attention began to turn to the rapidly growing energy problems of the less developed countries. Although fossil fuels were still relatively cheap and in apparently abundant

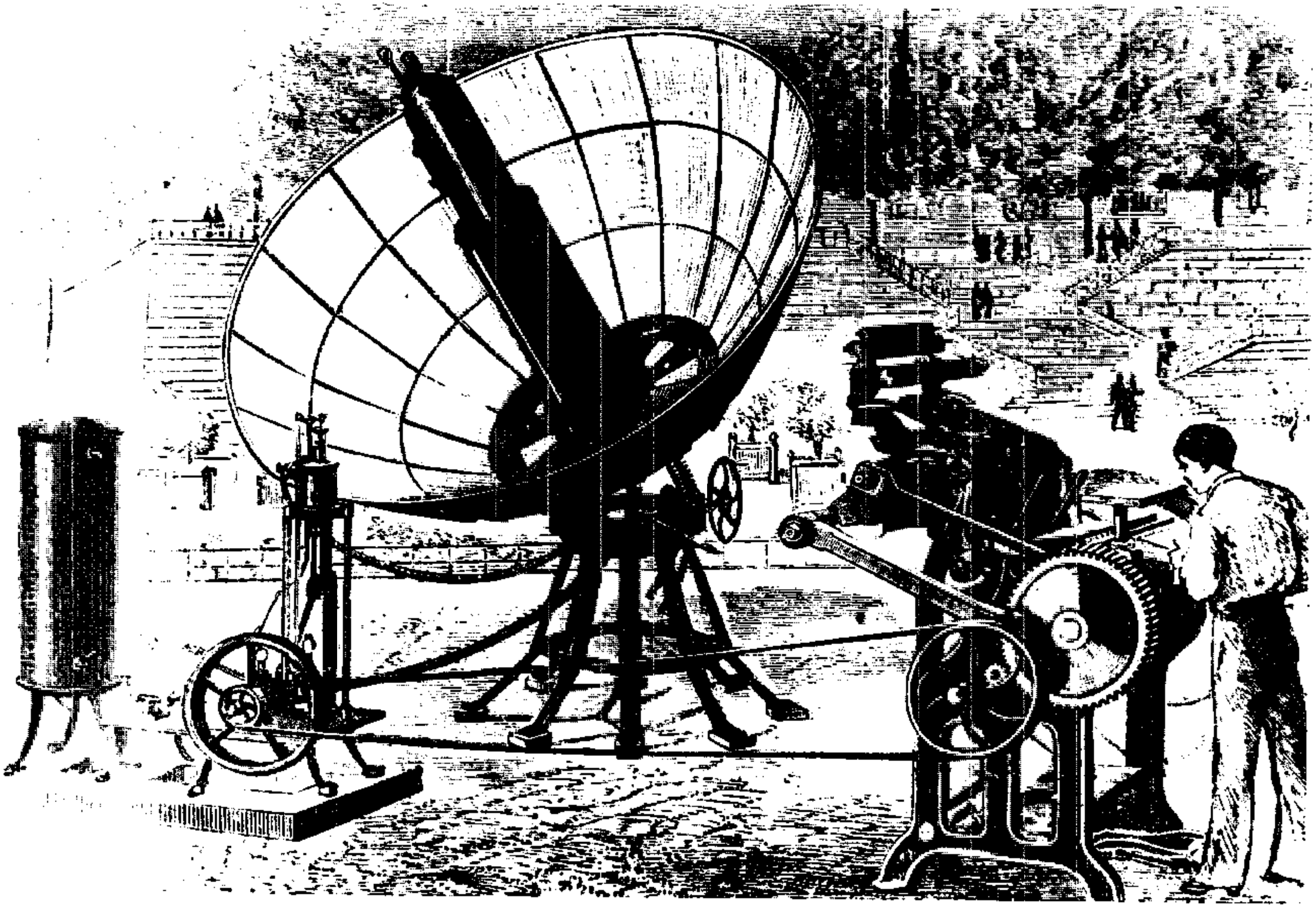


Figure 2. Solar Power System of Mouchot Used to Operate a Printing Press.

supply it was becoming evident that supplying the energy needs of the developing countries was not the same as that for the developed countries. This was due primarily to the very dispersed nature of their rural populations and the lack of transportation or other distribution networks which were a necessary adjunct to the conventional energy systems of the developed countries. Therefore, during the 1960's numerous groups and individuals began to seriously consider solar energy as an energy form which had the advantage of aiding decentralization and had the potential of providing self sufficiency at the village level.

The most active group in developing solar powered irrigation systems during this period was the French company, Societe Francaise d'Etudes Thermiques et d'Energie Solaire (SOFRETES) 8/. The basic system developed by SOFRETES utilizes flat plate collectors to heat water which passes through a heat exchanger (evaporator) in which an organic liquid such as butane or Freon is vaporized. The vaporized gas then operates a Rankine cycle reciprocating engine or turbine. The expelled gas passes through another heat exchanger (condenser) where it is condensed to the liquid phase by the cooling provided by the pumped water. The condensed organic liquid is then returned to the boiler by a pump driven by the engine or turbine. Figure 3 is a schematic of a typical SOFRETES solar water pumping system. Figures 4 and 5 are photographs taken of the 1 kW SOFRETES system near Khartoum, Sudan during the visit in July 1977. This facility, which began operation in April 1977, pumps water from a depth of 30 meters to a reservoir 8 meters above the ground and provides irrigation for one hectare. The total cost of this sytem was $50,000. Due to the developing market SOFRETES reported that a similar system could now be provided for about $25,000. However, even at this price they are acceptable for village use only with large government or donor subsidy. It has been estimated that the installed price must be in the order of $1,000 to $1,500 per kilowatt before small and medium-sized solar irrigation systems can provide the basis for economic and social changes 15/. Table II provides a summary of the characteristics of the major SOFRETES systems installed in various developing countries.

During the 1970's many additional solar irrigation systems were developed in the United States, the USSR and Israel. In the United States a major effort was the solar powered irrigation systems developed during 1976 and 1977 to meet the needs of the southwest United States. The current status of solar irrigation system development is summarized in Table III. More than a half dozen variations of solar irrigation systems have been constructed, five of which are summarized in Table III. As summarized in Table II SOFRETES has installed some 36 irrigation systems in Africa and Latin America, and many additional stations are being built for various countries. In addition, the first phase of a project with the Government of Mexico has just been completed which includes ten hydraulic pumps for village and livestock, plus an initial 25 kW station for irrigation. The 25 kW installation has been operating since September 18, 1975 and it operates according to the same principle as the 1 kW stations,

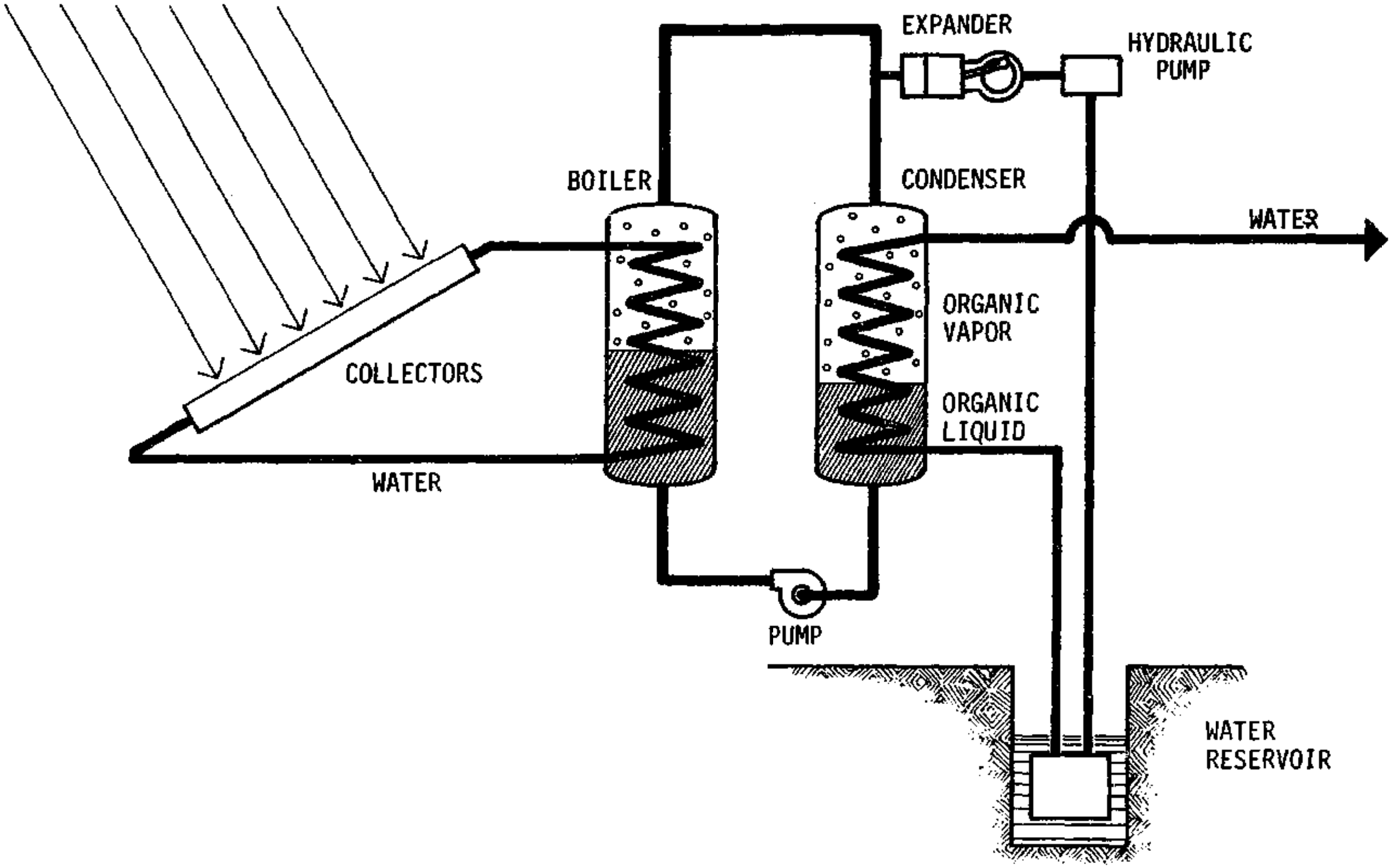


Figure 3. Schematic of a Typical SOFRETES Solar Water Pumping System.

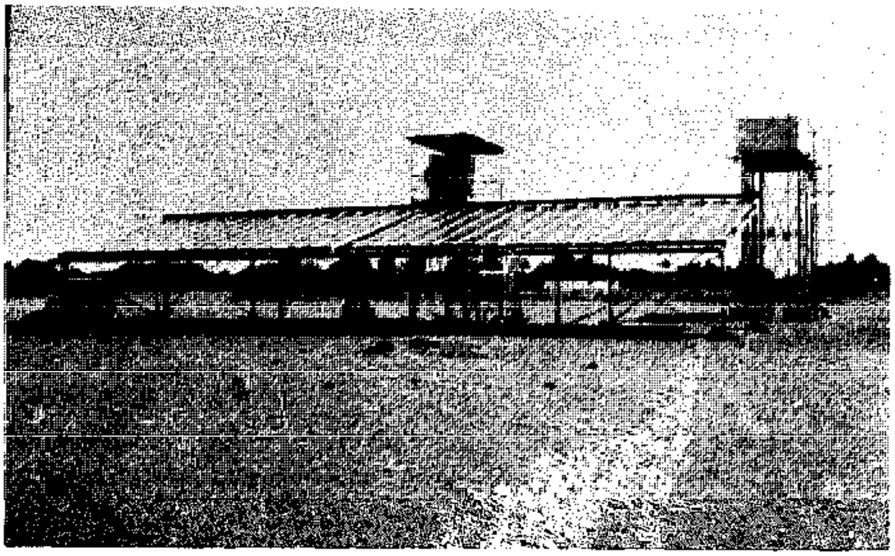


Figure 4. Photograph of 1 kW SOFRETES Solar Powered Water Pumping System Near Khartoum, Sudan.

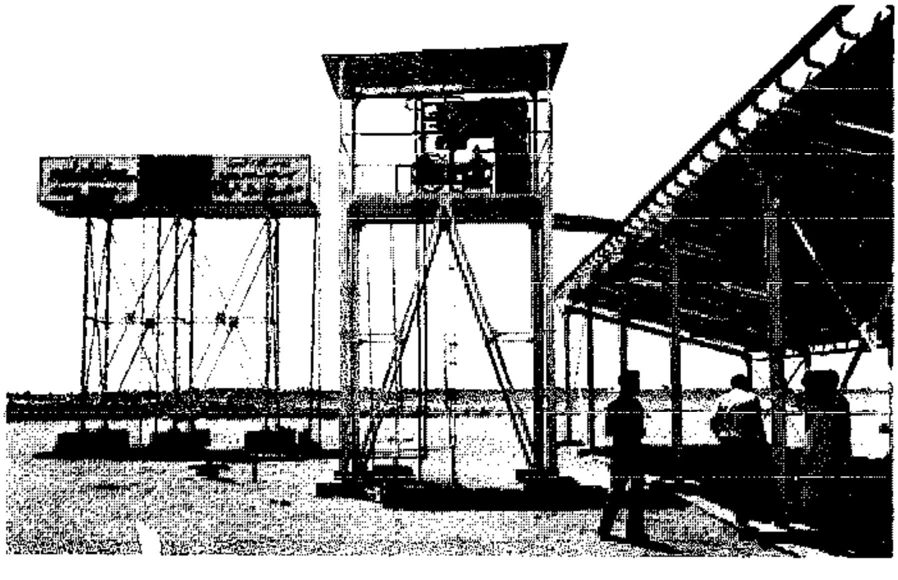


Figure 5. Photograph of the Organic Engine Pumping System and Water Reservoir of the 1 kW SOFRETES System near Khartoum, Sudan.

TABLE II

PUMPS INSTALLED BY SOFRETES

Location	Number of Pumps	Year of Installation	Area of Collector (m^2)	Output Capacity (m^3/hr)	Pumping Level (m)	Operating Time (hr/day)
Senegal-	7					
I.P.M.-Dakar		1968	88	6	25	5-6
I.U.T.-Dakar		1975-77	n.r.	n.r.	n.r.	n.r.
Niakhene		1976-77	n.r.	n.r.	n.r.	n.r.
Meouane		1976-77	n.r.	n.r.	n.r.	n.r.
Medina Dakhar		1976-77	n.r.	n.r.	n.r.	n.r.
Kanel		1976-77	n.r.	n.r.	n.r.	n.r.
O.N.U.D.I.-Test Pump		1976-77	n.r.	n.r.	n.r.	n.r.
Upper Volta-	4					
E.I.E.I-Ouagadougou		1971	30	2	20	5-6
E.R.-Ouagadougou		1975	75	3-5	45	5-6
Koupela (a)		1975	75	5	20	5-6
Djibo		1976-77	n.r.	n.r.	n.r.	n.r.

n.r. = Not Reported.

(a) = Hospital (with refrigeration installation).

(Continued)

TABLE II (Continued)
PUMPS INSTALLED BY SOFRETES

Location	Number of Pumps	Year of Installation	Area of Collector (m^2)	Output Capacity (m^3/hr)	Pumping Level (m)	Operating Time (hr/day)
Mauritania-	1					
Chinguetti (b)		1973	72	5	23	5-7
Niger-	1					
Niamey		1973	60	6-7	12	5-6
Mali-	2					
Dioila		1975	80	3	30	6
Katibougou		1976-77	n.r.	n.r.	n.r.	n.r.
Sudan	1					
Khartoum		1976	100	5	30	5-7
Kenya-	1	1976-77	n.r.	n.r.	n.r.	n.r.
Chad-	3					
Ati		1976-77	n.r.	n.r.	n.r.	n.r.
N'Gouri		1976-77	n.r.	n.r.	n.r.	n.r.
Karal		1976-77	n.r.	n.r.	n.r.	n.r.
Cameroon-	1	1976-77	n.r.	n.r.	n.r.	n.r.

n.r. = Not Reported.

(b) School.

(Continued)

TABLE II (Concluded)
PUMPS INSTALLED BY SOFRETES

Location	Number of Pumps	Year of Installation	Area of Collector (m^2)	Output Capacity (m^3/hr)	Pumping Level (m)	Operating Time (hr/day)
Abu-Dhabi-	1	1976-77	n.r.	n.r.	n.r.	n.r.
Madagascar-	1	1976-77	n.r.	n.r.	n.r.	n.r.
Cape Verde Islands	1					
St. Domingos		1976-77	n.r.	n.r.	n.r.	n.r.
Brazil-	1					
Paraiba Univ.		1976-77	n.r.	n.r.	n.r.	n.r.
Mexico-	11					
Sonora (b)		1974	90	3	12	5-6
Durango (b)		1974	90	4	40	5-6
Mexico		1974	MOVABLE DEMONSTRATION PUMP			
Potosi		1975	80	4	20	5-6
Mexicali		1975	80	7	20	5-6
La Cruz		1975	80	4	30	5-6
San Luis de la Paz (25 kW) (b)		1975	1500	150	54 & 30	5-6
(Other) - 4		1976	n.r.	n.r.	n.r.	n.r.

n.r. = Not Reported.

(b) = School.

TABLE III

SURVEY OF SOLAR POWERED IRRIGATION PUMPS

Parameter	SOFRETES (Typical)	SOFRETES (Khartoum)	ERDA (Willard)	Battelle (Gila Bend)	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 Cylinder	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 Transmission	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

except that the expansion engine is replaced by a turbine which drives an alternator. The second phase will include the installation of solar energy pumps throughout the country to equip wells where presently no installations exist. A 1 kW pumping station is being installed in the Emirate of Abu Dhabi for demonstration purposes; it will be located in Al-Akin at one of the government experimental farms. The largest SOFRETES system will consist of three 25 kW electric generators to be installed on the Niger River near Timbuktu in Mali.

The world's largest solar powered irrigation system was dedicated on April 25, 1977 at Northwestern Mutual Life Insurance Company's Gila River Ranch, southwest of Phoenix, Arizona 16/. The system, developed by the Columbus Laboratories of Battelle Memorial Institute, includes a 50-horsepower pump capable of delivering up to 10,000 gallons of irrigation water per minute at peak operation. The irrigation system, which features 5,500 square feet of parabolic tracking collectors, was developed as part of a multiproject cooperative program between Northwestern Mutual Life and Battelle Memorial Institute at a cost of 2.5 million dollars.

Other large solar powered irrigation demonstration systems using parabolic trough concentrators are being developed by ACUREX. The most recent is a 25 kW system in Willard, New Mexico which went into operation in 1977. Figures 6 and 7 shows the parabolic collector field and reservoir respectively for the Willard installation 17/.

The present trend in solar irrigation systems is to utilize concentrating collectors in order to increase the temperature of the working fluid and thus increase the overall efficiency of the system. By increasing the system efficiency, the required collector area is reduced proportionally assuming all else is constant. For example, consider the flat plate collector system of SOFRETES at Khartoum with an efficiency of 1 percent requiring a collector area of 100 square meters. If a concentrating collector could provide a similar system with an overall efficiency of 10 percent, then only 10 square meters of collector area would be required. Although one- or possibly two-axis tracking might be required for the collector, it could be expected that the total cost of the 10 m^2 concentrating collector system might be less than that for the 100 m^2 flat plate collector system. Also, the higher temperature provided by the concentrating system allows the use of a simple steam engine which may prove to be more adaptable to village use and available technology. Another factor which should be considered in the sub-Sahara is the very fine, continuously airborne dust. During the July 1977 visit to the SOFRETES system near Khartoum (shown in Figures 4 and 5), a substantial amount of dust was noted to have penetrated the seal between the double glass and the flat plate collectors. During the period of less than one year since installation about 5 percent of the collector area had become covered with dust. Because of the

Figure 6. Photograph of Parabolic Collector Field of the 25 kW Solar Powered Irrigation System at Willard, New Mexico.

Figure 7. Photograph of Water Reservoir of the 25 kW Solar Powered Irrigation System at Willard, New Mexico.

extremely fine particle size of the airborne dust a very good seal must be provided between the glass and the collector frame in order to prevent dust penetration. On the other hand, such fine dust is readily swept away from smooth, exposed surfaces by even a very low velocity breeze. Therefore the performance of concentrating collectors may be less affected by the fine dust of sub-Sahara Africa than flat plate collectors.

A two-axis tracking, parabolic trough, concentrating collector system was recently developed by Sunpower System Corporation of Tempe, Arizona 16/. This collector system is reported to be capable of providing the temperature necessary to operate a steam engine; a demonstration unit of the system is shown in Figure 8. Although the price of the Sunpower collector system was not available it has been reported that the ACUREX single axis tracking parabolic trough system including the thermal receiver is between $12 and $15 per square foot at the factory 18/. This price is of the same order as flat plate collectors.

When considering solar powered water pumping systems for sub-Sahara Africa it should be remembered that for most areas, only units between 1 and about 4 kW are required. This is based on normal village water requirements and the need for grazing. If fewer larger systems are located at some distance apart they tend to attract more people and larger herds of cattle which rapidly overgraze the available land. On the other hand, if more numerous small systems are provided at shorter distances the grazing is more dispersed and suitable grazing land is more easily maintained.

Assuming that many water pumping requirements can be met with a 2 kW system, then at 10 percent efficiency only a 20 m^2 collector area is required. This could be provided by a parabolic dish concentrator 5 meters in diameter. Although two axis tracking will be required for such a concentrator, the collector system has been reduced to a single component which may be easier to install and maintain than a larger area of parabolic trough collectors or 200 m^2 of flat plate collectors. Also, it is possible that a parabolic dish system of this size could be made as a portable unit which might be moved from one site to another and could easily be converted from water pumping to an electrical generating system. Such a parabolic dish is currently in production by Scientific Atlanta for use as an antenna for satellite communications. This dish is being considered as a prototype for a parabolic dish solar concentrator. Preliminary calculations have indicated that a concentration ratio of 500 and a working temperature of 315-375^{o} C are easily obtainable with this dish. The cost of such a collector on a production basis has been estimated to be about $10,000. It is possible that a complete package unit delivering 2-3 kW of mechanical energy could be mass produced for about $15,000 or of the order of $5,000 per kilowatt. Figure 9 is a photograph of the existing 5-meter diameter parabolic dish antenna produced by Scientific Atlanta. This antenna which weighs about 1 ton, is designed to operate in winds up to 65 km/hr (40 mph) and to survive in winds of 165 km/hr (100 mph).

