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9. ABSTRACT
This study assesses the feasibility of applying solar cookers extensively in rural Haiti, and it presents a preliminary design for a solar cooker based on Haitian requirements. Two such designs are presented. The study consisted of three phases: and initial study of solar cooking, and intensive study of Haiti and Haitian conditions, and a second, longer term study of solar cooking with emphasis on new designs and optimization of existing designs. Haitian conditions were found to be almost ideal for introducing solar cookers. Two cookers, the Telkes oven and a steel framed cooker, emerged from the tests as being most suitable for Haitian application. The Telkes ovens are capable of oven temperatures of 400°F or higher. The oven needs attention only every hour or so and there is little or no danger of food spillage while the oven is being moved. The steel framed cooker gives similar performance with regard to boiling water but needs more frequent attention to turning and reflector adjustment. The appendices include discussions of cooking with stored solar heat, on site versus centralized manufacture, programs for computation and data reduction, calculations for the Brace Research Institute solar steam cooker, a description of the steel framed cooker. They also give the trip report of the visit to Haiti, a status report on reflecting solar cookers used in Teotitlan del Valle, Oaxaca, Mexico, and a transcript of the narration from a motion picture on the last solar cooker project in Mexico. The report includes many figures showing various cookers, reflectors and uses. Future work should be aimed at further developing the steel framed cooker and further optimization of the Telkes oven designs.

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A FEASIBILITY STUDY

FINAL REPORT

Prepared by
Thomas E. Bowman
James R. Sharber
Joel H. Blatt

December, 1977

FLORIDA INSTITUTE OF TECHNOLOGY
Melbourne, Florida 32901

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PREFACE

This Final Report was prepared by Florida Institute of Technology to present the results of work done under Contract No. AID/ta-c-1333. The period of performance of the contract was July 1976 to September 1977.

The objectives of the study were to assess the feasibility of applying solar cookers extensively in rural Haiti, and to present a preliminary design for a solar cooker based on Haitian requirements. Two such designs are presented herein.

Principal Investigator was Dr. Thomas E. Bowman, Professor of Mechanical Engineering at Florida Institute of Technology. The work was performed under the supervision of Dr. Jerome J. Bosken, USAID Office of Science and Technology.

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The authors would like to acknowledge the contributions, often very great, of the large number of students who worked on this program at various times during the fifteen month period:

Narasaraju Yenamandra
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SUMMARY

The study consisted of three rather distinct chronological phases: an initial study of solar cooking, concentrating on work done by others in the past and on currently available solar cookers; followed by an intensive study of Haiti and Haitian conditions, both climatological and socio-economic; followed by a second longer-term study of solar cooking with emphasis on new designs and optimization of existing designs, incorporating what we had learned in Haiti.

During the initial study period we learned of only one solar cooker currently available on the United States market that might be suitable for use as a principal mode of cooking for a small family. This cooker, selling in 1977 for about $150 under the trade name Solar Chef, is apparently based on a cooker designed by W. Adams in Bombay, India, in the 1870's. The Adams cooker reportedly fed seven soldiers during January of 1878 in Bombay. The Solar Chef, as marketed, has a much more limited capacity, but can be modified to more closely resemble the Adams cooker, in which case it is much more suitable for "base load" usage.

There are also a large number of small, lightweight cookers on the market, including folding or collapsible types and styrofoam shapes. Most of these cookers are intended only as grills for cooking hot dogs or hamburgers, toasting bread, and the like, and are not adaptable to the modes of cooking and available food typical in the rural areas of a country such as Haiti. For the intended uses they often work very satisfactorily provided it is not too windy to set them up. Useful lifetimes are unknown, but presumed short in regular use.

We also found two cases of solar cookers, listed in the catalogs of distributors of solar equipment, that seemed on the basis of price and description to be competitive with the Solar Chef, but that reportedly are no longer available. In view of the current haphazard state of the solar equipment industry,

we assume that one or both of these cookers might reappear in the marketplace at some future date. We were unable to evaluate them, however.

The most notable aspect of the solar cooker literature is the decade or so of very extensive activity that began about 1953. During this period, a large number of researchers were active in this country, Canada, India, Egypt, Portugal, Israel, Holland, France, Burma, Barbados, and probably other places as well. The United Nations tested solar cookers in Italy, Thailand, and Jamaica. The Ford and Rockefeller Foundations both actively sponsored solar cooker research, the latter foundation funding extensive field trials in Mexico. The Umbroiler, a collapsible umbrella-type cooker designed and manufactured by Dr. George Löf, had been sold in the hundreds by 1961, and several other large solar cookers were commercially available at the time of the VITA study in the early 1960's. Telkes ovens were displayed at the Brussels World Fair and various trade fairs.

Performance of the best solar cookers of this period, such as the Wisconsin cooker, the Indian cooker, and the Telkes ovens, remains unsurpassed to this day. The technology was well developed. In our later work, we reproduced with remarkably good agreement the Telkes oven test results obtained by the United Nations Food and Agriculture Organization in 1959, but were not able to improve on them.

Our Haitian study included two trips to Haiti, one of which featured an extended trip by four-wheel-drive vehicle to the remote and very arid regions of the Northwest. One of the important results of this trip was a revision of our understanding of the meaning of "appropriate technology" in the Haitian context. We had begun our study with visions of perhaps devising cookers based on materials like clay, straw, etc. - diversion of activities related to pottery, basketry and the like to the making of solar cookers. We did not see much pottery or basketry in Haiti - we saw lots of ironwork. In the capital city, one sees countless men carrying thin, smooth surfaced reinforcing bars through the streets on their shoulders. The bars are used not just in concrete work, but for railings on stairs, guards over windows, grillwork, etc., normally fabricated at the point of use. Artisans convert empty 55-gallon steel drums into ornamental wall hangings that can be bought on virtually any street corner. Even in the provincial towns, iron grillwork and railings are very common. These observations were of course very welcome to us, and opened up a new avenue of approach to the design of solar cookers for Haiti.

In other respects, we found Haitian conditions to be near-ideal for the introduction of solar cookers. Two principles that seem to be widely adhered to among the poorer classes are especially relevant: nothing is ever thrown away, and the easiest way is the best way. The latter is an especially welcome change from what we are told is characteristic in many other cultures. We have every reason to believe that if solar cookers are introduced, and if they work well enough and last well enough that the net effect is to make life easier - some women currently spend several hours a day just collecting wood and carrying it home - they will be used.

Weather and geography were studied before we left, and as much meteorological data as possible was collected. The South is mountainous and verdant, with considerable rainfall, at least in certain seasons, and some areas are often cloudy. Locations where solar cookers could be used are limited. The Northwest is hilly and arid and very bare, and the sun shines incessantly; locations where solar cookers could be used are essentially unlimited. The North is more mountainous and less arid - more like the South - with a coastal plain that appeared very suitable for solar cookers. The Artibonite Plain, along the central coast, sustains a large rural population and is flat, sunny and dusty - another good area for solar cookers. Insolation measurements we made in December in Port-au-Prince and along the central coast and through the Northwest were higher than we have ever seen in Florida, and especially higher than the Florida values we obtained in the humid months of July and August when we did most of our testing.

The latter half of our study, after our return to Florida, was devoted to designing, building, and testing a variety of cookers. A steel-framed cooker, inspired in good measure by impressions formed in Haiti, was designed and fabricated. In its ultimate form, the frame supports a horizontal oven with a single-curvature parabolic reflector suspended below it; the reflector focuses solar energy through a narrow window in the bottom of the oven. The Telkes oven built from published plans in the first phase of our study was extensively modified, and two new Telkes ovens were built. The Solar Chef was extensively modified. A second cooker utilizing energy focused into the bottom of an oven was built, based on a sketch published in 1961. A 48-inch diameter spherical reflector was purchased and used for experiments on direct-focusing solar cooking. Extensive water boiling experiments were performed, including time to boil various quantities and the effects of placing pans of cool water next to a pan of boiling water. Cooking oil temperatures were recorded. Effects of opening doors, removing pan lids, off-design operation, passing clouds, strong winds, rain squalls, etc. were all studied.

Two cookers emerged from our tests and other evaluations as being especially suitable for Haitian application: the Telkes oven, and the steel-framed cooker that we developed and later dubbed the "F.I.T. Cooker", taking the initials of Florida Institute of Technology.

The Telkes ovens are capable of oven temperatures of 400°F or higher; a liter of water can be heated from 80°F to the boiling point in about forty five minutes; a liter of cooking oil can be heated to 300°F in the same time, and to 400°F within two hours. Up to three liters of water can be boiled at one time. Oven temperatures over 200°F persist for nearly an hour after sunset, even without covering the window and with a poorly insulated oven. The oven needs attention (aiming at the sun) only every hour or so, and there is little or no danger of food spillage while the oven is being moved.

The F.I.T. cooker, although tested less extensively, gives similar performance with regard to boiling water, and promises to be more versatile with regard to cooking stews or pan frying due to the heat entering the oven from the bottom rather than the top. It needs more frequent attention - turning and reflector adjustment are needed about every fifteen minutes. It is easier to move around, and seems easier to use than the Telkes oven.

All of the cookers are expected to perform better in Haiti than in Florida. In Florida, weather conditions vary from warm and humid to cool and dry. When the temperature is favorable for solar cooking, insolation is limited due to the high atmospheric moisture content, and when insolation is higher the temperature is often low enough to cause significantly higher heat loss. In Haiti, where hot, dry weather is common, both temperature and insolation reach levels that we never see in Florida, and the high levels occur simultaneously.

We entered into this study with one rather strong bias that affected our approach and should be mentioned at this point. Some earlier investigators in this field have attached paramount importance to virtues such as cheapness, lightweight, and portability. In our opinion, the most important virtues that a solar cooker aimed at "base load" use should have, beyond cooking effectiveness, are durability, stability, longevity, etc. Cheapness is of course desirable - but a cooker that is sturdy and long-lasting almost has to be much more expensive than one that is lightweight and portable. We are certain that anyone embarking on this study with a bias opposite to ours would arrive at a much different set of conclusions. From what we have learned about Haiti, though, we still believe that our bias is an appropriate one.

I. REVIEW OF EARLIER WORK

We learned that a very considerable amount of work was done on solar cookers in the late 1950's, but relatively little work since that time. The state of the art as of 1961 or so is very comprehensively summarized in two sources: the Proceedings of the United Nations Conference on New Sources of Energy, held in August 1961, and VITA Report No. 10, "Evaluation of Solar Cookers."

A. UNITED NATIONS CONFERENCE

The United Nations Conference included a session on Solar Cooking in which six papers were presented treating the design, construction, and testing of various solar cookers, and a seventh paper by the Nutrition Division, Food and Agriculture Organization of the United Nations, which had performed comparative evaluations of the two most common cooker types, the Telkes solar oven and the Wisconsin solar stove, during the Summer of 1959. In addition, Dr. George Löf presented an extremely valuable General Report on Solar Cooking and a Rapporteur's Summation at the end of the session.

Table 1 has been reproduced from Dr. Löf's General Report. "Insofar as possible, the tabulated data have been obtained directly from statements or figures in the papers, or they have been computed from such factual information. Some of the features, however, have required judgement and interpretation by the rapporteur, and are so indicated in the table. In certain instances, items have been omitted because of insufficient data in the papers."[1] Further descriptions and discussions of the individual cookers follow.

1. Stam Focusing Cookers

"Although three types of cookers are discussed by the author, most of the paper deals with a proposed spherical concrete or plaster reflector of four meters diameter." (See Figure 1). "The cooking vessels would be suspended from overhead supports and periodically adjusted to the changing focal position. Other uses

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1. Löf, George O. G.: "Use of Solar Energy for Heating Purposes: Solar Cooking." Paper GR/16 (5), Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II, United Nations Publication No. 63.I.39, pages 304-315. See also Löf, "Recent Investigations in the Use of Solar Energy for Cooking," Solar Energy, Volume 7, pages 125-133 (1963).

Table 1. Solar Cooker Characteristics
(from Löf, "General Report," Solar Cooking Session, UN Conference on New Sources of Energy, 1961.)

United Nations paper No.	S/24	S/87	S/100	S/75	S/101	S/110
Authors	Stam	Duffie, Löf, Beck	Löf, Fester	Abou-Hussein	Telkes, Andrassy	Prata
Cooker type	# Focusing	Focusing	Focusing	Oven	Oven	Combination
Reflector type	# Spherical	Paraboloid	Parabolicumbrella	Internal flat planes	External flat planes	Parabolic cylinder
Reflector material	# Aluminum foil on concrete or plaster	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 •)
Reflector dimensions	0.22 m dia # 4.5 m	1.22 m dia	1.17 m dia	(4) 1 288 cm²	(4) 43 cm sq	(2) 0.5 m × 0.8 m
Effective solar collection area	0.04 m² # ~ 10 m²	1.07 m²	1.02 m²	0.36 m²	0.56 m²	0.74 m²
Reflector focal length	# 225 cm radius	46 cm	46 cm	-	-	~ 1.05 m
Oven window				0.36 m² double glass	0.19 m² double glass	0.06 m² single glass
Cooking area	# (2) 30 cm dia •	~ 20 cm dia	~ 23 cm sq	~20 cm sq •	~ 25 cm sq •	20 cm × 50 cm •
Effective solar intensification	# ~ 50 •	~ 34	~ 20	~ 3 •	~ 3 •	~ 12 •
Minimum time required to heat one litre of water 20°C to 100°C	nr	15 min 15 min ª (minimum)	22 min	nr	~ 30 min ª 40 min (minimum)	26 min •
Effective cooking power, kW	nr	0.4-0.5 0.28 ave ª 0.38 max ª	0.25-0.4	nr	0.15-0.2 • 0.10 ave ª 0.12 max ª	0.15-0.25 •
Food cooking performance	nr	Good	Good	nr	Good	Good
Approximate weight, kg	# Hundreds	10	3	nr	~ 20 •	12 18
Thermal storage considered	# Yes	No	No	Yes	Yes	No
Total cooking capacity	nr	~ 4 kg •	~ 2 kg •	nr	~ 3 kg •	~ 4 kg • (2 vessels)
Portability	# None	Good •	Excellent •	Good •	Good •	Fair •
Need for positioning during cooking	# Moderate •	Frequent (15-30 min)	Frequent (15-30 min)	Occasional (30-60 min)	Occasional (30-60 min)	Moderate (25 min)
Suitability for baking and roasting	# Fair •	Poor •	Poor •	Good •	Good •	Good •
Suitability for stewing and frying	# Good •	Good •	Good •	Fair •	Fair •	Fair •
Durability	nr	Good •	Fair •	Very good •	Very good •	Good •
Use of native materials	# Good •	Fair •	Fair •	Fair •	Fair • # Good •	Fair •
Full scale cookers constructed and tested	No	Hundreds	See below	Yes	Yes	Yes
Field testing	No	Extensive	See below	No	Some	No
Commercial sale	No	No	Hundreds	No	No	No
Approx. cost or price	nr	$16 (factory)	$30 (retail)	nr	nr	~ $35 (factory)

• FAO tests (Paper S/116).
Proposed.
ª Rapporteur's computation or estimate.

nr Not reported.
~ Approximately.

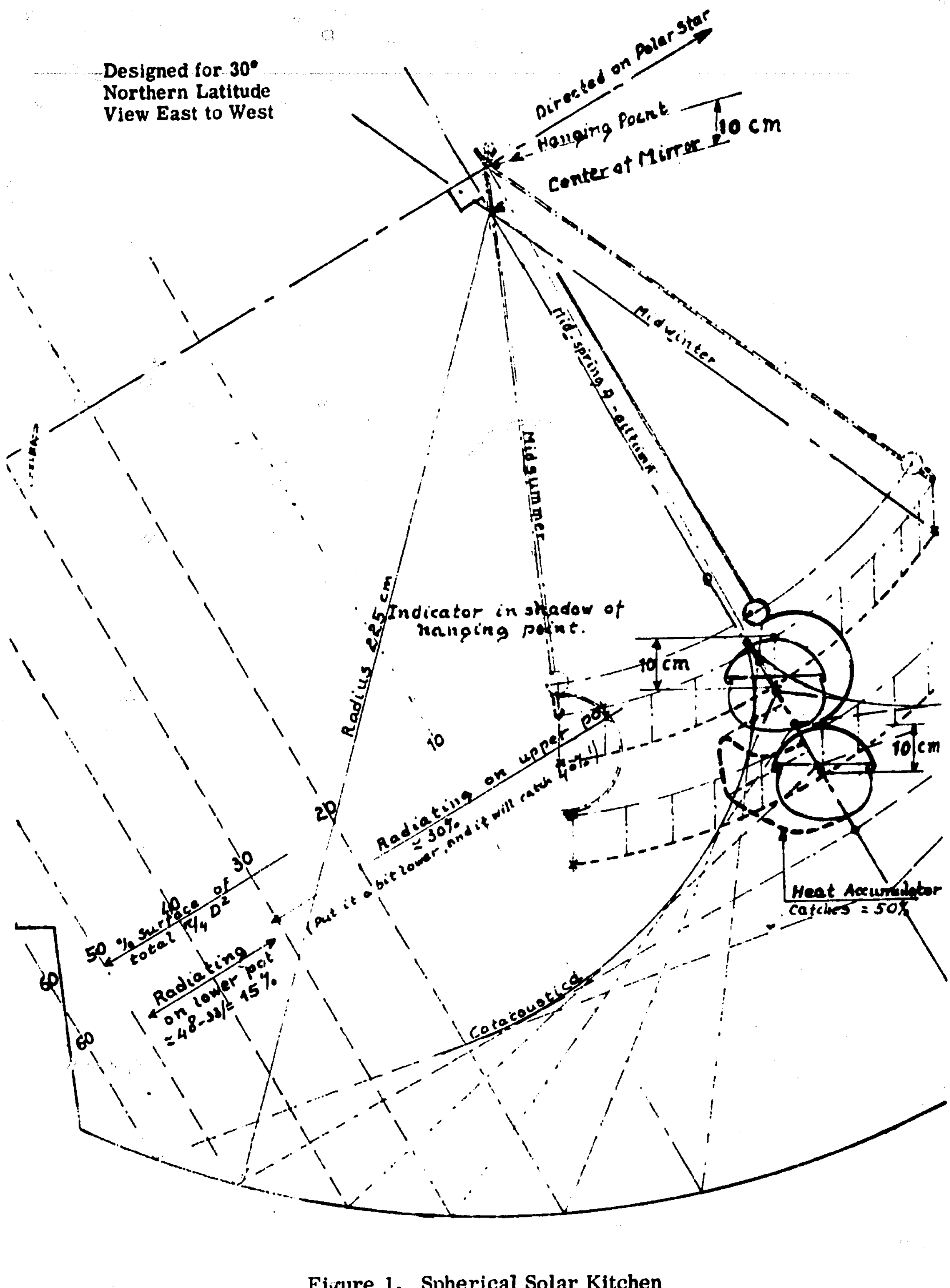

Figure 1. Spherical Solar Kitchen
(from Stam, "Cheap but Practical Solar Kitchens," Solar Cooking Session, UN Conference on New Sources of Energy, 1961.)

for the reflector would be in heating relatively large volumes of thermal storage materials for subsequent use in the warming of rooms on cold nights. The large focal area of a spherical reflector might permit simultaneous heating of separate cooking and heat-storage vessels. This design had not been built or tested when the paper was presented (August, 1961).

"Two other cooker designs have been suggested by the author. The first of these is an eccentric plaster paraboloid supported by the rim of a hole dug in the ground. The reflector would be about 1.6-meter diameter and the cooking vessel would be supported on a small tripod standing in the cooker shell. The unit could be turned and tilted occasionally to follow the sun. A reflective lining of aluminum foil has been suggested." (See Figure 2.) "Another proposal involves a parabolic cylinder on a north-south axis, rotated slowly by an hourglass device to follow the sun. Some type of heat-transfer fluid would be circulated through the hot tube to an insulated storage vessel. The heated fluid could then be subsequently used for cooking or other purposes."[2] (See Figure 3).

2. Wisconsin Cooker

These cookers, utilizing rigid plastic reflectors to focus solar energy on suspended, blackened cooking vessels, were developed at the University of Wisconsin over a period of years, and field tested in various Mexican villages in the states of Coahuila and Sonora in the North and Oaxaca in the South. Two papers at the Session were concerned with these cookers: a paper by Duffie, Löf and Beck on the Model 2 and Model 3 Wisconsin Cookers and field tests in Coahuila during 1960, and by the Nutrition Division, Food and Agriculture Organization of the United Nations, which tested a Wisconsin cooker and a Telkes oven in Rome during the Summer of 1959.

Figure 4 shows two views of a Wisconsin-type solar cooker. The photos were taken in January 1977 of a cooker that is featured in the ERDA/Honeywell traveling solar energy display. The poor condition of the reflective surface is evident. The actual origin of this particular model is unknown.

Tables 2, 3, and 4, reproduced from the FAO paper, present the results of the tests that they performed. The average time required to boil water in an aluminum pan was only slightly over one third the time required for the same result in the Telkes oven; the best times obtained with an earthenware pan are a little

2. Ibid, pp. 309-310. Aee also Stam, H., "Cheap but Practical Solar Kitchens," pages 380-391 of the same Proceedings.

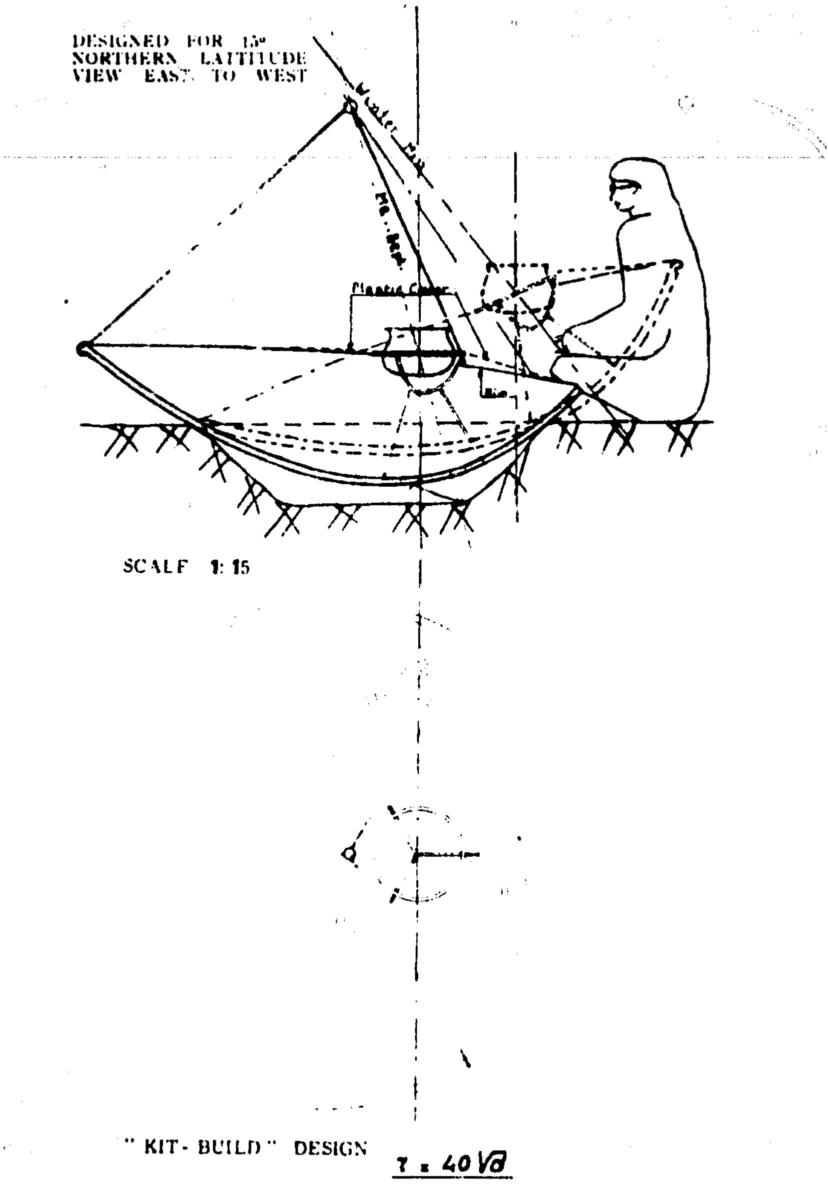

Figure 2. "Oyster-shell" paraboloid solar kitchen (from Stam, "Cheap but Practical Solar Kitchens.")

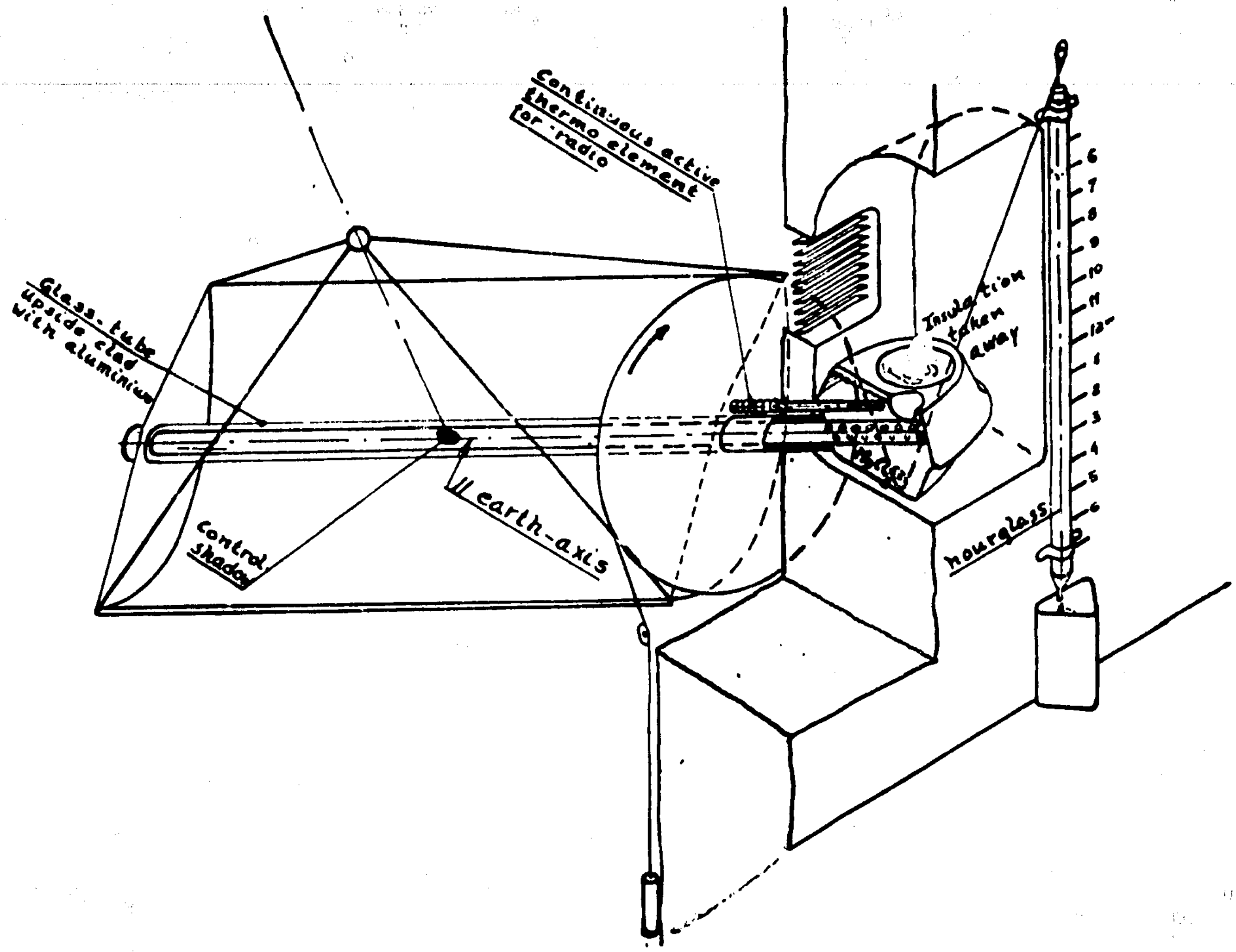

Figure 3. Solar kitchen using accumulated heat
(from Stam, "Cheap but Practical Solar Kitchens.")

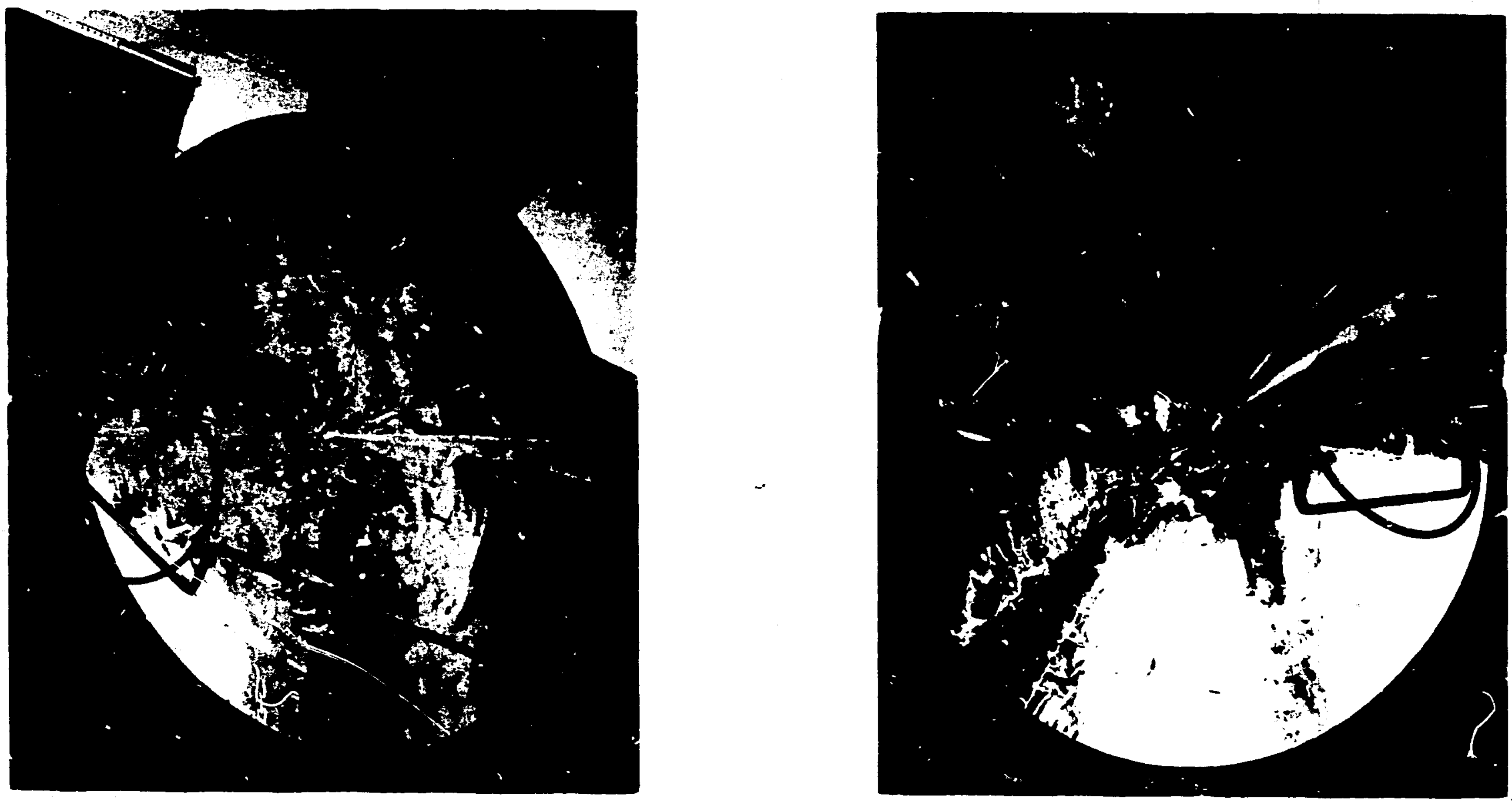

Figure 4. Two views of a solar cooker based on a rigid, focusing reflector.

Table 2. Wisconsin solar stove. Time required for 2 liters of water to reach 100°C using a covered aluminum pan painted black.

Air temperature (range)	Temperature rise of water to reach 100°C	Time to reach 100°C (min)	Weather	Remarks
30-34	83	39	Slightly cloudy and windy	
30-34	83	65	Slightly cloudy and windy	
31-33	83	50	Slightly cloudy and windy, sky not bright, haze	
31-33	83	52	Slightly cloudy and windy, sky not bright, haze	
29-33	84	45	Calm or slightly cloudy and windy, haze	
31-33	84	47	Slightly cloudy and windy, haze	
31-34	84	35	Calm and slightly cloudy and windy, haze	
31-34	82	38	Calm and slightly cloudy and windy, haze	Stove swings in wind
31-34	82	36	Calm and slightly cloudy and windy, haze	Stove swings in wind
31-34	82	33	Calm and slightly cloudy and windy, haze	
31-32	83	45 *	Particularly cloudy and windy	Sun covered 10 min
31-32	83	40 *	Particularly cloudy and windy	Sun covered 6 min
31-32	81	45 *	Particularly cloudy and windy	Sun covered 10 min
28-31	82	57 *	Particularly cloudy, moderate wind	Sun covered 23 min
28-31	81	65 *	Particularly cloudy, strong wind	Stove swings in wind; sun covered 5 min
28-31	81	75	Particularly cloudy, strong wind	
25-31	84	45	Calm to slightly cloudy and windy, haze	
25-31	81	38	Calm to slightly cloudy and windy, haze	
25-31	81	34	Calm to slightly cloudy and windy, haze	
25-31	81	30	Calm to slightly cloudy and windy, haze	
25-31	81	45	Calm to slightly cloudy and windy, haze	
27-34	83	45	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	81	32	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	81	40	Slightly cloudy and windy, haze	
27-34	80	55 *	Slightly cloudy and windy, haze	Sun covered 3 min
31-33	82	45	Very cloudy and windy	
28-30	84	40	Very cloudy, calm to slightly windy	
28-30	81	50	Very cloudy, calm to slightly windy	
28-30	81	32	Very cloudy, calm to slightly windy	
28-30	81	45 *	Very cloudy, calm to slightly windy	Sun covered 3 min
26-32	83	35	Calm to slightly or moderately cloudy	
26-32	82	30	Calm to slightly or moderately cloudy	
26-32	81	30	Calm to slightly or moderately cloudy	
26-32	83	32	Calm to slightly or moderately cloudy	
26-32	84	71 *	Calm to slightly or moderately cloudy	Sun covered 25 min
26-32	81	50	Calm to slightly or moderately cloudy	
27-32	84	50	Slightly cloudy and calm to slightly windy	
27-32	81	31	Slightly cloudy and calm to slightly windy	
27-32	81	45	Slightly cloudy and calm to slightly windy	
27-32	84	45	Slightly cloudy and calm to slightly windy	
27-32	81	72 *	Slightly cloudy and calm to slightly windy	Sun covered 30 min
24-31	85	38	Slightly cloudy to cloudy, north wind	
24-31	81	30	Slightly cloudy to cloudy, north wind	
24-31	82	33	Slightly cloudy to cloudy, north wind	
24-31	81	31	Slightly cloudy to cloudy, north wind	
24-31	82	35	Slightly cloudy to cloudy, north wind	
24-31	81	100 *	Slightly cloudy to cloudy, north wind	Sun covered 55 min
22-29	85	80 *	Haze, moderate wind, slightly cloudy	Sun covered 27 min
23-29	85	45 *	Calm to slightly windy, cloudy	Sun covered 12 min
		Average (39 tests) -- 41 min		

* Not included in average.

(from Nutrition Division, FAO, 'Report on Tests conducted using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959".)

Table 3. Wisconsin solar stove. Time required for 2 litres of water to reach 100°C using a covered earthenware pan

Air temperature	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Type of cover*	*Weather*	*Remarks*
24-31	80	55	Aluminium painted black	Haze, sky not light; cloudy, slightly windy	
24-31	81	150	Aluminium painted black	Haze, sky not light; cloudy, slightly windy	Sun covered 21 min
26-32	84	107	Aluminium painted black	Haze, sky not light, cloudy, slightly windy	Sun covered 25 min
26-32	77	68	Aluminium painted black	Haze	Sun covered 4 min
26-33	83	89	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	81	55	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	82	75	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	84	90	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	78	80	Aluminium painted black	Haze, calm to slightly windy and cloudy	
26-33	80	105	Aluminium painted black	Haze, calm to slightly windy and cloudy	
22-28	84	80	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	82	60	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	78	55	Earthenware	Haze, calm to slightly windy and cloudy	Stove moved every 15 min
22-28	85	90	Earthenware	Haze, slightly windy and cloudy	
22-28	78	75	Earthenware	Haze, slightly windy and cloudy	

(from Nutrition Dividion, FAO, "Report on Tests conducted using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959".)

Table 4. Wisconsin solar stove. Time required for 2 litres of water to reach 100°C using a covered aluminum pan painted black, with infrequent orientation of the stove and/or cloudy weather

Air temperature (range)	*Temperature rise of water (to reach 100°C)*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
28-31	81	150	Particularly cloudy, moderate wind	Stove not moved 70 min; sun covered 40 min
27-34	81	114	Haze, slightly cloudy and windy	Stove not moved 70 min; sun covered 30 min
31-33	83	205	Very cloudy and windy	Stove not moved 70 min; sun covered 90 min
28-30	82	90	Calm to slightly windy, very cloudy	Sun covered 43 min
26-28	84	55	Slightly cloudy and windy	Stove not moved 45 min
24-30	84	90	North wind, slightly cloudy, slightly windy	Stove not moved 60 min
24-30	83	83	North wind, slightly cloudy, slightly windy	Stove not moved 60 min; sun covered 33 min
24-30	81	100	North wind, slightly cloudy, slightly windy	Stove not moved 70 min; sun covered 30 min
24-30	81	80	North wind, slightly cloudy, slightly windy	Stove not moved 60 min; sun covered 26 min

(from Nutrition Division, FAO, "Report on Tests Conducted using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959".)

a little less than one half the best time (two hours) obtained with an earthenware pan in the Telkes oven. The conclusions reached by the FAO team were as follows: "In these tests it has been shown that water can be boiled considerably faster on the Wisconsin solar stove than in the Telkes oven. However, performance of the Telkes oven is less affected by infrequent positioning of the stove, by clouding of the sun, and by wind. In addition, it is necessary to consider that the Telkes oven is more expensive as well as more complicated than the Wisconsin solar stove, with greater risk of mechanical difficulties and more need for repairs and spare parts."[3] On this last point we wish to comment that there are a great many different versions of the Telkes oven, some of which are much worse than others with respect to periodic need for parts and repairs, and also that rigid focusing reflectors have encountered rather more long-duration survival problems than the better Telkes ovens.

The paper by Duffie et al, besides discussing cooker performance and costs, presents the results of field studies carried out in Mexico over a period of four years, using about 200 individual cookers. These studies were funded by the Rockefeller Foundation, and at the time of the Conference the most extensive tests had been carried out in the state of Coahuila, using cookers referred to as "Model 2" and "Model 3". The Model 2 results are reproduced in Table 5, and the results were summarized in the body of the report as follows:

"(a) Through the period January through August for which data are available, the 16 cookers were in use about 2/3 of the days on which use was possible. This use included cooking and also heating of irons and heating of water for washing.

"(b) The frequency of use, relative to days of possible use, apparently dropped during the summer months; however, the data are not complete for these months as indicated by the high number of 'unknown cooker days' indicated in the last column. During the spring months when observations were relatively complete, the use stayed in the range of 2/3 to 3/4 of the total possible cooker days, even though mechanical failures of some of the cookers began to be significant.

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3. Nutrition Division, Food and Agriculture Organization of the United Nations: "Report on Tests Conducted Using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959." Paper S/116, Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II. United Nations Publication No. 63.I.39, pages 353-358.

Table 5. Summary of use of 16 solar cookers, by month and weather conditions, Coahuila, Mexico, 1960.

Month	Weather conditions: Good weather[1]						Partially good weather[2]						Poor weather[3]						Weather unknown						Totals by month: All weather					
	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
January	9	144	90	0	0	35	4	32	22	6	0	27	4	0	7	5	0	11	1	0	0	0	0	16	18	176	119	11	0	89
February	17	272	192	0	0	5	3	24	36	0	0	0	8	0	0	16	0	0	1	0	0	0	0	16	29	296	228	16	0	21
March	27	432	334	0	18	48	3	24	39	0	2	2	1	0	0	3	0	13	0	0	0	0	0	0	31	456	373	3	20	63
April	16	256	172	0	36	22	3	24	22	7	9	5	3	0	0	0	0	0	8	0	0	0	0	128	30	280	194	7	45	150
May	9	144	86	0	29	6	4	32	31	1	12	3	4	0	5	2	8	16	14	0	0	0	0	224	31	176	122	3	47	249
June	No data																													
July	7	112	9	0	1	102	1	8	0	0	0	16	6	0	0	0	0	80	17	0	3	0	0	269	31	120	12	0	1	467
August	7	112	21	0	1	69	1	8	3	0	0	10	6	0	0	0	0	80	17	0	2	0	0	272	31	120	26	0	1	431
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	20	1	0	171	13	0	20	[illegible]	0	171
TOTALS BY WEATHER	92	1 492	904	0	85	287	19	152	153	14	25	58	32	0	12	26	6	200	71	0	25	1	0	1 096	214	1 624	1 094	41	114	1 641

[1] Good weather: over 4 hours of sustained sun during a day.
[2] Partially good weather: 1 to 4 hours of sustained sun during a day.
[3] Poor weather: less than 1 hour of sustained sun during a day, or too much wind to allow effective cooking.
A. Total number of days of the type noted in the group heading.
B. Possible cooker days:
(a) In good weather = good weather days × 16;
(b) In partial weather = partial weather days × 8;
(c) In poor weather = poor weather days × 0.
C. Actual cooker days: successful use of cooker observed during the day.
D. Ineffective cooker days: unsuccessful use of the cooker on any day is an ineffective cooker day.
E. Broken cooker days: when a cooker is specifically labeled as broken its days are counted as broken cooker days.
F. Unknown cooker days: when the use of cooker is unknown on any day, it is counted as one unknown cooker day.

(from Duffie, Löf, and Beck, "Laboratory and Field Studies of Plastic Reflector Solar Cookers".)

"(c) In spite of successful and trouble-free use in the laboratory, considerable mechanical troubles developed in field use. These resulted from wind damage and breakage of minor parts. (On the basis of these mechanical troubles, the model 3 cooker was designed.) This breakage resulted in non-acceptance of the cooker for some families who suffered loss of valuable food from the cooker on its failure. Wind damage was particularly significant, and any cooker design must be made to withstand moderate winds if damage is to be avoided. After a total of 14 months, three of the original 16 cookers are in use with 13 unusable due to mechanical failures, two of the three in use are in excellent condition.

"(d) The reactions of the families to the cookers varied. Classifying the cookers as 'successful' or 'unsuccessful' (a subjective rating by the anthropologist based on the family reaction, extent of use, care for cooker, etc.), the initial reactions were successful at the beginning of the study for 13 of 19 users, with five of the initial successes becoming unsuccessful later in the period of cooker use. Some of this loss of acceptance was due to mechanical failure.

"(e) The usual cooking fuels of the people of this village are wood and oil, with some families using wood exclusively (gathered or purchased), and some using a combination of wood and oil. The success of the families in cooker use was about the same for both groups, and in this relatively small sample success with the cooker did not appear to correlate with need for it or financial success."[4]

The Model 3 cooker had been designed in 1960 to overcome some of the difficulties reported with the Model 2 cooker. It had a different frame design that resulted in a lower and more stable cooker, and was probably also sturdier. These revised cookers had been tested for two months at the time of the report and during that time the user experience had been much better than with the Model 2 cookers. "The new model has so far been satisfactory from the mechanical point of view, is more wind resistant, and easier to use ... it was found that four of the new cookers have been used almost 100 percent of the possible days since introduction, and the fifth about 75 percent of the possible days."[5]

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4. Duffie, J.A., Löf, G.O.G., and Beck, B.: "Laboratory and Field Studies of Plastic Reflector Solar Cookers." Paper S/87, Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II. United Nations Publication No. 63.I.39, pages 339-346.

5. Ibid.

A later field study performed in the southern part of Mexico emphasized local fabrication of the cookers, and is described later in this section and in Appendices A and B.

3. Portable Focusing Solar Cookers

Similar to the Wisconsin cooker, but with a folding, umbrella-type reflector, was a cooker reported by George O. G. Löf and Dale A. Fester, shown in Figure 5. Löf and Fester reported some very encouraging cooking times (Table 6), and also discussed "modifications for routine cooking," such as a stronger structure.[6] Additional data are quoted regarding successful use of the cooker in Sweden. As shown in Table 1, "hundreds" had been sold at the time of the UN Conference under the trade-name "Umbroiler." Further testing of this cooker was carried out by the VITA solar cooker team; the results, which were not entirely favorable, are treated later in this section.

4. Telkes Oven

The article by Telkes and Andrassy discussed in general terms the ovens that had already been in use for many years, exhibited at several trade fairs and the Brussels World Fair, etc. A typical design is shown in Figure 6. Recent improvements in design were also discussed, the key feature being a double-walled basket-weave oven body, filled between the walls with locally-available insulation material and coated on the inside with clay or cement to form a smooth hard finish. The results of cooking tests performed in the New York area were also presented.

A description of the operation of the Telkes oven, including a brief statement of its advantages relative to the direct-type cookers, follows:

"Solar cooking ovens consist of a well-insulated oven body, capable of holding larger volumes of food in several cooking utensils. The insulated oven prevents the loss of heat from pots or pans to a considerable degree. Solar energy is admitted to the interior of the oven through a 'window' and is augmented by flat reflectors. Adjustment in orientation to 'follow the sun' is less frequently needed, once every half hour or hour being sufficient. Heat from the sun can

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6. Löf, G.O.G., and Fester, D.A.: "Design and Performance of Folding Umbrella-Type Solar Cooker." Paper S/100, Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-23 August, 1961), Volume 5, Solar Energy: II. United Nations Publication No. 63.I.39, pages 347-352.

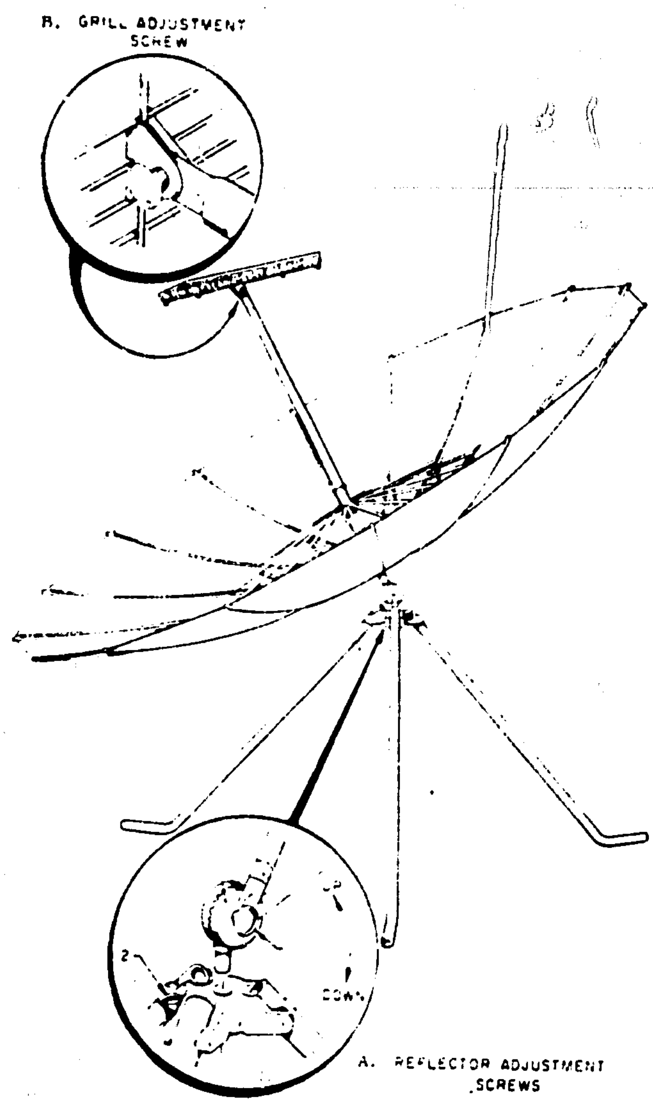

Figure 5. Diagrammatic sketch of folding, umbrella-type solar cooker (from Löf and Fester, "Design and Performance of Folding Umbrella-Type Solar Cooker.")

Test No	1	2	3
Direct solar radiation (btu/ft^2 hr)	320	299	273
Wind velocity (mph)	3.0	3.3	3.4
Ambient air temp (°F)	70	50	52
Amount of water (qt)	1.0	1.0	1.0
Initial water temp (°F)	70	62	62
Final water temp (°F)	202	202	202
Time required to boil water (minutes)	20	23	27
Incident radiation on 11 ft^2 of unshaded reflector (btu)	1 172	1 260	1 350
Heat transferred to water, q_u (btu)	275	291	291
Heat loss from kettle, q_l (btu)	32	45	53
Heat retained by kettle, q_r (btu)	12	13	13
Collection efficiency (per cent)	27.2	27.7	26.5
Net efficiency, solar to water (per cent)	23.5	23.1	21.6

Type of food	*Cooking time*
Grilled frankfurters	8-12 minutes
Grilled hamburgers (ground meat patties)	10-15 minutes
Grilled beef-steaks (1 inch thick)	15-20 minutes
Grilled trout (fish)	10-15 minutes
Potatoes in black-bottom pressure cooker (for average family of 5)	30 minutes
Eggs fried in black-bottom pan	5 minutes
Coffee (1 quart):	
Boiled	20 minutes
In percolator	25 minutes

Table 6. Performance data reported for the folding umbrella-type cooker solar cooker (from Löf and Fester, "Design and Performance of Folding Umbrella-Type Solar Cooker.")

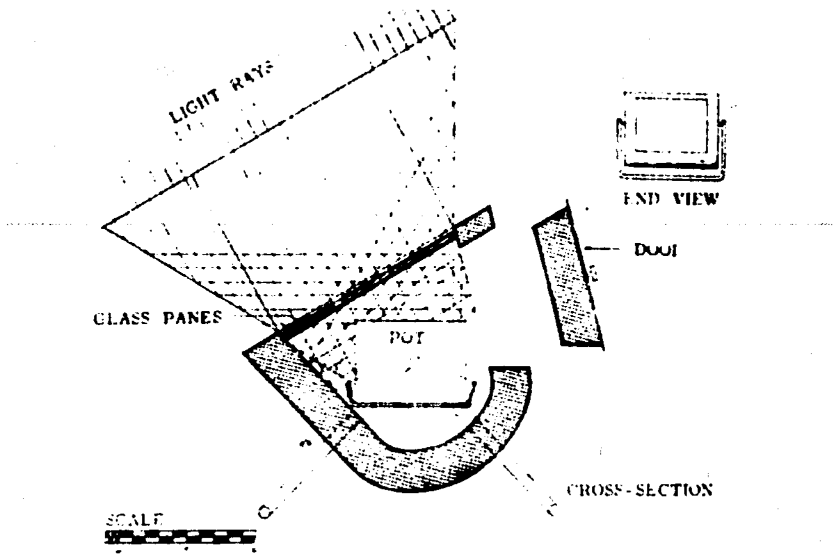

Figure 6. Cross-section view of a common Telkes oven design.
This design features a fixed cooking pot and rotating, cylindrical outer shell.
(from Telkes and Andrassy, "Practical Solar Cooking Ovens.")

be stored inside the oven, accumulating heat when the oven is not used for cooking. The stored heat is released when food is placed into the oven and cooks it more rapidly, or keeps the food warm for some time when clouds intervene, or even after sunset. Solar ovens can cook larger quantities of rice or vegetables and are able to roast meats and bake bread. This cannot be done with the parabolic reflector-type solar cooker."[7]

Since the functioning of the oven depends to a considerable extent on the storage of heat, the authors discussed the alternative heat storage materials at some length. Bricks, stones, or sand can be used; the authors also discuss the greater performance possible through use of phase-change materials, such as mixtures of alkaline materials or of anhydrous alkaline sulfates.

The cooking test results presented by the authors were all obtained on clear days, although it was claimed that nearly as good results could be obtained on hazy or partly cloudy days "with the help of the pre-heated heat storage platform". A quantitative description of how this would work out in practice was

7. Telkes, M., and Andrassy, S.: "Practical Solar Cooking Ovens." Paper S/101, Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II. United Nations Publication No. 63.I.39, pages 394-399.

not presented. It was also claimed that oven temperatures of 400 - 430°F could be attained in the vicinity of New York and 460°F in the country at noon on a clear day. Presumably those are the temperatures reached by an object of some sort placed in the oven - perhaps a thermometer bulb - but neither the nature of the object nor the dependence of its temperature on its size, shape, and surface characteristics was discussed. The interpretation of temperature measurements taken inside an oven heated by solar radiation entering through a window is not at all so straightforward as the interpretation of temperature measurements inside a normal wall-heated oven. Finally, the authors state that "Food placed in the solar heated oven (with two square feet of window area) absorbed 560 - 600 btu/hour, on reasonably clear days. This amount of heat is sufficient to raise the temperature of 4 pounds of the usual foods from 70°F to the boiling point, during one hour."[8] How long the oven was pre-heated, or how much of the heat absorbed by the food came from the heat storage material, was not indicated.

The actual cooking tests are of interest, and are quoted in their entirety:

"Rice. One pound and 1.2 pounds of water in a flat pan cooks in 45 minutes, without stirring or other attention. Water is absorbed completely and rice is perfectly cooked.

"Lentils. One pound requires 4 pounds of water. The mixture was standing at room temperature for 12 hours to soften the lentils and cooked for 2 hours, until done.

"Dry peas and black beans. One pound requires 4 pounds of water and was softened for about 12 hours. Peas and beans must be cooked for 3 to 4 hours until they are sufficiently tender.

"Roasts. The oval roaster can hold up to 8 pounds of meat (beef, veal, pork, etc.). Roast beef, 8 pounds, required 3 hours. Roast pork, 7 pounds, required 3.2 hours. Two chickens - 4 pounds - were completely roasted in one hour. On clear days, the roasting time is approximately the same as in conventional ovens.

"Stews. Stews, containing meat and vegetables, required about 2 hours cooking until the meat was sufficiently tender.

"Bread, rolls and cakes. Two loaves of bread - 2 pounds - baked in 45 minutes; rolls required about 30 minutes; cake - 3 pounds - one hour. The baked food

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8. Ibid. p. 397.

was uniform in texture, and the results comparable to baking in conventional ovens.

"Fruit preserves. Two pounds of fruit were mixed with one pound of sugar and 0.5 pounds of water. Cooking time was three hours, producing preserves which were filled into containers and sterilized in the oven, in the usual way. These tests indicate that the solar oven can be used for the preparation of preserved and 'home-canned' foods."[9]

A Telkes oven was also tested by the FAO and reported on in the paper quoted earlier with regard to the Wisconsin cooker. The oven tested had a 2 cubic foot capacity with a double glass window and a hinged door at the back; the four aluminum reflectors were each 350 - 400 square inches in area, and angled at 110 - 120 degrees from the glass front. Tests were similar to those performed with the Wisconsin cooker, and are presented in Tables 7, 8, and 9. The FAO also conducted tests, of the Telkes oven only, in Thailand and Trinidad, and reported that a number of native dishes were prepared quite successfully in the oven in Thailand, and that higher empty oven temperatures could be obtained in both locations than in Rome. The comparisons drawn in the summary of the report between this oven and the Wisconsin cooker have already been quoted, in connection with the Wisconsin cooker.

A more extensive discussion of the design of this type of oven was presented by Maria Telkes in an earlier paper,[10] including a very extensive bibliography. Two additional designs presented in that paper are shown in Figures 7 and 8.

The triangular oven is shown with the window at a 30^{o} angle to the horizontal - a good average for southern latitudes, but for best performance additional tilting one way or the other, as a function of time of day, would be required. "The advantage of the triangular oven is that it is relatively simple to fabricate. The stove can be placed directly on a table or the ground. The disadvantage of the oven is that it must be tilted by lifting its front or back edge. If this tilt is more than 20 or 30^{o}, food may be spilled."[11]

9. Ibid., pp. 397-398.

10. Telkes, M.: "Solar Cooking Ovens." Solar Energy, Volume III, No. 1 (January 1959), pages 1 - 11. A photograph of a Telkes oven is featured on the cover of this journal.

11. Ibid., p. 8.

Table 7. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered aluminum pan painted black.

Air temperature (range)	*Oven temperature (range)*	*Temperature rise of water to reach 100°C*	*Time to reach 100°C (min)*	*Weather*	*Remarks*
30-34	109-117	83	100	Slightly cloudy and windy	
30-34	105-110	83	120	Slightly cloudy and windy	
31-34	100-117	83	110	Slightly cloudy and windy, haze	
32-33	110-113	83	115 *	Very cloudy, moderate wind	Sun covered 15 min
28-32	80-110	83	150 *	Cloudy, moderate to strong wind	Sun covered 21 min
28-32	60-110	83	140 *	Cloudy, moderate to strong wind	Sun covered 17 min
26-31	35-115	83	120	Calm, haze to slightly windy, slightly cloudy	
27-34	110-112	81	120	Calm, haze to slightly windy, slightly cloudy	
27-34	95-120	84	120	Calm to slightly windy, haze	
27-30	90-110	84	145 *	Cloudy, slightly windy	Sun covered 43 min
27-30	103-117	81	105	Cloudy, slightly windy	
26-32	97-117	83	105	Calm, slightly cloudy	
27-32	95-115	85	120	Calm, slightly cloudy	
27-32	95-100	84	150 *	Calm, slightly cloudy	Sun covered 30 min
26-30	80-115	85	105	Bright sun, north wind, slightly cloudy	
26-30	105-120	82	92	Bright sun, north wind, slightly cloudy	
26-30	95-110	83	108	Slightly windy and cloudy	
23-30	63-105	85	165 *	Cloudy	Sun covered 51 min
22-28	85-118	84	100	Calm, haze, slightly cloudy	
22-27	36-115	85	140	Calm, slightly cloudy	
			Average (14 tests) — 112 min		

* Not included in average.

(from Nutrition Division, FAO, "Report on Tests Conducted Using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959.")

Table 8. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered earthenware pan

Air temp (range)	Oven temp (range)	Temperature rise of water (to reach 100°C)	Time to reach 100°C (min)	Type of cover	Weather	Remarks
27-32.	50-115	83	165	Earthenware	Calm or slightly windy	Sun covered 30 min
27-33.	100-120	84	150	Aluminium painted black	Haze	
27-33	70-117	79	135	Aluminium painted black	Slightly windy and cloudy	Sun covered 15 min
27-33	100-107	76	130	Aluminium painted black	Slightly windy, haze	
26-33.	86-112	83	165	Aluminium painted black	Sky not bright, haze, slightly windy	
22-26.	95-119	85	135	Earthenware	Slightly cloudy and windy	Stove moved every 15 min
22-26	100-115	77	165	Earthenware	Slightly cloudy	Stove not moved 75 min Sun covered 7 min
21-28.	74-120	85	150	Earthenware	Haze, slightly windy	Stove moved every 15 min
21-28.	95-105	75	150	Earthenware	Haze, slightly windy	Sun covered 1 min
22-28	100-120	83	120	Aluminium painted black	Calm, haze	Stove moved every 15 min
22-28.	55-118	85	150	Aluminium painted black	Sky not bright, haze	Stove moved every 15 min
22-28.	107-95-107	80	165	Aluminium painted black	Sky not bright, haze	Stove not moved 75 min Sun covered 11 min
24-31	84-105	79 (did not reach 100°C)	180	Aluminium painted black	Slightly windy and cloudy	Sun covered 20 min

Table 9. Telkes oven. Time required for 2 litres of water to reach 100°C using a covered aluminum pan painted black, with infrequent orientation of the stove and/or cloudy weather

Air temperature (range)	Oven temperature (range)	Temperature rise of water (to reach 100°C)	Time to reach 100°C (min)	Weather	Remarks
31-34	107-115	80	100	Slightly windy and cloudy, haze	Stove not moved 70 min
26-31	109-117	81	105	Calm or slightly windy, haze	Stove not moved 75 min
27-34	100 —	81	140	Cloudy	Sun covered 45 min
27-30	90-105	81	115	Slightly cloudy and windy	Stove not moved 65 min
26-32	104-110	84	100	Cloudy	Stove not moved 70 min
27-29	110-84-99	85	180	Slightly windy	Sun covered 40 min Stove not moved 70 min
26-30	75-100	85	245	Calm, haze	Sun covered 35 min

(from Nutrition Division, FAO, 'Report on Tests conducted using the Telkes Solar Oven and the Wisconsin Solar Stove over the period July to September 1959.')

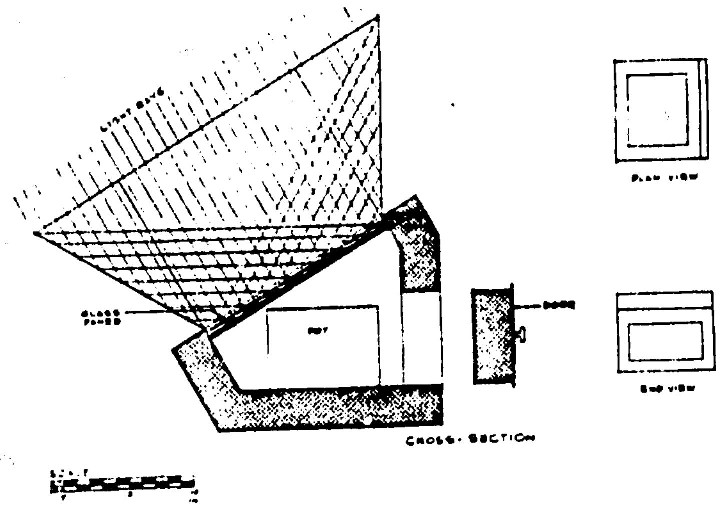


Figure 7. Triangular solar oven
(from Telkes, "Solar Cooking Ovens.")

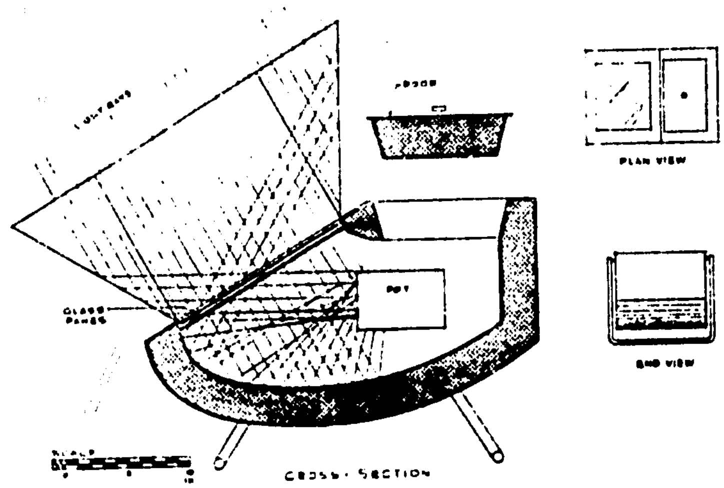


Figure 8. Pot stove
(from Telkes, "Solar Cooking Ovens.")

The "pot stove" was designed to permit access to the cooking vessel from above, as in more conventional cooking, rather from behind as in the other Telkes ovens. The oven itself is lined with reflective material rather than being painted black, and the pot must be black - hence the functioning of the stove seems quite different from the other ovens designed by Telkes, and one wonders about the heat storage characteristics of this oven.

Dr. Telkes also reported on experiments performed where equivalent oven temperatures were measured by sensing the temperature reached by a black plate, with one side insulated and the other side exposed to the sun through a series of one to three windows. The windows were surrounded by four or eight mirrors in some cases, the mirrors being either second-surface glass or Alzac, a proprietary mirror-finish aluminum. The results were as follows:

SOLAR HEATING EXPERIMENTS

Black plate, backed with 4-in. insulation; window area 1 sq ft; 4 silvered glass mirrors; 4 Alzak triangular reflectors.

Reflectors used:		First Series		Second Series	
Mirrors	Triangles	Sun Btu/sq ft/hr	Temperature (average °F)	Sun Btu/Sq ft/hr	Temperature (average °F)
3 glass panes					
4	4	272	456	266	470
4	0	301	440	294	438
0	0	279	320	288	356
2 glass panes					
4	4	284	450	282	442
4	0	301	404	290	403
0	0	292	290	284	309
1 glass pane					
4	4	280	409	286	409
4	0	273	370	286	359
0	0	272	261	290	262

Black plate, backed with 4-in. insulation; window area 1 sq ft; 4 Alzak reflectors; 4 Alzak triangular reflectors

Reflectors used:		First Series		Second Series	
Mirrors	Triangles	Sun Btu/sq ft/hr	Temperature average °F	Sun Btu/sq ft/hr	Temperture (average °F)
3 glass panes					
4	4	269	464	245	460
4	0	276	434	272	430
0	0	280	335	270	320
2 glass panes					
4	4	286	447	262	451
4	0	286	380	277	420
0	0	264	303	289	288
1 glass pane					
4	4	252	370	271	416
4	0	234	348	264	360
0	0	234	244	242	242

The author includes a very interesting paragraph on pot stirring - obviously a problem with oven-type cookers - in which she contends that this activity is only necessary when cooking over a fire, and can be dispensed with in solar cookers of the type shown.

5. Internally Reflecting Solar Ovens

The "pot stove" of Maria Telkes was an example of a solar oven using reflective surfaces both inside and outside the oven. An Egyptian author at the UN Conference, M.S.M. Abou-Hussein, presented a short paper on a cooker with internal reflectors only, as shown in Figure 9. No actual cooking data were presented. Löf summed up the advantages and disadvantages of this approach as follows:

"The author claims several advantages for moving the external reflectors to the inside of the oven. Greater protection from damage due to mishandling, abrasion, and the wind, and the greater capture of diffuse radiation because of larger glass window area are cited. Nonspecular reflection from the internal reflectors would be more completely captured inside the oven. However, the larger glazed area involves the disadvantage of greater heat losses.

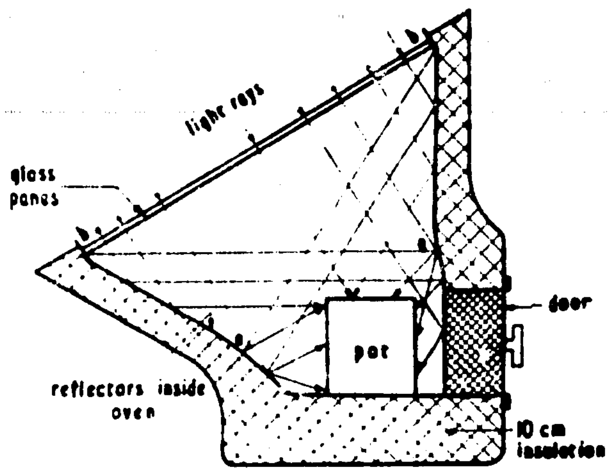
"In an insulated oven, most of the thermal losses are through the glazing, so tripling the glazed area would be expected to reduce the net heat available for cooking. This additional thermal loss, probably at least double that from an oven with external reflectors of equal area, should outweigh the gains due to increased capture of diffused radiation. The conclusion that a solar oven with a large window and internal reflectors is more effective than the 'conventional' type therefore does not appear well supported."[12]

6. Cylindro - Parabolic Solar Cooker

This design, shown in Figure 10, is described by the author, Prata, as combining the best features of the direct-type focusing (Wisconsin) solar cooker and the box-type (Telkes) solar oven.[13] Löf points out that it is better described

12. Löf, G.O.G.: "Recent Investigations in the Use of Solar Energy for Cooking." Solar Energy, Volume 7, No. 3 (1963), pages 131-132.

13. Prata, S.: "A Cylindro-Parabolic Solar Cooker." Paper S/110, Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II. United Nations Publication No. 63.I.39, pages 370-379.



(A_p = area of plane ee = 900 cm^2.

A_r = area of reflectors, intercepting rays, about 5.7 A_p)

Figure 9. Box-type solar oven with reflectors inside (from Abou-Hussein, "Temperature-Decay Curves in the Box-Type Solar Cooker.")

