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# MANUAL ON SOLAR DISTILLATION OF SALINE WATER

S. G. Talbert, et al

Battelle Memorial Institute
Columbus, Ohio

April 1970

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# Manual on Solar Distillation of Saline Water

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The manual is a comprehensive treatise on the state of the art of solar distillation for appraising water-supply potential of solar stills and assisting in the design of practical plants. Information was obtained from literature review and from correspondence and discussions with solar still designers from many countries. The manual includes a historical review, solar still technology, data of meaningful value from basin-type solar stills that have been operated for extended periods, economics, overall appraisal of solar distillation, and procedures for sizing and building solar stills. Glass and plastic designs are described and their advantages and disadvantages pointed out. The manual deals mainly with the so-called simple basin-type and more sophisticated designs are not included nor are solar water heaters or other uses of this form of energy. Capital costs of large stills having areas larger than 1000 $ft^2$ is shown to be as low as \$1.00/$ft.^2$ of basin area with water costs between \$3-\$4.00 per 1000 gals. The costs for small family size units are near \$4.00/$ft.^2$ of basin area and water costs range from \$15 to \$30/1000 gallons. Long-term tests of better materials are recommended if costs are to be lowered.

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# Manual on Solar Distillation of Saline Water

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UNITED STATES DEPARTMENT OF THE INTERIOR • Walter J. Hickel, Secretary
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The Department works to assure the wisest choice in managing all our resources so each will make its full contribution to a better United States—now and in the future.

## FOREWORD

This is one of a continuing series of reports designed to present accounts of progress in saline water conversion and the economics of its application. Such data are expected to contribute to the long-range development of economical processes applicable to low-cost demineralization of sea and other saline water.

Except for minor editing, the data herein are as contained in a report submitted by the contractor. The data and conclusions given in the report are essentially those of the contractor and are not necessarily endorsed by the Department of the Interior.

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# SECTION 1. SUMMARY

This manual, prepared under the sponsorship of the U.S. Office of Saline Water, is a comprehensive treatise on the state of the art of solar distillation. Its primary purposes are to apprise water-supply planners of the potential of solar distillation and to assist them in designing practical plants. Information for the manual was assembled from an extensive review of the literature and from correspondence and discussions with solar-still designers from various countries. The cooperation of all those who contributed is gratefully acknowledged by the authors. Wherever possible, references to information sources are included in the text; a large bibliography is also provided in Section 10.

The manual begins with an historical review. This is followed by descriptions of the larger installations of basin-type solar stills that have been tested sufficiently to enable the collection of meaningful data. Many additional stills are described in Section 9. Several sections examine the subject of solar still technology and the effects of numerous variables on productivity. Next, the subject of economics is discussed, followed by an overall appraisal of solar distillation. A concluding section deals with procedures for sizing and building solar stills.

The appeal of obtaining something "free" from nature has stimulated many inventors to try their creative skills in designing solar distillers. Consequently, numerous solar still designs have been proposed. Many kinds of stills have been built for laboratory experimentation; some have been evaluated in pilot-plant sizes; and a few have been constructed for commercial usage. In the preparation of this manual an attempt was made to classify the various designs into recognizable categories in which there are realistic data and to present the kind of information that will assist solar-still designers in making logical choices of design features for their particular situations.

In applications requiring solar-distilled water in quantities above 50 gpd, the basin-type still has been used almost exclusively, and where a permanent installation has been intended, glass has been the preferred cover material. Where a temporoary or semipermanent installation (up to a maximum of 5 years) is planned, or in isolated locations where transportation of glass would be difficult, plastic covers should be considered. New developments in materials could, of course, alter these trends. A variety of still designs, particularly as affected by choice of materials, can be envisaged in three categories: (1) permanent installations built in the field by a construction company, (2) factory mass-produced units with minimum field assembly, and (3) hand-made structures designed to be built with locally available material and semiskilled labor. Each category has its own particular economic advantage in specific situations. Because of this, it is not possible to generalize that one particular type or design of still will be economically superior in all situations. Thus, continued experiments with a variety of solar still designs are indicated.

Current state of the art of solar distillation is fairly well understood from the standpoints of the thermodynamic and geometric effects, and it is generally agreed that the simple solar still has the best immediate potential. Thus, this manual treats mainly the so-called simple basin-type solar still; that is, stills based on evaporation of brine from a horizontal basin placed under a sloping transparent cover on which condensation occurs. Designs that use solar concentrators are not included, other than occasionally in reference to a particular designer's work. Likewise, solar water heaters are not covered, nor are combination devices that unite water production with another function such as salt production.