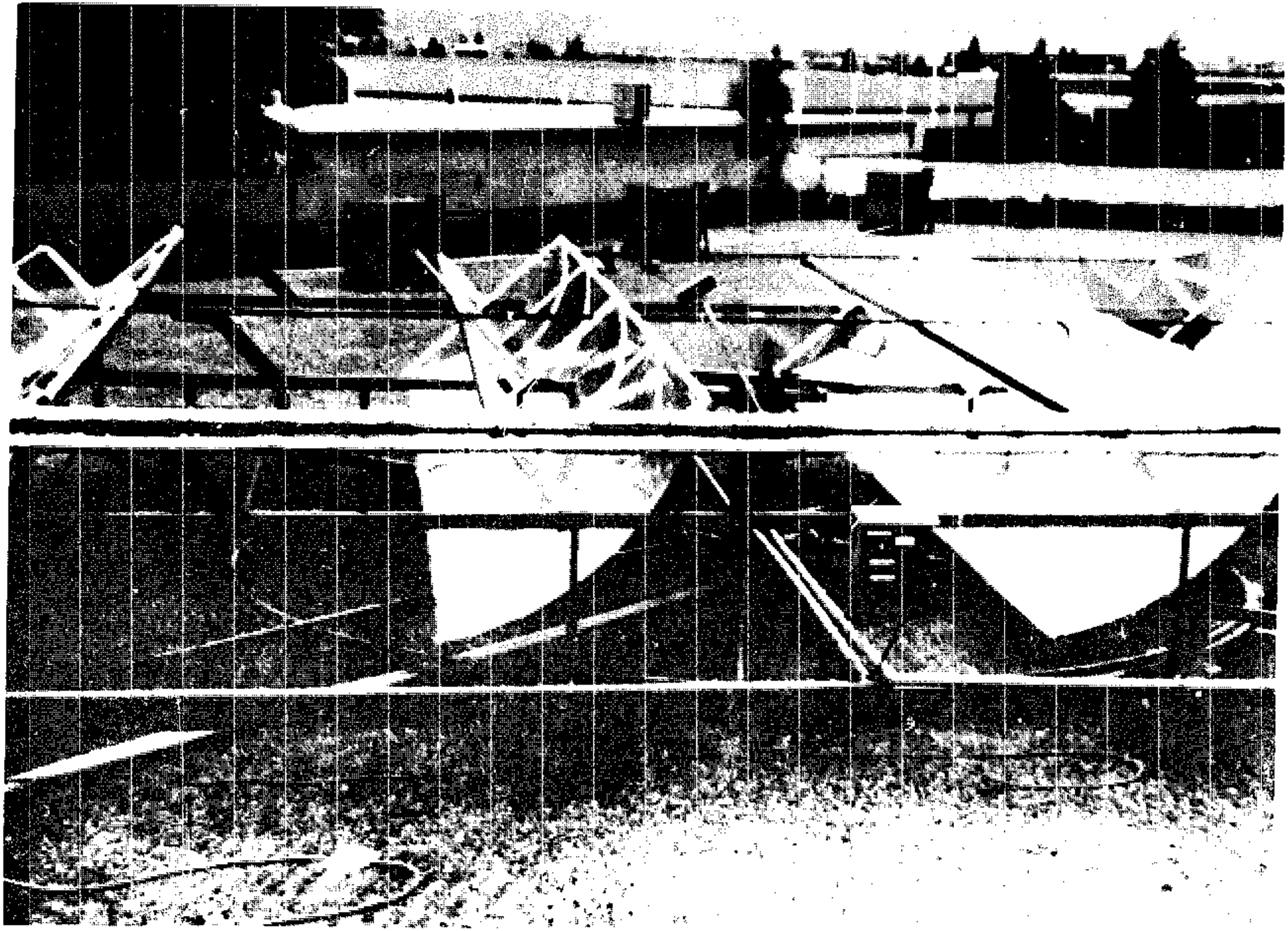


Figure 8. Photograph of Two-Axis-Tracking, Parabolic Trough, Concentrating Collector System Developed by Sunpower System Corporation of Tempe, Arizona.

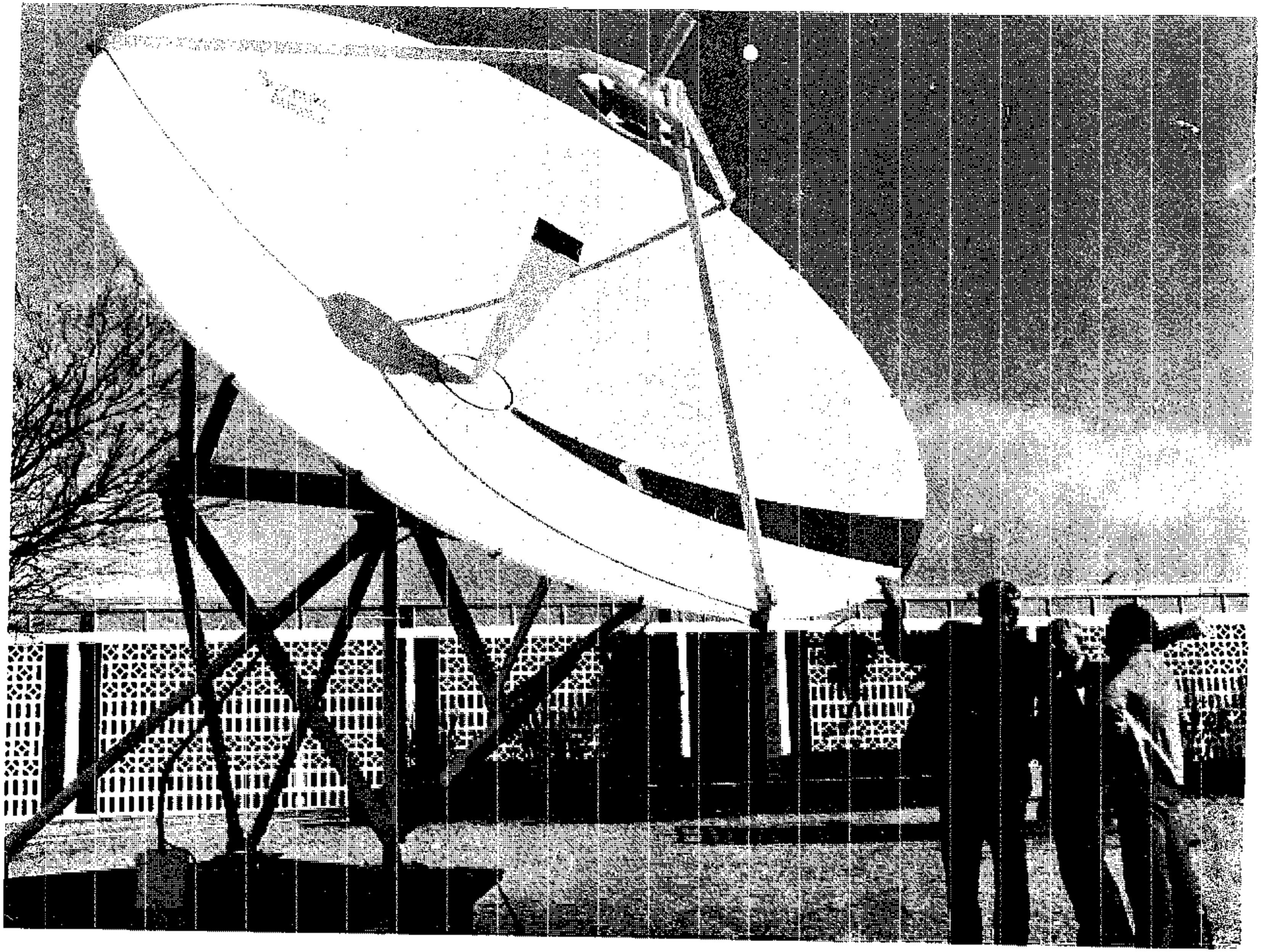


Figure 9. Photograph of the Existing 5-Meter Diameter Parabolic Dish Antenna Produced by Scientific Atlanta.

The development of a large, two-axis, automatic-tracking paraboloid dish solar concentrator does not require new basic technology. An 8.14-meter diameter solar concentrator using a two-axis tracking system has been in operation in Algiers, Algeria since 1954. The reflective surface is electropolished aluminum and the device has a gross weight of approximately 40 tons. This solar concentrator, shown in Figure 10, is used as a solar furnace for very high temperature research.

The same collector concept has been selected for the United States Department of Energy's Solar Total Energy - Large Scale Experiment Number 2, to be constructed at the site of a textile manufacturing plant at Shenandoah, Georgia. This installation will use on the order of 200 tracking paraboloid dishes, five to seven meters in diameter. Since the necessary manufacturing technology development for commercially viable paraboloid dish solar collectors is already planned and will be accomplished under Department of Energy sponsorship, a practical, low-cost collector of this type will be available in the near future.

A solar electric power system based on a 6-meter tracking paraboloid dish collector has been advertised by Omnium-G of Anaheim, California. This system, shown in Figure 11, is reported to deliver 7.5 kW of electricity and 8.8 kW of waste thermal energy at 95° C when operating in bright sunshine; the cost is $32,000 without storage. This and the above examples illustrate the maturity of tracking dish technology.

At the same time that advances were being made to develop more efficient and economical solar collecting/concentrating systems, various other groups were working to develop simpler and more reliable pumping systems. The University of Florida developed a very simple solar pump in which the only moving parts are two non-return valves 19/. A boiler is connected by a U-tube to a vessel containing non-return valves at inlet and outlet. The inlet valve section is connected to the water which is to be pumped. The water in the boiler is heated and turns into steam, forcing water through the outlet valve from the vessel. When the steam reaches the bottom of the U-tube, it passes rapidly into the vessel and condenses, causing the inlet valve to open as a vacuum is formed. Another version of this pump has been developed in England by the AERE Harwell 19/ and has a very simple closed cycle hot air cylinder instead of the boiler used by the University of Florida. A solar pump developed in India 20/ uses pentane vapor generated under pressure in a flat plate solar collector as the power source. Both an air-cooled and water-cooled version are being studied.

B. Survey of Solar Cookers

Man has made use of the sun's energy for drying and partially cooking his food since the beginning of recorded history. About 100 years ago efforts began to develop various types of solar collectors to provide the heat for cooking of food which up until that time had been provided by wood or fossil fuels. Unlike the efforts to develop solar water pumps and irrigation systems, work on solar cookers has been a continuous development during the

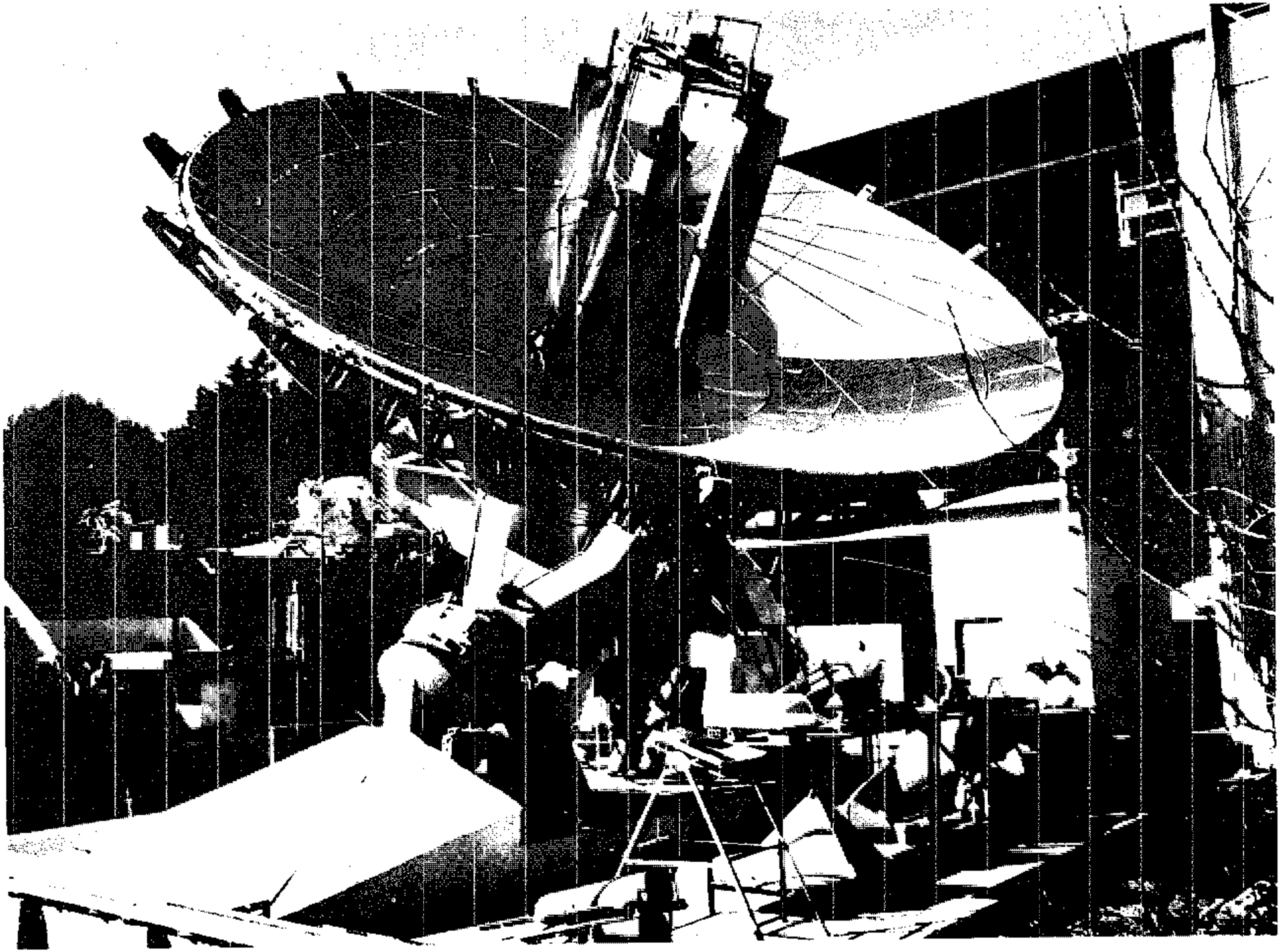


Figure 10. Photograph of Two-Axis Parabolic Dish (8.14 Meter Diameter) High Temperature Solar Furnace Near Algiers, Algeria.

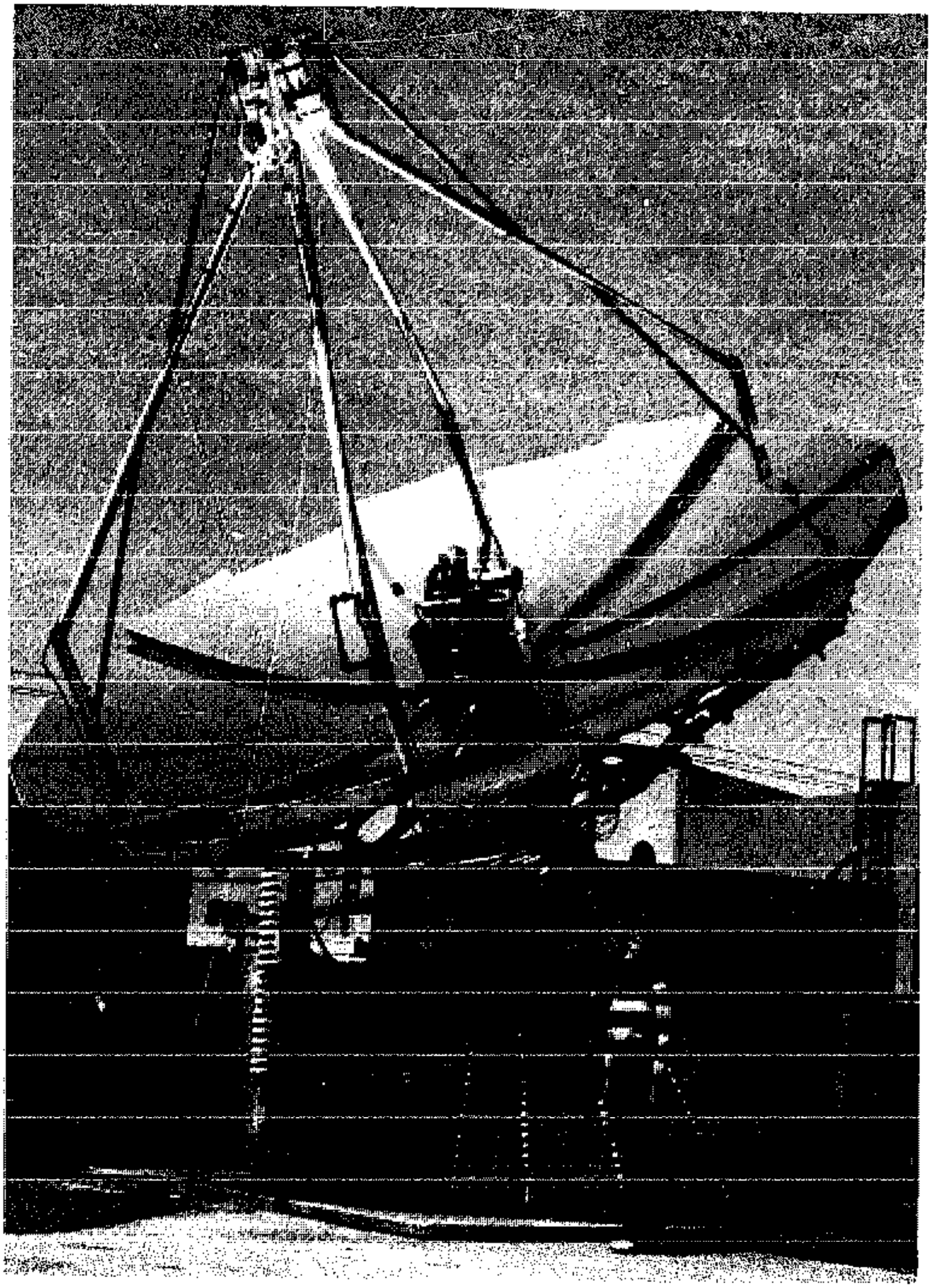


Figure 11. Photograph of OMNIUM-G's Solar Powered Electrical Generating Plant Using 6-Meter Diameter Parabolic Dish Concentrator.

past 100 years. Therefore it was considered appropriate to begin this survey of solar cookers with a short history of their development before summarizing the current state of the technology.

1. A Short History of Solar Cookers

The first solar cookers were described by Mouchot 14/ who had been commissioned by the French Emperor, Napoleon III, to develop solar cooking devices for the French Colonial troops in Africa. He used a parabolic concentrator to focus solar radiation onto a cooking pot, which was suspended from a stand.

In the United States, C. G. Abbot 14/ built several cooking ovens using cylindrical parabolic reflectors to concentrate solar radiation onto a blackened tube protected by a glass enclosure. A small solar cooker designed by Abbot was exhibited at the Smithsonian Institution Museum in Washington. In this cooker, cylindrical parabolic reflectors automatically tracked the sun by means of a clockwork mechanism. However, the cost of this system was too high for a commercial market to develop.

During the early 1930's, solar cooking experiments were continued by Mourin 14/ primarily for the French colonies. Unfortunately these experiments resulted in no significant use of solar cookers.

M. L. Ghai 21/ of the National Physical Laboratory of India attempted to solve the solar cooking problem by using a parabolic reflector, with a pot supported at the focus. The Devidayal Industries manufactured this device for a limited time with the intent of commercializing it, but the cost was too high to be attractive.

The results of tests of cookers have been described by Mathur and Khanna 22/, National Physical Laboratory of India, New Delhi, who state that "Since tradition in cooking method plays a very major part, it is doubtful if much could be done yet in changing traditional methods....efforts made to introduce solar cookers in villages have completely failed."

Several solar devices were exhibited at the UNESCO Conference on Wind Power and Solar Energy in New Delhi during October 1954 23/. Practically all the solar cookers had manually adjustable mirrors mounted in a frame, reflecting solar energy to an uninsulated pot. It was necessary to adjust each mirror, individually and frequently, to reflect solar radiation to the pot, thus making it somewhat unattractive to the sophisticated housewives.

Several papers on solar cookers were presented at the United Nations Conference on Solar Energy, Wind Power and Geothermal Energy in Rome during August 1961 24/. Three of the seven papers of that conference session were concerned with the design and use of focusing cookers. Two papers were presented on solar ovens. Comparative studies of heat delivery rates with both types were also reported, and a cooker designed to combine the best features of oven and focusing systems also was described. Results of field studies concerned with the practical daily use of a solar cooker were reported in another paper. All but one of the six cookers discussed were built and tested.

The most serious problem with the direct, concentrating collector type solar cooker was reported to be that it was outside the average housewife's everyday experience. Few housewives could become attached to the idea of sitting or standing in the yard while dinner is cooking. Even in such lands as India and the poorer countries of Africa, where fuels and money are scarce, large-scale demonstrations of solar cookers never led to their adoption by people who would have benefited most. The reason: the equipment, the procedure, the whole cooking process was not something done by generations of ancestors. With this in mind, Farber 25/ at the University of Florida designed a solar powered cooking range with 24 hour cooking capability. This device incorporated a parabolic concentrator, a heat storage unit and a range top cooking unit inside the house. The heat transfer fluid proposed for this unit was cottonseed oil and the storage media was a phase change salt. Unfortunately, there is no way to evaluate the value of such a solar cooking system since it has not yet been built.

2. Summary of Solar Cookers

In reviewing the papers, patents and discussions on solar cooking, it was important to identify the principal requirements for the successful use of a solar cooker in the less developed areas of the world. They may be summarized as follows: (a) The unit must cook foods effectively; it must therefore provide energy at a sufficient rate and temperature to properly cook desired quantities and type of food. (b) It must be sturdy enough to withstand rough handling, wind and other hazards. (c) It must be sociologically acceptable and fit in with the cooking and eating habits of the people, i.e. provide for cooking to be done in the shade and if possible at times when the sun is not shining. (d) It must be capable of manufacture with local materials and by local labor. (e) It must be possible for the user to obtain a cooking unit at a sufficiently low cost for him to realize financial savings by its use.

The needs for solar cooker development and applications have been amply cited in all of the papers reviewed. As pointed out previously, they are the result of the scarcity of cooking fuels, principally wood, their high cost, their wasteful use and the resulting deforestation. Although cooking requires only a relatively small portion of the world's total energy consumption, the aggregate individual and family impact of substantial cooking fuel replacement in less developed countries could be great. Major benefits would be derived from the use of dried animal wastes for fertilizer rather than fuel, conservation of trees and other ground cover, and the reduced outlay of limited funds for fuel purchases.