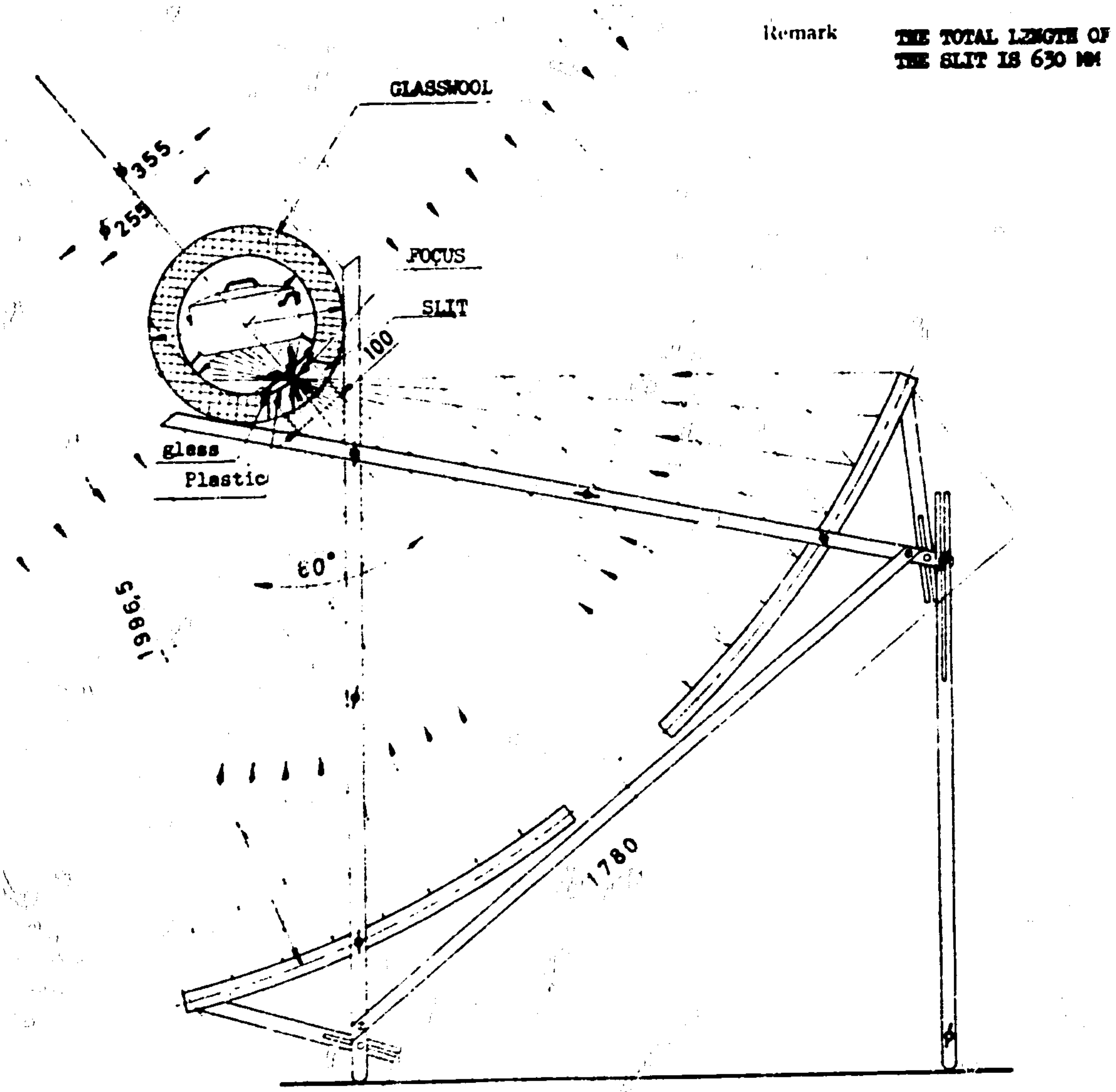


Figure 10. Schematic diagram of the cylindrical oven with line-focus reflector (from Prata, "A Cylindro - Parabolic Solar Cooker.")

as being an oven-type cooker with a considerably reduced window area to minimize heat loss. Disadvantages include the required high quality of the reflector to obtain a narrow focal line coinciding with the slit in the cylindrical oven, and the presumably greater complication involved in adjusting the reflectors and periodically moving them.

Prata performed a number of cooking tests, as shown in Table 10. The tests were performed in Lisbon, Portugal, in May 1961. Tests were also performed with a Telkes oven for the sake of comparison. The author found that his cooker could cook 2 - 8 times as much food as the Telkes oven in the same amount of time, and concluded that since the solar collection area was only 55 percent greater for his cooker, the effective efficiency of his cooker was 1.8 times that of the Telkes oven. (Löf points out that comparisons of this sort based on quantity of food cooked are not as meaningful as might appear at first glance.) Prata also conceded that his cooker required more frequent position adjustment than the Telkes oven.

B. THE VITA STUDY

VITA Report No. 10, "Evaluation of Solar Cookers," describes the results of tests and other evaluations of a large number of solar cookers that were available at the time the report was prepared. Unfortunately, the report carries no date and it is difficult to tell exactly when it was written. Since the most recent of the various references cited are the UN papers quoted above, and since there are many indications that some of the work described in the VITA report must have been performed without knowledge of the content of the UN papers, we assume that the report must have been published in 1962 or 1963.

Quoting from the Introduction to the report, "... models of six commercially available cookers were purchased and three others were built from descriptions in the literature. Two original VITA designs were also built and tested. In addition, such information is included as is available for those designs which have come to VITA's attention, but which were not included in the present test program because of lack of availability or other difficulties in obtaining test models."[14]

The results are summarized in Table 11, which is reproduced from the VITA report. Additional descriptions of the cookers follow.

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14. VITA Report No. 10, "Evaluation of Solar Cookers." Prepared through the facilities of the Office of Technical Services, U.S. Department of Commerce, in cooperation with Volunteers for International Technical Assistance, Inc., for the Department of State, Agency for International Development, Communications Resources Division, Publications and Technical Services Branch.

Table 10. Results of cooking tests, cylindro - parabolic cooker (from Prata, "A Cylindro - Parabolic Solar Cooker.")

Food cooked	Direct solar radiation (cal/cm² min) 9 h	12 h	15 h	Duration	Remarks
Boiling 3.76 kg of potatoes	1.122	1.224	--	10.25 h-12.25 h	Largest amount of food that would go into the stove
Boiling 2 kg of potatoes	1.122	1.224		10.20 h-11.38 h	
Boiling 1 ltr of string-beans and 1 ltr of cornmeal	1.214	1.295	1.132	12.25 h-14.05 h	
Roasting 1 ltr of cornmeal	1.214	1.295	1.132	14.10 h-14.40 h	
Baking a cake, 0.710 kg	0.92	0.978 (fog)	0.851	10.00 h-11.15 h	
Frying fish and eggs	0.92	0.978 (fog)	0.851	11.32 h-11.47 h	
Roasting a 2 kg chicken	0.690	0.805 (fog)	0.736	14 h-16 h	The chicken was perfectly cooked and delicious

Table 11. Comparative data on 12 solar cookers (from VITA Report No. 10.)

Cooker +	Type ++	Reflector Area (m^2)	Focal Length (cm)	Weight (kg) Net	Weight (kg) Packaged	Approx. Size (Packaged) (Inches)	Performance	Retail Cost (Dollars)	Estimated Manufacturing Cost (Dollars
Wisconsin Design (2.1.1)	D-R	1.2		9-10			***		8.66-16.17
Boeing Reflector[1] (2.1.7)	D-R	.21	36	0.45		22 x 22 x 4	***		18.00
Thew Cooker (2.1.2)	D-R	.64	45	3.5	6.2	42 x 42 x 8	**	29.50	[illegible]
Burmese Design (2.1.3)	D-R	2.5	~ 60	13.2	20.	52 x 52 x 10	--	12.00	
Fresnel Type[2] (2.1.4)	D-R	1.	~ 60	5.3 10.	7.	50 x 50 x 10	***		< 5.00
Solar Chef[3] (2.2.1)	D-F	0.5		1.3	2.5	25 x 16 x 6-1/2	—	19.95	12.00
Umbroiler[4] (2.2.2)	D-F	1.2	45	1.4	2.4	29 x 10 x 4	*	29.50	15.00
Solnar (2.2.3)	D-F	Ellipsoid ~ 1.	45	3.7	4.2	22 x 10 x 3	*	37.50	10.00-12.00
Inflatable Type[5] (2.2.4)	D-F	1.3	~ 50	0.2	.25	5 x 5 x 1	**		< 5.00
Oven Design, Telkes (2.3.1)	I-F	0.46		13.6			***		
Oven Design, Oosh (2.3.2)	I-R	~ 0.2		18.2			*		
Conical Paper Ref. (2.3.3)	I-R	0.59		0.72	1.07	11 x 11 x 6	*	3.98	2.00

+ Numbers in this column refer to corresponding sections in text.
++ D = Direct; R = Rigid; I = Indirect; F = Folding or Collapsible.

*** = Very Good
** = Good
* = Fair
— = Unacceptable

1 Reflector only. Manufacturing cost is based on a 36-inch reflector.
2 Not optimized for weight.
3 Our model may not have been optimum.
4 Performance tests hindered b ind; better support possible.
5 Data refer to reflector wit frame.

Rigid Reflector Types:

1. Wisconsin Cooker

"Probably the best known direct cooker, and the one which is the standard against which all other cookers must be compared, is the molded plastic reflector developed at the Solar Laboratory of the University of Wisconsin.

"The most recent model uses a drape-formed, high-impact polystyrene shell of 48 inches diameter and 0.060 inch thickness, stiffened at the rim with a ring of 0.5 inch diameter, thin-wall aluminum tubing... A reflective lining of aluminized mylar polyester film is applied to the shell."[15] This cooker was described in the paper by Duffie, Löf and Beck presented at the UN Conference (see above). The VITA report estimates a two year lifetime for the metal parts of the reflector. The various University of Wisconsin and UN/FAO test results and Mexican user experience reported at the UN Conference are quoted. It was also reported that the study team was unable to obtain an example of this cooker.

2. Thew Cooker

"The best commercially available cooker that VITA studied is produced by Garrett Thew Studios of Westport, Connecticut. The reflector is 89 centimeters in diameter and is made of spinning a sheet of aluminum 1/32 inch thick against a paraboloid form built up out of several layers of thick plywood... The edges are then rolled back to improve stiffness. A simple, inexpensive support of bent iron rods is used. This requires some blocking by stones or stakes driven into the ground, particularly when the sun is high... The pot must be removed from its support for adjustment for either altitude or azimuth."[16] Test results were only partially satisfactory: "The inhomogeniety of the focal spot leads to local overheating and occasional cracking of ceramic pots and makes frying inconvenient. However, the cooker performs well in preparing small quantities (about 1 pint) of rice or stew. It heats one liter of water at a rate of 2 to 3^0 per minute and is quite suitable for pan-broiling individual portions of meat. For family size cooking it would have to be scaled up to a surface area of at least a square meter."[17]

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15. Ibid.
16. Ibid.
17. Ibid.

3. Burmese Cooker

"A number of cookers described in the literature use strips of polished metal, riveted together, to form a more or less adequate approximation of a spherical parabola. One of these, developed in Burma, has been reproduced by us from blue prints obtained through the designer, Dr. Freddy Ba Hli. Reflectivity and mechanical rigidity of this reflector is poor and the focal spot is very large and diffuse. It is impossible to center a pot properly and the heat is inadequate to bring a quart of water to boiling in spite of the large reflector size. Furthermore, the equipment is hard to stabilize on a windy day, although it is very heavy (13 kg.)."[18]

4. Fresnel-Type Reflector

This cooker was designed by the VITA team performing the evaluation, and was judged by them to give the best results of any cooker actually tested. (Note that the Wisconsin cooker was not among those actually tested.) It is made by cutting a series of rings out of a flat sheet of 1/8-inch Masonite, removing sectors, and rejoining the cut ends to form a concentric array of nesting collars that focus light when lined with aluminized Mylar and mounted on a wooden frame. A 46 inch diameter reflector with 30 inch focal length was tested. "On a clear day, it delivers in excess of 500 watts to a focal spot about 6 inches in diameter. ... In the empirical cooking tests, six portions (4 cups) of rice were prepared in 30 minutes and a small chicken was browned in an open pan and completed in a closed pan in 30 minutes total cooking time. No adjustment of the cooker was necessary during the cooking, although it was slightly defocused at the end of the cooking period. Large (6-inch) pancakes were prepared with very uniform browning in a small enamel frying pan with a black bottom. A simple type of bread (English muffin) was also quite successfully prepared using the black aluminum pan. Four muffins were baked at once, requiring about 20 minutes (10 minutes on each side). In general, cooking time and performance were comparable to that of a small surface burner on an electric range or a small electric frying pan or casserole...

"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."[19]

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18. Ibid.

19. Ibid.

5. Boeing Reflector

These tests actually involved Wisconsin-type cookers utilizing lightweight composite parabolic reflectors. The reflectors were loaned by their manufacturers, Boeing Aircraft Company. Each consisted of a fiberglass-reinforced-epoxy/aluminum honeycomb/fiberglass-reinforced-epoxy sandwich, parabolic in shape, with a vacuum-deposited aluminum reflective surface, protected by a vacuum-deposited silicon oxide coating.

"A rough test of its efficiency made by the snow melting techniquo gave a value of 437 watts per square meter. The spun aluminum cooker, which served as the standard at the time of these tests, gave a value of 300 watts per square meter under identical conditions."[20] In spite of this apparently outstanding performance, no cooking tests or other tests of any sort were reported. The quoted cost estimate of $18 each for 36-inch collectors in lots of 1000 seems optimistic to us, even allowing for the higher value of dollars at the time of the estimate. The VITA report also emphasizes the unsuitability for local manufacture.

Other techniques that could be used for producing focusing reflectors are mentioned in the VITA report, including soil-cement lined depressions in the ground, molded vermiculite-aggregate, wire-reinforced concrete shells, and papier maché shells. One of the more interesting approaches was introduced by the Goodyear Tire and Rubber Company for aerospace applications: "The mold-shape is produced by simply inflating an aluminized plastic balloon. This then becomes the reflecting wall of the finished reflector after being backed up by a rigid foamed plastic. The cost of materials for such a reflector is probably less than $2 for a 48-inch reflector."[21] All of these reflectors depend on reflective linings, and are limited by the short lifetime of these linings and the relative difficulty (except in the Goodyear case) of cutting, fitting, and attaching plane segments to the curved shell surface - see the photograph of the Wisconsin solar cooker in the ERDA - Honeywell traveling exhibit, Figure 4.

Another method mentioned for making parabolic reflectors consists of rotating a pan containing a liquid resin. The surface takes on a parabolic shape, as in the well-known high school physics experiments, and once it hardens a reflective film can be applied as with the other methods. The focal length is

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20. Ibid.

21. Ibid.

stated to be $f = (38.4/w)^2$, where f is the focal length in feet and w the angular velocity in revolutions per minute. As an example, however, they state that a 3 foot focal length requires a speed of 22/7 rpm, which does not agree with their equation. The report emphasizes the high quality of the reflectors made by this method, but also the high cost due to the large amount of resin needed. Presumably this problem exists even if the pan itself is parabolic, due to the shell thickness required to overcome surface tension/contact angle effects.

Collapsible Reflector Types:

1. Solar Chef

This cooker, no longer marketed as far as we could determine, bears no relationship to the cooker currently marketed under the same trade name, which we tested. "The reflector consists of two thin plastic sections about 60 x 40 centimeters, which form a sort of cylindrical parabola. The plastic is vapor coated with aluminum and the two sections can be stacked. The support structure consists of a pointed rod to be stuck into the ground and four other support pieces. Altitude and azimuth adjustments require removal of the pot. The evaporated aluminum coating on our purchased cooker was very thin and transparent. The focal spot was diffuse and matched the pot poorly. We did not succeed in bringing water to a boil with our model and therefore abandoned further tests. This weak performance must be attributed in part to the inadequate collector area."[22]

2. Umbroiler

This cooker is the one described in the paper by Löf and Fester at the UN Conference. "Our studies show that the focal point is quite diffuse, due partly to the folds in the cloth, and partly to fluttering of the cloth in a stiff wind. ... Considerable difficulty was encountered on windy days because this cooker tended to blow over. ... Cooking performance was adequate, but the 400 watts reported could not be obtained. It is interesting to note that one unit has tested to 60°N Latitude in Sweden and cooked satisfactorily."[23]

22. Ibid., page 16

23. Ibid., page 17

3. Solnar

Also referred to as the Tarcici cooker, this unit is manufactured in France and marketed internationally, primarily for backpackers and campers. "The reflector consists of two sets of 18 reflecting blades forming a fan-like array. The curvatures are such that the assembly approximates a paraboloid of revolution. The tripod frame and metal carrying case is ingeniously combined to form a one-piece assembly, including a grill. Adjustment of cooker orientation without removing the pot, although possible, is difficult. The focal spot is very diffuse, consisting of somewhat overlapping areas. In our model, the grill was poorly centered on the spot. Thus, the pot had to be put near the edge of the grill, causing instability and occasional spilling. Maximum output was only about 200 watts per square meter. ... A reflector made on this principle but with a different support may merit consideration."[24]

4. Inflatable Plastic Reflectors

"In the 48-inch diameter prototypes that VITA constructed, there was no difficulty in concentrating sunlight sufficiently to ignite paper. However, several difficulties arose. One was the problem of maintaining air within the reflector. An appreciable rate of reflector deflation occurred, either because of pin-hole leaks or because of permeation itself. Furthermore, the reflector surface fluttered in the wind, causing defocusing. Another mild disadvantage of this design is that there are two extra interfaces between the vessel and the reflector, with the radiation passing twice through each. The direct radiation from the sun to the reflector is normal to the interfaces; the reflected radiation from the parabola passes through the interfaces at angles of incidence which become progressively less favorable from the center to the rim. Each passage of the radiation through an interface results in reflection loss. However, this is simple to remedy by increasing the reflector size. Another problem is that these reflectors can be damaged if handled very roughly. Finally, the lightweight and high surface area tended to make this cooker unstable in a strong wind."[25]

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24. Ibid., pp. 17-18

25. Ibid., pp. 18-19

In summary, the VITA team points out that none of the collapsible models they tested was adequate from the point of view of stability in wind, although they can be cheap and shipping and distribution would be relatively simple. Their main application would seem to be in nomadic societies, and hence their potential for application in Haiti is low.

Oven-Type Cookers:

1. Telkes Oven

This type of oven was described in the paper by Telkes and Andrassy at the UN Conference, and a number of different versions and variations are possible. The oven tested by the VITA team had a square base, 48 cm on a side, and was 41 cm high with one side cut off at a 45° angle. The sides and bottom were plywood lined with black-painted sheet metal, and the window (the 45° surface) was double-glazed. The window was surrounded by four 34 cm square polished aluminum reflectors and four triangular polished aluminum corner reflectors. The reflectors were fixed in place relative to the window. "Although the temperatures reached were low ($315^{\circ}F$ on a day when outdoor temperature was $46^{\circ}F$), the oven could be used to cook simple dishes with such foods as meat, rice and potatoes by increasing the ordinary cooking time."[26] The report does not indicate how the temperature was measured, and we believe it is worth bearing in mind that the significance of any temperature quoted for the interior of an enclosure heated by radiation through a window is questionable - the only measurement that we are willing to attach any significance to is the temperature of a representative object within the enclosure. The VITA report goes on to quote the results obtained by the Food and Agriculture Organization of the United Nations in their testing of the Telkes oven (see above), and the data presented in the paper by Telkes and Andrassy. It is worth noting that in the paper by Telkes (Solar Energy, January 1959) a similar configuration, but better insulat , gave black plate temperatures of 447 and $451^{\circ}F$.

2. Gosh Oven

This oven is even simpler than the Telkes oven, being simply a rectangular plywood box with a hinged double glass top lid that served as an oven door. A second hinged lid (outside of the glass door) served as a reflector. The model tested was 56 cm long, 45 cm wide, and 32 cm high. "The reflector was one flat sheet of polished aluminum supported by a system of light bars and flat

26. Ibid., p. 21

sheet metal strips which could not hold the reflector in any breeze. The interior was a sheet metal, painted black. ... The maximum temperature reached with this model was 238°F at an ambient temperature of 45°F. The reflector would stay in position only in calm weather and frequent adjustments were needed. This design should perform much better at high solar altitudes, as in the tropics. The tests made in Schenectady at solar altitudes between 30 and 40° are probably not indicative of its performance under optimum conditions."[27] As noted above, it is not evident that a representative cooking vessel would reach the same equilibrium temperature quoted for the temperature sensor.

3. Folding Paper Conical Reflector

This cooker's chief distinction seems to have been a retail price of $3.98. The VITA team reported that it was useful for heating frankfurters, and estimated that it would last for twenty to thirty uses provided it could be protected from moisture.

4. Cylindro - Parabolic Solar Cooker

This cooker was described by Prata at the UN Conference (see above). We could not be certain from the VITA report whether they had actually tested the cooker or not, but assume that they did not since it is not included in the table of comparative data.

C. LATER FIELD TESTS OF THE WISCONSIN COOKER

The paper by Duffie et al presented at the UN Conference covered field tests performed up to the time of that conference. A final field test program was performed at some time after the conference, in Teotitlân del Valle, Oaxaca, Mexico. We know of no written report covering that project, but we did rent a single-reel 16 mm film treating the subject, and prepared a written transcript of the soundtrack of the film. This transcript is included as Appendix A of this report.

As a project, the significant difference associated with the final phase was the fact that the cookers were fabricated on-site, using materials that were available locally or in the nearest large town. Presumably, it was expected that in addition to the other benefits that would accrue from local fabrication the users would also have more pride in their solar cookers and more incentive to make

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27. Ibid., pp. 21-22

them work. In terms of the cookers themselves, the major difference between these cookers and earlier models was the use of a mosaic of small, second-surface glass mirrors as the reflector surface in place of a reflective film. The reason for this change was undoubtedly the limited lifetime of reflective films, and the virtual permanence of second-surface glass mirrors.

The movie prepared by the University of Wisconsin covers in some detail the fabrication of the cookers, but the use of the cookers is covered only slightly, and the results of the project are not covered at all. There is one sequence showing a native woman steadying the cooker with one hand while placing a pot of food on it, and adjusting it. Although the cooker appears to be rather unstable, the narrative comments that the cooker shown is a laboratory model, and that the actual cookers made in Teotitlán are even less sturdy.

In order to ascertain the ultimate outcome of the project, a colleague, Dr. George Abdo, who visited relatives in Mexico this Christmas, was asked to travel to Teotitlán and inquire about the solar cookers and whether they are still in use. Dr. Abdo found that they have not been used for several years, and was fortunate in being able to find Sr. Fortino Olivera, who was identified in the movie as having been the principal solar cooker artisan in the village. Sr. Olivera explained that while the mirrors themselves had lasted well, they had not remained attached to the parabolic shells, and hence the cookers had been abandoned. Dr. Abdo's report is included as Appendix B.

D. INDIAN SOLAR COOKER

Of considerable interest to us - and apparently relatively unknown in the western world - is a cooker that was developed in India in the early 1950's,[28,29,30,31] and put into mass production by two firms prior to 1962[32]. This cooker was not reported on at the UN Conference, and VITA reported that in spite of considerable effort they had not been able to obtain either a model or accurate design details for this cooker.

28. Ghai, M. L.: "Solar Heat for Cooking." Journal of Scientific and Industrial Research, Vol. 12A, pages 117-124 (1953).

29. Ghai, M. L.; Bansal, T. D.; and Kaul, B. N.: "Design of Reflector-Type Direct Solar Cookers." Ibid, pages 165-175.

30. Ghai, M. L.; Khanna, M. L.; Ahluwalia, J. S.; and Suri, S. P.: "Performance of Reflector-Type Direct Solar Cooker." Ibid, pages 540 ff.

31. Ghai, M. L.; Pandher, B. S.; and Harikrishandrass: "Manufacture of Reflector-Type Direct Solar Cooker." Ibid, Vol. 13A, pages 212 ff (1954).

32. Khanna, M. L.: "Solar Heating of Vegetable Oil." Solar Energy, Vol. 6, No. 2, pages 60-63 (1962).

The cooker is essentially quite similar to the Wisconsin cooker, except that the reflector is spun aluminum (as in the case of the Thew cooker), polished and anodized. In addition, the top 9.4 inches of the 43 inch diameter paraboloid is cut off horizontally to allow easier access to the cooking vessel from behind the reflector, and a circular portion is removed from the center, where the shadow of the cooking vessel would fall, to save material, allow easier alignment, and to allow passage of a steel brace to support the cooking vessel.

Khanna reported on tests performed with the cooker on a hot, still day in New Delhi; as seen in Figure 11 and Table 12, the results are quite impressive. Although the amount of oil involved is never stated, enough information is included in Table 12 to allow it to be calculated: on the basis of an assumed specific heat of slightly less than 0.5 Btu/lbm-^{o}F for mustard oil, the total mass of mustard oil must have been approximately 2.2 lb. (1 kilogram).

Khanna also briefly refers to field tests performed on a similar commercial model in Somaliland, in which an "overall utilization efficiency" of 32 percent was measured, as compared to 33.9 percent obtained in the laboratory tests of Table 12 and Figure 11.

We are currently attempting to learn more about these cookers - whether they are still in production, how widely they have been distributed, what user experience has been, etc.

E. MORE RECENT CONTRIBUTIONS

1. Brace Institute Steam Cooker

A cooker that was significantly different from those discussed at the UN Conference and in the VITA report was described by A. Whillier in 1965. Whillier took note of the disadvantages of the Wisconsin-type cooker and its failure to gain full acceptance in the Mexican field trials, and listed a number of conclusions regarding the prerequisites for a practical and acceptable solar cooker, the first two of which were that adjustment of position during the day should not be necessary, and that the food-holding part of the system should be separate from the solar collector.

The result was a collector in which a finned pipe lies horizontally in an east-west direction, with a circular-cylindrical reflector behind it as shown in Figure 12. At one end the pipe is connected to the insulated outer vessel of a double-boiler type cooker. The pipe is filled with water, and as the sun hits the finned pipe (from both sides) the water in it boils and the resulting steam

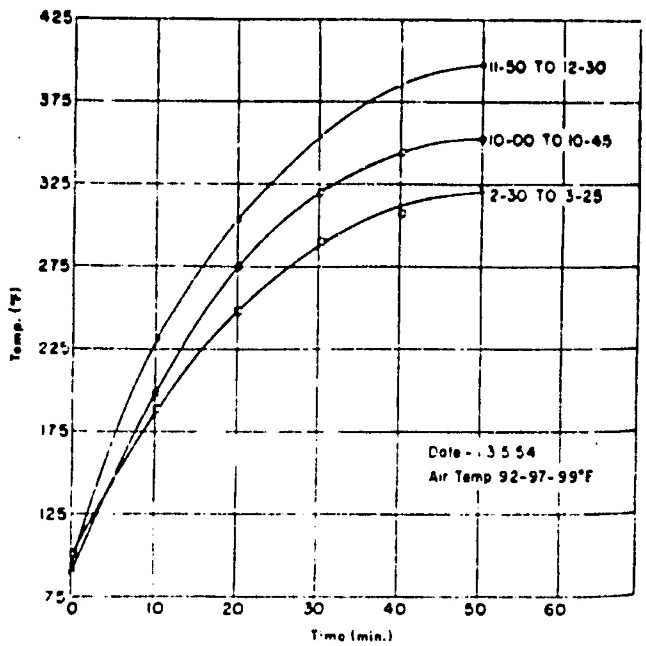

Figure 11. Variation of oil temperature with time at different times of the day (from Khanna, "Heating of Vegetable Oil.")

Table 12. Heat balance of vegetable oil heated by reflection-type solar cooker (from Khanna, "Heating of Vegetable Oil.")

Time, min. after start	5	10	15	20	25	30	35	40
Oil temp., °F	146.5	198.0	242.0	274.0	[illegible]	318.0	332.0	345.0
Thermocouple temp., °F	[illegible]	216.0	246.0	[illegible]	[illegible]	305.0	313.0	317.0
Atmospheric temp. °F	92	92	93	93	93	94	94	94
$(d\theta/d\tau)_o$, °F/min	10.9	9.0	7.5	5.5	4.0	3.5	2.8	1.8
$(d\theta/d\tau)_{couple}$, °F/min	7.5	6.0	5.0	4.0	2.9	2.3	1.4	0.37
Wind velocity, ft/sec	2.272	2.272	2.272	1.942	1.942	1.942	2.008	2.008
$h_r = 1 + 0.22V$								
Q_c, Btu/hr	700.3	578.3	481.9	353.4	257.0	224.9	179.9	115.7
Q_e, Btu/hr	62.9	50.3	41.9	33.5	24.3	19.3	11.7	3.1
Q_{ce}, Btu/hr	298.7	427.3	536.4	562.7	634.3	683.3	730.2	745.4
$\sum Q_c + Q_e + Q_{ce}$	1061.9	1055.9	1060.2	949.6	915.6	927.5	921.8	864.2

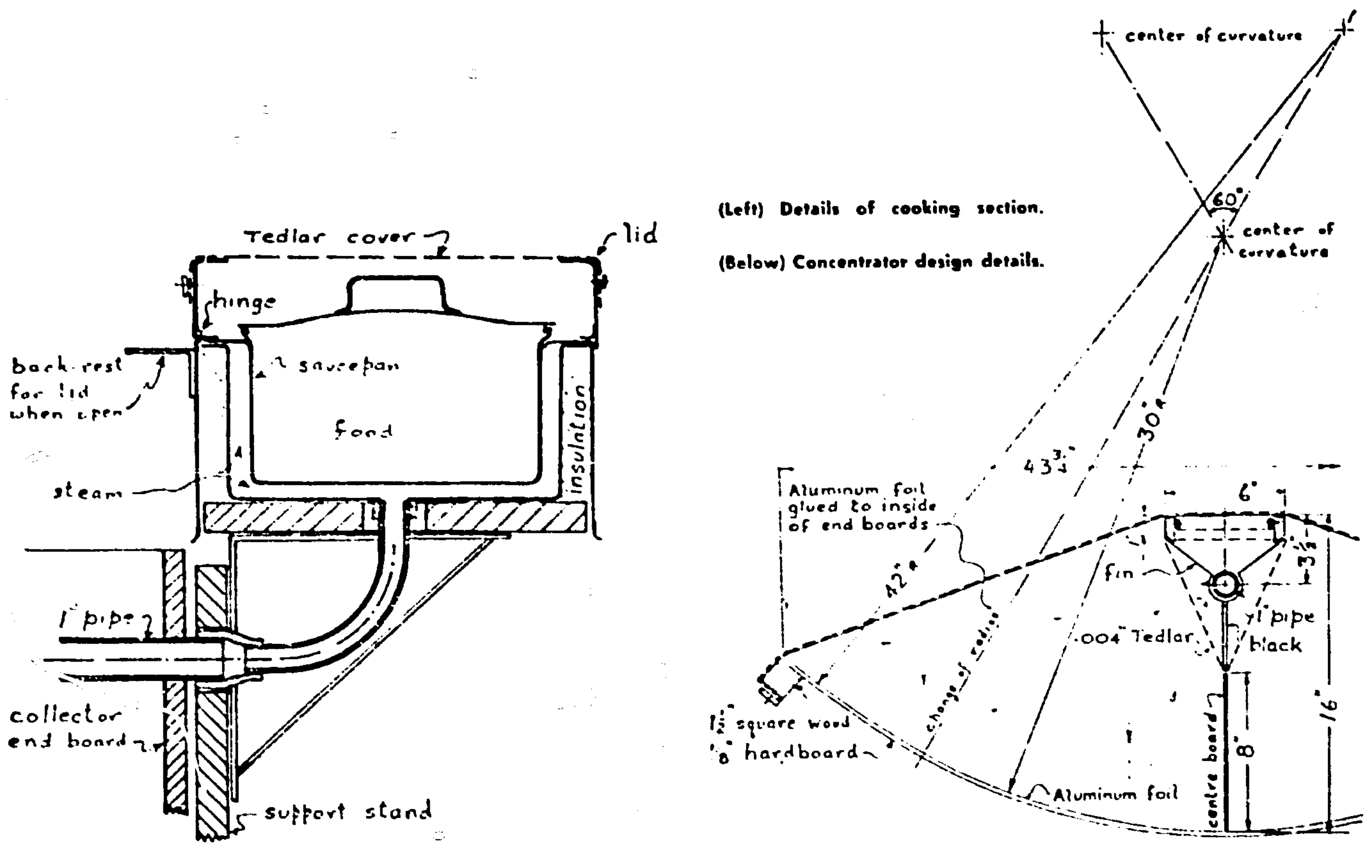

Figure 12. Brace Research Institute cooker details
(from Whillier, "A Stove for Boiling Foods Using Solar Energy.")

rises into the steam jacket around the cooker and thence vents to atmosphere. The lost water is made up by water from the steam jacket, which is initially partially filled with water to act as a standpipe reservoir. A necessary consequence of this system is that the cooking pot temperature cannot actually reach the boiling point of water, unless of course some means of pressurizing the system is introduced.

This cooker is of especial interest for our study, since some twenty similar cookers were installed by the Brace Institute at a school in Miragoâne, Haiti, a few years ago. The Miragoâne cookers represented a slightly different design in which the solar collectors were flat-plate type rather than reflectors, and were fixed in position, whereas the cylindrical reflector collectors could be pivoted about the east-west (pipe) axis. The Miragoâne experiment ended in total failure, in contrast to the University of Wisconsin's limited success in their Mexico experiments, quoted by Whillier as the impetus for his design of a new type of cooker. A similar cooker fabricated by us also failed to cook food. These cookers, and the reasons for their poor performance, are discussed at greater length in a later section of this report. Quotes selected from Whillier's presentation of his own test results will serve to clarify some of the problems associated with this type of cooker:

"Water in the focal tube will begin to boil each morning at about 8:45 a.m. (in Barbados, 13 degrees North latitude, with ambient temperature between 80°F and 90°F) ... Water in the food pot never quite boils, and usually remains at about 4 degrees F below the boiling temperature of the water in the focal tube. ... Food begins to cook shortly before 11 a.m. and continues until about 3 p.m. ... Solar cooking is best suited for long, slow cooking, such as of stews."[33] The length of time required to heat the food in the cooking pot is also commented on elsewhere, and the author asks for suggestions regarding "a non-evaporating, non-scaling and non-corroding additive (that) could be placed in the water in the solar boiler so as to raise its boiling point about 5 degrees F... with resulting faster cooking."[34] He might have added non-toxic and non-expensive as the additive would almost have to be in contact with the cooking vessel if not the food itself, and a certain amount would almost surely be lost in this distillation process even if it did have a high boiling point. The flat-plate-colllector version of this steam cooker is described at greater length in a later section.

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33. Whillier, A.: "A Stove for Boiling Foods Using Solar Energy." Sun at Work, Volume 10, No. 1, pages 9-12 (1965).

34. Ibid.

2. Tabor Multi-Mirror Cooker

A potentially very significant improvement on the Wisconsin-type direct reflection cooker was developed by Tabor[35] in Israel in the middle 1960's. Rather than using a single large reflector with polished aluminum or aluminized plastic film as a reflective surface, or a myriad of small flat glass mirrors glued to a plastic paraboloid, Tabor's reflector uses twelve concave glass mirrors mounted in a paraboloidal array on an iron framework, as shown in the diagrams of Figure 13. The mirrors he used were common shaving mirrors, twelve inches in diameter, which he said were obtainable at $0.30 each in reasonable quantities in 1966. The mounting system for the mirror array and cooking pot is essentially the same that was used for the Wisconsin Model 3 cooker, except that the horizontal axis of rotation is at the center of a circle passing through the focal point and the ends of the reflector array, rather than through the focal point (cooking pot). The vertex of the paraboloid is approximately at the center of the center mirror in the long row of mirrors, no mirror is more than two diameters from the vertex, and none is above the vertex. The optical reasons for this skewed array, in conjunction with the low rotation axis, are treated by Tabor in a very lucid fashion; the practical reasons include keeping the mirrors lower at low sun angles (stability and low wind load), keeping the reflected rays on the bottom of the pot rather than the sides, and keeping the reflected beams more nearly normal to the pot bottom.

The results are shown in Table 13, reproduced from Tabor's paper. As Tabor points out, these results (558 watts delivered, 22 minutes to bring 1.84 liters of water from ambient to boiling) are slightly better than the results that have been reported for 48-inch diameter Wisconsin-type cookers, even though the 12-mirror cooker had only 70 percent as much reflector area. The reasons given by Tabor for this performance advantage are the high reflectivity of second-surface glass mirrors relative to front surface mirrors that are subjected to weathering, and the fact that the geometry of his mirror arrangement allows angles of incidence of the reflected light at the cooking pot that are more nearly normal to the pot surface.

In addition to the performance advantage, other advantages of Tabor's design seem to be the ease of on-site fabrication (with mirrors shipped in), low cost, long life (due to second-surface mirrors), ease of repair (mirror replacement), and stability and ease of use since the reflector is closer to the ground at low sun angles, due to the lower pivot point.

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35. Tabor, H.: "A Solar Cooker for Developing Countries." Solar Energy, Vol. 10, No. 4, pages 153-157 (1966).

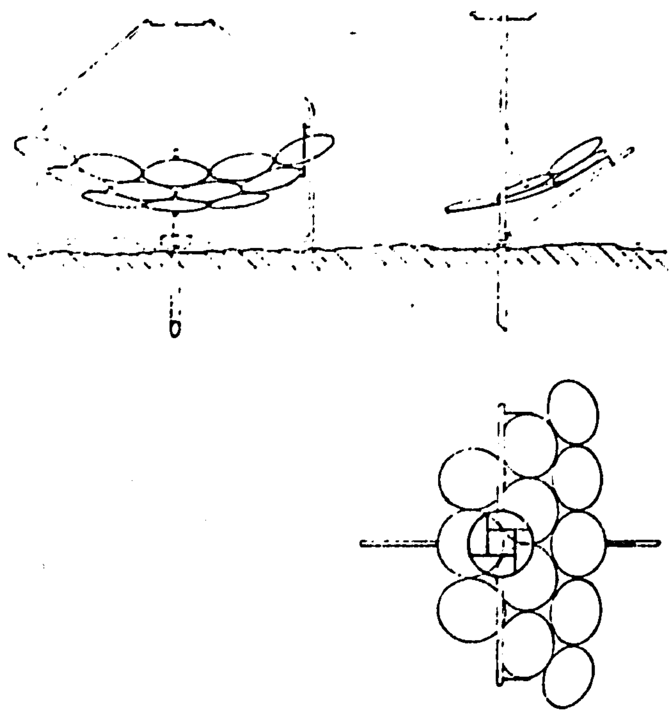

Figure 13. Schematic (three views) of Tabor multi-mirror focusing-type cooker (from Tabor, H., "A Solar Cooker for Developing Countries.")

Table 13. Heating Tests on Tabor Cooker
(from Tabor, H., "A Solar Cooker for Developing Countries.")

1. Test of heating water in 2-1/2 litre kettle (aluminum) containing 1840 cc of water. Total heat capacity 1927 cals/^{o}C. Test conducted at 12.15 hours. 10.XI.65.Lat. 32^{o}. Solar altitude 40^{o}. (No shadow of kettle on mirror).

2. Measured solar intensity (direct radiation) 1.28 cals/cm^{2}, min.

3. Measured rate of rise of temperature - with kettle at ambient temperature: 4.3^{o}C per min.

4. Measured rate of rise of temperature without mirror (due to sunshine falling on kettle) = 0.15^{o}C.

5. From (2) and (3), rate of heating with mirror = 8286 cals/min = 578 watts.

6. From (2) and (4), rate of heating without mirror = 289 cals/min = 20 watts.

7. Net heat gain from mirror 7997 cals = 558 watts.

8. Projected area of 12 mirrors = 7880 cm^{2}, solar heat input = 10,100 cals/min.

9. Net efficiency from (7) and (8) = 78%; Gross efficiency from (5) and (8) = 82%.

   The above results are without heat loss from the kettle.

10. Water boiling test - Time to heat kettle and contents from 14.5^{o}C to 97^{o}C* = 22 minutes, Ambient temperature 18^{o}C: light wind, Thus average rate of heat gain is 7.23 k cals per min; this compares with 8.29 k cals per min with no heat losses.

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* Local boiling point.

3. Russian Folding Cooker

Umarov et al[36] reported in 1972 on a very ingenious folding version of a Wisconsin-type cooker which could be assembled in various configurations to serve as an umbrella, sunshade, tent, etc., as well as a cooker. The cooker configuration is shown in Figure 14. The reflector surface is made of twelve segments, stamped on a paraboloidal die from 1.5 mm aluminum sheet and polished mechanically and electrically. Test results showed 36 minutes to bring 4 liters of water to boil, a commendable figure in view of the measured incident radiation of only 700 w/m^2, although it is worth noting that the reflector, at 1.5 m. diameter, is some 50 percent larger than the 48 inch Wisconsin reflectors usually used as a standard of comparison.

It should be mentioned that "Version III", which gave the best test results, is described as follows: "The heat receiver (cannister of capacity 5 liters, diameter 18 cm) is mounted in a cannister of capacity 8 liters, diameter 22 cm. The clearance between the cannisters was filled with asbestos."[37] How the reflected radiation found its way to the inner cannister is not clear.

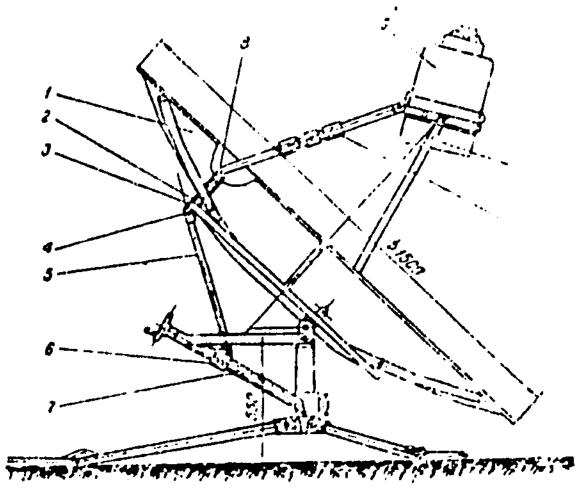


Figure 15. Folding solar cooker: 1) reflector; 2) screw; 3) adjusting ring; 4) lugs; 5) traveling rod; 6) clutch; 7) rotating screw; 8) rod; 9) heat receiver (cannister); 10) offset tube; 11) two-way screw.

36. Umarov, G.Ya.; Alimov, A.K.; and Abduazizov, A.: "Multipurpose Portable Cooker." Geliotekhnika, Vol. 8, No. 6, pages 41-43 (1972).

37. Ibid.

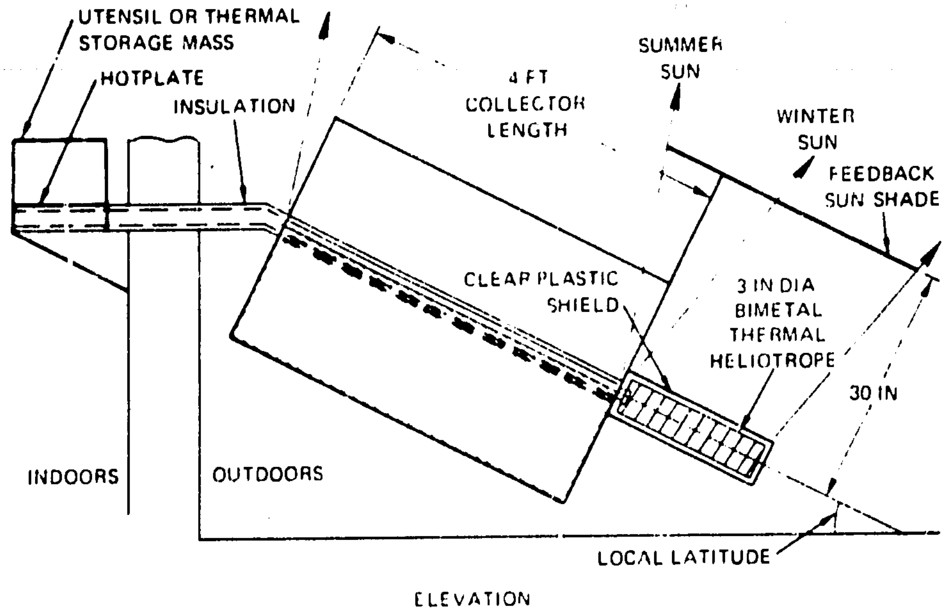
4. Swet Solar Kitchen

C.J. Swet[38,39] has presented conceptual designs for solar kitchens utilizing heat pipes, evacuated tubes or entire enclosures, high performance working fluids and automatic sun tracking utilizing a bimetallic helix with variable shading, as shown in Figures 16, 17, and 18. The version shown in Figure 17 is described as a "low technology" version with a projected cost of under $100, although no supporting calculations or other justification for this cost figure have been presented. To our knowledge, no prototype of this cooker has ever been constructed or tested.

Figure 16. Swet Solar Kitchen in use - artist's conception (from Swet, C.J., "A Universal Solar Kitchen.")

38. Swet, C.J.: "A Universal Solar Kitchen." Paper presented at the Seventh Intersociety Energy Conversion Engineering Conference, 1972, and also published as Report No. APL/JHU CP 018, Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md. 20910 (July 1972).

39. Swet, C.J.: "A Prototype Solar Kitchen." Mechanical Engineering, Vol. 96, No. 8, pages 32-35 (August 1974).



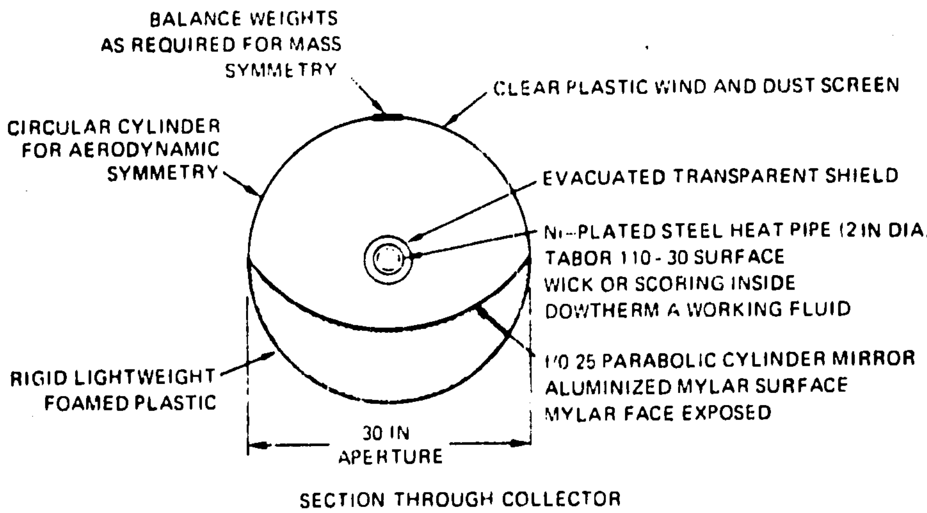


Figure 17. Swet Solar Kitchen - conceptual design for "low technology" version (from Swet, C.J., "A Universal Solar Kitchen.")

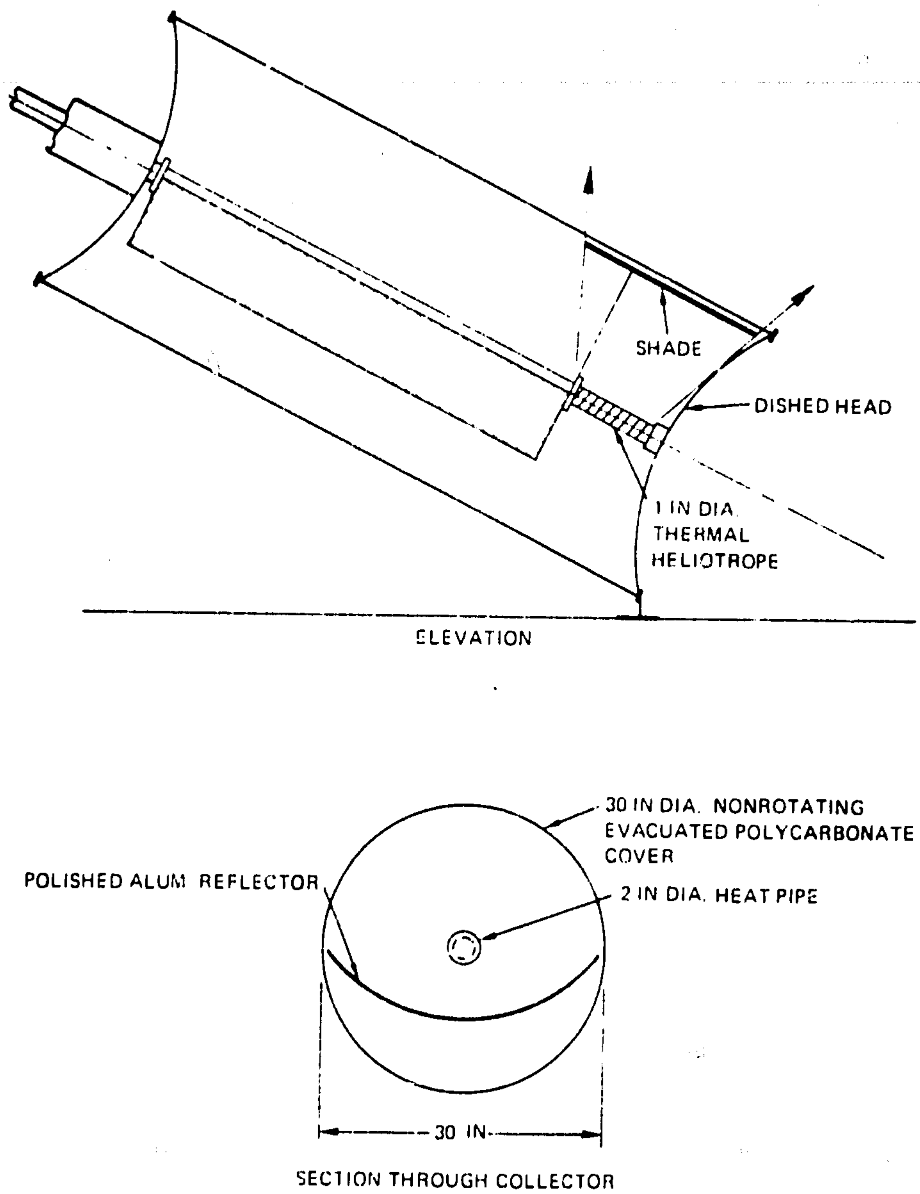


Figure 18. Swet Solar Kitchen -
conceptual design for alternate version with 30 inch diameter vacuum chamber
(from Swet, C.J., "A Universal Solar Kitchen.")

F. OTHER PUBLISHED WORK ON SOLAR COOKERS

A very comprehensive bibliography on solar energy was published by ERDA in 1976: Solar Energy - A Bibliography, TID-3351-RIP1, March 1976. A separate section is devoted to Solar Cooking (Volume I, pages 448-451). Because of the comprehensiveness of the ERDA bibliography, no separate bibliography is included in this report.

II. DESCRIPTION OF COMMERCIAL SOLAR COOKERS AND PLANS

The purpose of this section is to describe all of the cookers that have been either purchased by us, or constructed on the basis of plans obtained from various sources, as well as others that might be available but were not purchased for various reasons, as stated. All prices quoted were current in the second half of 1976.

1. Solar Chef

Figure 19 shows a cooker purchased from the Sedona Solar Shop, P.O. Box 3072, West Sedona, Arizona 86340. The cooker price was $140 plus shipping. It is seen to be a variation on the Telkes oven theme, utilizing sixteen second-surface glass mirrors arranged around a cooking "box" which simply consists of a flat black metal back surface and a glass cover with a spherical wooden handle, visible in the photograph. An adjustable rack in the box allows cooking vessels to be held relatively level, as long as the cooker is not moved with the vessel inside. The cooker is free to rotate about a vertical axis, and pivot about a hinge on one side of the base, and is held in position by two stepped wedges. It is not possible to aim the cooker at the sun when the sun is lower than about 45° from the horizon. Aiming is facilitated by a small peg that casts no shadow when the cooker is aimed properly. The cooker itself is made primarily of wood and fiberboard, well-painted. Only the smallest pots can be accomodated in the cooker, although steaks, hamburgers, small loaves of bread or cakes, chickens, etc. - the sort of items it was obviously designed for - present no problem.

This cooker is markedly similar to the earliest example of a solar cooker that we know of, a 28-inch diameter cooker described in Scientific American nearly 100 years ago.[1] Writing from Bombay, India, Adams states that "the rations of seven soldiers, consisting of meat and vegetables, are thoroughly cooked by it in two hours, in January, the coldest month of the year in Bombay, and the men declare the food to be cooked much better than in the normal manner."

Our Solar Chef was eventually revised substantially prior to the second phase of our testing, as described in Chapter VII. After revision, the cooker was actually even more like Adams' original design than the commercial version.

2. Edmund Cat. No. 71,653

Figure 20 shows a cooker purchased from Edmund Scientific Co., Barrington, N.J. 08007, at a retail price of $13.95. It is simply a styrofoam parabolic cylinder, 13 by 13 inches, lined with reflective foil. Food to be cooked is pressed onto the skewer, which

1. Adams, W.: "Cooking by Solar Heat". Scientific American, June 15, 1878, p. 376.

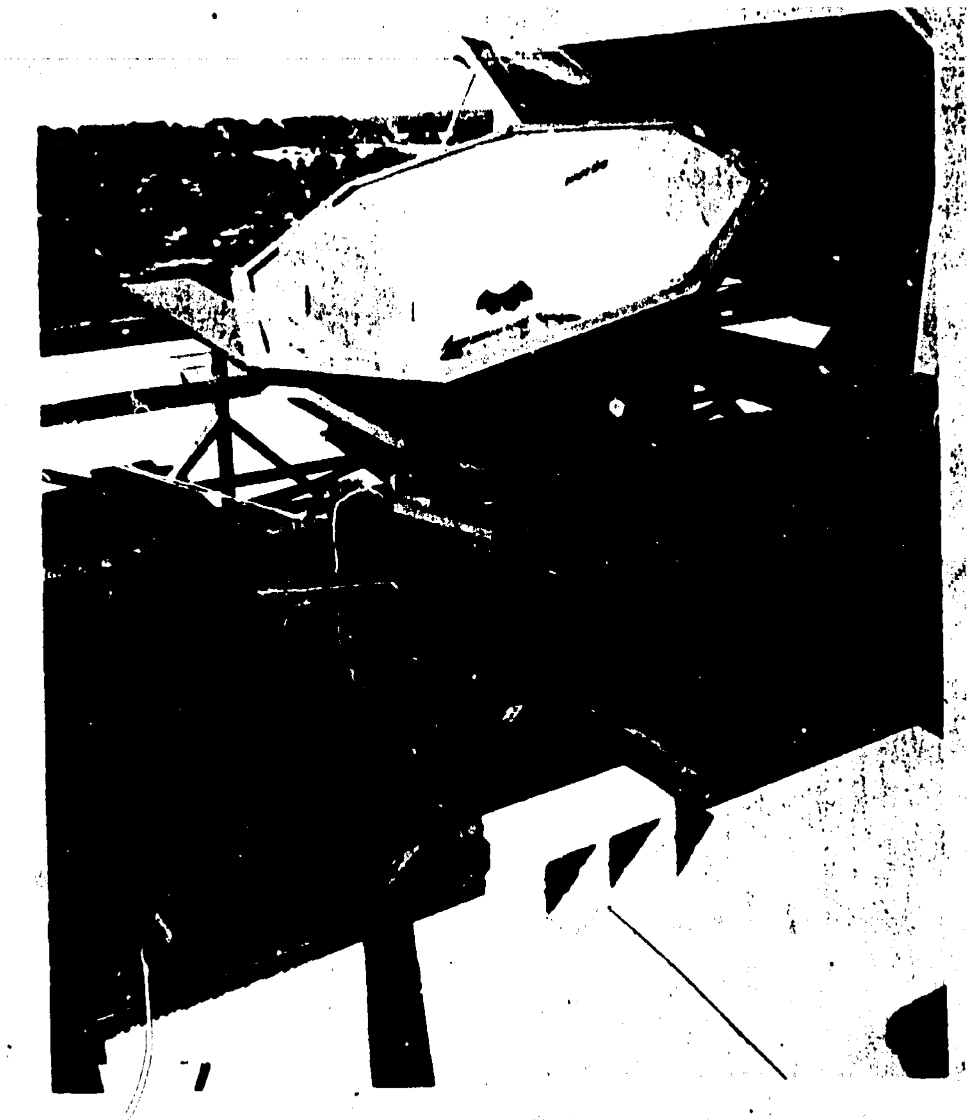


Figure 19. "Solar Chef" cooker in position at F.I.T.

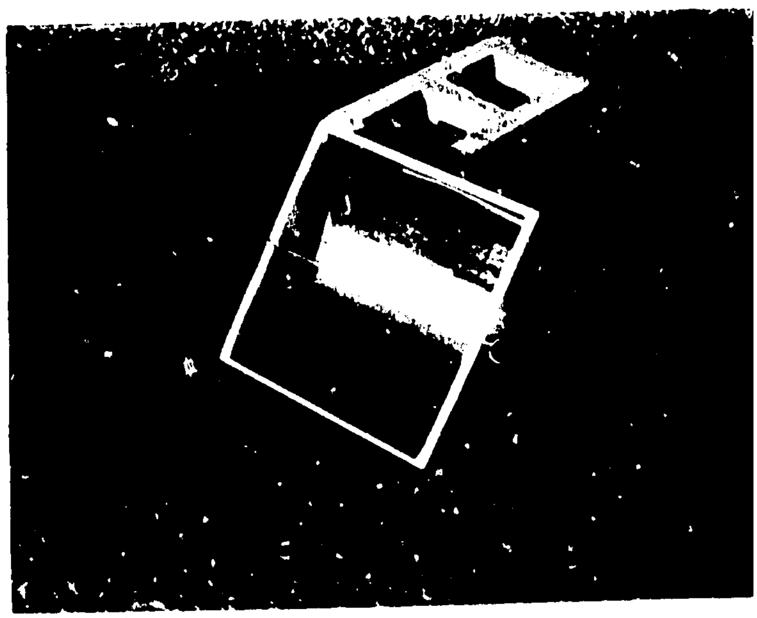


Figure 20. Portable Solar Cooker

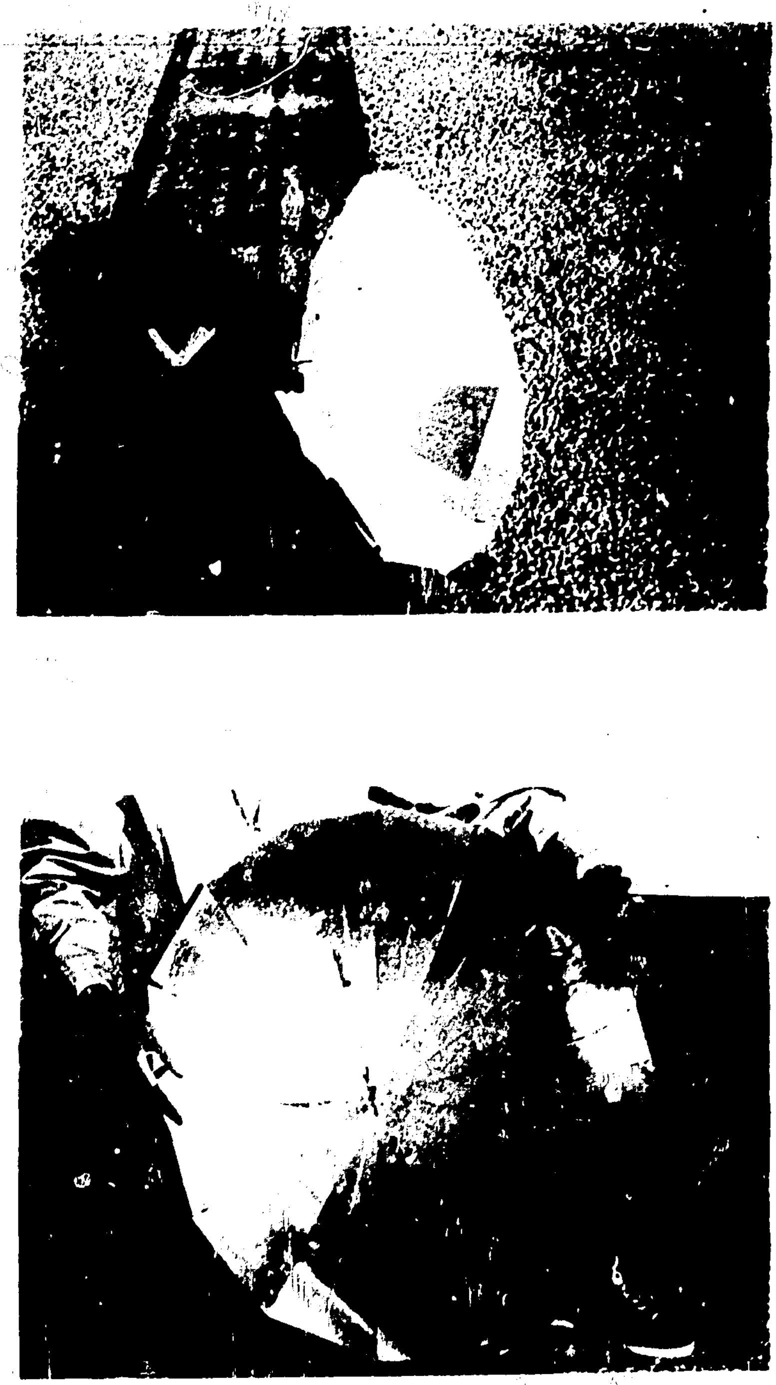


Figure 21. Folding Solar Cooker

lies along the focal line of the reflector, and wrapped with dull black foil. The black foil is not re-used. The cooker weighs less than a pound, and is aimed by means of a swinging metal back brace. An external means of holding the cooker in place is necessary in any breeze.

3. Edmund Cat. No. 72,148

Figure 21 shows a second cooker purchased from Edmund Scientific Co. This cooker, a small scale, folding version of a Wisconsin-type cooker, retailed at $24. It consists of sixteen aluminum leaves only 0.012 inch thick, that lock together with slots and tabs to form a very approximate paraboloidal reflector. The "stand" consists of three wire legs and a wingnut to adjust tilt. A very small pot can presumably be suspended from the curved tube seen in the photos. Diameter of the reflector is about 36 inches. The upper photo shows the reflector turning severely downwind and flapping; the pot support indicates the direction in which the reflector is supposedly pointing. The concrete block is resting on a wire cross piece between two of the legs to keep the cooker from blowing away. In the lower photo, an assistant is attampting to hold the reflector still so that a better photograph could be made. Wind velocity in both cases was 12 to 15 mph.

4. Rodgers Solar Oven: "Patio Champ"

This cooker is listed in the catalog of Solar Usage Now, 450 E. Tiffin St., Bascom, Ohio 44809, at a retail price of $170 (Cat. No. 9072). Attempts to purchase it over a period of several months were unsuccessful, and we were eventually informed that it is no longer available. On the basis of the description, we assume that it was a Telkes oven.

5. Rodgers Solar Oven: "Back Packer"

Also marketed by Solar Usage Now, at a retail price of $35 (Cat. No. 9071), this cooker appears to be a smaller version of Cat. No. 9072, above. The cooking volume is listed as 120 cubic inches, which is slightly smaller than a cube five inches on a side. Because of the small size, it was decided not to attempt to purchase and test this cooker.

6. Solar Grill

This unit is marketed by A to Z Solar Products, 200 E. 26th Street, Minneapolis, Minn. 55404, at a retail price of $39.50 (Cat. No. 9060). It is a version of a Telkes oven with a very flat oven box capable of holding four hamburgers or six hot dogs. The oven is made of molded plastic and black-coated aluminum, with folding reflector plates and aluminum stand. The oven box is double glazed and insulated. With reflectors and legs folded, the dimensions of the entire unit are 16 by 16 by 5 inches. Because of its small size and unsuitability for boiling or stewing food in a pot, it was not purchased.

7. Solar Hot Dog Cooker

This unit is also marketed by A to Z Solar Products, at a retail price of $8.25. It is very similar to the cooker shown in Figure 20 above, except that it is slightly larger - 13-1/2 by 18 inches - and made of cardboard and fiberboard rather than styrofoam. It was not purchased since skewer-type cookers were of little real interest in this project.

8. Wisconsin-Type Cooker

We do not know of any cooker of this type that is currently available commercially. The Solar Usage Now catalog lists such a cooker, with a 48 inch diameter aluminum reflector, at $139.95, but they informed us that, like the large Rodgers Solar Oven, it is no longer available. The same supplier can furnish spherical second-surface acrylic reflectors in sizes up to 48 inch ($70). Our cooking tests using one of these reflectors are described in Chapter VIII.

9. Brace Institute Steam Cooker

The cooker shown in Figure 22 was made according to plans available from Brace Research Institute, Faculty of Engineering, McGill University, Ste. Anne de Bellevue 800, Bellevue, Canada. The plans are entitled "Solar Steam Cooker, do it yourself leaflet L-2", revised October 1972, by Ron Alward, and are sold for $1.25. The cooker is similar in operation to one described in Whillier's paper, which was covered in the preceding section. The important difference in the construction is the collector itself, which in this case is a flat plate absorber in a double-glazed wood and sheet metal box of outside dimensions 62 x 21.5 x 4 inches. The absorber is a single galvanized iron pipe tied with baling wire to an aluminum fin that extends 10 inches out from the pipe on either side, and is only 0.025 inch thick. The effectiveness of a fin of aspect ratio 400 is discussed in the evaluation section and Appendix F, as well as the problem of lack of good thermal contact between fin and tube.

The Brace Institute design includes a 45 degree angle of inclination for the collector, and lack of adjustment of this angle. Since the cooking box is supported by the water/steam pipe, and only standard plumbing fittings are used, the design is constrained by the 45 degree elbow below the cooking box. The justification for this angle, given in Whillier's paper, is that in the tropics this inclination will be ideal at some time early in the morning and late in the evening, and that during the middle of the day when the sun is higher in the sky the increased radiation intensity and higher atmospheric temperature will tend to compensate for the decreased effective collector area. Our own limited insolation measure-

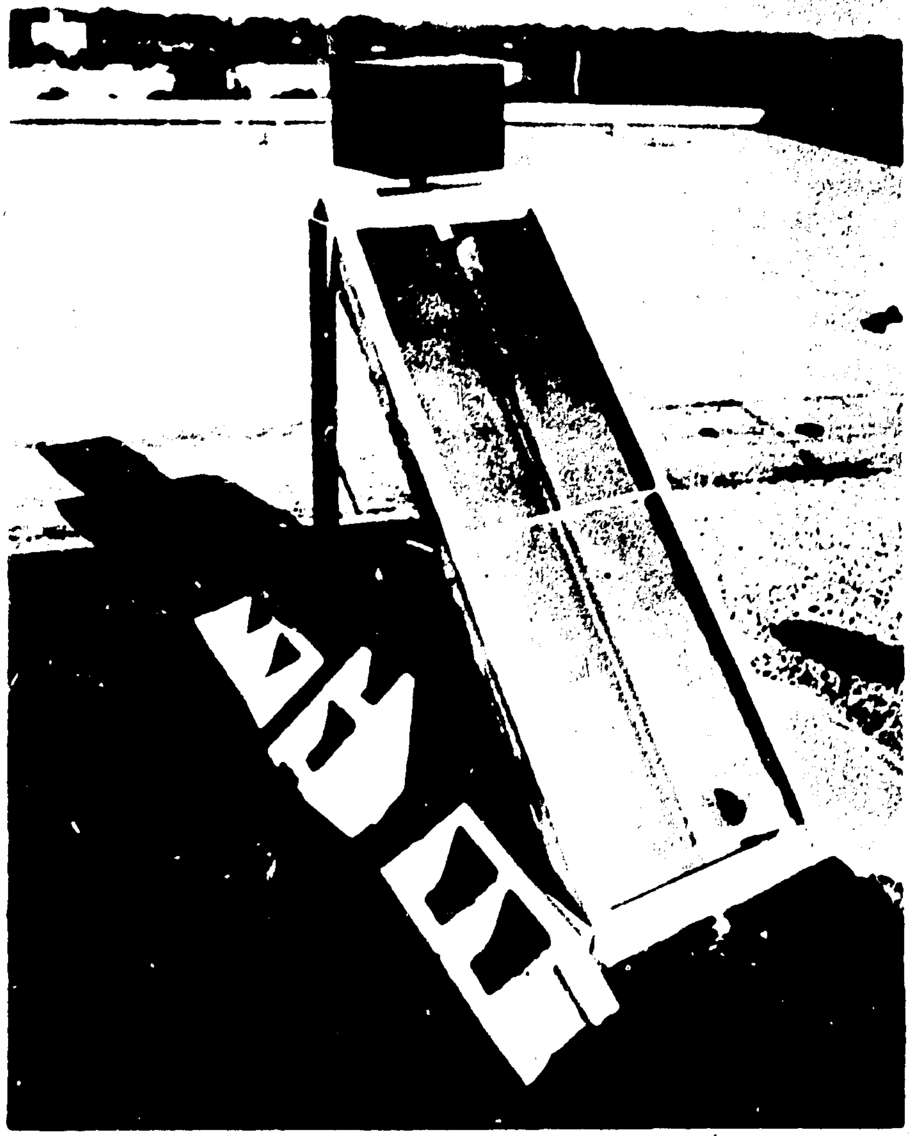


Figure 22. Solar steam cooker fabricated at F.I.T. in accordance with Brace Institute plans.

ments in Haiti did not indicate any significant variation with sun angle in the amount of radiation falling on a properly aligned receiver as long as the sun was more than 25° or so above the horizon, as is typical in dry climates. In other words, proper alignment is no less important at noon than at 9 a.m., for example.

The cooking box is fabricated of sheet metal, and insulated except for the lid.

The entire cooker is rotated about a vertical axis to follow the sun during the day.