A marked increase in the commercial use of solar stills has taken place in the past few years. At least three companies are marketing small solar stills in the United States. There are presently about 20 solar distillers with basin areas larger than 1,000 $ft^2$ in various countries of the world. The total area of these basins is over 284,000 $ft^2$ and the average total productivity is about 20,000 gpd. The largest solar still built thus far is on the Greek island of Patmos. Its basin area is 93,000 $ft^2$, and the anticipated annual average productivity is around 6,900 gpd. The collection of rainwater at Patmos increases the yearly output of fresh water about 75 percent.

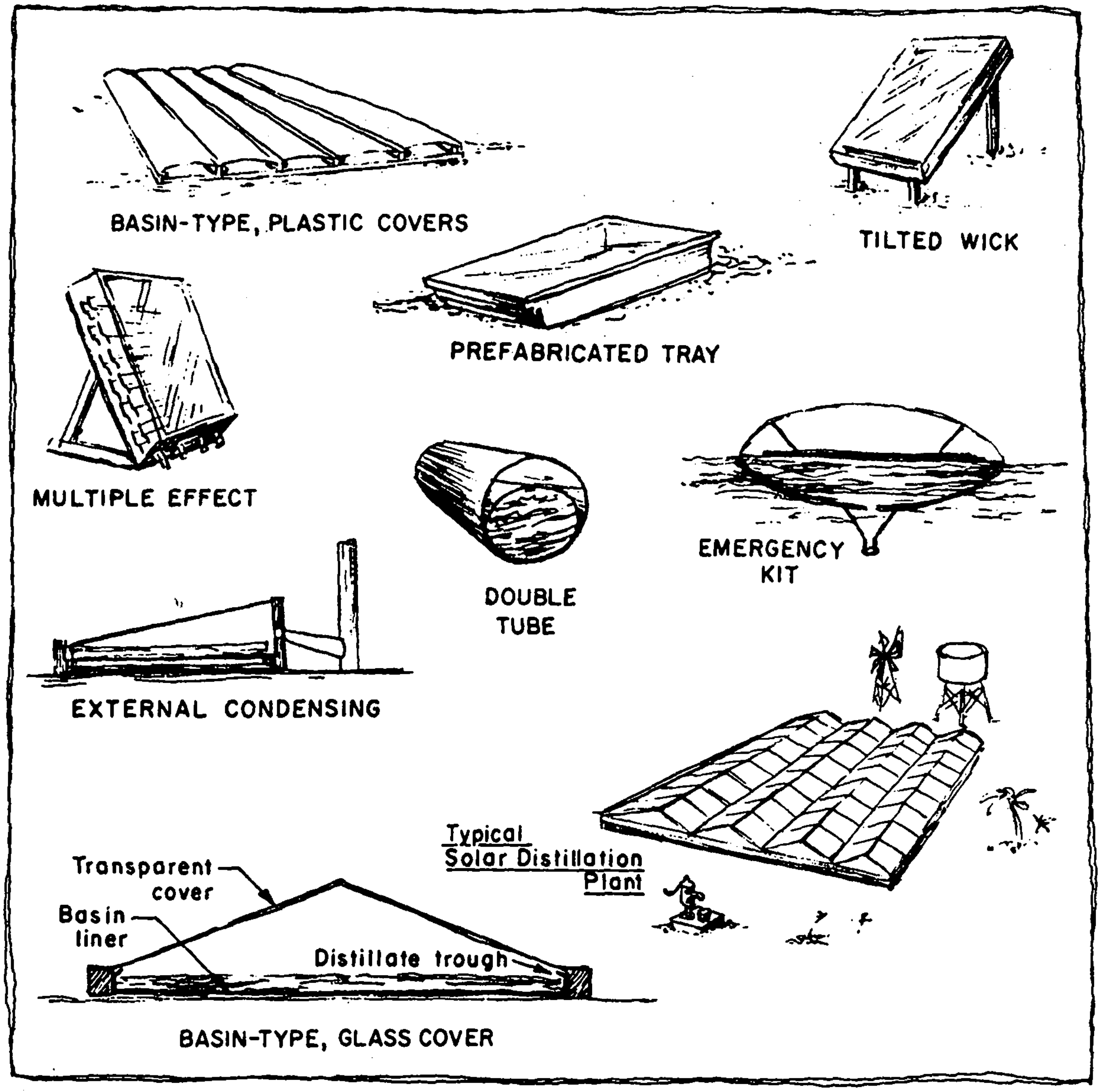
0,0704 gpd/ft = $\frac{0.0704 \times 3,78 \times 10}{0,0929}$ = 2,87 l/m²/day

1 gallon = 3,78 l.