Before summarizing the state of solar cooker development, solar cookers will be briefly described according to the type of cooker. Basically they may be considered as (a) simple direct solar cooking devices where the cooking takes place at the point of solar concentration or collection, and (b) advanced solar cookers in which the thermal energy from the solar collector is transferred to a remote area by means of some heat transfer fluid and/or the solar cooker system incorporates some type of energy storage.

a. Direct Solar Cookers

Direct solar cookers may be classified as (a) concentrating parabolic and spherical dish or trough collectors where the heat at the focus of the collector directly heats either a vessel containing the food or the food itself and (b) ovens or food warmers which are insulated boxes with transparent covers in which solar energy is collected by direct radiation or by radiation from some type of reflective surface.

i. Parabolic Concentrator Cookers

The most familiar type of solar cooker is the parabolic dish collector which heats food either directly or in a bowl or pan placed at the focus of the collector. These collectors have been the subject of continuous investigation throughout the past 100 years. Figure 12 is a photograph of a parabolic dish solar cooker which was taken at the laboratory of l'Office de l'Energie Solaire, ONERSOL, in Niamey, Niger. Typical elements of this cooker are (a) a "U" frame which supports the parabolic concentrator and food support. A vertical-axis support is located at the bottom of the "U" frame so that the entire assembly is free to rotate in a bearing to follow the sun in its east-west motion, (b) a horizontal bar which connects the top of the open ends of the "U" frame and supports a platform or grill on which the food or food containing vessel is placed. This bar provides a horizontal axis about which the concentrating reflector pivots so that the food support is always at the focal point of the concentrator. This axis permits the cooker to be adjusted in the azimuth plane, (c) the parabolic concentrator which collects the solar radiation and concentrates it onto the cooking platform, and (d) a positioning or holding device which permits the azimuth position of the collector to be maintained without further attention by the operator. In this photograph the azimuth holding device consists of two flat plates attached to the triangular shaped pivot arms which connect the dish to the horizontal axis supporting the cooking platform. Holes in these flat plates permit a pin to engage the vertical arms of the "U" support and hold the azimuth position of the concentrator. To cook with this device the operator stands behind the collector and turns the entire assembly until it faces the direction of the sun. He then raises the back of the parabolic concentrator until the concentrated solar energy is focused on the cooking surface. He then locks the concentrator in this position with

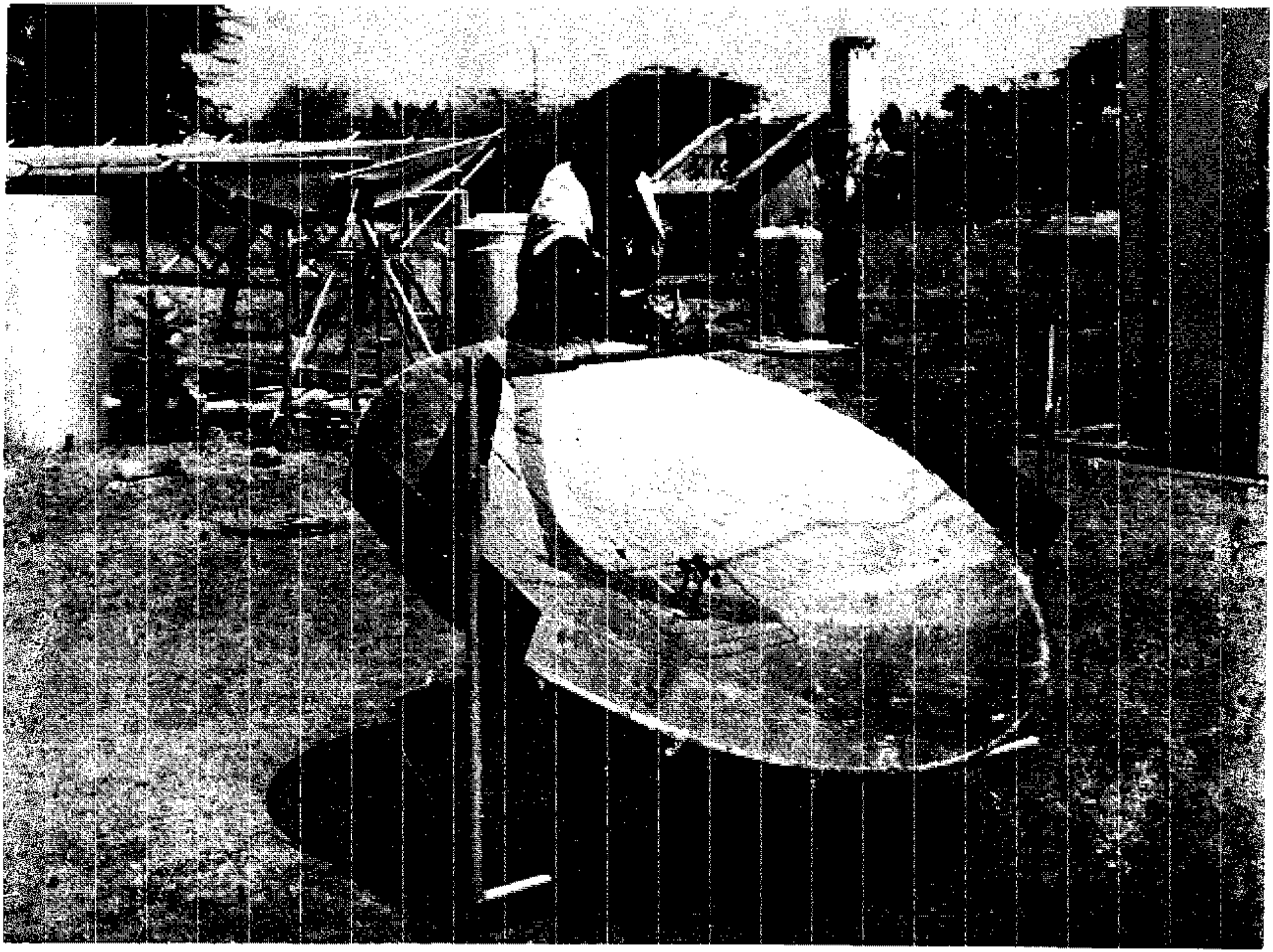


Figure 12. Photograph of a Parabolic Dish Solar Cooker at the Laboratory of l'Office de l'Energie Solaire, ONERSOL, in Niamey, Niger.

the holding pin. Once properly adjusted, and depending upon the type of food being prepared, the cooker can be left unattended for 15 to 20 minutes before the parabolic concentrator must be readjusted to accomodate for the sun's relative movement. Although not in production, the cooker shown in Figure 11 has been manufactured in some quantity by ONERSOL and is being demonstrated in Niger. This parabolic concentrator is formed from sheet metal and covered with aluminum foil. On the day that this photograph was taken the direct solar radiation was about 800 W/m^2 and a wooden board held at the focal point began to cnar in about 20-30 seconds. A similar type of cooker is shown in Figure 13. This cooker was fabricated by the Solar Energy Laboratory in Bamako, Mali. The concentrating collector in this case was fabricated from triangular shaped semgments of sheet aluminum which were bolted together to form the parabolic shape. The aluminum sheet was polished to give a reflective surface. Figure 14 shows another type of concentrating collector consisting of a number of individually focused glass mirrors arranged in a parabolic geometry so that the focal points of all mirrors coincide at the cooking platform. This system of multiple mirrors is the same as that developed by Tabor 26/.

ii. Ovens and Food Warmers

Solar ovens or food warmers typically use some concentration of solar radiation in an insulated chamber with a transparent cover (glass) for trapping the heat ("greenhouse" effect). Telkes 27/ has summarized some of the potential advantages of solar ovens as: (a) capability for baking or roasting, (b) requires less focusing and orientation than the parabolic/ spherical concentrating collectors, (c) cooking pots and pan are protected from the wind, (d) several pots or pans can be used at the same time, (e) heat can be stored permitting the preparation of food in partly cloudy weather, and (f) food can be kept warm after sunset. Figures 15 and 16 are schematic drawings of a solar oven and a solar stove respectively, designed by Telkes. Figures 17 and 18 are photographs of these devices 27/.

The temperature of a solar oven can be increased by adding additional solar concentration from some type of concentrating collector. An example of this concept is shown by the schematic in Figure 19 by Prata 24/. Figure 20 is a photograph of an experimental model of this solar oven.

Figure 21 is a photograph of a solar food warmer developed by Brace Research Institute. The warmer consists only of glass covers over a food warming area. The walls and bottom of the warming area are black to increase solar absorptivity. Concentration by reflective surfaces generally is not used in warmers since temperature requirements are relatively low.

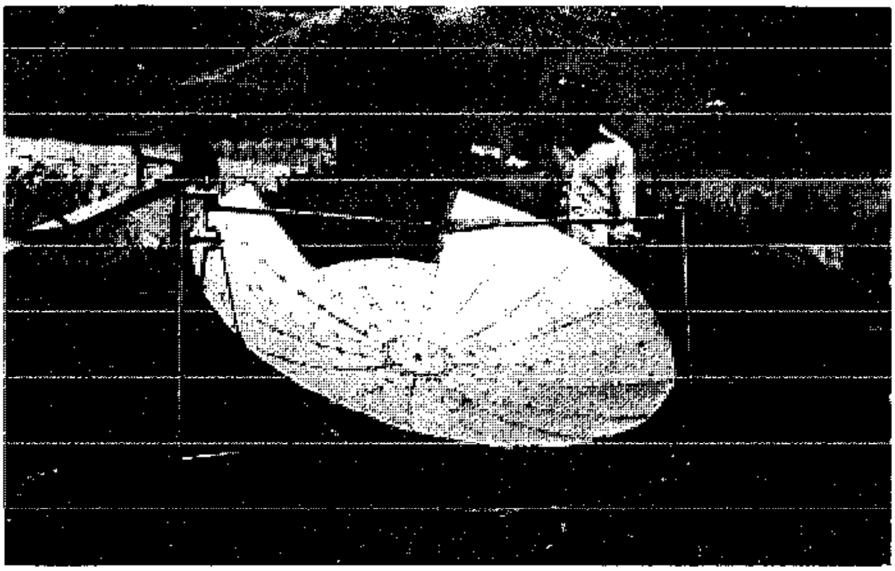


Figure 13. Photograph of Parabolic Dish Solar Cooker at the Solar Energy Laboratory in Bamako, Mali.

Figure 14. Photograph of Multi-Mirror Solar Cooker at the Solar Energy Laboratory in Bamako, Mali.

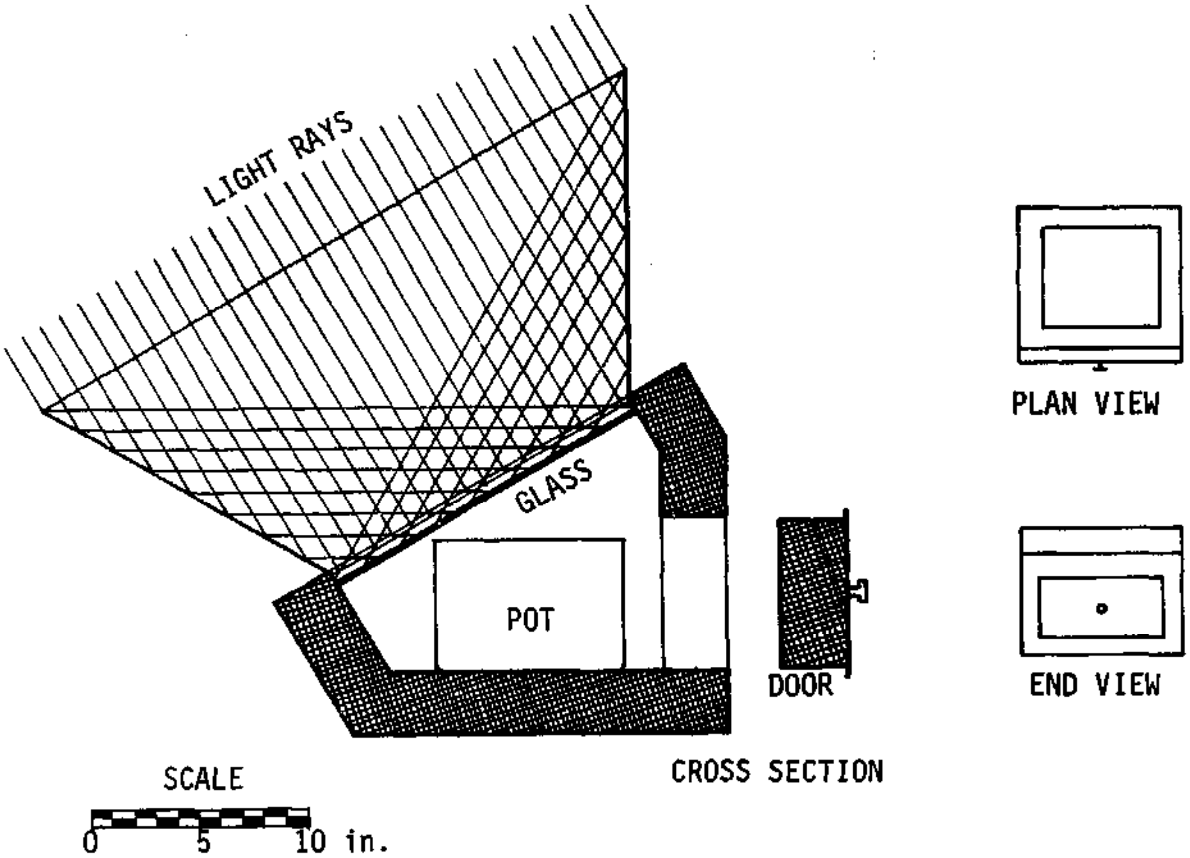


Figure 15. Schematic of a Solar Oven Designed by Telkes.

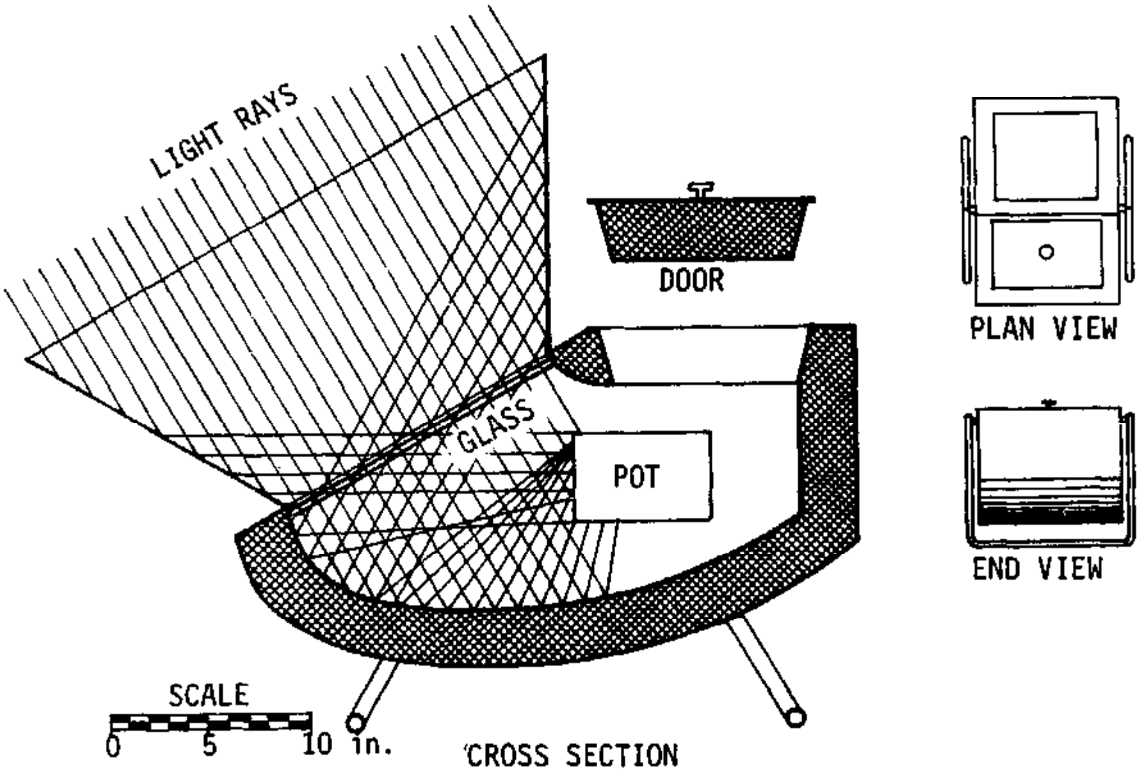


Figure 16. Schematic of a Solar Stove Designed by Telkes.

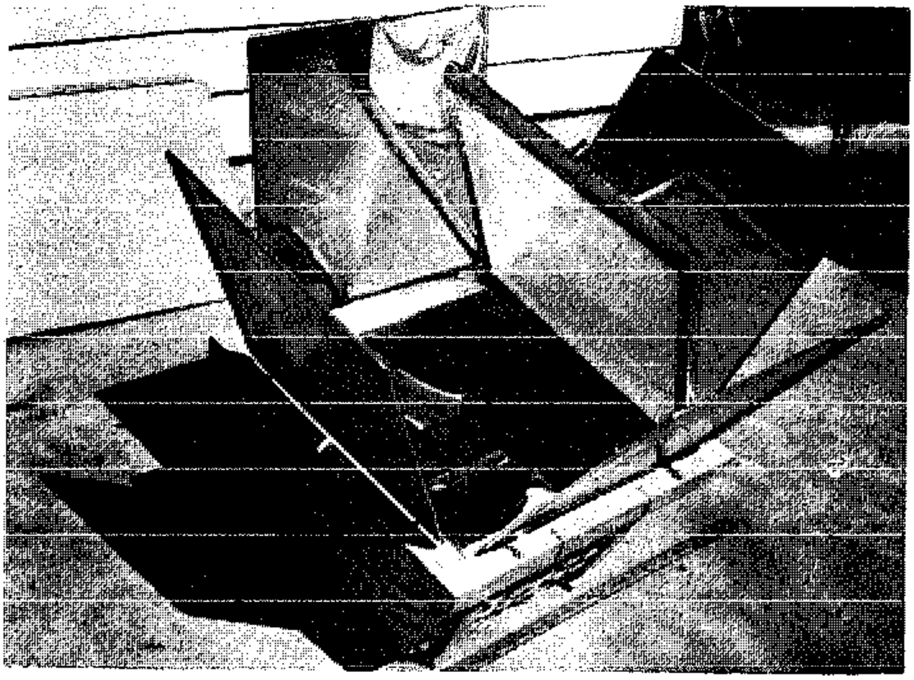


Figure 17. Photograph of a Solar Oven Designed by Telkes.

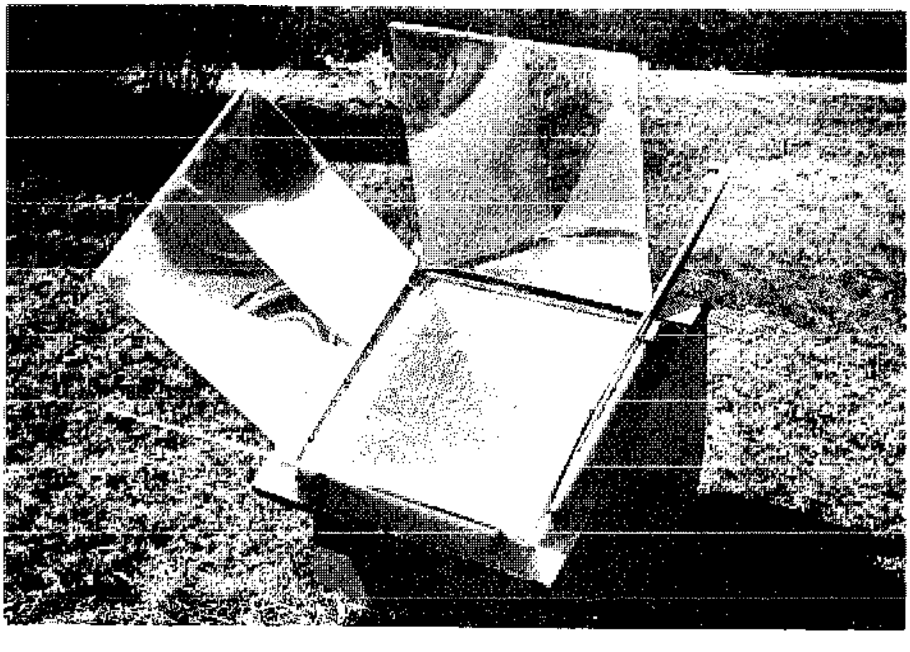


Figure 18. Photograph of a Solar Stove Designed by Telkes.

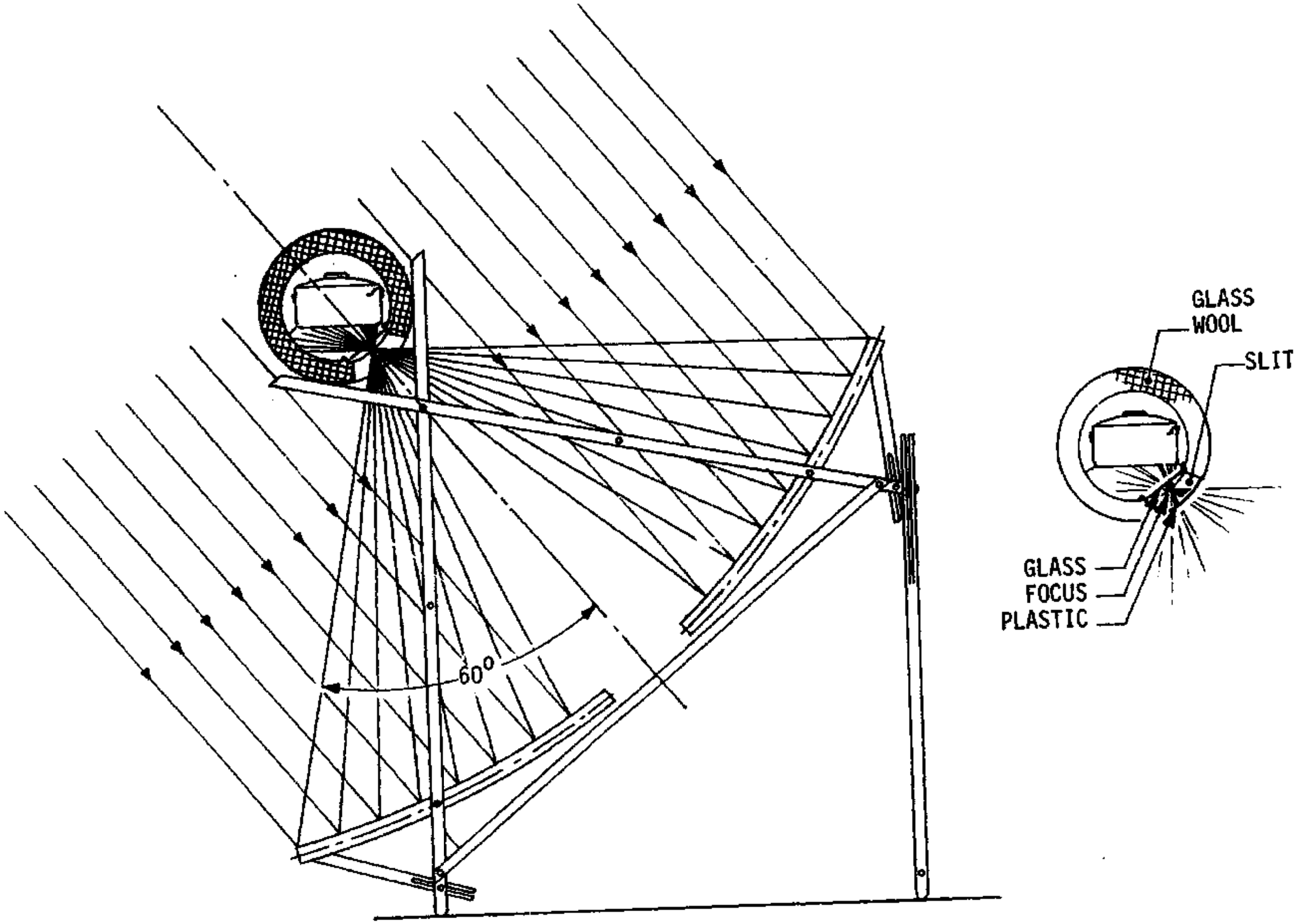


Figure 19. Schematic of a Solar Oven Designed by Prata.