10. Telkes Oven with Movable Reflectors

Figure 23 shows an oven made according to plans by D. S. Halacy, Jr., originally published by Macmillan Co. as a chapter in the book Fun with the Sun. They have also been published in The Mother Earth News, issue No. 25, pages 26 - 28 (January 1974).

This oven differs from others of its type in that the reflectors are movable, and hence it is possible to "track" the sun, although with some loss in performance, by simply moving the reflectors and not tipping the oven. Except for the brace for the top reflector, however, there is no provision for holding the reflectors in place, and the reflectors themselves are thin sheets of unsupported aluminum. Because of the impossibility of using the oven as designed on any but the least windy days, our prototype was modified by the addition of masonite panels behind the aluminum sheet.

The oven was originally insulated with two inches of aluminum-backed fiberglass insulation.

Food is added to the oven through a door in the rear. In this respect, and with regard to overall configuration, the oven is quite similar to the triangular oven shown by Telkes in her 1959 paper - see Figure 7.

This oven was later modified very considerably, as described in Chapter VII.

11. Others

The six solar cookers listed above as being currently marketed are the only ones we know of being manufactured in this country. The Tarcici cooker, manufactured for many years in France under the trade name "Solnar", is believed to be still manufactured in small quantities by Dr. Tarcici in Switzerland; a few years

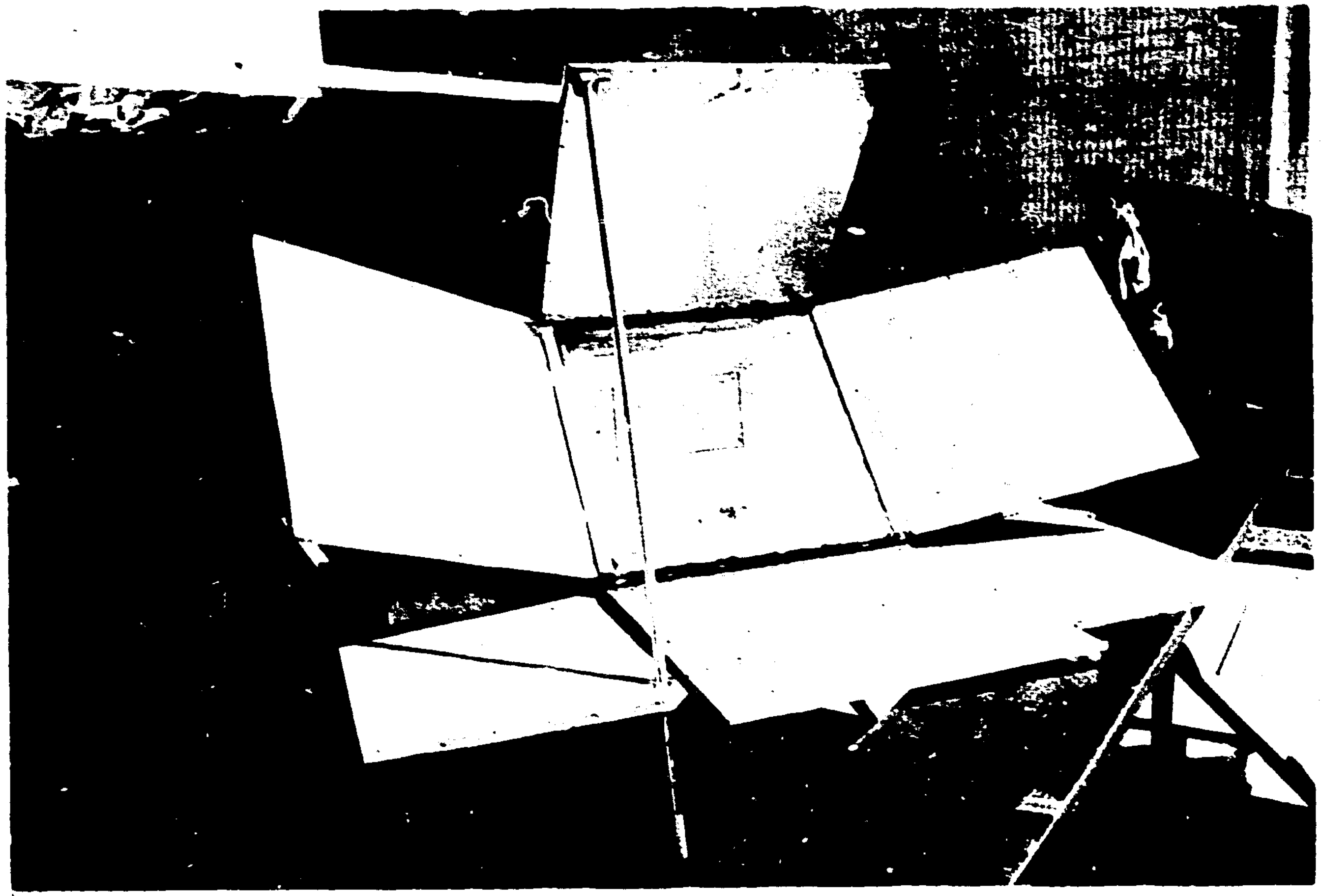


Figure 23. Variation of Telkes oven with movable reflectors, fabricated at F. I. T. in accordance with "Mother Earth News" plans.

ago it was available from Intercontinental Enterprises Company, 69 Stewart Avenue, Eastchester, New York, 10707 at a price of $160. Tests of this cooker were included in the VITA study - see page 39 above. An example of the cooker is said to be on permanent exhibition in New York City's Museum of Modern Art.

A patent was issued in 1973 to Merton R. Clevett and assigned to Solar Products Corp., 3500 East First Avenue, Denver, Colorado, 80206, for a "Solar Stove" that appears to be somewhat similar to the Solar Chef. In a letter dated February 20, 1975, to Mr. William Rhodes of the State Department, Mr. Robert E. Deline of Solar Products Corp. referred to the cooker as the Solar Sunflower Stove and stated that it had not been put in production. Our own inquiry dated August 27, 1976, was not answered.

III. SUMMARY OF HAITIAN CONDITIONS

The study team visited Haiti during the period December 12-20, 1976, to obtain first-hand knowledge of weather conditions, cooking customs, 'lifestyles,' terrain, and other factors that might affect the eventual design and application of solar cookers in that country. A detailed chronological trip report is presented in Appendix C. In this section, we summarize our findings with regard to various specific topics that were of interest to us.

A. WEATHER

Prior to going to Haiti, we obtained solar and meteorological data for Haiti and performed calculations to ascertain factors such as optimum solar collector orientation. The results of these efforts are presented in Chapter IV below.

While in Haiti, the general optimism that we had regarding Haitian weather was amply confirmed. The December weather was warm, dry, and very sunny everywhere we went, and especially in the Northwest. Cloud cover was virtually nonexistent during our stay. Solar irradiation measurements, performed using a hand-held radiometer held perpendicular to the sun's rays, are listed in Table 14. Most measurements were made independently by two different investigators and then compared. Also included in Table 14 is information on local cooking times, based on our questions to local people in each area.

Of especial interest is the rapidity with which high insolation measurements were obtained early in the morning at Anse Range, where lack of vegetation allowed a clear view of the horizon. Almost as soon as the sun cleared the horizon (7:15 a.m.) readings over 200 Btu/ft^2-hr were obtained, and climbed steadily to over 90% of the normal midday (300-310) reading by 9:00 a.m. In Florida, early morning humidity has always resulted in much lower early morning readings, although the midday peak is approximately the same in December as the Haitian measurement. The 3:00 p.m. and 3:45 p.m. measurements at Terre Neuve and Jean-Rabel were also higher than we have seen in Florida so late in the afternoon in the wintertime, although the difference in length of day accounts for at least part of this difference. All of these data indicate that a large percentage of the total radiation measured in Haiti, at least on the two days covered by our measurements, is direct radiation from the sun - relatively little is diffuse or re-radiated. This conclusion is borne out by a series of measurements (not included in Table 14) made between 1:20 and 1:45 p.m. on December 16, when a number of scattered

Table 14. Radiation measurements (normal to sun's rays) and normal cooking hours at selected locations in Haiti

Location	Date	Time	Measured Insolation (Btu/ft^2-hr)	Normal Cooking Hours
Port-au-Prince (U.S. Embassy)	22 November 1976	Noon	310	------
Port-au-Prince (U.S. Embassy)	14 December 1976	Noon	305	------
Magnant (near Miragoâne)	15 December 1976	2:30 p.m.	260	6:00 a.m. and 3:00 - 5:00 p.m.
Saint-Marc	16 December 1976	10:15 p.m.	310	------
Gonaives	16 December 1976	11:00 a.m.	310	8:00 - 10:00 a.m. and Noon - 3:00 p.m.
Bassin	16 December 1976	Noon	305	6:00 a.m. - Noon and 3:00 - 5:00 p.m.
Mountains above Bassin	16 December 1976	1:30 p.m.	310	------
Terre Neuve	16 December 1976	3:00 p.m.	315	8:00 a.m. - 8:00 p.m.
Desert Near Anse Rouge	16 December 1976	5:00 p.m.	70	------
Anse Rouge	17 December 1976	7:15 a.m.	205	8:00 a.m. and 3:00 - 6:00 p.m.
Anse Rouge	17 December 1976	8:20 a.m.	250	8:00 a.m. and 3:00 - 6:00 p.m.
Anse Rouge	17 December 1976	8:45 a.m.	275	8:00 a.m. and 3:00 - 6:00 p.m.
Baie-de-Henne	17 December 1976	10:15 a.m.	300	7:30 a.m. and 2:00 - 6:00 p.m.
Bombardopolis	17 December 1976	11:20 a.m.	305	6:00 a.m. and 2:00 - 5:00 p.m.
Mole Saint-Nicholas	17 December 1976	1:00 p.m.	300	------
Jean-Rabel	17 December 1976	3:45 p.m.	250	7:30 - 8:00 a.m. and 2:00 - 5:00 p.m.

(Note: Length of day (sunrise to sunset) in Haiti on December 15 is 10 hours, 48 minutes (north coast) to 10 hours, 56 minutes (south coast).)

clouds were passing overhead. It was found that the radiometer needle dropped very quickly from 305-310 down to near zero as a cloud passed over the sun, and climbed as quickly as the cloud passed. Readings with the cloud between the sun and the instrument were significantly lower than similar readings made in Florida.

The significance of this conclusion regarding the percentage of direct radiation is that the direct component is the only radiation that can be used effectively by a focusing-type (Wisconsin) cooker. If our mid-December measurements are typical of year-round Haitian conditions, it would be expected that focusing cookers would perform measurably better in Haiti than in Florida. Oven-type cookers would also perform better because of the use of reflectors for energy concentration, but the difference would not be as pronounced since the oven window accepts radiation from many directions, and total mid-day insolation is as high in Florida as in Haiti. The length of time during which cooking is feasible is of course greater in Haiti, at least during the Winter.

B. COOKING TIMES

We were very interested in when, during the day, the major part of the cooking was done, since the amount of dislocation of customs and habits that would be associated with changing to solar cookers depends on whether people would have to cook and eat their meals at unaccustomed or inconvenient times. Our concern with this potential problem increased when we encountered many women cooking on the sidewalks (under street lamps) in certain areas of Port-au-Prince at 11:00 p.m. and later.

What we found was considerable variation from village to village and region to region, and in some places variation according to time of year - different practices during planting and harvest times, in particular. The most prevalent practice, however, was a single main meal taken in the early afternoon. Outside of Port-au-Prince, the use of artificial light seems not at all widespread, and cooking after dark is uncommon. In some cases, food prepared earlier in the day was eaten after dark, either cold or only slightly warm. Table 14 lists some of the "normal" cooking hours that were given by various local people that we interviewed.

Very few people outside of Port-au-Prince eat three prepared meals per day, as far as we could determine. One or two are most common, and we were told in some areas that many people are no longer able to actually cook any food because of the difficulty of obtaining wood or charcoal. Morning meals often consist of no more than coffee, and vary in time from before sunrise to mid-morning. Relatively little charcoal seems to be used during the early morning hours.

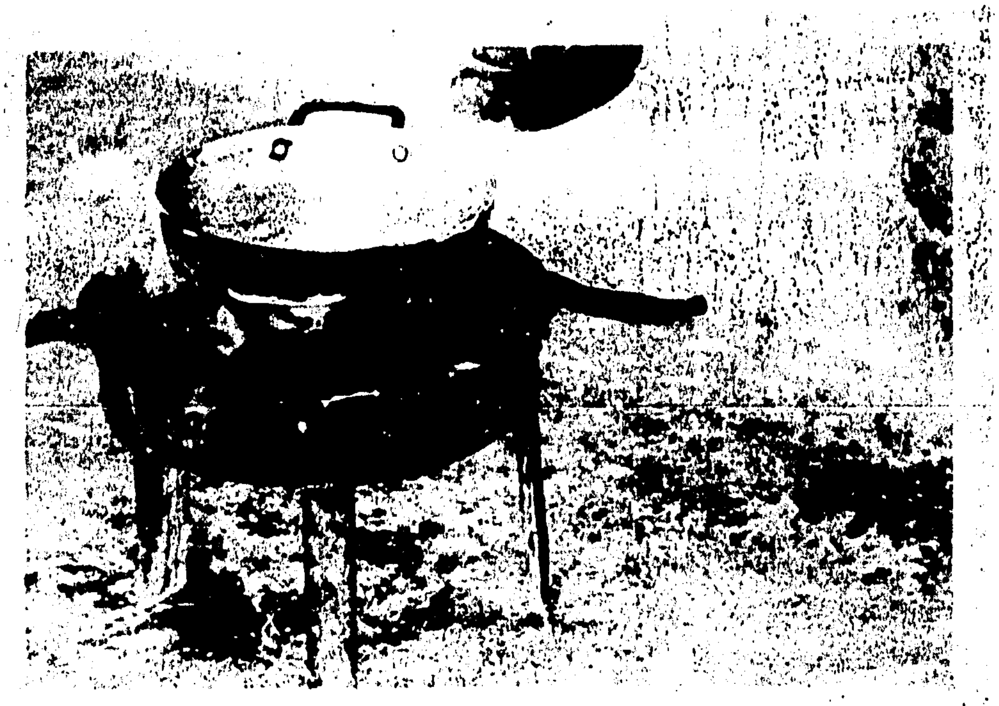
As important as what we learned about eating customs were the repeated indications that the Haitians are a very flexible and adaptable people, not as set in their ways or tradition-bound as people in many other cultures, including probably our own. The primary prerequisite for adopting new ways of doing things or new daily routines seems to be whether or not it reduces their workload. If the result is to make life a little easier, they are anxious to try it. Many people in many areas spend a significant part of each day hunting for wood to cook with, and walk great distances to find it. We were told by more than one woman that they would be glad to change their cooking routines by almost any amount if they could be spared the task of searching for wood.

C. COOKING METHODS

Extensive interviews with many people at HACHO nutrition centers and elsewhere (see Appendix C) indicated that most cooking consists of boiling - cereals, beans, corn, plantains, some meat, etc. Meat is often deep fried, but usually after being boiled first, and the extent to which this frying is done varies from village to village, as does the amount of meat eaten. Skillet frying is not done as far as we could determine. For meat, it might be reasonable to think in terms of replacing deep frying with skillet frying if the latter is more easily carried out with any given solar cooker design.

Marinades, which are made from a batter and deep fried something like hush-puppies, were sampled by the team at Fond-Parisien. We did not encounter marinades anywhere else, but were told that they are occasionally prepared. The cooking of marinades is shown in Figures 24 through 26, which also show a typical cooking fire, prepared in a ventilated basket, and an average-sized cooking pot. Most of the pots we saw were somewhat round-bottomed, like this one.

Figure 24. Cooking, sheet one (Fond-Parisien).
Top: charcoal/wood fire in typical fire basket.
Bottom: batter for marinades.



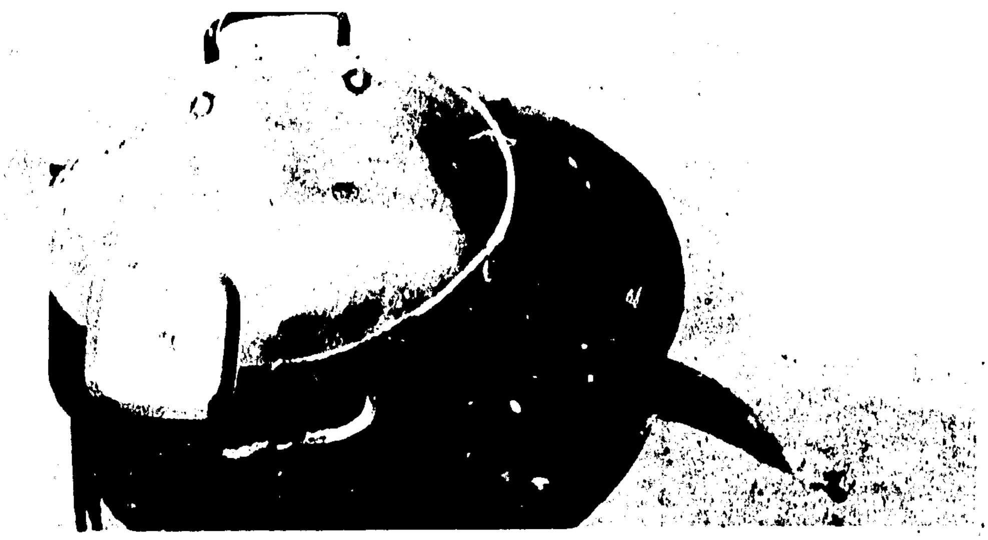


Figure 25. Cooking, sheet two (Fond-Parisien): heating oil for marinades. Temperature of the oil is over 300°F.

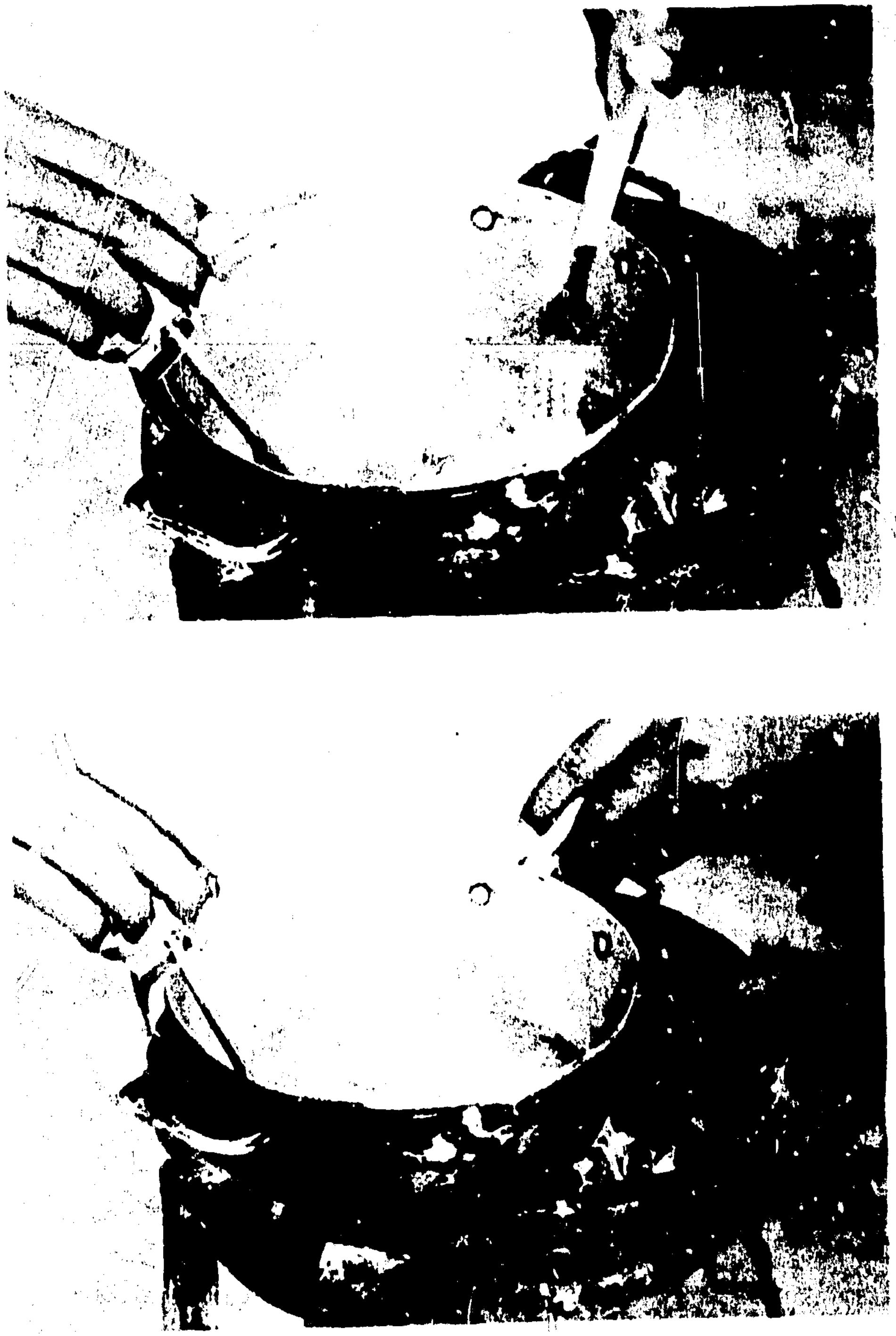


Figure 26. Cooking, sheet three (Fond-Parisien): frying marinades.

Figure 27 shows the size of a normal bag of charcoal (top), and the cooking of a thin, flat bread on an iron sheet over a charcoal fire (lower). The lower picture was taken in one of the lushest regions that we passed through. The bread was cooked for a very short time, at an apparently low temperature, and then stacked in the flat, unheated pan on the left for sale to the public. This type of bread could probably be cooked very readily using solar energy, although none of the cookers described in the preceding sections seems to be suitable since none has a large, flat heated surface.

The bread we commonly encountered around the country was not the tortilla-like bread of Figure 27, but rather a thicker, white, apparently unleavened bread made in bakeries in some villages and sold to inhabitants of that village and others in the vicinity, or made in the larger towns and sold throughout the surrounding areas. We did not hear of this bread being made by individuals for their own consumption. A village bakery - in this case a very recently-completed one - is shown in Figure 28. The oven, which could not be photographed because of lighting problems, was a very large affair with a small door and very thick walls. Heat was provided by burning charcoal below the cooking part of the oven. On the outside, the oven was approximately an eight-foot cube, filling most of the back of the bakery.

At Port-de-Paix, we stayed at a small regional hotel that had just been opened, and was still being constructed. Cooking methods in the hotel kitchen were found to be quite similar to those used by individuals, except for being carried out indoors, as seen in Figures 29 and 30. Three charcoal baskets in a large concrete pedestal (on the right in the top photo, Figure 29) had been provided for cooking; the only fire that was going when we visited the kitchen was in a portable charcoal basket on the floor.

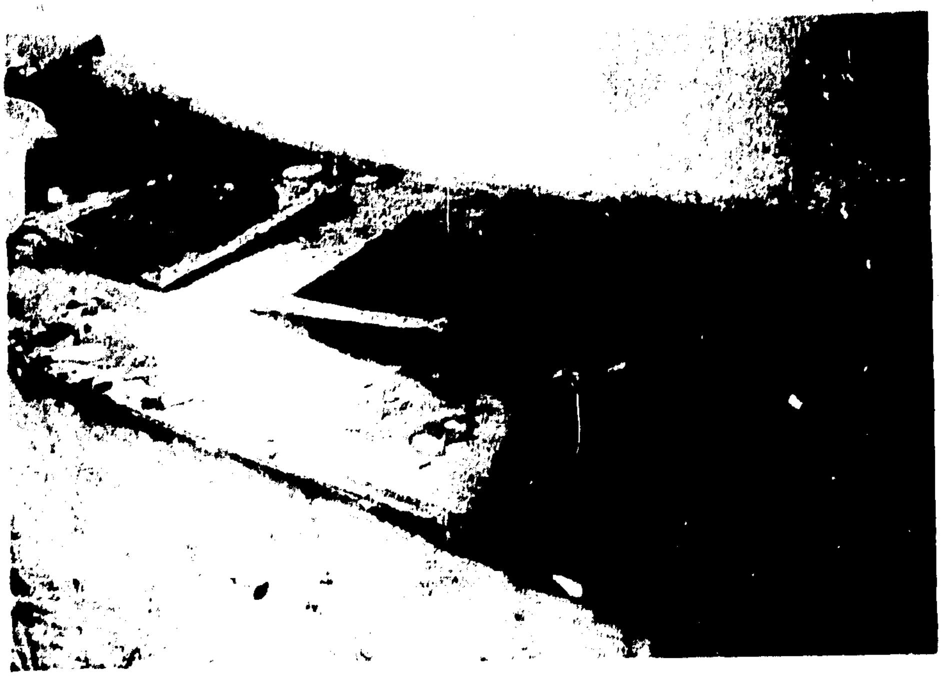
Other typical cooking scenes are shown in Figure 31. In the top photo, the charcoal fires are built on the ground, between three stones which support the cooking pot. (In this photo, we are not certain that the very large pot being heated contains food.) In the lower photo, portable charcoal baskets are being used.

We stopped at a HACHO nutrition center in Bassin, shown in Figures 32 and 33, and attempted to photograph the cooking area. Here the cooking was done atop a large concrete pedestal, similar to the one in the hotel at Port-de-Paix except that there were no built-in charcoal baskets. Each fire was surrounded by three stones that also supported the cooking pots, as in the upper photo in Figure 31. It was encouraging to see that the women preparing the food seemed

Figure 27. Cooking, sheet four. Top: a typical charcoal bag, as used at Fond-Parisien. Price fluctuates seasonally between 60¢ and 80¢ per bag. Bottom: woman cooking flat tortilla-like bread for sale to passers-by, on the road between Léogâne and Miragoâne. The fire is between three stones by the boy's feet.

Figure 28. Cooking, sheet five. HACHO bakery at Bassin.

Figure 29. Cooking, sheet six. Hotel kitchen at Port-de-Paix. Water is heating on a small fire on the kitchen floor (both photos); main cooking area is on the right in top photo (see also next page).



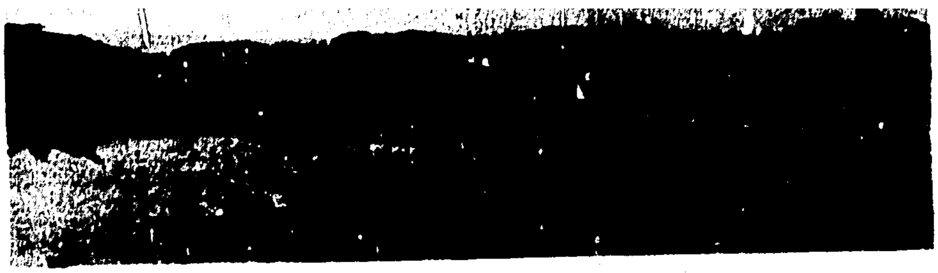


Figure 30. Cooking, sheet seven. Hotel at Port-de-Paix.
Top: three charcoal baskets in the hotel kitchen
(see also preceding page).
Bottom: view looking toward the center of town.

Figure 31. Cooking, sheet eight. Roadside scenes.
Top: a small commercial establishment between Croix-des-Bouquets and Fond-Parisien; note tall pot being heated over three stones and other three-stone arrangements to the left.
Bottom: on the road between Léogâne and Miragoâne.
At least three portable, three-legged charcoal baskets can be seen.

Figure 32. Cooking, sheet nine: HACHO nutrition center at Bassin. Two views of the cooking area. Fires are built on elevated concrete platform, with three stones to support cooking vessels.

Figure 33. HACHO nutrition center at Bassin (continued)

happy to adjust to stand-up cooking, a fairly radical departure from the customary method of sitting on a very low stool to tend a fire built on the ground. The cooking area was behind the building and semi-enclosed, resulting in the strong sunlight - shadow problem that made photography difficult in Figure 32; more success was had photographing the children and the food in the dining area in front of the building, Figure 33.

Cooking pots are manufactured in Haiti and imported, in a variety of sizes and shapes, as seen in Figures 34 and 35. These displays were arranged in front of a row of small shops facing the market square in Léogâne. All of the cooking pots we saw for sale were aluminum, and most (those made in Haiti) were cast. Also visible in the upper photograph are porcelain pans, presumably not used for cooking, and three charcoal baskets.

D. LOCATION AND SPACING OF HOUSES

Perhaps even more important than cooking methods and customs, from the point of view of the acceptability and feasibility of solar cookers, is the question of what sort of setting people live in. For example, we saw many villages in Haiti that were in such lush settings that there were no open, sunny areas in the immediate vicinity. In other cases, although the surrounding countryside had been stripped bare, large trees had been saved in the village proper to provide shade. Fond-Parisien, which was seen in the upper photo of Figure 27, was one such example. The upper photo in Figure 36 shows still another type of problem. Although there are no trees in sight, the houses themselves are built so close to one another that the only way a solar cooker could be used would be to set it up in a field outside of the village.

The lower photo in Figure 36 shows another typical situation: a small village at the edge of a wooded area. Although solar cooking would be feasible here, it might be inconvenient for some of the inhabitants. We need hardly mention, however, that the inhabitants of villages such as this are much more accustomed to walking considerable distances than are most Americans. It is also worth noting that, while cooking is typically done at home, Haitian women customarily walk long distances to do their laundry in a river or stream, and might easily adapt to a similar regimen for cooking. Also beneficial in this respect is the fondness of the Haitian women, as noted by many observers, for activities such as marketing and washing where they can get together with other women to talk and gossip as they work. Even in remote areas, we noted an obvious enjoyment of

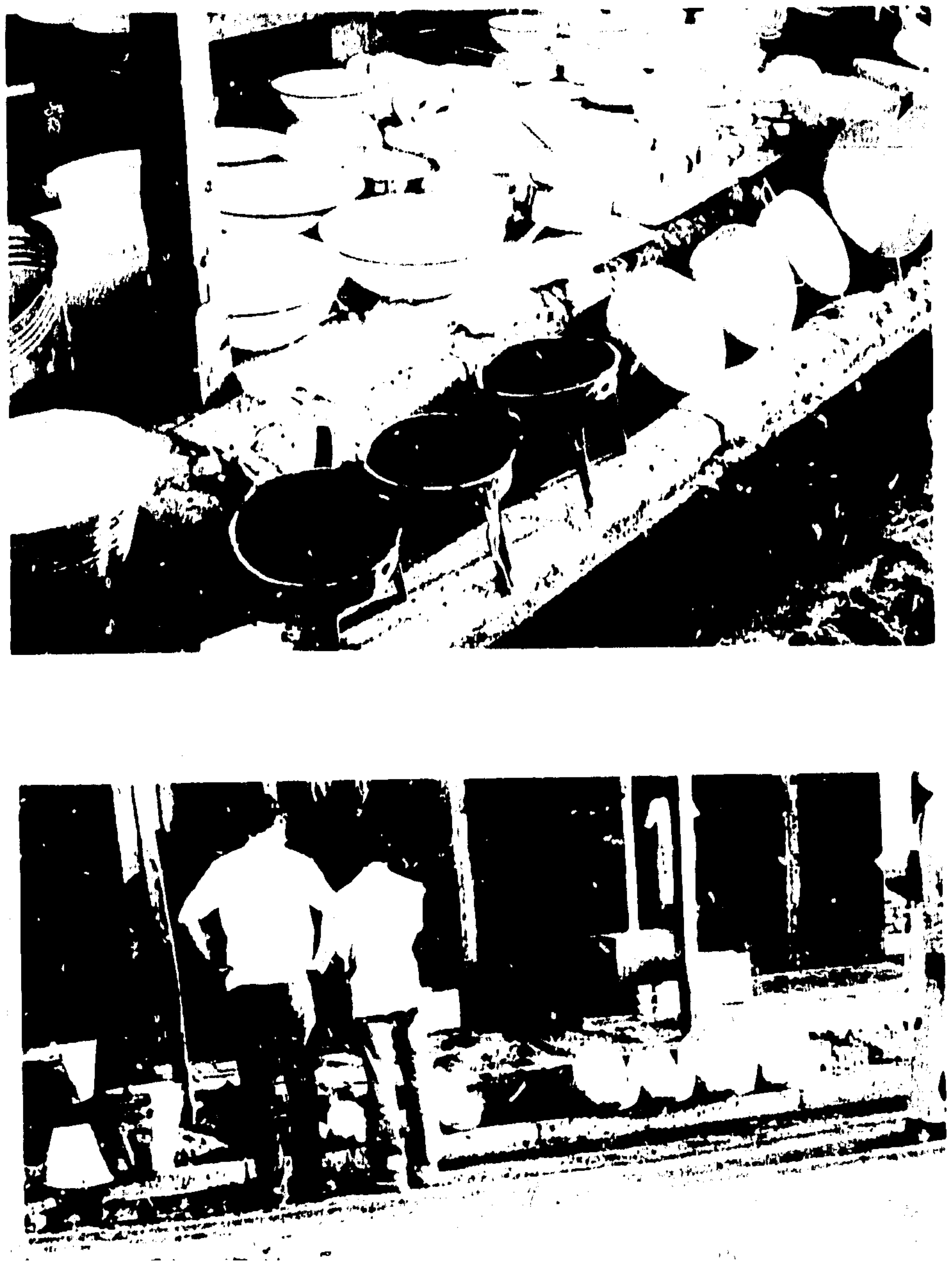


Figure 34. Cooking, sheet eleven: cooking utensils for sale in the marketplace at Léogâne.

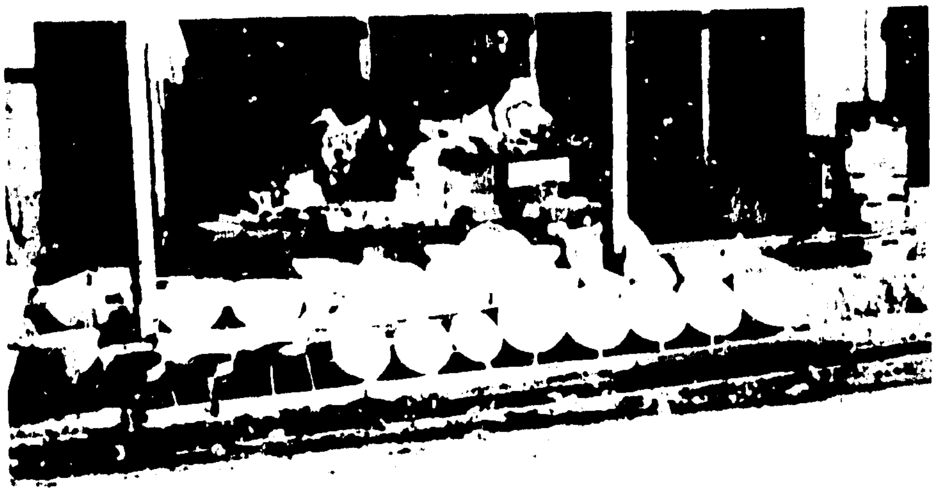


Figure 35. Cooking, sheet twelve: cooking utensils for sale in the marketplace at Léogâne (continued).

Figure 36. Villages, sheet one. Top: close-spaced houses in a tree-less setting, between Port-au-Prince and Croix-des-Bouquets. Bottom: open-spaced houses on the edge of a wooded area, between Croix-des-Bouquets and Fond-Parisien.

community activities, doing things together, crowds, etc. There seems to be a strong likelihood that the idea of a community solar cooking area away from the village might not be an unattractive one.

The upper photo in Figure 37 shows a large town, Anse Rouge, with very little vegetation and limited open areas. The picture is taken from the HACHO mission, just outside of town, looking toward the town.

The lower photo in Figure 37 shows a virtually ideal setting for solar cooking - a coastal village with no local vegetation and scattered houses, with abundant room for solar cookers near the houses.

The upper photo in Figure 38 shows a larger coastal town, Baie-de-Henne, with little vegetation and larger open areas than we saw in Anse Rouge. The lower photo, taken along the main road between Port-au-Prince and Cap Haitien where it crosses the Artibonite plain, shows a more typical example of house spacing than the extreme cases of some of the earlier photos. In this photo, only a couple of large trees are visible; on the other side of the road, there were more large trees, but they were still rather widely spaced. In villages such as these, the advantages of a solar cooker that would be portable enough to allow daily movement to avoid shadows is obvious.

In conclusion, it can be said that Haitian towns and villages are extremely diverse, and range from those where it would not be possible to find any place to set up a solar cooker to those where a solar cooker could be set up almost any place. In between are villages where good solar cooking areas exist nearby but outside the village, or in one open part of a town, or where solar cooking would be practical if the cooker could be moved from one side of the house to the other or away from a tree, depending on time of day.

A final conclusion that is almost entirely subjective is our impression that, while cooking methods can probably be changed with little difficulty, the villages themselves will not be changed. The Haitians are not a nomadic people, although there seems to be a significant migration to Port-au-Prince. It does not seem logical to expect villages to be moved, or new villages to come into existence, just for the sake of solar cooking.

E. SOLAR COOKERS AT MIRAGOÂNE

At Miragoâne, an exceptionally pretty town on the northern coast of the long east-west peninsula that comprises the southern portion of Haiti, approximately twenty of the Brace Research Institute steam cookers described in the preceding

Figure 37. Top: looking toward Anse Rouge from the HACHO mission, with HACHO hospital in right foreground and charcoal boats in right background. Bottom: an open-spaced coastal village in a tree-less setting, between Anse Rouge and Baie-de-Henne.

Figure 38. Top: Baie-de-Henne, a coastal town with few trees and a large central open area.
Bottom: moderately-spaced houses in an area of some trees, in the Plaine de L'Artibonite between Saint-Marc and Gonaives.

chapter had been installed a few years ago in a school run by the Roman Catholic Church. The school is situated on a rather steep hillside overlooking the sea, and a building with a flat concrete roof had been constructed for the cookers at the highest corner of the grounds. The cookers had been arranged in three rows, of six or seven two-pot cookers each, on the roof of this building. Only one row remains, and it is not in use.

A portion of the remaining row is shown in Figure 39, as well as a close-up of one of the steam boxes. The cookers are similar to the one we built, described in the preceding section. The important differences are as follows:

1. The Miragoâne cookers are wider, with two risers leading to the steam box instead of one (see Figure 40) and room for two pots in the steam box.

2. The Miragoâne cookers are constructed with three layers of glass window rather than just two. The third layer of glass adds significantly to the cost of the cooker, especially since glass is an import-only item in Haiti, and is of questionable benefit since dirt seems to have ready access to the inner glass layers.

3. Each collector box contains four runs of water-filled tubing (two per riser) rather than just one as in the plans distributed by the Brace Research Institute. This difference will go far to correct one of the most obvious shortcomings of the design as published - the very great distance of much of the collector surface from the water tube, resulting in a rather small part of the heat collected ever finding its way into the water.

The collectors in Miragoâne were mounted at the customary 45 degree angle (see preceding section) on support structures made of concrete blocks, pipe, and steel angle, as shown in the top photo in Figure 41. The orientation, facing east-southeast, was puzzling at first until we learned that all cooking at the school must be completed by 11:30 a.m., when the children eat lunch and then go home. Even considering this constraint, and the fact that the school is closed each year from the end of June to mid-October, the collectors are probably too far from the horizontal to be optimally effective. In June, for example, at these tropical latitudes the noonday sun is actually farther north than directly overhead. Optimum solar collector angles for Haiti are discussed in the next chapter. In this application, the optimum angle is also affected by the fact that the collectors are facing a group

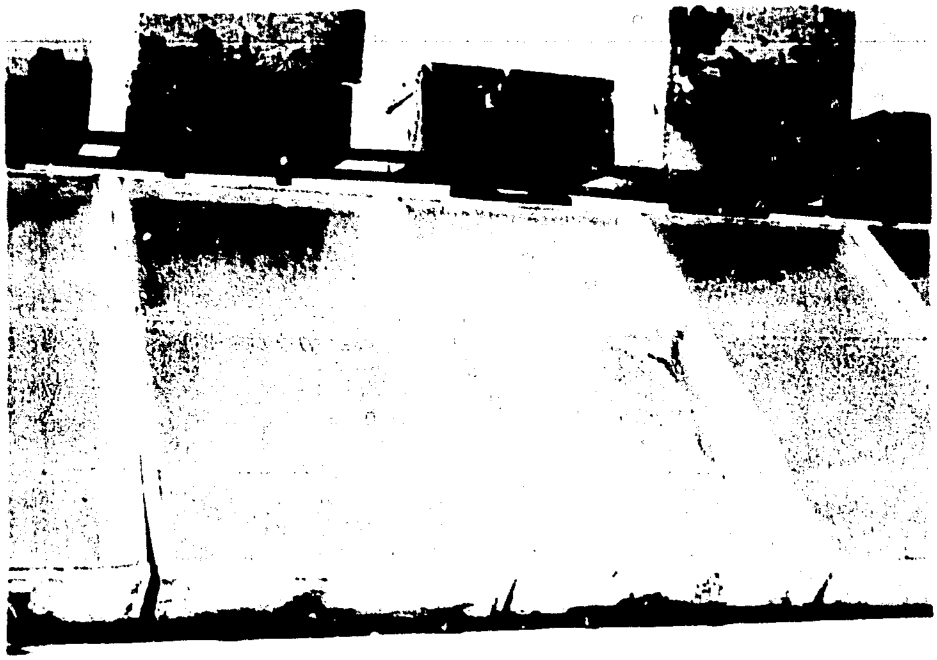


Figure 39. Solar Cookers at Miragoâne, sheet one.
Top: triple-glazed collectors and cooking boxes - part of the existing row of seven units.
Bottom: close-up of one of the seven two-hole cooking boxes, with top open.

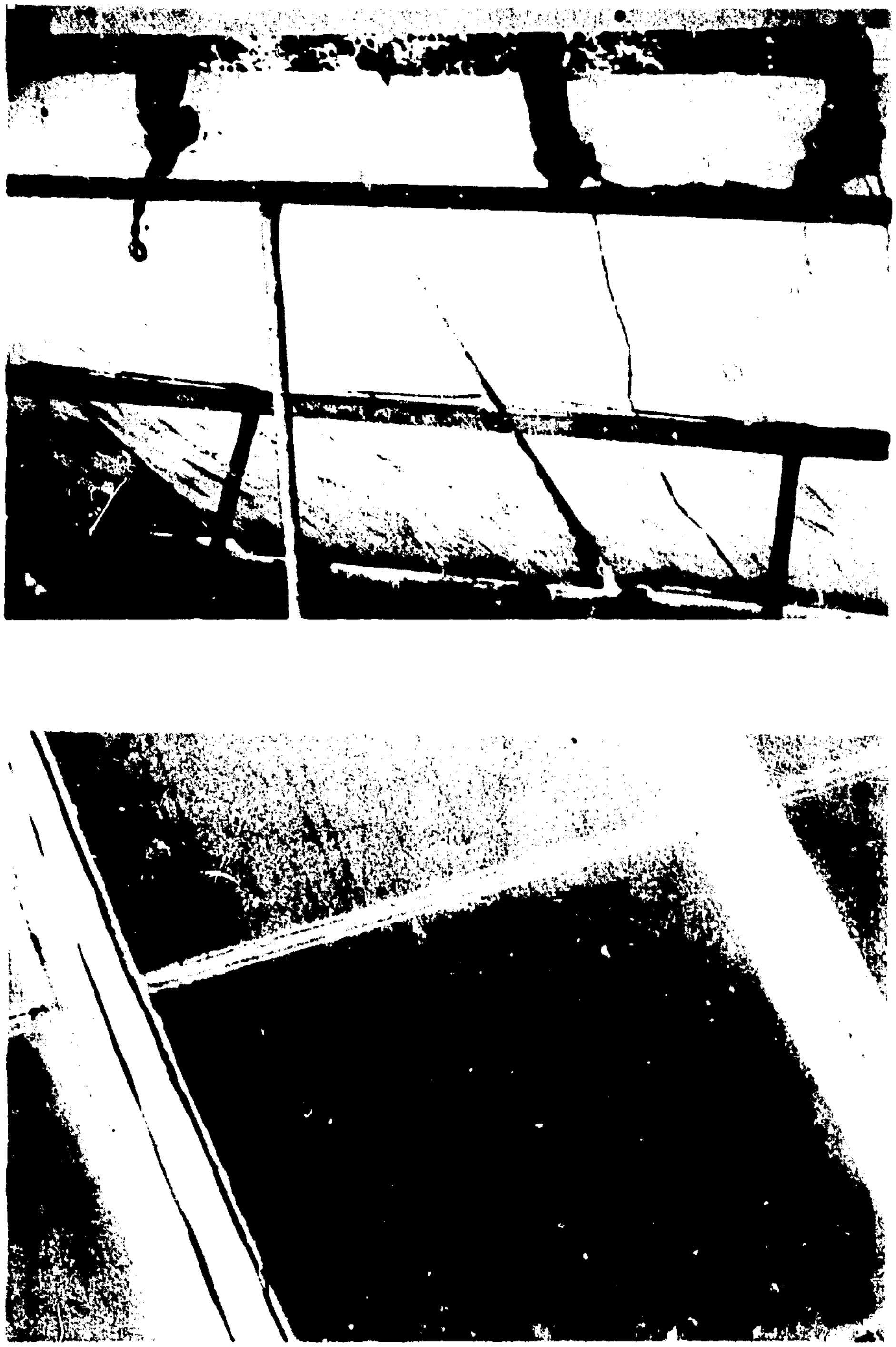


Figure 40. Solar cookers at Miragoâne, sheet two.
Top: back view of collectors, with steam
pipes rising to cooking boxes outside of the field of view.
Bottom: close-up of a collector panel, showing four tubes
pressed into sheet metal absorber surfaces, and a joint in the glazing.

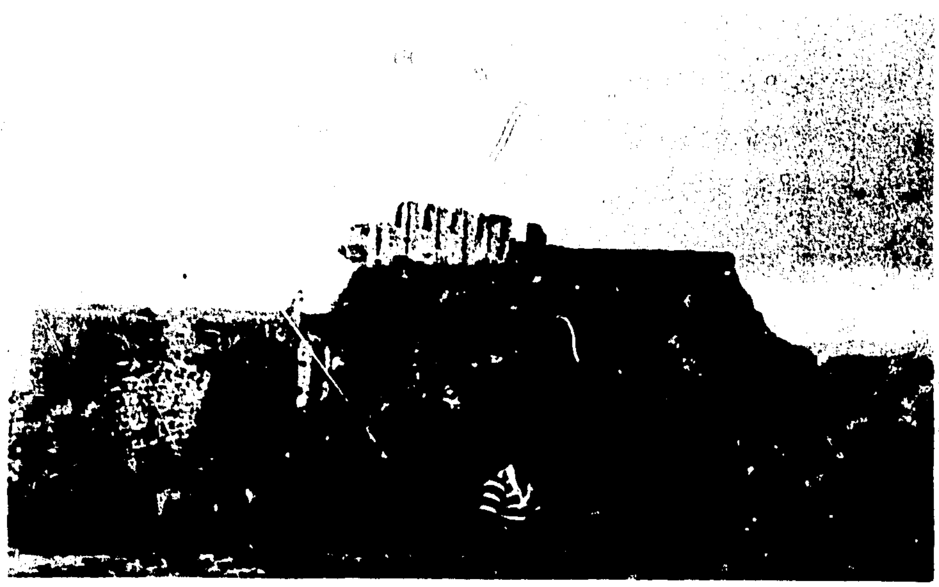


Figure 41. "Rooftops". Top: members of the study team and Ing. Tibor Nagy taking notes on the solar cookers at Miragoane. In the foreground is supporting structure and rubble from one of the two dismantled rows of cookers. Around the existing row of collectors are (left to right) Bowman, Nagy, Yenamandra, Mongabure, Von Lignau (Blatt is behind the camera.)
Bottom: The Citadel, with Yenamandra in the foreground.

of tall trees that would block the sun at low angles, resulting in the optimum angle being even more nearly horizontal.

Construction of the steam boxes relied extensively on materials that are notorious for their susceptibility to moisture damage, as seen in the lower photo of Figure 39. The tops are insulated with spun fiberglass insulation, held in place with iron or mild steel straps that had rusted through almost everywhere. The two-hole board that holds the cooking pots is made of un-tempered fiberboard. Except for the outer sheet metal, the steam boxes were in a rather advanced stage of decay. The outer sheet metal is galvanized and hence in good condition, although the flat black paint is peeling off badly.

The nuns had attempted to use the cookers for one academic year. They told us that the cookers had never really worked. They would cook rice, cereal, etc., but only very very slowly and when finally cooked the food was soggy and unappetizing. The food had to be in the cooker at 7:00 a.m. to be ready by 11:00 a.m. Early morning cloudiness was an especial problem, as clouds would have to be gone by 9:00 a.m. for there to be any chance of success. The cookers were used more for hot water for washing up, etc., than for actual cooking.

These experiences with this particular cooker were very much in agreement with our preliminary test results. Although a number of very obvious improvements could be made to the design, and the orientation could be much improved, especially if cooking could be done more nearly during the middle of the day, one overall constraint on this type of cooker is the fact that the food cannot be brought quite to the boiling point of water. The design of this type of cooker is discussed in more detail in Section V below.

Figure 42 shows a solar water heater that had been built by the nuns on another rooftop, using two of the collectors removed from the cooker arrays. As a water heater, the performance was reported to be satisfactory.

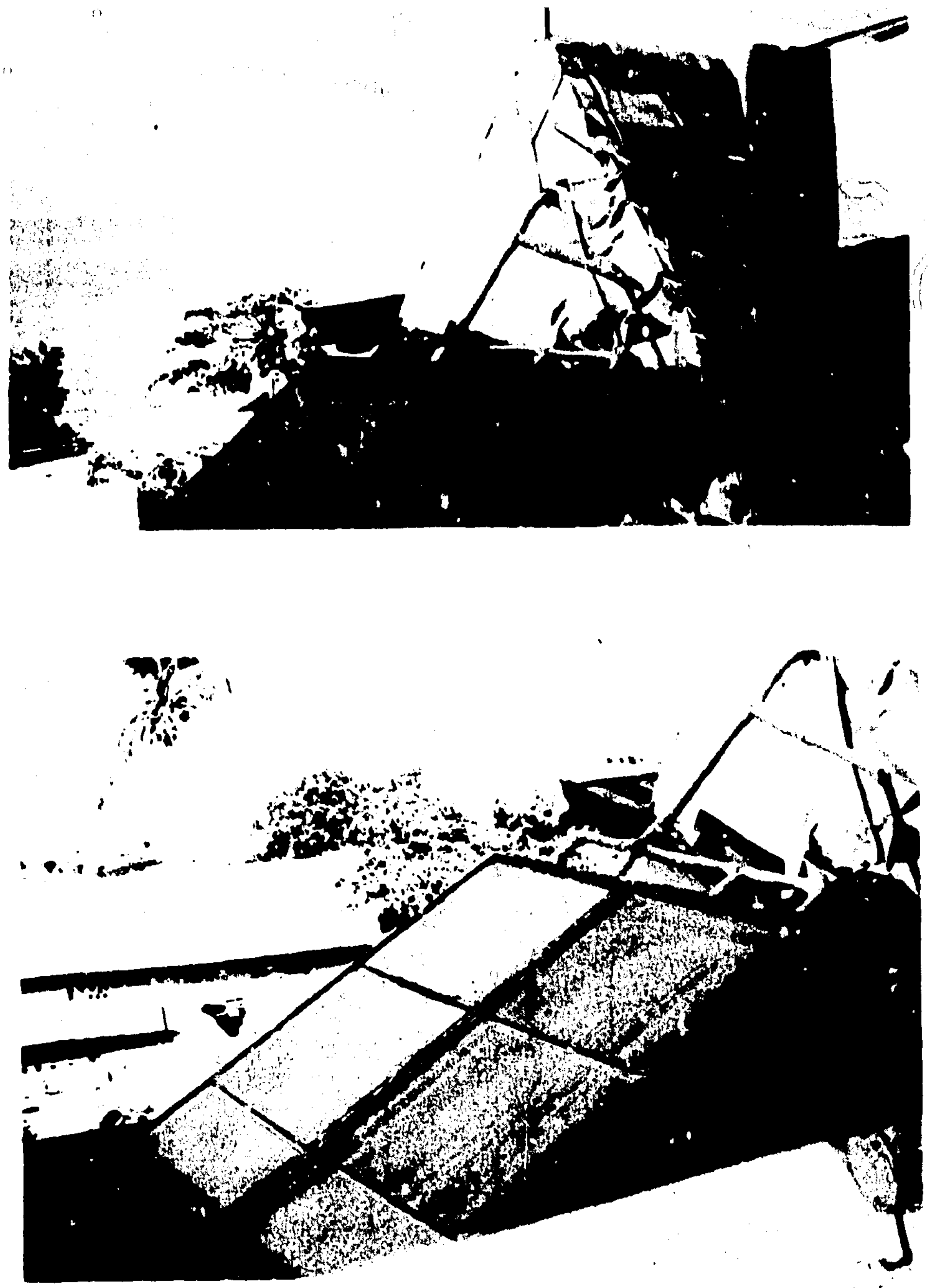


Figure 42. Solar water heater at Miragoane,
using two collector panels from the dismantled rows of solar cookers.
(The reflection in the lower right corners results from
the photos having been taken through an open jalousie window.)

F. DEFORESTATION

A peripheral interest relative to our primary task of evaluating the applicability of solar cookers in Haiti and the influence of Haitian conditions on cooker design, but nevertheless related to our study, is the problem of deforestation. During our travels through Haiti we saw many treeless areas, but it was usually difficult to determine with certainty how long they had been treeless if, indeed, trees ever had grown at any particular location. We do know that accounts from the early days of the U.S. occupation of Haiti (which began in 1915) refer to a deforestation problem even then, and accounts from still earlier would tend to indicate that Haiti was much more heavily forested at one time than it is now. We also saw areas where the last trees had obviously been removed in the recent past, and areas of especially severe erosion.

Figure 43 shows a very arid-looking area north of Port-au-Prince. Trees are visible along the crest of the hill, but none on the plain. This area is very extensive, and was very dry and dusty when we were there. It is reasonable to believe that, with the intense sunlight, the dryness is in large part due to the absence of trees, and that if a good stand of trees were established the character of this area would be quite different.

Figure 44 and the top photo in Figure 45 show scenes that are typical of the region around Anse Rouge. Cacti in all sizes and shapes grow everewhere, and the terrain is laced with gullies up to two meters or more in depth. In the lower photo in Figure 44, a cactus is seen about to fall into the gully as the bank is being eroded away beneath it. In other places huge cacti were lying in gullies where they had recently fallen due to the ground being washed out beneath them.

The most serious erosion we saw in actively-used agricultural lands was in the northern coastal area between Jean-Rabel and Port-de-Paix. The lower photo of Figure 45 was taken as we were first entering this area; as we proceeded farther along the road the sun sank too low for photography. We saw mile after mile of tree stumps as in the photo, large areas in which the topsoil had been stripped away, and an almost indescribable number of rocks. In many fields rocks had been piled into cones about one meter in diameter by one meter high to clear patches of dirt for planting; the rock cones nearly touched each other and covered more land than they left clear. HACHO officials in Gonaives told us that reforestation of the more level land had not been successful because the young trees interfered with the agricultural activities that were being desparately pur-

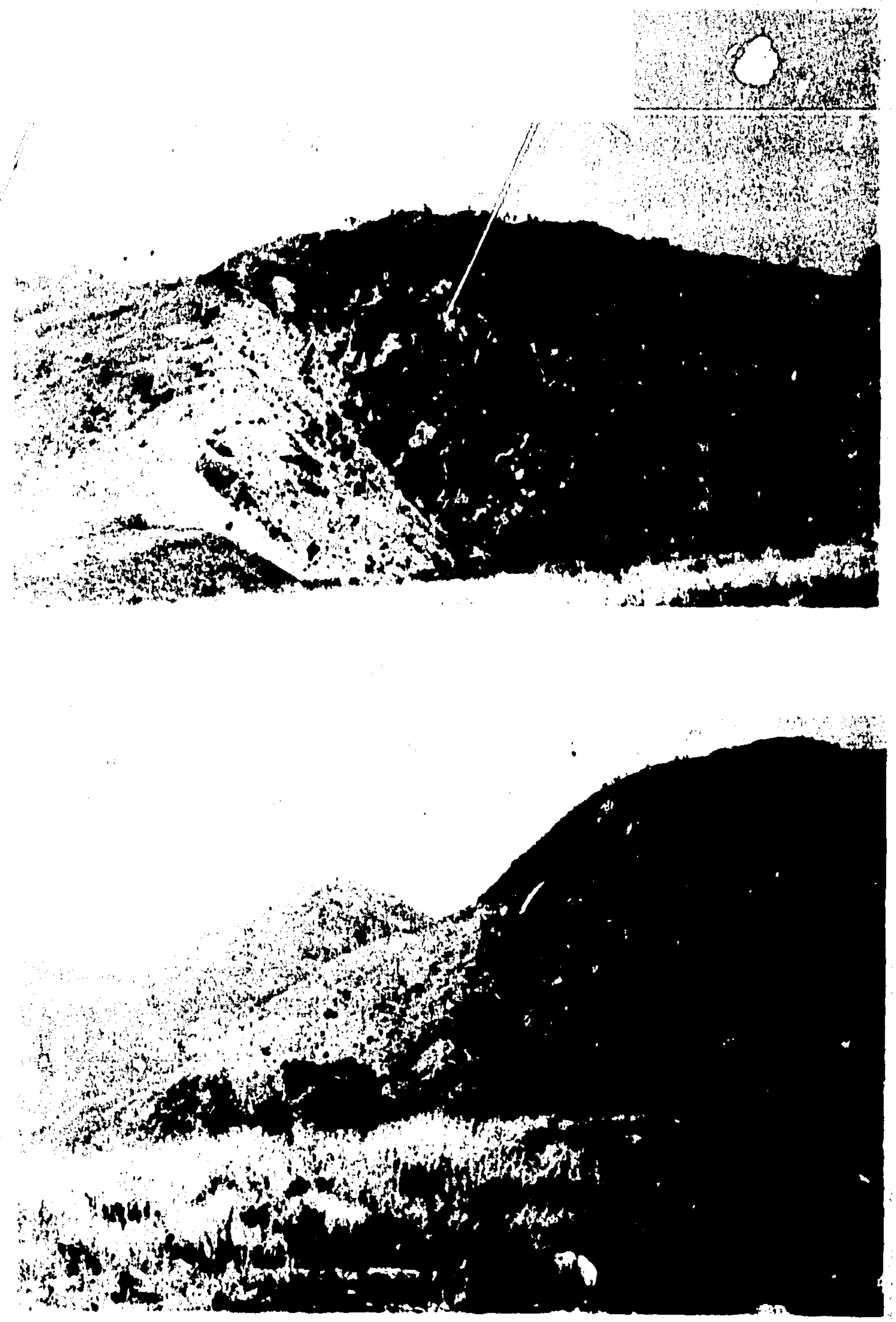


Figure 43. Deforestation, sheet one. The Chaine des Matheux, by the coast between Port-au-Prince and Saint-Marc. This area is said to have been heavily forested at one time.

Figure 44. Deforestation, sheet two. Cactus forest, with deep erosion, between Anse Rouge and Baie-de-Henne. Considerable amounts of dead wood can be seen lying on the ground, but no standing trees remain.

Figure 45. Deforestation, sheet three. Top: cactus forest between Anse Rouge and Baie-de-Henne, continued.
Bottom: entering area of extreme soil loss and erosion between Jean-Rabel and Port-de-Paix. Note the number of tree stumps.

sued, but that terracing and reforestation of the steepest slopes higher up the mountains was achieving some success, although it is certainly a long and arduous task. We saw some examples of terracing that had been done. Even if caterpillar tractors, front-loaders, etc. were available for this work it would seem to be difficult to use them effectively due to the steepness of the terrain and the numbers of large rocks.

G. CHARCOAL MAKING

Another peripheral interest was the process of making charcoal for cooking, since most charcoal used outside of Port-au-Prince is the type made in the field rather than "charbon moderne", or briquets made in special plants.

Figure 46 shows a bed of wood branches being prepared for charcoal making. Figure 47 shows an area nearby that had been used for charcoal making, presumably for a considerable period of time. Out of the field of view to the right is a large area of tree stumps, indicating the apparent source for this activity. In contrast to the surrounding area, where vegetation, grasses, etc. grew in some profusion, nothing at all was growing in the area that had been stripped of trees.

In these three figures, the vegetation is seen to be rather lush. The largest amount of charcoal-related activity that we saw was along the south and west coasts of the northwest peninsula - the towns of Anse Rouge, Baie-de-Henne, and especially Môle Saint-Nicholas, whence charcoal is shipped to Port-au-Prince in beamy gaff-rigged sailboats of perhaps ten meters length. In Môle Saint-Nicholas we saw small mountains of charcoal all through the town, other large stacks of bagged charcoal, ships being loaded, people carrying sacks of charcoal through the streets, charcoal being made throughout the surrounding hills, and tree branches, etc. being carried in from still farther away. Since there is very little vegetation left in this entire corner of the country, it is questionable how much longer this activity can continue, although we did see some areas where the cactus was being cut for charcoal.

H. MISCELLANY

Figure 49 shows a bridge construction project being carried out by a French company, but using mostly Haitian workmen. The modern construction methods form an interesting contrast with the very primitive appearance of much

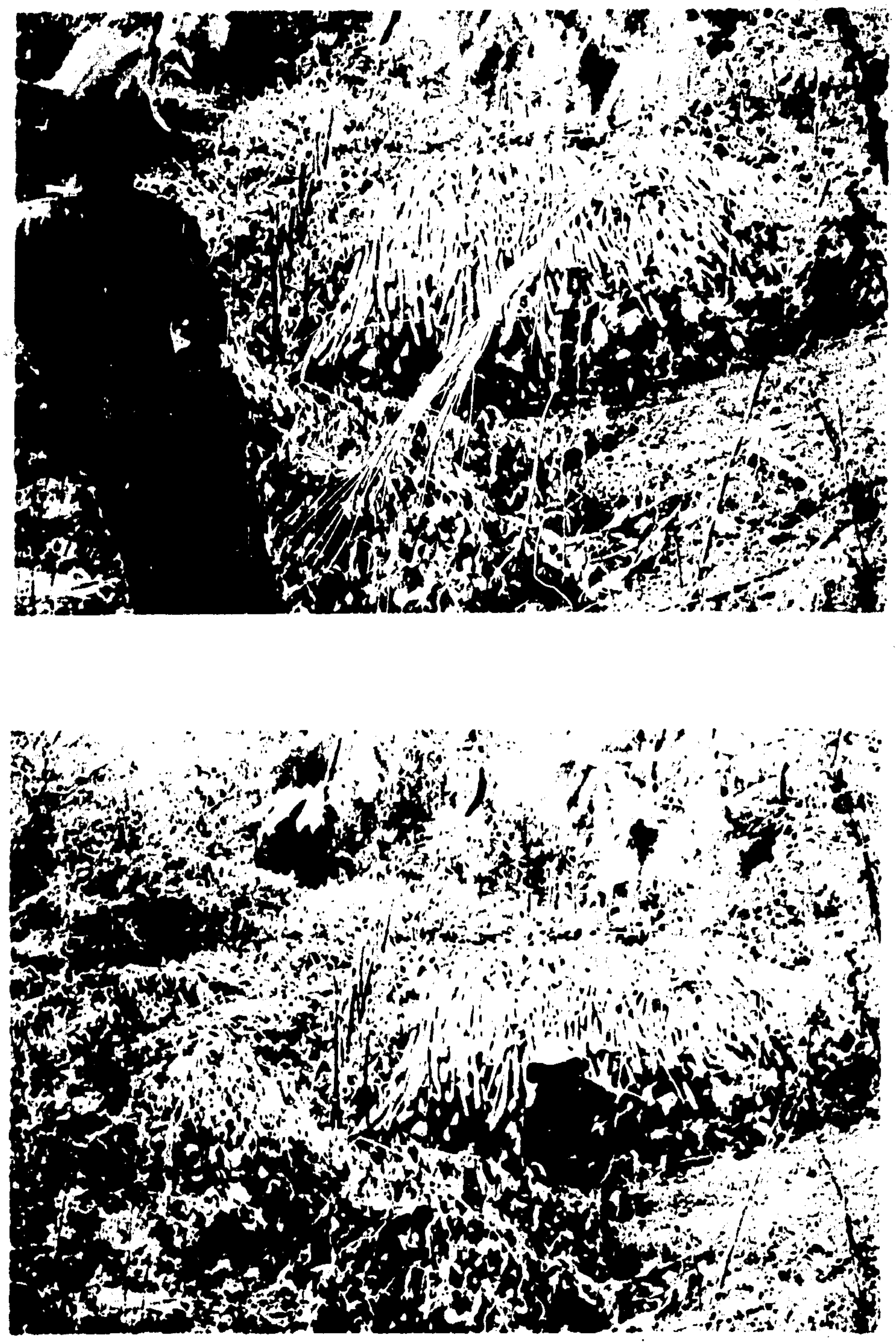


Figure 46. Charcoal making, sheet one: bed of tree branches being prepared prior to burning, near Petit-Goave.

Figure 47. Charcoal making, sheet two: the site of previous charcoal-making activities, near Petit-Goave.

Figure 48. Charcoal making, sheet three. Top: charcoal-making in the early morning, near Port-de-Paix.
Bottom: close-up of unburned wood on the periphery of the old charcoal-making site, near Petit-Goave.

Figure 49. Modern slip-form concrete construction: a bridge over the Riviere Artibonite, at Lafond.

of the surrounding towns and countryside, and serve as a reminder of the sort of thing that can be done in Haiti with a certain amount of outside help. We believe it is not too far-fetched to conclude that if a project of this magnitude can be carried out successfully in rural Haiti, then the widespread introduction of solar cookers is also feasible even if the cost per cooker is substantial compared to the average annual income of the users. The extent to which the cookers would actually be used, once distributed, depends on many factors, including the effectiveness of the cookers, their durability and ease of maintenance, the effectiveness of whatever training program is required to prepare a user to cook with them and perform any required daily cleaning and maintenance, and the establishment if possible of a long-term maintenance program using technicians traveling through the country to perform major repairs and advise users on proper methods of use and minor repair.

Our final stop before returning to Florida was the Citadel, near Cap-Haitien, and the top photo in Figure 50 shows the study team in the Citadel. The lower photo in Figure 50 is included simply because it shows a very typical rural scene (except for the U.S. Embassycarry-all) of a sort not depicted in earlier photos. Cooked food as well as fresh vegetables, chickens, etc. can be bought in the marketplace, the cooking being done on the spot.

The study team plus two guides, minus Dr. Blatt (holding camera), standing by Christophe's grave in the Citadel. Left to right: guides, Sharber, Yenamandra, Mongabure, Bowman, Von Lignau.

Figure 50. Cross-roads market-place between Leogane and Petit-Goave.

IV. SOLAR AND METEOROLOGICAL DATA ACQUISITION AND COMPUTATIONS

A. INTRODUCTION

One question of prime importance in determining the feasibility of using solar cookers in haiti is whether or not meteorological conditions allow sufficient solar radiation to reach ground level. Haiti's latitudes (18^{o} - 20^{o} N) and general weather patterns are particularly attractive. The temperature in the Port-au-Prince area is typically in the 80's with temperature change between summer and winter rarely exceeding 10^{o}. Rainfall is heaviest between April and June and between August and November but even during these months it occurs most frequently at dusk, and at night, and days tend to be clear and sunny (Area Handbook for Haiti, 1973). In some mountainous areas, the presence of clouds does exclude the continuous use of solar cookers, but for most of Southern Haiti, some of the Cul-de-Sac, and much of the Artibonite Plain increased solar evaporation produces an arid climate ideal for the application of solar cookers.

In making the meteorological accessment, we have obtained weather and solar records from Haiti and nearby stations. These records have been complimented by calculations of the hourly and daily solar irradiation and by computation of the monthly averaged atmospheric transmission factors. In the following sections we describe the data obtained and calculations made and present our conclusions. Appendix D contains descriptions and listings of the computer programs developed for the calculations and data analysis.