1 ft = 0,0929 m²

Solar distillation of salt water appears well suited to the supply of potable water to small communities where the natural supply of fresh water is inadequate or of poor quality, and where sunshine is reasonably abundant. The capital cost of large permanent-type solar stills is shown to be as low as \$1 per $ft^2$ of basin area, which is equivalent to \$10 to \$15 per daily gallon output, depending on the yearly amount of solar radiation and rainfall collection. The corresponding distilled water cost is between \$3 and \$4 per 1000 gallons. These water costs are generally lower than those associated with other desalination equipment in plant sizes of up to perhaps 50,000 gpd. However, long-term testing of the better materials now being used in solar stills is needed because the economics of solar distillation is such that long life with minimum maintenance is essential if the cost of fresh water by this means is to be within the range of \$3 to \$4 per 1000 gallons. = 3730 Liter = 3,78 m³ also ~\$1 per m³

For small family-size solar stills now commercially available, the first cost is about \$4 per $ft^2$ of basin area, and the resulting distilled water cost may range from \$15 to \$30 per 1000 gallons. Despite these relatively high costs, family-size stills appear to have a role in the total scheme of desalination.



## SECTION 2. HISTORY OF SOLAR DISTILLATION

A historical summary of solar distillation is presented here to show the chronology and magnitude of the total effort, and to emphasize the more important designs. Most of the stills mentioned in this historical section are further described with photographs and sketches in Sections 3 and 9.

Several brief historical reviews of solar distillation are available in the literature – Telkes (430 and 434)*, Daniels (119), Nebbia and Menozzi (372), Lawand (290), Howe (250). An extensive bibliography consisting of several volumes on the general subject of saline-water conversion has been published by Delyannis (139) covering the time period from antiquity through 1962.

Although solar energy has long been used for various distillation processes (e.g., obtaining perfumes and medicines from flowers, herbs, grasses, etc.), Lawand wrote (290) that the first specific reference to the use of solar distillation for obtaining fresh water from sea water was by an Italian, Nicolo Ghezzi, in 1742, who proposed the following method (Nebbia and Menozzi, 372):

> Perhaps placing a cast iron vase containing sea water in such a manner that the sun's rays will strike it (and during mild days and seasons, not an insignificant amount of vapor will be formed) and if the spout of the vase is shaded from the sun, it will result in a more copious and more extended flow of fresh water.

The earliest, significant solar distillation plant on record was the relatively large greenhouse-type** solar still designed by Mr. Charles Wilson in 1872 and constructed in Las Salinas, Chile. Interestingly, the name means "The Salines", and evidently was a location where solar evaporation ponds had been used on a commercial scale for the extraction of salt (Petersen, 380). A detailed description of the design and operation of this still was reported by Harding (202) in 1883. The 64 separate water basins were constructed of wood planking and timber framework with sloping glass covers. The total glass area was 51,200 $ft^2$ and the water surface area was about 48,000 $ft^2$. It was also reported that when the still was new it produced upwards of 6,000 U.S. gallons of fresh water daily, primarily for watering mules working in a mining operation. After the opening of a railway, the need for fresh water diminished and the still was allowed to deteriorate to the extent that the production rate fell to about one-half that of the original still. Nevertheless, Telkes (430) reports that the installation was operating in 1908, 36 years later, although the size and design of the stills appears to have changed considerably. Hirschmann reports (214) that this distiller was in industrial use for more than 40 years and was abandoned only after the construction of the first pipeline which brought potable water from the Andes to Antofagasta. Today, only traces of the foundation remain (Howe, 250), together with ditches and a large amount of small pieces of glass (Hirschmann, 214). Another solar still, similar to the original design and located in the vicinity, at the Oficina Domeyko mine, was reported by Isaac Arce (40) as having operated for some time with success. According to the designer's granddaughter (Coo, 108), Charles Wilson was a Swedish engineer who was transferred to Chile in 1863. She stated that he made many enemies when he tried to publicize his invention which would provide fresh water for the plains and for domestic use and thereby assist in the development of the northern Chile country. The invention was considered such a threat to the business of the water vendors that, on one occasion, they attempted to assassinate him. She concluded that the timely opportunity of his work was

*Numbers in parentheses refer to references given in the Bibliography – Section 10.