Figure 20. Photograph of the Solar Oven Designed by Prata.

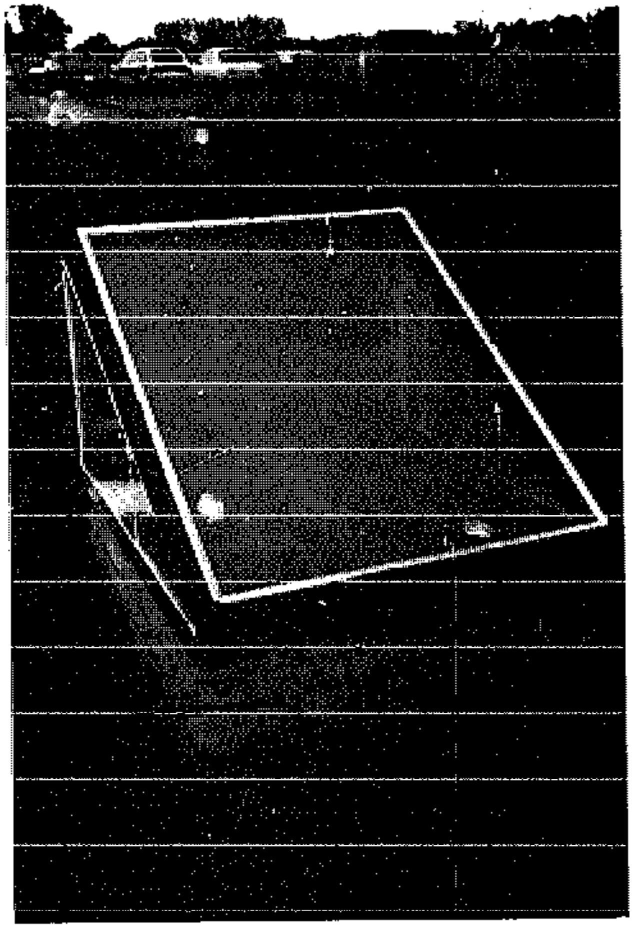


Figure 21. Photograph of a Solar Food Warmer Developed by Brace Research Institute.

b. Advanced Solar Cookers

In order to overcome the problems of cooking in the direct sunshine and of cooking only when the sun is shining two advanced solar cooking concepts were surveyed. The first involved the use of a heat transfer system to permit cooking to be done in a shelter. The second involved the use of some type of energy storage system which would permit the cooking to be done in the evening or at other times when the sun was not shining.

i. Heat Transfer Systems

Various types of heat transfer systems have been proposed for bringing the heat generated in a solar collector into a sheltered area where the heat can be used for cooking. As previously discussed, heat transfer systems form the basis for most solar thermal systems used to operate mechanical devices. For example, in the SOFRETES water pumping system (see Figure 3) the hot water from the flat plate collector is transferred to the evaporator where the collected heat is used to vaporize an organic liquid. In a similar manner, flat plate collectors have been used to heat water to produce steam which in turn heats a remote hot plate. Unfortunately the maximum temperature obtainable with a flat plate collector is of the order of 140° C and as the working fluid temperature approaches this temperature the efficiency of the system becomes so low as to be useless. One example of such a system is illustrated in the photograph in Figure 22. This photograph was taken at the solar energy laboratory of the University of Khartoum, Sudan. The heat transfer pipe leads from the top of the sloping collector down to a hot plate located to the left of the collector support structure. The collector consists of a series of longitudinal pipes which run the length of the collector and are connected in parallel by headers at the top and bottom. Water is permitted to fill about three quarters of the length of the tubes and is sealed off by means of a valve. The system is then allowed to reach thermal equilibrium which is about 140° C at 3½ atmospheres absolute pressure. By opening a valve leading to the hot plate the steam is allowed to condense on the hotplate releasing the heat of vaporization to the plate. The problems associated with this collector are (a) the relatively low hot plate temperature which would be suitable only for light stewing or water heating chores (b) the low efficiency of the system and (c) steam under pressure presents potential safety hazards in the village environment. Figure 23 is a perspective view of a similar system developed at Brace Research Institute. In this case the heat from the steam passes directly into a cabinet heater or oven.

In order to increase the temperature of the cooking unit, concentrating solar collectors, usually parabolic or cylindrical trough, have been proposed to heat oil which is circulated through a pipe or tube type receiver (heat exchanger) located at the focal line of the trough. The heated oil is then used to transfer the collected heat to a hot plate or stove located in the dwelling or other sheltered area. Oil is proposed instead of water in these

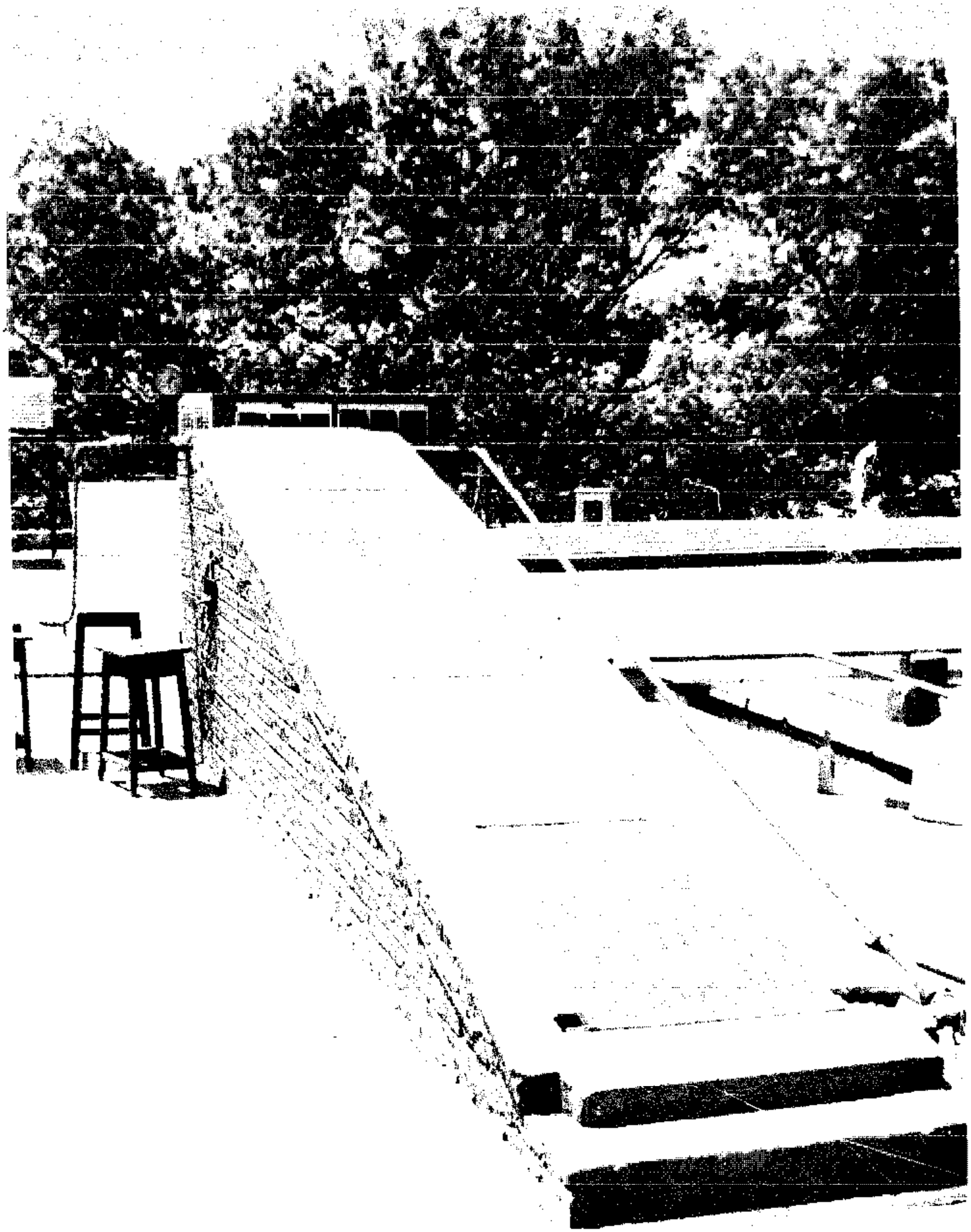


Figure 22. Photograph of a Solar Steam Hot Plate System at the Solar Energy Laboratory of the University of Khartoum, Sudan.

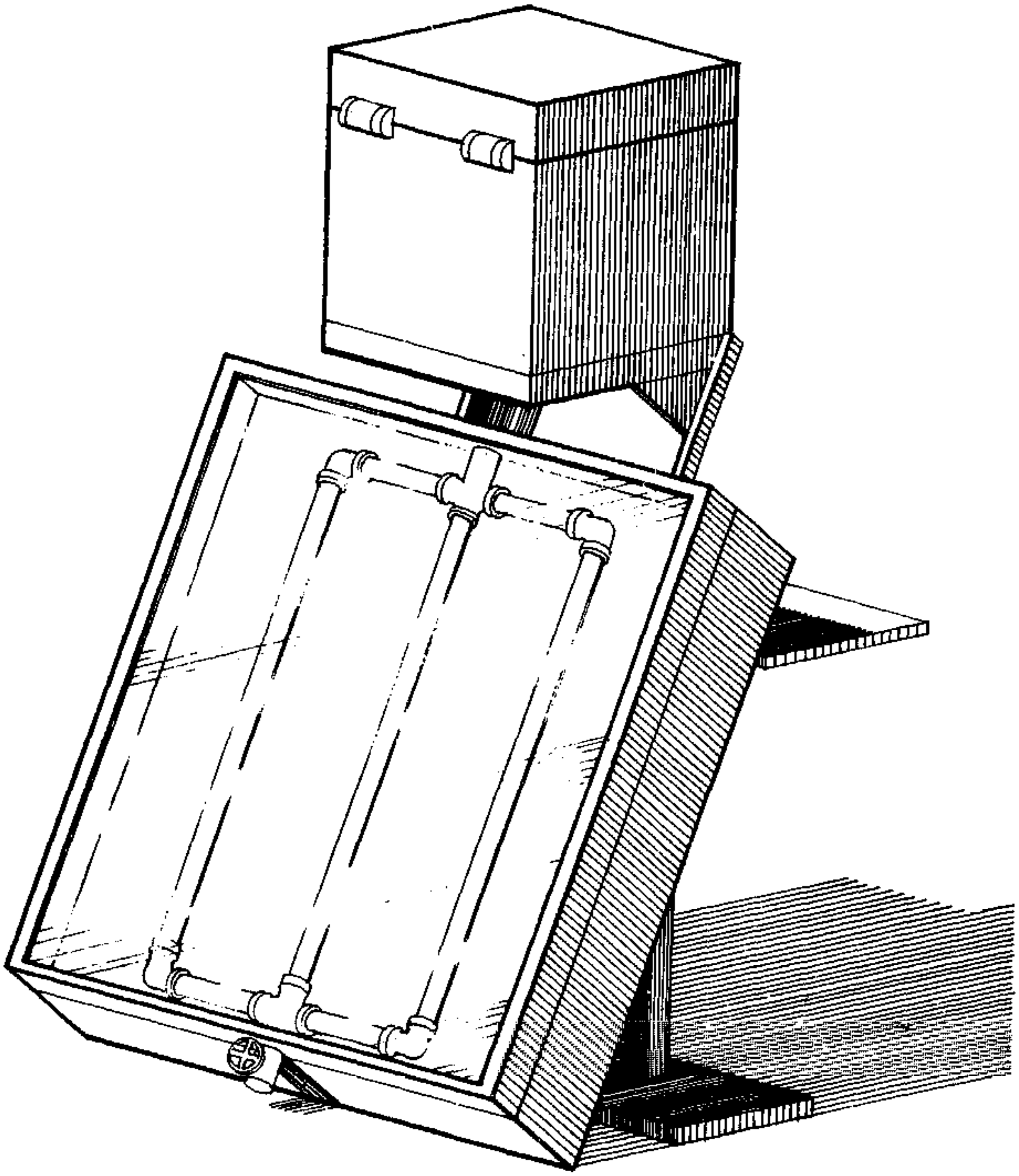


Figure 23. Perspective View of Solar Steam Cooker Developed By Brace Research Institute.

heat transfer systems because it will remain a liquid at atmospheric pressure at the temperatures provided by the trough collectors (175-200° C). Figures 24, 25 and 26 are artist concepts of two heat transfer solar cooking systems proposed by Stam 24/ and Swet 28/. Because line-focus, linear trough collectors are used in this concept some type of one-axis tracking is required in order to keep the concentrated energy focused on the heat transfer pipe. In Figure 24 this is provided through a weighted pulley arrangement in which the downward movement of a driving weight is caused to coincide with the speed of flowing sand in an hour-glass. Through this pulley action the rotation of the trough follows the east-west motion of the sun at 15 degrees per hour. Figures 25 and 26 show a concept which uses an "automatic" tracking system. A bimetal "heliotrope," in the axis of the trough, reacts to direct heat from the sun to rotate the trough until a "sun-shade," attached to the trough, moves between the "heliotrope" and the sun, casting its shadow on the "heliotrope."

Figure 27 is an artist's rendering of the solar cooking heat transfer/ storage system proposed by Farber 25/. This system differs from the previous two in that a two separate heat transfer loops are used. One loop receives energy from the collector and transfers it to a thermal storage medium (phase change material). The second loop receives heat from the storage medium and transfers it to the cooking area. This system is much more complex than those shown in Figures 24-26 and involves pumps and valves which would provide the "automatic" type of operation required in a technical society where solar energy was being used to replace or augment energy sources such as electricity or gas. However, even the "simple" systems proposed by Stam and Swet (Figures 24,25) may be too complex and expensive for the rural village in sub-Sahara Africa. Unfortunately, this cannot be determined at this time since these systems are only in the design stage and prototype systems have yet to be built.

ii. Energy Storage Systems

Several methods are available for storing the energy required for cooking. Among these are sensible heat, latent heat of fusion and chemical energy.

(a) Sensible Heat

Sensible heat refers to the heat capacity of a material and is expressed as the heat in calories required to raise one gram of the material one degree Celsius. The reverse situation is also true in that the same number of calories of heat are released when one gram of the material is lowered one degree Celsius. Of the commonly available materials water has the highest heat capacity; one calorie per gram per degree Celsius ($1\ \text{cal gm}^{-1}\text{-}^{o}\text{C}^{-1}$). Unfortunately, since the boiling point of water is only 100° C, water cannot be used to provide sensible heat for cooking above this

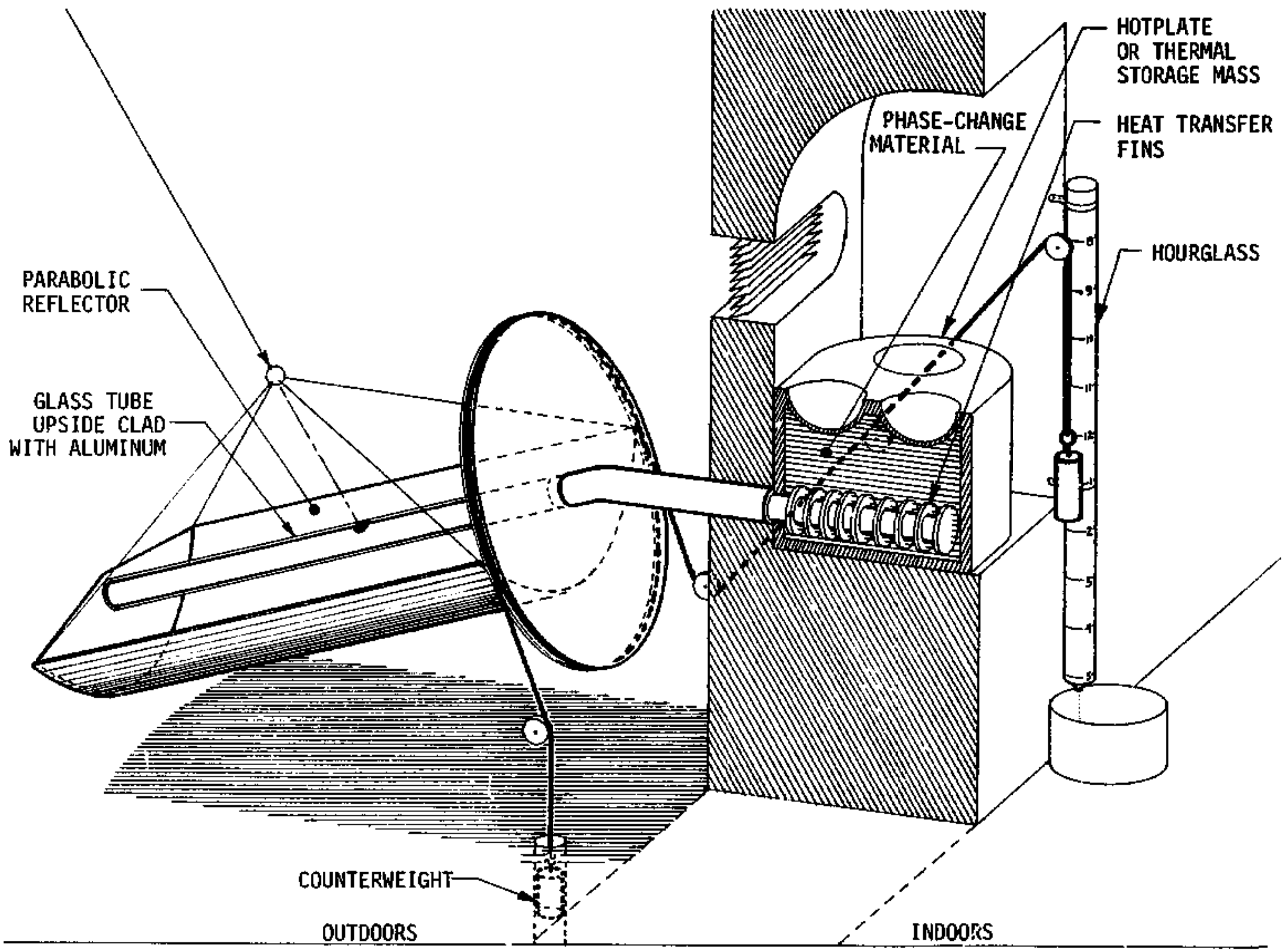
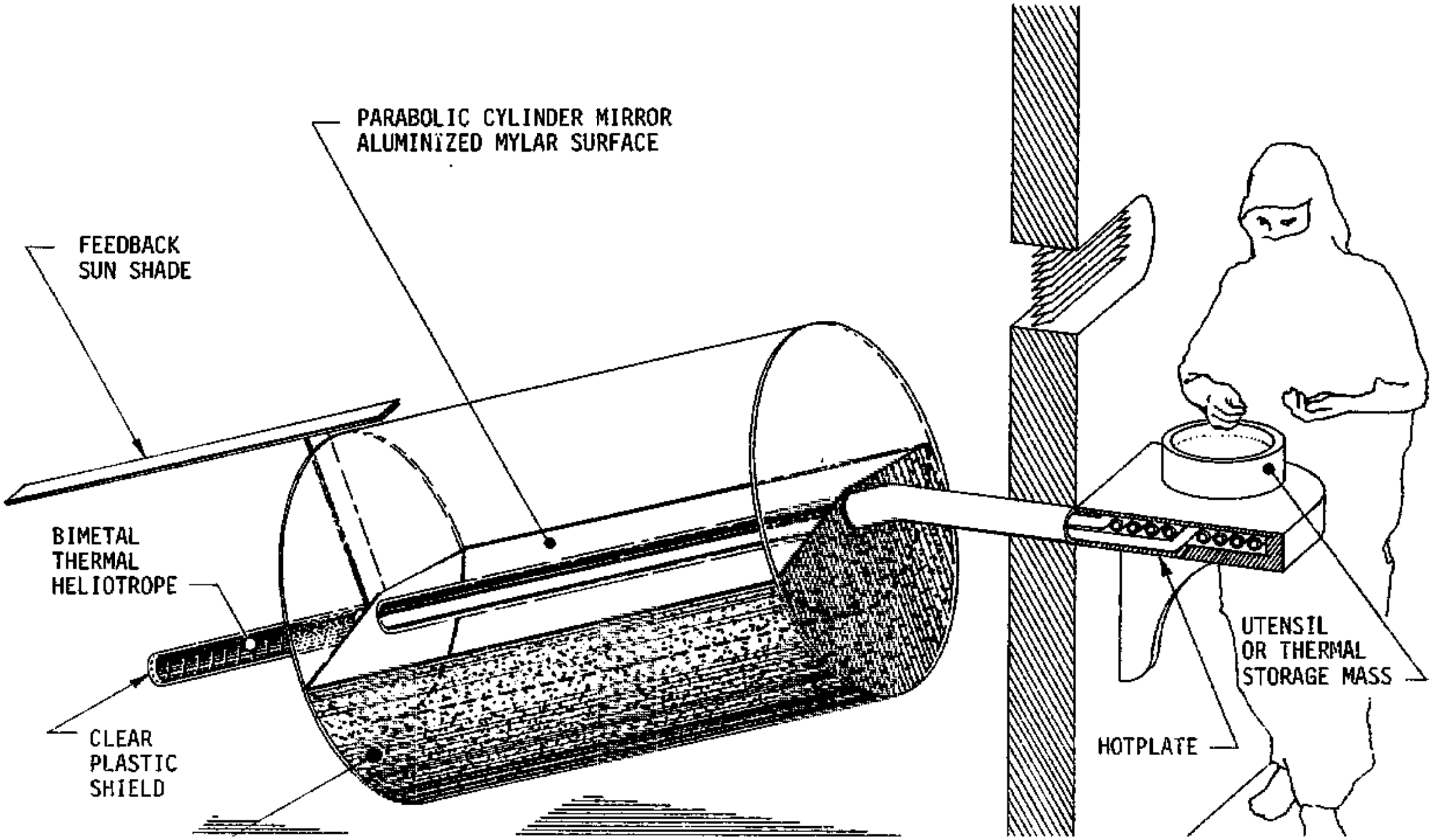


Figure 24. Artist Concept of a Heat Transfer Solar Cooking System Proposed by Stam.