B. SOLAR AND METEOROLOGICAL DATA ACQUIRED

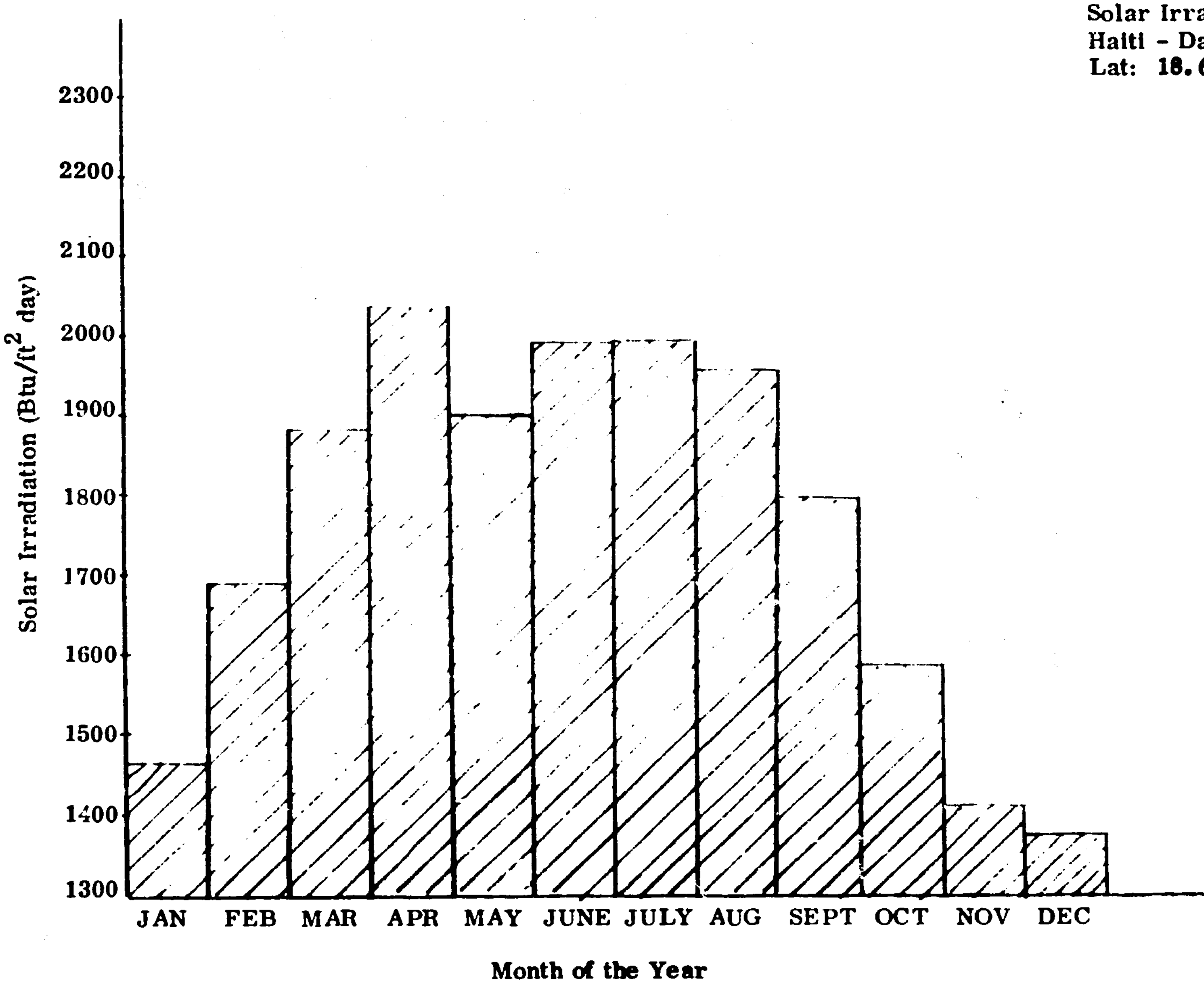
Solar Irradiation. Solar irradiation has been measured at Damien (lat: 18.6° N, long: 72.17° W), Haiti during the years 1963-1967. The available records, obtained with the assistance of the U.S.A.I.D. Mission, provide the day-long totals of radiation striking a horizontal surface at ground level for this period. Monthly averages of the daily values are shown in Figure 51. The depression in the graph during May results from the increased rainfall and cloudiness during this month. These values of solar irradiation, which represent the only long-term values we have been able to obtain for Haiti, have been used to determine an effective monthly atmospheric transmission factor given in Table 16 of the computations section. The method of calculation is presented in that section.

Additional data were obtained for San Juan (lat: 18.17° N, long: 66.04° W) and Swan Island (lat: 18.10°N, long: 56.02°W) from the report of the Wisconsin Group World Distribution of Solar Radiation (Löf et al., 1966). These are the nearest stations to Haiti reporting solar radiation measurements and quite by coincidence their latitudes are practically the same as for Damien. The observations, graphed for San Juan in Figure 52 and for Swan Island in Figure 53, are monthly averages of daily totals based on 3-6 years of data taken prior to 1965.

Cloud Cover. Because of the difficulty of obtaining hourly weather records for Haiti which included cloud cover data, we looked at available records accumulated at Guantanamo Naval Base (lat: 19.9° N, long: 75.14° W) in southeast Cuba. Ten years of hourly meteorological records were obtained from the National Climatic Center, Asheville, North Carolina. The hourly cloud data was displayed in the format shown in Figure 54 which shows the

Figure 51.

Solar Irradiation - Monthly Averages
Haiti - Damien (1963-67)
Lat: 18.6 ^{o}N, Long: 72.10^{o}W



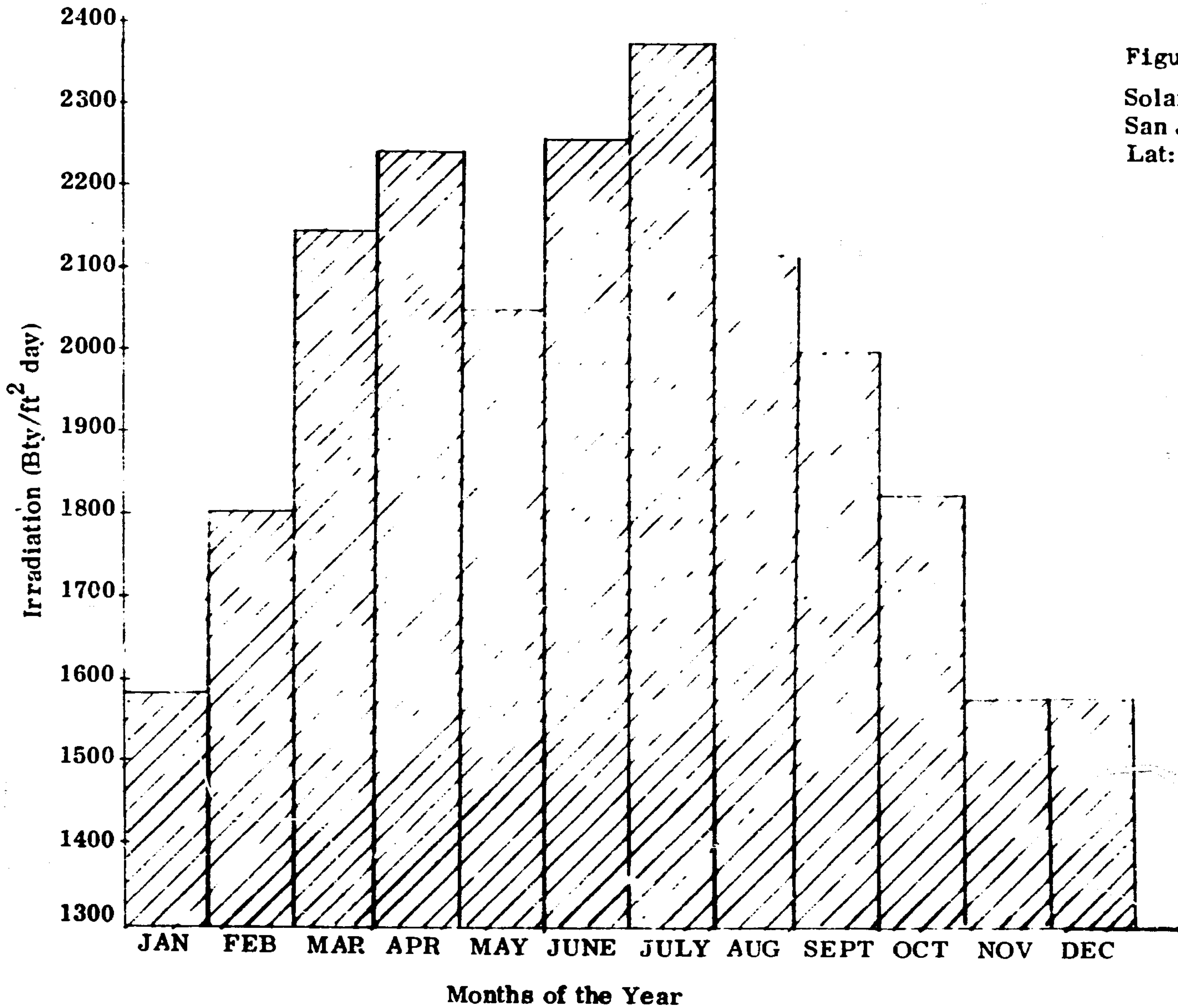


Figure 52.

Solar Irradiation - Monthly Averages
San Juan, Puerto Rico
Lat: 18.17°N, Long: 66.04°W

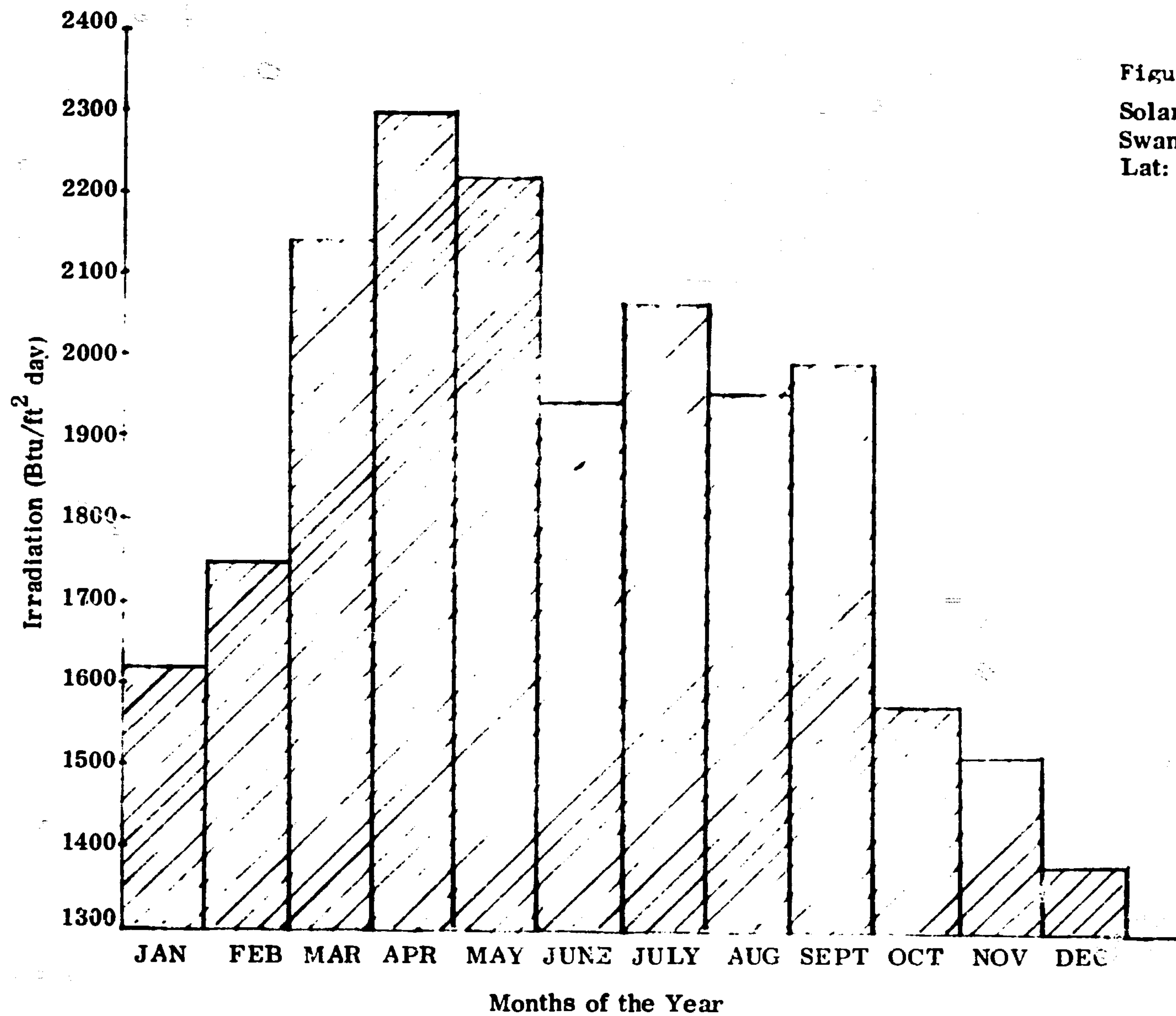
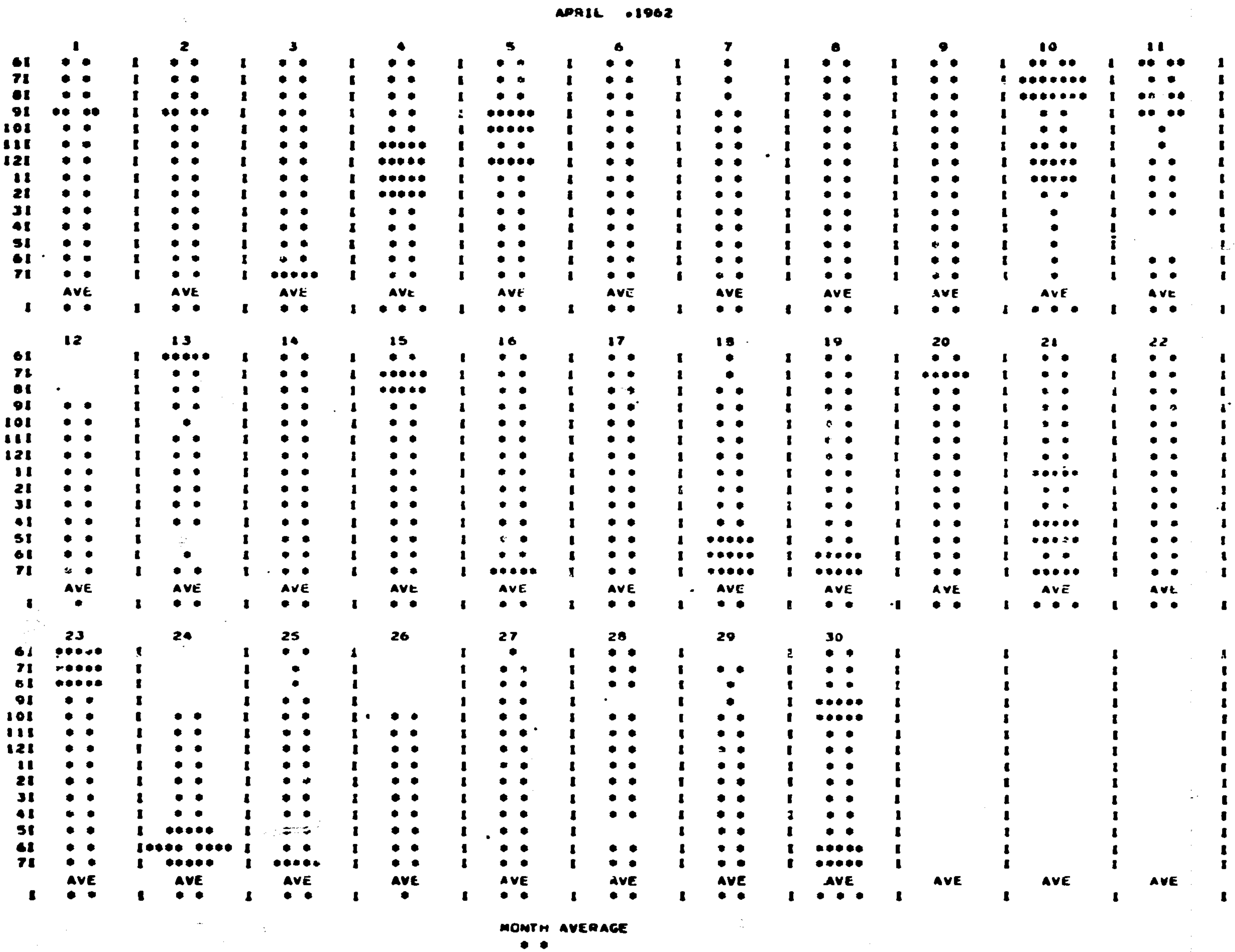


Figure 53.
Solar Irradiation - Monthly Averages
Swan Island
Lat: 18.10°N, Long: 56.02°W

Figure 54. Cloud Cover Over Guantanamo Naval Base (Lat: 19.9° N; long: 75.14°)



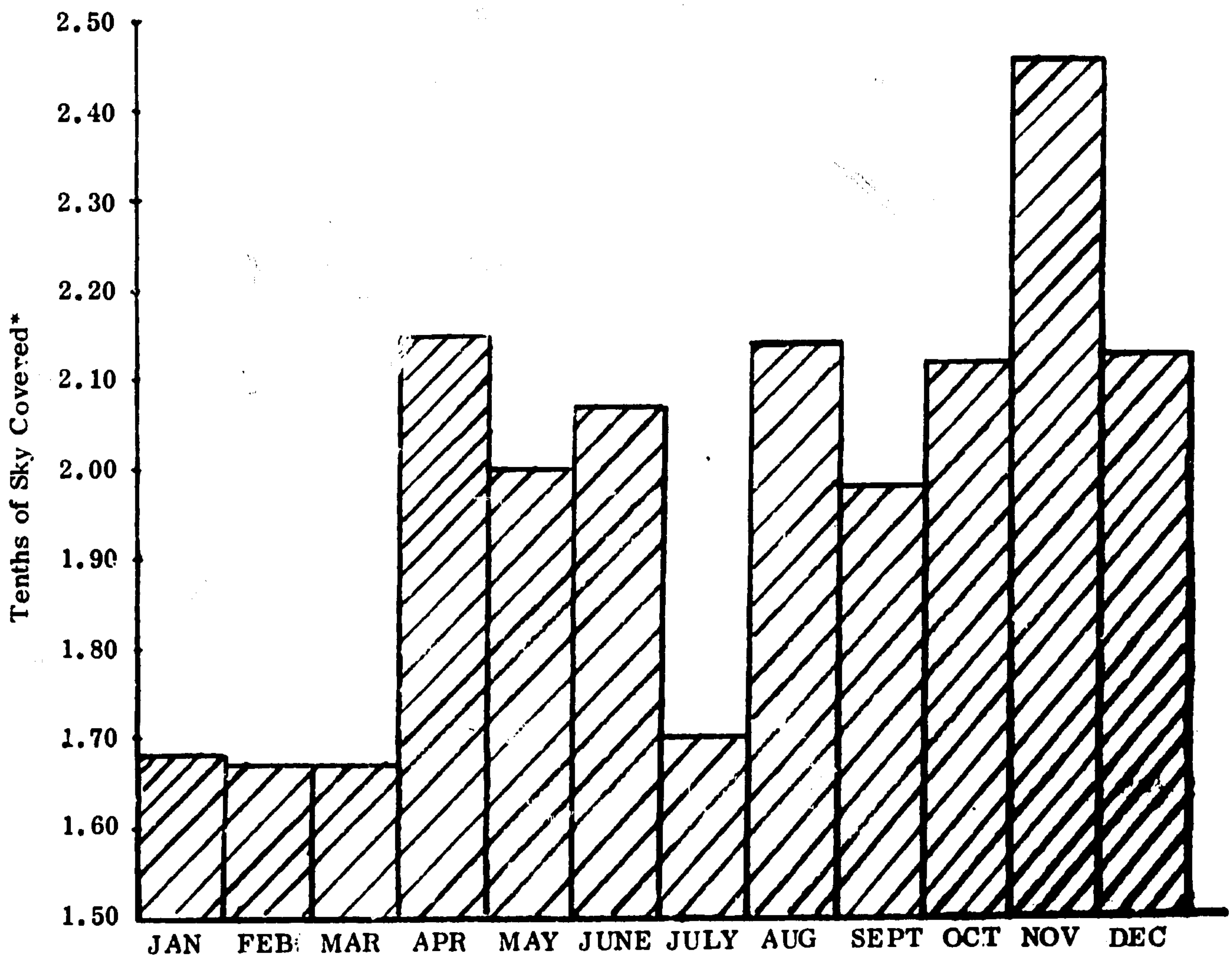
data for April, 1962. Cloud cover (or sky cover) is recorded as integers from 0 (clear sky) to 10 (fully overcast) where it is understood that the integer represents the number of tenths of the total sky covered by clouds. In the display format, the number of tenths recorded for a given hour is represented by the same number of asterisks. The numerals across the page represent days of the month, while those along the left column represent local time hours of the day. The format provides an easy method of spotting conditions which might adversely affect a solar cooking effort (for example, heavy cloudiness at a certain time every day.) However, no serious condition has yet been detected and in fact the cloudiness is quite tenuous year round as shown by the graph of Figure 55 which plots the monthly averages of cloud cover for 1962. We note that the monthly averaged cloudiness never exceeds 3 tenths.

Rainfall. We have obtained a map of the distribution of the average annual rainfall over Haiti as well as some yearly totals for Grand Riviere du Nord, Cap Haitien, San Louis du Nord, Port de Paix, Quanaminth, and Gonaives. The rainfall map also shows the monthly distributions of rainfall for all the reporting stations. The rainfall amounts can be taken as only a crude estimate of day conditions since, as we have already mentioned, rainfall often occurs at night in Haiti. However, rainfall is generally less in the northwest and in the southern region with the exception of the tip of the southern peninsula. Also rainfall rates increase toward the border between Haiti and the Dominican Republic, a result of the increasing elevation.

C. COMPUTATIONS

Optimum Collector Tilt Angle. Our first objective was to compute the optimum angle at which any solar collector must be tilted in order to collect the

Figure 55.
Monthly Averaged Cloud Cover
Guantanamo Naval Base, Cuba
Year: 1962.



* 10: Fully Overcast
0: Clear Sky

maximum radiation striking Haiti and Melbourne, Florida (for the purpose of testing) at any time of the year. To accomplish this a computer program was developed which computed the direct solar irradiation (Btu/ft^2 h) for any latitude at any time of day or year striking a collector tilted at any specified tilt angle. The day-long totals of solar energy collected at various tilt angles were used to select the optimum tilt angle for that day recorded. The computation was made for the 21st day of each month; the results are presented in Figures 56 and 57 for Haiti and Melbourne, respectively. The computational method is that outlined in Chapter 59 of the ASHRAE Applications Handbook, 1974; details of the computer program are provided in Appendix D. The first program was written for programming on the HP-25 hand calculator. Parameters used in the program are given in Table 15. The parameter A is the adjusted solar intensity at the top of the atmosphere, an average value for the U. S. for each month. It and the atmospheric extinction coefficient B were determined by Threlkeld and Jordan (1958) so that the direct solar radiation incident on a horizontal surface can be written in the form

$$I_{DN} = A\, e^{-B/\sin\varepsilon}$$

where ε is the solar elevation angle.

Atmospheric Transmission Factor. The day-long solar irradiation data taken by the National Meteorological Service of Haiti (Figure 51) provide us with a means of determining an average atmospheric transmission factor - one which takes into account all parameters which affect transmission through the atmosphere, i.e., water content, dust particle content, and the amount of overhead air mass which varies depending on the station and with the season. In determining this transmission factor, we have used an existing

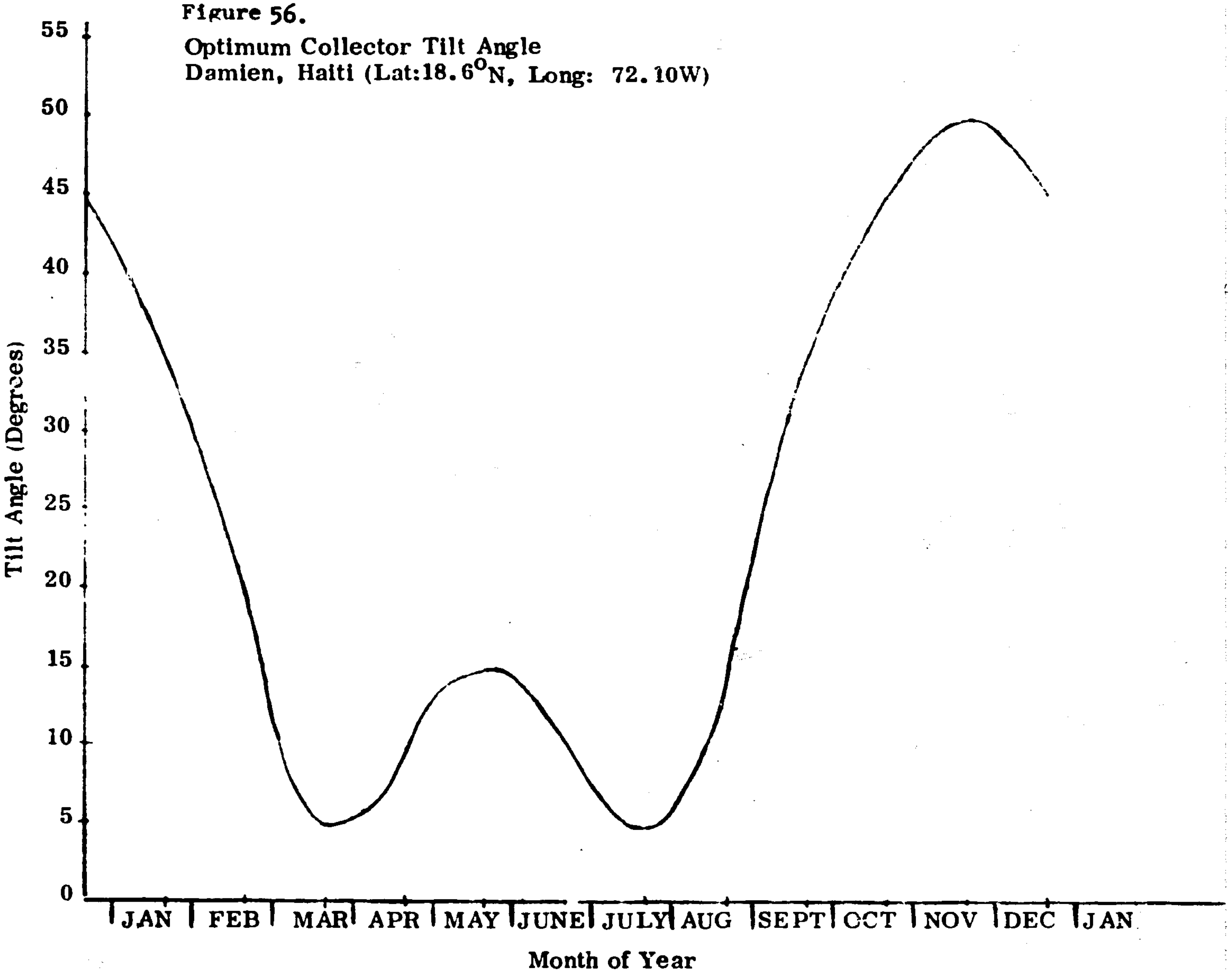


Figure 56.
Optimum Collector Tilt Angle
Damien, Haiti (Lat:18.6°N, Long: 72.10W)

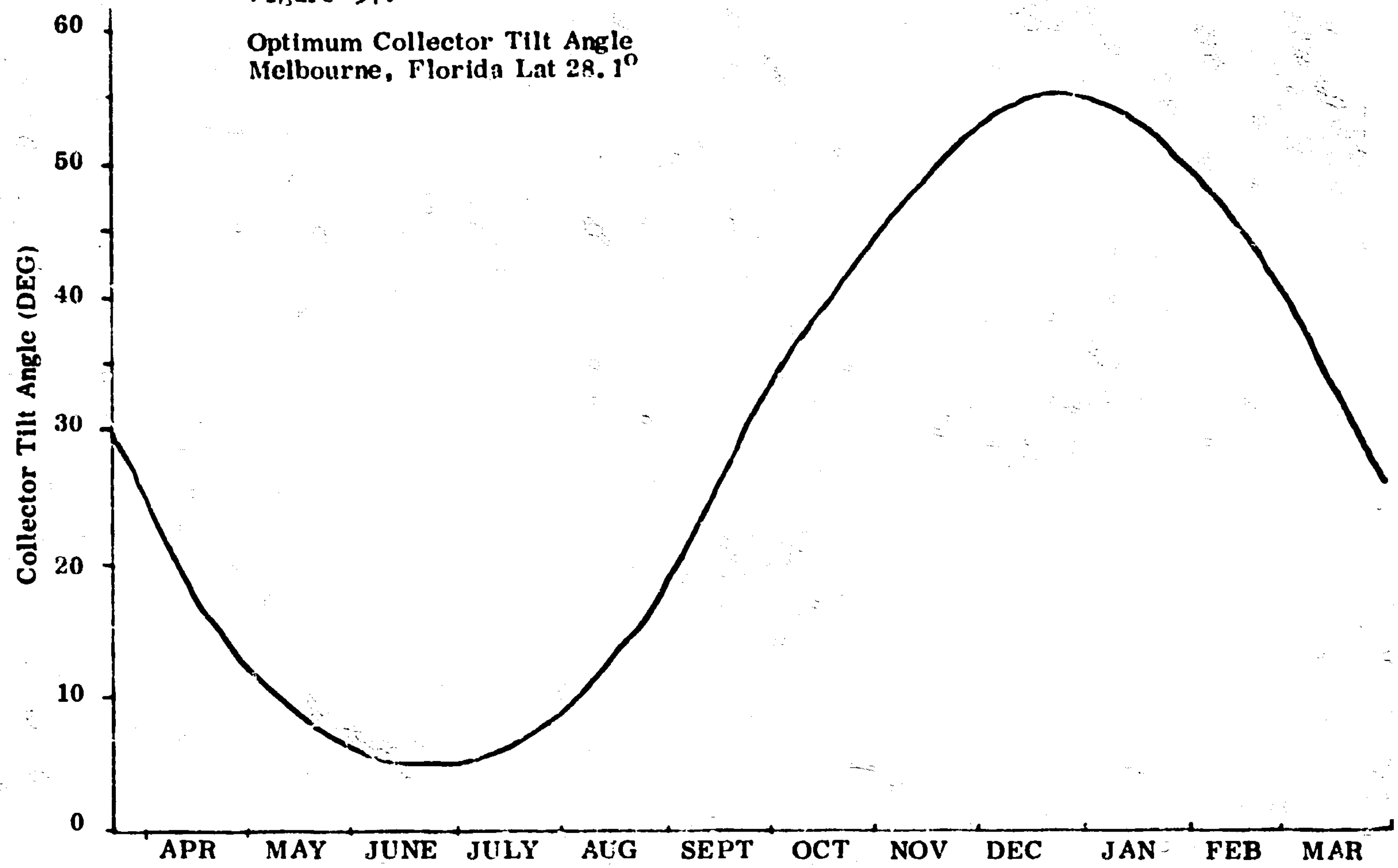


Figure 57.

Optimum Collector Tilt Angle
Melbourne, Florida Lat 28.1°

Table 15. **Parameters Used in the Computation of Monthly Solar Irradiation***

Month	Day of Year	Declination (Deg)	A (Btu/ft^2h)	B (1/m)
Jan**	21	-19.9	390	0.142
Feb	52	-10.6	385	0.144
Mar	80	0.0	376	0.156
Apr	111	+11.9	360	0.180
May	141	+20.3	350	0.196
Jun	173	+23.45	345	0.205
Jul	202	+20.5	344	0.207
Aug	233	+12.1	351	0.201
Sept	265	0.0	365	0.177
Oct	294	-10.7	378	0.160
Nov	325	-19.9	387	0.149
Dec	355	-23.45	391	0.142

*1974, ASHRAE Applications Handbook, Ch 59

**All values shown in the table apply to the 21st day of the month.

computer program which calculates the day-long solar irradiation incident on a horizontal surface at any specified location. The varying earth-sun distance is taken into account, but no atmospheric parameters are introduced. The result is the day-long total of solar radiation incident on the top of the atmosphere. This value can be compared with the amount actually measured at ground level to obtain the transmission factor. The average monthly transmission factors shown under Column T of Table 16 are defined by the following equation

$$H_A = T H_O$$

where H_O is the monthly average of the day-long irradiation, H_A is the monthly average of the measured (actual) value of solar irradiation and T is the transmission factor. The other columns of Table 16 are the noon hour value of solar radiation incident on the top of the atmosphere and the ratio of this quantity to the day-long value. This provides straightforward comparison between noon hour and day-long radiation values.

D. CONCLUSIONS AS OF JANUARY, 1977

Generally speaking the climate of Haiti is suitable for using solar cookers. We do note that Figure 51 shows relatively low values for solar irradiation in the months of November and December. Therefore on some days during these months the time available for use will be reduced. For example, in computing the average noon hour irradiation for December (with the aid of Table 16) we obtain a value of 182 Btu/ft^2 h striking a horizontal surface. If the cooker collector is placed at a tilt angle of 50°, the collected solar radiation becomes 182 / cos 50° or 283 Btu/ft^2 h. The cookers under consideration in this study require approximately 200 Btu/ft^2 h incident radiation for effective operation. The shape of the daily irra-

TABLE 16. MONTHLY AVERAGES OF DAY-LONG SOLAR QUANTITIES* FOR DAMIEN, HAITI

(Lat: 18.21° N; Long: 72.10° W)

Month	H_0	H_A	H_N	T	R
January	2503.0	1482.1	353.6	0.597	.141
February	2827.7	1618.4	386.9	0.574	.137
March	3177.7	1875.1	418.1	0.594	.132
April	3420.7	1948.2	433.2	0.571	.127
May	3515.4	1902.4	432.0	0.542	.123
June	3525.6	2038.8	427.1	0.578	.121
July	3504.2	2008.1	427.5	0.573	.122
August	3427.8	1971.1	429.1	0.573	.125
September	3241.6	1786.8	420.3	0.550	.130
October	2918.4	1585.0	393.9	0.538	.135
November	2572.5	1463.9	360.2	0.564	.140
December	2388.4	1321.0	341.0	0.553	.143

* H_0 Calculated irradiation (Btu/ft² day)
H_A Measured irradiation (Btu/ft² day)
H_N Noon value of irradiation (Btu/ft² h)
} Horizontal Surface

T Transmission Factor H_A/H_0

R Noon/day ratio H_N/H_0

diation curve indicates that even on this "average" December day, the cooker can be used 2-3 hours either side of noon.

Direct measurements made on the field trip to Haiti on a clear day in December show that by about 8:20 am the direct radiation normal to the sun-earth direction was about 250 Btu/ft^2 h. A maximum value of about 310 Btu/ft^2 h was recorded at noon. Therefore on clear days cooking can be done from about 7:00 am to 5:00 pm.

One additional consideration is that of climatic region. Obviously in the mountainous areas where frequent rainfall and cloudiness are present solar cookers could only be used intermittantly. However, Northwest Haiti and much of the southern peninsula can definitely be regarded as favorable regions for employing solar cooking devices.

E. REFERENCES

1. Area Handbook for Haiti; U. S. Government Printing Office, Washington, D.C., 1973.

2. Löf, G. O., J. A. Duffey, and C. O. Smith; World Distribution of Solar Radiation, Engineering Experiment Station Report No. 21; July, 1966.

3. "Solar Energy Utilization for Heating and Cooling", Chapter 59, ASHRAE Applications Handbook, 1974.

V. DESCRIPTION OF THE INITIAL EVALUATION PROCESS

A. INTRODUCTION

At approximately the halfway point in our one-year study, we attempted to quantitatively evaluate the cookers we had seen up to that time, for the purpose of selecting the best concepts for continued and more exhaustive testing, eliminating from further consideration those concepts least likely to be suitable for Haitian application, and identifying areas where rather obvious improvements seemed to be indicated. In this chapter and the one following we present the methods and results of that evaluation, based partly on our own tests but also, where possible, on previously published test results.

B. BASIS FOR EVALUATION

For the sake of making comparative evaluations between cookers, a total of fifteen characteristics or evaluation points were listed, and assigned weighting factors, as detailed below. The weighting factors are somewhat arbitrary, but were chosen on the basis of what we know of Haitian conditions. The advantages of this sort of quantitative comparison include the fact that the final matrix is visually a good way of presenting a number of different comparisons on a single chart, and the numerical totals of all the weighted ratings provide a convenient means of separating the best from the worst of the systems being compared, although fine differences in total points are not too significant and should not be relied on to any great extent. In the case of the solar cookers being compared, it may well be that two cookers scoring within fifty points of each other are both practical and competent systems, with different virtues that would indicate one cooker for certain local conditions within Haiti, and the other for other local conditions.

1. Time to Boil Measured Amounts of Water (Weight: 10)

This test has been the most commonly used one in the past, as in the cases of the UN/FAO tests and the VITA project. The results indicate the heating power (watts) of the cooker, its efficiency, and its effectiveness in bringing a quantity of food up to cooking temperature - the important variable in the cooking time required for any dish that is cooked by boiling. Since boiling is the primary mode of cooking in Haiti, we gave maximum weight to this characteristic.

2. Maximum Temperature of Measured Amounts of Oil (Weight: 4)

If oil rather than water is in the cooking pot, the highest temperature re- reached might be considerably higher than the boiling point of water. If so, the cooker can be used for deep frying in addition to boiling. Although we determined (see Section III) that it is not vital that a solar cooker perform this function for successful use in Haiti, it would be a valuable asset. The weighting assigned above reflects our assessment of the relative importance of this feature for Haitian conditions.

3. Energy Storage (Weight: 7)

A cooker that stores some energy will give better performance on days when scattered clouds periodically block the sun, and if the storage is sufficient cooking can be extended into the late afternoon or even into the evening. With less storage, the cooker might at least be capable of keeping food warm into the evening.

Earlier work in this field (Section II above) has shown that, at least for those cookers made in any quantity to date, those that are best in terms of characteristics 1 and 2 above have no energy storage as part of the cooker (the pot itself will store a small amount of energy, and of course the contents store thermal energy), while cookers with energy storage aren't as high performers in terms of speed and power. A possible exception is Prata's cylindro-parabolic cooker, which may have both speed and storage. Energy storage will result in longer times to bring the cooker up to temperature from the cold (early morning) condition unless energy storage is accomplished primarily by a change of phase at a fairly high temperature, or by means of removable storage material that can be placed in the already-heated oven at a time when cooking activity is low. A cooker with good energy storage and an effective means of delivering the stored energy to the food could achieve very fast cooking times (time to heat water to boiling) in cases where the food is introduced into a pre-heated oven.

4. Capacity (Weight: 6)

By capacity we mean the amount of food that can be accepted by the cooker. Since Haitian cooking takes place almost entirely in pots, capacity was determined on the basis of the size and/or number of cooking pots that a given cooker can accept.

5. Versatility (Weight: 4)

By versatility we mean the ability to perform various types of cooking, such as frying eggs, baking bread, etc. The weight factor for this item is rather low since most of the potential first users of solar cookers in Haiti - the people who are most in need of relief from dependence on wood for cooking - do almost all of their cooking in a boiling mode.

6. Other Measures of Cooking Effectiveness (Weight: 5)

This category was reserved for any factors associated with performance of the cooker that were not specifically covered by the preceding categories.

7. Ease of Use (Weight: 10)

One of the most important factors for the success of a solar cooker is the matter of how easy it is to use. How often does it have to be realigned (to follow the sun) to keep cooking, how difficult is it to realign, does the food have to be removed and then replaced, etc.? Does food spillage affect the performance of the cooker, and how difficult is it to clean? Can it be used by a person in a normal standing or sitting position, or is a gymnast required? How much training is required to use it properly?

8. Ease of Maintenance (Weight: 5)

All cookers require periodic maintenance of some sort, which might include painting, lubricating, adjusting, tightening, polishing, replacing parts, etc. The score in this category reflects both the predicted frequency and magnitude of these activities.

9. Durability (Weight: 8)

We have tested one commercial cooker that didn't even survive its first use, and another that sat outdoors for a year without major deterioration, but that needed replacement of a fragile glass cover that was broken repeatedly in spite of great care in handling. We have not seen a commercial cooker that is more than mediocre in the crucial area of durability, which we regard as extremely important for any item designed for regular, daily use. As a minimum, we believe a solar cooker should be expected to hold up for five years of continuous use without major breakage or deterioration, given a moderate amount of routine maintenance.

10. Wind Stability (Weight: 8)

Another shortcoming, to a greater or lesser extent, of almost all the cookers in the first series of tests is the matter of wind stability. To be useful, a cooker should "stay put" in a strong breeze. Cookers that blow away, spill food, or lose their optical integrity when subjected to winds of 10-20 miles per hour may be useful for backpackers, but they are not likely to be regarded as useful by a housewife, in Haiti or anywhere else, who needs a dependable means of cooking for her family. Wind stability is of course a problem because of the fairly large solar collector required, which tends to act as a sail. We believe a solar cooker should be stable in a 15 mile per hour wind without securing it so rigidly that it cannot be moved to follow the sun.

11. Portability (Weight: 5)

In some Haitian applications, as pointed out in a preceding section, a solar cooker would have to be moved during the day by distances of about 2 to 5 meters to avoid shadows; portability in this context refers to this scale of movement only, since the Haitians are not nomadic. In some cases, requirements for portability and wind stability might be at cross-purposes. However, portability for short distances does not necessarily require light weight, depending on the nature of the cooker.

12. Materials Cost (Weight: 8)

13. Cost of Imported Manufactured Items (Weight: 8)

The major part of the economic evaluation of the cooker is included in these two factors. Labor costs are relatively low in Haiti, and besides, jobs created in connection with building solar cookers would also be helpful for the country, especially if overseas markets for the cookers (such as the U.S.) could be developed. For the country as a whole, especially in view of the high level of unemployment, the real cost of the cookers might be just the total of the materials required and items such as glass mirrors, bolts and nuts, piano hinges, etc., that would have to be imported.

For each of these items, we based the score on a formula of 10 minus one point per $5 of cost, based on a rough estimate in terms of 1977 dollars, with no score below zero. However, if a cooker used $80 worth of material and no imported manufactured items, for example, we would regard $30 worth of the material as "imported" and score the cooker zero and four in these two categories rather than zero and ten, and similarly for a cooker that used more than $50 worth of imported manufactured items (the entire cooker, for example) and little or no locally purchased materials.

14. Ease of Manufacture/Labor Cost (Weight: 6)

In spite of the foregoing considerations, the labor cost does have to be considered, although with a lower weight factor in this case. Also included in this category are factors such as any special equipment needed to manufacture the cookers, and the skill level required of the workers. Of interest in this category is the question of how much of the fabrication can be done at the site and how much, if any, must be done in one or more special shops that could be established in Haiti. In our deliberations to date, however, we have not been able to establish a strong preference for one mode of construction or the other as a general principal. Each has its advantages and disadvantages (see Appendix E). The design of a cooker is very much affected by decisions on how and where it is to be built.

15. Transportability within Haiti (Weight: 6)

This category applies to whatever materials, manufactured items, etc. must be carried to the site where a cooker is to be used. Weight, bulkiness, fragility, and need for careful packing are all important. Although Haiti is geographically very small, many areas are only reached after many hours of driving at very low speeds along bumpy, winding jeep trails, and fording streams and rivers.

C. MEANS OF EVALUATION

The testing that was done in the first part of the program was qualitative in nature. Figures 58 and 59 show the solar cooker test area on the roof of the Crawford Science Building at Florida Institute of Technology. The building is located in Melbourne, Florida, at latitude 28°04'. Tests were performed using inexpensive aluminum cookware purchased in the U.S., as shown in figure 60. All surfaces were black anodized by a local firm, at a cost (in quantity) of two dollars per square foot of surface. A cast aluminum Haitian cooking pot was also used for testing, but was kept in an as-purchased condition.

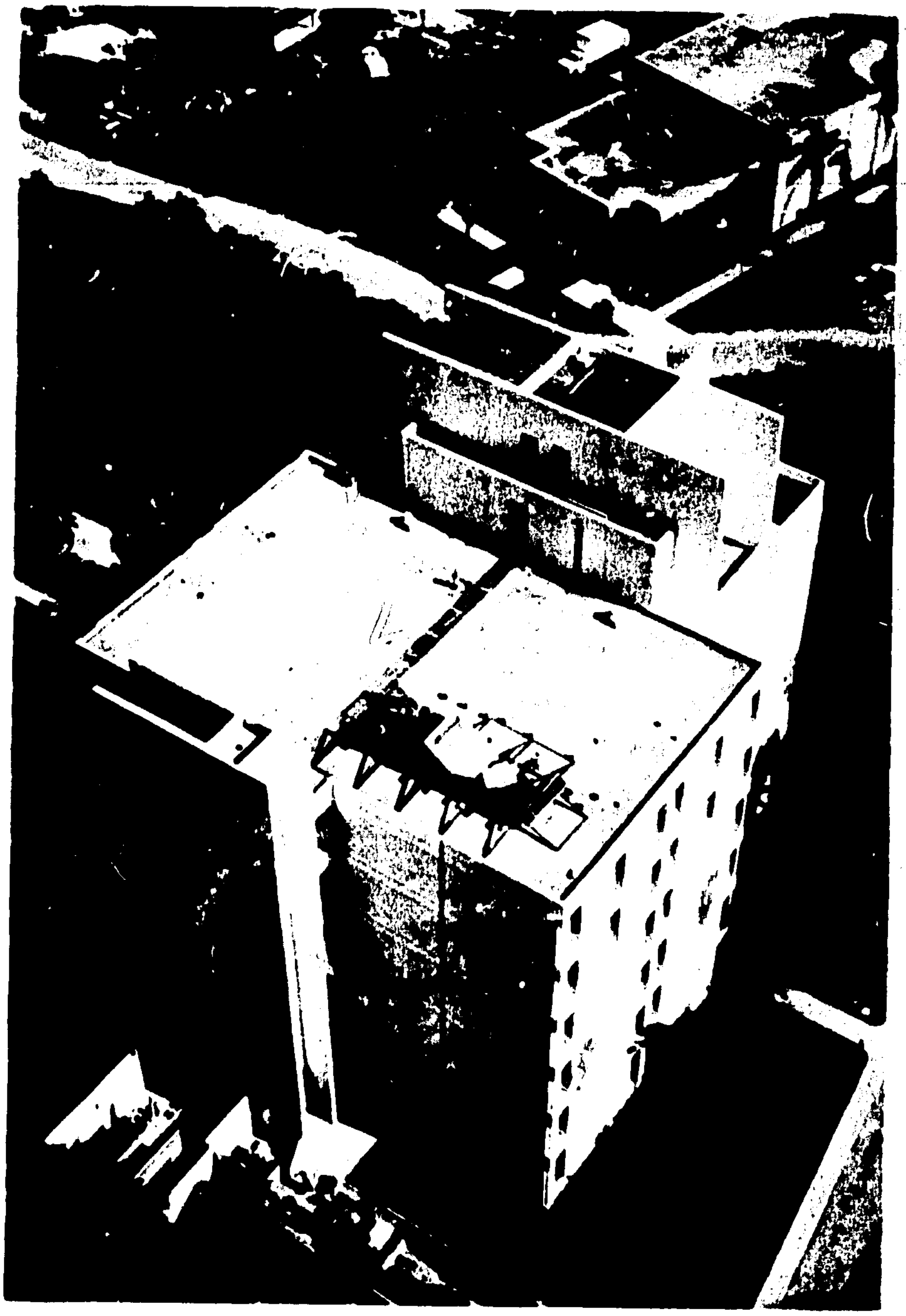


Figure 58. Solar cooker test area on the roof of the Crawford Science Building at FIT, November 1976.

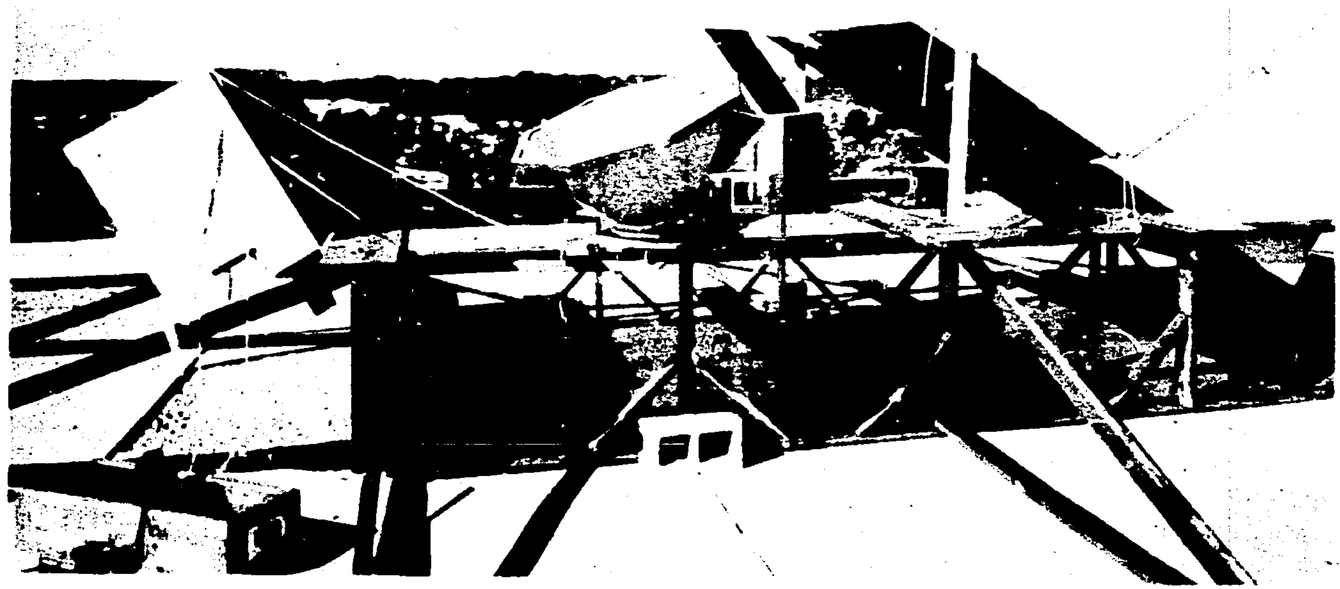


Figure 59. The solar cooker test area at FIT - November 1976.

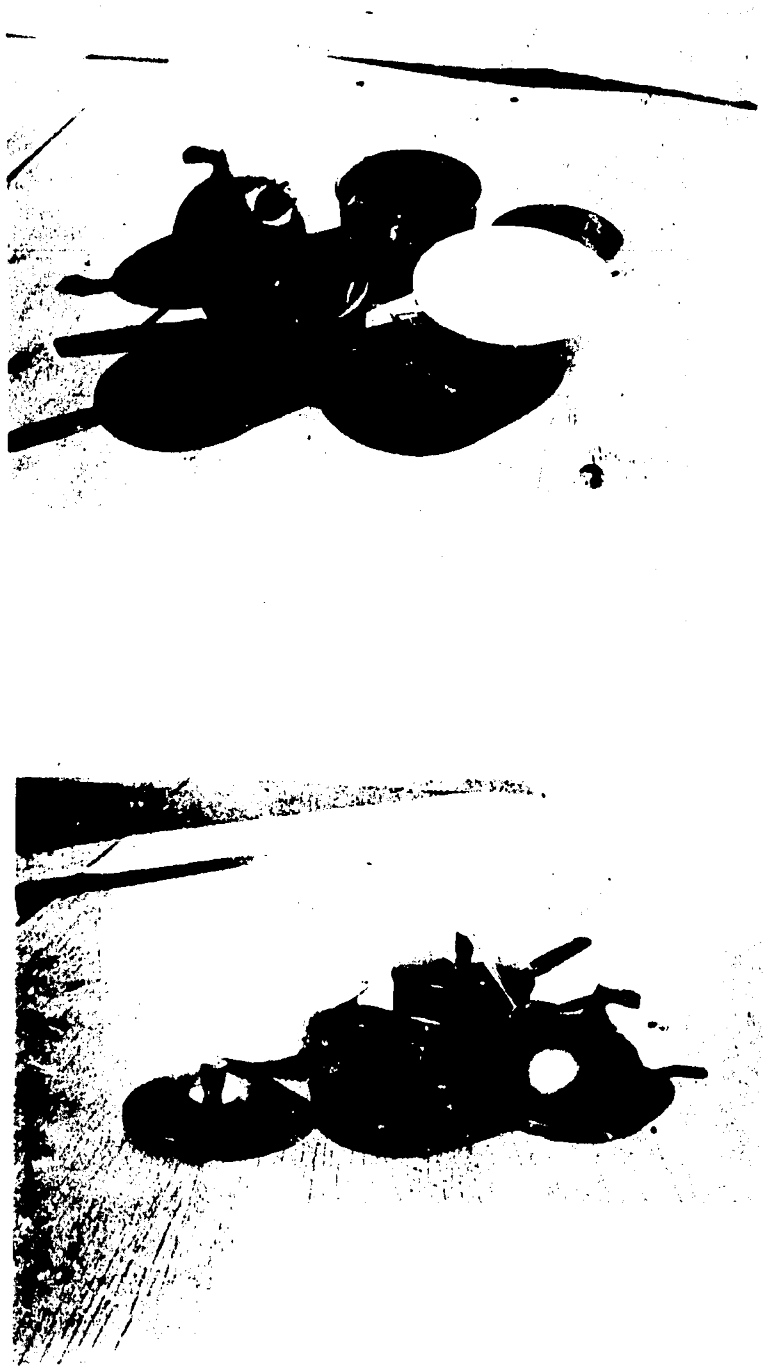


Figure 60. Black anodized cooking pans and cast aluminum Haitian cooking pot used in the solar cooker test program.

D. SUMMARY

The evaluation characteristics listed above can be categorized as follows:
Cooking performance - items 1 through 6 - total weight = 36
Use factors - items 7 through 11 - total weight = 36
Economic factors - items 12 through 15 - total weight = 28
The total of all the weight factors is 100, so that if each item is evaluated on a scale of 1 through 10, the total possible (a "perfect" score) would be 1000. An example of how the matrix works is given in the next section.

It will be noted that economic factors were given a relatively small portion of the total 1000 possible points. We don't mean to downgrade economic factors, but do feel that the proper approach is to first design a cooker that will be optimum with regard to cooking performance and use factors, and then find a way to manufacture it cheaply, rather than first designing a cheap cooker and then trying to find a way to make it work well. A cooker that doesn't perform well will never be used regardless of cost. On the other hand, decisions regarding maximum permissible cost of a cooker that does perform well and is easy to use and durable are really somewhat beyond the scope of this study, as they depend on who would pay for the cookers, how they might be incorporated into other help programs, how much the cost (in time or money) of wood or charcoal increases, how much the cost of alternate fuels - primarily kerosene - increases, and various other changes in local and world economic conditions. At any rate, it seems clear that any cooker whose projected cost is truly exorbitant would probably not be recommended regardless of how high it scored on our rating system.

Similarly, we have tended to avoid much of the terminology commonly used in the field of appropriate technology, although appropriate technology considerations are implicit in items 14 and 15. We believe over-emphasis on materials that are already locally available, and fabrication methods that are overly simple and require no special tools, is likely to result in a cooker that does not perform well and cannot be made to perform well. To have a major impact on Haiti, solar cookers will have to be produced in quantities of thousands or tens of thousands. If an aluminum extrusion of a certain shape is needed, for example, the proper question is not how readily available such an extrusion currently is in Haiti, if indeed it currently exists in Haiti, but rather how cheaply it could be delivered to Haiti in the desired quantities. The ultimate cost per cooker might well be so low that it would be foolish to compromise the design of the cooker just to avoid the use of the extrusion. Similarly, we need to ask what Haitian workmen can be trained to do rather than just what they can do with existing skills. If centralized production is anticipated, very extensive training of a small number of talented workers might be justified. Anyone who has driven a car in Port-au-Prince will be aware that large numbers of Haitians have learned to operate these machines with a precision and gusto that are rare in the U.S.

It has often been pointed out that new types of equipment, such as solar cookers, are more readily accepted by a native populace if they make use of familiar materials such as stone, clay, basketry, etc. We pursued this question rather extensively while we were in Haiti, and concluded that the use of familiar materials is not an important factor in that country. In fact, the Haitians are said to be more willing to accept something that is strange and foreign than a similar object, adapted to better suit their traditions, if they sense that the latter object is somehow "second-rate" compared to what they could get if they lived in a country with a more advanced economy. Numerous foreign construction projects are currently underway in haiti, as well as social projects by various international charitable organizations; there seems to be very little resistance to foreign ways and ideas compared to some newly emerging nations

On this same general subject, we would like to quote a statement made by George Löf in 1961, which we wholeheartedly endorse:

"From the sociological standpoint, the cooker must fit the cooking techniques and schedules of the people using it. This point has been heavily stressed by several speakers (at the UN Conference). It is possible that it has been overstressed, because there is a danger that technical inadequacy in a particular cooker may be blamed on some social factor or other. It is my contention that a cooker of eminently sound design and modest cost will succeed in many areas of the world, where customs do not have to be extensively modified. Notice the immediate acceptance of electricity in developing areas - and the substitution of tractors and diesel pumps for horses and human power. These are probably even greater social revolutions than solar cooking will be. I do not mean that the social factor is not important in solar cooking development, but I caution against mistaking a technical failure for a social rejection."[1]

1. Löf, G.O.G: "Rapporteur's Summation" (Solar Cooking Session), Proceedings of the United Nations Conference on New Sources of Energy (Rome, 21-31 August 1961), Volume 5, Solar Energy: II. United Nations Publication No 63.I.39, page 331.

VI. RESULTS OF INITIAL EVALUATION

A. EVALUATION MATRIX

Initial evaluations were made on the "Solar Chef" brand cooker and the two small cookers marketed by Edmund Scientific, and on the Telkes oven with movable reflectors and Brace Research Institute solar steam cooker that were built from plans. Evaluations began in August 1976 for the purchased units, and in November for those we made. Only limited cooking tests were possible due to the uncommonly cold, rainy, and cloudy Winter that Florida experienced from November 1976 through February 1977.

A preliminary evaluation matrix is shown in Table 17. Also included in this matrix are the Wisconsin focusing cooker and Telkes oven with fixed reflectors, because of the extensive tests and other user results that have been published for these two solar cookers, including the comparative tests performed by the FAO.

A point-by-point discussion of the matrix follows. The matrix is presented primarily as an example of the nature of the evaluation process, and as a means of eliminating the least suitable cookers from further consideration and presenting the reasons for this decision.

1. Time to Boil Measured Amounts of Water

In this category, the Wisconsin cooker is the standard against which all others must be compared. The FAO tests showed that under the test conditions (warm and hazy to partly cloudy) approximately 40 minutes was required to heat two liters of water to boiling (average of 39 tests), while nearly two hours was required for the Telkes oven under similar conditions. On this basis we gave the Wisconsin cooker a score of ten and the two Telkes ovens scores of 4. Under more clear sky conditions, the Wisconsin cooker time would improve considerably - 15 minutes for one liter of water has been reported - and it is doubtful that the Telkes oven, which makes better use of indirect radiation under conditions such as those of the FAO tests, would show comparable improvement. On the other hand, we are not certain that the FAO tests made optimal use of the energy storage capability of the Telkes oven to obtain rapid heating of water.

In our preliminary tests, it appears that the Solar Chef will heat water somewhat faster than the Halacy version of the Telkes oven, and hence it has been given a score of five.

Table 17. Preliminary Evaluation Results - Seven Cookers

	1. Time to boil water	2. Maximum temperature	3. Energy storage	4. Capacity	5. Versatility	6. Effectiveness, other	SUBTOTAL	7. Ease of use	8. Ease of maintenance	9. Durability	10. Wind stability	11. Portability	SUBTOTAL	12. Material cost	13. Import item cost	14. Ease of manufacture	15. Transportability	SUBTOTAL	Total Score
Wisconsin Cooker*	10	10	0	5	5	5	215	7	2	2	7	10	202	4	8	7	9	192	609
Solar Chef	5	3	1	2	5	1	106	5	5	4	8	10	221	8	9	5	4	190	517
Edmund skewer cooker	0	0	0	0	0	0	0	10	5	3	0	10	199	10	10	9	10	274	473
Edmund collapsible paraboloid cooker	0	0	0	1	0	0	6	2	0	0	0	10	70	9	10	4	10	236	312
Telkes oven[1], fixed reflectors*	4	9	10	10	6	5	255	10	7	5	7	10	281	6	9	5	3	168	704
Telkes oven[2], movable reflectors	4	8	3	10	6	5	202	7	4	1	1	10	156	7	9	5	5	188	546
Brace solar cooker	0	2	0	3	0	0	26	10	3	2	10	10	261	8	7	5	6	186	473
Weight	10	4	7	6	4	5	36	10	5	8	8	10	36	8	8	6	6	28	100

* Based on previously published results - unit not tested by us to date.

1 Best case.

2 As designed by D.S. Halacy and published by <u>Mother Earth News</u>.

The Brace steam cooker will not bring water quite to a boil, and the Edmund skewer cooker will not accomodate a pan of water at all. The Edmund paraboloid cooker will only hold very small pans of water, and the structure was not adequate to allow our testing even with these small quantities. All three of these cookers therefore received scores of zero.

2. Maximum Temperature, Measured Amount of Oil

Once again, the Wisconsin cooker was the standard. Tests of the similar Indian cooker showed that under ideal conditions a kilogram of oil could be brought to 398°F within an hour, and we assumed that a well-constructed Wisconsin cooker (which actually has a larger reflector) would achieve comparable results. On the basis of a minimum possible cooking temperature of 175°F, the score for this category was based on the formula

$$10\left(\frac{T_{max} - 175}{225}\right)$$

resulting in a score of 10 for the standard, the Wisconsin-type cooker. For the purpose of this preliminary evaluation, all other maximum temperatures were estimated, since we had not yet performed tests of this nature ourselves and have not seen other tests of this nature reported in the literature. "Oven temperatures", meaning the temperatures reached by black plates, thermometer bulbs, or other temperature sensors placed in the ovens, have been reported or advertised for Telkes ovens, the Solar Chef, and others; there is no guarantee, however, that a kilogram of oil in a black-surface, closed pan will reach the same temperature (or, indeed, that it will not reach a still higher temperature.) It should be noted that Telkes measured black plate temperatures of approximately 400, 450, and 460°F in single-, double-, and triple-glazed ovens respectively. On the other hand, deep frying was not included in her list of cooking modes possible with this oven, although it should be possible if oil temperatures actually would reach these levels.[2]

3. Energy Storage

A Telkes oven can be constructed using insulation with relatively high thermal capacity (specific heat), so that when a cloud passes in front of the sun or the sun sets, heat will continue to be supplied to the food by the storage medium. Stones, bricks, or sand can be used for this purpose at very low cost.

2. Telkes, M.: "Solar Cooking Ovens." Solar Energy, Vol. III, No. 1, pages 1-11 (January 1959).

Alternatively, it has been suggested that phase-change material - a salt that would melt when heated to normal oven temperature - be used, but we know of no working prototypes that have ever been built and assume that the problems involved in permanently sealing the phase-chamber material in a jacket around the oven would result in greatly increased cost. For our purposes, we took as a standard a Telkes oven well-insulated with solid material that would be readily available in Haiti, such as rocks. The first Telkes oven we constructed used spun fiberglass insulation, and hence the only energy storage was that associated with the air in the oven, the air trapped in the insulation, and the sheet metal and glass of the oven. We very crudely estimated that the energy storage (which is noticeable in use) is about one-third what could be obtained by use of bricks or stones. The Solar Chef has still less energy storage, although it could probably be improved by adding material of high thermal capacity to the back of the black rear wall of the cooking enclosure. In this case, a permanently sealed container of phase change material might be easier to incorporate than in the Telkes oven, although achieving good thermal contact of the material with what would be the top surface of its container would be a problem.

The three focusing cookers do not store energy, although the cooking vessel itself might store some. The Brace steam cooker does store energy in the heated water, but the stored energy cannot be used for cooking since boiling stops as soon as the insolation drops, and without boiling there is no mechanism for heat transfer to the cooker. All four of these cookers were scored zero.

4. Capacity

A Telkes oven can be virtually any size that a person might wish to build. Our other ratings, including cost, are based on the oven we built, which will easily accommodate two good-sized containers of food and is in that respect the largest of the cookers we tested. We therefore gave scores of 10 to the two Telkes ovens.

The Wisconsin focusing cooker can only accommodate a single pot, although with a 48 inch reflector the pot can presumably be fairly large. For our purposes, it was rated 5. The Solar Chef is also limited to a single pot, but in this case the pot size is quite limited, so we gave it a rating of 2. The Brace steam cooker can be made in varying widths to accommodate various numbers of pots, but all of our ratings, including cost, are based on the single-pot size that we built. Since cooking effectiveness was so poor with the moderate-sized pot that will fit into our cooker, we assume a larger pot full of food would be quite impossible. On the basis of the pot size, a score of three was given.

The Edmund skewer cooker is not designed to cook food in pots, and hence had to be scored zero. The Edmund paraboloid cooker, even if it could stand up by itself and maintain its reflector shape, could only hold a miniscule pot, and hence was given a score of one.

5. Versatility

As far as we know, none of the cookers designed to date will allow surface frying without considerable modification, and hence no cooker was given a score of 10. The Telkes ovens, which can boil, bake, and roast, but as far as we know cannot deep fry, were given scores of 6, and the Wisconsin cooker, which cannot bake or roast but probably can deep fry, was given a score of 5, as was the Solar Chef, which has approximately the same range of capabilities as the Telkes ovens except for restrictions due to space limitations within the glass cover. The Brace steam cooker, which can neither boil, bake, fry nor roast, but does heat food to near the boiling temperature, was given a zero, as were the Edmund cookers.

6. Other Measures of Effectiveness

Scores in this category were based on a "neutral" rating of 5, with points added for special advantages, and subtracted for special disadvantages, not adequately accounted for in other sections.

For the purpose of this preliminary rating, the Brace steam cooker was sharply down-rated for the reported soggy, unappetizing nature of foods cooked using the units installed in Haiti, and the Solar Chef for its inability to point at the sun at low solar angles. The Edmund cookers were down-rated for their totally inadequate size, stability, and structural integrity for routine cooking of significant quantities of food, and also in the case of the skewer-cooker for the cost of the blackened foil that must be wrapped around any food cooked.

7. Ease of Use

The assumed "best case" Telkes oven is as shown in Figure 6, where the cooking pot and oven are supported separately on a common frame, such that the oven can be tilted - including the reflectors - without disturbing the cooking pot. With this oven, periodic alignment is a simple procedure if a sight of some sort is provided to indicate correct alignment, and the oven was awarded a score of 10.

In the Halacy version of the Telkes oven, the oven is not tilted and only the side reflectors are fixed. The upper and lower reflectors are moved in conjunction with the elevation of the sun. Because of the difficulty of determining the correct position of these reflectors at any given time, and the lack of adequate provision for holding the reflectors in place, we judged this oven to be much harder to use. A similar oven with all reflectors fixed, in which the oven is tipped to point at the sun (see Figure 7) would be even more difficult to use, in our opinion, because of the danger of spilling food, the need for stops to keep pots from sliding around, etc.

In the Solar Chef the food is placed on a multi-position wire rack. Whenever the cooker is moved (in elevation) the food must be removed, the rack readjusted, and the food replaced. We judged this method relatively difficult to use.

One of the Brace steam cooker's few advantages is the ease of use - one simply puts the food in, periodically turns the cooker, and waits. We gave this cooker full points, as well as the Edmund skewer cooker, which is extremely simple to use. The other Edmund cooker was given very low points because of the frustration we experienced trying to get it to stand at any desired angle on the three wobbly wire legs, even indoors out of the breeze. We never have been able to set it up outdoors.

The Wisconsin cooker was given fairly high points, but was marked off because of the long reach to the cooking pot, the fact that the user might have to stand in front of the reflector to reach the cooking pot, and the fact that the entire framework moves considerably as the pot is put into position or removed. These opinions are based primarily on what we saw in the movie prepared by the University of Wisconsin, based on their final Mexican project. Removal of the heated pot, in particular, might require three hands in many instances. The Indian cooker seems to be better thought out with regard to ease of use.

8. Ease of Maintenance

None of the cookers received especially high marks in this area. Any cooker that depends on aluminized films or polished aluminum for its reflective surfaces is vulnerable to spilled food, dirt and sand, and atmospheric corrosion and with metallized plastic films (such as Mylar), the reflective layer being on the back of the film, the film itself is subject to ultraviolet degradation, becoming cloudy after a year or two of exposure and consequently performing less well. Duffie, Lappala and Löf of the University of Wisconsin reported[3] a reduction in reflectivity of aluminized Mylar from an initial 87% to 60% after 1.5 years exposure in Madison, Wisconsin. Since the problem is probably proportional to the total solar radiation received, it is expected to be much more severe in equatorial and desert regions.

Cleaning, polishing, or replacement of these surfaces constitutes a relatively difficult maintenance task. The only alternative seems to be the use of rigid second-surface reflectors. Plane glass mirrors are commonly used, but the only use of curved glass reflectors we know of is the Tabor cooker, using several small shaving-type mirrors. Curved second-surface acrylic reflectors have just become available commercially, and one was purchased and tested later in the program. Whether degradation of the front plastic layer is as much a problem as in the case of aluminized Mylar (also technically a second-surface reflector) remains to be seen. Still another approach is to glue a myriad of small plane glass mirrors to a curved shell, as in the case of the final design tried by the University of Wisconsin in Mexico.