PARABOLIC CYLINDER MIRROR
ALUMINIZED MYLAR SURFACE
FEEDBACK
SUN SHADE
BIMETAL
THERMAL
HELIOTROPE
CLEAR
PLASTIC
SHIELD
UTENSIL
OR THERMAL
STORAGE MASS
HOTPLATE

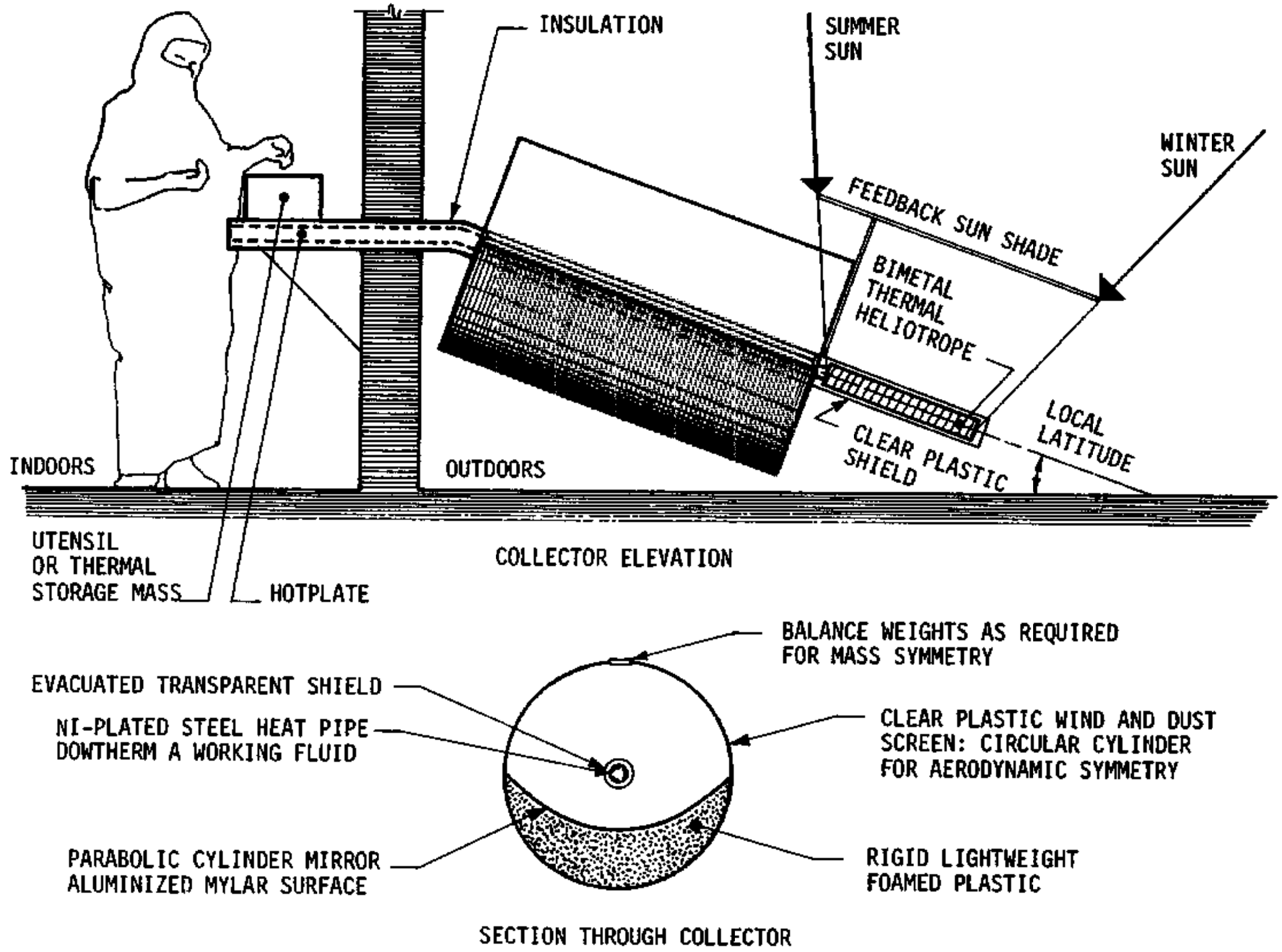


Figure 26. Artist Concept of Heat Transfer Solar Cooking System Using Automatic Tracking Proposed by Swet.

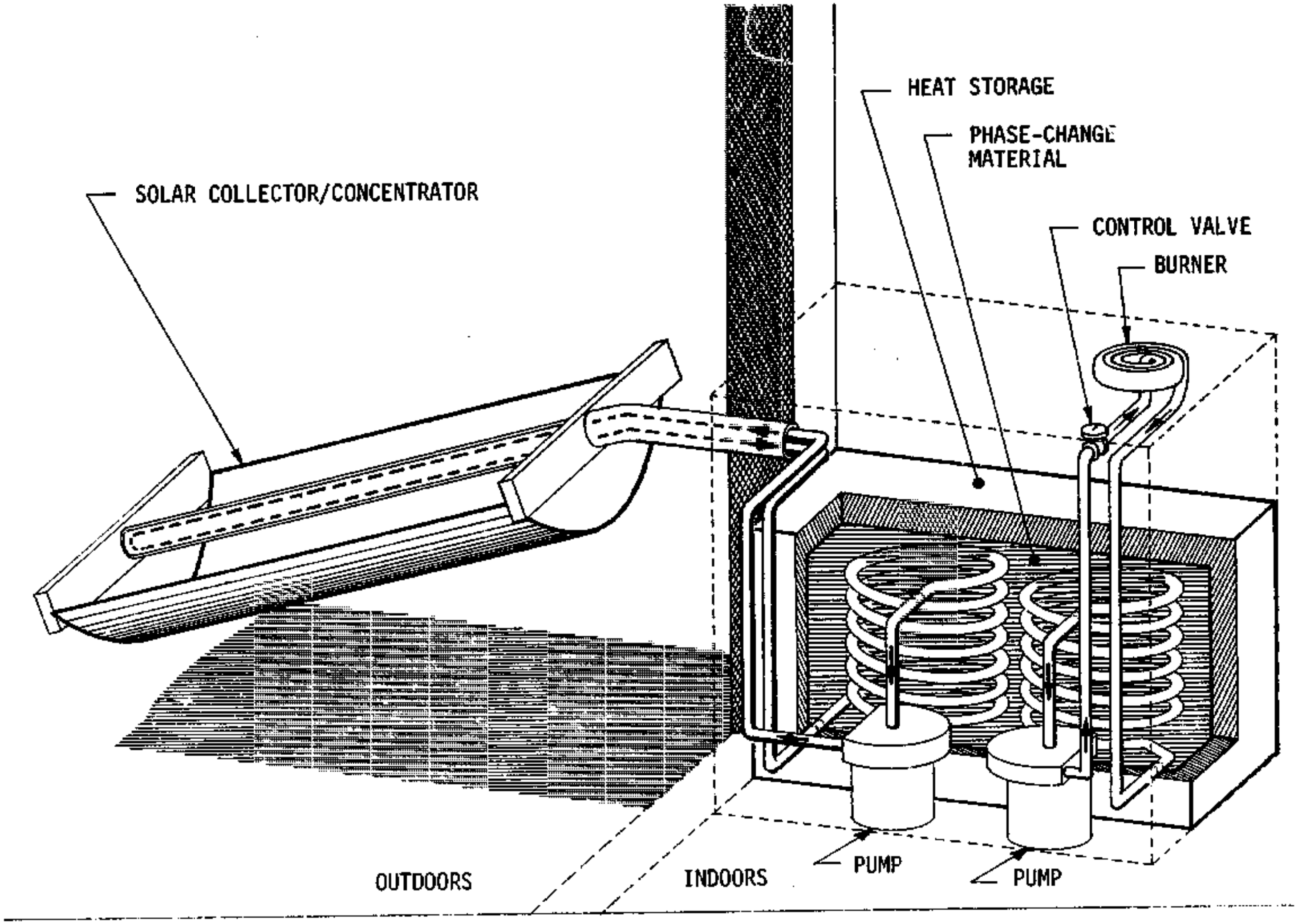


Figure 27. Artist Concept of the Solar Cooking Heat Transfer/Storage System Proposed by Farber.

temperature without using pressurized vessels which would present technical and safety problems in a primitive or non-technical environment. Considering readily available materials which can be conveniently stored and used at temperatures of about 150^{0} - 200^{0} C, oils and rocks appear to be the most promising. Available oils in the LDC's of Africa are vegetable oils such as peanut and cottonseed. The heat capacity of these oils is about 0.48 cal gm $^{-1}$ ^{0}C $^{-1}$ and rock is about 0.2 cal gm $^{-1}$ ^{0}C $^{-1}$. The most economical storage system might be expected to be a combination of rock and oil in which the major portion is a rock bed through which oil circulates and serves as the heat transfer medium. A rock bed of properly sized stones provides a large surface area and the tortuous path of the oil through the bed ensures rapid heat exchange. Assuming a bed of 70 percent by volume of rocks and 30 percent oil the combined heat capacity would be about 0.28 cal gm $^{-1}$ ^{0}C $^{-1}$.

In order to determine the amount of material required to store the energy necessary to cook a meal for a typical family of six persons it is necessary first to know the amount of energy presently used to do the cooking. Moumouni estimates that the average family of six consumes about 3 tons of wood per year in rural as well as urban areas of the Sahel. This reduces to about 7 kg (15 pounds) per day. If we assume that the open fire which is typically used in this area is between 5 and 10 percent efficient, then the heat which is utilized in the cooking process is provided by the equivalent of about ½ kg (1 pound) of wood. Using a typical heating value for wood of 4,700 cal/gm (8,500 Btu/pound) the daily amount of heat which is utilized in cooking for a family of six is about 2.35×10^{6} calories (9,300 Btu). If we assume that half of the heat is to be stored for cooking when the sun is not shining then our storage system must store 1.2×10^{6} cal (4,650 Btu). The heat capacity for the storage system is 0.28 cal gm $^{-1}$ ^{0}C $^{-1}$. Assuming that the temperature of the storage system will be 30^{0} C above the cooking temperature, then 30^{0} C x 0.28 cal gm $^{-1}$ ^{0}C $^{-1}$ = 8.4 cal which will be the heat available from each gram of material. Since we need 1.2×10^{6} calories then 1.2×10^{6} calories ÷ 8.4 cal/gram = 1.4×10^{5} grams. The density of the mixed storage medium is about 2 gm/cc, thus the required volume of storage will be 1.4×10^{5} grams ÷ 2 gm/cc = 7×10^{4} cc = 70 liters (about 20 gallons). This is the volume of storage required if we assume 100 percent efficiency in recovering heat from storage and 100 percent efficiency in cooking with the stored heat. Since the combined storage-cooking efficiency of the system probably would not be more than 50 percent, then a storage system of about 140 liters (40 gallons) would be required. Even for this low cost system, the cost for the tankage, insulation and oil probably would be out of reach of the typical village family. However, there may be special applications, for example where community cooking is practiced, where this concept should be pursued further.

(b) Latent Heat of Fusion

The latent heat of fusion of a material is that amount of heat required to melt a specific amount of the material at its melting temperature. Many investigators have attempted to design systems to utilize the heat of fusion of various materials in order to economize on the amount of material required to "store" a given amount of energy. For example, the melting point of the mixed salt $NaNO_2$-NaOH is 240° C (464° F). The heat of fusion of this salt is about 58 cal/gram, which is the amount of heat required to melt one gram of $NaNO_2$-NaOH at 240° C. Therefore, in freezing one gram of this material 58 calories would be released at 240° C. As pointed out in the previous section, the sensible heat for a typical oil is about 0.48 cal gm^{-1} $^{o}C^{-1}$. Therefore in order to obtain the same amount of thermal energy in oil to be used at 240° C with 1° C temperature drop, about 120 grams or 120 times as much oil by weight would be required as $NaNO_2$-NaOH. An alternative storage method would be to raise the temperature of one gram of oil 120° C above 240° C or to 360° C (680° F) in which the same amount of energy would be available above 240° C. (This latter case is not practical in the case of oil since most oils are chemically unstable when used above about 600° F).

The typical design for a heat of fusion storage system uses a series of pipes or a coil of tubes in a tank filled with the salt (or other material) with the desired heat of fusion. Concentrated solar energy is used to heat an oil (or other heat transfer fluid) to a temperature above the melting temperature of the salt. This hot fluid passes through the tubes or pipes in the tank and melts the surrounding salt. The melting salt will remain at its melting temperature until all of the salt becomes liquid. Beyond this point the temperature of the liquid salt will increase according to its heat capacity (storing sensible heat) until it approaches the temperature of the oil in the tubes. To recover the stored energy, oil to heat the cooking unit is circulated through tubes submerged in the melted salt. As the salt freezes on the outside of the tube walls the heat of fusion is transferred to the oil at the melting temperature of the salt. Theoretically it would be possible to maintain the temperature of the oil going to the cooking unit at the melting temperature of the salt until all the salt became solid. Unfortunately, this has not been realized in practice because of the thermal resistance which is presented by the frozen layer of salt on the tubes. That is, heat cannot be transferred from the still liquid salt through the frozen salt layer and into the tubes containing the oil at a high enough rate to maintain the oil at the melting temperature of the salt: the temperature required for cooking. Even with these difficulties heat of fusion storage concepts continue to attract attention and research in this area will continue.

For the purpose of this report, a survey was made of possible candidate salts which would have melting temperatures and heat of fusion values suitable for use in cooking. A list of candidate salts is given in Table IV.

A survey was made of all simple compounds with melting points between 130° C and 200° C. The thermal storage capacity for each compound was tabulated in terms of the number of kilograms and liters of liquid required to provide the

TABLE IV

SELECTED PROPERTIES OF SALTS CONSIDERED FOR LATENT HEAT OF FUSION ENERGY STORAGE

Eutectic Mixture	Composition Mole (%)	Point (Measured) (^oC)	Density At Melting Point (gm/cc)	Heat of Fusion (Measured) (cal/gm)
Al_2Cl_6		194	1.22	114.8
$LiNO_3$		254	1.78	90.87
Na_2CO_3-Na_2O -NaOH	6.5-7.4-86.1	288	1.88	56.4
$NaNO_2$-NaOH	27 - 73	240	1.83	58.33
$NaNO_3$-KNO_3	54 - 46	222	1.96	23.60
$NaNO_3$-NaOH	70 - 30	248	1.91	37.76
NaCl-$NaNO_3$ -Na_2SO_4	8.4-86.3-5.3	287	1.94	42.44
NaBr-NaOH	22.3 - 77.7	261	2.02	38.67
$Ba(NO_3)_2$-$LiNO_3$	2.6 - 97.4	253	2.13	87.43
$Ca(NO_3)_2$-LiCl	40.85 - 59.15	270	1.87	40.07

heat required for cooking a meal for a family of six. Of the materials surveyed, Al_2Cl_6 had the highest heat of fusion of about 90,000 cal/liter. On this basis about 14 liters (about 4 gallons) of liquid Al_2Cl_6 would be required to cook a meal for a family of six persons, assuming 100 percent efficiency or 28 liters (8 gallons) on the same basis that 40 gallons of the rock and oil were required. Although this is only about one fifth of the volume of heat storage material compared with the sensible heat storage system it still represents a technology yet to be realized and probably not suitable for village use.

A recent effort to develop a high temperature heat of fusion thermal storage system was reported by Honeywell 29/. The experiment employed a cube-shaped tank, approximately eight feet on a side, which contained the latent heat storage medium; 99 percent $NaNO_3$ and 1 percent NaOH. Tubes at the bottom of the tank carried the charging steam used to melt the salt, and tubes at the top of the tank carried feedwater for steam generation. In order to remove the salt which solidified on the heat removal tubes at the top of the tank, mechanical scrapers were developed. Laboratory scale experiments revealed difficulties with the scraping system and the system's ability to recover heat, and the program was cancelled without further development.

The concept of encapsulating an organic phase-change salt within metal tubes has been considered at Georgia Tech. The tubes would be placed inside a rectangular tank, and energy would be charged or withdrawn by circulating a heat transfer oil around the tubes. This system could overcome the difficulty of heat recovery experienced with the Honeywell system without the use of mechanical scrapers. However, the reliability of the sealed tubes is uncertain and if a tube containing nitrate salts should leak into a tank of hot oil, a catastrophic fire could result.

Augmented heat storage by use of cottonseed oil and by use of heat-of-fusion and heat-of-transition of several materials has been considered for use in solar cooking systems by Stam 24/, Abou-Hussein 24/, Telkes and Andrassy 24/, Farber 25/ and Swet 28/. Telkes and Andrassy have compared the heat-storage capacities of several materials in the 150° to 200° C range. A mixture of alkali nitrates provides heat-of-fusion storage at 150° to 160° C, and mixtures of anhydrous alkaline sulphates undergo a solid phase transition between 191° and 239° C, with a latent heat of about 60 calories per gram. An oven containing about 3 kilograms of the sulphate mixture in the form of a flat-bottom slab is described in this paper. However, since solar cookers seldom reach the high transition temperature of the alkali sulphate mixtures during cooking, these materials would be of little use except where the heat could be provided by preheating an empty oven.

Stam 24/ suggested the use of hydrated magnesium chloride (melting point 117° C) and magnesium palmitate (melting point 121° C) as heat-storage materials in specially shaped vessels supported at the focus of the large spherical reflector proposed. He has discussed the use of a total quantity of 40 liters for effective storage and subsequent cooking. Tests with these materials are not reported. Unfortunately these storage temperatures are not adequate for most types of cooking, even for boiling, since the temperature-driving force would be very small.

Farber 25/ at the University of Florida, designed a sophisticated solar cooking device that is capable of 24 hour service. (See Prior Figure 27). Cottonseed oil, a fairly common substance in the south, is used as the heat transfer and heat storage medium. The cottonseed oil coming from an experimental solar heated pipe is claimed to have reached temperatures between 340° - 425° C.

The successful incorporation of thermal storage into solar cookers would improve the commercial attractiveness of these devices. However, the development of cheap, harmless, and dependable materials having high thermal capacity, moderate weight, and adaptability to cooker designs requires further research and experimentation.

(c) Chemical Energy

Chemical energy can be realized by using a system of reversible chemical reactions in which energy can be absorbed or released according to the reactions taking place. Solar energy in the form of heat can be used to drive the reactions in one direction and heat is recovered when the reaction is reversed. Chemical storage has the advantage that energy is not lost during the time period of storage as in the case of thermal storage. An example of a chemical system utilizing heat of solution of acid is under investigation by VITA. This concept is based on the fact that heat is generated when concentrated acid, in this case sulfuric acid, is mixed with water. Preliminary calculations based on the energy needed to cook for a family of six (1.2×10^6 calories) would require a two chamber, 21 liter (6 gallon) stainless steel reaction vessel to hold the two liquids. Assume that both liquids are mixed in one chamber; when this chamber is exposed to direct solar radiation water would be distilled from the acid solution in one chamber into the other chamber. Heat energy for cooking would be released when the container is inverted mixing the acid and water. This concept is only in the experimental stage and many technical obstacles must be overcome, not the least of which is the necessity to use sulfuric acid, a highly toxic and dangerous substance, as the base material. In addition the 6 gallon, 2 chamber stainless steel container probably would be prohibitively expensive; and filled with 27 kilograms (50 pounds) of liquid would be difficult to manipulate and dangerous to handle. Most other processes which involve heat of solution, such as sodium hydroxide in water, are equally dangerous, expensive and of excessive weight and bulk. Although interesting in concept, chemical storage, at the present state of technology, does not appear suitable for African village use.

3. Summary of Solar Cooker Development

The current status of solar cooker development is summarized in Table V. About two dozen variations of workable solar cookers have been made, seven of which are summarized in Table V.

The essential features of these seven types of solar cookers were obtained directly from statements or figures in the papers, or were computed from such factual information. Some of the features, however, have required judgment and interpretation and are so indicated in the table. In certain instances, items have been omitted because of insufficient data in the papers.

It is interesting to observe that the cookers described in the papers are all different. Even the reflector materials differ from each other in almost every case. Of the practical cookers actually built, the solar-collection areas vary from 0.36 to 1.07 square meters. A three-fold range of solar energy collection is therefore covered. There is not much difference in the maximum size of vessel that can be heated in the various cookers, except for the combination reflector-oven of Prata 24/ and range top cookers of Farber 25/ and Swet 28/.

Probably the most significant measure of solar-cooker performance is the "effective cooking power" shown in the table in kilowatts. The tabulated values have been obtained by converting the authors' data on water heating or other use to these units. The figures refer to the rate of energy delivery to the cooking vessel and its contents under clear sky weather conditions. These values are seen to vary from about 0.15 kW for the solar oven of Telkes and Andrassy 24/ and the reflector-oven combination of Prata 24/, to 0.6 kW for the parabolic cylinder of Swet 28/. The folding cooker described by Lof and Fester 24/ has a power output slightly below that of Duffie, Lof and Beck 24/ in the 0.25 to 0.4 kW range. Tests by the FAO generally confirm these capacities, but because of less than ideal solar conditions, maximum outputs of the Telkes-Andrassy oven was 0.15 kW and of the Duffie-Lof-Beck focusing unit was 0.39 kW. The computed or measured periods required for heating one liter of water from room temperature to the boiling point are also shown in the table. These vary from about 15 minutes for the rigid plastic paraboloid to one-half hour for the solar oven. By comparison, the normal heating time on a wood fire or a kerosene burner should be 5 to 10 minutes.

The quantity of food that can be cooked with each of these units is not readily estimated from the data presented. In the oven-type cookers, the limiting factor is the volume of the oven enclosure. The combination unit of Prata appears to have the highest internal volume and is designed for simultaneous use of two cooking vessels. In the focusing cookers without heat storage facility, quantities are limited primarily by the area of the

TABLE V

SURVEY OF SOLAR COOKERS

	Stam (Proposed)	Duffie Lof, Beck	Lof, Fester	Abou-Hussein	Telkes Andrassy	Prata	Ghai	Tabor	Farber, Ingley (Proposed)	Swet (Proposed)
Cooker Type	Focusing	Focusing	Focusing	Oven	Oven	Combination	Focusing	Focusing	Hot Plate	Hot Plate
Reflector Type	Parabolic Cylinder	Paraboloid	Parabolic-Umbrella	Internal Flat Plates	External Flat Plates	Parabolic Cylinder	Paraboloid	Paraboloid	Parabolic Cylinder	Parabolic Cylinder
Reflector Material	Aluminum Foil on Plastic	Aluminized "Mylar" Plastic Film on Polystyrene Shell	Aluminized "Mylar" Laminated to Fabric, on Umbrella Frame	Polished Aluminum Sheets	Anodized Aluminum Sheets (Coated Aluminum Foil)	Nickel Plated Brass Sheet (Nickel Plated Aluminum)	Anodized Aluminum Sheets	Copper Backed, Silvered-glass Plane Mirrors	Polished Aluminum Metal Sheets	Aluminized "Mylar" on Lightweight Foamed Plastic
Reflector Dimension	1.6m x0.98m	1.22m dia	1.17m dia	(4) 1288 cm^2	(4) 43cm sq	(2) 0.5m x 0.8m	0.11m dia	(12) 29.3cm dia	n.r.	1.22m x 0.91m
Effective Solar Collection Area	n.r.	$1.07m^2$	$1.02m^2$	$0.36m^2$	$0.56m^2$	$0.74m^2$	$0.67m^2$	$0.79m^2$	n.r.	n.r.
Reflector Focal Length	25 cm	46cm	46cm	---	---	∿1.05m	45.7cm	76cm	n.r.	23cm
Oven Window	---	---	---	$0.36m^2$ Double Glass	$0.19m^2$ Double Glass	$0.06m^2$ Single Glass	---	---	---	---
Cooking Area	(2) 30cm dia*	∿20cm dia	∿23cm sq	∿20cm sq*	∿25cm sq*	∿20cm x 50cm*	68cm sq	∿29cm dia	n.r.	n.r.
Effective Solar Intensification	n.r.	∿34	∿20	∿3*	∿3*	∿12*	n.r.	∿28	n.r.	n.r.

*Computed or Estimated by Lof.

n.r. - Not Reported.

∿ - Approximately.

(Continued)

TABLE V (Continued)

SURVEY OF SOLAR COOKERS

	Stam (Proposed)	Duffie Lof, Beck	Lof, Fester	Abou-Hussein	Telkes Andrassy	Prata	Ghai	Tabor	Farber, Ingley (Proposed)	Swet (Proposed)
Minimum Time Req'd to Heat one Liter of Water 20° to 100° C	n.r.	15 min @ 15 min (minimum)	22 min	n.r.	∿30 min @ 46 min (minimum)	26 min*	n.r.	12 min	n.r.	n.r.
Effective Cooking Power kW	n.r.	0.4–0.5 @ 0.28 avg @ 0.38 max	0.25–0.4	n.r.	0.15–0.2* @ 0.10 avg @ 0.12 max	0.15–0.25*	0.13	0.5	0.27–0.6	0.6
Food-Cooking Performance	n.r.	Good	Good	n.r.	Good	Good	Good	Good	Good	n.r.
Approximate Weight, kg	n.r.	10	3	n.r.	∿20*	12–18	n.r.	20	n.r.	n.r.
Thermal Storage Considered	Yes	No	No	Yes	Yes	No	No	No	Yes	Yes
Type of Storage Media	Mag. Chloride, Mag. Palmitate	---	---	Sulfate Na,K,Ca	Anhydrous Alkaline Sulfate	---	---	---	Cotton-seed Oil	$LiNO_3$
Temp of Storage Media	Heat of Fusion	---	---	191°–239° C	300°–400°F	---	---	---	800° F	500° F
Total Cooking Capacity	n.r.	∿4 kg*	∿2 kg*	n.r.	∿2 kg*	∿4 kg* (2 vessels)	∿2 kg*	n.r.	n.r.	n.r.

@ - F.A.O. Tests.

*Computed or Estimated by Lof.

n.r. - Not Reported.

∿ - Approximately.

(Continued)

TABLE V (Concluded)

SURVEY OF SOLAR COOKERS

	Stam (Proposed)	Duffie Lof, Beck	Lof, Fester	Abou-Hussein	Telkes Andrassy	Prata	Ghai	Tabor	Farber, Ingley (Proposed)	Swet (Proposed)
Portability	None	Good*	Excellent*	Good*	Good*	Fair*	Fair*	Fair	None	None
Need for Positioning During Cooking	None*	Frequent (15-30 min)	Frequent (15-30 min)	Occasional (30-60 min)	Occasional (30-60 min)	Moderate (25 min)	Frequent (15-30 min)	None	None	None
Suitability For Baking & Roasting	Fair*	Poor*	Poor*	Good*	Good*	Good*	Poor*	Poor	Good	Good
Suitability For Stewing & Frying	Good*	Good*	Good*	Fair*	Fair*	Fair*	Fair*	Good	Good	Good
Durability	n.r.	Good*	Fair*	Very Good*	Very Good*	Good*	Good*	Good	Good	Good
Use of Native Materials	Poor	Fair*	Fair*	Fair*	Fair*, #Good*	Fair*	Good*	Good	Good	Good
Full-Scale Cookers Constructed & Tested	No	Hundreds	See Below	Yes	Yes	Yes	Yes	Yes	No	No
Field Testing	No	Extensive	See Below	No	Some	No	Some	Yes	No	No
Commercial Scale	No	No	Hundreds	No	No	No	No	No	No	No
Approximate Cost or Price	n.r.	$16 (Factory)	$30 (Factory)	n.r.	n.r.	~$35 (Factory)	$14-18	$7-8	n.r.	$100

*Computed or Estimated by Lof.

n.r. - Not Reported.

~ - Approximately.

pot support and by the rigidity of the frame members supporting the vessel. In all the units, there is practical limitation imposed by the maximum acceptable duration of the cooking operation; the greater the quantity, the longer is the period for heating to cooking temperature. Also, with the focusing cookers, rate of heat loss from the walls of the vessel to the surroundings place a practical limit on the total exposed surface of the cooking vessel. All factors considered, however, it appears that the approximate maximum quantities of food that can be practically cooked on these units vary from two to four kilograms, as shown in the table. Most of these capacities are adequate for a family meal, but the one-dish limitation on all but the combination unit is a drawback. Sectional cooking vessels could be used if more than one food were to be cooked on the other units or several small utensils might be usable. Most of the cookers appear to have adequate capacity for cooking simple meals for the average low-income family.

For applications in less developed countries, where import of manufactured goods is often difficult, the question of whether solar cookers can be locally built, particularly by use of native materials, becomes important. None of the cookers appear to be ideally suited in this regard. All types require at least some components or materials from industrialized countries or from factories in the countries concerned. The focusing types involve metallized plastic films, molded plastic reflector shells, and shaped metal components. Ovens require glass or plastic films, polished aluminum, and (desirably) sheet metal for the oven box. Fortunately, all of these cookers could be made in small industrial establishments, using local labor and various amounts of native materials. If the unit proposed by Farber should prove practical, nearly all of the labor and materials could be locally supplied. These factors affect cooker cost, and it is clear that the maximum utilization of local components and skills is desirable.

Several optimistic estimates of solar cooker costs have been made in the past, but most of these figures have been based on inadequate data. However, those costs shown in the table appear to be based on sound information. The two parabolic types are in the same cost range, the rigid plastic paraboloid of Duffie, Lof and Beck having an estimated factory price of $16 (medium quantity production) and the folding umbrella type of Lof and Fester having a published retail price of $30 (small quantity production). Considering the customary wholesale and retail selling costs and profits, the factory price of the umbrella-type should be roughly comparable with the rigid paraboloid type. The third figure is an estimated $35 factory cost for the combination focusing-oven type of Prata. It should be recognized, however, that this estimate is based on laboratory models whereas the other two are based on hundreds of cookers already made. The $35 price may therefore be more uncertain than the others, and it is possible that it might be reduced by modifications in design, materials and fabrication methods. Previously published figures on the costs of other solar cookers include $14 to $17 for the solar cooker developed in India, $25 for the "solar-chef," a small collapsible focusing type, and $4 for a two-foot diameter conical aluminized-paper reflector delivering heat to a small pan. The price of a solar powered range, which seems to hold a great deal of promise for the less developed countries, could not be obtained.

4. Development of Low Cost Solar Cookers for Village Use

Because of the long and continuous history of concentrating, parabolic/cylindrical dish solar cooker development and because of their proven capability to perform numerous cooking chores, detailed attention was given to reviewing the attempts of various investigators to simplify and economize on the construction of these devices. Also during the visit to the solar energy laboratories in Niger, Mali and Senegal, attempts were made to learn as much as possible about efforts to introduce these cookers into village life and to obtain specific reasons why these cookers were not accepted. The following sections will consider 1) the construction of low cost parabolic reflectors and 2) the introduction of parabolic cookers into village use.

a. Survey of Low Cost Solar Concentrators

The concentrators summarized below have been selected on the basis of cost and simplicity of manufacture. Anyone skilled in the use of simple hand tools, such as a hammer, a saw, and a screwdriver, can not only construct it, but also repair it if and when necessary. Furthermore, it is believed that local construction of this cooker would facilitate its introduction into a developing area from a psychological and sociological point of view.

i. Fixed Soil-Cement Spheroidal Reflector

A fixed, spheroidal reflector may be made by forming a spheroidal depression in the ground. This depression is lined first with a mixture of soil and cement to stabilize the shape and then with aluminized plastic. The symmetrical depression is formed by swinging a pendulum, or blade, fastened to a wire which is secured at a fixed point above the ground on a tripod. After the rough shape is hollowed out, a shallow layer of an aggregate and cement mixture is placed in the depression, smoothed with the blade and wetted. When this has set, and after some further smoothing of the surface, a reflective lining or aluminized Mylar pressure-sensitive tape is applied.

The advantages of this reflector are its simplicity and ease of construction in the field. The orientation can be fixed during construction so as to make the reflector usable during the desired time of day. The cost of material for the laboratory models, exclusive of the reflective lining was reported to be less than a dollar 30/.

The disadvantages of this cooker are its lack of mobility, which might result in physical damage due to weather conditions, and the limited period of time during which it can be used (estimated at 4 hours a day).

ii. Lightweight Molded Aggregate Reflector

The most successful reflector of this type is a dish 1.07 meter (42 inches) in diameter with a focal length of 0.46 meters (18 inches). It is formed over a mold and is made of a vermiculate aggregate reinforced with wire with a supporting rim of thin-wall tubing. The surface is lined with aluminized plastic and plastic tape. The total weight is about 23 kilograms (50 pounds). The reflector mount is a wooden post in the ground, arranged to pivot about its axis. The top edge of the reflector leans against the post and its lower edge is supported at variable distances from the post on an arm secured to the post 30/.

The advantages of this type of cooker are the simplicity of the mounting device and its component parts and the possibility of using locally available materials and labor for its construction. Major disadvantages are the weight of the reflector, which makes it cumbersome to handle, and the fact that the reflective lining is difficult to apply.

Another inexpensive method of fabricating this type of reflector has been suggested by J. R. Jenness 31/. A convex, wire-reinforced, plaster paraboloid die is cast from a centrifugally formed concave parabolic mold. The surface of the die is coated with wax, then a layer of wood pulp, paper-mache or laminated newspaper is spread over it. After a few layers are built up, they are pressed to squeeze out excess liquid. The process is repeated until the compressed laminate is 3 to 6 millimeters (1/8 to 1/4 inch) thick. Then the rim of a wooden "wagon wheel", reinforcing framework is glued in place. Woven basketry is suggested as an alternative method of reinforcement. After removal from the die, strips of aluminum foil are pasted on the surface. Finally, a stiff hoop is clamped to the front surface. Jenness states that the process would require 6 to 8 hours of labor. The cost of materials is this reflector is estimated to be about $10 in the United States. No test results were given and it was not stated whether any such reflectors were ever produced.

iii. Spun Liquid Plastic Reflector

An interesting method for producing parabolic mirrors is described by P. B. Archibald 32/. A liquid in a revolving horizontal pan takes the shape of a paraboloid, and a liquid resin suitably catalyzed to harden after this form is taken will retain this shape. With the development of the epoxy resins, satisfactory material has become available. EPON 828, catalyzed with 5 percent piperidine and cured at 80° and 90° C has been found to give satisfactory results.

The focal length of the finished reflector is controlled by the speed of rotation of the pan. The formula for the focal length may be simplified to $\sqrt{f} = 38.4/\text{rpm}$, where f is the focal length in feet. Additional resin may be poured onto the first surface after it has set. In general, superior surfaces are obtained on the second or third pour. Reinforcing material such as fiberglass can be placed on the surface before the second surface is poured.

The quality of the reflectors produced to date is better than anything that can presently be made without the use of grinding and polishing techniques. This is, however, not a significant factor in cooker considerations. The estimated weight of such a 0.91 meter (36 inch) diameter reflector is about 14 kilograms (30 pounds) for a 12 millimeter (1/2 inch) thickness. The cost of the epoxy resin for this size reflector is estimated at $25-$35. Although this technique could perhaps be used for making a master mold, it does not appear that this offers a practical solution for low cost solar cookers.

iv. Fresnel-Type Reflector

The use of the principle of the Fresnel reflector in a solar cooker is thought to be unique among the various known solar cooker designs 30/. The Fresnel reflector concentrates light and heat by means of several simple curved reflecting surfaces. This is in contrast to the doubly-curved reflecting surfaces of the typical parabolic dish reflector. This reflector was developed and tested by VITA and is constructed of 3 millimeter (1/8 inch) Masonite to which aluminized Mylar is cemented. By cutting a series of rings out of the Masonite, removing sectors and rejoining, a series of nesting collars are formed that focus light. These collars are supported in a simple wooden frame. The design is simple enough to permit construction with the tools, skills and materials (except for the aluminized Mylar) that are locally available throughout most of the world.

The most serious drawback of this cooker is that which plagues other designs as well: the deterioration of the aluminum reflecting surface of the cooker due to weathering. Even bulk aluminum loses its high reflectivity on exposure to the elements. On the other hand, this design allows convenient replacement of the reflective material whenever dictated by a loss in performance.

v. Drape Formed Polyester Parabola

Only one example was found of a solar concentrating cooker which was fabricated by village labor using essentially locally available material and which also found considerable use in the village itself. The basic unit consists of a parabolic concentrator developed at the University of Wisconsin 33/. These collectors were introduced into three villages in Mexico during 1959-1961. Construction of the parabola was accomplished in several stages. First a male mold was formed from a concrete mound with the parabolic contour developed by rotating a wooden template of the proper profile on a vertical axis projecting through the center of the mound. After the concrete mold cured it was coated with a parting agent and covered with newspaper. Alternate layers of polyester resin and fabric were drape formed over the mold until a shell thickness of about 1/16 inch was obtained. The shell was stiffened by incorporating a locally forged metal band into the rim of the plastic shell during the shell forming operation. After the shell had been left to dry (cure) for several hours it was lifted from its mold and the inside surface lined with reflective material. In this case small squares of glass mirrors were cemented to the shell. The basic construction of the cooker was the same as that presently used in Niamey, Niger and shown in Figure 11. In the Mexican village situation the horizontal axis/cooking support was formed from iron strips by the village blacksmith. The "U" frame support was fabricated from wood by local carpenters. With the exception of the polyester resin which was obtained in Mexico City, all other materials were provided locally. The process of cooker building took between 8 and 32 hours of labor, and the cost of materials was about $15.

b. Introduction of Solar Cookers into Village Use

At the beginning of this survey certain assumptions were made as to the reasons for the lack of acceptance of solar cookers in the villages of the less developed countries. Generally these reasons were: too expensive, too complicated, not the customary way of cooking, different taste of food, cooking possible only for the noon meal, cooking must be done while standing in the sun, etc. Therefore, it was hoped that this survey would uncover some technical innovation or design concept that would suggest a solar cooker or cooking system that would overcome one or more of the problems which prevented village acceptance. The review of heat transfer systems and energy storage systems, reported in previous sections, was carried out in order to evaluate the possibility of using these technologies to overcome the problems of cooking in the direct sun or being able to cook only the noon meal. However, both of these systems would add to two other problems: cost and complexity of the system. Therefore, another objective of this survey was to review efforts to introduce solar cookers into village life in order to quantitize the relative importance of each of the problems which prevented cooker acceptance in the village.

It was generally assumed that there were many relatively extensive efforts to introduce solar cookers into village use. It had been reported that extensive field trial efforts had been carried out in India, Mexico and Morocco and that they had not resulted in social acceptance of solar cookers 34/. Although many sources referred to the field efforts in India, documentation of these efforts could not be located. Also, the program to introduce cookers into Morocco could not be documented. Therefore, as the survey progressed, it became apparent that the literature was essentially void of documented, serious, long-term efforts to introduce solar cookers into village life. The only case found was a four-year effort by the University of Wisconsin to introduce parabolic concentrating cookers into three villages in rural Mexico during 1958-1961 24/. Some 200 cookers of several models were used as various designs evolved. This program was the combined effort of anthropologists and solar energy scientists and involved the development of solar cooker fabrication techniques which were carried out by local inhabitants using locally available materials (see previous section on "Drape Formed Polystyrene Parabola"). A review of this program was prepared as a 16 mm film: "Solar Cookers: Something New Under the Sun," by Professor James Silverberg, cultural anthropologist on the program 33/. The results of this program suggested that the past failures of efforts to introduce solar cookers into village use may be related more to the effort made to accomplish the diffusion of the technology rather than to technical or mechanical problems with the cookers themselves.

An important aspect of this program was the fact that there was continuous contact with the village people throughout the solar cooker introduction program. Anthropologists went to live in the village where the studies were made, they observed reactions to the cooker and also studied a variety of economic and cultural aspects of village life which affected the reactions of the people to the innovation. It was emphasized that careful planning of field studies and careful observation of results were necessary to obtain significant information. An important factor in the successful use of the final model of the cookers, developed during the course of this program, was the contribution made by the villagers to the design itself. Some of the conclusions of this effort 24/ were:

1. A reflective type cooker with a 1.2 meter (4 foot) diameter reflector, properly used can deliver a maximum of about 600 watts, can perform many cooking operations, and is best adapted to wet cooking. Assuming that 500 watts can be realized for a period of 4 hours and that cooking will be 70 percent then 1.2 x 10^6 calories will be available for cooking which is the energy required to prepare a meal for a family of six.

2. These cookers have been used for preparation of a wide variety of foods including beans, stews, soups, meat, tortillas, eggs, etc. They can be used for frying and also for baking by addition of a small oven over a heat absorber plate.

3. In climates of good solar radiation and in locations of reasonable need, where the reflective type cooker adapts itself reasonably well to the cooking and eating habits of the people, there appears to be good prospects for successful use of the cookers.

4. A limited number of families in northern Mexico have been "successful" users of the Wisconsin cookers for periods of time ranging from two months to fourteen months. The acceptance of the first model was described as initially successful in 13 of 19 families with a loss of

> acceptance by 5 of the 13 after several months of use and after some mechanical failures. The acceptance of the second model was excellent and the major problem of the first model appeared to have been solved. In the first three months of use, the units were used on more than 90 percent of the days on which use was possible.

Considering the fact that this program was conducted more than 15 years ago in an area where conventional energy sources (wood and oil) were not considered to be scarce, a remarkable degree of acceptance was realized. In light of the current wood shortage in many less developed countries and the fact that much wood could be saved by cooking during the daytime only, it might be expected that presently available concentrating solar cookers would have a good chance for acceptance in the villages of sub-Sahara Africa, assuming that careful planning is made for the field tests. A recent conversation with the author of the film which described the effort in Mexico 33/ confirmed the importance that must be attached to proper planning of any program to introduce technology into a village. Based on the results of the Mexico program, he is considering a program to introduce these cookers into India.

During the visit to the solar energy laboratory at Bamako, Mali, concern was voiced about the general assumptions that have been expressed by so many people about why solar cookers are not accepted by people at the village level. It is their opinion that such assumptions are based on comments made by the villagers with only a casual acquaintance with the solar device. It has been their observation that most efforts to introduce solar cookers in the village consist essentially of treating the cookers as gifts to the village with the expectation that they will be used after only a brief period of instruction. Lack of use after this period is interpreted as lack of suitability for the village situation. Because of this, a serious effort to diffuse existing concentrating solar cookers into villages in Mali will be undertaken in the near future. The primary purpose of this effort is to obtain the information needed to establish whether or not solar cookers are adaptable to village use in Mali, and if not, exactly why not.

Only one current effort to introduce solar cookers into the rural village situation was identified during the course of this survey. This one was sponsored by the Danish AID organization Danchurchaid to provide 250 parabolic dish aluminum concentrators to Upper Volta (West Africa). Frames and supports for these dishes were fabricated locally. The reflective surface was provided by applying an aluminized plastic film to the surface of the dish. Fifty cookers were sent to villages near Pô, Kongrusse and Banfora. It was reported that during the first year of this program the solar cookers were well received and there had been no problem in getting the local women to understand the system and to see its advantages. During May 1978, a visit was made to the village near Pô in southern Upper Volta. During this visit about eight cookers were used to demonstrate their ability to cook all of the local native dishes. Figure 28 shows one of those cookers being used to broil a chicken. It was found that the local women not only were proficient in the use of the cooker, but had made technical innovations in their design and use.

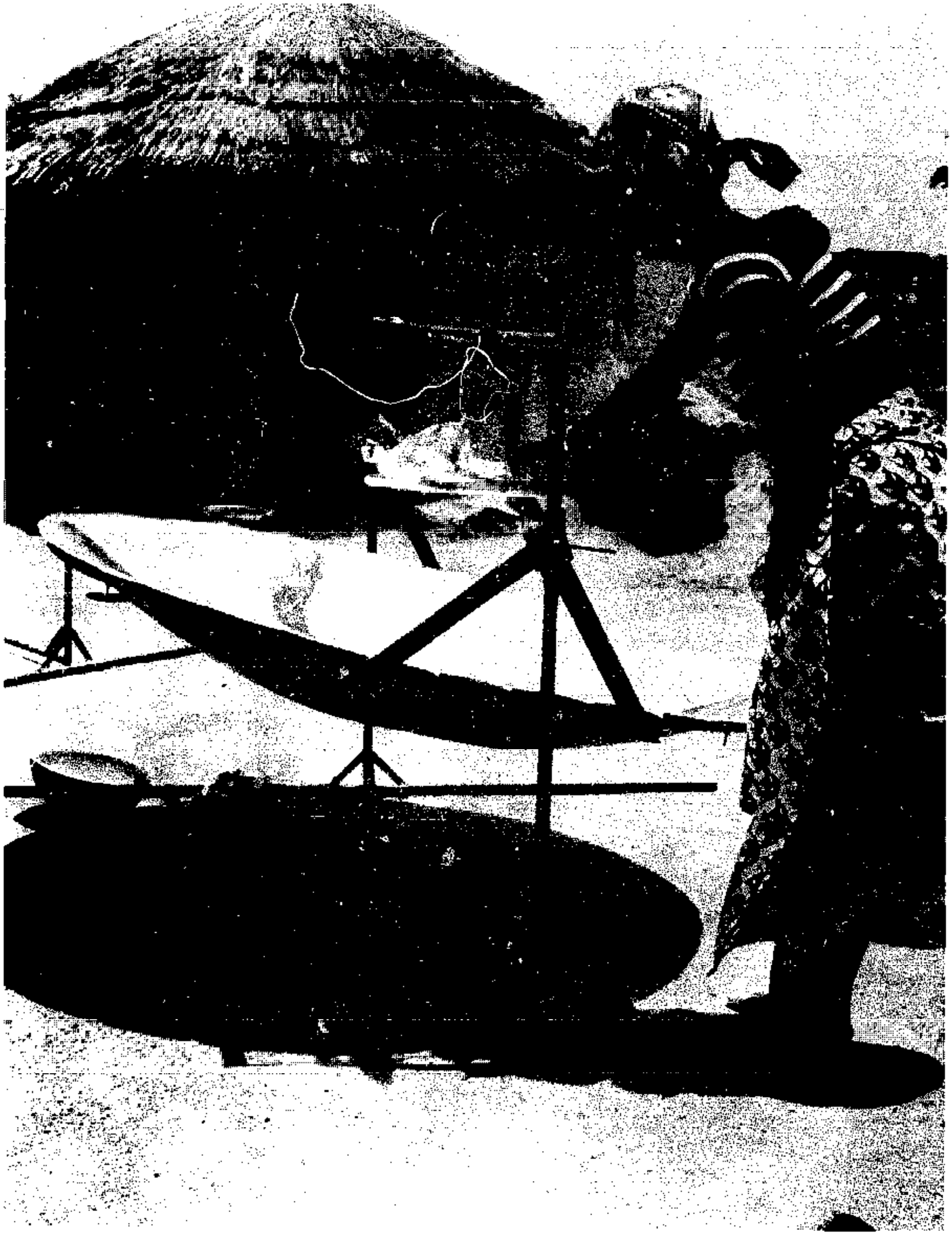


Figure 28. Photograph of Solar Cooker Developed by Danchurchaid Being Used to Broil a Chicken in a Village Near Pô, Upper Volta.