Since this final attempt to overcome the short life and difficult replacement of aluminized films in the Wisconsin cooker ended as essentially a maintenance failure - the glass mirrors were too difficult to glue back in place, so the cookers were scrapped - we were forced to give the Wisconsin cooker low marks for ease of maintenance. The Solar Chef was given low marks because of breakage of the multi-segment glass cover, even with very careful use, and the difficulty of gluing new glass segments into place, and because of the frequent painting needed to protect the fiberboard parts from the elements. The Edmund skewer-cooker was given low marks because of the use of a reflective film, although the fact that the surface to which it is glued has simple, not compound, curvature resulted in higher marks than otherwise would have been the case. The fact that the Edmund paraboloidal cooker could not be set up outdoors without serious damage resulted in zero points. In the Halacy version of the Telkes oven, steam from the cooking pot condenses in the fiberglass insulation, resulting in greatly diminished insulation value and a mess in the oven; the problem is compounded by the fact that the insulation is not removable without removing the glass - a very difficult

3. Duffie, J. A.; Lappala, R. P.; and Löf, G. O. G.: "Plastics in Solar Stoves." Modern Plastics, Vol 35, Nov. 1957, pp. 124-125, 260, 261.

operation that is at least partly one of maintenance. This problem would be alleviated if the insulation space could be carefully sealed - both from the oven interior and the elements-but some redesign might be necessary, especially with regard to the fitting of the glazing. The glass windows of the Brace steam cooker are especially vulnerable to damage, and are somewhat difficult to replace, and scale accumulation in the collector tube probably will require major dismantling, and replacement or cleaning with a special tool, at regular intervals.

The "best case" Telkes oven could probably be designed as a very low maintenance unit, especially in view of the planar reflecting surfaces, but in view of the maintenance problems inherent in all the cookers we have worked with we hesitated to give it full marks.

9. Durability

Durability is a major shortcoming of every solar cooker we have seen. The Wisconsin cookers failed in use in Mexico because of relatively short lifetimes as built (2 - 3 years) and difficult maintenance operations to return them to the as-built condition (and probably in part because of lack of any organized maintenance operation, hiring of a solar cooker repairman, etc.). Window glass has broken in every cooker we have tested that uses untempered glass - in the Telkes oven because of wind blowing the reflector against the glass, in the Solar Chef because of the difficulty of handling the fragile glass cover while removing a cooking pot, and in the Brace steam cooker (and the Telkes oven as well) because of over-constraint of the glass and uneven expansion of the collector box when placed in the sun. Glass windows typically reach temperatures where the glass is relatively weak and may break as a result of internal stresses even if the edges were not constrained. Tempered glass or plastic such as Kalwall "Sunlite Premium" is probably required. The Solar Chef has also developed a mildew problem, and some deterioration of fiberboard surfaces, due to being left outdoors, a condition that it was apparently not designed for. In addition, hinge screws have pulled out due to moisture infiltration. The Halacy version of the Telkes oven has required complete rebuilding due to lack of support for the reflectors, which are ungainly and subject to high wind loading. The cooker box on the Brace steam cooker is inadequately supported, and the top is not adequately constrained.

A part of the reason for the durability shortcomings of these cookers is the emphasis in some cases on lightweight and portability, the extreme cases being the Edmund cookers. In other cookers, the problem has been the use of inappropriate materials whose chief benefit is ready availability for the do-it-yourself builder. Neither of these reasons for lack of durability is an important factor in designing a cooker for volume production, for regular use under Haitian conditions. Still another reason for lack of durability has been apparently hasty engineering design effort, especially in the case of some units where glass breakage occurred during our testing. We firmly believe that a serious design effort, with attention to details and proper selection of materials, could result in an oven-type cooker (or a steam cooker) that would be extremely durable, capable of well over the five years of constant use without major maintenance that we have set as a goal, yet within reasonable cost limitations.

10. Wind Stability

The only solar cooker we have seen with no wind stability problems is the Brace solar steam cooker. The Solar Chef has relatively little problem because of its weight and the fact that the reflectors are built into a very rigid structural unit; the only wind problem occurs when the cooker is tipped near its maximum operating angle and the wind is from behind the unit, in which case the unit could swing forward on its hinge, past its maximum angle, with disastrous results. The Wisconsin cooker, using a lightweight plastic paraboloid four feet in diameter and with relatively little structural support, is assumed to be difficult to use on a windy day, although the later designs were said to be a considerable improvement over the first (Model 1 and 2) designs in this respect.

The Telkes oven we built gave us serious problems in the wind because of lack of adequate structural support for the reflectors, and hence was graded down severely - perhaps too much so, as relatively simple design modifications would solve the major portion of this problem, and movable upper and lower reflectors are not fundamentally incompatible with wind stability. Similarly, the "best case" Telkes oven with fixed reflectors and a pivoting oven was assumed to be on a par with the Wisconsin cooker because of the size of the "sail area", although if the oven is relatively heavy and structurally well-designed the wind stability would be better.

The two ultra-light-weight Edmund cookers have no inherent wind stability whatever, and considerable problems result in use.

11. Portability

The only portability criterion we have established concerns moving the cookers short distances to avoid shadows. Since none of the seven cookers considered presents any problem in this respect, all were given full marks. The Wisconsin cooker, and probably some others, would require mounting fixtures to be located at each point of use for the cooker to be portable.

12. Materials Cost

The scores indicate our rough estimates. The Wisconsin cooker received a fairly low score because of the amount of polyester resin required in the final version. Earlier versions using high-impact polystyrene shells - vacuum formed or drape formed - might be significantly cheaper. The new second-surface acrylic reflectors are not cheap - retail price for a 48 inch reflector was $70.00 in March, 1977.

13. Cost of Imported Manufactured Items

The scores again indicate our rough estimates. Whether a given item was considered under this category or the preceding was somewhat arbitrary. The Brace cooker received the lowest score in this category because of the large amount of glass required.

14. Ease of Manufacture

The Wisconsin cooker was given the highest score in this category because of the demonstrated success with on-site manufacture in Mexico, although not nearly as high as we would have awarded if the people who were trained to make them had continued to do so after the University of Wisconsin team left. Lowest score went to the collapsible Edmund cooker, which uses reflector segments manufactured by a simple stamping operation that does require a special die. The other cookers were considered to be essentially similar in terms of ease of manufacture except for the Edmund skewer cooker, which is based on a simple styrofoam shape.

15. Transportability

The Edmund cookers received very high scores here, if nowhere else, because of their small folded size and light weight, and the Wisconsin cooker received a high score since it can be built on-site, with only metal strap, plastic resin, small glass mirrors, and the like requiring transportation. The Telkes ovens and Solar Chef were assumed to be items that would be manufactured in some single facility and transported to the site, and were scored in accordance with the estimated package size as pre-assembled items, except that the two fixed reflectors on the Halacy (movable reflector) oven were assumed to be folded for shipment and deployed and supported on-site. It was assumed that the Brace steam cooker collector and cooker boxes would be manufactured separately at a single fabrication shop and transported to the site, where they would be joined together and mounted on a base structure that would be made on-site.

B. SUMMARY OF RESULTS

It is noteworthy that the highest scores went to the Telkes oven and the Wisconsin cooker - units whose basic designs date from the 1950's, and which were considered the standards against which other cookers had to be compared at the UN Conference in 1961, and by the VITA study team. It is also interesting that our assumed "best case" Telkes oven scored far higher than the Wisconsin cooker (whose performance is much less a function of design specifics, for a given size and assumed quality of reflector), while the actual Telkes oven that we tested scored lower than the Wisconsin cooker.

Later in our study, it became evident that an additional category in this initial evaluation should probably have been safety. In addition to the usual minor hazards associated with any high-temperature surface, other significant hazards arose in connection with the focusing reflector used later for our attempt to simulate a Wisconsin cooker. Energy at the focal point is very intense, and if the reflector is mis-aligned - as it often might be when not actually in use - it can set fire to a person's clothing in very short order, and probably also to dry vegetation. Eye damage seems to be a possibility as well. These problems were exaggerated by the relatively long focal length - about 2 meters - of the reflector we were able to purchase, and would be less with a reflector with a closer focal point, but the hazard nevertheless seems to be of some concern, and is something that does not exist with the oven-type cookers.

The individual cookers are discussed below, in order of their rankings in our evaluation.

1. Telkes Oven, Fixed Reflectors, Best Case Assumption

The very high score indicated the need to build a Telkes oven in accordance with our "best case" assumptions and test it with the other cookers to see how closely it will approach our expectations. In the ratings, this design was assumed to excel overall in the performance categories, because of its capacity, versatility, and high temperature potential, and also in the use categories because of high ease of use, ease of maintenance, and durability ratings. Not surprisingly, perhaps, its score in the economic categories was the lowest of the seven cookers.

2. Wisconsin Cooker

The Wisconsin cooker scored rather well in the performance categories but did poorly in the use categories because of problems in the areas of ease of use, ease of maintenance, and durability. Since substantial improvements have been suggested in all three areas, it is conceivable that this cooker's "score" could be improved by up to 100 points. The Indian cooker, which is essentially a variation on the same theme, is judged to be much easier to use because of the cutaway at the top of the paraboloid and the means of mounting the cooking pot on a brace passing through a central hole in the cooker, which has the advantage of facilitating the achievement of proper focus. The advent of second-surface acrylic spherical reflectors may solve the very major reflective surface problems that caused low scores in both the maintenance and durability categories. In addition, the Tabor multi-mirror focusing cooker may well represent a solution to all three problems, as the concept is readily adaptable to almost any planform, with little maintenance other than occasional replacement of broken mirrors. This configuration may also result in both lower cost and better wind stability, the latter a result of the higher solar collection efficiency claimed by Tabor and consequent smaller total area.

It is noteworthy that the Wisconsin cooker received a higher score in the economic categories than any of the other cookers being seriously considered, in spite of having the lowest score in the two actual cost categories. It should be pointed out, however, that the improvements just discussed would probably result in lower scores in the ease of manufacture and transportability categories, where the Téotitlan version of the Wisconsin cooker excelled because of successful on-site manufacture.

3. Telkes Oven, Halacy Version

This oven received very low overall scores in the use categories, due to problems we had with poorly supported reflectors, insulation that could not withstand moisture and was not sealed from water vapor generated during cooking, and glass breakage, all of which were primarily the result of design flaws. The cooker was rebuilt and improved prior to further testing.

This oven also might have scored considerably higher if it had not lacked the energy storage capability that is sometimes regarded as one of the strong points of oven-type solar cookers.

4. Solar Chef

This unit is the only commercially available solar cooker we have tested to date that has any potential for use as the primary means of cooking food by a family in Haiti or elsewhere. It has some drawbacks, most of which are associated with the fact that it was designed for occasional use in backyards in the U.S. rather than the sort of application we have in mind. It can only be used during the middle of the day, when the sun is high in the sky, and will not accommodate cooking vessels of much more than about one liter capacity. Foods that require long cooking times are inconvenient since the food must be removed from the cooker while the cooker is being tipped up or down, and then replaced. The glass cover over the food is elegant but fragile. There is no provision for energy storage. Nevertheless, the things this cooker can do are done in a competent and straightforward manner, and the reflector surfaces are not affected by age, weathering, or food spillage. We later modified the cooker in several respects, achieving greatly increased capacity and ease of use with no measurable loss in performance.

5. Brace Research Institute Solar Steam Cooker

If this cooker could be made to cook food, its rating would be more or less on a par with the Telkes oven and the Wisconsin cooker. It excels in categories such as ease of use and wind stability, and has the potential for an ideal combination of centralized manufacture and local assembly and base construction (see Appendix E). We believe that continued effort should be devoted to improving this cooker, or designing new cookers from scratch that would use the same basic principle - indirect cooking with a heat transfer fluid to transfer heat from the solar collector to the separate cooker.

A number of very specific problems can be identified that might be partially responsible for this cooker's failure to perform well. Thermal contact between the fluid tube and the receiver plate is very poor, as the tube is simply pressed into the plate to form a grove and held in place with baling wire. The plate itself is much too large for a single tube - even if it were soldered or brazed to the tube, it would at best act like a fin of aspect ratio 400 or so. Consequently, very little of the energy received by the regions of the plate farthest from the tube can be expected to flow along the plate to the center and then jump the gap to the tube and pass through the tube wall to the water being heated. A sample calculation is included in Appendix F. The collector box is not well insulated. The cooking box is not well enough sealed to prevent steam from escaping, nor is there provision - hydrostatic or otherwise - for slightly pressurizing the water-steam system. Whether correcting these faults would result in satisfactory cooking performance or not was not determined during the course of our study.

6. Edmund Skewer Cooker

7. Edmund Collapsible Paraboloid Cooker

Neither of these cookers is judged to have any potential for applications other than backpacker or novelty use, and testing of them did not continue. Both were purchased as representative examples of the class of inexpensive solar cookers currently on the market, and were subjected to preliminary qualitative testing to ascertain whether or not they held any interest for our study; it was our conclusion that they did not.

C. DISCUSSION AND CONCLUSIONS

All solar cookers that have been built or discussed to date can be categorized as follows:

1. Direct focusing types
2. Oven types
3. Combined oven-focusing types
4. Indirect types

The direct focusing types include the series of University of Wisconsin cookers using plastic paraboloidal reflectors; the cookers formerly manufactured in India using asymmetric aluminum paraboloidal reflectors; the Tabor cooker (Israel) using an asymmetric spheroidal array of concave glass mirrors; the cooker formerly manufactured by Garrett Thew Studios of Westport, Conn., using an aluminum paraboloidal reflector; the cooker developed by Dr. Freddy Ba Hli in Burma using a reflector made of aluminum strips riveted together; the VITA cooker using concentric masonite rings to form a crude Fresnel reflector; cookers suggested by Stam of Holland, Duffie of the University of Wisconsin, Jenness of HRB-Singer, Inc., State College, Pa., and others using reflectors made of concrete, plaster, soil-cement, papier-mache, vermiculite aggregate, etc.; a cooker developed by von Oppen in India using a woven bamboo basket with a papier maché inner surface; the Umbroiler cooker using a folding mylar-rayon reflector, developed by George Löf of the University of Wisconsin; the Tarcici cooker manufactured in France under the trade name "Solnar", using two folding, fanlike arrays of reflecting blades; a small cooker marketed by Edmund Scientific Co., Barrington, N.J., using the same principal but in a considerably less elegant configuration; and a variety of other small cookers using collapsible reflectors or two dimensional (parabolic cylinder) reflectors and skewers to hold small food items. Of this long list, we know of none currently available commercially except the last-mentioned small collapsible and skewer-types, which we tested. Our results confirmed that these cookers would not be useful for routine, everyday cooking. A 48-inch spheroidal plastic reflector for use in a large direct focusing cooker could not be obtained in time for our initial evaluation due to long delivery delays, but it did eventually arrive and was used in the final tests described in Chapter VIII.

A large supply of 12-inch diameter shaving mirrors in plastic frames was obtained for the purpose of fabricating a cooker similar to that described by Tabor. We were never able to design a framework, however, that would combine all the required attributes and still be economically feasible and suitable for manufacture in a low-technology, light industry environment. Among the requirements for the framework are the following:

1. Compound curvature within well-controlled limits.*

2. Stiffness, to avoid deformation in moderately strong winds.

3. Means of securely attaching a large number of individual reflectors.

4. Means of adjustment at the mirror attachment points to allow proper aiming of the mirrors during initial fabrication.

5. Provision for removal and replacement of individual mirrors in the field.

6. A secure base structure allowing two-axis rotation of the mirror array and a means of securing the array in any position.

In conjunction with the problem of econcmic feasibility, it should be noted that the mirrors we bought, although not of scientific quality by any means, cost us an order of magnitude more than the price (30 cents each) quoted by Tabor in 1966. We have not found a source of cheap mirrors.

Oven types include a series of ovens designed by Maria Telkes using insulated boxes with glass windows surrounded by plane reflectors - the boxes may or may not use insulation material of high thermal capacity for energy storage, and may or may not tip up and down independently of the cooking vessel; an oven designed by N. K. Gosh in which the window faces vertically upward and there is only one reflector; a variation of the Telkes designs by D. S. Halacy, Jr., in which the oven does not tip but the reflectors do; a prototype built by Abou-Hussein of the University of Cairo, Egypt, in which the reflectors were inside the oven (behind a consequently much larger window) rather than outside; and the Solar Chef, marketed by the Sedona Solar Shop, West Sedona, Ariz., which uses a larger number of plane reflectors (16) surrounding a cooking enclosure that consists simply of a black, insulated back surface and a glass cover. We have purchased and tested a Solar Chef, and have built and tested a Telkes oven according to Halacy's plans, with moderate success in each case.

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* How close the limits have to be depends on focal length of the mirrors. Short focal lengths, which are necessary for compactness, safety, and ease of use, require closer limits. This requirement can probably be met rather easily using a welding jig.

The only combined oven-focusing type cooker we know of was a prototype built by S. Prata in Portugal, in which the reflector consisted of two parabolic cylinders that focused the sun's rays onto a slit in an oven. Prata's published results were quite encouraging, and we constructed a cooker based on his plans for inclusion in our final tests.

Indirect types mean those in which the actual cooker is separate from the solar collector, with a heat transfer fluid to carry energy from the collector to the cooker. The Brace Research Institute at McGill University has designed cookers on this principle, and built a number of prototypes, including a fairly large installation at Miragoâne, Haiti. C. J. Swet of the Applied Physics Laboratory of Johns Hopkins University has presented conceptual designs for another type of indirect cooker. The Brace cookers were not successful in Haiti, or in our tests of a unit built according to their plans, and the Swet concepts appear to be far more expensive, complex, and difficult to build than anything else we have seen. We nevertheless believe that this basic approach to solar cooking would be extremely attractive if it could be made to work, and have directed some of our efforts since the beginning of the program toward investigating the feasibility of indirect cooking. Some of these efforts are described in the following chapter.

The primary conclusions from our initial tests and evaluations can be summarized as follows:

1. Both direct focusing and oven type solar cookers can be effective and practical means of cooking food.

2. Performance of oven type cookers is much more susceptible to design variations than in the case of the direct focusing cooker, where reflector size seems to be the only parameter having an important effect on performance.

3. The ease of use of both direct focusing and oven type cookers is a strong function of design variations.

4. Careful attention to the design of oven type cookers is expected to pay major dividends in both improved performance and ease of use, and should be a major emphasis in the latter part of the study (see following chapters).

5. Redesign of direct focusing cookers for improved ease of use should be based on the optical considerations presented by Tabor in 1966. Methods of economical fabrication and mass production of either reflector arrays or large single reflectors are of primary importance in this regard.

6. The production of sturdy, cleanable, long-life compound-curvature reflectors at moderate cost has always been the chief obstacle to widespread use of direct focusing cookers, and we see no indication that this obstacle has been overcome. (See also the discussion of the acrylic second-surface reflector in Chapter VIII, Section D.) Tabor's alternative - using a number of smaller curved glass mirrors - might be economically feasible but we are doubtful that the economics of a practical, easily fabricated array has yet been demonstrated. The University of Wisconsin alternative - using a very large number of very small plane glass mirrors - might also be a feasible solution, but the only large-scale application was unsuccessful.

7. The Telkes oven, which uses plane reflectors, avoids this problem but is plagued by high cost resulting from the large reflector area/collection area ratio inherent in this design (due to the fact that the reflector must be more than 45° away from being normal to the sun's rays.) The cost of glass windows (also necessarily large in a Telkes oven) and reflectors together represent the major part of the cost of a Telkes oven. (See Chapter VIII, Section E, for a discussion of the use of plastic window glazing.)

8. The combined oven-focusing type cooker, although not included in the preliminary tests, appears to be a potentially attractive solution to the last-mentioned problem. With the reflector behind the oven rather than in front of it (as seen by the sun) it is possible for the reflector to be nearly perpendicular to the sun's rays, and hence much smaller. Because of the line-focus, the window can also be substantially reduced in size. On the other hand, the simply-curved mirror can be readily fabricated of plane glass mirror strips - perhaps clamped to avoid reliance on adhesives - hence overcoming the major problem (point 6 above) with direct focusing cookers.

9. Indirect cookers appeared especially attractive to us at the beginning of the program, and received considerable emphasis during the first months of the program, some of which are described in the following chapter. The results were generally not encouraging. The advantages associated with being able to separate the actual cooker from the solar collector still seem attractive. This method had to be given a low priority during the latter portion of the program, however, because of the many unresolved questions

associated with the more successful cooking methods.

10. In view of the foregoing, primary effort during the latter portion of the program was directed toward three objectives: design, development, and testing of improved Telkes ovens; tests using the acrylic second-surface focusing reflector currently available commercially; and new concepts (and testing of the Prata concept) combining the direct focusing and oven methods of solar cooking.

VII. DESIGN AND DEVELOPMENT OF NEW COOKERS

A. INTRODUCTION

The final conclusion at the end of the preceding chapter indicated the direction that was taken during the latter portion of our study: design, development and testing of new cookers of two basic types, oven and combined oven and direct focusing, testing of a large acrylic second-surface focusing reflector, and testing of the Prata combined-type cooker. In this chapter, the design and development portions of these efforts will be described. Testing of the new cookers, and of the acrylic reflector and the Prata cooker, are described in the following chapter.

This chapter also includes a description of our earlier efforts to develop other approaches for indirect cooking, and a report of a fairly extensive (and successful) modification carried out on the "Solar Chef" cooker by one of our student assistants. These topics are treated in the first two sections, following.

Our work on combined-type cookers resulted in a design that seems to have considerable merit, which is now referred to as the "F.I.T. Cooker". This cooker is described in the final section of this chapter.

B. OTHER APPROACHES FOR INDIRECT COOKERS

Two of the most obvious reasons for the Brace cooker's low performance are the very primitive solar collector, and the use of water vapor at atmospheric pressure as the heat transfer medium. Our initial efforts were therefore directed at the use of more sophisticated collectors, heating vegetable oil or other inexpensive, non-toxic, high boiling point liquid to temperatures that hopefully would be significantly above the boiling point of water. The fluid would have to be pumped to the cooker by a simple pump of some sort, perhaps hand or foot operated.

The better commercial flat plate collectors are normally capable of heating water to above the normal boiling point at low flow rates, although the efficiencies at these temperatures are quite low. In addition, retail prices run from 10 to 25 dollars per square foot of collector, a rather high price in view of the six to twelve square feet of collector area required for a solar cooker.

We therefore investigated the feasibility of using a concentrating, non-focusing collector. These collectors are capable of higher temperatures than flat plate collectors, and higher efficiencies at elevated temperature, although the efficiency at lower temperatures is usually not as good. In addition, material costs per square foot of collector area are often much lower than for flat plate collectors.

A concentrating, non-focusing collector that has received a lot of attention is the compound parabolic collector (CPC) devised by Winston[1] on the basis of optimization principles developed for the purpose of design of instrumentation for use in the field of Cerenkov radiation. This collector, sketched in cross-section in Figure 61, collects radiation over the entrance aperture (L) of width d_1 and an angular field of view θ_m (half angle of acceptance) and concentrates it onto an absorber (S) of width d_2. The trough consists of two distinct reflecting parabolas whose axes are inclined at angles of $\pm\ \theta_m$ with respect to the optic axis of the collector. The concentration ratio is the ratio d_1/d_2 and the acceptance half angle θ_m is given by $\theta_m = \sin^{-1}(d_2/d_1)$. This design should not be confused with the simple parabolic collector.

The principal advantages of this "ideal" parabolic collector are:

1. There is no need for daily tracking of the sun; only seasonal adjustments are required.
2. The efficiency for collecting diffuse light is higher than for focusing collectors. The fraction of the total sky light collected (that which would fall on a flat plate collector) is the reciprocal of the concentration factor.

A collector based on this design, with major dimensions chosen in accordance with Winston's principle but truncated to reduce material cost without seriously diminishing performance, was built by us, as shown in Figures 62 and 63. Considerable difficulty was experienced in getting the aluminum reflector to take the proper parabolic curvature at all places, as can be seen. No transparent cover was fitted - such a cover would increase cost and decrease the amount of insolation reaching the absorber, but would reduce the heat loss. For the sake of experimentation and our feasibility evaluation, the collector was larger (16 square feet projected area) than would be used for an actual cooker, and a simple electric pump was used to circulate the working fluid.

In addition to this collector, we purchased a large "double exposure" type collector from Falbel Energy Systems Corp. of Stamford, Conn. In this collector,

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1 Winston, Roland: "Principles of Solar Concentrators of a Novel Design." Solar Energy, Vol. 16, pages 89-95 (1974).

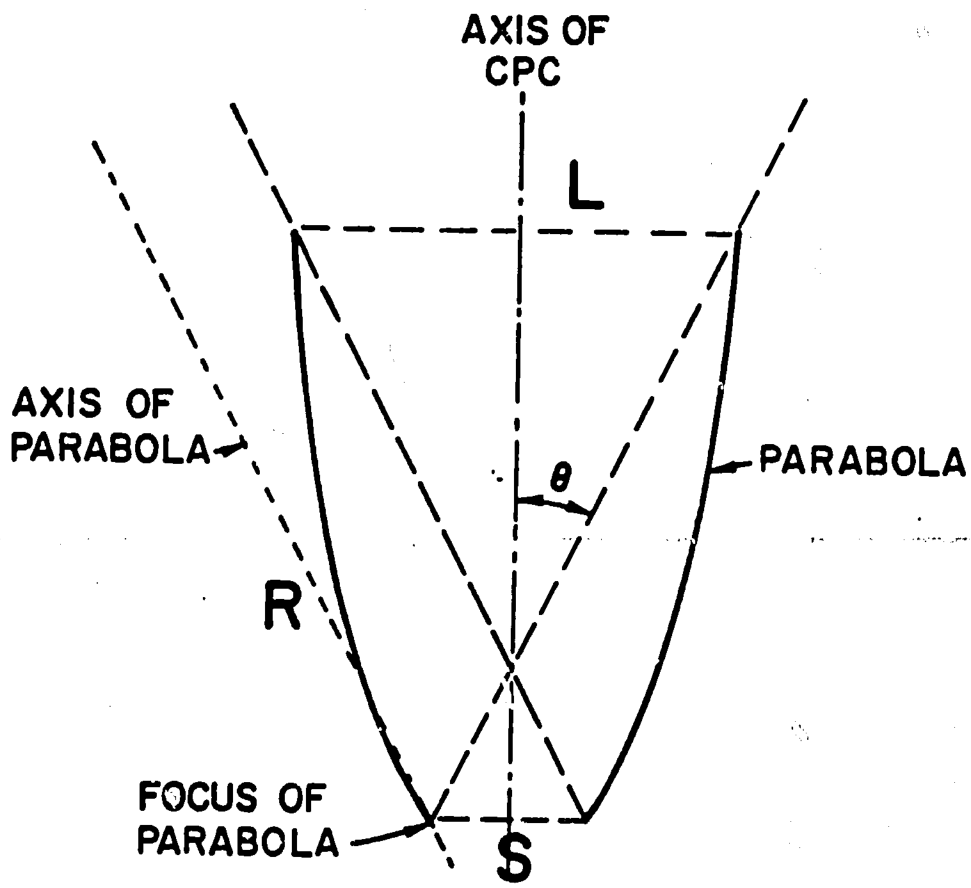

Figure 61. Cross-section of CPC.

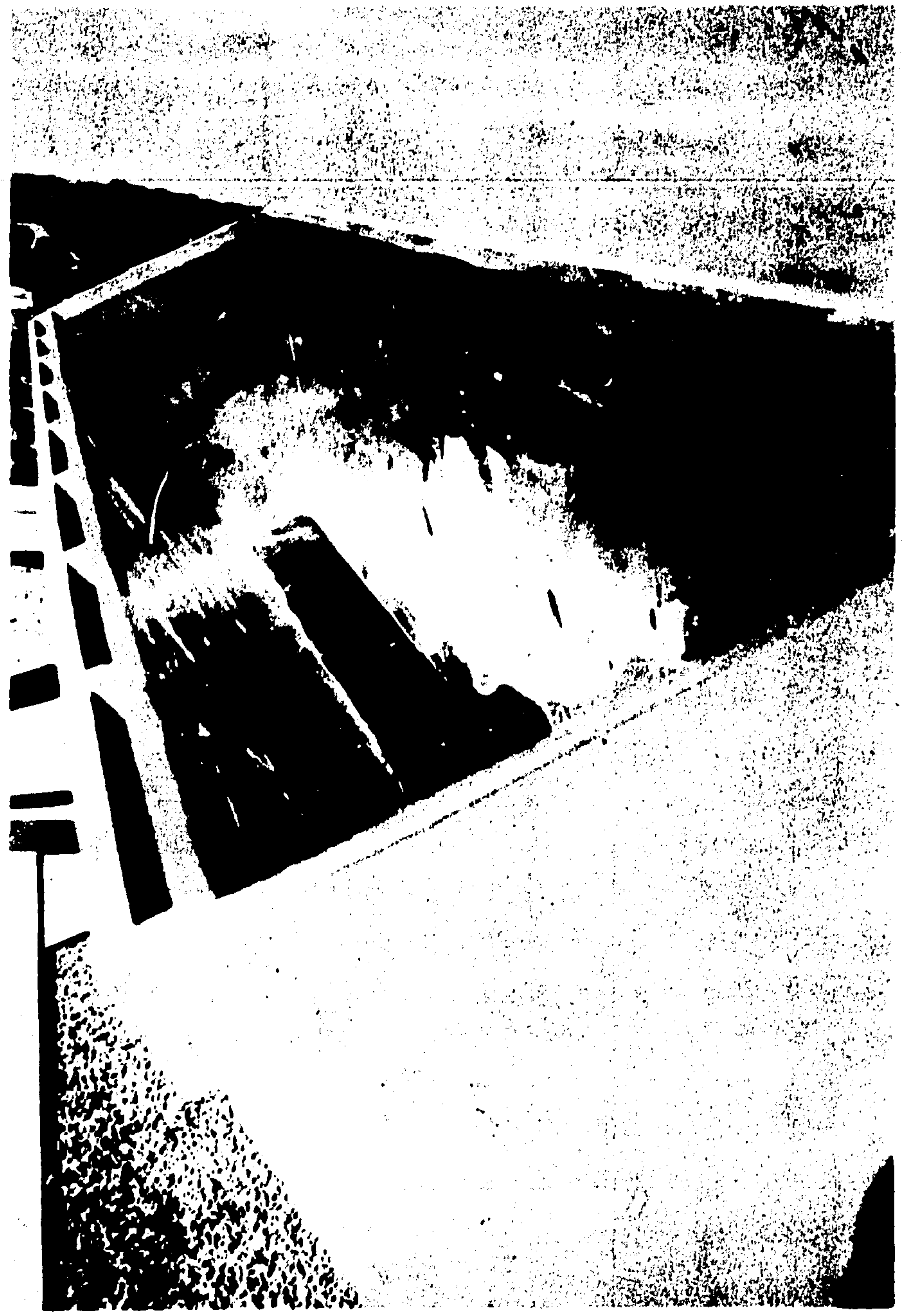

Figure 62. Winston-type concentrating, non-focusing solar collector fabricated at FIT - top view.

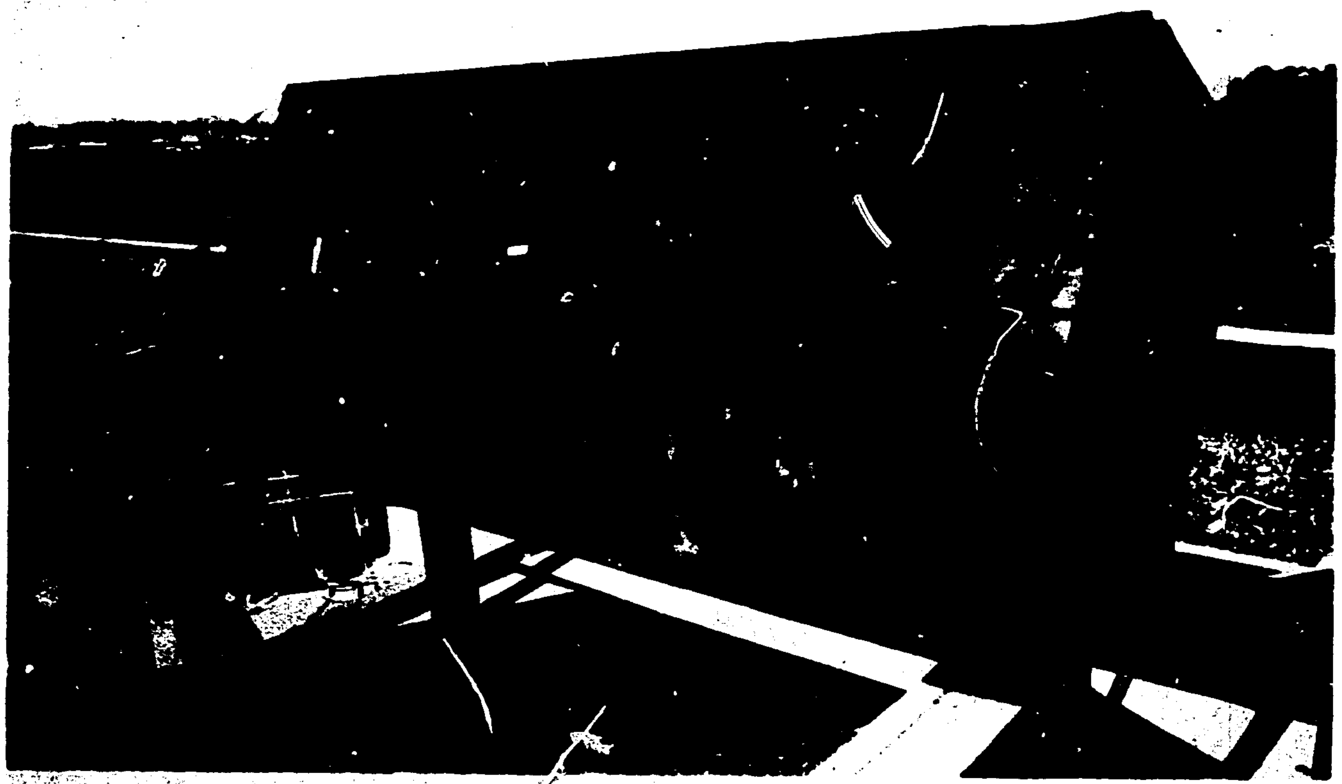

Figure 63. Winston-type collector, back view, with experimental cooker at left in background.

concentration is achieved by directing sunlight to the back of a flat plate collector panel via reflecting surfaces, at the same time that other rays from the sun impinge on the front. Additional concentration results from a movable flat reflector in front of the collector that can be adjusted to direct still more insolation to the collector. Effective area of this collector is about 60 square feet, although how effectively all the area is used is questionable. Quality of this unit is very poor in many respects, and assembly was quite difficult. The unit can be seen in Figures 58 and 59, where it is readily identifiable by its great size. This collector has also been used with the prototype cooker and pump shown in Figure 63.

Preliminary tests using these two collectors were somewhat disappointing, even allowing for the fact that conditions were far from optimum and that considerable improvement in test setup was needed. Highest temperatures obtained (in November) were 160°F. In both cases, heat loss was undoubtedly the problem. Our Winston collector should have had a transparent cover over the absorber (or perhaps at the entrance aperture, where it would be easier to install but much more expensive and less effective). Our reasoning was that the only chance this collector would have of being economically feasible for a solar cooking application would be if it could be made to work without glazing. The Falbel collector seems to have an inherent lack of insulation that is really not compensated by the "double-exposure" feature, and we see no way to effectively insulate such a large heated volume.

Dr. Erich Farber and his co-workers at the University of Florida have also been developing indirect cooking concepts using vegetable oil, but results of their work have not yet been published, to our knowledge.

C. MODIFICATIONS TO THE "SOLAR CHEF"

The "Solar Chef" cooker, manufactured and sold by the Sedona Solar Shop, Sedona, Arizona, performed very well for us, as described earlier, but was rather limited in various respects. The main limitations were as follows:

1. The cooker could only accommodate small food items, and in particular was very restricted regarding the use of pans or pots of any size.

2. The cooker could not be tipped far enough to point at the sun when the sun was within 40° or so of the horizon.

3. Food had to be removed from the cooker and the collapsible rack repositioned each time the angle was changed.

4. Since the cooker was tipped using wedges and was not constrained from tipping too far, a wind gust from behind the oven with the oven tipped up could result in catastrophe.

The most evident difference between this cooker in its currently marketed configuration and the original version described by Adams in 1878 is the size and shape of the glass enclosure for the cooking space. Adams' enclosure used nine pieces of glass - eight rectangular vertical sides and a horizontal, octagonal top piece - rather than eight triangular glass pieces meeting at the center as in the current version. The result was a much roomier enclosure, much better able to accommodate a pot or pan. We therefore built a new glass enclosure similar to that of Adams and used it for all of our later tests. The oven volume was still restricted compared to the larger Telkes ovens we tested, but so was the reflector size and aperture area.

Using the larger cover allowed us to construct a swinging rack, fixed on a frame to the back surface of the cooker, in place of the adjustable rack used previously. With the swinging rack, gravity keeps the cooking pot level as the oven is tipped and hence it is not necessary to open the oven and remove the food when the oven is tipped.

We also discarded the wedges and used a simple hinged brace to secure the oven at various angles, thus preventing wind damage.

A wooden box with a hinged lid was built as a new base for the cooker, allowing better insulation of the back of the cooking region. At the same time, the cooking volume was further increased by extending the back (black) surface downward into the box a few centimeters.

The modified cooker is shown in Figure 64. Comparison can be made with Figure 19, showing the original "Solar Chef".

We would like to especially acknowledge the contribution of Wolf Eckroth, an undergraduate student working on the project, who designed and implemented all of these modifications.

D. MODIFICATION OF THE TELKES/HALACY OVEN

This oven originally featured hinged, movable reflectors, as described earlier. The movable feature resulted in more problems than benefits, and precluded the use of corner reflectors to further increase the concentration of solar energy, so the movable reflectors were discarded and replaced by a

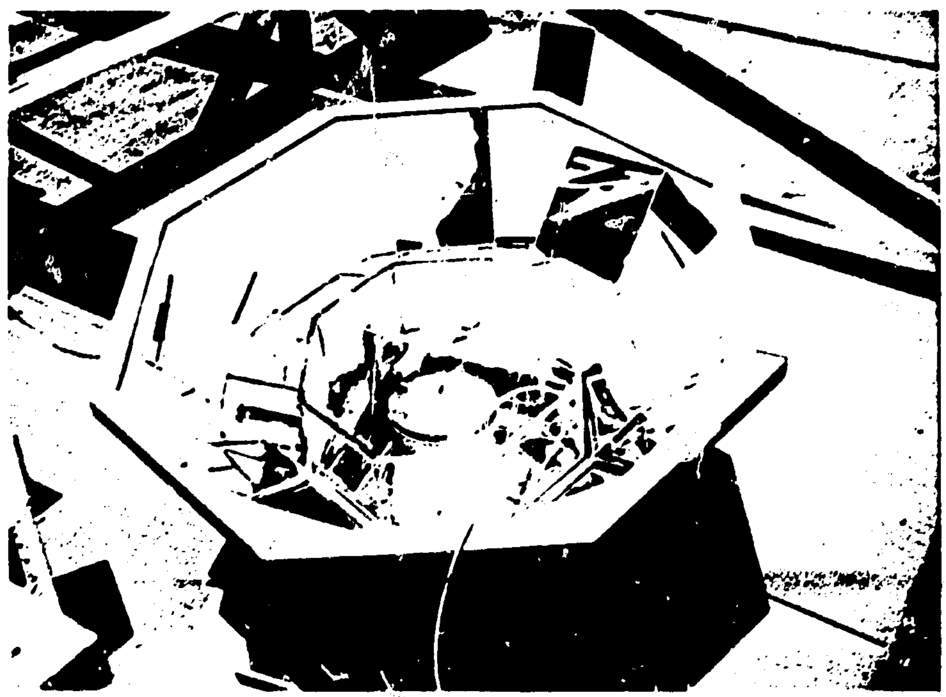

Figure 64. "Solar Chef", as modified for greater capacity.

fixed array of reflectors, as shown in Figure 65. By fixing the reflector positions and filling in the corners, the structural integrity was greatly improved, in addition to increasing the amount of solar energy directed into the oven. In addition, the fixed-reflector oven is much easier to use since proper alignment is greatly simplified. Since adjustable restraints for movable mirrors are not required, fabrication is also simplified. The corner reflectors, although they only increase the total amount of solar energy collected by 15% to 20%, have the advantage of directing most of their reflected rays into the center of the oven where they have the most effect, as discussed in Chapter IX, Section C.

The original insulation for this oven was fiberglass. Problems were incurred due to moisture entering the insulation, both from the inside of the oven (steam) and from outside due to lack of adequate sealing. To avoid this problem and to attempt to gain maximum performance by using an insulation with the lowest possible thermal conductivity, the fiberglass was replaced with foamed-in-place urethane insulation. Insulation thickness was somewhat variable, from one to two inches. Insulation materials are discussed at greater length in the following section.

The original double-glazed window was made of ordinary double-strength window glass. This glass broke in a number of places, and was finally replaced with Kalwall "Sun-Lite Premium II" translucent fiberglass-reinforced-plastic. Glazing materials are discussed at greater length in Chapter VIII, Section E.

E. STUDY OF INSULATION MATERIALS

In the preceding section, we discussed the problem of water uptake by fiberglass insulation, which seriously compromises the insulating value of the insulation and also results in some deterioration, so that after a period of time the insulation cannot just be dried out and reused. A further problem was associated with the temperature limitation of the insulation, or at least of the binder used. Like most common insulating materials, fiberglass batts and board are limited to maximum operating temperatures of about 250°F - well below the operating temperature reached by well-designed Telkes ovens, for example. The urethane foam was subject to the same limitation, and this insulation charred and smoked noticeably during use. Combined with the known toxic/carcinogenic properties of the urethanes, we would strongly discourage its use in any solar

Figure 65. Telkes/Halacy oven, after fitment of the fixed reflector array. The glass window has also been replaced with translucent fiberglass-reinforced plastic at this point.

cooker. The actual effects of eating food that has been exposed to trace amounts of fumes from overheated urethane insulation are not known, so far as we could find out, but it seems to be a probable hazard.

In considering insulating materials with higher maximum temperature capability, it becomes obvious that such capability is normally accompanied by both higher price per unit volume, and higher thermal conductivity, as shown in Figures 66 and 67. An inexpensive grade of firebrick, which we used during some of our developmental work, has no temperature problems whatever in our applications, but it is considerably more expensive than even the foamed-in-place urethane, and its thermal conductivity is about four times as great as the urethane. Asbestos board, widely used in metallurgical laboratories, is both more expensive than this firebrick, and not as good an insulator. Calcium silicate, capable of 1200°F temperatures, is a better insulator than firebrick and also cheaper, and was used in the "F.I.T. Cooker" described in Section H below.

At the lower temperatures, the graphs show the advantages of urethane foam boards and Celotex Technifoam, both of which enjoy a very good combination of low conductivity and low cost. Glass fiberboard conducts about twice as much heat as these two, but is also inexpensive and of course is the most readily available of the three. Noteworthy is phenolic foam, which is capable of operating at slightly higher temperatures (300°F) with a thermal conductivity as good as fiberglass and some other advantages, such as being inert and not retaining moisture. We believe this material is just in the process of being made commercially available, and do not know what price range will be established for it.

Examination of Figures 66 and 67 indicates one material - Foamglas - which seems to be especially suitable for solar cookers, and we used this material for all of our work in the latter stages of our program. Although capable of 900°F temperatures, Foamglas is sold at a price per unit volume comparable to fiberglass board. Its advertised thermal conductivity is about fifty percent higher than fiberglass insulation and two and a half times higher than urethane, but better than any insulation we have found that is capable of temperatures greater than 300°F. Foamglas is a proprietary insulating material manufactured by Pittsburgh Corning Corporation, and according to the manufacturer it "is composed of minute, individually sealed glass cells encompassing ... insulating air space(s)."

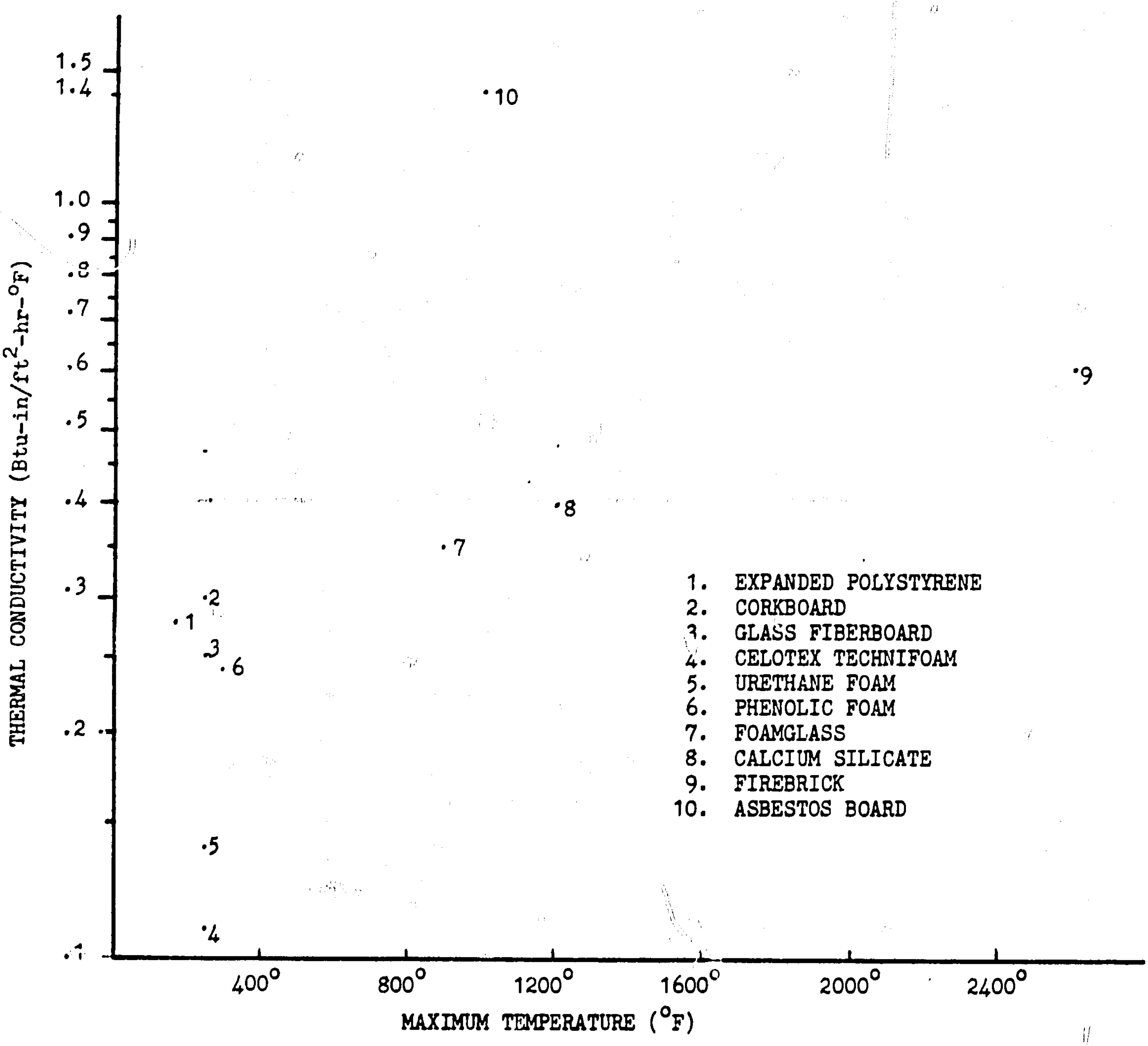

FIGURE 66. Thermal conductivity versus maximum temperature for several insulation materials.

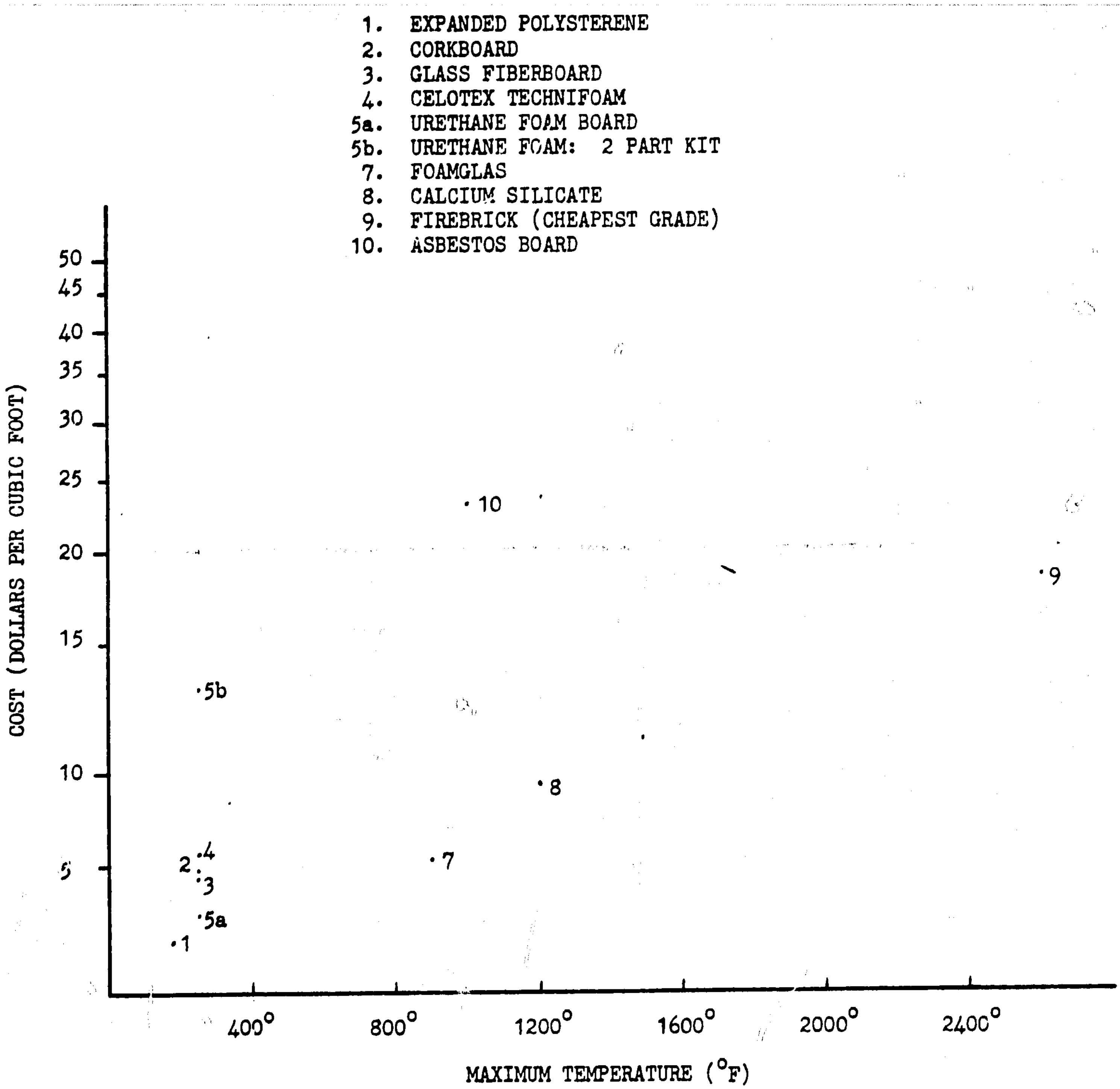

FIGURE 67. Cost versus maximum temperature for several insulation materials.

In appearance and density it seems similar to firebrick except for its color, which is black. In addition to its attractive combination of price, thermal conductivity, and temperature capability, it has several other properties which make it attractive for solar cookers, not the least of which is its rough, black surface. It is also entirely inorganic, incombustible, impervious to moisture, lightweight (8.5 lb/ft^3, or 136 kg/m^3) and dimensionably stable. In addition, it possesses a fair degree of structural strength, is rigid (modulus of elasticity is listed as 150,000 psi or about 1000 MPa) and can support compressive loads up to about 100 pounds per square inch (7.0 kilograms per square centimeter).

The following section describes our first use of this insulating material.

F. DESIGN AND DEVELOPMENT OF A "FOAMGLAS" TELKES OVEN

The Telkes oven described in Section C above possessed four major disadvantages that seriously compromised its usefulness as a solar cooker, in spite of its remarkably good performance:

1. The insulation reached temperatures well above its nominal maximum and degraded noticeably, including production of possibly hazardous fumes.
2. Tipping the oven was difficult and awkward because of the oven's size and weight and the fact that it had to be tipped about its back corner.
3. Since pans of food or water rested on the floor of the oven, the food had to be removed during the process of tipping the oven, and placement of a pan of water, say, was quite difficult with the oven tipped up.
4. The door was so small that large pots and pans could not be placed in the oven, hence negating to some extent the value of the oven's otherwise large size. In addition, the small door made it difficult to reach into the oven to remove pan lids, stir pan contents, move items around in the oven, etc., and resulted in numerous annoying burns.

For all these reasons, it was decided to design and build a new oven rather than attempt further modifications to this oven. The new oven was intended to be slightly smaller and much lighter than the Telkes/Halacy oven, but with somewhat more usable volume inside, and to be based on Foamglas as both the insulating and structural material. The resulting oven is shown in Figure 68, and in cross-section in Figure 69. It should be explained that the strange arrangement of insula-

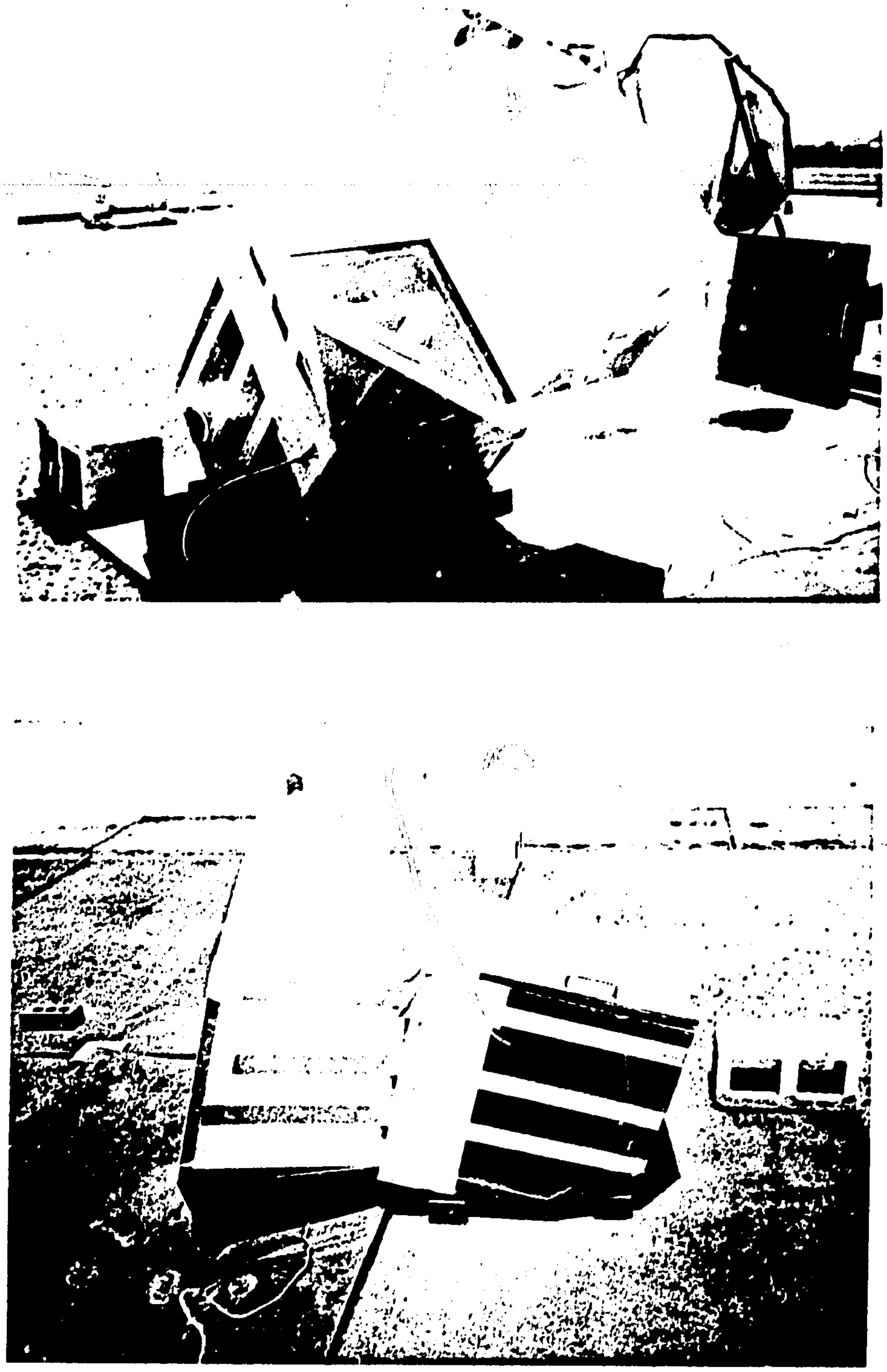

Figure 68. The Foamglas Telkes oven. The lower photo shows the oven aimed as close to the horizon as possible without elevating the base.

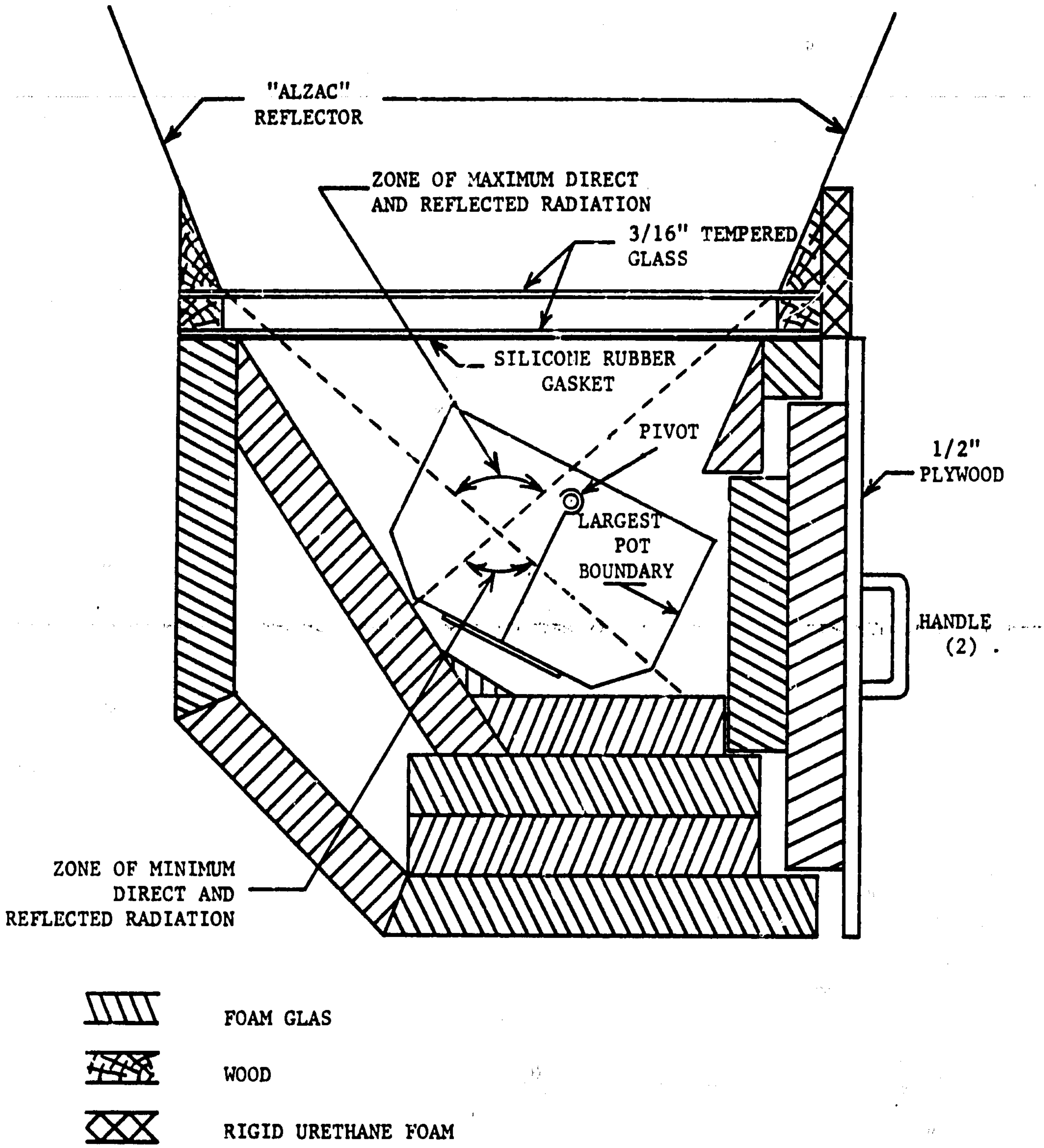

Figure 69. Section view, Foamglas Telkes oven.

SCALE 1" = 5"

tion evident in Figure 69 resulted from a need to reduce the internal volume of the oven to reduce heat loss. The original oven consisted simply of a shell of two inch Foamglas, with a layer of fiberglass-reinforced polyester on the outside to hold all the individual blocks in place. After initial testing produced disappointing results, additional blocks of Foamglas were stacked inside and glued to the inside of the door (right) to reduce the volume. Actual useful volume was probably not reduced nearly as much as total volume in view of the desirability (which became more obvious later in the program) of placing the receiver (object to be heated) as near the window as possible; see, for example, the zones of maximum and minimum direct radiation shown in Figure 69. Almost all of the volume removed was in the zone of minimum radiation.

The window of this oven was tempered glass, used to avoid the breakage problems encountered with ordinary glass. Unfortunately, the glass became a major cost element as a result; we paid $27.50 for the two sheets of 22" by 22" tempered glass. To reduce the weight of the total cooker, lower the center of gravity and reduce the time needed to fabricate the reflector, a monocoque structure of "Alzac" mirror-finish aluminum was used rather than an array of glass mirrors. "Alzac" is a tradename for aluminum sheets that have been highly polished and then anodized to preserve the reflective surface. The reflector was fabricated from four pieces of Alzac, as shown in Figure 70, riveted together with backing strips at the edges and a stiffening rim around the top. One disadvantage of this reflector is the cost, as two sheets of Alzac are needed, 2' x 6', at a cost of about $30 per sheet for the thinnest gauge available. Further comparisons between glass mirrors and Alzac reflective aluminum are presented in Chapter VIII, Section E.

The four main reflector surfaces are set at an angle of 65° to the plane of the window (25° away from the sun's rays) in this oven, rather than 60° as is more common with Telkes ovens, and are slightly truncated relative to the maximum length that can reflect light through the windows. Selection of angles and lengths is treated in Chapter IX, Section C.

This design addresses the four problems listed above for the Telkes/Halacy oven as follows:

1. Use of Foamglas insulation eliminated maximum temperature problems.
2. Tipping was made easier, primarily by elimination of the lower rear

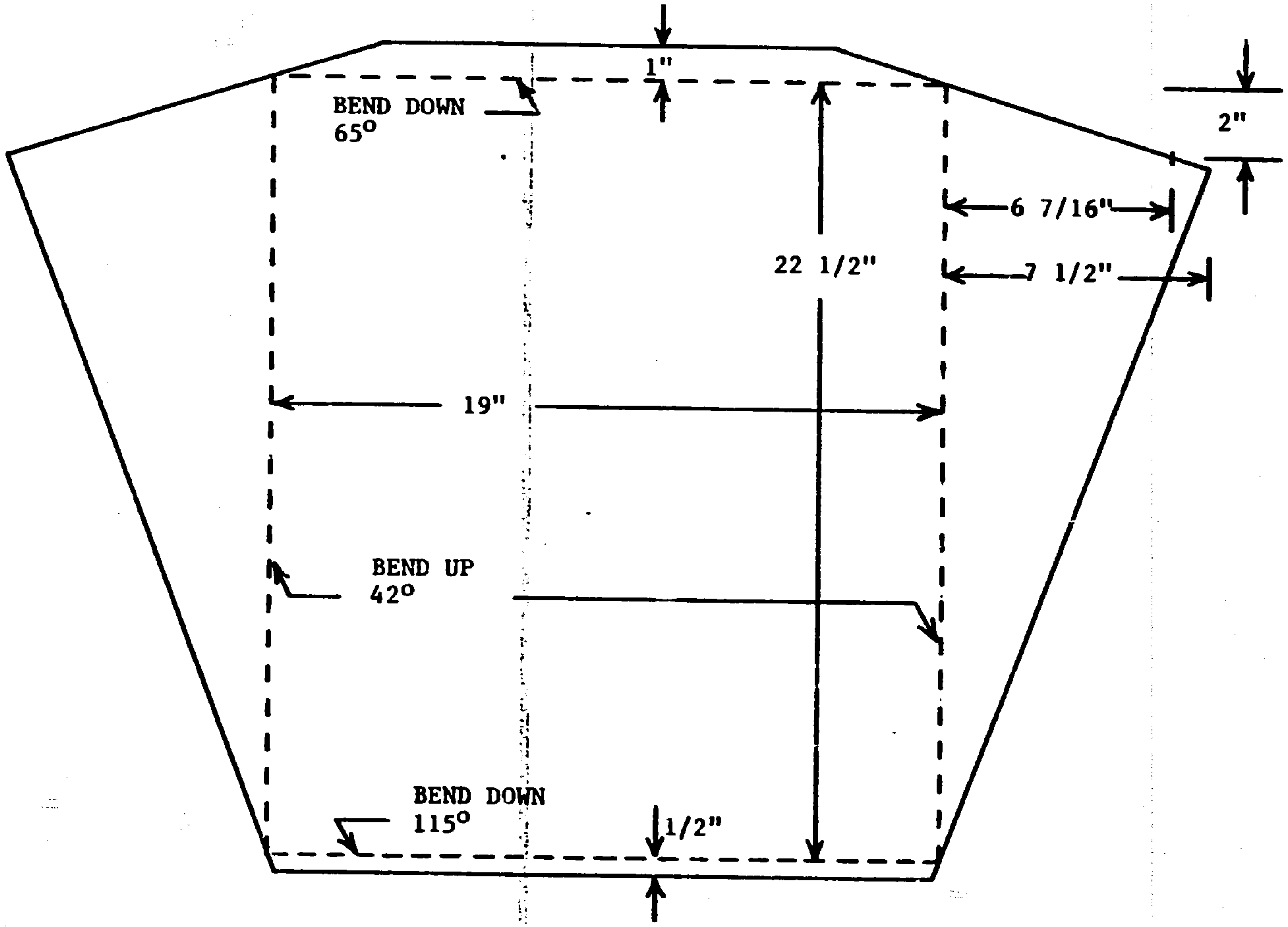

Figure 70. "Alzac" reflector element for Foamglas Telkes oven; four are required for each oven.

SCALE 1" = 5"

corner (lower left in Figure 69). The lighter weight and lower center of gravity also helped. This oven has been stabilized, in all winds that we have encountered, by four bricks, two on either side, blocked against the appropriate surfaces (the left vertical, lower horizontal, and 45° surfaces in Figure 69).

3. A swinging rack, as shown in Figure 71, eliminated all problems of placement and spillage of pans in the oven.

4. The door covers the full width of the oven, and most of the height. The heat loss from the oven when the door is opened is consequently greater, but did not seem to be a major problem in the testing reported on in the following chapter.

Further changes would be made for a "third-generation" Telkes oven. In particular, the overall shape would be revised in accordance with the principles outlined in Chapter IX, Section C, below. A return would probably be made to glass mirrors for economic reasons (thin glass mirror tiles can currently be bought at retail for less than $0.70 per one-foot-square tile) and because of the ease of cleaning without danger of scratching or abrading the surface. The use of a fiberglass-reinforced plastic outer skin is rather costly, and should probably be replaced with a sheet metal box, which we assume would be cheaper in Haiti if not Florida and allows more latitude in the attachment of the reflector shell to the oven, and in the placement of the window.

To be equivalent to the 1½ inches (approximate average) of urethane insulation used in our modified Telkes/Halacy oven, approximately four inches of Foamglas should have been used. We used about half that amount. The maximum temperatures reached by the Foamglas oven were a bit lower than in the modified Halacy oven, although still quite high, and the smaller amount of insulation was probably the reason. The outside surfaces of the walls became noticeably warm in places. Because of the low cost of the insulation relative to other oven components, it might be worthwhile to increase the insulation thickness, especially if the window and reflector could be reduced in size as a result. Thicker insulation might be especially worthwhile if the oven were to be used at northern latitudes during cold weather, but of relatively little value in Haiti. We believe this question warrants further investigation.

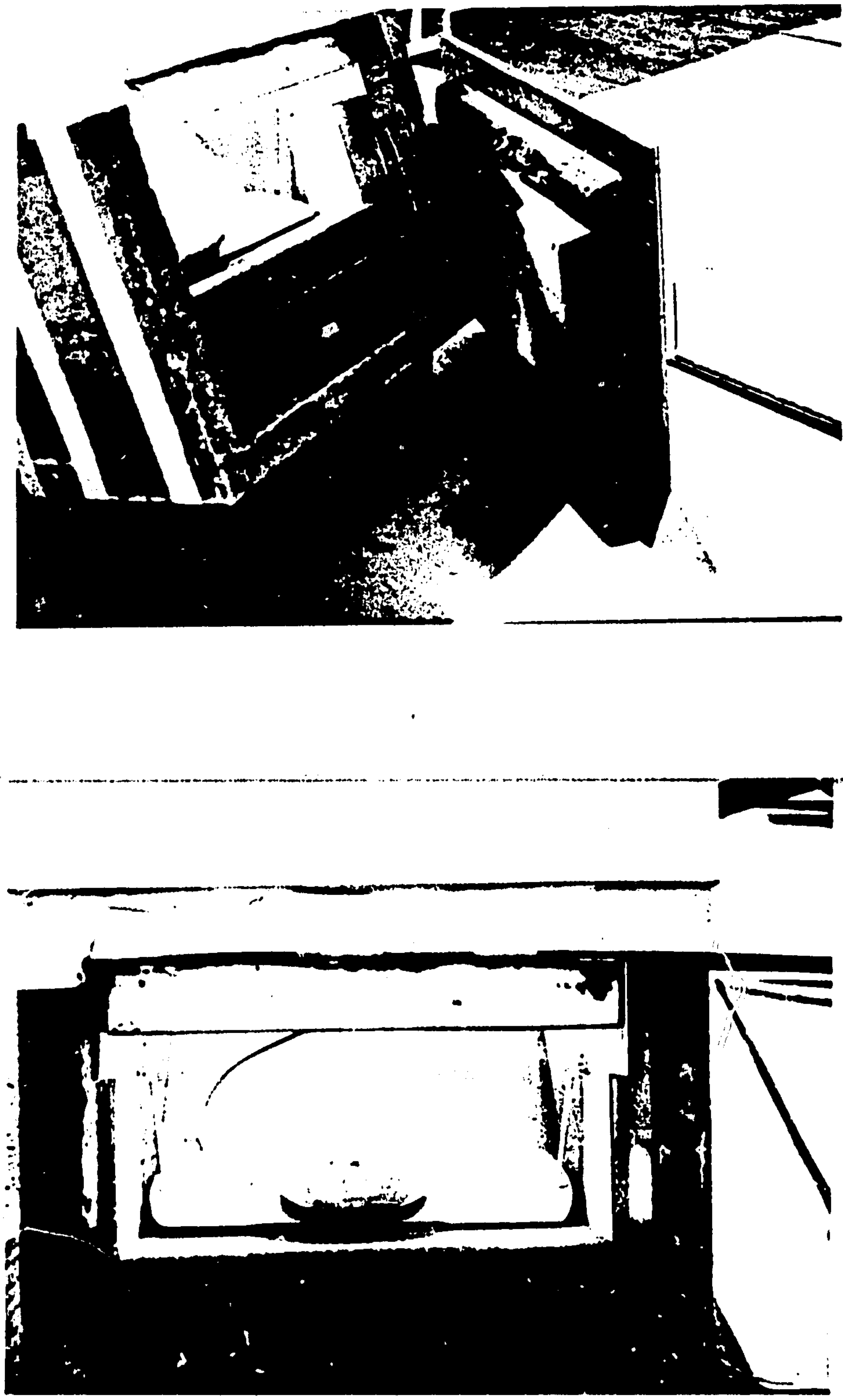

Figure 71. Interior views, Foamglas Telkes oven.

Perhaps a minor point is the fact that the sheet aluminum supporting the pivots for the swinging rack was on the inside of the oven, reflecting some heat back out the window. We did not want the pivots to penetrate the insulation, as a serious heat leak would result. With thicker insulation, the support structure could be sandwiched between two layers of insulation, with the pivots penetrating only one layer.

It should be noted, when considering some of the design and construction details of this oven, that it was built as an experimental prototype and was not intended to be identical in every detail to an oven intended for use in Haiti. In some cases, expensive alternatives were chosen for the sake of expediency. The important thing was to get the oven to an operational state as quickly as possible, regardless of cost (within limits) so long as the overall size and characteristics could be reproduced more cheaply at a later time.

G. DESIGN OF MINIMAL-SIZE TELKES OVEN

Figure 72 shows a Telkes oven that was designed shortly before the Foamglas oven described in the preceding section, primarily as an exercise to see whether a very small oven could be made to work. This oven uses an eight inch square double-glazed window in an iron frame, that serves as a door as well. The reflector consists of glass mirrors. The insulation was initially firebrick, but this was later replaced with Foamglas. The outer skin is sheet steel. The enclosure is just large enough to accommodate a small (one liter) kettle on a swinging rack. Provision was made in the experimental prototype (as in the case of the oven described in the preceding section) for a thermocouple lead to penetrate the oven wall. The mirrors are set at a 60° angle relative to the plane of the window.

H. DESIGN AND DEVELOPMENT OF THE "F.I.T. COOKER"

One of the most common questions directed at us as we worked on solar cookers was, "Well, that's all fine, but can you fry an egg?" Now frying an egg, or bacon, etc., is a very simple thing that requires little energy and fairly low temperatures, and everyone knows that you can fry an egg on New York sidewalks on a hot summer day, but it still represents a task that none of the cookers described thus far is particularly well suited for. In a Telkes oven with a swinging rack, the

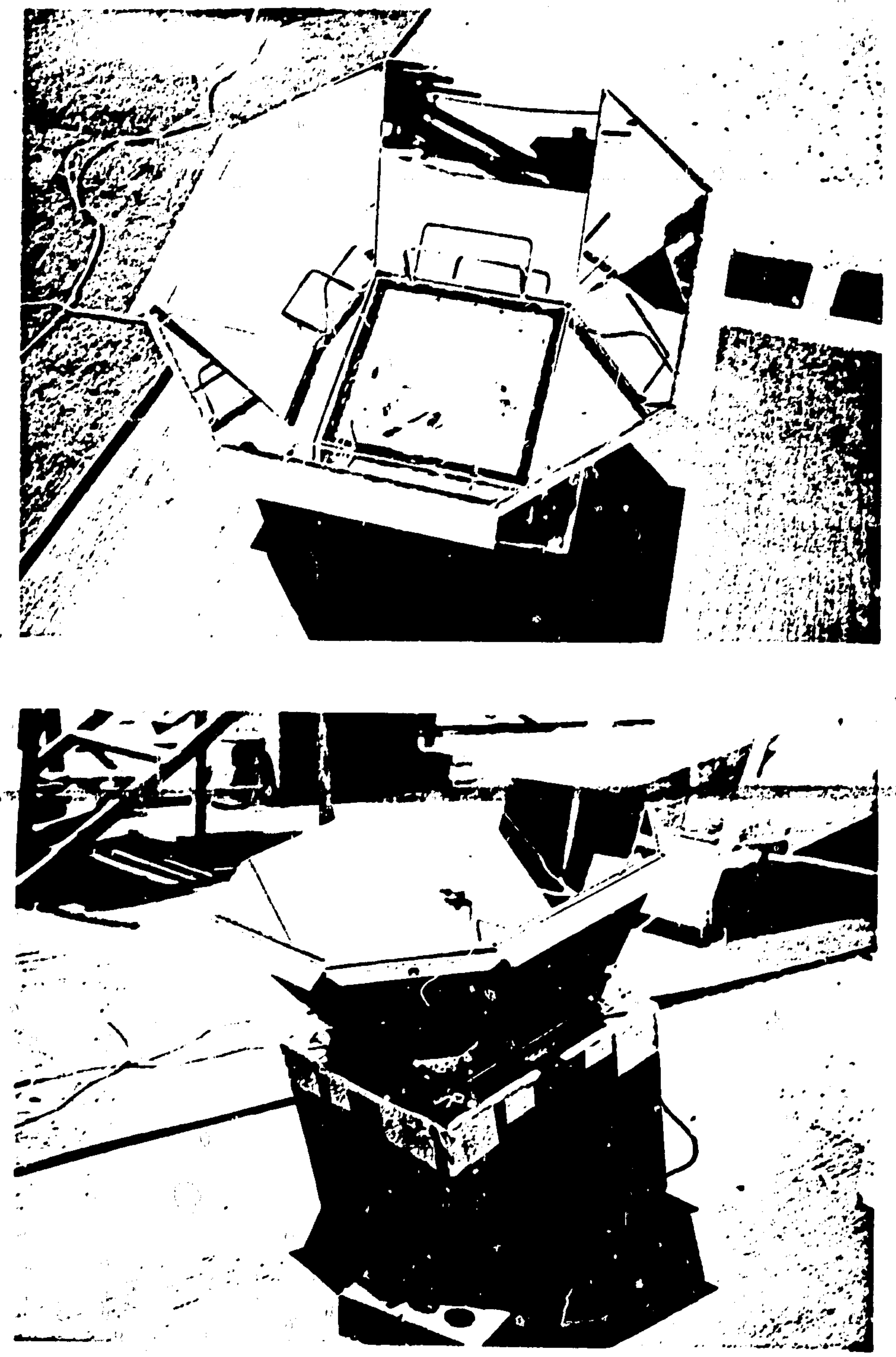

Figure 72. Small Telkes oven.

lack of a fixed, stationary, horizontal surface is a problem, as is the relatively limited access. In a Telkes oven without a swinging rack, the establishment of a horizontal surface is also a problem. In the Wisconsin cooker there is again the problem of locating a more or less stationary, horizontal surface at the focal point, plus the fact that the cook would probably have to stand between the sun and the reflector.

In addition to the problem of pan or griddle frying, which is probably not very crucial from the perspective of rural Haiti, there is also a potential problem with Telkes ovens associated with the fact that the main heat input is from above rather than below, as in most cooking. We still are not certain what the effects might be in cooking a thick stew, say, of altering the convective mechanism in this way. Perhaps convection would be so reduced that it would not be possible to obtain an evenly cooked stew without frequent stirring (also a problem in a Telkes oven).

Considerations such as these led us to consider - primarily as a diversion at first - the design of a cooker that would incorporate a fixed, stationary, horizontal cooking surface heated by reflection from below. If such a cooker could be made to work, at modest price and with the cooking surface at a reasonable height, it would probably be much easier to use and much closer in function to cooking over charcoal, or gas, or an electric range, than any of the other methods.

Since the cooking surface should have reasonable size, we did not feel constrained by the requirement of a point focus and hence were particularly interested in the possibilities of using a line focus, hence avoiding all the problems of compound-curvature reflectors described in the preceding chapter. As the idea evolved, then, we envisioned a rigid steel framework - some sort of A-frame structure - supporting a flat plate, with a singly-curved parabolic reflector suspended below the flat plate. The whole structure would be turned to follow changes in the sun's aximuth during the day, and the reflector would be rotated (about a horizontal axis) to follow changes in the sun's elevation. Because the configuration is basically two-dimensional rather than three, the cook would have ready access to the cooking surface from the side. The steel structure on which the cooker would be based had evolved from our observations in Haiti of the very common use of this structural material, and the large number of artisans with well-developed welding and steel-forming skills.

This concept began to receive our serious attention when we realized that Tabor's optical arrangement - utilizing an eccentric parabola pivoted about the center of a circle passing through the focal point and the ends of the parabola - was ideally suited to our needs. With this arrangement, the reflector really could stay roughly below the receiver (cooking surface) and most of the reflected rays would hit the receiver at something approaching normal incidence even at low sun angles.

An extensive period of design studies based on graphical ray tracing to select a best focal length and chord length for the parabola and location for the cooking surface was followed by final design and fabrication of a prototype, which used a plane vertical reflector above and behind the cooking surface to increase the amount of energy received at the cooking surface, especially at low sun angles. It soon became apparent that as long as the cooking surface was fully exposed, it would not be useful for much more than frying eggs and bacon. A pan of water placed on the surface would not reach a boil, because of heat loss.

By analogy with the Wisconsin cooker, we suspect that if a smaller circular cooking surface had been used with a point-focus reflector, this last result might have been different. Since we were trying to avoid the problems inherent in compound-curvature reflectors, and wanted to let the cook stand next to the cooking surface, we did not investigate this possibility.

What we did was to gradually enclose the plate more and more fully, until eventually the plate had been replaced by a rectangular oven with a long, narrow window in the bottom. The flat plate cooking surface was replaced, when cooking food in pots, with an open grating. At this point, the original virtue of accessibility that we sought had been pretty seriously compromised, but the cooking performance was so impressive that we thought this loss was not too significant. Accessibility is still considerably better than other candidate cookers since the oven volume is large, the entire front of the oven opens on hinges (see Figure 73), and the cook can stand right next to the oven because of the two-dimensional nature of the configuration. It also still features a horizontal surface that never tips or swings, and primary heat addition from the bottom as in normal cooking over a fire or range. Compared to a Telkes oven, it has a much smaller window - a cost advantage - due to the focusing of the incoming radiation, and also a smaller reflector - two feet by four feet, in the prototype we tested, compared to over twenty square feet of reflector in the Foamglas Telkes oven, and even more in the Telkes/Halacy oven.

Figure 73. The FIT cooker in its August 1977 configuration.

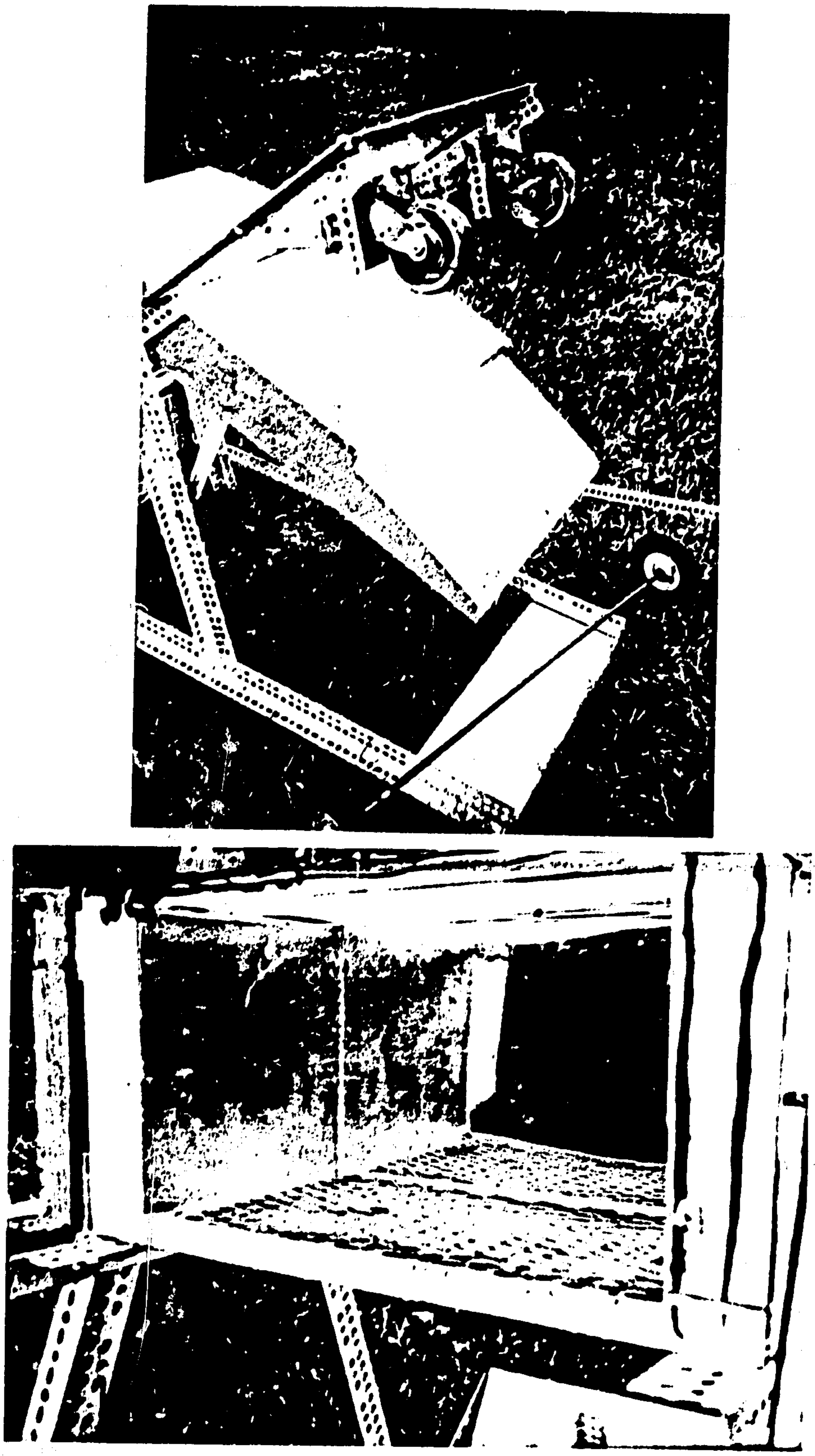

Figure 74. FIT cooker prototype. The top photo shows wheels being added, September, 1977. The lower photo is a close-up of the oven interior.

Our prototype, shown in Figures 73 and 74, used calcium silicate insulation, 2½ inches thick, on the back and two ends, and urethane foam, 3/4 inch thick (later replaced with one inch Foamglas) on the unglazed portion of the bottom. The door was made by bonding Kalwall Sun-Lite Premium II translucent fiberglass-reinforced plastic on each side of a 3/4 inch wood frame. The top was originally simply a layer of Kalwall Sun-Lite Premium II bonded to the top of the oven, with a wood rail across the front for stiffening and to carry the gasket for the door. Later, the wood rail was extended all the way around the top and a second layer of Kalwall Sun-Lite was bonded to the top of the rail, resulting in a very significantly improved performance. The glazing on the top and door was intended to increase the incident radiation relative to opaque surfaces, but this gain may be largely offset by increased heat loss through these surfaces. Fabrication would be simplified if this glazing were replaced by insulation. Because of the "dirty" (white powder) characteristic of this insulation, all three insulation blocks were first built into aluminum boxes, and the aluminum boxes then were riveted together with two aluminum channels across the bottom, to form the oven. In the future we would use Foamglas for its greater insulating value and lower cost, and build it into a sheet metal outer box, with the inner surfaces of the insulation exposed as in the Foamglas Telkes oven.

Bonding, in this oven as in others, was with silicone adhesive/sealant, a viscous, gap-filling substance that can withstand temperatures to 500°F, and cures at room temperature to a pliable, compressible, rubber-like substance.

This cooker is described further, with drawings showing most details, in Appendix G.

VIII. FINAL TESTS OF COOKERS

A. INTRODUCTION

The final series of tests under this program was carried out during late May, June, July, August, and early September, 1977, with a few tests continuing at periodic intervals through the Fall. For these tests, an instrumentation console consisting of five strip chart recorders and one digital thermometer was built up, and a temperature/humidity recorder was also kept continuously running. One of the strip chart recorders was dedicated to a solar pyranometer, a horizontally oriented device that measures total solar flux, or global flux: indirect and diffuse radiation as well as direct solar radiation, from throughout the hemisphere viewed by the instrument. It should be noted that, if the radiation were all direct, the measurement indicated by this instrument should be sine θ times that indicated by a hand-held radiometer aimed at the sun (such as we used in Haiti), θ being the angular elevation of the sun above the horizon.

The other four strip-chart recorders were used for recording temperatures, which could be input from any of ten points in the test area. Temperature sensors were copper-constantan thermocouples sealed in stainless steel sheaths. Any of the temperature sensors could also be connected to the digital readout. Accuracy was checked periodically, and was always found to be within $\pm$ 5°F, usually within $\pm$ 3°F.

During the course of the summer, quite a large volume of data was collected. A thorough, systematic analysis of the data was not undertaken, in part because the test period was also a period of intensive development and modification of the highest-rated cookers, and because the tests themselves were learning exercises in which we looked at the effects of a variety of different factors and events on the cooker performance. The primary value of many of the tests was an immediate benefit rather than any long-term benefit, because the cooker itself was modified after the test. We have, however, selected a few representative tests for presentation in the following section. Results of these tests were typical, and do much to describe the behavior of some of the cookers.

B. COMPARATIVE TESTS, THREE TELKES OVENS, MODIFIED "SOLAR CHEF" AND F.I.T. COOKER

Figures 75 through 82 are indicative of some of the results that we obtained during the Summer. All of these figures are direct reproductions of the strip-chart recordings and include notes made on the chart paper as the tests progressed that are usually unreadable as reduced here, and probably irrelevant in most cases. Time increases upward in the records; temperature or insolation increases to the right.

Figure 75 shows results obtained with the first of our large, fully successful cookers, the modified Telkes/Halacy oven described in Section D of the preceding chapter. A series of very successful tests were performed using this oven during the last days of May and early June, ending as the ever-growing cracks in the oven's double-glazed window caused rapidly worsening performance later in June. In Figure 75, showing a test on June 3, the left curve is insolation, the center curve is the indication given by a thermocouple lying in the oven, and the right-hand curve is the temperature recorded by a probe in a vessel containing one liter of water that was placed in the oven as soon as it had attained an apparent maximum temperature. The "oven temperature" probe was exposed to the sun in this case; somewhat lower readings were normally found if the probe was shaded, and if submerged in a pan of oil it usually seemed to read somwhere between the readings that would be given by sunlit or shaded probes. As discussed earlier, the significance of the temperature indicated by an exposed probe in a solar oven is questionable. Whether sunny or shaded, its equilibrium temperature will not be the same as that of a larger object with different surface properties, in the same oven.

In Figure 75, we see that as the sun rose (times given are in Eastern Daylight Time) it first struck the pyranometer at about 8:07 AM, at which time the reading rose from around 60 Btu/ft^2-hr (the level of diffuse and scattered radiation at this time) to about 140 Btu/ft^2-hr. At this time, the oven was still mostly shaded by a taller section of the building just east of our rooftop test area. Enough sun was hitting the oven - at the top of the top mirror - to bring its temperature to about 90°F. Following a cloudy period from 8:15 to 8:25, during which the oven temperature rose 10°F, the sun's rays then fell directly on the oven and its temperature rose rapidly and steadily to 340°F in 55 minutes. Starting at 9:20, a 15 minute cloudy period dropped the oven temperature to about 300°F. At 9:35 the sun returned - the pyranometer now reading 240 Btu/ft^2-hr due to the sun's rays being more nearly normal to the sensor - and within 25 minutes the indicated temperature had gone off-scale at 400°F. (The highest oven

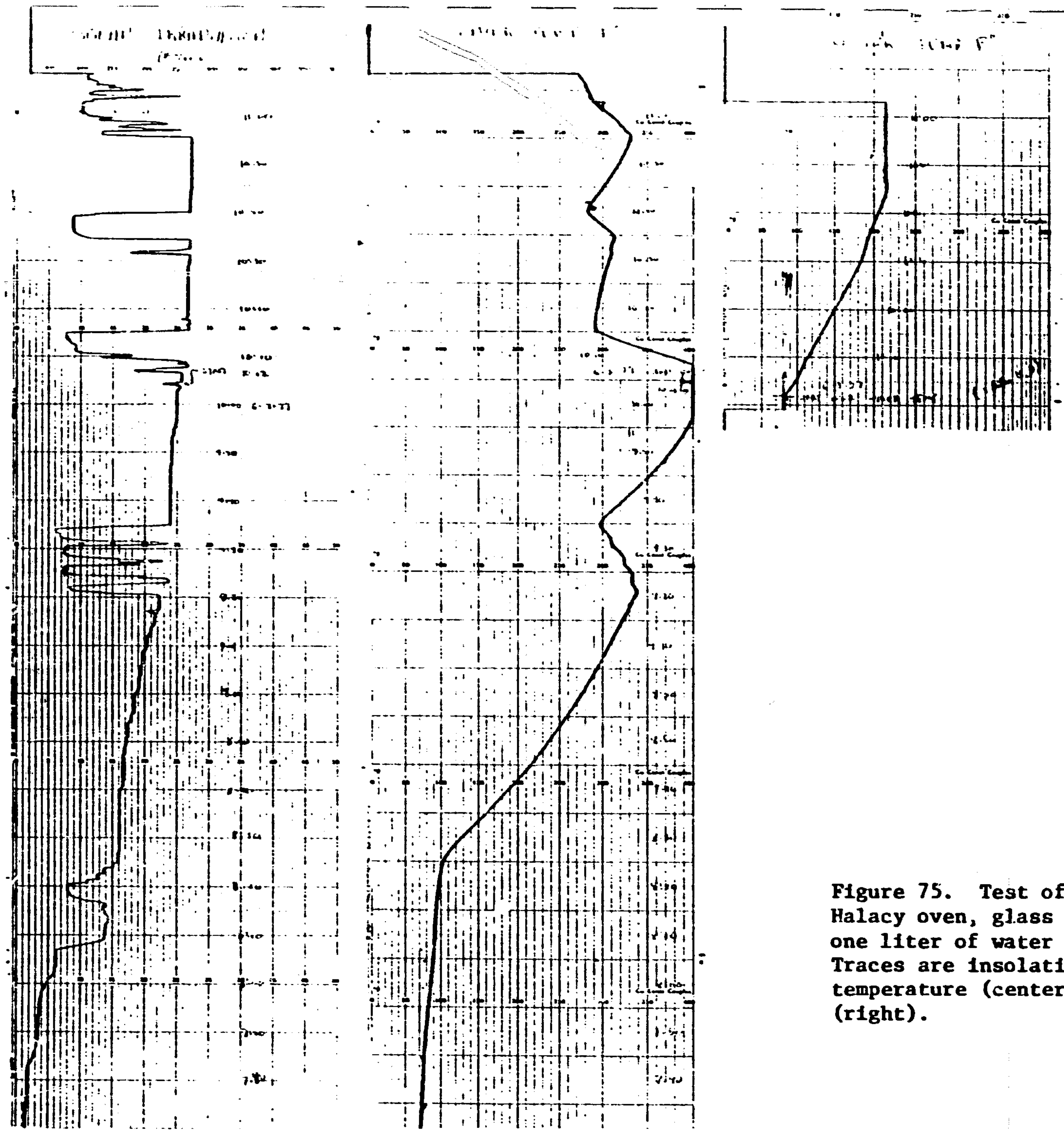

Figure 75. Test of modified Telkes/ Halacy oven, glass window (broken), one liter of water placed in hot oven. Traces are insolation (left), oven temperature (center), water temperature (right).

temperatures we saw on the digital thermometer were in the neighborhood of 450°F, although for this particular test the digital thermometer was not used.) At 10:02 AM, one liter of water at ambient temperature (80°F) was placed in the oven - at this time the indicated oven temperature is assumed to have been about 415°F, by extrapolation. Within five minutes clouds began to block the sun, and when the oven temperature came back on scale it was dropping rapidly, and continued to drop, due both to the pan of cool water and the clouds, until the sun again fell on the oven, at which time the oven temperature was about 290°F. During all this period the water temperature was climbing rapidly, due primarily to heat gain from the oven because of the temporarily cloudy condition.

During the next fifteen minutes of bright sun at 265 Btu/ft^2-hr, the oven temperature rose to 310°F and the water temperature rose at a greater rate. More clouds between 10:30 and 10:40 dropped the oven temperature to about 285°F, and caused a reduction in the rate of water temperature rise. The water reached the boiling point at 10:45 AM, 43 minutes after being placed in the oven. For approximately eight of the forty three minutes there had been full cloud cover - insolation less than 100 Btu/ft^2-hr - and for another six minutes or so the insolation had been less than 200 Btu/ft^2-hr. Bright, unimpeded sunlight had existed for about 25 minutes.

Similar results, in terms of time to boil, were obtained earlier and later than this test. A few days earlier, 1.5 liters of water had required one hour twenty minutes to climb from 90°F to the boiling point in the modified Telkes/Halacy oven. On July 12, with a glass window that by then was badly broken, one liter of water boiled in one hour twenty five minutes; only occasional clouds passed in front of the sun on that morning. On July 21, a perfectly clear morning, one liter of water climbed from 115°F (we were slow connecting the instrumentation) to the boiling point in 45 minutes. On August 9, after the broken glass had been replaced with translucent diberglass-reinforced plastic glazing, one liter of water initially at 90°F boiled in a little under an hour.

Figure 76 shows the results of testing much later in the summer, August 16, which was the first day that the F.I.T. Cooker in its final configuration - an oven-type receiver with double-glazed top - was tested (center trace). At the same time, our modified "Solar Chef", which had been in use for several weeks, was also tested for the sake of comparison (right curve). On this morning, the sky was cloudless. Measured horizontal surface insolation (left curve) was generally a bit lower than on June 3, partly because of the sun not climbing

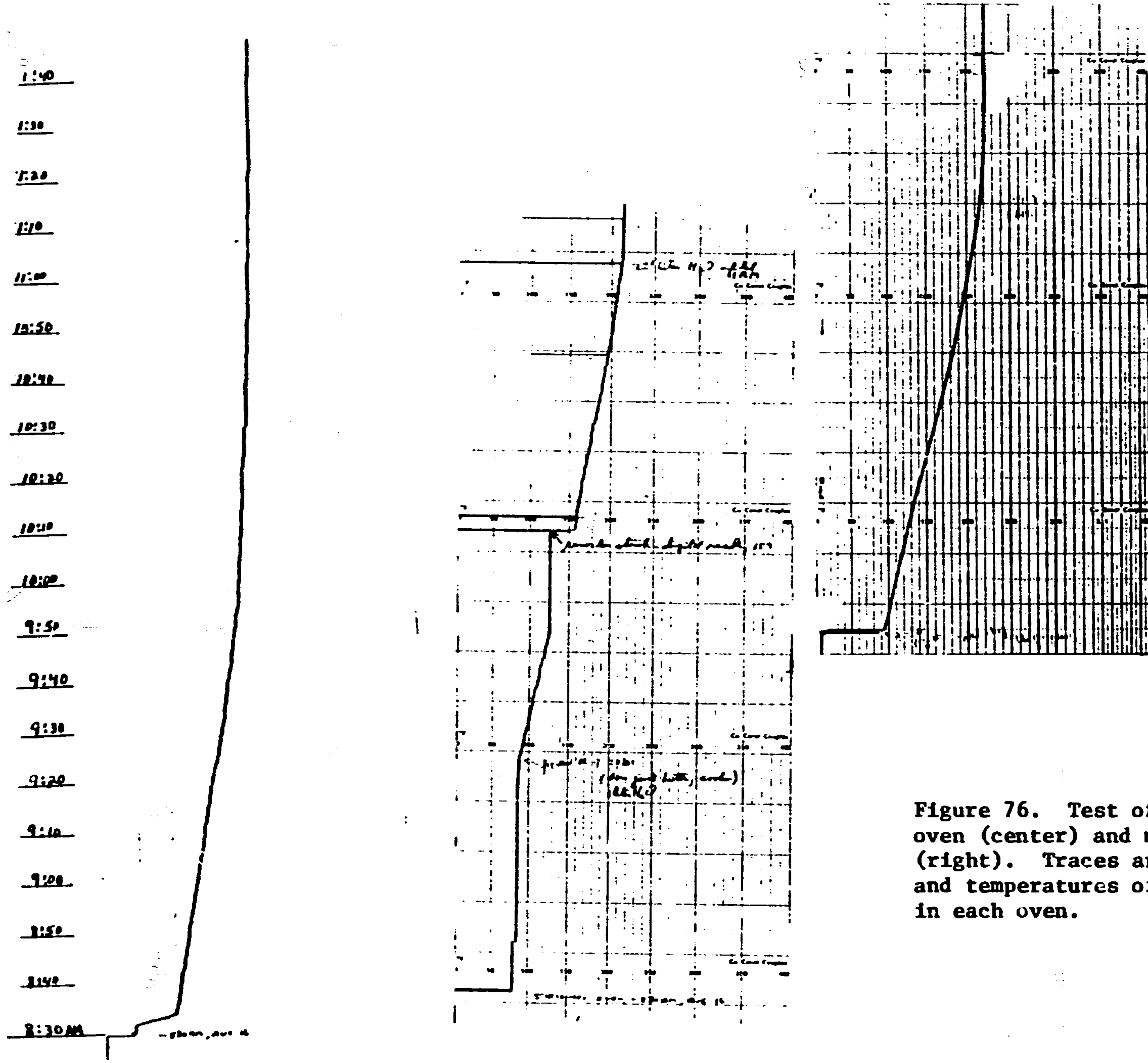

Figure 76. Test of Foamglas Telkes oven (center) and modified Solar Chef (right). Traces are insolation (left), and temperatures of one liter of water in each oven.

as high in the sky eight weeks after summer solstice and probably in part because of a generally greater level of atmospheric water vapor. The fact that with full sun on the pyranometer, only 100 Btu/ft^2-hr was indicated at 8:35 AM and 150 and 200 weren't reached until 9:10 and 9:50, respectively, is a strong indication of the amount of early morning water vapor in the air on this day; see, for comparison, the August 29 trace in Figure 77. July, August, and September were quite rainy in Florida, as is usually the case, with most of our testing being confined to the morning hours due to afternoon cloud cover nearly every day.

In the August 16 test, the sun began falling on the pyranometer (which is elevated, and farthest from the shadow source) between 8:30 and 8:35 AM, and did not reach the F.I.T. Cooker's reflector (low, and closer to the tall portion of the building) until 9:20, when the cooker was first aligned. As soon as it was aligned, the modified Solar Chef was set up, and it can be seen that the water temperature there had already reached about 95°F when the instrumentation was connected at 9:35 AM. Each cooker contained one liter of water, with a temperature probe measuring the water temperature. In the Solar Chef, we experienced a slight measurement problem that occurred frequently in our top-heated cookers: the probe was not fully submerged in the water, and because of the much higher temperature existing just above the water surface the resultant reading was a few degrees too high. At 10:00 AM, the water temperature was about 155°F in the F.I.T. Cooker (the trace appears irregular because of a sticky recorder pen) and 135°F in the Solar Chef. At 10:30 AM the indicated temperatures were 190°F and 183°F. The water began to boil in the F.I.T. Cooker at 11:00 AM, and in the Solar Chef at 11:10. Time to boil was about one hour forty minutes in each case - a little more than twice the time obtained in the June 3 test of the Telkes/Halacy oven, but still quite acceptable.

As soon as the water in the F.I.T. Cooker began to boil, a second liter of cool water was added, in a separate container. The temperature sensor remained in the first container. As we had hoped, the first container of water was not affected - it continued to boil. We had learned earlier that a second liter of water placed in the Telkes/Halacy oven causes a drop in temperature of a previously-boiling container of water. In the F.I.T. Cooker, the greater concentration of solar energy directly on the pan apparently acts to counter-balance heat transfer from the hot pan to the cool pan. (The Solar Chef, even as modified, does not accommodate two pans at once.)

At the same time that these tests were being performed, we were investigating the performance of the Telkes/Halacy oven in a non-tipped mode. Tipping was such a problem with this oven that we wanted to see how it would perform if it were just rotated to follow the sun, but never tipped back from the position where the floor is horizontal. The strip chart record is not reproduced here, but it shows that, starting with an empty oven at 9:00 AM, the oven temperature climbed to 365°F in the first hour and twenty minutes, then slowly fell as the sun climbed higher in the sky, dropping to 300°F by 11:50. At that time 3 liters of water (the maximum amount that the oven would normally bring to a boil in a reasonable time) was added, dropping the oven temperature rapidly to 165°F. The oven temperature stayed low until nearly 3:00 PM, and the water did not boil until well past 4:00 PM.

Similar results had been obtained on the preceding day. One liter of water placed in the oven at 10:15 AM boiled in an hour and a quarter - much longer than the times obtained previously. At 12:20 a second liter of water was added in a separate pot, and caused the first water to stop boiling. We couldn't get it to boil again, and eventually stopped trying until 3:00 PM. At that time the water was still at 175°F; we aligned the oven and it boiled in about fifty minutes.

On another occasion, we had placed three liters of water in the non-tipped Telkes/Halacy oven at about noon, and waited 5.5 hours for it to boil. Temperatures at half hour intervals starting at 12:30 PM were 115°F, 128, 136, 143, 147, 155, 166, 178, 190, 209. The improvement in performance through the afternoon, as the sun dropped, is apparent.

A large amount of data on the modified Solar Chef, beyond that reproduced here, was obtained. A series of tests in mid-July gave the following results:

July 15: one liter of water boiled in just under an hour and a half. Except for a 3.5 minute cloud just after the test began, the morning was perfectly clear, insolation measured at 235 Btu/ft^2-hr at the beginning of the test (10:25 AM) and climbing to 245 at the end. Ambient temperature was 86°F, relative humidity 58%, wind at 5 to 7 miles per hour. In the afternoon, the empty cooker was preheated to a maximum attainable value of 223°F, and one liter of water at 120°F was added. The water temperature rose by more than 50°F in the first half hour, but it never did boil because of partly cloudy conditions and the need to terminate the test at 4:50 PM when the sun dropped too low for this cooker to be able to follow it. Wind in the afternoon was 10 to 15 miles per hour, ambient temperature 90°F.

July 19: One liter of water boiled in about one hour forty five minutes. We were investigating performance with a minimum of attention to the cooker: it was realigned only twice during this period. The morning was partly cloudy almost all the time, but insolation was 240 to 250 Btu/ft^2-hr between clouds. Ambient temperature 90°F, humidity 68%, wind 5 to 7 miles per hour.

July 20: One liter of water was placed in the cooker, and the cooker aligned, at 9:55 AM. The cooker was adjusted (aimed) again at 10:15, 10:40, and 11:00. The water boiled at about 11:15 (one hour twenty minutes). Weather conditions: scattered clouds, 85°F, 74% relative humidity, wind at 10 to 12 mph, insolation 225 to 250 Btu/ft^2-hr between clouds.

July 21: One liter of water at 120°F when data recording began (10:23 AM) boiled one hour later. Clear sunshine at 220 to 235 Btu/ft^2-hr, 86°F, 70% relative humidity, wind velocity 3 to 5 mph. This test coincided with a test of the modified Telkes/Halacy oven briefly mentioned above. From the same starting point, and with a broken glass window, the water in the Telkes/Halacy oven boiled fifteen minutes sooner.

Figure 77 shows one of our few all day tests, and the first test made with the Foamglas Telkes oven after the interior volume was reduced. On this day, August 29, some early morning cloudiness gave way to full, bright sunshine from shortly after 10:00 AM until 1:00 PM, at which time a fast-moving storm with strong winds and very black clouds rolled in . The pyranometer cover was replaced at this point and we left the test area for about an hour and a half, although the actual duration of the storm was only about fifteen minutes. The afternoon was partly cloudy, with fifteen to twenty minutes of hard rain beginning about 4:25 PM. After the rain passed, the sky was clear once again. Morning insolation was about the same as on August 16: 215 Btu/ft^2-hr at 9:45 AM, 230 at 10:30, 235 at 11:30, 250 at 1:00 PM. If anything, the early readings were better on this day (two weeks later), indicating less atmospheric water vapor.

One liter of water was placed in the oven at 10:10 AM, and the sensor, which had been lying exposed in the oven, was placed in the water. Because of the pan used (the Haitian cast aluminum bowl, capacity 1.6 liters, shown in Figures 35 and 60, with an aluminum top that we made) the temperature probe barely reached the

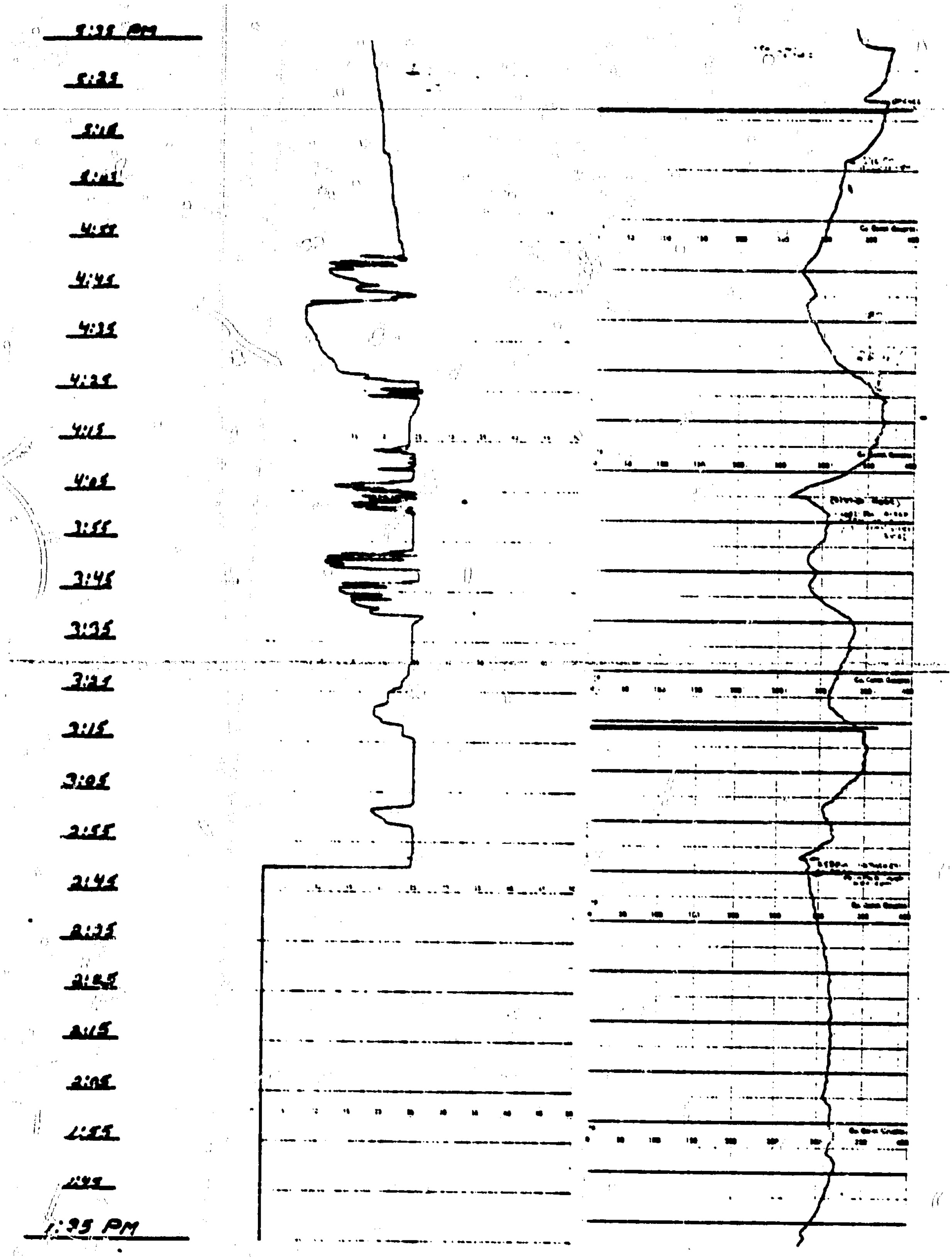

Figure 77. Test of Foamglas Telkes oven. Left trace is insolation; right trace is temperature of one liter of water until 1:00 PM, oven temperature thereafter. (continued next page.)

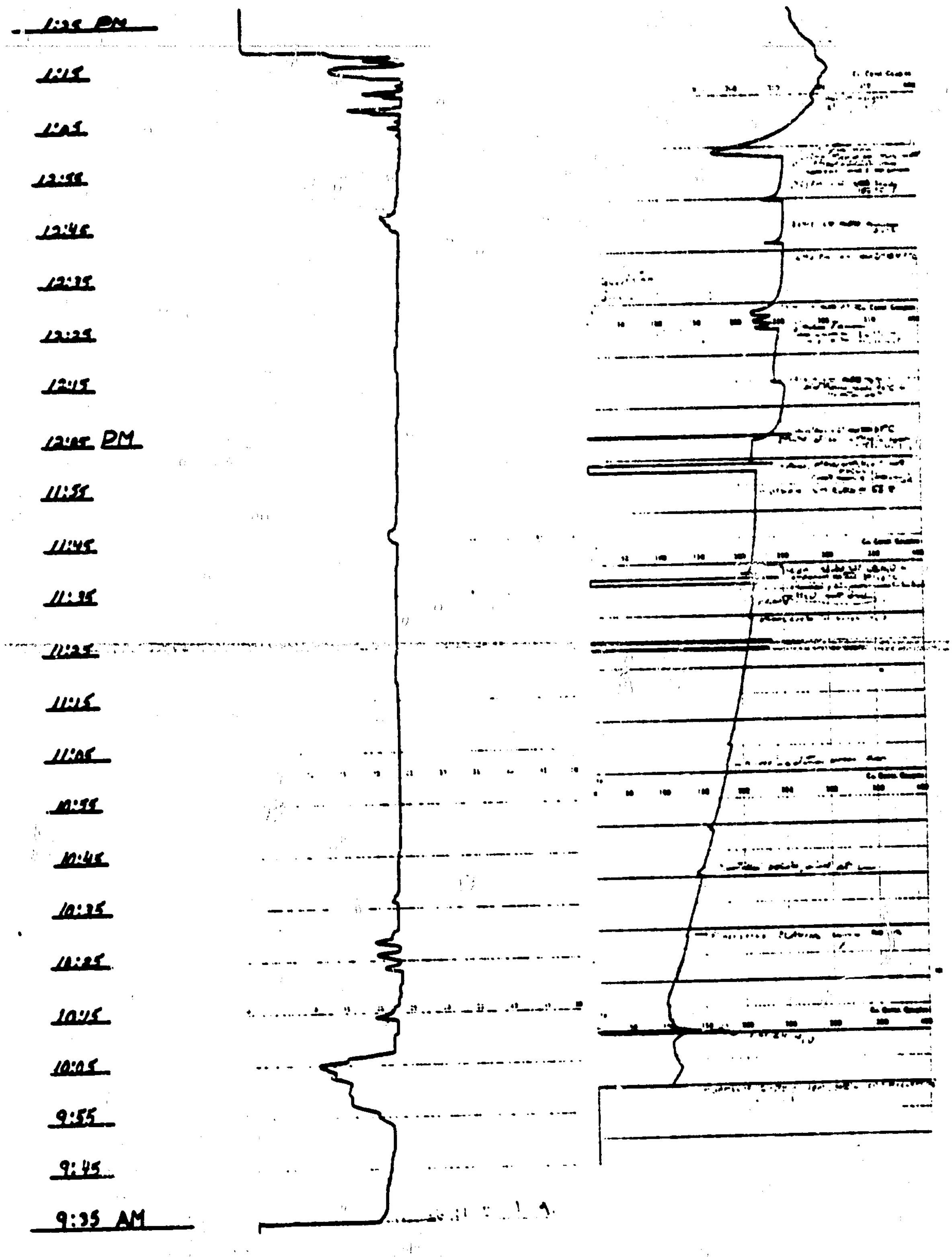

Figure 77. (continued).

water, so the recorded temperature dropped for several minutes before it stabilised, and thereafter was probably always several degrees too high. During the first hour, modifications were being made to the oven door, an alignment indicator was added, and other last-minute changes, but the indicated water temperature climbed to 190°F after 60 minutes in spite of this activity. The indicated temperature reached the boiling point at 11:30 AM, but shaking the cooker to slosh the water around dropped the indicated temperature by 5°F, another indication of the measurement problem we encountered. Another kettle containing a second liter of water was added to the oven at 11:40 AM; initial temperature of this water was 38°C due to its having been in the sun all morning. Within fifteen minutes, the temperature of the second liter of water had climbed 20°C (36°F) and the temperature of the first liter had stopped climbing - opening the door and inspecting the contents indicated that the water in the Haitian pot was not boiling. A realignment of the oven just past noon caused a dramatic rise in indicated temperature in the Haitian pot, probably just the result of the sun hitting the top of the pot more directly and heating the vapor space. At 12:15, two hours after the start of testing, the oven was opened and a dial thermometer used to read both water temperatures: 96°C in the Haitian pot, 78°C in the second kettle. Fifteen minutes later, the first liter was boiling and the second liter was at 89°C. Another twenty minutes - one hour and ten minutes altogether - were required for the second liter to boil. These times to boil are probably not too significant because of the amount of door-opening, top-removing, etc. that was going on, and the fact that the oven was not pointed very directly at the sun at times.

At 1:00 PM the oven was emptied because of the impending storm, which turned out to be of short duration. The sensor was left in the oven, and during the next fifteen minutes of partial clouds before the sun was obliterated the indicated oven temperature climbed from 175°F when the door was replaced to 310°F. When we eventually returned to the test area at 2:50 PM (see continuation of Figure 77) we found that the storm had only caused a drop to 255°F, after which the temperature had climbed to 320°F and then gradually fallen to 290°F after two hours in the same position. Pointing the oven to the sun's new position caused the temperature to climb to 350°F in twenty minutes, after which it dropped to 310 with a passing cloud, climbed to 335, and then dropped to 280°F. At this time the door was opened, at a cost of 15°F, and then the oven was realigned after seventy minutes in the same position. Better aim resulted in a climb to 365°F - the highest temperature yet for this oven - in fifteen minutes. Fifteen to twenty minutes of rain dropped the temperature to a still-high 275°F, after which it rose again to 320°F. An adjustment at 5:12 PM, after another seventy minutes in one position, brought the temperature back to 365°F. At 5:35 PM, the temperature sensor was moved to a shady location behind the swinging rack, causing a drop in indicated temperature from 370°F to a stable 330°F. Hence we concluded that the oven was maintaining a temperature in the neighborhood of 350°F even at this late hour, with the sun dropping low in the sky. At 5:45 we turned off the recorders and left the test area, with the oven aimed at the horizon at the approximate point where the sun would set. Returning at 8:00 PM, well after sunset, we found the oven temperature was still approximately 200°F - a good indication of its ability to keep food warm for a late evening meal.

Figure 78 shows the first run of the small Telkes oven, with 0.5 liters of water (center curve), on August 31. The sky was very clear, although a poor connection between the pyranometer and its recorder caused the signal to be periodically interrupted, and off entirely for nearly an hour prior to the final repair at 12:30 PM. The small quantity of water reached the boiling point in two hours. 1.5 liters of water was placed in the Foamglas Telkes oven (right-hand curve) about a half hour after the small Telkes test started, and boiled in one hour forty minutes - no longer, really, than the time required for one liter in the same oven.

Two liters of water in two containers took a bit longer - just over two hours - to reach a boil in the Foamglas oven on September 3 (Figure 79). This time agrees well with the results obtained by the FAO in 1959, which recorded times of 92 to 165 minutes to boil two liters of water in a black aluminum pan in a Telkes oven. If only the runs with reasonably continuous sunshine are considered, their longest time to boil was 140 minutes and the average was 112 minutes, about thirteen minutes less than our result. In our test, the sun was covered for about 22 minutes. In other tests, we determined that both the Foamglas oven and the F.I.T. cooker were capable of bringing three liters of water (in two pans) to a boil in times on the order of two to four hours, depending on the weather.

On August 18, a full liter of water had been tested in the small Telkes oven. It did reach a boil, but only after four hours, fifteen minutes. On the afternoon of August 31, in very clear weather, a test was made with an empty oven.

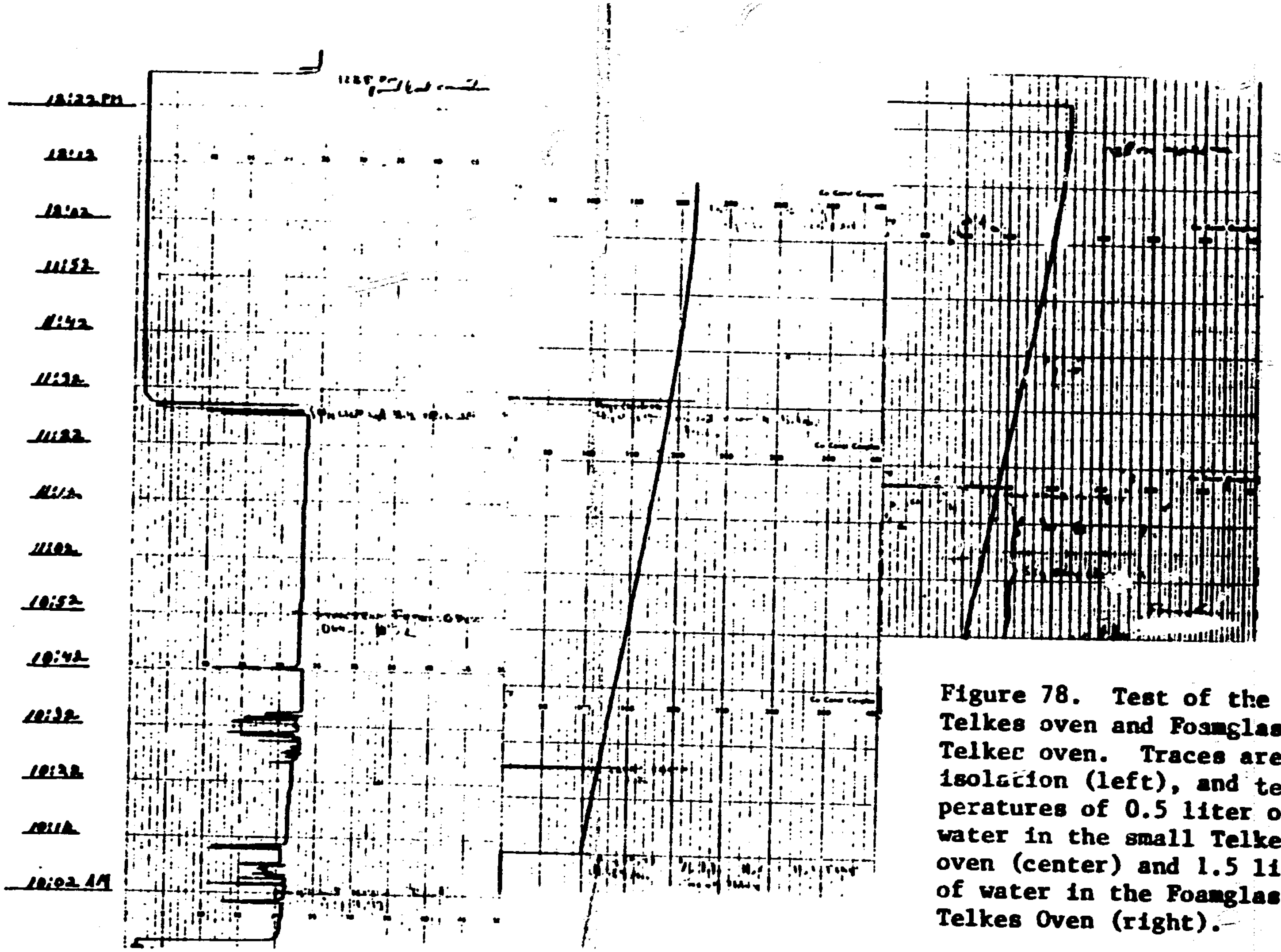

Figure 78. Test of the small Telkes oven and Foamglas Telkes oven. Traces are isolation (left), and temperatures of 0.5 liter of water in the small Telkes oven (center) and 1.5 liters of water in the Foamglas Telkes Oven (right).

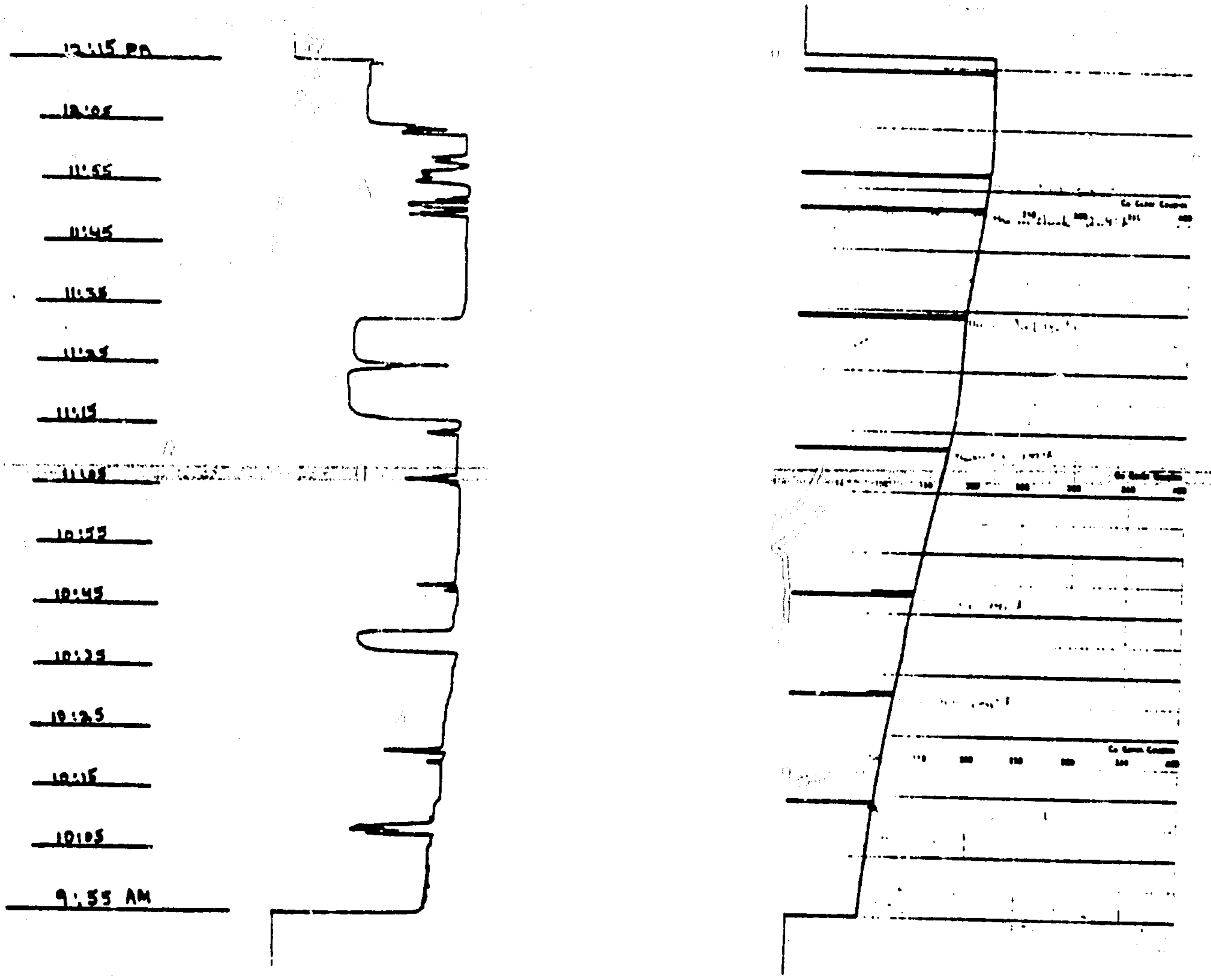

Figure 79. Test of Foamglas Telkes Oven. Left trace is insolation; right trace is temperature of two liters of water.

Maximum indicated temperature was 280°F, much lower than obtained with the larger Telkes ovens. The reason is believed to be the relatively large ratio of surface area to window area in this oven. In other words, not the small size of the oven per se, but the fact that the oven was actually made too large, for the size window used, in the interests of having something that a kettle could be placed in.

All of the tests described thus far - except the empty oven tests - have involved boiling water, as did most of the solar cooker work that preceded our studies. The lengths of time required to boil various amounts of water is probably more indicative of cooking effectiveness than any other single parameter, especially if cooking is going to be mainly by boiling. Because of the phase change, though, these tests do not allow the high temperature capability of the cookers to be probed. We therefore performed some tests in which cooking oil was used in place of water. Because the oil does not boil in the operating temperature range of these solar cookers, it allows maximum attainable temperatures to be measured. In addition, it does not place the heat load on the cooker that hot, rapidly evaporating water does, and hence steeper temperature rises can be obtained.

We performed two series of tests using oil - one in late May with the modified Telkes/Halacy cooker, and the other in the Fall with the Foamglas Telkes oven. The F.I.T. Cooker has not been tested with oil.

In three days of testing in late May, the oil in the modified Telkes/Halacy oven reached maximum temperatures of 345°F, 375°F, and 400°F. In the two tests that started from ambient temperature, 300°F was reached in 42 minutes in one case and 48 in the other. 350°F was reached in 70 minutes. In the third test oil at 200°F at noon reached 400°F at 1:50 PM. These results are worth comparing with those obtained using the Indian direct-focusing cooker (Figure 11). In the best of those tests, 300°F was reached in twenty minutes and 350°F in thirty minutes; the maximum temperature was 398°F. Our experiments, performed under less ideal conditions (cooler, and probably lower insolation) and with an oven-type cooker whose advantages are not supposed to include speed, did indeed need more than twice as long to reach equal temperatures, but also equaled the focusing cooker's maximum temperature and would undoubtedly have been faster had the oven been pre-heated.

These tests are also interesting because of the good agreement with the FAO data. In thirty Telkes oven tests performed in Trinidad, Jamaica, maximum empty oven temperatures ranged from 134°C to 204°C (273°F to 399°F) with an average value of 176°C (349°F). Six other empty oven tests in Rome gave maximum temperatures ranging from 152°C (306°F) to 204°C (399°F).

Figure 80 shows the results of an oil temperature experiment in the Foamglas Telkes oven on October 6. One liter of oil was used. The oil and oven temperatures have been superimposed by tracing one record onto the other. Starting at 10:00 AM, with occasional clouds and best insolation values starting at 235 Btu/ft^2-hr and climbing to just over 250, the oil temperature climbed to 320°F in 95 minutes. The indicated oven temperature initially climbed much faster than the oil temperature, but then more slowly and the temperatures approached each other. With both temperatures at about 320°F, the day suddenly became increasingly cloudy. Interestingly, the oil temperature continued to climb to a maximum of 340°F, while the indicated oven temperature fell. As the cloudiness became more extreme, the oil temperature fell, and when the clouds passed both temperatures climbed rapidly past 350°F. The test had to be ter~~minated at this point so the student conductor could attend class.~~

On the next day (Figure 81) there were fewer clouds, and more oil (1.5 quarts) was used. The indicated oven temperature was always higher than the oil temperature, so the records could be simply superimposed without tracing. The initial temperature rise was slow, as might be expected this early in the morning (still Daylight Time) in October, and with some clouds. When the test was terminated after two hours forty minutes, the oil was at 330°F and still rising with no decrease in slope.

Our most recent experiment was performed on November 8 (Figure 82). On a clear day, but starting before 9:00 AM (Eastern Standard Time by now) with insolation below 150 Btu/ft^2-hr, a still larger quantity of oil (1.4 liters) took nearly two hours to reach 300°F, at which time the measured insolation was still under 225 Btu/ft^2-hr. Just as the temperature reached 300°F, the oven door was opened and water was sprinkled on the top of the oil pan to demonstrate to a group of visiting grammar school students that it really was hot and we weren't tricking them. The result was a drop in temperature of fifteen to twenty degrees. The temperature then climbed again, gaining about 50°F in a half hour and passing 340°F by the time the test was terminated.

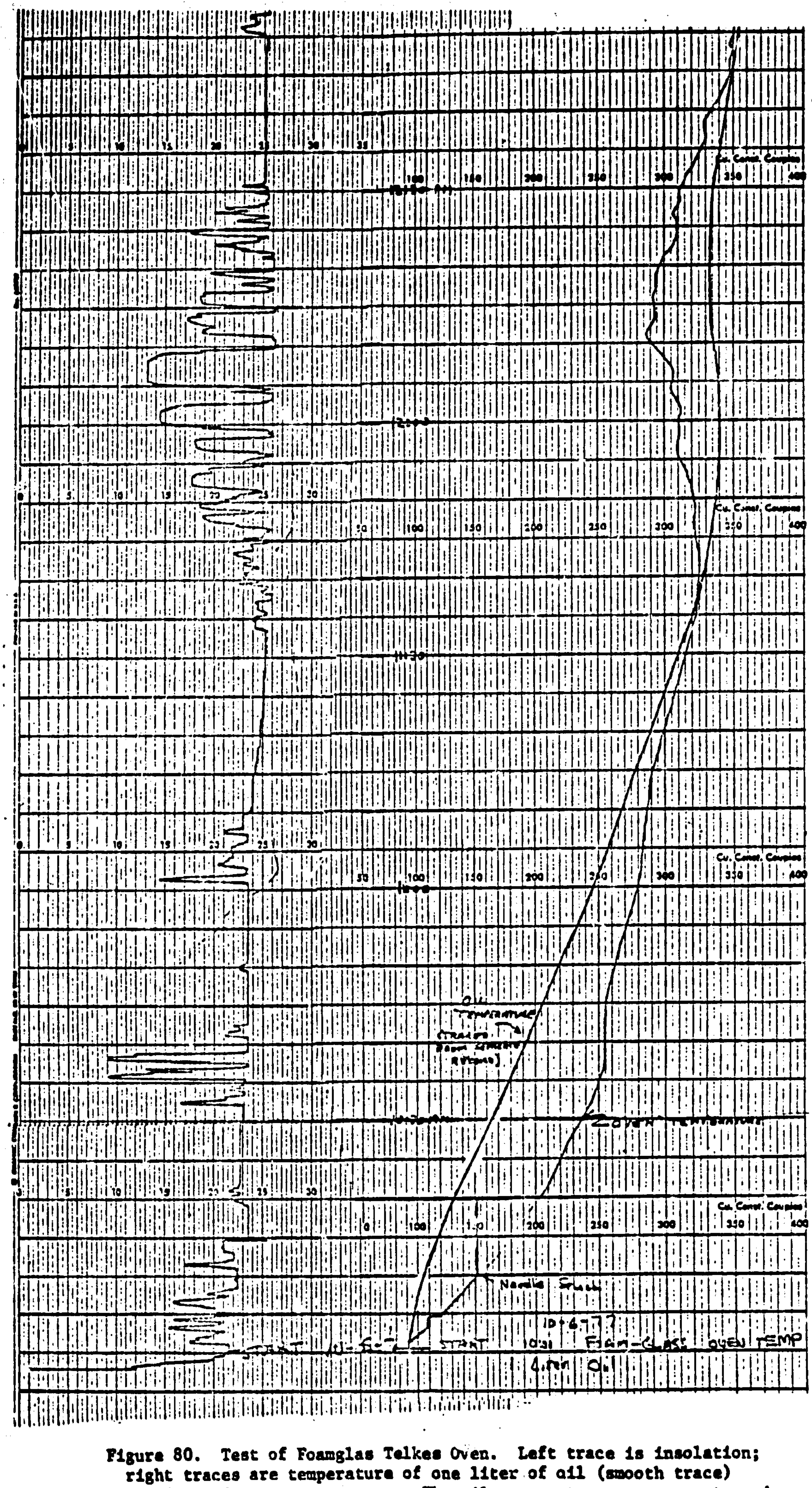

Figure 80. Test of Foamglas Telkes Oven. Left trace is insolation; right traces are temperature of one liter of oil (smooth trace) and indicated oven temperature. The oil temperature curve was traced onto this record from the original, separate record.

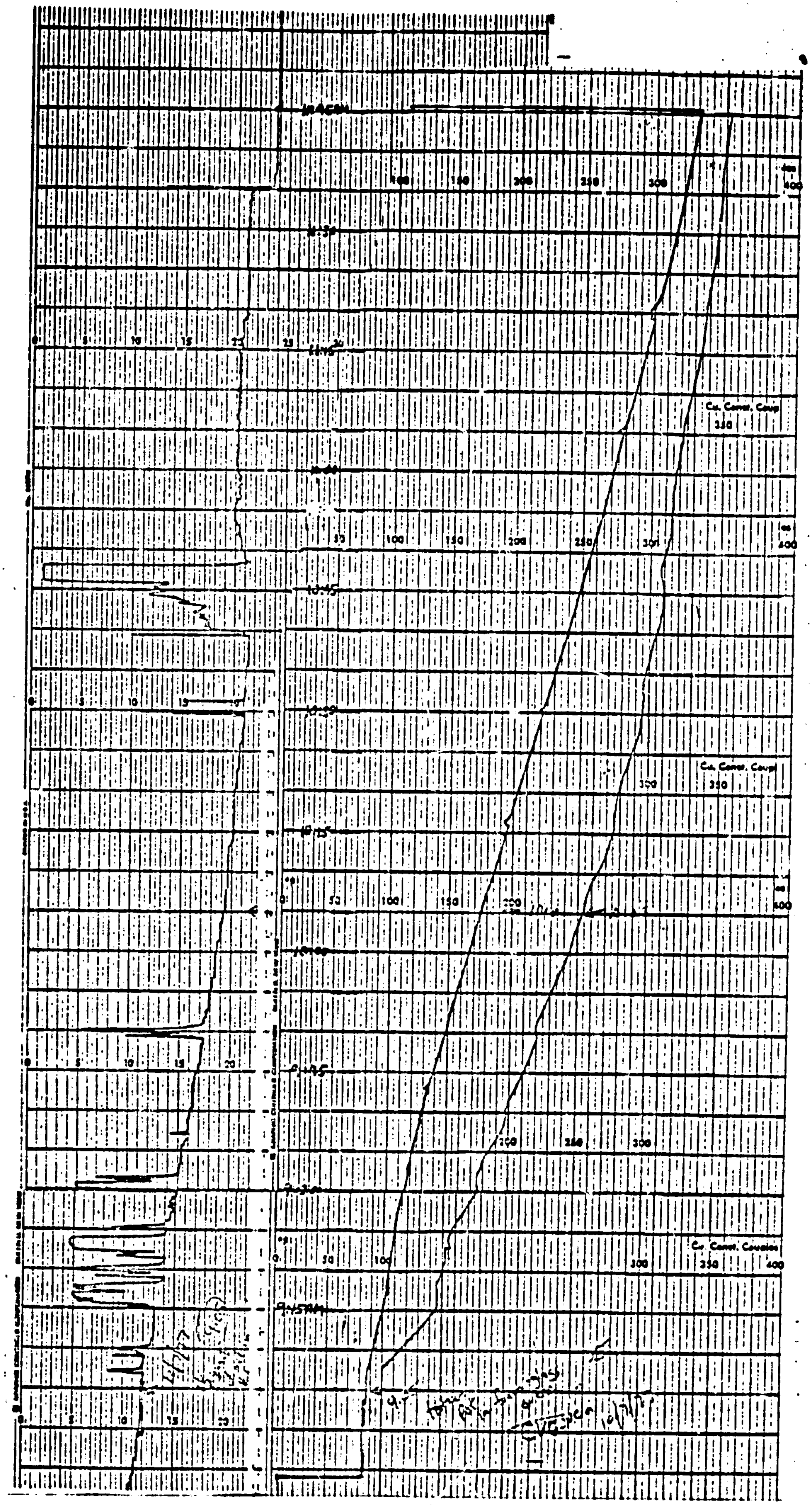

Figure 81. Test of Foamglas Telkes oven. Left trace is insolation; center trace is temperature of 1.5 quartes of oil; right trace is indicated oven temperature.