C. Survey of Wood Burning Stoves

The primary incentive for introducing solar cookers into village use is the reduction in the consumption of firewood which would result. Therefore, in this survey only solar cookers originally were being considered as a means for reducing the use of firewood. This type of approach to the problem has been described by Howe 35/ as "research devoted to applied technology according to energy source". That is, most researchers attempt to develop better solar cookers, solar heaters, windmills, etc. Relatively little research is based upon a general task orientation, for example attempting to examine all of the methods available for pumping water or cooking. Therefore, when considering how inefficiently wood and charcoal currently are being used for cooking it became apparent that some attention should be given to examining the possibility of developing better wood burning stoves. Howe suggests that improving the heat retention of charcoal braziers or developing a multi-purpose clay stove-oven would help to conserve existing traditional organic fuels. Introducing more than one technology for cooking would have additional appeal from the standpoint of field tests, since additional information could be obtained during a given period of village instruction. Also comparative data might be obtained that might not otherwise be possible. Therefore the decision was made to include in this program a survey of the state-of-the-art of wood burning stoves. This will include: 1) a short history of wood burning stove development and 2) recent efforts to develop simple wood burning stoves for village use.

1. A Short History of Wood Burning Stoves

Lawrence Wright 36/ reports that the oldest evidence of fire is found in caves of the Stone Age, blackened hearths and carbonized bones. These bones were not necessarily the result of cooking; they may have served as a fuel. Even today, in some areas bones are more plentiful than firewood, and valued more for the fire than for the stock-pot. The first indoor hearth was a shallow pit lined with stones, or the flat top of a low heap of slabs, set in a center of the dwelling away from the walls. This primitive central hearth had a higher stone hollowed on one face, as a fireback. Large stones, put around the fire to contain it, served to support the newly developed cooking-pots. Europe in the Stone Age, with its damp climate and ample forests, both demanded good fires and provided ample fuel for them. Cooking improved when settled cultivators and stockbreeders displaced nomadic hunters and came up with innovative ideas in pottery-making. Instead of being roasted, or parboiled in water heated indirectly by dropping hot stones into it, food could be boiled over the fire. Soups and stews appeared. Permanent settlements went up, with substantial rectangular timber houses of wattle-and-daub, each with a central fireplace, or even a combined hearth and baking-oven in an outer kitchen.

In the Iron Age, circular or oval huts were found with a hearth near the center. Wrought iron andirons to support the burning logs have been found on Iron Age sites. There may also have been horizontal iron bars laid between them to carry the cooking-pots, or to serve as spits.

Many variations of the above concepts were incorporated in the subsequent designs of cooking stoves, but none made any significant contribution to the growth of civilization. Early in the 18th century Benjamin Thompson, also known as Count Rumford, designed a basically simple cook stove. His principle was: not to produce heat till wanted, or not in excess, to conserve it with insulation, and to use it before it was lost. Cooks, up until then, had received about as much heat from the fire as the food being cooked. After the introduction of the Rumford cooking stove special additional hearths had to be provided to keep the cooks warm. The Rumford stove was unlike anything seen before. It was a massive brickwork affair with a flat top. In the top were a large number of small holes, into each of which a cooking utensil was accurately fitted, with only its double-insulated cover and handle projecting. Below each utensil was a small separate fireplace, comprising a grate, an ashpit, and a door to regulate the air. Only the larger fireplaces were refueled from below; to the others fuel was added from above when needed, or the fire revived by increasing the draft. From each little fire, a flue ran around the utensil before going to the exit flue. Two roasting ovens were heated by a separate fire, and a hot-water boiler by the nearest fire in use. Figure 29 is a sketch of one of his large ranges which were U-shaped to fit conveniently around the working space. He also designed "small ovens for poor families" and a "portable kitchen furnace" with a suspended fire-chamber and the heat channeled around the stew-pan. The fire chamber consisted of a conically tapered grate which was suspended like a bird's nest inside of and separated from the walls of the stove. This design essentially insulated the fire chamber from the outer wall. The confining of the heat, as well as the suspension allowing ready access of air, provided the prototype for the ranges which followed. A sketch illustrating the principle of Rumford's design is shown in Figure 30. Unfortunately, Rumford's cooking ranges never came into wide use until a century after his death.

About 1840 the "close range" or "kitchener" appeared. This was more of a stove than an open fire, having a small fire-box that could be shut in front and a completely sealed-in chimney opening above. This functioned relatively well except that, when little cooking was going on, the fire could not be significantly reduced except by removal of some front bars, the doors of the smoke-chamber, and part of the hot plate. In Brown's Patent Universal Cooking Apparatus of 1840, the boiler was heated by a flue. It was placed on the cooking-top at the side away from the fire. An original addition was the "Automatic Roasting Jack," a Dutch oven with a vertical spit. When this was set before the fire, a tube beneath it engaged with the air-inlet to the fire, and the draft drove a fan to turn the spit.

In Sylvester's range of 1842, only one side of the boiler was exposed to the fire, but this side was ribbed inside and out to increase heat transfer. The bottom of the oven was open to the bottom of the fire which was claimed to be beneficial since the hot air which passed over the meat had the effect of roasting rather than of baking.

The Mechanic's Magazine of 1844 remarks: "The variety of articles of this kind devised of late years, seems almost to preclude the possibility of any considerable novelty. The enormous cooking ranges of our portly ancestors

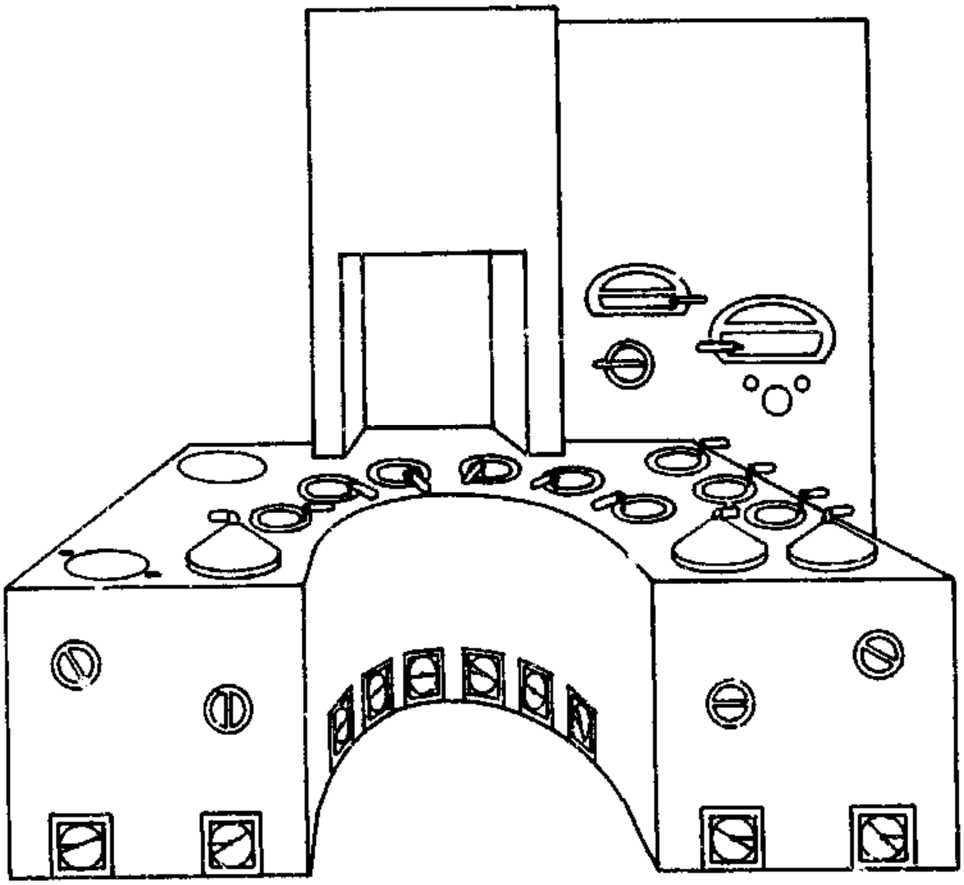


Figure 29. Sketch of Rumford's Large Cooking Range.

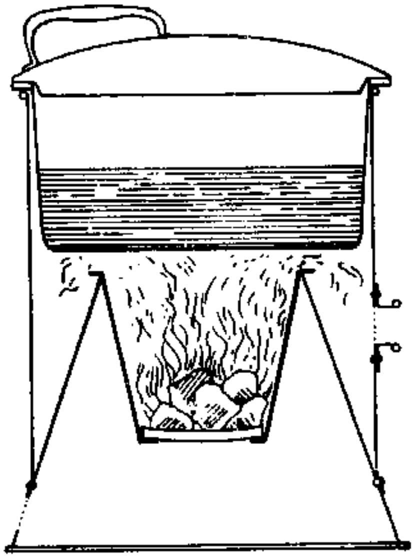


Figure 30. Sketch of Small Cook Stove Illustrating Principle of Rumford's Design.

had few properties in common with the convenient, compact, and almost elegant structures which have succeeded them. In the former, the grand operations of roasting and boiling were affected, as we may say, by main force of heat, without contrivance, adjustment, or economy; in the latter, all the operations required by the most refined cuisine are effected by one fire, at little cost, and with extraordinary convenience."

Warr's cooking apparatus of 1844 had a better-placed boiler; one face formed a raking fire-back, and the flue passed under and up behind it. The size of the fire-chamber was reduced by a plate moved by rack-and-pinion, which provided fuel economy between meals.

Harrison's Economical Derby Range of 1846 was a three-in-one unit that could be used as a closed-stove, a semi-closed stove, or an open fireplace. These types of ranges, due to their versatility, were extensively used in England.

Throughout the 1800's in America iron stoves and ranges were manufactured in great variety and quantity 37/. As opposed to the bulky ranges in England, these ranges were less massive and could be transported from place to place with little difficulty.

The successive improvements of the cast-iron range in America were largely modifications of the Pennsylvania Dutch oven; a special grate which had long been used in fireplaces and an ash chest along with a roasting oven were added. The roasting oven was heated by combustion gases from above and below.

Philo Penfield Stewart (1798-1868), a missionary and teacher, made pioneering contributions towards the shaping of the cooking range. Stewart's Oberlin Stove is generally recognized as the starting point for the modern range. The basic features of Stewart's design were: utmost concentration of the heat source; free suspension of the fire chamber like a bird's nest, as in Rumford's range; the surrounding of this chamber by air; perforation of the chamber walls, which as in Rumford's model taper toward the bottom. By around 1840 the cast-iron cooking stove had taken on a very impressive appearance having a base and superstructure. It drew the same interest in its time as the streamline-kitchen a century later. As in other fields, the most active period of invention was from the middle 1850's to the 1870's. An advertisement of 1848 listed the manifold possibilities then available: combined coal and wood firing, movable grates, storage space, etc.

Figure 31 is a photograph of a scale model of a late 19th century wood burning stove manufactured by the Atlanta Stove Works. The high thermal efficiency of these stoves was demonstrated by cooking a breakfast of eggs, bacon, grits and coffee with the heat generated by burning a copy of the Sunday newspaper.

Figure 31. Photograph of a Scale Model of Late 19th Century Wood Burning Stove Manufactured by the Atlanta Stove Works.

With the advent of coal gas the cooking ranges became somewhat less elaborate and the designs concentrated more on the efficient utilization of heat. About the middle of the first half of the 20th century interest in gas fired ranges began to develop in the United States and England. Demonstration kitchens were put on view where a wide variety of gas-cooked dishes proved how well this versatile fuel could serve the household. People, who could afford them, quickly accepted this mode of cooking and never went back to the solid fuel stoves.

While this revolution in cooking methods and cooking ranges was taking place in most of Europe and America, the whole of northern and central Africa was still using the primitive methods of open wood fires for cooking. Even today this is the principal method of cooking food in the villages of the Sahel and Sudanese zones of Africa. In stark contrast to the situation that existed in primitive times in Europe or even in these zones of Africa in the last century, ample supplies of wood are not readily available or cheap. On the contrary, wood for cooking is scarce and where it must be bought accounts for 10 to 20 percent of income of a typical family. In addition, and more seriously, the use of wood in these areas is resulting in deforestation and desertification; a critical global problem.

2. Recent Efforts to Develop Simple Wood Burning Stoves

Considering the problems of the less developed countries and particularly those bordering the Sahara in Africa, a significant reduction in the use of wood for cooking could be realized by using a very simple elementary wood stove of the 18th century Rumford design. Not only must the stoves be simple, they must also be cheap, or at least the cost must be commensurate with the life of the stove and the wood saved in cases where wood is bought.

During the past few years a growing interest has been evidenced in energy conservation and energy self sufficiency at the individual family level and by the do-it-yourself enthusiast. This has resulted in a revival of interest in wood burning stoves and books have been published which show how to build efficient, simple, low cost wood burning stoves. Many of these devices may be adaptable to village use in the LDC's. A selected list of these publications is included in the Bibliography.

Of the material reviewed in this survey, a project at the Brace Research Institute is typical of recent efforts to develop a simple and cheap wood burning cookstove which was designed for village use 38/. This stove was built from an inexpensive, mass produced galvanized bucket. The bucket was modified by providing an expanded metal grate about six inches from the top of the bucket. This grate supported charcoal (firewood) above which was placed the cooking vessel. The bucket served to confine the fire to the area of the cooking vessel. Total cost for this cookstove was reported to be about $1.50.

This cooker has not been field tested and at this time it is not possible to determine its suitability for village use. Because of its construction it is possible that with typical family use the lifetime of the stove may be relatively short. However, even with this simple and cheap design it has been reported that this stove should effect a 50 percent saving in the wood required for cooking.

In considering the design for an efficient, simple wood burning cookstove it is important not only to confine the fire to the cooking area but to conserve the heat produced by minimizing heat loss to the surrounding area such as the walls of the fire container, itself. Both of these conditions are met by the very efficient, ancient Japanese earthenware cooker, the Kamado. Figure 32 shows the major components of the Kamado; there are two basic parts: 1) the outer container consisting of the base and a lid with flue and cover and 2) the fire container which includes the firebox, ring and grate and the grill. All components, except for the grill, are made of ceramic to minimize the heat conduction from the firebox to the container and to the surroundings. Also the fire box itself is constructed so that it has minimum contact with the outer container. With this design the Kamado cooker is essentially a double wall vessel similar to a thermos bottle. The fire is built on the grate which is located between the firebox and the ring support for the grill. The temperature is controlled through proper draft by adjusting the damper at the top and the draft door in the base. A meal for six to eight persons can be prepared on as few as 14 charcoal briquets. This cooker can be used for baking, boiling, frying and barbecuing. Figure 33 is a photograph of a Kamado cooker.*

The basic design features of this ancient Japanese cooker are easily applicable to the village situation since it can be constructed from low cost local materials and with available village know how. To demonstrate this, a small wood burning cookstove was constructed from a 5-gallon paint can. The components of this cooker are shown schematically in Figure 34. The paint can serves essentially as a support structure for the firebox and other internal ceramic components. These components were kept simple in design to be within the state-of-the-art ceramic craftsmanship and materials of the village.

This simple cookstove consists of five essential components: 1) 5-gallon paint can and lid, modified by cutting a vent hole in the lid and a vent hole at the base of the can to control draft, 2) two ceramic blocks or stones to support the grate, 3) ceramic grate to support the fire, made of a circular disc of ceramic with holes or air passages to admit air for combustion, 4) ceramic liner which is a circular shell to insulate the fire from the can and 5) a metal grill or other structure to support food which is being cooked. A pan or other vessel could be supported directly on the ceramic liner. In Figure 34 the top of the ceramic liner is below the top of the can so that baking could be done by placing the baking vessel on the grill or ceramic liner and covering with the lid. If grilling were to be done, taller grate supports could be used so as to raise the ceramic liner to the top of the can, thus raising the grill to the top of the can for easier access.

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*Information and photographs courtesy of Kinuura Yaki-Kamado, Pachinko House, Atlanta, Georgia.

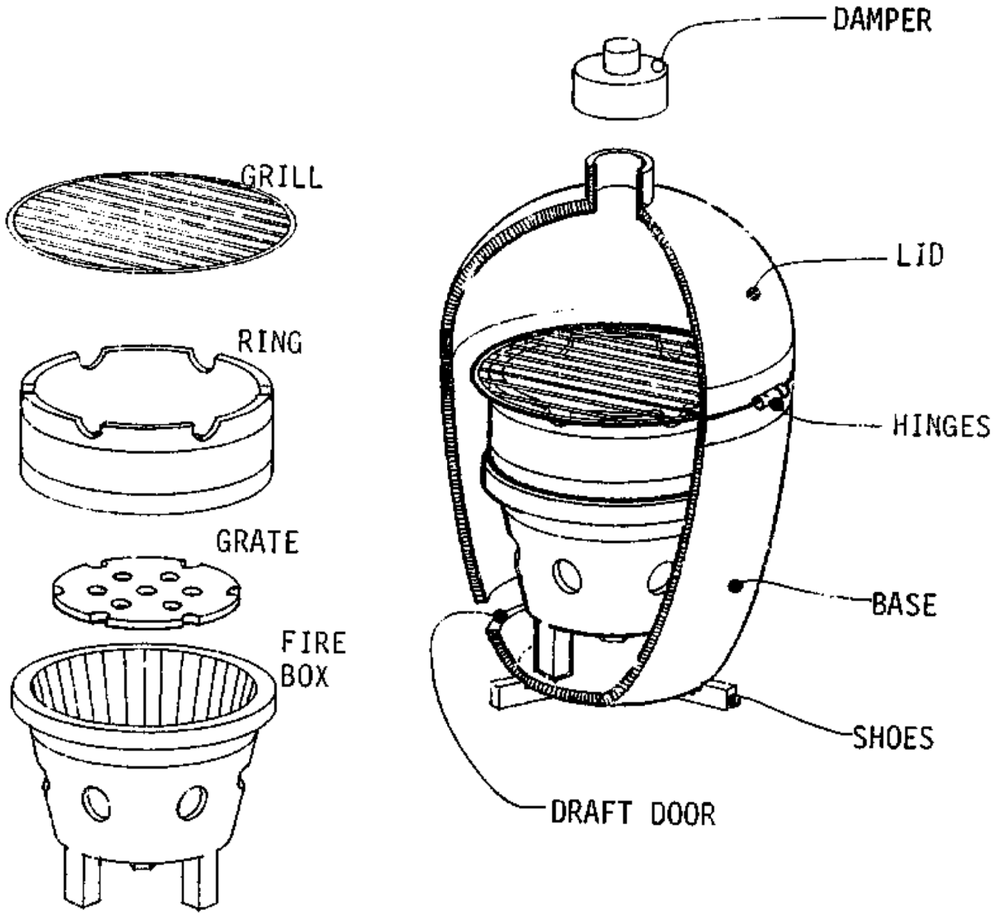

Figure 32. Sketch Showing Major Components of Japanese Kamado Cooker.

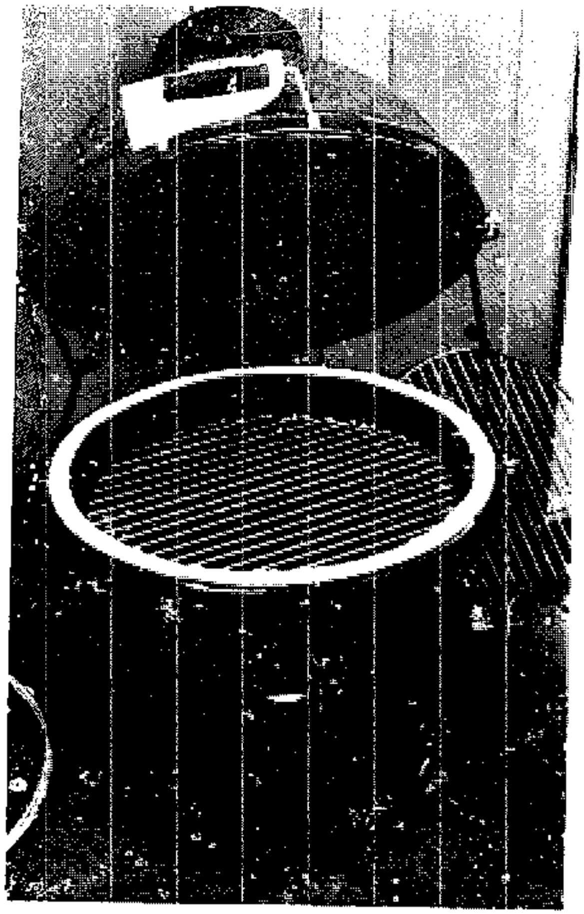

Figure 33. Photograph of a Japanese Kamado Cooker.