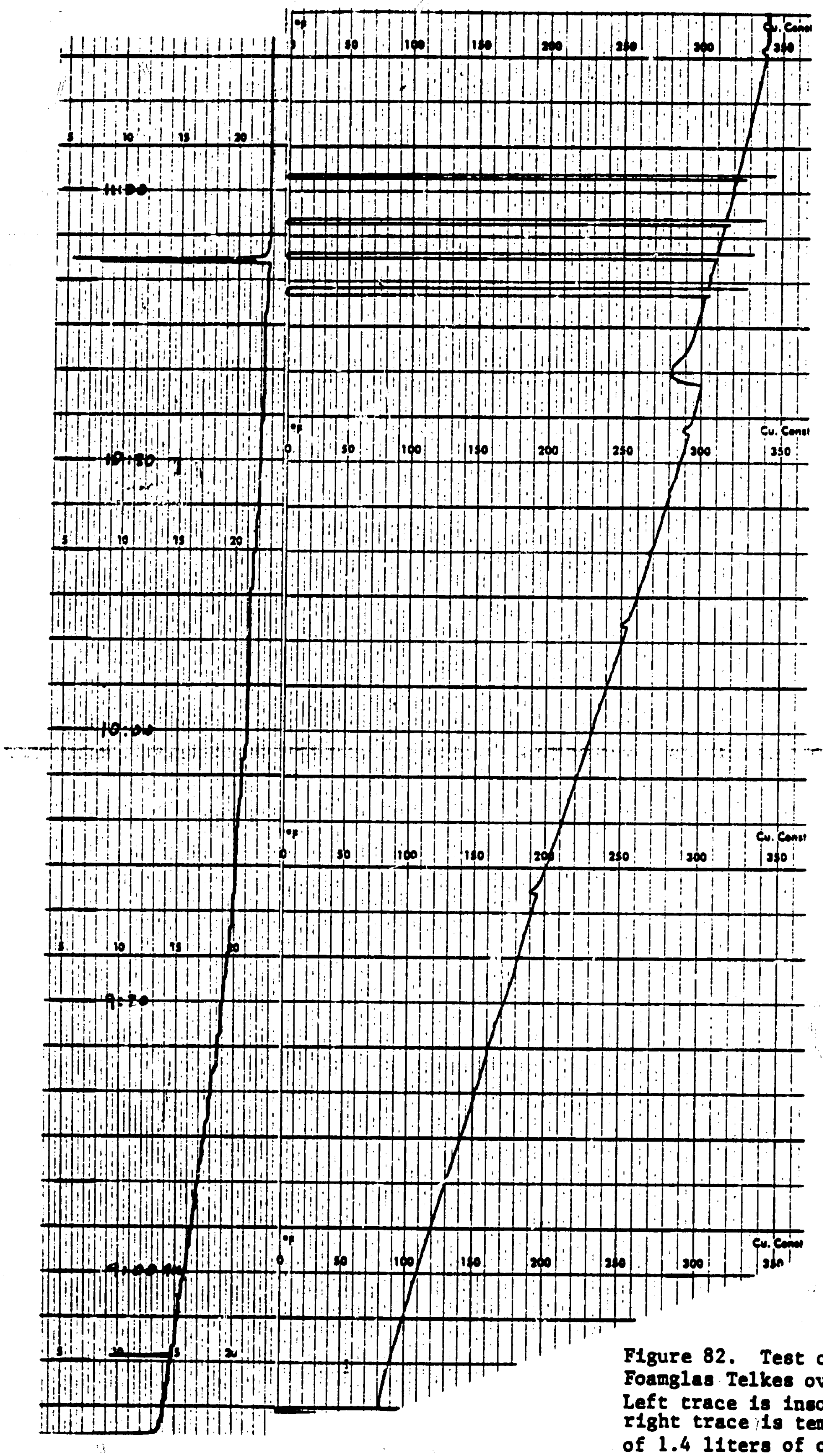

Figure 82. Test of
Foamglas Telkes oven.
Left trace is insolation;
right trace is temperature
of 1.4 liters of oil.

Our test results are especially positive with regard to the Telkes ovens. The modified Telkes/Halacy oven, tipped to always point at the sun, showed the highest performance: 400°F oil temperatures, boiling a liter of water in under forty five minutes, heating a liter of oil to 300°F in about forty five minutes, all under less than optimum weather conditions. In the arid regions of Northwest Haiti, the performance would undoubtedly be even better. The Foamglas Telkes oven performed well, but not on the same level: 350°F or higher oil temperatures, boiling two liters of water in two hours, and heating a liter of oil to 300°F in eighty five minutes. The lower performance was to be expected, since the oven was not as well insulated and used a somewhat smaller window and reflector, in spite of having a useful capacity at least as great as the first oven. With the improvements discussed in the next chapter, it is expected that the oven performance will be improved at no increase in cost - actually less cost if the cost of the Alzac reflector is charged against the current oven. If these improvements are realized, then the next step would be the design of a cheaper oven along the same principles, using a smaller window/reflector and/or less insulation, that would give up some performance for the sake of lower cost. These two improved ovens - one designed for high performance, the other for low cost - could then be taken to Haiti for comparative field testing to evaluate the real significance, if any, of the performance differential, under Haitian conditions.

It is noteworthy that our small Telkes oven, even though its window and reflector were too small for the oven volume, did perform acceptably for a limited range of duties.

The modifications made to the Solar Chef cooker were deemed to have greatly improved its capacity and versatility, at no measurable cost in terms of performance. In its current state it seems acceptable for Haitian application - it will accommodate a reasonably large pan of food, and cook it in a reasonable time. The only proviso is that a more durable glass cover would be required. When compared to the Foamglas Telkes oven, however, this cooker's performance does not seem as impressive to us as it did earlier in the program, when it was our only really good performer. The Foamglas Telkes oven clearly outperforms it - higher temperatures, faster cooking times - even without the indicated improvements, and is also much easier to use, has much greater capacity, and can be used with the sun at any position. It is, of course, more expensive because of the much larger and more complex oven box.

The F.I.T. Cooker has not been tested as thoroughly as these other cookers, as it was under development almost throughout the program. What data we have indicate that its performance is more or less on a par with the Foamglas Telkes oven. We expect this cooker can be significantly improved by redesign of the oven box - it could be smaller without really restricting the capacity, allowing both better insulation and a smaller shadow cast on the reflector. In addition, we are in the process of designing a second cooker - "F.I.T. Cooker II" - along the same general lines but with a much different reflector arrangement that will allow a greatly increased reflector area at no increase in cost.

C. REPRODUCTION OF THE PRATA "CYLINDRO-PARABOLIC" COOKER

The Prata concept was discussed in Chapter I, Section A, and shown in Figure 10 of this report. The results reported by Prata - all of which were actual cooking results, and hence rather qualitative - did look attractive. As a result, we reproduced his cooker in accordance with Figure 10; the result is shown in Figure 83.

Structurally, this cooker leaves quite a lot to be desired. The four legs move independently and with little or no constraint. The oven is free to turn and slide in it cradle. The center of gravity is high and off-center - two legs are barely loaded. The reflectors have no torsional stiffness, so each side is adjusted and clamped individually. Wind stability is poor, and our reflectors sustained some wind damage. Securing the window and rack against the circular-cylindrical oven walls is difficult.

Operation of the cooker is very difficult. Turning it to follow the sun is best done by two people because of the independent motions of the legs. There is a danger of spilling food or dropping the oven from its cradle when turning the cooker. Pivoting the reflectors to follow changes in the sun's elevation must be done every few minutes, as the slit is narrow and not perpendicular to the reflections from either mirror.

With proper attention, however, the performance is more than satisfactory. One liter of water was boiled in thirty five minutes on one occasion, and fifty three minutes on another. Testing was difficult, and not extensive. We believe the F.I.T. cooker, which operates on somewhat the same basic principle but has a rigid structure and needs much less attention, should give comparable performance and be a more acceptable alternative.

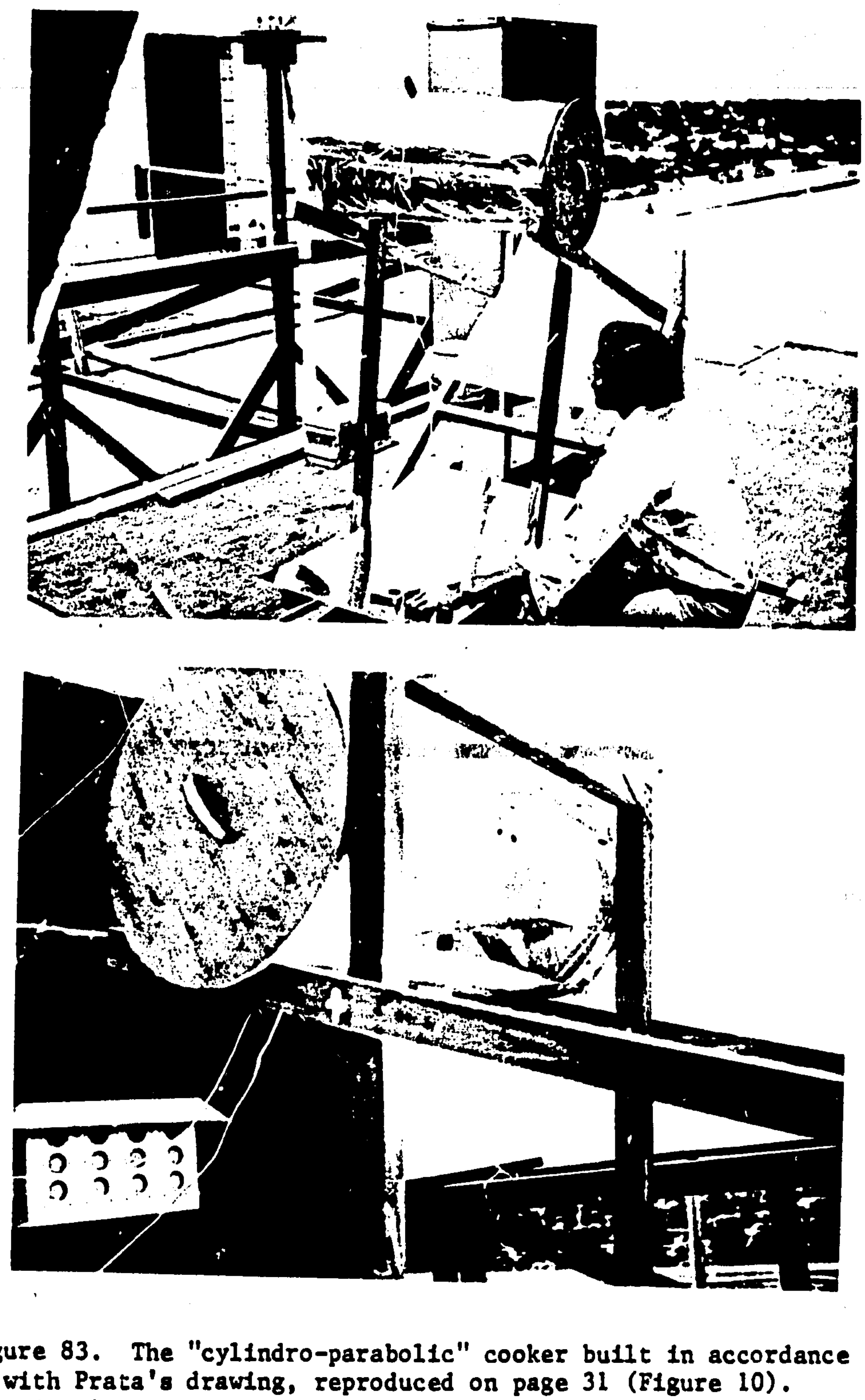

Figure 83. The "cylindro-parabolic" cooker built in accordance with Prata's drawing, reproduced on page 31 (Figure 10). The insulation has been removed in the vicinity of the window (lower photo) following incidents in which the insulation was set on fire when the focal region ddeviated away from the window.

We would like to acknowledge the contribution of Robert Drury, an undergraduate student assistant working on our project, who was responsible for building and testing this cooker. By the time he was finished he had successfully cooked various foods, such as rice and biscuits, in the cooker, and amply demonstrated its successful cooking performance.

D. DIRECT FOCUSING COOKER

The back-silvered acrylic reflectors discussed at various points earlier in the report are currently being manufactured, and we were eventually successful in obtaining a 48-inch example. The radius of curvature of this reflector was much larger than we had anticipated, and resulted in a focal region six to seven feet from the reflector. With such a long focal length, placing the receiver (cooking pot) high enough that reflected energy will strike the bottom, even with the sun high in the sky, is just not practical. A second disadvantage of this reflector is its extreme flexibility - it is essentially a large, thin sheet of plastic. Even storage is a problem - standing it on edge, for example, causes a semi-permanent set. A final disadvantage is that the surface with the reflective coating is not protected, and scratches very easily. On the other hand, the surface that needs to be clean can be cleaned readily, with little apparent danger of compromising the optical qualities of the reflector.

Due to the long focal length, it was not possible to build anything that could properly be called a Wisconsin-type cooker. In an attempt to simulate the Wisconsin cooker's performance, we did fabricate a steel rim into which the reflector could be clamped, with an adjustable stand. A gallon paint can was painted flat black and used as a receiver, supported about 5.5 feet from the ground by a second framework. Focusing was most readily accomplished by moving a piece of scrap lumber around in the vicinity of the focal point; when smoke erupted from the wood, we knew we had found the focal point and the reflector could be adjusted until the focal point coincided with the receiver.

Quantities of water up to about a liter could be boiled in fifteen minutes or less - a most impressive performance. We were never successful, however, in bringing a two-liter quantity of water to a boil, even when we insulated the top, back and sides of the receiver can. Local boiling on the side receiving the reflected sunlight did occur, almost immediately, but it was not possible to bring the rest of the water even near the boiling point. We assume that if we could have reflected energy to the bottom rather than the side of the can, we could have boiled this larger quantity of water. The FAO tests of the Wisconsin cooker (see Table 2) used two liter quantities of water, and reported an average time to boil of 41 minutes, best time 30 minutes (repeated several times) under apparently less than ideal conditions, although insolation values were not recorded. We are not aware of any published results treating larger quantities of water. It would be expected that time to boil would increase faster than water quantity, since with this approach to solar cooking the heat loss is a function of the quantity of water in the pan. We cannot estimate, however, the maximum amount of water that could be boiled in a direct-focusing cooker with this size reflector.

The FAO commented, in their test report, on problems with the cooker swinging in the wind, and we certainly experienced the same problems, although in part they were due to our quick-and-dirty structural setup. Moving of the focal point caused problems - we burned paint, and even burned holes through our receiver can when the focal point wandered above the water surface.

What to do with the reflector when not actually in use appears to be a potential problem. If the focal point is not on a cooking vessel, it is liable to be somewhere else. If a person inadvertently put a face or hand in the focal region the result would be painful at best. If the focal point were to fall on clothing or dry vegetation it might start a fire.

In summary, we cannot claim to have advanced the state of the art of this mode of solar cooking one iota, and do not have as much experience with it as we would like. We tend to have a prejudice against it based on the past failures of Wisconsin cookers and Indian cockers to gain user acceptance, in spite of apparently very good design and widespread distribution. Fabrication of a representative prototype was stymied by lack of a suitable reflector that is presently available "off-the-shelf" at a reasonable price, and by our strong desire to avoid reflectors that would have to be replaced or re-surfaced at frequent intervals.

At the time this report is being written, we have just learned of the distribution of some 250 solar cookers using large (15 square foot) parabolic reflectors in Upper Volta, by a Danish organization, and are attempting to learn more. Our evaluation of direct-focusing cookers would certainly be affected by the results of the Upper Volta program.

E. REFLECTOR AND GLAZING MATERIAL COMPARISONS

The materials cost for the Foamglas Telkes oven prototype is regarded as prohibitive. The largest contributor to this problem is the reflector, which in the Telkes design is very large in area relative to the amount of solar radiation collected. Approximately $60 worth of reflective aluminum (Alzac) is needed for our prototype. Although this cost would probably be reduced somewhat in the case of bulk purchase, it would probably never be competitive with the cost of glass mirror tiles, which can currently be purchased at retail for approximately $0.67 per square foot, or $13.50 for enough tiles for one reflector. Since these glass mirrors are also regarded as being more permanent, and are less "foreign" to Haitian customs and usage, we would plan to use them almost exclusively in the future. Even the F.I.T. cooker, which uses a curved reflector, could be built of plane glass mirrors if the reflector were segmented into long thin strips.

In terms of performance, we have not been able to identify any significant difference between Alzac and back-silvered glass in tests of Telkes ovens using both types of reflector, although we have not been able to make direct comparisons on otherwise similar ovens. A few pieces of Alzac were put in place next to the ocean in July for long-term weathering tests, but have not seriously deteriorated to date. We have a somewhat subjective sense that the Alzac on our Foamglas Telkes cooker is less "shiny" than pieces that have stayed in the lab, but have not made quantitative measurements. We have noticed that the Alzac is much more difficult to clean to a high standard once it has acquired water spots, tree sap, etc., than is glass.

Another important cost factor is the oven window, which in our Foamglas Telkes oven uses approximately $27 worth of tempered glass (although perhaps half or more of this cost results from the fact that the glass had to be special-ordered in small quantities). Ordinary glass (untempered) is not recommended because of its low strength at oven temperatures - the breakage problems we have encountered with ordinary glass would be intolerable in an actual field-use application. Plastic glazing materials are less expensive than tempered glass, but also less permanent. In addition to degrading slowly due to both elevated temperature and ultraviolet exposure, it is possible that some cooking fumes might affect the plastic. We do know that Telkes ovens have performed very well for us using both glass and plastic windows. The modified Telkes/Halacy oven seemed to give better performance with a glass window, even though cracked, than with the plastic that replaced the glass, but the fact that the weather was better when glass was used than later on contributed to the better performance.

"Appropriate technology" considerations seem to be of substantial merit in selecting reflector and glazing materials. Glass windows and glass mirrors are well-known and well-understood in Haiti and most other parts of the world, even if they are not as common or taken for granted as in this country. People know what they are, how to work with them, and how to replace them if broken. The same cannot be said for Alzac or plastic glazing. These materials would have to be introduced into the country specifically for solar cookers. The users might seriously damage them just as a result of lack of familiarity. Once damaged, they might never be replaced due to lack of available material of the same type and ignorance of the fact that window glass or glass mirrors would serve the same purpose.

Tempered glass, although uncommon except in car windows, would probably not be treated differently from window glass, and we see no problems. In the unlikely event of breakage, replacement with window glass would have, if anything, a beneficial effect on performance, at least prior to breakage.

Our Foamglas Telkes oven used one quarter inch thick tempered glass, which is the thinnest we could obtain on a custom basis. Thinner tempered glass would be amply strong, and would let more of the incident solar energy into the oven.

In summary, we have found no reason in any of our testing or other evaluations not to use glass windows and reflectors other than the high price of tempered glass. Glass mirrors are economically attractive, and glass windows and mirrors both seem more permanent and better suited to Haitian conditions than any of the alternatives.

IX. FINAL EVALUATIONS AND CONCLUSIONS

A. OVERALL COOKER EVALUATIONS

Detailed discussion of our evaluations have been presented in the preceding three chapters. Two basic types of cookers have emerged from those evaluations as meriting recommendation for Haitian application: the Telkes oven, and the F.I.T. cooker. Both are inherently sturdy, long-lasting, stable cooker configurations that have demonstrated good performance in our cooking tests. Both are capable of being scaled up to a size where they could serve large groups or small communities, and as such would become reasonably permanent fixtures in the villages they served. Neither is cheap, in terms of either materials or the amount of skilled or at least semi-skilled labor needed for fabrication.

Cookers of the type originally designed by Adams, such as our modification of the "Solar Chef", would also be suitable for Haitian application but are not being recommended because of the similarity to the Telkes oven, which seems to be inherently more powerful and more versatile.

Direct-focusing cookers such as the Wisconsin cooker, for many years the "front-runner" among solar cookers, are not being recommended for three reasons:

1. We have yet to see a solution to the compound-curvature reflector problem that is sturdy enough, durable enough, and cleanable enough, at a reasonable cost.

2. Use of these cookers is more difficult, requires more skill and more constant attention, and involves somewhat more danger to the user.

3. The cookers are not as versatile with regard to quantities or numbers of items that can be cooked at one time, or ability to keep food hot into the late evening hours, and perhaps with regard to the types of cooking that can be carried out.

The Tabor cooker, using shaving mirrors, might solve the first problem and alleviate the second, but accurate assembly of an array of mirrors appears to be a problem.

We know of no other cooker that can be recommended at this time. We have probably had some bias from the beginning against insubstantial, unstable, short-lived cookers that could be built cheaply, and it is conceivable that someone could concoct a distribution scheme that would make cheap solar cookers, replaced every year or so, say, a feasible proposition. Barring possibilities of this nature that are somewhat out of the scope of our study, our recommendation has to be confined to the Telkes oven and the F.I.T. cooker, which both have a range of capabilities unequalled by any inexpensive cooker we have heard of, and would have lasting value for the users.

B. COMPARISONS BETWEEN TELKES OVENS AND THE F.I.T. COOKER

Calculations were made of the amount of insolation received at the windows of each of the three Telkes ovens, and the F.I.T. cooker. Reflectivity of the reflectors was always assumed to be 0.83, and alignment was assumed to be perfect - that is, 83% of the sunlight striking the reflectors was assumed to reach the window. Transmissivity of the windows was not considered - we only calculated the amount impinging on the outside of the windows. In the case of the F.I.T. Cooker, graphical methods were employed to find the projected reflector area and to correct for the oven shadow, for various sun positions. The results are plotted in Figure 84, for various values of the solar elevation. Incident solar radiation was assumed to follow a clear air model:

$$I(\theta) = I_o/\exp(0.357\ (\sin\theta)^{-.678}),$$

where I_o is the solar constant, 1353 watts per square meter. "Big Telkes" in the plot refers to the modified Telkes/Halacy oven. The power of the F.I.T. cooker was calculated two ways: the lower curve takes account only of radiation reaching the bottom window via the reflector, while the upper curve also takes into account radiation falling directly on the double-glazed top and door.

The curves illustrate a number of points:

1. The performance advantage of our first Telkes oven relative to the Foamglas Telkes oven is partly due to the fact that the larger window and reflector result in about 17% more power.

2. The F.I.T. cooker is close to the Foamglas Telkes oven in incident power for low sun angles, but then dips when the sun is higher in the sky due to the oven's shadow falling on the reflector.

3. Reduction of the glazed area in the F.I.T. cooker will probably have to be compensated for by an increase in reflector area.

4. The maximum possible power entering our small Telkes oven is substantially less than 200 watts under any conditions.

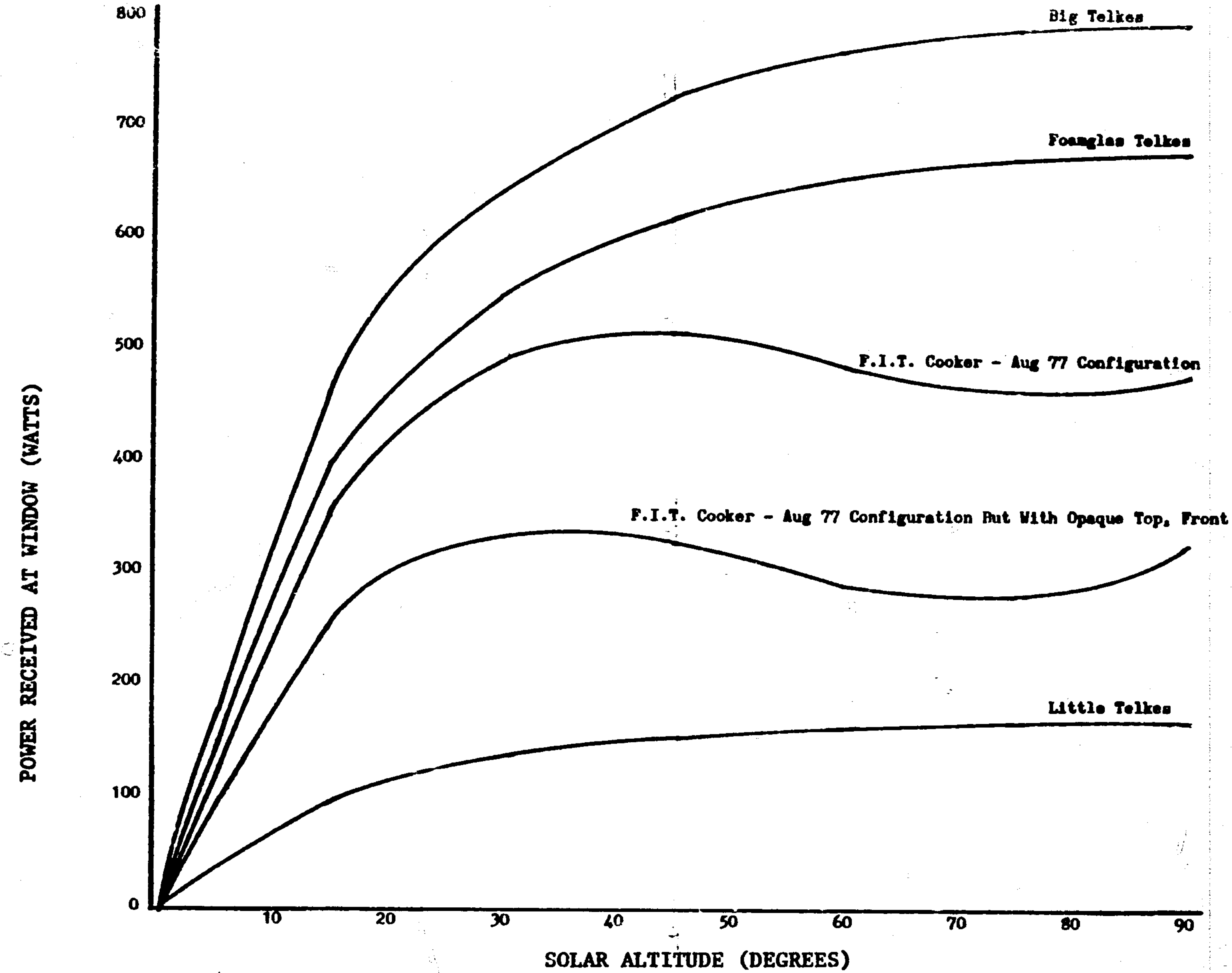

Figure 84, Solar cooker power vs sun position. Desert clear air standard atmosphere was assumed, with all radiation assumed to be direct.

In its current configuration, the F.I.T. cooker does not enjoy much cost advantage over the Telkes oven. The reflector is a little over one third the size of the reflector used on the Foamglas oven in terms of surface area, which is what costs money, not projected area. The oven itself is smaller, simpler, and cheaper. On the other hand, the need for a rigid steel framowork and wheels counterbalances these cost advantages. The total glazed area of the two ovens is comparable.

Most of the glazed area of the F.I.T. cooker is associated with the top and door, which is somewhat wasteful since the sunlight entering these areas is not concentrated in any way. We are anxious to experiment with ovens in which all of this glazing is eliminated, leaving only a single window in the bottom. At this point there should be a cost advantage relative to the Telkes oven, since with glass mirrors, tempered glass for windows represents the greatest single cost element. The high concentration of energy at the F.I.T. cooker's bottom window means the window can be small, and since it is at the bottom it should not have to be double-glazed. The successful performance of the Prata cooker indicates that the oven should function with only a single bottom window, although the reflector will probably have to be larger - the Prata cooker used fifty percent more reflector area than the F.I.T. Cooker.

Assuming the performance of the two cookers to be roughly the same, the F.I.T. Cooker should be somewhat easier to use due to the relatively stationary oven, horizontal oven floor and greater versatility due to the heat being supplied from below. The two ovens should both be good for keeping food hot after sunset, although the window of the Telkes oven should probably be temporarily covered for best performance in this mode. The Telkes oven has the advantage of needing less frequent attention - an hourly adjustment is adequate, and even longer intervals are sometimes feasible, whereas the F.I.T. Cooker needs to be adjusted every fifteen minutes or so.

Reflector fabrication is the most difficult aspect of building either oven - both reflectors require a large number of steps and some reasonably accurate measuring, cutting, and bending.

C. DESIGN CRITERIA, TELKES OVEN

The Telkes oven allows considerable design variation with regard to both the oven itself, and the reflector. We found that a lot could be learned about the design of Telkes ovens by various ray tracing exercises. Figure 85 shows one example, an exercise performed in connection with the analysis of one of our early concepts for a second generation Foamglas Telkes oven. The long parallel lines represent the sun's rays, the vertical fields being those that are coming directly through the window and the diagonal fields representing reflected rays. It can be seen that there is a triangular zone of particularly intense radiation next to the window, and a zone at the bottom of the oven that receives only direct radiation. We sought, with our later designs, to place as much of the receiver (cooking pan) trajectory as possible in the zone of maximum radiation, and to design the oven such as to minimize the size of the zone of minimum radiation.

The reflector in a Telkes oven must be at an angle of more than 45° from the plane of the window. An angle of 45° would result in reflection parallel to the window. In most Telkes ovens, the reflector angle is 60°. In Figure 86, three reflector positions are shown: 60°, 62.5°, and 65°. Also shown are the farthest rays that will be reflected back to the indicated window opening: the rays that will just intersect the far edge of the window. It is seen that as the reflector angle increases from 60° to 65°, more solar energy can be collected, but that the length of the reflector (the distance from the near edge of the window to the intersection of the farthest ray) increases much more rapidly than the aperture width. It can also be seen that as the angle increases, the reflected rays reach the window less obliquely and hence the amount of energy absorbed in passing through the glass will be decreased. In addition, referring back to Figure 85, the size of the zone of maximum radiation will be larger. Since the direction of the reflected rays changes by two degrees for every one degree change in reflector orientation, the effect is especially pronounced. With a 60° reflector, for example, the reflected rays impinge on the window at an angle of 60° from the normal; with a 65° reflector, they are only 50° from the normal.

As a result of these considerations, we chose to use a larger reflector angle (smaller angle with respect to the sun's rays) in our Foamglas Telkes oven than the customary 60°; 65° was chosen. The next step was to do a ray tracing sketch for this angle, as shown in Figure 87. We chose to truncate the reflector at the point shown rather than fabricating the maximum useful reflector. The

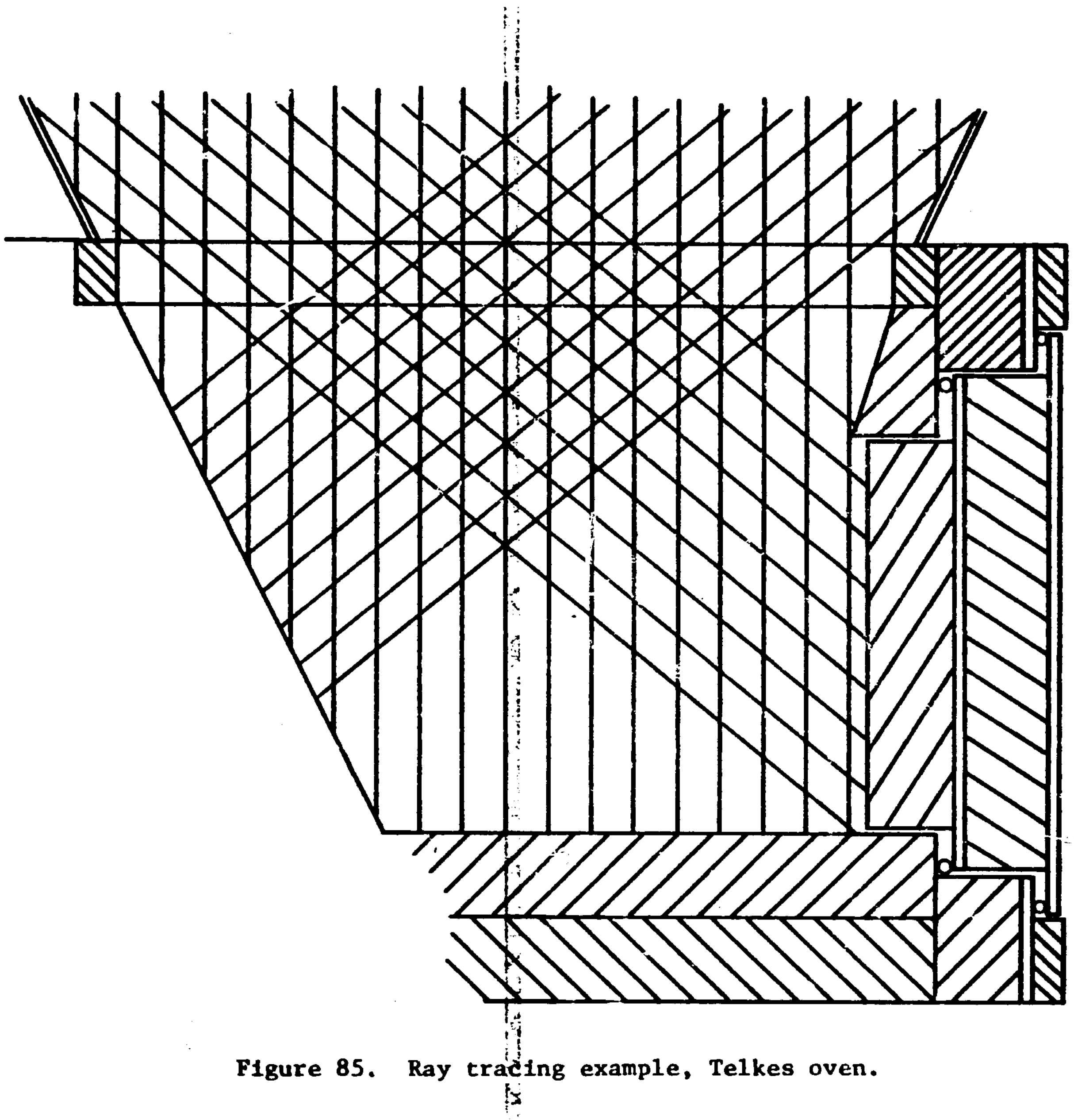

Figure 85. Ray tracing example, Telkes oven.

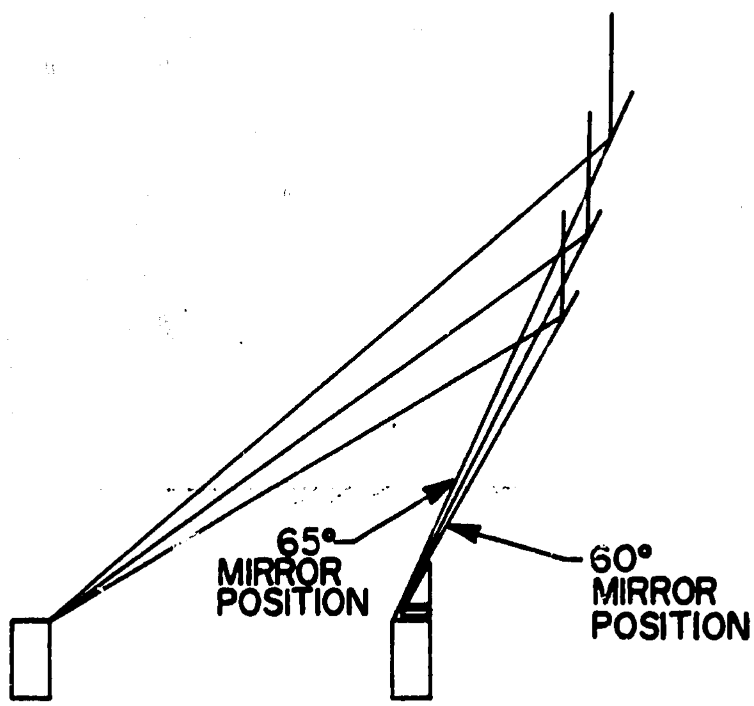

Figure 86. Paths of outside rays of the beam of useful solar energy for three reflector angles, Telkes oven.

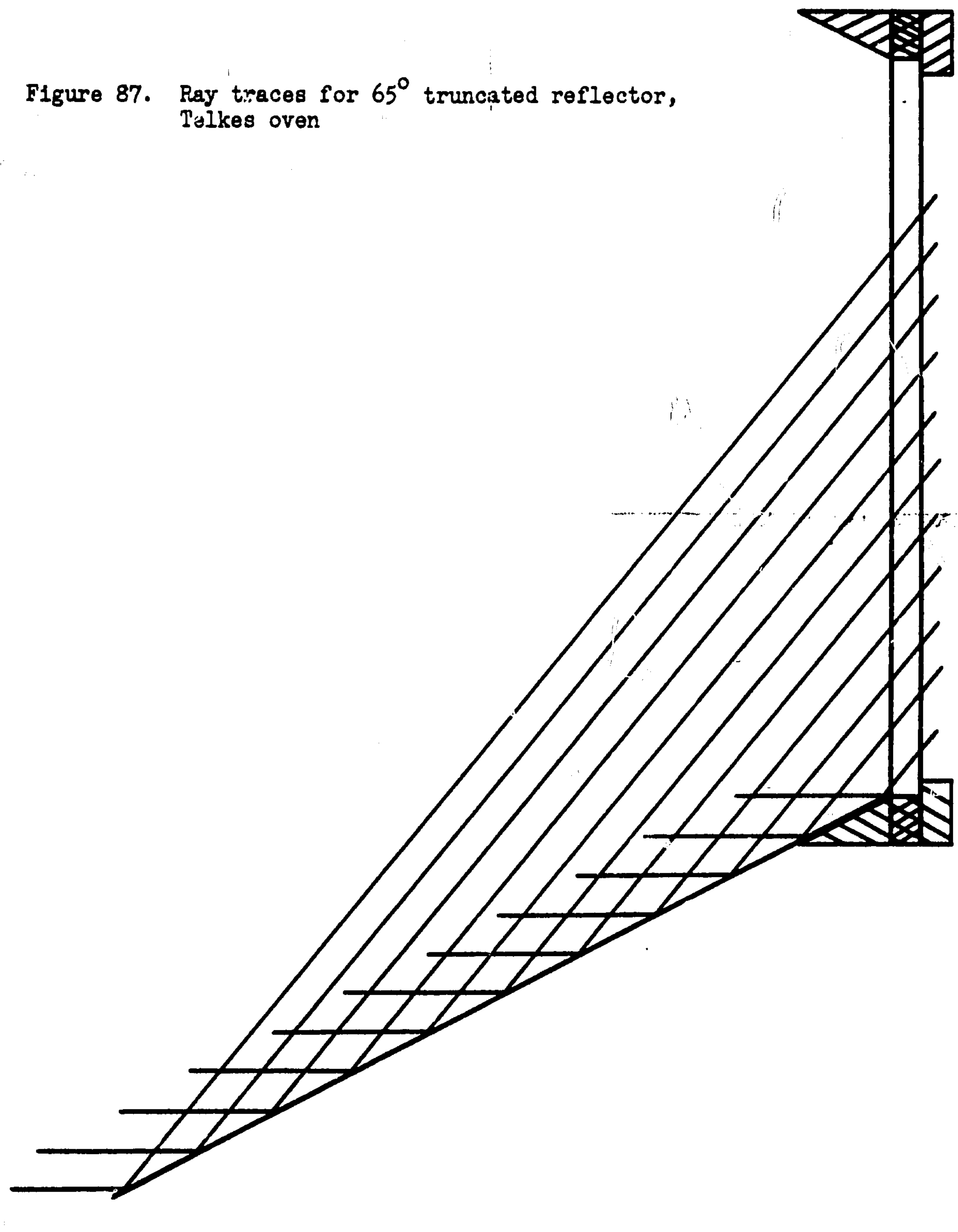

Figure 87. Ray traces for 65° truncated reflector, Telkes oven

additional energy gained by extending the reflector the rest of the way to the point shown in Figure 86 would be reflected to the top corner of the oven, where it would be of somewhat lessened benefit, and in addition the maximum useful reflector would include regions along the top edges not being used by the oven any time the oven was not pointed exactly at the sun.

Actual reflector size will probably be selected on the basis of material availability - standard manufactured mirror sizes - in most cases, so it is informative to look at the effect of variations in reflector angle for given length. In Figure 87, if the reflector angle with respect to the window were decreased to, say, 60°, more solar energy would be collected due to the greater aperture width. At the same time, more of the reflected energy would be absorbed by the windows, since they would look thicker to the transmitted rays, and once in the oven the rays would intersect the walls closer to the window - not as much of the bottom of the oven would "see" the reflector. If, on the other hand, the angle were increased, less radiation would be absorbed by the window and it would penetrate deeper into the oven, but the amount of energy collected begins to decrease rapidly as the angle increases.

These comparisons are not very quantitative, and we are not proposing that 65° represents any sort of optimum angle. We have presented the considerations that are important, and believe the subject warrants further study.

The foregoing discussion has been of a two-dimensional nature, and of course the configuration is really three-dimensional. An appreciation of those aspects that are not apparent in this two-dimensional approach can be gained by looking at the oven from the point of view of the sun, Figure 88. Of especial interest here is what happens to the energy reflected by the four corner reflectors. These rays impinge on the window in the regions enclosed by the four dashed triangles. It is apparent that most of this energy ends up in the center of the oven, and perhaps not so apparent that it passes through the window at a more favorable angle than the energy reflected by the larger side reflectors. It should be noted that the triangular corner reflectors could be made longer to good advantage, and the same could be said even if the side reflectors were not truncated. It is ironic that when we fabricated this reflector, we trimmed material from this portion of the Alzac sheet (see Figure 70) so that all eight top edges would be in the same plane. We did not realize at the time that we were throwing away very valuable reflector surface.

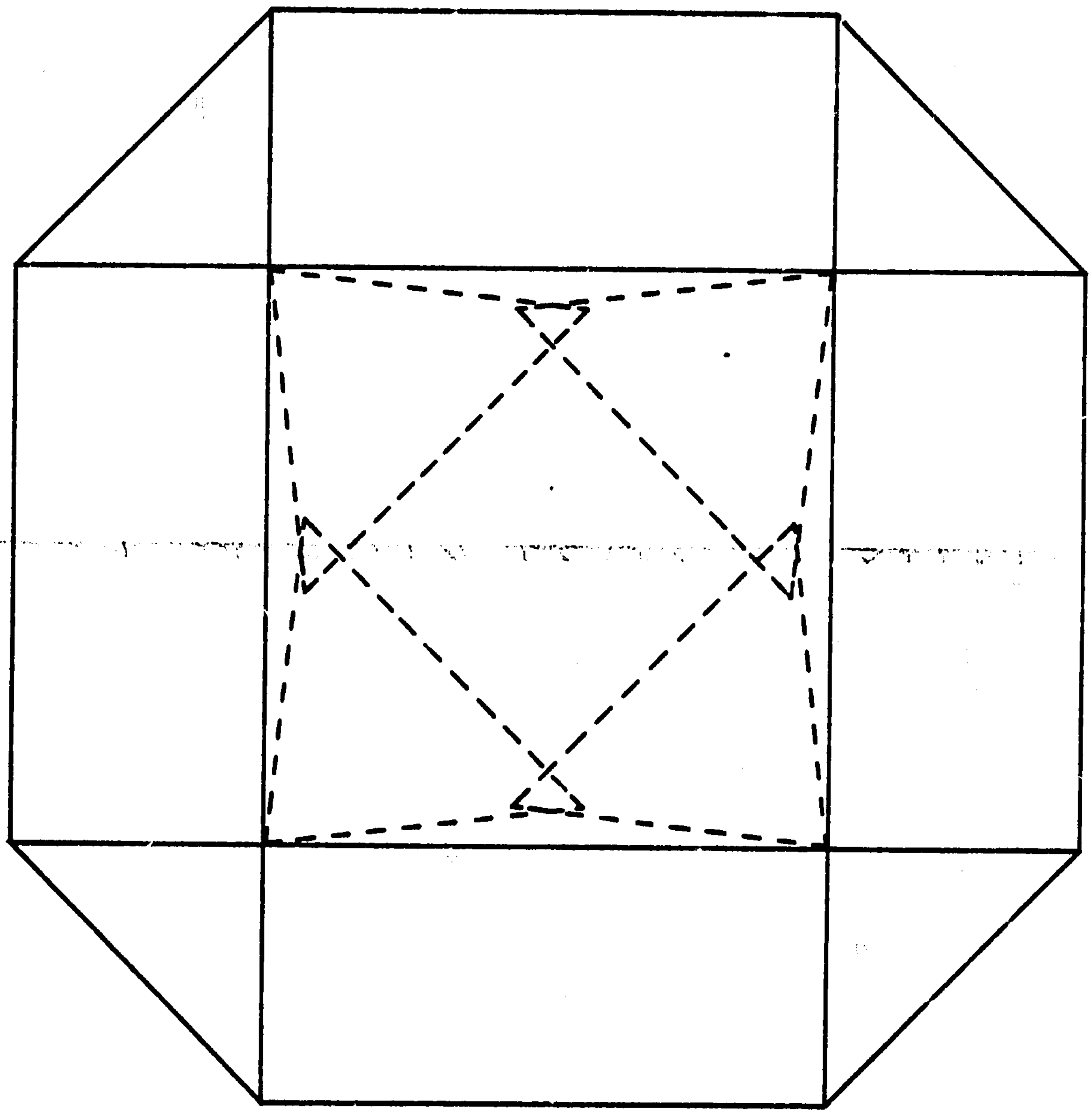

Figure 88. Foamglas Telkes oven reflector and window as seen by the sun. Triangles indicated by dashed lines are portions of window receiving reflected rays from the corner reflectors.

SCALE 1" = 6"

A three dimensional visualization of the pattern of energy paths within the oven can be grasped if the two views of Figure 85 and Figure 88 are studied together. The zone of maximum radiation looks something like a pitched roof on a cruciform-shaped house, inverted, with the energy reflected by the corner pieces superimposed on this pattern.

In seeking an optimum reflector angle, it is probably best to bear in mind that the corner reflectors, which represent 15% to 20% of the total reflected energy, will always be at a steeper angle than the side reflectors, and hence the optimum angle should be slightly smaller than the value that would be chosen by considering the side reflectors alone.

It should be pointed out that all of the foregoing discussion of radiation zones has been concerned with direct and reflected radiation only. The hot walls will also reradiate to other parts of the inside of the oven, and the reradiation is presumed to be uniform in all directions. The interior walls have also been assumed to be black (non-reflecting), as in the case of Foamglas insulation. In addition, we have been assuming the window is made of plane glass panes. If translucent plastic glazing is used, the rays will emerge from the window material at various different angles and there will not be such distinct radiation zones.

The number of layers of glass used in the window is also a concern, especially in view of the cost of tempered glass. With oven temperatures of well over 200°F for almost any form of cooking, and capable of reaching 400°F and higher when the oven does not contain boiling water, the insulating value of a single pane of glass is really not adequate. In fact, thicker insulation on the rest of the oven would be wasted in this case because of the large heat loss through the window. Two panes with an air gap of one-half inch or so is far better, because of the insulating value of the air gap. Increasing the size of the gap much past one-half inch is probably not justified. The insulating value increases little because of the onset of buoyant convection in the larger gap, driven by the very large temperature differential. Also, the effective window opening seen by the reflected rays decreases as the total window thickness increases, especially for reflector angles of 60° or less. Using three panes of glass with two air gaps does increase the insulating value, but as the number of panes increases the amount of incoming energy absorbed by the glass also increases, in addition to the cost increasing.

Telkes also addressed the problem of the best number of glass panes, and collected data on the equilibrium temperature reached by black plates backed by four inches of fiberglass insulation, behind one, two, and three panes of glass of unreported thickness, with one-half inch spacing.[1] Her data for the case where the window is surrounded by a reflector consisting of four silvered glass mirrors on the sides, at 60°, with Alzac corner triangular reflectors, are plotted in Figure 89 as a function of incident radiation. The rather substantial advantage of two panes over a single pane is apparent, as is the marginal (but measurable) gain realized when a third pane is added.

Both the Telkes data and our own analysis and experience lead us to the conclusion that the proper number of glass panes in a Telkes oven, for most applications, is two. Three would give slightly better performance if cost were not an important consideration. The cost saving realized by using a single pane only would probably be lost due to the larger window/reflector size needed for a given capacity to obtain acceptable performance.

In designing the oven, we believe two principles should be uppermost: best use of the maximum radiation zone and minimization of the minimum radiation zone, as discussed above, and minimization of the surface area of the oven. We recommend the following procedure:

1. Selection of the largest size pot to be used (diameter and depth) and window size. Our experience indicates that a window opening a little less than twice the largest pot diameter makes a good choice. Both cooker power and cost are roughly proportional to the square of the window opening. Excessive pot height is costly in terms of oven size - about 70% of pot diameter causes no problems.

2. Select a pivot point high enough on the pot for good stability.

3. Rotate the pot envelope about the pivot point through about 75°, representing the actual trajectory of the pot as the cooker takes on all positions between pointing at a sun straight overhead and a sun 15° above the horizon. (At more northern latitudes, the straight overhead position could be replaced by a realistic maximum sun elevation.) The total sweep of the pot envelope defines the inside dimensions of the oven. Dimensions will be more reasonable if the corners of the pot envelope are rounded, as they often are in actual pots.

4. The plane of the inside surface of the oven window is parallel to the pot bottom with the pot in one extreme position (the sun overhead position) and as close to it as possible without touching any part of the swept area.

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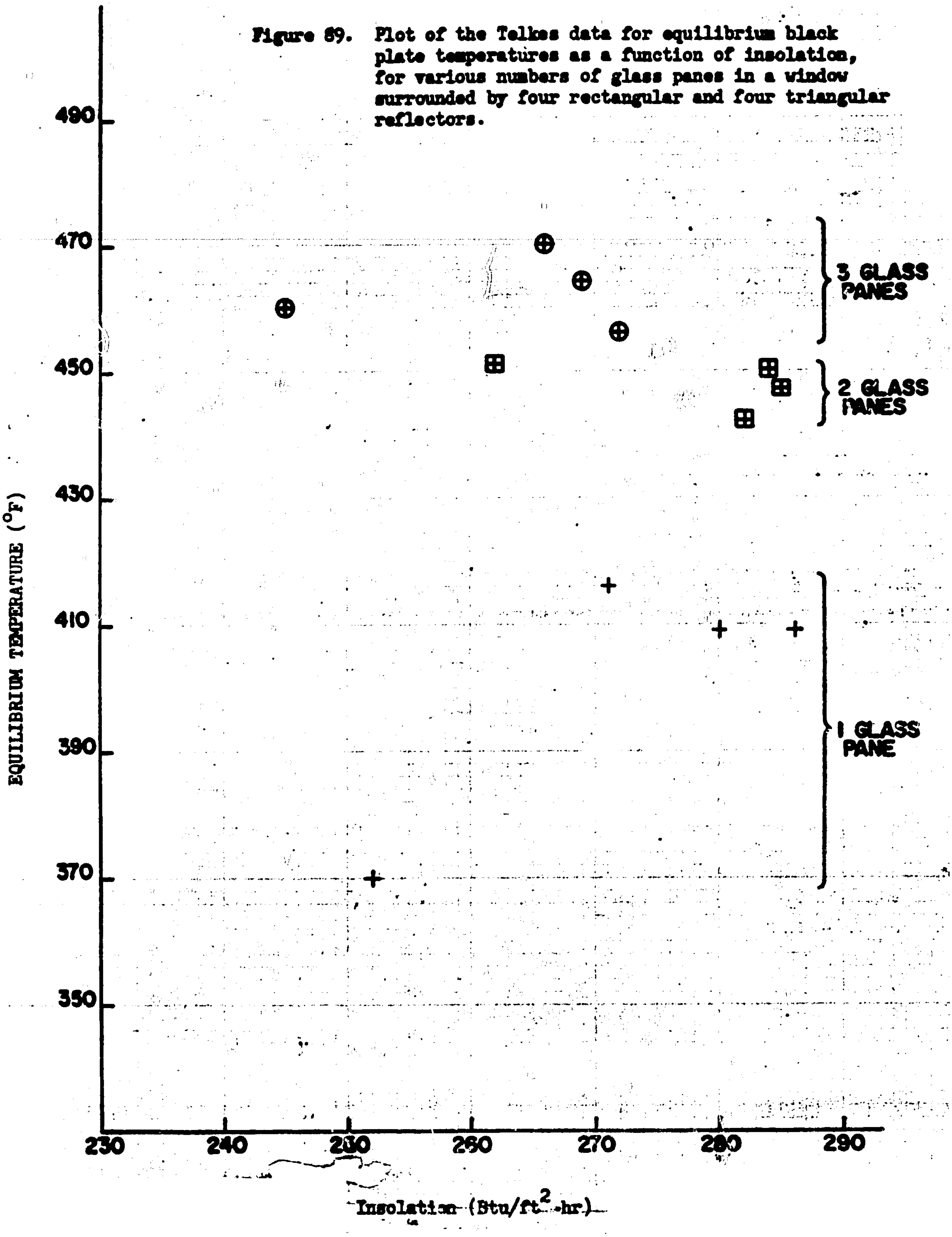
1. Telkes, Maria: "Solar Cooking Ovens". Solar Energy, Vol. III, January, 1959, pp. 1 - 11.

Figure 89. Plot of the Telkes data for equilibrium black plate temperatures as a function of insolation, for various numbers of glass panes in a window surrounded by four rectangular and four triangular reflectors.



5. The plane of the inside surface of the door is perpendicular to the window plane and as close to the pivot point as possible without touching any part of the swept area.

6. The plane of the inside bottom surface is parallel to the window plane and tangent to the swept area.

7. Using these three intersecting planes, the exact location of the window opening should be selected and the fourth boundary of the oven interior picked as a plane tangent to the swept area and intersecting the window plane at a suitable point relative to the window itself.

8. In most cases, the window will be square and the remaining two oven walls will be perpendicular to the window plane, and suitably located relative to the window edge.

9. The length of the reflector, measured in the plane of a side reflector surface from the outside surface of the window to the edge of the reflector, should be any convenient measure slightly greater than the window opening, selected on the basis of minimum wastage of available materials.

10. Once the reflector length has been established, the angle should be chosen, in the neighborhood of 60° to 65° or so, on the basis of ray tracing considerations as discussed above.

Figure 90 presents both an example of the application of this technique, and our chosen design for a Telkes oven suitable for use in Haiti. The pivot is supported by a sheet metal fabrication between the layers of Foamglas. Outer surface is a sheet metal box, 18 to 24 gage. The closeness of the bottom of the oven to the window, good use of the zone of maximum radiation, and small size of the zone of minimum radiation are all apparent. The oven was designed for a maximum pot size of ten inch diameter, seven inch depth, using a nineteen inch square window opening. Although only a single ten inch pot can be accommodated at one time, two nine inch diameter by seven inch deep or three six inch diameter by seven inch deep pans can be used simultaneously because of the oven's width (perpendicular to the paper in Figure 90).

D. DESIGN CRITERIA, F.I.T. COOKER

Design criteria for the F.I.T. cooker are not as elaborate as those presented for the Telkes oven in the preceding section, and center mainly around the reflector.

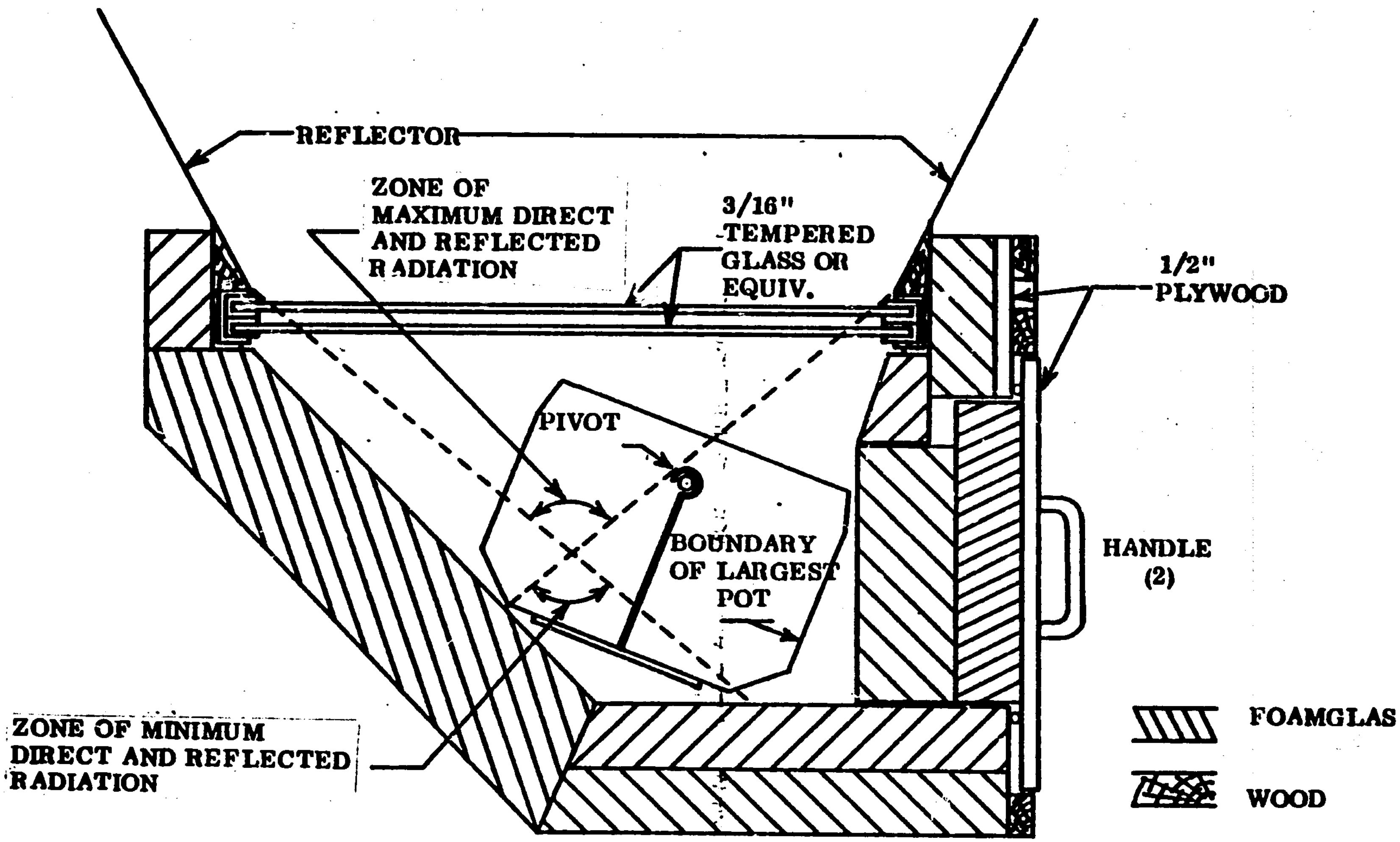


Figure 90. Design of the Foamglas Telkes oven: recommended configuration.

SCALE: 1" = 5"

The first step is to select a "design point" for the sun - the sun elevation at which the reflector will yield a perfect focus - and a height above ground for the focal point (the bottom window of the oven). We selected a solar elevation of 60°, for simplicity, and a height of forty eight inches for our prototype. The choice of height is a very important one - the higher the oven can be, the more power the cooker can have, but the harder it will be to use because of the need to stand on a bench or stool.

The next step is to draw a circle through the focal point, tangent to the ground, and a line through the focal point in the direction of the sun's design point location. The vertex of the parabolic reflector will be on this line, and the ends will be where the parabola intersects the circle; as the sun moves, the parabola will pivot about an axis coincident with the center of the circle.

The next step is to select a suitable focal length for the reflector. Short focal lengths place the parabola close to the oven so that the acceptance angle of the oven window has to be very large, but as the focal length increases the chord length of the parabola, and hence the power of the cooker, has to decrease. We selected a 36 inch focal length for our prototype. The selection should probably be based on a certain amount of graphical investigation. With the 36 inch focal length and 48 inch diameter circle the chord length of the reflector is 42.5 inches.

With the design point location of the focus and vertex of the parabola, and the pivot point and parabola ends, the reflector could be built. Our next step, however, was to perform a ray-tracing exercise based on these parameter values. We looked at three sun positions - straight overhead, 60° above the horizon (the design point), and 30° above the horizon - and traced reflected rays from nine points on the parabola. As expected, they converged on the focal point for the 60° sun position, and crossed a horizontal plane through the focal point at various locations from the design focal point to two inches behind the focal point with the sun straight overhead, and from the focal point to two inches ahead of the focal point with the sun 30° above the horizon. We noted that if the pivot point and reflector were moved vertically upward two inches closer to the oven, the images at the same horizontal plane would be more spread out in all three cases, but in no case would the image spread more than two inches in either direction from the focal point. In other words, the spreading in the off-design cases would be on the side of the focal point that received no energy before the reflector was raised. Hence there was no disadvantage to raising the reflector, which in turn allowed us to extend the reflector another two inches on the end toward the sun. We also extended the reflector 3.5 inches on the end away from the sun, where ground clearance is not critical, to achieve a total chord length of 48 inches, compared to the original 42.5.

In practice, our reflector produced a much sharper apparent focus, for all sun angles, than the ray traces would indicate, for reasons that are still unknown to us. In no case did the focal region spread over the 2.5 to 3 inches indicated by our graphical investigation.

With the reflector defined by the chosen parabola, and the pivot point and oven window located, the cooker can be built. Necessary ground clearance can be obtained by properly locating the wheels, resulting in an oven higher than the initially selected value by the amount of ground clearance chosen. The window size, like so many other parameters, is a trade-off - the wider it is, the more it will cost and the more heat loss from the oven will occur, but the narrower it is, the more frequently the reflector will have to be adjusted. The width used in our prototype is 6.5 inches.

Further details, and drawings, of our prototype cooker are presented in Appendix G. It should be noted that for our prototype we built the structure out of slotted steel angle, which is readily available in the U.S. and ideal for experimental purposes as the structure can be modified very simply and quickly. We assume that in Haiti the structure would be welded rather than bolted, and would use the thin steel rod that is already used extensively for so many purposes, both ornamental and structural, in that country.

E. CONCLUSIONS

1. The state of the art of solar cooking as of the early 1960's was at a rather high level and in many cases represented good engineering and clever design. Solar cookers worked well and in fact there is good evidence that one design, the Adams cooker, worked well a century ago.

2. Conditions in the arid regions of Haiti are very favorable, in almost every respect, for the application of solar cookers.

3. The failure of programs in Mexico and India involving extensive distribution of solar cookers resulted partly from failure to establish permanent training and maintenance activities* and partly from reliance on point-focus reflectors.

* An assumption in the Indian case.

4. Point-focus reflectors are tremendously successful at boiling limited quantities of water very quickly, but they have longevity problems, need periodic refurbishing or replacement, and in other respects do not represent the best use of solar energy for routine, daily cooking for a group of people.

5. Of the solar cooker designs available prior to our study that we reviewed and/or tested, the Telkes oven was clearly the most satisfactory in terms of almost every important parameter: versatility, ease of use, durability, effectiveness over a wide range of conditions, safety, etc.

6. The Telkes oven is deceptively difficult to design properly, and allows an almost infinite number of parametric variations. Poorly conceived designs work either not at all, or at a level far below the design's potential. We have presented some design criteria, and one design that we believe should have a very acceptable performance. (We have not built an oven to this design, which was conceived at the end of the program as a natural outgrowth of an earlier design that worked well for us.)

7. Another cooker, conceived by us during the program and building on earlier work by Prata and Tabor, is at present approximately equal to the Telkes ovens we developed and tested in terms of overall performance, ease of use, durability, and cost considerations.

8. Future work should be aimed at further developing this "F.I.T. Cooker" and further optimization of the Telkes oven designs.

9. Widespread application in Haiti might be eased considerably if these designs could be scaled up to sizes suitable for serving larger numbers of users.

APPENDIX A

TRANSCRIPT OF THE NARRATION FROM A MOTION PICTURE ON THE LAST SOLAR COOKER PROJECT IN MEXICO, BY THE UNIVERSITY OF WISCONSIN

"Reflecting solar cookers were developed at the University of Wisconsin's Solar Energy Laboratory to provide savings in fuel, cash, and forestry resources in sunny areas where such needs were felt. Under a Rockefeller Foundation grant to Dr. Milton Barnet, a team of anthropologists has been studying the acceptance and use of the solar cookers in three Mexican villages. In their last research village, the anthropologists developed a local production technology to increase the sample of cookers for their study, to facilitate cooker use after the study ended, and to assess whether reactions to the cooker would change if repairs and replacements could be made locally, and if some villagers were involved in cooker success. Thus, the villagers of Teotitlán del Valle in the Mexican state of Oaxaca were presented, not only with a new artifact, but with a technology for producing it.

"A Teotitlán woman uses one of the cookers built and supplied by the Solar Energy Laboratory under the direction of Dr. J.A. Duffie. This model cooker itself resulted from earlier anthropological field study. It is lower and more conveniently accessible. It has more stability against wind or animals, and is more durable than its laboratory predecessors. She focuses the parabolic reflector by accurately rotating and tilting it.

"Ground is cleared and leveled to provide a foundation for a convex mold. The parabolic reflector shells are shaped on such a mold, and careful preparation will provide a permanent mold on which one reflector after another can be shaped to specifications. The leveled ground is fortified with cement and packed by tamping. The convex mold will give a parabolic form to the reflectors, so that they can properly concentrate the sun's rays on the cooker grill. Proper focusing of the solar cooker will furnish more than 500 watts of heat in favorable weather, the capacity of an ordinary electric hot plate.

"Plywood is used to make a parabolic scraping blade that will shape the mold. The parabola is drawn in a simple fashion using a carpenter's square. The dimensions of the parabola are determined vertically by the 45 centimeter or foot and a half focal length between the grill and the center of the reflector, and horizontally by the 60 centimeter or two foot reflector radius.

"Making the parabolic reflectors was the most unprecedented problem for the established craft technologies of the village, requiring the emergence of a previously non-existent specialist. The several technological stages shown are based on the suggestions of Dr. Farrington Daniels of the laboratory, and those of anthropologists. However, numerous improvements were made by Portino

Olivera, a village weaver, shown here, who became the principal solar cooker builder and a specialist in the craft of making solar cookers. After the parabola is drawn, the scraping blade is sawed out so that it can be pivoted at the center of the mold, and rotated to shape the mold through the various stages of its construction.

"Copper tubing edges the scraping blade in order for it to shape the final surface of the mold smoothly. Adjustment of numerous bolts permits the scraping blade to be clamped with great stability onto its pivot.

"The pivot is an iron rod that is pounded deeply into the ground and carefully checked with levels for absolute perpendicularity.

"When the blade has finally been lowered and leveled to its proper position, construction of the mold can be begun. First, concrete is mixed. Then rocks are piled around the pivot rod, and concrete is thrown around and on top of these rocks to make the resulting structure permanent. The rough parabolic outline of the emerging mold is constantly checked with a scraping blade. A layer of coarse concrete coats this rough mold and its surface is carefully shaped by continuous rotation of the parabolic scraping blade. Low spots are filled in, ridges scraped down. A thin, almost pure cement coating is added as a final surface for the mold. It too is smoothed and shaped with the rotating blade.

"When dry, the finished mold is scraped and polished. Steel wool may be used, even wax. A layer of newspapers soaked with motor oil is used in Teotitlán del Valle to provide for separation between the mold and the reflector shell being produced. Any excess oil is carefully blotted off.

"Construction of the reflector shell is then begun, using a liquid polyester resin plastic mixed with a drying accelerator. This will give a stiff and permanent shape to flexible material such as fiberglass or cloth. In the village, a locally available muslin, or manta, is cut into triangular sections and laid on the mold. Every effort is made to avoid wrinkling. The cloth becomes saturated with the plastic already spread on the mold and with additional applications of plastic. It might be noted that both the plastic and accelerator are readily available in Mexico City, although the plastic is among the more costly items in local cooker building. These are the only items of the cooker being produced which could not be procured in Teotitlán, or in the nearby markets at Oaxaca.

"Finally, a layer of burlap is laid on, and this too is soaked with plastic. Shells have been made of muslin alone, and of burlap alone, but the mixture shown seems to provide the greatest strength for the amount of plastic used.

"To strengthen the reflector shell, particularly along its rim, an iron strap ring is built. A carpenter blacksmith in Teotitlán does this job. This is placed atop the still wet layers of muslin and burlap. The outer edges of these materials are then cut. After cutting, they are soaked with plastic, and then carefully tucked up around the iron rim. The completed reflector shell must then be left to harden over night, before it can be removed from the mold.

"One of the carpenter blacksmiths makes a square, U-shaped frame for the cooker. He marks, then saws, and finally will chisel notches out of the two wooden uprights that will be assembled with the crosspiece to make the frame. They will be fastened together with wooden pegs, and with small supporting corner braces of iron. The design is the same as the tubular aluminum frame of the laboratory cooker shown earlier, so that the reflector hangs between the upright arms of the frame, and both frame and reflector rotate horizontally together for azimuth adjustment. They rotate around an iron rod imbedded in the ground, and for this purpose a heavy iron sleeve is bolted onto the frame.

"Another carpenter blacksmith marks one of the two iron strap lengths, which are then bent by pounding and further shaped by hand so as to form half circles at their centers. In building such cooker parts, the technological skills of already existing village craft specialists were simply turned to new tasks, and indeed, several modifications were made by the carpenter blacksmiths and were incorporated in Teotitlán cooker building, as shown here.

"When the two iron strap parts are riveted together they form a ring that will support the cooking vessel at the cooker's focal point. The remaining arms of this grill crosspiece will rest on the upright arms of the square U-frame. From them, a reflector itself can swivel always at focal length, which permits adjustment of its angle of elevation as desired.

"The new reflector shell, having hardened over night, is slowly loosened and removed from the mold, which then becomes available for producing another reflector shell. The newspaper adhering to the shell is stripped off, or soaked with water and scraped off, to make the convave surface of the shell completely smooth and ready for lining with some reflecting material.

"The carpenter blacksmith makes two flanges to suspend the reflector from the grill crosspiece at the proper focal length. The focal length determines the length of these flanges and the location of the hole through which the grill crosspiece arms are to pass. The flanges are bolted to opposite sides of the reflector shell through its iron strip rim. In assembling the cooker, the arms of the grill crosspiece are passed through the flange holes to provide suspensions for the reflector shell. To mount the cooker frame, its iron sleeve envelops a solid iron rod, previously pounded into the ground for all but a third of its one meter length. The cooker is here assembled to have its shell lined with a mosaic of mirrors. They are glued with the same polyester plastic used earlier. Those shown are one inch square but larger mirrors, 4 or 5 centimeters square, are also successful. The mirrors must be cleaned of any dried plastic deposits or smudges since these would diminish heating efficiency. Some cookers are lined with aluminized tapes like mylar, Scotchcal, and aclon. Such lightweight linings are required if a weaker, cheaper shell of papiermache is made. A rope is attached to the reflector rim and tied around the frame to control the reflector's elevation angle.

"Thus, another cooker is finished. You have seen the processes of this technological innovation: the local production of a solar cooker in Teotitlán del Valle. Cookers can be made in the village for between $5.00 and $16.00, and between 8 and 32 hours of labor depending on the materials used. The cooker being focused by the woman is a forerunner of that whose production you just witnessed. Its plumbers' piping and conduit tubing make it sturdier, more durable, but also more costly. This reflector is adjusted with a chain that hooks over a bolt on the frame. A pot of frijoles, or beans, is put on the grill, and the grease on the blackened bottom of the pot quickly begins to smoke as the cooker is focused. The beans come to a vigorous boil in the strong sun within 10 or 15 minutes.

"Successful continuance of this new technology at Teotitlán del Valle ultimately depends on the successful acceptance and use of the solar cookers themselves. However, the existence of a local village technology, able to repair, replace and multiply the cookers in use, should prove an asset to their acceptance."

APPENDIX B

STATUS REPORT ON REFLECTING SOLAR COOKERS USED IN TEOTITLÁN DEL VALLE, OAXACA, MEXICO

by

George Abdo

Associate Professor of Mathematics

Florida Institute of Technology

Teotitlán del Valle is about thirty kilometers east of the city of Oaxaca and about seven kilometers along a dirt road off the main highway. In December, 1976, I interviewed three persons who had at least heard of the cookers; the last one, Fortino Olivera, seemed to be by far the most knowledgeable.

Mr. Olivera said that the cookers had been used during three consecutive seasons about fifteen years ago and that he had helped in their construction. A season is the entire year less the Spring, which is the rainy season in Oaxaca. The cookers were used every day of the season. After three years, maintenance became a problem: the mirrors started to fall off.

Even though Mr. Olivera was taught how to make the glue to paste back the mirrors, he indicated that it was easier to go back to the burning of wood than to repair the cookers. Incidentally, one of the glue ingredients had to be imported from Mexico City. I had the opportunity to see a couple of bases still on the ground where the cookers had been set and a reflector with some missing mirrors which Mr. Olivera has kept in a room.

Mr. Olivera suggested that the solar cooker experiment be tried in the coastal areas in the vicinity of Jamiltepec where wood is unavailable. He also indicated that he would be glad to assist or orient anybody in such an experiment.

APPENDIX C

TRIP REPORT ON THE F.I.T. STUDY TEAM'S VISIT TO HAITI, 12-20 DECEMBER, 1976

Sunday, December 12

Team arrived in Port-au-Prince (PAP) approximately 1:30 p.m. The rest of the day was spent getting installed at the hotel, renting a jeep, visiting portions of PAP, etc. Discussion with Mr. Von Lignau (a businessman of PAP and the father of our interpreter). He indicated that most of PAP cooks with charcoal, even the well-to-do - it is significantly cheaper than bottled gas. [Figures we were given were $2/week for charcoal for 2/3 of the cooking ($12/month full time) versus $9/month for gas for 1/3 of the cooking ($27/month full time)].

The richer people in PAP employ cooks, who are accustomed to using charcoal. Later discussions (especially with HACHO workers in Anse Rouge and Gonaives), observation of charcoal shipping activities at Môle-St-Nicholas, and extensive charcoal making and collecting in north-western Haiti lead us to conclude that most of the charcoal shipped is intended for use in PAP. It seems unlikely that solar cookers can make major inroads in PAP because of the high density of housing and lack of unshaded open space.

Monday, December 13

Meeting with USAID staff: Raymond Douglas, Tibor Nagy and Elias Tamari. Appointments were made for the rest of Monday and Tuesday. Excellent concrete, cement and stone work are available in PAP. The Haitians have first-rate native stone-workers. Iron work is also of high quality and readily available throughout PAP. Structural iron is imported and fabricated locally into more complex shapes (primarily by electric arc welding in PAP). Aluminum is imported, but whether in structural shapes or ingots was not determined. Apparently there is an aluminum foundry near PAP which makes the cooking pots widely used by the natives. Plywood, masonite, glass, and mirrors are not made in Haiti according to USAID information. Concrete and cement are made in PAP. We found out later from HACHO officials that there are skilled carpenters in Haiti, but not a lot of them - maybe one or two - in some towns. Judging from the stores in PAP, ornamental wood working is a major Haitian craft, primarily for tourists and export.

Ing. Nagy indicated that an improvement in stove design that would allow more efficient use of charcoal would represent a major saving and would be applicable in PAP, where solar cookers might not be suitable. He also indicated that, if possible, our solar cookers should incorporate a charcoal stove, either for additional heat for frying or for occasional use on cloudy days or in the evening. Such a built-in stove could be designed to minimize losses in charcoal cooking through modern design.

11:00 - Meeting with Mr. Chris Schiefflev (CARE) and Fr. Carlos Perrera (CRS)

[Note: CARE, CRS-Catholic Relief Services, CWS-Christian World Services, together are referred to as VOL-AGS (volunteer agencies) by USAID.]

Grain and vegetable oil are imported - the oil is used for deep fat frying. There is total dependance on charcoal cooking. Mr. Perrera indicated that he felt that the natives must be involved in the construction of a cooker if they are to accept and use it and also he felt that there was no way that the natives could afford a cooker (it seems that most of the cost must be borne by an outside agency with the rest either built by the user or bought with work-for-pay money under one of the several public or community works projects under HACHO or CARE or a similar organization.) Everybody stressed that the cooker must require zero maintenance, but cleaning glass is no problem. In fact, the native cooking pots that we saw in Fond-Parisien were scrubbed bright. It was suggested by Mr. Perrera that since the Haitian peasant takes all his possesions inside his house at night for safekeeping, the stove should be extremely portable - this would also make it useable in the fields (as in a coumbite). An alternative idea is to have a large massive cooker that is not at all portable, but is a permanent fixed installation - more suitable for stone work, for example. The idea of an iron framed oven which would be shipped to the country and fitted into a locally built stone oven was suggested by us. The frame could act as a packing crate for the mirrors and glass cover. In addition, the door frame and a door would be included to be set in the stone work.

12:30 - ONNAC (Community Council Organization)

Dr. Darrieus: They operate two schools under the Department of Agriculture and are working on a six-zone module of economic centers, each of which would support 30 literacy centers - this program to start in March or April. Darrieus indicated that they would be interested in being included in groups that teach the use of solar cookers and that they would be happy to use institution-sized cookers in their schools and centers. He indicated that the community centers are really run by the VOL-AGS, and that he felt that for the poorer parts of the country boiling was more important than frying - frying was mainly done on special occasions.

2:10 - CWS, Gary Ambrose

Repeated that frying is mostly done on festive occasions. Main dishes are rice and beans. He said that there are certain food taboos that we should find out about - some areas might be anti-meat, for example - we did not see any evidence of this, but did not ask specifically. The poorer areas again get one meal a day, usually in the afternoon. They like bread, so a solar oven would be useful. Major problem areas in project are (1) communication and (2) transportation, both of which are very primitive. He indicated that McGill University had installed a large solar still on Ile de la Gonave - 50' x 100', of concrete. In theory it should give 300 gallons/day, but 100-200 gallons/day is more typical. It works all but about three days a year.

Walt Nicholson, Food for Peace Program

Described the food aid program from the U.S. Wheat, corn, soy products, powdered milk, blended foods with wheat or corn base called WSB and CSM, cracked wheat, and vegetable oil make up most of the foods. Almost all are prepared exclusively by boiling.

3:20 - Mme. La Fontaine, Women in Development

Largely involved in female education, studies of women's role in marketing chain, etc. She felt that the women would accept a solar cooker even if it was not made locally - she made the point that if it could boil water for the babies it would be regarded as a good idea, especially in poor areas where charcoal cannot be bought and wood is not available. Baking in large ovens has been reserved for the men, so women are reluctant to do that, but bread is an important element in the Haitian diet for those who can get it.

Some typical cooking hours were given by her and Elias Tamari: 5 a.m., leave home after coffee, go to fields (at sun-up); return home from fields, 5 to 6 p.m. (sun-down) for main meal. (This does not appear to be true throughout the country or throughout the year.) Both people emphasized the idea of community cooking in the nutrition centers or community centers as a good idea for those areas where the centers exist.

Tuesday, December 14

8:45 - Meeting with HACHO Assistant Director-Duchatelier, Ellis Franklyn

Recommended we speak to community counsil at Anse Rouge. They felt that a Solar Cooker would find easier acceptance if parts of it were locally made.

They were concerned with how a family could afford a cooker - indicated that $6 to $7/month was a typical income for the head of a family. In their area (mainly the northwest) the main foods are corn meal (maize) and beans, and rice and beans. The main meal is served at 2 p.m. with cooking, by the women, between 12 and 2 p.m. The women work in the fields only at harvest time. Again they emphasized the importance of bread baking, which is done in the earth in some areas, in charcoal-fired stone ovens in others, and on flat plates over charcoal in still other areas. Fish are fried (later we found out that they are often steamed). They both felt that there would be no problem introducing solar cookers in HACHO areas, as charcoal is made mainly for sale - but there could be an acceptance problem in areas where charcoal is readily available (we later found that in many of these areas, most of the charcoal is for export to PAP, and there is often little available for local consumption, especially for those with little money).

10:30 - Ing. Jadotte, CONADEP (similar to our EPA)

Agronomes Voltaire and De Latour, INORAM (research agency of Ministry of Agriculture, concerned with natural resources and mines).

Agronome La Roche, IDAI (concerned with development of agro-industries.)

M. La Roche indicated that the natives would make more money cutting the wood for crafts (but they cannot if they need it for charcoal). A charcoal substitute is being studied for use in PAP, based on agricultural wastes which are currently (1) used for process heat in the sugar cane industry or (2) burned as waste. (This would work especially if solar process heat were used in sugar cane processing - we discussed this with HACHO in Gonaives.) The problem of the loss in income and unemployment of the charcoal makers and sellers was brought up - this appears to be a major industry and replacing it will certainly take the support of GOH, and probably more than that.

Tuesday Afternoon - Trip to the East, Fond-Parisien

Observed "Howard Johnson" roadside cooking stands - used three rocks or iron charcoal pot.

In Fond-Parisien we observed a cooker in action, measured 300-350^{o}F (but not reliable) - similar to a fondue pot. Cooked fritters made of meal (marinades). Everybody was interested in solar cookers. Charcoal cooking itself took little attention other than adding charcoal and shaking out the ashes. Cooker does not appear very efficient - much of the heat is wasted. Cooking the marinades took nearly constant attention however. The people buy bread but would like to make it locally. They do most cooking with steam or by boiling in water. Frying has lots of splatter - they need to get at top of pot. There was considerable wind and dust. Charcoal is made locally, and the price varies with the season. It is getting hard to get - they have to go farther and farther to get it, but during the dry season when there is no cash crop, it is their only source of income. Prices: October to January, $0.80/bag, January to April $0.70/bag, April to September, $0.60/bag. Bag is approximately 3 cubic feet (see Figure 27), and lasts a six person family about 2 weeks (one meal per day).

Wednesday, December 15

Trip South to Miragoâne

Vialet: interview with Fr. Amery; in this area, much of the cooking is by boiling except for fish, bananas and plantains which are fried often after boiling first. There is a lot of shade in this village - probably too much for solar cookers. He said there is plenty of wood, and charcoal is not used. Typically the peasant eats one meal a day at about 1 or 2 p.m. If there is enough food, there may be a light meal in the evening - usually reheated food from the noon meal. Coffee at 5 to 6 a.m. The area is quite fertile and there is considerable use of fried foods. A local bakery would be an advantage, although there are a few bakers in Miragoane and Petit-Goave. They eat maize, plantains, rice (from Miragoane) and bananas.

Miragoane

Solar cooker installation by McGill University. Two cookers were converted for use as a hot water heater, which is shaded in the a.m. - the heater was not moved to an unshaded roof because of (a) insufficient water pressure (b) no more pipe (all fittings are of galvanized threaded pipe). The sister indicated that they would be happy to test another solar cooker installation but they hoped that there would be more technical assistance than they had in the past.

Magnant - interview with Fr. Rioux and Fr. Olichon (French missionaries)

Had two more McGill units, but never installed - there is little shortage of wood in this area. They would be happy to try to introduce workable solar cookers in their area, but were emphatic that the training program be carefully carried out under their tutelage. Charcoal made in area is exported to PAP. Main meal is at 3 to 5 p.m., with coffee in the a.m. (5 to 6 a.m.) The closest bakery is

2 - 3 km., so a local bakery would be helpful. Most food is boiled in water, except for fish (sometimes) and bananas (or plantains). There are local stone masons and also local iron workers. They are making stone ovens for baking - the preference in this case is for the user to work standing up rather than sitting. There would be no problem of acceptance of a solar cooker if it worked. A cooperative cooker would be effective also. In some areas where there is little agriculture, charcoal selling is the main source of income. These priests have good communication with 15 parishes serving about 100 villages and could get good feedback from the villages, but again felt that their people, rather than outsiders, should teach the villagers use of the cookers. Solar insolation 260 BTUH/ft^2 @ 2:30 p.m.

Thursday, December 16

11:00 - Gonaives HACHO Headquarters

Fritz Morisset, director. Set up our program for next two days. He indicated main meals were at 12 and 3 p.m.

12:07 - Bassin, HACHO Nutrition Center

Mme. Lucienne Ch'erichel. Food is boiled at the center - four "meals"/day. They start cooking at 6 a.m. for an 8 a.m. meal, which is bread and milk, boiled starch, cereal, vegetables, corn meal if available. At 10 a.m., juice. At 12, the main meal is boiled kidney beans and/or rice, vegetables, wheat and cornmeal, fried meat if available. At 2 p.m., milk. (Milk is made from powder.)

In the country, they generally do not start cooking until 3 p.m. (In the wet season, they make coffee in the a.m., the rest of the year they are too poor for this). They also cook potatoes. Many of their people eat only one meal a day - they cook indoors on a three-stone stove. They have a local bakery (a community council/HACHO project). There is a severe shortage of wood - sometimes they have to spend three to four hours looking for wood. Some people gather wood for three to five days, some every day. They mostly boil food (rice, sweet potatoes, plantain, beans, manioc - almost no meat eaten). The nutritionist felt that if the natives did not have to gather wood, they would have no objection at all to standing in the hot sun to cook.

Goat meat is boiled for up to two hours in water to soften, water is boiled off, then oil, spices and tomato paste are added and it is fried. When cooked, vegetables are added. It was felt that the frying step could be left out.

310 BTUH/ft^2 at 1:20 p.m. and 1:45 p.m., in the mountains, dropping to 30 when clouds passed.

2:35 - Terre-Neuve, HACHO Regional Center

In mountains, very lush region. The HACHO people indicated that the cooking habits were similar to those in PAP with coffee, 12 p.m. lunch, 8 p.m. dinner. In April to July, they have the Grand Coumbite (planting). The peasant may have a hut on his land which is far away from his home. Those left at home (children) get home from school at 4 p.m., cooking starts at 6 p.m. and is in the charge of the older men or women or an older child. Some cook with wood, some with charcoal - readily available. Charcoal costs 40-45¢/bag. The Nutritionist, Josette Bastien, indicated that most people in the village have land outside the village - the charcoal comes from west of the town and is harvested from a spiney bush which grows all over but kills the soil by drying it out. Typical foods were millet, beans, rice, plantains, bananas, peas, vegetables and occasionally a little meat, which is boiled, then fried. Most of the other foods are boiled.

Evening - Anse Rouge

Major charcoal shipping area (desert outside had 70 BTUH/ft^2 at 5 p.m.) No water, electricity, but no charcoal problem - it is a major industry here. We repaired the diesel generator for the HACHO hospital. Total lack of tools, spare parts, etc. even in a fairly large town. We were told that repairs to the generator would take up to three months by the traveling HACHO mechanic.

Friday, December 17

9:15 - Baie-de-Henne

Agricultural Co-op. Plenty of charcoal available here - they recognize the problem but see the economic difficulties if charcoal production is stopped. Foods are corn, beans, plantain, fish, vegetables. Two meals a day; 7:30 a.m.: fish corn, plantains, bread and coffee. 2:00 p.m. for some, 6:00 p.m. for others: corn, rice, beans, meat or fish, plantains. All food is normally boiled, meat and potatoes are sometimes fried. Fish and some vegetables are also fried after boiling. The people eat better here than on the plateau, partly because of the fish and (implied) the charcoal industry. There is a bakery.

10:20 - Bombardopolis HACHO office, M. Saintfort

Charcoal is not made here, but this is a major shipping point - so much is shipped that often there is little left for local cooking. They were very receptive to the idea of solar cooking. The people eat potatoes, corn; one meal per day, often eaten in the field - a communal meal (maybe only during harvest or planting time, April in the mountains, May to August in the plains and then October and November.) January to April is the "dead period" - they depend on HACHO food-for-work programs. Part of the food is eaten at work, the rest is carried home - meal is cooked from 3 to 6 p.m.; beans, corn, petit mille (millet), plantains, bulgar wheat, flour, fish, meat and a little rice. Almost everything is boiled, but there is some frying (fish). Fried fish is considered dessert. The main meal is in the afternoon; they often start cooking at 2 p.m. to be ready by 5 p.m During the coumbite there will be a small meal at noon in the field. They were interested in the possibility of solar heat for canning and for process heat - tomato paste, alcohol distilling, etc. Small rum (clairin) distillaries are common throughout Haiti. They indicated that reasonably skilled masons and carpenters were available in most villages.

3:00 - Jean-Rabel HACHO Office

Really supported idea of solar cooker - indicated that the main meal was between 3 and 4 p.m., but there could be two or three meals per day if they had enough food. Rice, corn, plantains, beans, manioc, sweet potatoes, fish and meat on market days - 2 days/week typically (for those better off). All boiled except potatoes and sweet potatoes, which are boiled and then fried, as is meat. Again we found that charcoal selling is the main resource of the poor people - no local problem getting charcoal. We saw extensive charcoal making and shipping during this entire trip.

Saturday, December 18

Return to Port-au-Prince with stop in Gonaives for further discussion at HACHO headquarters. Meeting with Fritz Morisset again and with Chris Conrad, an American with long experience in this area. Discussed at some length the heavily eroded and rocky area between Jean-Rabel and Port-de-Paix, and HACHO activities with regard to terracing and reforestation. Considerable progress has been made with terracing, although it is a very slow and difficult job. Reforestation has been successful on the steeper upper slopes, but not in areas where any sort of agriculture is possible as the farmers put up with the young trees for only a while before they get in the way and are removed. We also discussed the need for possible exports and alternate sources of income for the Northwest, which is currently both very poor and very dependent on the charcoal trade, threatened by dwindling sources of the raw material. We also discussed the potential of solar energy for process heat in local agriculture-based industries.

Sunday, December 19

Travel to Cap Haitien prior to returning to Florida. This area is considerably more lush and prosperous looking than the areas farther west that we visited, and is tourist-oriented. We did not see any charcoal-shipping activity, but did see indications of charcoal-making.

Conclusions of Trip

1. We received a number of different comments relating to meal time and number of meals per day; as a general statement, those who can afford more than one meal per day do not usually have much problem getting fuel, so we aim first for the one meal group, early in the afternoon or early evening. Since there appears to be enough sunlight to cook by 7:30 a.m. even in December, cooking for a morning or noon meal is not unreasonable, but some other means will have to be used to make coffee at 5 or 6 a.m. (before daybreak). If the main meal is eaten after sundown, it could be kept warm in a well-insulated oven-type cooker.

2. Although there was some frying done even in the very poorest areas, boiling was the main method of cooking, and this is one of the easiest things to do with solar energy. If all the boiling was done with a solar stove, then there would be a large reduction in charcoal usage. Most if not all the foods can be prepared by boiling and we were told that it would not be too severe a problem to convince people to boil instead of fry if they then did not have to buy or find charcoal. Frying could still be done on festive occasions.

3. Since the poorest areas which we investigated (in the northwest) were largely charcoal exporting areas with relatively little charcoal used locally (compared to that shipped), the adoption of solar cookers should not significantly affect the local economy - in fact, it should mean more charcoal available for export to PAP and other non-rural areas. It may take some convincing on the part of the GOH to prevent resistance from the larger charcoal merchants and local government officials.

4. The net result of replacing charcoal cookers with solar cookers on the deforestation of the northwest will be fairly small, since most of the charcoal is exported. Until (a) a charcoal substitute is found for PAP and (b) a substitute economy is found for the northwest to replace charcoal making, there is not much hope for reforestation and erosion control in some areas.

5. In other areas of Haiti, where there is not a large charcoal export business, the local acceptance of solar cookers will depend on (a) how easy it is to get wood, (b) how much open area is available in the villages to cook, (c) how well the people adapt to cooking outdoors, (d) how well solar cooking adapts to the local cooking style, e.g., how important is frying vs. boiling (e) how effective the training program is, and (f) whether an effective program for continuing technical assistance, maintenance and repair is established.

6. In a number of villages, interest was expressed in a solar bakery or oven, either on a single family scale, or for a group of families, or for a community oven.

7. The difficulty of maintaining any complex device was stressed to us many times, and it was felt that cleaning of glass was the most that should be expected. Any aiming device must be very simple and sturdy.

8. We got conflicting inputs on whether a heavy fixed installation would be preferable to a light, portable one. Most agreed that the natives should help in the construction if possible. Local materials and skills imply the use of stone, cement and iron, with wood a possibility where it is available. Because of the difficulties of transport, any parts shipped must be rugged, or easily packed. Any instructions should be as pictorial as possible and in Creole. A cheap battery powered tape recorder might be a useful instructional aid in some areas, if supplemented with visual aids and a working cooker.

9. All stressed the problem of obtaining technical aid and feedback during the experimental stage, prior to large scale cooker introduction. During the introduction, technical aid should be available. Introduction should be carried out through as many branches as possible: GOH agencies, the VOL-AGS, HACHO, etc.

10. Unless a suitable non-charcoal cooker can be found for PAP and other urban areas, or a charcoal substitute can be found, the cutting of trees for charcoal and the subsequent erosion will continue. Replacing the charcoal cookers in the country will enable the peasants to cook their food but will not affect the cutting of wood for PAP, etc., since this is the peasants' only cash crop in many areas.

11. A combined cooker, using charcoal and sunlight,has been suggested. This would solve several problems: (a) the problem of frying, (b) the problem of making early coffee, (c) the inefficient use of charcoal could be reduced in an efficient cooker.

12. Solar process heat aroused considerable interest - in Haiti it would be very effective.

13. More solar stills need to be built and more reliable ones need to be designed.

14. Solar water heaters might be very effective in Haiti (PAP).

APPENDIX D

PROGRAMS FOR COMPUTATION AND DATA REDUCTION

This section contains information on the following computer programs:

1. Solar Irradiation I, Description and Program Listing.
2. Solar Irradiation II, Program Listing, Example Output.
3. Cloud Cover, Program Listing.

"SOLAR IRRADIATION I"

PROGRAM TO CALCULATE SOLAR IRRADIATION IN HAITI

In applying solar technology to cooking in Haiti a knowledge of available solar energy is essential. In particular, we must determine the seasonal, daily and hourly variations and those meteorological phenomena which cause the variations.

The program described below represents the first step of the above goal. It calculates the intensity of solar energy (solar irradiation or insolation in Btu/ft^2 hr), at a specified time of day at a specified geographical location, incident on a surface tilted at any angle with the horizontal.

Variables used in the program and other pertinent quantities are shown in Figure D1, which shows the collector surface (aligned perpendicular to the north-south line for this study) tilted at angle Σ, and where the xy-plane is the horizontal plane, z is vertically upward, $\hat{s}$ is a unit vector pointing toward the sun, $\hat{n}$ is a unit vector normal to the collector surface, ϕ is the solar azimuth, ϵ is the solar elevation, and θ is the angle between $\hat{s}$ and $\hat{n}$.

The program inputs are:

1. Solar declination, δ.
2. Station latitude, L.
3. Solar hour angles, H (or times of day for which the calculation will be made).
4. Collector tilt angle(s), Σ.
5. Solar intensity, A, at the top of the atmosphere. The value used in this program is taken from Table 1 of Chapter 59 of the <u>1974 ASHRAE Applications Handbook</u>. The values of A in this

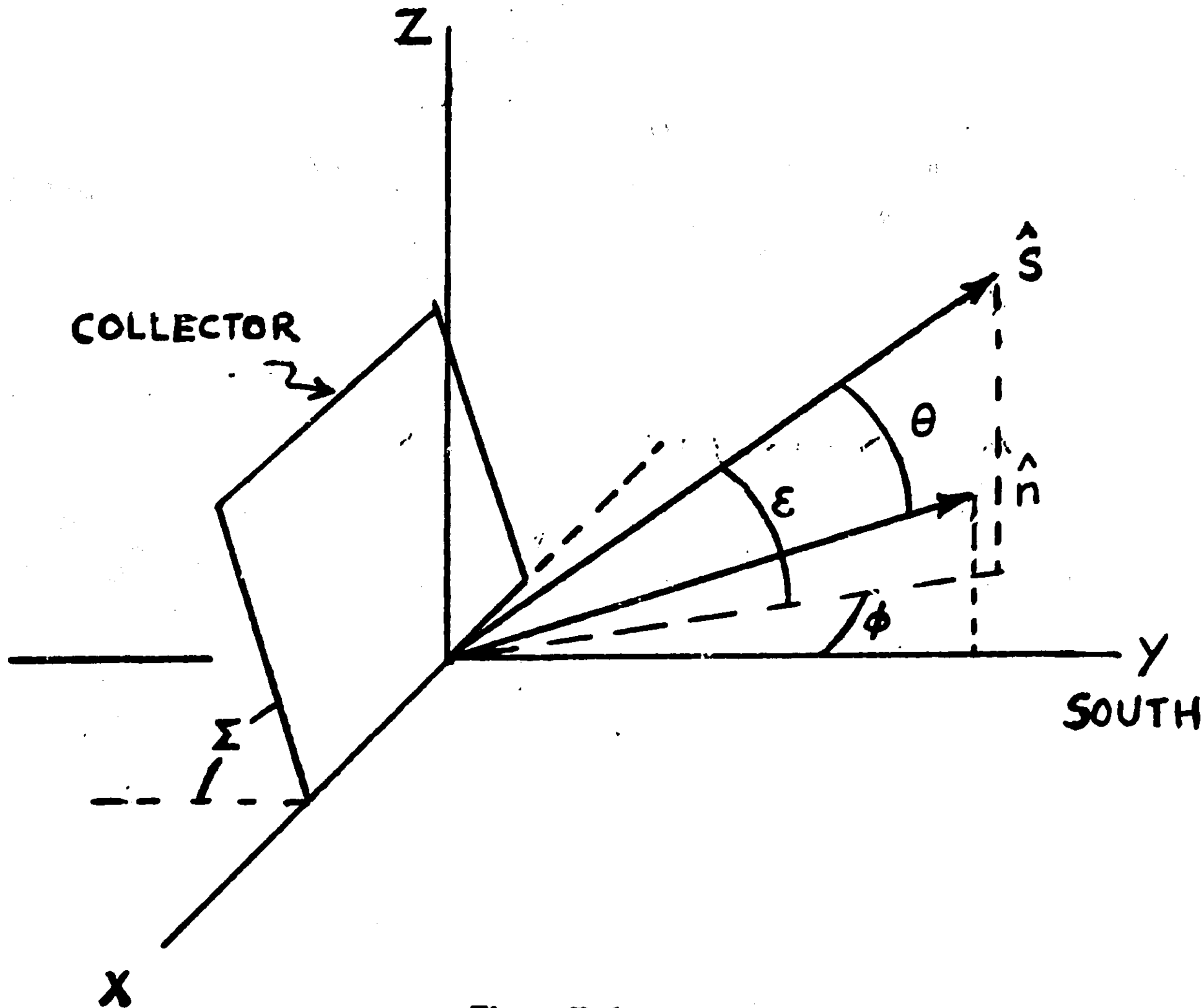


Figure D-1

table are different from the solar constant because they have been adjusted to provide agreement with the results of Threlkeld and Jordon (1958) who incorporated the average monthly variation of intensity due to atmospheric moisture and dust content and the varying distance of the earth from the sun.

6. Atmospheric extinction coefficient, B, also taken from Table 1 of the 1974 ASHRAE Applications Handbook.

Computations:

1. Solar elevation angle ε.

$$\varepsilon = \sin^{-1} (\cos L \cos \delta \cos H + \sin L \sin \delta)$$

2. Solar azimuth angle ϕ.

$$\phi = \sin^{-1} (\cos \delta \sin H/\cos \varepsilon)$$

3. Angle between the collector normal and earth-sun line.

$$\cos \theta = \cos \varepsilon \cos \phi \sin \Sigma + \sin \varepsilon \cos \Sigma$$

4. Direct solar intensity $I_{D\theta}$ incident on the collector.

$$I_{D\theta} = A\, e^{-B/\sin \varepsilon} \cos \theta$$

In its present form the program is run on an HP-25 (Hewlett-Packard) calculator. The storage entries and program steps are listed in Tables D-1 and 2 respectively.

TABLE D-1: STORAGE ENTRIES

Register 0	Station Latitude L
Register 1	Solar Delination δ
Register 2	Tilt Angle Σ
Register 6	Intensity A
Register 7	Atmospheric Attenuation B

TABLE D2: PROGRAM STEPS

Program Step	Command (Matrix)		Command (as shown on key)	Program Step	Command (Matrix)		Command (as shown on key)
01		31	ENTER↑ (hr angle)	26		71	÷
02	14	04	f sin	27	15	04	g $\sin^{-1}$
03	23	04	STO 4	28	14	05	f cos
04		22	R↓	29		31	ENTER↑
05	14	05	f cos	30	24	05	RCL 5
06	24	00	RCL 0	31	14	05	f cos
07	14	05	f cos	32		61	X
08		61	X	33	24	02	RCL 2
09	24	01	RCL 1	34	14	04	f sin
10	14	05	f cos	35		61	X
11		61	X	36	24	02	RCL 2
12	24	00	RCL 0	37	14	05	f cos
13	14	04	f sin	38	24	05	RCL 5
14	24	01	RCL 1	39	14	04	f sin
15	14	04	f sin	40		61	X
16		61	X	41		51	+
17		51	+	42	24	06	RCL 6
18	15	04	g $\sin^{-1}$	43	24	07	RCL 7
19	23	05	STO 5	44	24	05	RCL 5
20	24	04	RCL 4	45	14	04	f sin
21	24	01	RCL 1	46		71	÷
22	14	05	f cos	47	15	07	ge^x
23		61	X	48		71	÷
24	24	05	RCL 5	49		61	X
25	14	05	f cos				

- SOLAR IRRADIATION II -

```
$JOB            18059.KP=29.TIME=15.PAGES=99 WTR 77 PHYSICS DEPT.
C    ************************************************************************
C
C            THIS  PROGRAM  CALCULATES  THE  SOLAR  IRRADIATION  FOR
C                  ANY  LATITUDE  AND  LONGITUDE.
C
C    ************************************************************************
         REAL INTENS.INITIL.INC.LAT.LONG.NOON
         INTEGER DATE(3).STATN(7)
         DIMENSION FLUX(20).ATTNTN(20)
         COMMON  FLUX.ATTNTN.NOON.DELTA
C           DAY  IS  FROM  1 TO OLK. DATE  IS  THE  MONHT.
C           STATN  IS  THE  NAME  OF  THE  CITY  FOR  THE  RUN.
C           LAT  IS  THE  LATITUDE  OF  THE  COLLECTER.
C           INITIL  IS  THE  INITIAL  VALUE  OF  SIGMA. THE  TILT  ANGLE.
C           INC  IS  THE  CHANGE  OF  THE  TILT  ANGLE.
C           FINTIL  IS  THE  FINAL  TILT  ANGLE.
C           STRTTM  IS  THE  STARTING  TIME  OF  THE  RUN.
C           DLTTM  IS  THE  CHANGE  IN  TIME.  FINTM  IS  THE  FINAL  TIME.
C
       1 READ(5.500.END=25) DAY.DATE.STATN.LAT.INITIL.INC.FINTIL.STRTTM.
        1 DLTTM.FINTM
     500 FORMAT(F20.7.3A4.7A4.F18.7./6F12.7)
C           LONG  IS  THE  LONGITUDE.  TMZN  IS  THE  LONGITUDE  OF  THE
C     TIME  ZONE.
         READ(5.505)LONG.TMZN
     505 FORMAT(2F20.5)
C           DELTA  IS  THE  SOLAR  DECLINATION.
          READ(5.506)DELTA
     506 FORMAT(F10.5)
C           NOON  IS  THE  LOCAL  NOON.
         NOON=12.0-(.06667*(LONG-TMZN))
C           N  IS  THE  NUMBER  OF  HOURS  AND  THE  THE  NUMBER  OF  INPUT
C     TO  (A) FLUX  AND (B)  ATTENUATION  THAT  WILL  BE  READ.
         N=(FINTM-STRTTM)/DLTTM
         N=N+1
C           SIGMA  IS  THE  ANGLE  OF  THE  COLLECTER.
         SIGMA=INITIL
         WRITE(6.600) DAY.DATE.STATN.LAT
     600 FORMAT(1H1.//50X.'THE DAY IS'.F10.3/50X.'THE MONTH IS  '.3A4/
        1 20X.'THE STATION IS'.7A4.'AND ITS LATITUDE IS'.F10.3///)
         READ(5.555)(FLUX(K).K=1.N).(ATTNTN(L).L=1.N)
     555 FORMAT(4F20.7)
       2 CALL SOLAR(N.DAY.LAT.SIGMA.STRTTM.DLTTM.FINTM)
         SIGMA=SIGMA+INC
         IF(FINTIL-SIGMA) 3.2.2
       3 WRITE(6.603)
     603 FORMAT(2X.'END OF DATA SET')
         GO TO 1
      25 STOP
         END

         SUBROUTINE SOLAR(N.DAY.LAT.SIGMA.STRTTM.DLTTM.FINTM)
         REAL INTENS.LAT.NOON.INTEN1.INTEN2.INTEN3
         DIMENSION FLUX(20).ATTNTN(20)
         COMMON  FLUX.ATTNTN.NOON.DELTA
         PI=3.141593
         CONVRT=PI/180.
         WRITE(6.666) SIGMA
     666 FORMAT(1X//20X.'THE TILT ANGLE IS'.F7.3.1X.'DEGREES'//9X.'HOUR'.7X
```

```
     1 'SOLAR',9X,'SOLAR',6X,'ATMOSPHERIC',3X,'ATTENUATION',6X,
     2 'SOLAR'/3X,'UT',4X,'ANGLE',4X,'ELEVATION',3X,'DECLINATION',
     3 6X,'FLUX',8X,'FACTOR',8X,'IRRADIATION'/)
      KOUNT=1
       SAVE=0.
C        THE  STARTING  TIME  FOR  LOCAL  SUNRISE.
      UT=NCON-STRTTM
C        HA  IS  THE  HOUR  ANGLE  AND  IS  FROM  THE  ZENITH.
   10 HA=(NOON-UT)*15.
C        CONVERTING  TO  RADIANS.
      RAD1=LAT*CONVRT
      RAD2=HA*CONVRT
      RAD3=SIGMA*CONVRT
      DELTA=DELTA*CONVRT
C        EPSILN    IS  THE  SOLAR  ELEVATION.
      EPSILN=ARSIN((COS(RAD1)*COS(DELTA)*COS(RAD2))+SIN(RAD1)*
     1  SIN(DELTA))
      PHI=ARSIN(COS(DELTA)*SIN(RAD2)/COS(EPSILN))
      DELTA=DELTA/CONVRT
      IF(EPSILN.LE.0.)GOTO11
C        INTENS  IS  THE  SOLAR  INTENSITY.
      INTEN1=FLUX(KOUNT)*EXP(-ATTNTN(KOUNT)/SIN(EPSILN))
       INTEN2=(COS(EPSILN)*COS(PHI)*SIN(RAD3))+SIN(EPSILN)*COS(RAD3)
       INTENS=INTEN1*INTEN2
      SAVE=SAVE+INTENS
C        CONVERTING  BACK  TO  DEGREES.
      EPSILN=EPSILN/CONVRT
      PHI=PHI/CONVRT
      WRITE(6,601) UT,HA,EPSILN,DELTA,FLUX(KOUNT),ATTNTN(KOUNT),INTENS
  601 FORMAT(1X,F5.2,1X,F8.3,6X,F7.3,3X,4(F10.3,4X))
       GOTO12
   11 WRITE(6,611)UT
  611 FORMAT(1X,F5.2,5X,'  THE SUN CAN NOT BE SEEN ')
   12 IF(KOUNT-N)13,14,14
   13 UT=UT+DLTTM
      KOUNT=KOUNT+1
      GO TO 10
   14  WRITE(6,612)SAVE
  612 FORMAT(//,20X,' THE TOTAL IRRADIATION FOR THE DAY WAS  ',F15.5)
      RETURN
      END

 SENTRY
```

SAMPLE OUTPUT (S. R. II)

THE DAY IS 111.000
THE MONTH IS APR
THE STATION IS DAMIEN, HAITI AND ITS LATITUDE IS 18.600

THE TILT ANGLE IS 0.000 DEGREES

UT	HOUR ANGLE	SOLAR ELEVATION	SOLAR DECLINATION	ATMOSPHERIC FLUX	ATTENUATION FACTOR	SOLAR IRRADIATION
6.10	90.000	3.771	11.900	360.000	0.100	1.534
7.10	75.000	17.006	11.900	360.000	0.100	61.109
8.10	60.000	31.970	11.900	360.000	0.100	135.675
9.10	45.000	46.102	11.900	360.000	0.100	202.405
10.10	30.000	60.334	11.900	360.000	0.100	254.283
11.10	15.000	74.064	11.900	360.000	0.100	287.069
12.10	0.000	83.300	11.900	360.000	0.100	298.274
13.10	-15.000	74.064	11.900	360.000	0.100	287.069
14.10	-30.000	60.334	11.900	360.000	0.100	254.283
15.10	-45.000	46.102	11.900	360.000	0.100	202.405
16.10	-60.000	31.970	11.900	360.000	0.100	135.676
17.10	-75.000	17.006	11.900	360.000	0.100	61.110
18.10	-90.000	3.771	11.900	360.000	0.100	1.534

THE TOTAL IRRADIATION FOR THE DAY WAS 2182.42400

THE TILT ANGLE IS 5.000 DEGREES

UT	HOUR ANGLE	SOLAR ELEVATION	SOLAR DECLINATION	ATMOSPHERIC FLUX	ATTENUATION FACTOR	SOLAR IRRADIATION
6.10	90.000	3.771	11.900	360.000	0.100	1.925
7.10	75.000	17.006	11.900	360.000	0.100	62.073
8.10	60.000	31.970	11.900	360.000	0.100	136.030
9.10	45.000	46.102	11.900	360.000	0.100	202.253
10.10	30.000	60.334	11.900	360.000	0.100	255.225
11.10	15.000	74.064	11.900	360.000	0.100	288.735
12.10	0.000	83.300	11.900	360.000	0.100	300.193
13.10	-15.000	74.064	11.900	360.000	0.100	288.735
14.10	-30.000	60.334	11.900	360.000	0.100	255.225
15.10	-45.000	46.102	11.900	360.000	0.100	202.253
16.10	-60.000	31.970	11.900	360.000	0.100	136.039
17.10	-75.000	17.006	11.900	360.000	0.100	62.074
18.10	-90.000	3.771	11.900	360.000	0.100	1.925

THE TOTAL IRRADIATION FOR THE DAY WAS 2194.29300

THE TILT ANGLE IS 10.000 DEGREES

UT	HOUR ANGLE	SOLAR ELEVATION	SOLAR DECLINATION	ATMOSPHERIC FLUX	ATTENUATION FACTOR	SOLAR IRRADIATION

- CLOUD COVER -

```
$JOB              18059,KP=29,TIME=04,PAGES=30 WTR 77 MCDONALD, M
C
C ***********************************************
C  THIS PROGRAM WILL TAKE INTEGER VALUES FOR THE CLOUD
C     CONDITIONS  OVER A NUMBER OF YEARS AND CONVERT
C       TO A STRING OF CHARACTERS.
C ***********************************************
C
        IMPLICIT INTEGER*2(A-Z)
        INTEGER*4 MONTH,DVC
        REAL C,CN,SAVE,DAYS,HOLD,FNLSVE(14,33,12),XTIMES(12),YTIME
        DIMENSION MONTH(3,12),WRTDY(11),HOUR(24),SKY(24),IWAIT(154),
       1AVE(5,11),GRAPH(55),CODE(5,11),WTHR(12),OUT(5)
       2,LSTMNT(12),CNTMNT(12)
       0,UNKNWN(5),CHCK(24)
        DATA WTHR/'0','1','2','3','4','5','6','7','8','9','-',' '/,
       1LSTMNT/12*0/,CNTMNT/12*0/
       2,BLNK/'  '/,FNLSVE/5544*0./,XTIMES/12*0./
       3,UNKNWN/'-N','O ',' D','AT','A-'/
       4,IWAIT/154*0/
        REWIND10
C
C  READ IN THE MONTHS AND THE CODE FOR THE PRINT OUT.
C
        READ(5,500)((MONTH(I,J),I=1,3),J=1,12),((CODE(K,L),K=1,5),L=1,11)
  500   FORMAT(20A4/16A4/40A2/15A2)
        READ(5,5999)AAA,AST1
 5999   FORMAT(2I2)
        AST2=AST1+AAA
        DVC = 10
        ISTART=0
        ISTOP=0
        SAVE=0
        HOLD=0.
        YTIME=0.
C
C READ IN THE DATA FOR AN ENTIRE DAY
C
    1   READ(DVC,502)YEAR,MNTH,DAY,(HOUR(N),SKY(N),N=1,24)
  502   FORMAT(9X,3I2,3(I2,40X,A1,37X),7(/15X,3(I2,40X,A1,37X)))
        IF(YEAR.GT.AST2)GOTO25
        IF(YEAR.GE.AST1 .AND. YEAR.LE.AST2)GOTO2
        GOTO1
    2   IF(ISTART)3,3,6
    3   ISTART=ISTART+1
    4   IYEAR=YEAR+1900
        WRITE(6,605)(MONTH(N,MNTH),N=1,3),IYEAR
  605   FORMAT(1H1,50X,3A4,' ,',I4/)
        MNT=MNTH
        XTIMES(MNTH)=XTIMES(MNTH)+1.
        IF(MNT.EQ.2.AND.DAY.EQ.29)YTIME=YTIME+1.
        FIX=0
        COUNT=1
        GOTO7
    6   IF(MNTH.EQ.MNT)GOTO7
        GOTO115
C
    7   FIX=FIX+1
        IF(FIX.GT.11)GOTO15
        WRTDY(FIX)=DAY
```

```
          HR=1
      8   IF(HOUR(HR)-6)9,10,10
      9   HR=HR+1
          GOTO8
C
C   FIND THE SKY CONDITION
C
     10   C=0.
          DO 12 J=1,14
          CNT=0
          DO 11 N=1,12
          IF(SKY(HR).EQ.WTHR(N))CNT=N
     11   CONTINUE
          IF(CNT.EQ.12)CNT=1
          IWAIT(COUNT)=CNT
          COUNT=COUNT+1
          CN=CNT
          C=C+CN
          SAVE=SAVE+CN
           FNLSVE(J,DAY,MNTH)=FNLSVE(J,DAY,MNTH)+CN
           IF(HOUR(HR).EQ.19)GOTO13
          HR=HR+1
     12   CONTINUE
C
C  SET THE VALUE OF THE AVERAGE FOR THE DAY
C
     13   DAVE=C/14. +.3
          DO 14 N=1,5
     14   AVE(N,FIX)=CODE(N,DAVE)
          GOTO1
C
C  THIS SECTION WILL TAKE THE VALUE AND CONVERT TO THE CHARACTER
C
     15   FIX=FIX-1
    115   DAYS=WRTDY(FIX)
          WRITE(6,616)(WRTDY(N),N=1,FIX)
    616   FORMAT(7X,10(I2,9X),I2)
          DO 16 N=1,11
     16   WRTDY(N)=0
C
C  HERE IS WHERE THE VALUE FOR THE MONTH IS SET
C           AND THIS IS WHERE THE DATA FOR THE AVE FOR THE TOTAL
C           NUMBER OF YEARS IS SET
C
          COUNT=1
          TIME=5
          DO 20 I=1,14
          TIME=TIME+1
          TME=I+5
           IF(TIME.EQ.13)TIME=1
          DATUM=1
          IGO=I+140
           DO 18 J=I,IGO,14
          KNT=IWAIT(J)
           IF(KNT.EQ.0)KNT=1
          DO 17 K=1,5
          GRAPH(DATUM)=CODE(K,KNT)
     17   DATUM=DATUM+1
     18   CONTINUE
          WRITE(6,619)TIME,(GRAPH(L),L=1,55)
```

```
  619 FORMAT(1X,I2,11('I',5A2),'I')
   20 CONTINUE
      DO 21 J=1,154
   21 IWAIT(J)=1
       WRITE(6,622)((AVE(J,K),J=1,5),K=1,11)
  622 FORMAT(7X,11('AVE',8X)/3X,11('I',5A2),'I'/)
      DO 100 J=1,11
      DO 100 K=1,5
  100 AVE(K,J)=CODE(K,1)
      IF(ISTOP.EQ.1)GOTO126
      IF(FIX.EQ.11)FIX=0
      IF(FIX.EQ.0)GOTO7
      IF(MNTH.EQ.MNT)GOTO1
C
C  THIS IS  WHERE THE INDIVIDUAL  MONTHLY AVE IS SET
C
  126 MAVE=SAVE/(14.*DAYS)+.3
      LSTMNT(MNT)=LSTMNT(MNT)+1
      CNTMNT(MNT)=CNTMNT(MNT)+MAVE
      DO 23 I=1,5
   23 OUT(I)=CODE(I,MAVE)
      WRITE(6,624)(OUT(J),J=1,5)
  624 FORMAT(50X,' MONTH AVERAGE '/50X,5A2)
      IF(ISTOP.EQ.1)GOTO26
      SAVE=0
      GOTO4
   25 ISTOP=1
      GOTO115
C
C   FINALLY THIS IS WHERE THE  MONTHLY AVE IS SET FOR THE TOTAL NUMBER
C        OF YEARS
   26 WRITE(6,627)LSTMNT(1)
  627  FORMAT(1H1,20X,' THIS IS A ',I3,3X,' YEAR '/35X,
     1' AVERAGE OF THE'/35X,' SKY CONDITIONS OVER CUBA '//)
      DO 27 J=1,12
   27 LSTMNT(J)=CNTMNT(J)/LSTMNT(J)
      DO 30 I=1,12
      HOLD= LSTMNT(I)
      DO 28 J=1,5
   28 OUT(J)=CODE(J,HOLD)
      WRITE(6,629)(MONTH(K,I),K=1,3),(OUT(L),L=1,5)
  629 FORMAT(30X,3A4,2X,'I',5A2,'I',//)
   30 CONTINUE
       IF(YTIME.EQ.0.)YTIME=1.
      DO 33 MNT=1,12
       DO 33 DAY=1,33
        DO33 HR=1,14
      IF(MNT.EQ.2.AND.DAY.EQ.29)GOTO31
      IF(FNLSVE(HR,DAY,MNT).EQ.0.)GOTO32
      FNLSVE(HR,DAY,MNT)=FNLSVE(HR,DAY,MNT)/XTIMES(MNT)+.3
      GOTO33
   31  FNLSVE(HR,DAY,MNT)=FNLSVE(HR,DAY,MNT)/YTIME + .3
      GOTO 33
   32 FNLSVE(HR,DAY,MNT)=1.
   33 CONTINUE
      DO 42 MNT=1,12
      WRITE(6,634)(MONTH(N,MNT),N=1,3)
  634 FORMAT(1H1,30X,' AVERAGE FOR    ',3A4,/)
      DAY=0
      IDAY=1
```

```
      DO 40 CNT=1,3
      DAY=IDAY
      IDAY=IDAY+10
      TIME=6
      JK=0
      DO 35 J=DAY,IDAY
      JK=JK+1
      WRTDY(JK)=J
      IF(WRTDY(JK).GT.31)WRTDY(JK)=0
   35 CONTINUE
       WRITE(6,636)(WRTDY(N),N=1,11)
  636  FORMAT(7X,10(I2,9X),I2)
      DO 40 HR=1,14
      KNT=0
      DO 38 LSTDAY=DAY,IDAY
      IHOLD= FNLSVE(HR,LSTDAY,MNT)
      IF(IHOLD.LE.0.OR.IHOLD.GE.12)IHOLD=1
      KNT=KNT+1
      DO 37 J=1,5
   37 AVE(J,KNT)=CODE(J,IHOLD)
   38 CONTINUE
      WRITE(6,639)TIME,((AVE(K,L),K=1,5),L=1,11)
  639 FORMAT(1X,I2,11('I',5A2),'I')
      TIME=TIME+1
      IF(TIME.EQ.13)TIME=1
   40 CONTINUE
      WRITE(6,641)
  641 FORMAT(3X)
   42 CONTINUE
      STOP
      END

$ENTRY
```

APPENDIX E

ON-SITE VERSUS CENTRALIZED MANUFACTURE

On-Site Advantages

- Transportation of materials to site is simpler, cheaper than transportation of finished product
- More local pride and user pride in the finished cooker
- More suitable for very heavy or bulky designs
- Can make use of on-site materials - stones, etc.
- Cooker can be tailored for local terrain, other conditions
- Local repair more feasible if cooker was locally built
- Construction activities provide work for people in widespread areas and poorest areas

Centralized Advantages

- Fewer workers to train
- Greater production efficiencies possible
- Availability of skilled workers
- Availability of subcontract-type services
- Feasibility of using specialized tools and other equipment
- Feasibility of using highly-trained workers
- Wider range of fabrication methods and techniques can be used
- Export of cookers to other countries is a possibility
- Warehousing, parts inventories, etc. could be combined with production facility
- Production facility could be used for repairs also
- Production facility would provide base of operations for technicians who would travel around the country

APPENDIX F

CALCULATIONS FOR BRACE RESEARCH INSTITUTE SOLAR STEAM COOKER

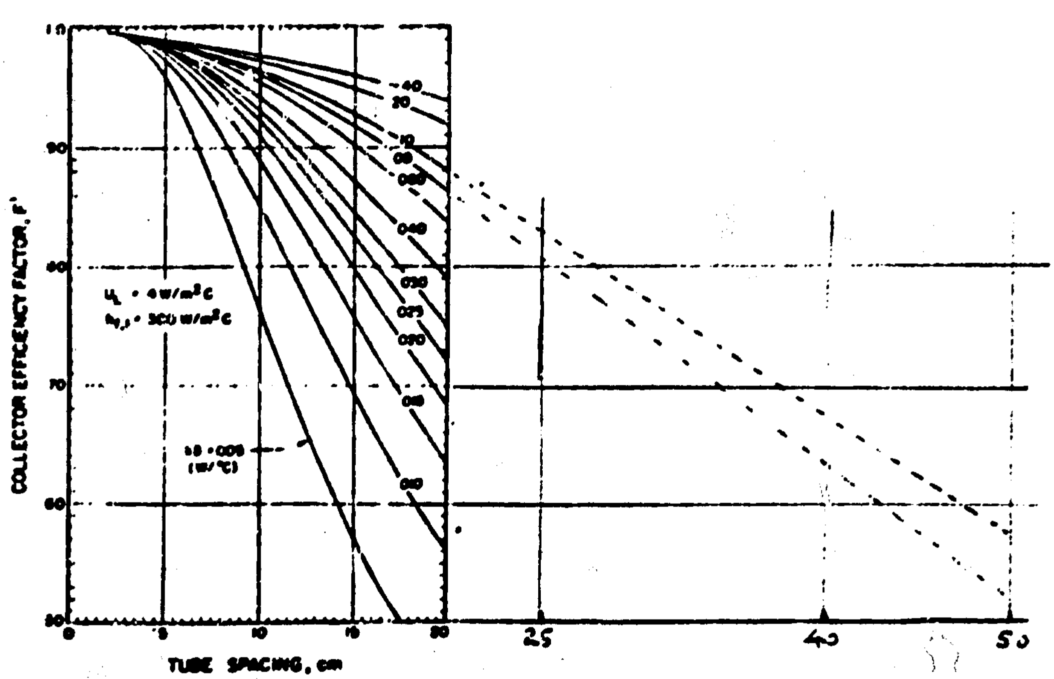
It was mentioned in the text that one of the main problems with this unit is the poor thermal design of the collector panel; a few calculations will serve to illustrate the point.

One of the most obvious shortcomings is the use of a single water tube to collect heat from a panel that is 19.6 inches wide. In the design of a flat plate solar collector, one important parameter is tube spacing - the distance between tubes, or width of the collector plate divided by the number of tubes. The graph at the bottom of the page, taken from a paper by Beckman that was presented at the NSF-RANN Workshop on Solar Collectors for Heating and Cooling of Buildings, New York, NY, November 1974, presents the effect of tube spacing for typical collector parameters in terms of a "collector efficiency factor" - the ratio of energy collected in the working fluid to energy that would be collected in the case of contiguous tubes. We have drawn in straight line extrapolations of two curves of interest, since the graph as presented only goes to 20 cm tube spacing and the Brace collector has an effective spacing of 50 cm (19.6 in.)

The Brace collector uses an aluminum absorber plate of .025 inch thickness (δ). The best aluminum alloys have thermal conductivities (k) on the order of 175 watts/meter - ^{o}C, giving

$$k\delta = (175)(.025)(.0254) = 0.11 \ w/^{o}C$$

If our assumed extrapolation is approximately correct, then at 50 cm we have an efficiency factor of about 0.6. If the same absorber plate contained two tubes, the spacing would be 25 cm. and the efficiency factor would be about 0.84, and three tubes (17 cm) would give 0.93. Therefore, if the Brace collector is otherwise



comparable enough to normal flat plate solar collectors for these curves to be indicative, addition of a second fluid tube to the existing collector would improve performance by a factor of (.84/.6 = 1.4), or about 40%, while three tubes would result in (.93/.6 = 1.55), or a 55% improvement. We do not know what effect the fact that, in the Brace cooker, the tube is not thermally attached to the absorber plate would have on these conclusions.

Another way to look at the same problem is to calculate the required temperature gradient in the absorber plate. We can do this in terms of the amount of energy that would be collected by a normal flat plate collector under the desired working conditions. The inlet and outlet fluid temperatures for the cooker application can be taken as $212^{\circ}F$; if we assume an ambient temperature of $80^{\circ}F$ and solar radiation at 310 Btu/ft^2-hr, then $\Delta T/I = (212-80)/310 = 0.43$ ft^2-hr-$^{\circ}$F/Btu. A few published or advertised flat plate collector efficiencies at this value of $\Delta T/I$ are as follows:

Chamberlain single-glazed, flat black:	0.28
Chamberlain double-glazed, flat black:	0.39
Chamberlain single-glazed, black chrome:	0.44
Chamberlain double-glazed, black chrome:	0.48
Falbel Delta Model 31-AC	0.29
Solarvak	0.52
KTA Model KT 3-24	0.52
GE Model TC-100	0.62
Calmac "Sunmat"	0.38
Ametek	0.49
Sunworks "Solector"	0.48
Sunearth	0.43
Miromit	0.37
PPG	0.30

The KTA and GE collectors are tubular concentrator types, and in addition the GE and Solarvak collectors are partially evacuated, so are not entirely comparable to the others. Among the others, we see a range of efficiencies from 0.28 to 0.5. For an absorber plate of width 19.6 inches, and insolation at 310 Btu/ft^2-hr, this gives a range of 142 to 253 Btu/hr collected per foot of collector panel. If the collector contains only one tube, and the collector plate is again .025 inch aluminum, then the temperature gradient in the plate next to the tube* is

$$\frac{dT}{dx} = \frac{Q/L}{k\delta} = \frac{\frac{1}{2}\begin{Bmatrix}142\\253\end{Bmatrix}\frac{\text{Btu}}{\text{ft-hr}}}{(0.111\ \text{w}/^{o}\text{C})(3.413\ \text{Btu/w-hr})(1/1.8^{o}\text{C}/^{o}\text{F})}$$

$$= \begin{Bmatrix}337\\601\end{Bmatrix}\ ^{o}\text{F/ft}$$

or about one degree Fahrenheit per inch for each one percent efficiency of the collector. Although this temperature gradient decreases with distance from collector tube, it is clear that with only one tube, much of the collector plate must reach very high temperatures to drive the heat flux at any reasonable efficiency.

The plate temperature will be elevated still higher above the temperature of boiling water due to the temperature difference between the plate and the pipe, which is difficult to predict but is probably large due to the poor thermal contact between plate and pipe. The temperature drop through the pipe wall is not large, however, even though it is one to two orders of magnitude greater than it would be in the case of thin-wall copper tube. If we assume the heat enters the pipe uniformly over the circumference, the temperature difference through the pipe wall is given by the equation

$$\Delta T = \frac{(Q/L)\ln(r_o/r_i)}{2\pi k}$$

where Q/L = heat transfer per unit length

r_o = outside radius

r_i = inside radius

k = thermal conductivity

The Brace design uses 3/4 inch nominal, Schedule 40 steel pipe, r_o=1.05", r_i= 0.824", k=30 Btu/ft-hr-^{o}F. For our previous range of values for Q/L, then, we have

$$\Delta T = \begin{Bmatrix}0.18\\0.33\end{Bmatrix}\ ^{o}\text{F}.$$

Actual temperature drop through the pipe wall would be approximately twice the values calculated since the heat enters through only one half the circumference of the pipe.

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*Assuming all the heat flux to the tube comes from the absorber plate, half from each side. Energy due to that sunlight that falls directly on the tube is neglected.

APPENDIX G

DESCRIPTION OF F.I.T. COOKER

This solar cooker consists of (1) the oven box, (2) a parabolic-section reflector pivoted about a point vertically below the oven box, and (3) a frame to support items (1) and (2), with wheels for portability and alignment.

The oven box (1) is a rectangular parallelopiped, insulated on the back and ends and double glazed on the top. The lower surface includes a central, glazed slit, the length of the oven, with insulated strips either side of the slit. The front surface is a door, double-glazed and hinged on one end. A rack to support cooking pots, etc. rests on the insulated strips adjacent to the slit.

The reflector (2) is a parabola, designed such that with the sun at 60° elevation and the reflector properly positioned, the sun lies in the plane defined by the vertex and the focal line of the parabola. The reflector is located such that, in this position, the focal line is centered on the oven slit. The reflector is pivoted about an axis vertically below the center of the slit. The ends of the reflector, when positioned as described above, are slightly outside a circle centered on the pivot axis and passing through the back edge - that is, the north edge if the cooker is facing due south, as for example at solar noon on any day at a point north of the Tropic of Cancer.

The support structure (3) is a frame, as described in the attached sketch, resting on two pivoting casters and two rigid casters.

The unique feature of this solar cooker consists of the optical arrangement, used in conjunction with an oven. A similar optical geometry, consisting of a paraboloidal array of small focusing mirrors, the entire array pivoting about an axis passing through the center of a circle drawn through the focal point and the extreme edges of the reflector array, was developed by Tabor[1] for use with a direct focusing cooker. The combination of focusing reflectors with an enclosed oven was developed by Prata[2], who used two symmetric parabolic reflectors pivoted about axes through the vertex lines. The invention consists in the combination of the Tabor geometry with the Prata cooking arrangement, which allows the Prata cooker to be made in a much sturdier, easier-to-use, more effective configuration.

Comparison tests have also shown that less reflector area is required than in Prata's case, and hence lower manufacturing cost.

In operation, the entire assembly is periodically turned about a vertical axis to face the sun, and the reflector is also tipped to follow changes in the sun's elevation above the horizon in such a manner that the focal line remains approximately stationary. With this optical configuration, rotation of the parabola about its pivot axis is 2/3 of the change in elevation of the sun. That is, relative to its central position when the sun's elevation is 60° (the design point), the parabola is swung upward 20° when the sun is at 30°, and is swung downward 20° when the sun is directly overhead. At the same time, the focus is compromised, being perfect only at the design point (60°). The image spreading is small relative to the width of the slit for solar elevation angles greater than about 20°, and is always smaller than in the Prata design. The practical benefits of this optical arrangement are based on the fact that the reflector does not extend as high in the air at any sun angle due to its being truncated on one side near the vertex, and especially at low sun angles due to the 2/3 rotation factor. The low reflector enhances stability and minimizes wind loading.

The slit in the oven box is wide enough to allow discrete rather than continuous adjustment of the reflector. The reflector is typically adjusted to place the focal line at one edge of the slit (back in the morning, front in the afternoon). As the sun rises or sets with the mirror stationary, the image or focal line, which is very bright and hence easily seen, moves across the slit; when it reaches the far end, the reflector is adjusted to move the image line back to the original edge. Since the reflector pivot is vertically below the slit, the image moves in a horizontal direction.

Literature Cited

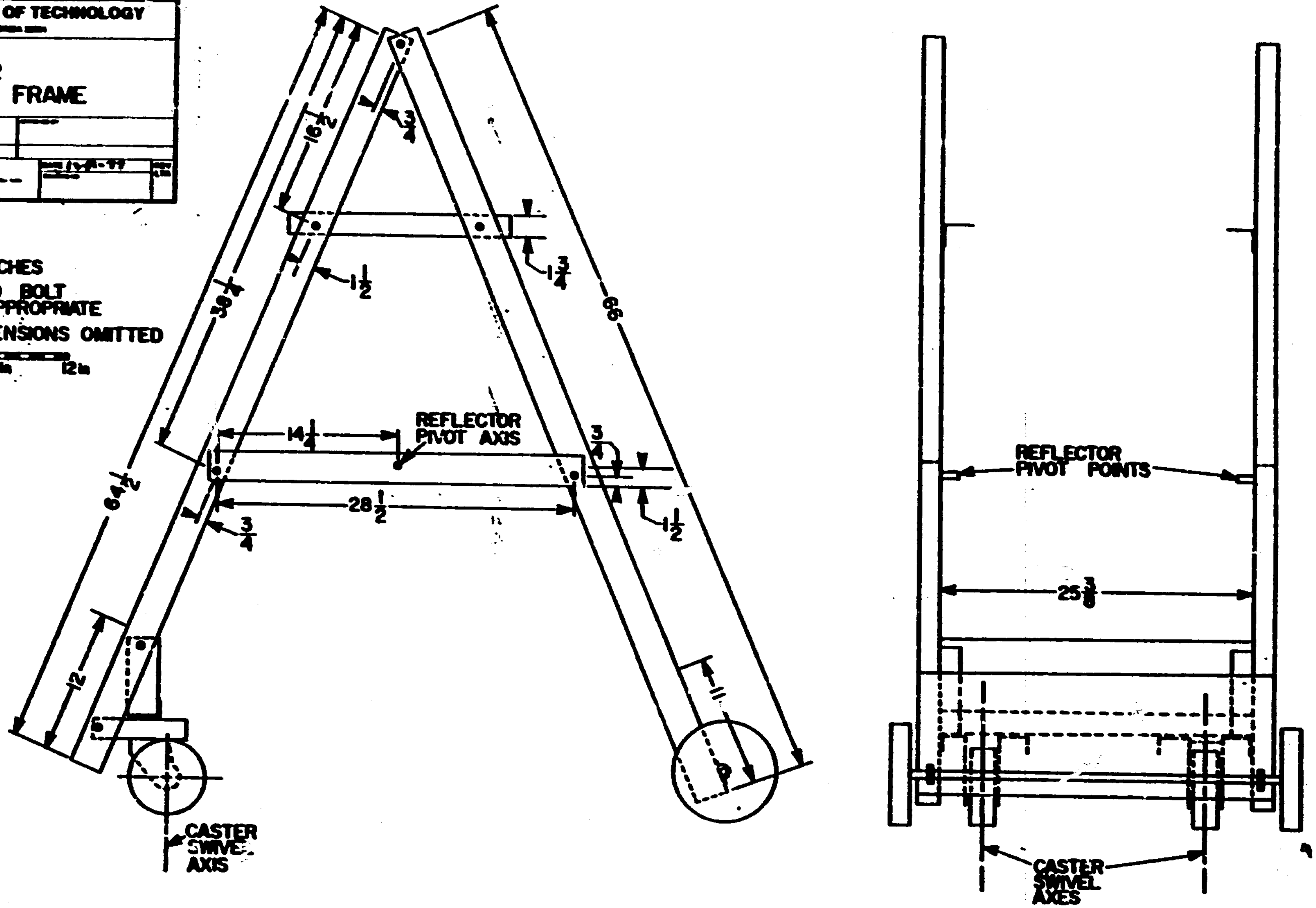
1 Tabor, H.: "A Solar Cooker for Developing Countries." Solar Energy, Volume X, No. 4 (1966), pages 153-157.

2 Prata, S.: "A Cylindro-Parabolic Solar Cooker." Paper S/110, Proceedings of the United Nations Conference on New Sources of Energy.

FLORIDA INSTITUTE OF TECHNOLOGY

FIT COOKER
STRUCTURAL FRAME

NOTES
DIMENSIONS IN INCHES
BOLT CENTER TO BOLT CENTER WHERE APPROPRIATE
UNIMPORTANT DIMENSIONS OMITTED
SCALE 0 6in 12in



APPENDIX H

COOKING WITH STORED SOLAR HEAT

A paper with this title, by C. A. Hall, C. J. Swet, and L. A. Temanson, has just been sent to us by Dr. Hall; the paper was prepared for presentation at the 1977 Annual Meeting of the International Solar Energy Society in India. The paper describes a new concept that would allow the cooker to be divorced from the solar collector in both space and time - a very significant objective, if it can be achieved. The actual cooker is referred to as a "heat package" and described as follows:

"The heat packages will contain a chemical system capable of absorbing energy from the sun, storing it, and releasing the heat on demand at a temperature near 300°C. The choice of a chemical system will be guided by the results of research and development tests recently completed. A possible candidate is the ammoniated salts of magnesium chloride and calcium chloride. To charge this cooker, ammonia is driven from the high temperature salt bed ($MgCl_2$) to the ambient temperature salt bed ($CaCl_2$) where it combines with the salt. Heating this low temperature bed slightly will dissociate the ammonia and then it returns to the high temperature bed, reacts with the salt exothermally, freeing heat for use in cooking.

"The heat package would be prepared for use by placing it towards the back of the ... solar heater .... When the package has been charged, it can be stored until heat is needed. When heat is desired, the valve is opened allowing the chemical reaction to be reversed which generates heat at about 300°C. These packages could be used for cooking, heating, or any other domestic or industrial purpose.

"Once all of the ammonia has recombined with the magnesium chloride in the container, the package could be returned to the central solar heater where it would be recharged through the dissociation of the ammonia via solar energy. The heat packages would be completely sealed and unbreakable.

"After the packages have been recharged, they can be removed from the central solar heater and stored until needed. These packages when used, as for example in food preparation, would have the definite advantage over existing solar cookers in that 1) meals could be prepared inside buildings, and 2) cooking could be done even on cloudy or rainy days and at night."

This concept had not been tested as of the time the paper was presented, and we do not believe any plans for testing were described.