BASIC COMPONENTS OF JAPANESE KAMADO COOKER
(Courtesy of Pachinko House, Atlanta, Georgia)

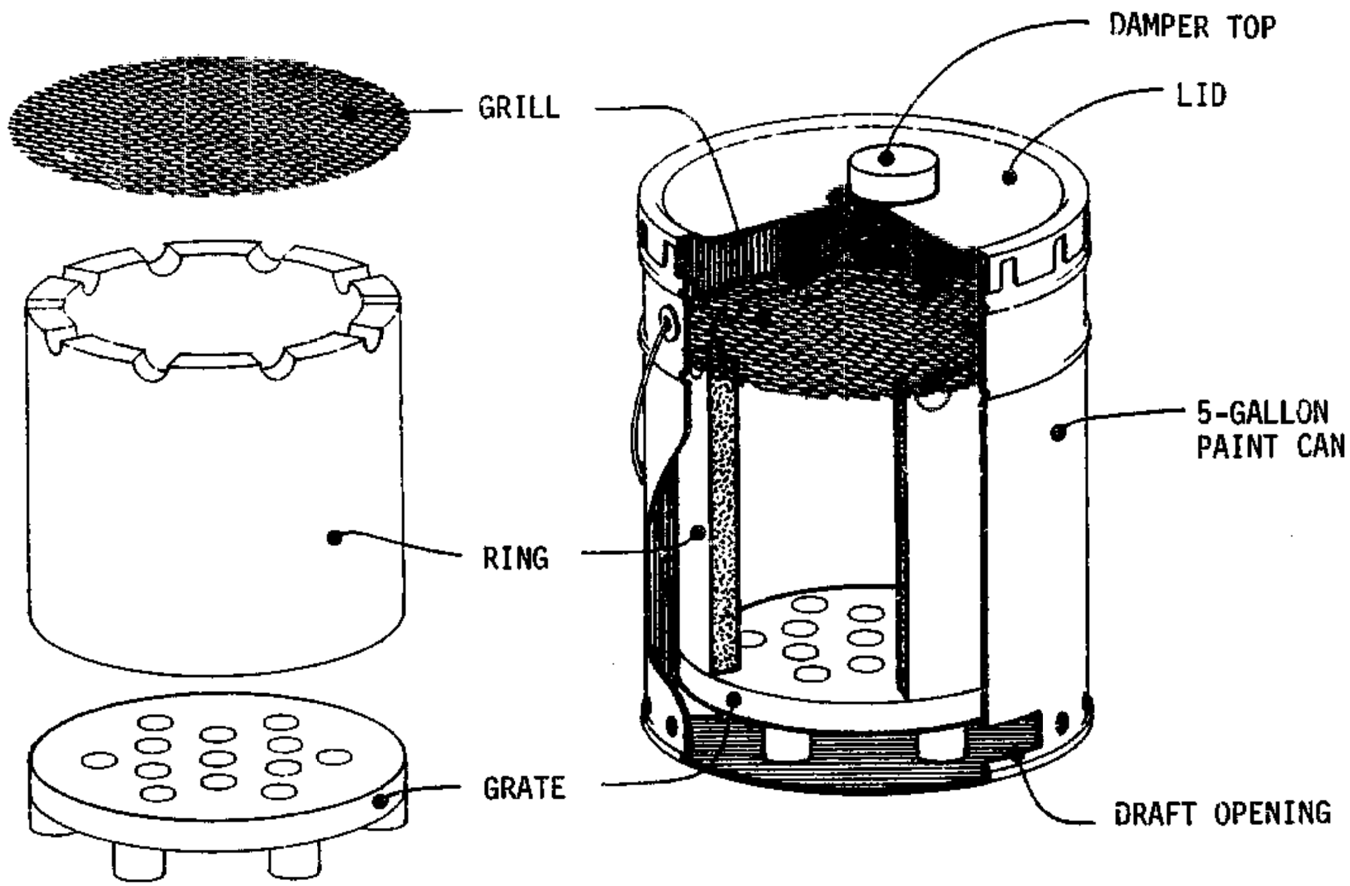

Figure 34. Schematic of Wood Burning Cook Stove Constructed from a 5-Gallon Paint Can.

The ceramic components used in this cookstove are simple disk and cylinder shapes which are easily fabricated and which minimize the danger of breakage due to thermal shock. Also, this design can utilize ceramic components of relatively low strength so that they need not be fired in a high-temperature kiln. If local clays do not have sufficient thermal shock resistance, then a mineral from Nigeria could be considered. This mineral, when mixed with clay, produces a ceramic with excellent thermal shock resistance. Figures 35 and 36 are photographs of the demonstration cookstove made at Georgia Tech. Time did not permit the fabrication of a ceramic liner so this component was simulated by rolling a piece of sheet metal to form a shell which was insulated from the can by a ceramic fiber blanket. The cost of the materials was less than $5.

This cookstove was not intended to represent a final design but to illustrate that simplicity, efficiency and village craftsmanship can be combined to develop a potentially effective, low-cost cookstove. If it is not practical to use a 5-gallon paint can, then a simple sheet metal shell could be rolled to form and open-ended support structure. This could be placed directly on the ground since there is no requirement for a bottom. A clay disk could be used to form the top. Figures 37 and 38 were taken at the ONERSOL plant in Niamey, Niger and illustrate sheet metal fabrication technology. available in that African town. At ONERSOL complete solar collectors and hot water tanks are fabricated from aluminum sheet and tubes. Clearly, the rolling of cylindrical shapes from galvanized steel sheet would be a simple task. Local ceramic craftsmen could provide all of the other (ceramic) components.

Since the 5-gallon can or the sheet metal shell represent the only imported part of this cooker, it should be more economical for the village if some already imported commodity could be shipped in the 5-gallon can. In time, and as village use increases, it is possible that the entire cookstove could be fabricated from local ceramic materials.

Figure 39 is a photograph of a brick kiln in Niamey. This illustrates the industrial scale on which ceramics are produced in the major cities of the sub-Sahara. It also illustrates another application for which large quantities of wood are consumed to provide thermal energy. It is estimated that this brick plant probably consumes about 2000 kg (5000 pounds) of wood daily. This is a good example of the reason to consider all uses of wood when studying ways to reduce deforestation and associated desertification. Also, such applications as brick firing represent a reasonably sophisticated industrial operation and the development of solar technology to provide the heat for a brick kiln may be much easier to implement than the introduction of solar cookers. Further, one solar heated brick kiln would have the same wood conservation value as the use of thousands of cookers. However, the technology does not yet exist for firing bricks by solar energy, so that this application is a long range one requiring a relatively large research and development effort.

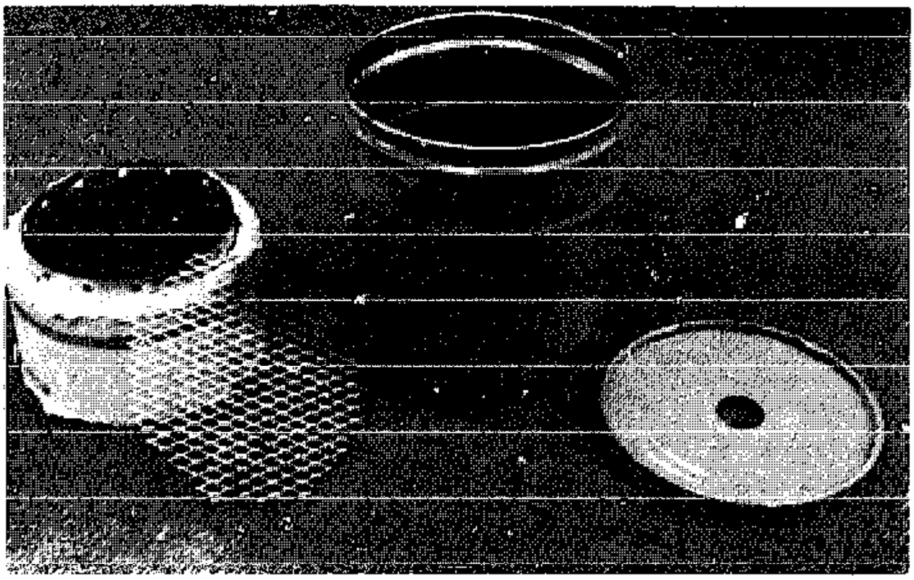

Figure 35. Photograph of Components of the Demonstration Cook Stove Fabricated at Georgia Tech.

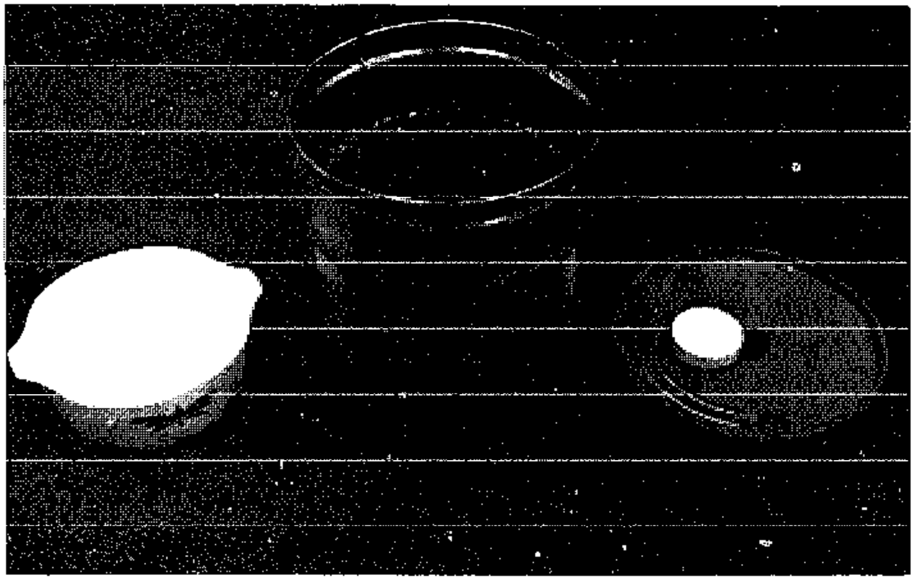

Figure 36. Photograph of Demonstration Cook Stove Fabricated at Georgia Tech.

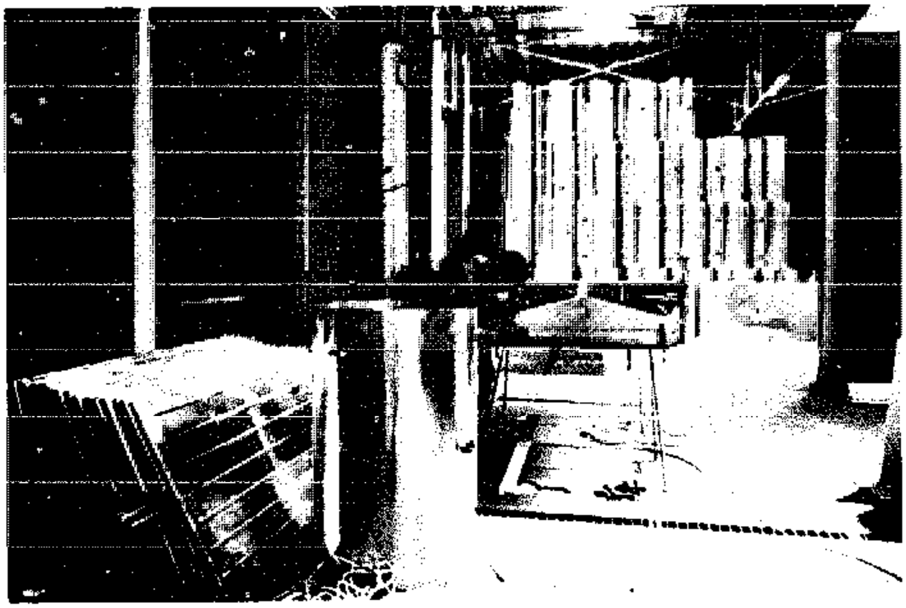

Figure 37. Photograph Showing Manufacture of Hot Water Tank and Solar Collectors at ONERSOL Plant in Niamey, Niger.

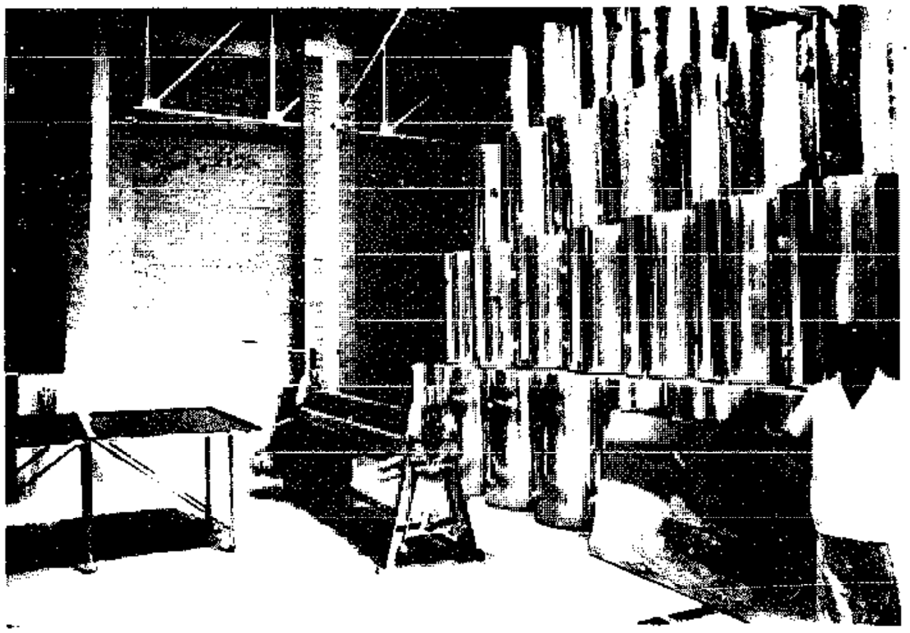

Figure 38. Photograph Showing Rolled Hot Water Tanks at ONERSOL Plant in Niamey, Niger.

Figure 39. Photograph of a Wood Fired Brick Kiln Near Niamey, Niger.

V. SUMMARY AND RECOMMENDATIONS

This report has presented the results of a survey of the state-of-the-art of solar powered irrigation pumps, solar cookstoves and wood burning stoves in order to give direction to efforts to apply these devices to the energy needs of the less developed countries.

Particular attention was given to sub-Sahara Africa, where extensive use of wood for cooking and low rainfall have combined to accelerate the problem of desertification. The use of solar cookers and more efficient wood burning stoves could significantly reduce the consumption of firewood; the wide use of solar irrigation pumps could provide the water needed to reclaim land for agricultural and energy purposes. The following section will summarize the finding of this survey and recommend future work in each of these areas.

A. Solar Powered Irrigation Pumps

Solar powered water pumping systems for irrigation have been widely distributed in many countries in Africa and in Mexico. More than 36 organic Rankine cycle systems using flat plate collectors have been installed by SOFRETES and many more are under construction. A committee to fight against the lack of water in the Sahel has agreed that solar water pumps offer the only practical means for providing water for their widely dispersed and remote irrigation needs.

Solar water pumps using flat plate collectors are very inefficient and presently too expensive to find the wide use in sub-Sahara Africa that is necessary to halt desertification. Present, large scale irrigation systems in the United States use more efficient parabolic trough concentrating collectors and are expected to provide water at less expense than the flat plate system. However, the small power capacities required for the dispersed needs of Africa (1 to 3 kW) suggest that point focus concentrating collectors (parabolic dishes) could provide the basis for more conventional steam-driven power units. Such a unit would lend itself to production as a "portable" package and hopefully at a low enough cost to rapidly expand its use in sub-Sahara Africa. Presently parabolic dish antennas are being mass produced for satellite microwave communication systems so that much of the concentrator fabrication technology and tracking system design are already developed. The principal area for development is in the design and testing of a suitable heat exchanger, selection of heat transfer fluid and the integration of the thermo-mechanical machinery and water pump.

It is recommended that a detailed study be undertaken to determine the economic and technical feasibility of developing a 2-3 kW solar powered irrigation system using a parabolic dish concentrator based on existing microwave antenna production technology. It would be the objective of this study to develop a 2-3 kW solar system with a cost of $5,000 per installed kW.

B. Solar Cookers

Solar cooker development and experimentation has spanned the past 100 years. The principal type of cooker uses a parabolic or spherical-dish type concentrator where the cooking takes place at the focal point of the concentrator. Although many laboratories throughout the world have experimented with this type of solar cooker, they have not found widespread acceptance at the village level. Generally, the reasons given for non-acceptance are: too expensive, too complicated, not traditional, danger of getting burned, cooking must be done in direct sun, cooking can only be done during the middle of the day etc. Although these or similar reasons are given universally, it was found that they are based more on opinion rather than on extensive documented efforts to diffuse this technology into the villages of the less developed countries. In fact, a four year effort to introduce such cookers into three villages in Mexico indicated that, with village participation in cooker development and fabrication, there is a good probability of acceptance in areas where wood is scarce. Therefore, it appears that simple concentrating cookers may find acceptance in the villages of sub-Sahara Africa if a serious program of introduction, instruction and education is undertaken and if the local people can become involved in their development, fabrication and maintenance.

In order to overcome the limitations of the concentrating dish solar cooker of working only during the day and in the direct sun, other types of cookers were evaluated. These were systems that permitted the cooking to be done at a point remote from the solar collector and/or that stored the collected heat for use at a later time. The first system uses a heat transfer fluid (oil) to transfer the heat from the solar collector into a sheltered area. Although interesting in concept, this system requires relatively complex plumbing and provides indirect cooking which will be very expensive by village standards and which would appear very complex to the village housewife. However, no records were found where these systems had been built thus there is no experience available from which to evaluate the actual potential of this system.

The storage systems which were considered in this survey were those capable of storing energy by using: 1) heat capacity (sensible heat) of cheap solids (rocks) and liquids (oil), 2) the heat of fusion of various salts, and 3) chemical energy such as heat of dilution of acids (H_2SO_4). Only the sensible heat system appeared to be practical. However, the amount of material required, 140 liters (40 gallons) of oil and rock, and the associated plumbing needed to cook a meal for a family of six would represent a cost beyond the reach of the average village family. In addition to cost, serious technical problems and safety hazards must be dealt with before storage would be a viable alternative for cooking in the village.

From the results of the survey of solar cookstoves, it is recommended that a detailed study be made of the program to introduce solar cookers into Mexico and that it be considered as a prototype pilot effort to introduce direct, dish type concentrator solar cookers into the villages of sub-Sahara Africa. A prototype collector should be developed based on the materials and level of technology and handicraft available at the village level. This study should be coordinated with cultural anthropologists and a joint program of solar cooker introduction into the village should be planned in detail.

On a long term basis, a program should be undertaken to construct prototype solar cooking devices using a heat transfer system which would permit cooking to be carried out in a shelter. Such a hardware construction and evaluation program is needed to determine the possibility of developing cheap and simple solar heat transfer systems which have the potential of being introduced into the village as a second generation solar cooker.

C. Wood Burning Stoves

Progress in the development of wood burning stoves has been found to parallel technological and economic development. As populations and economies increased, more efficient use was made of available resources. Unfortunately, at the present time in sub-Sahara Africa most wood or charcoal used for cooking is consumed either in open fires or inefficient charcoal or wood stoves. However, the history of wood stove development provides the basic design information needed to construct simple, cheap and efficient cookstoves which could significantly reduce the amount of wood required to cook the meal for a village family. If combined with the simple direct solar cooker this stove could provide an additional saving in the wood required for cooking when the sun was not shining. Also, in some villages the meals cooked in the evening or early morning are small when compared with the mid-day meal and, therefore, would require a relatively small, simple and potentially very cheap cooker. A small demonstration wood burning cooker was built from a 5-gallon paint can to illustrate a design which could be constructed with the technology and materials available at the village level.

Based on the results of this survey it is recommended that a simple wood burning stove be designed using the materials available in a selected African village. The cookstove will incorporate the basic design principles of the simple and very efficient ancient Japanese ceramic Kamado cooker. The design will be modified as necessary to accomodate the existing ceramics and ceramic technology in the village. In the event that local clays have inadequate thermal shock resistance, consideration should be given to using a mineral from Nigeria; this mineral (when added to clay) has been used to make ceramic cookware with excellent thermal shock resistance.

The program to introduce this cooker into the village should be incorporated into the detailed program recommended for the solar cooker and coordinated with the cultural anthropologists.

D. African Solar Energy Workshop

The results of this survey, including visits to four of the countries of sub-Sahara Africa, have emphasized the urgent need in these countries for energy to pump irrigation water and energy to replace firewood as fuel for cooking. The human suffering and ecological damage which are resulting from extensive wood cutting, deforestation and desertification can be relieved only through dedicated efforts by the local governments with technical assistance from the developed countries of the world. Also, this survey has identified solar water pumps as probably the only practical means for providing water for the extensive irrigation needs of sub-Sahara Africa, and simple solar cookers and wood burning stoves as the most practical and rapid way to reduce the extensive cutting of firewood. The use of wood for various industrial thermal processes might also be reduced by the use of solar energy.

Sixteen countries of sub-Sahara Africa have been identified as the ones most affected by the problems of deforestation caused by the extensive cutting of firewood and the devastating effects of inadequate water for agriculture and the support of life. All of these countries have abundant solar energy and most have some level of solar energy research or commercial activity. The solar energy laboratories in Sudan, Niger, Mali and Senegal were visited during the course of this survey and these countries are actively developing solar energy devices to provide the heat for cooking and to provide energy for pumping water for irrigation. During this survey it has become apparent that the level of technical expertise, experience, facilities, resources, problems, needs, etc., is not equal in all of the countries of sub-Sahara Africa. Although the problems are essentially common among these countries and probably common solutions will be found, the approach and ability to realize solutions to these problems are as diversified as the countries themselves. Therefore, it appears that there is a serious need to improve lines of communications within the countries involved and between those countries and the developed countries which have the technology and resources necessary to help solve their energy and ecological problems.

The solar energy expertise, experiences, capabilities and resources of the developed countries and their applicability to the energy needs of the less developed countries need to be made known to the countries of sub-Sahara Africa. Likewise, specific information concerning details of the energy problems together with relevant social, cultural and economic implications of utilizing alternative energy resources must be made known to the concerned experts in solar energy, sociology and anthropology. Probably the quickest and most effective way to establish these lines of communication and to transfer this information would be through the medium of an international workshop. Although there have been many international seminars, congresses, meetings and workshops on solar energy related to less developed countries and rural areas, these activities have dealt primarily with the technical problems and developments related to solar devices.

This workshop would concentrate on the energy/ecological problems within each country of sub-Sahara Africa and the relationship between existing economic, social and cultural conditions and the present use of energy. Solar energy developments and activities in these countries would be discussed only as they are related to efforts to solve the specific energy problems previously identified. The solar technology presented by the developed countries would be limited to off-the-shelf solar technology or very short range solar developments directly related to the most critical energy needs of sub-Sahara Africa.

The 16 countries of sub-Sahara Africa identified in this survey should participate in the workshop. Visits have been made to the four major solar energy laboratories in this area and all four agree with the need for the workshop. Candidate participants from all 16 countries can be identified easily. Ideally, there should be two participants from each country; one should be a person who is directly associated with adapting solar energy to the energy needs of his country and the other should be a person familiar with the village life and customs and how they are affected by the present energy/environmental problems, and how they have been or may be affected by the introduction of solar and other alternative energy resources.

It is recommended that this workshop be held in Atlanta, Georgia, during 21-25 May 1979. This is the week preceding the next International Congress and Exhibition of the International Solar Energy Society (28 May-1 June 1979). By conducting the workshop at this time it will be possible for the participants to remain and attend the solar energy congress, to obtain the latest information on solar energy developments throughout the world and to visit displays and exhibits of the latest hardware and other practical, operating solar energy devices. Hopefully, such a concentrated exposure to solar energy technology would encourage the participant to develop or accelerate the development and application of solar energy technology to help provide the energy needs in his own country.

May of 1979 would appear to be an appropriate time for the workshop because of type of information which would be presented: documentation of current energy uses and projections for the future; establishment of current and projected energy resources; identification of all past and present attempts to introduce solar energy technology into village use; summary of past and present solar energy activities and plans for future solar energy activities. Also, since one of the primary objectives of this workshop is to document and summarize all possible efforts to diffuse solar energy technology into the villages of the area, it is hoped that advanced announcement of this workshop will encourage the initiation and/or acceleration of such programs. The results of these efforts should provide the data needed to identify the technical problems which prevent the use and/or acceptance of solar devices at the village level. From these data it should be possible to prioritize the technical/social problems facing the acceptance/use of specific solar energy devices (solar cookers, water pumps) in the village. This information will provide the guidance needed so that future technical development programs will be able to concentrate on solving actual technical/social/cultural problems rather than those which have been assumed to exist.

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