**The descriptive phrase, "greenhouse-type", has frequently been used to identify a solar still which contains a shallow rectangular tray or pool of salt water beneath a transparent cover comprised of glass panes sloping downward in two directions from a ridge, as a greenhouse roof.

not understood because personal interests were more powerful than the social benefit represented by that work.

In 1875, Mouchot began reporting (351) on experiments using a metal mirror having a linear focus with a water boiler located along its focus. He also investigated such things as distillation of alcohol, cooking of food, fusion, sublimation, etc., using solar energy. C. G. Abbot has more recently developed a similar device (32 and 33) and was granted a patent (494).

The simple solar still apparently received little further attention until 1926, when the French government announced a contest and offered a prize for a design of a portable solar still suitable for supplying fresh water to Colonial troops in Africa. The results of this contest have been published (Boutaric, 92 and 93). One type was similar to the Las Salinas design, whereas two other models used reflectors which focused solar energy onto a boiler.

During the period 1926-1930, it is reported (Gomella, 185; Baum, 59) that the following persons conducted work with simple glass-covered solar stills: Richard (Monaco) (399-402), Maurian and Brazier (338, 339), Ginestous (Paris and Tunis) (177, 178), Seltzer (Algiers), LaParola (Bengasi ? ) (280), and Veynberg (USSR) (479, 480).

In the early 1930's work was conducted by Trofimov (451) and by Tekuchev (424) of the USSR. Trofimov proposed a tilted-wick design and Tekuchev studied the fabrication of stills with a wettable ribbed surface (Baum, 59).

Table 1 lists the many investigations on solar stills reported for the years 1940 to the present. The remainder of this historical review follows the chronological format of Table 1.

It is interesting that numerous solar still programs were initiated in the 1950's, particularly in the single year 1953, about 1 year after the U.S. Office of Saline Water was created and began to stimulate interest in the serious need to plan for future desalination.

Maria Telkes. During World War II, Dr. Maria Telkes invented a small, inflatable solar still for use on life rafts (Telkes, 427). Work began at MIT in late 1942 and Telkes has stated that more than 200,000 units were eventually produced as standard equipment for life rafts on aircraft and ships. These stills were small plastic units designed to float on the sea when inflated. The circular model had a transparent hemispherical top and a weighted conical bottom which collected distillate. A black absorbent pad of cellulose sponge material was supported horizontally within the unit and this was saturated with sea water before inflation, and during operation if it became dry. The excess sea water was allowed to drop into the bottom for a few minutes, and then drained out before attempting to collect fresh water. The black absorber had an area of 2 $ft^2$ and the still would produce up to 2 pints of fresh water on a clear summer day. During the development of this emergency solar still, a method was devised to treat the Vinylite to obtain film condensation on the cover and also to prevent an objectional taste in the fresh water produced.

After World War II, Dr. Telkes continued research efforts on small glass-covered solar stills (Telkes, 428, 430). Two designs were proposed, one for the tropics and another for the temperate zones. The tropic design had a symmetrical roof with both sides of glass sloped at 45 degrees. In the temperate design (for the northern hemisphere) the south-facing cover was glass and the north slope of the roof was made of a thin reflecting material tilted to best reflect the sun's rays onto the basin. The channels and supports were redwood and the evaporating pan was formed using a black plastic sheet which rested on a 1-in.-thick pad of insulation. An electrically heated still was used to eliminate the cyclic fluctuation of the sun and weather so as to better evaluate the effect of other variables on the production rate. Dr. Telkes reported (430) that:

TABLE 1. RECENT ACTIVITY ON SOLAR STILLS

| Investigator | Dates |
|---|---|
| Massachusetts Institute of Technology, New York University, etc. (Telkes) | 1942-Present |
| Virgin Islands (Rounds, Löf) | 1948-1949 |
| University of California (Howe, Tleimat, et al.) | 1952-Present |
| University of Wisconsin (Daniels, Duffie) | 1952-Present |
| Battelle Memorial Institute (Bloemer, Eibling, Löf, et al.) | 1953-Present |
| Löf, George | 1953-Present |
| Australia, CSIRO (Morse, Read, et al.) | 1953-Present |
| Algeria (Gomella, Savornin, Lejeune) | 1953-Present |
| Italy (Nebbia) | 1953-Present |
| Bjorksten Laboratories (Lappala) | 1954-1959 |
| South Africa, CSIR (P. W. D.-Pretoria, Cillie, Whillier, Odendaal) | 1954-Present |
| Cyprus (Fitzmaurice) | 1954-1955 |
| Kenya (Blake, Ramsay) | 1954-? |
| Chile (Hirschmann) | 1955-Present |
| USSR (Baum, Brdlik, et al.) | 1956-Present |
| France (Trombe, Foex, Gomella) | 1956-Present |
| Senegal, West Africa (Masson) | 1956-1961 |
| India (Khanna, Mathur, Datta, Garg, Ahmed, et al.) | 1957-Present |
| Iran (DeJong) | 1957-? |
| Georgia Institute of Technology (Grune, et al.) | 1958-1962 |
| Spain (Blanco, Fontan, Barasoain) | 1958-Present |
| Franklin Institute (Erb) | 1958-1961 |
| Morocco (Ambroggi) | 1958-? |
| Sunwater Company (McCracken) | 1959-Present |
| Egypt, National Research Center (Hafez, Sakr) | 1960-? |
| Hummel, Richard | 1960-? |
| University of Arizona (Hodges) | 1961-Present |
| Hay, Harold | 1961-Present |
| McGill University (Lawand, Selcuk, et al.) | 1961-Present |
| Taiwan (Wang) | 1961-? |
| Japan (Kobayashi) | 1961-Present |
| Tunisia (A.E.C.) | 1962-Present |
| Leslie Salt Company | 1962 |
| Aqua-Sol, Inc. (Eckstrom) | 1963-Present |
| Greece (Church World Service, Delyannis) | 1964-Present |
| Cape Verde Islands (Eckstrom) | 1965-Present |
| Ethiopia, Haile Selassie I University (Hobbs) | 1965-? |
| U.S. Water Conservation Laboratory (Jackson) | 1965-? |
| Pakistan (A.E.C.) | 1967-Present |
| Solar Sunstill, Inc. (Delano, Raseman) | 1968-Present |

(1) An insulated base was beneficial,

(2) The efficiency increases with ambient air temperature,

(3) Wind velocity does not have an appreciable influence,

(4) Shallow water layers in the basin were most desirable (less than 1/2 in. recommended),

(5) Large solar distillers may use a continuous feed of seawater,

(6) The glass surface could be used for rain catchment.

In 1951, Dr. Telkes designed a 4 by 50-ft glass-covered, greenhouse-type still which was built on the seashore in Cohasset, Massachusetts (Telkes, 432, 433). It had an insulated wooden tray, 45-degree double-sloped glass covers, and gave a maximum yield of 1.2 lb/$ft^2$-day (0.14 gal/$ft^2$-day) in the summer.

Dr. Telkes has also reported many experiments with tilted-wick stills which were sponsored by OSW (Telkes, 432, 434-440). These designs involved black fabric surfaces which were saturated with a continuous feed of saline water and covered with glass or plastic. The assemblies were designed to be tilted at a fixed angle to best intercept and absorb the solar energy. This work culminated in the construction of 20 tilted-wick stills, each having 25 $ft^2$ of absorber area, which were tested for OSW during 1960-61 at Battelle's research facility near Daytona Beach, Florida (Battelle, 54).

Dr. Telkes has also conducted work on multiple-effect solar stills (Telkes, 435-438). The first stage could be heated by absorbing solar energy, and the subsequent stages are heated by condensing vapor from the previous stage. Multiple layers of evaporator wicks, vapor transmitting films, spacers, porous condenser materials, and waterproof films are used. An electrically heated prototype of 10 stages was tested, but the heat input rate was approximately 10 times higher than could have been supplied directly by solar energy.

Virgin Islands. In the winter of 1948-1949, a small experimental solar still was built in the Virgin Islands on the island of St. John and later moved to the island of St. Thomas (301). This unit was planned as a forerunner of a proposed 1000-gpd installation on St. John (Hollingsworth, 228), which was never built. The apparatus was similar to those developed by Telkes and was designed with her assistance. The basin was 4 ft wide by 9 ft long, the wood framework was elevated above ground, and the basin floor was insulated with 2-in.-thick "Foamglas". The upper surface of the insulation was waterproofed with a black asphaltic emulsion. The two sloping glass covers were pitched at 45 degrees and the triangular ends were also of glass. The depth of the salt water was usually between 1/2 to 2 in. The unit produced a daily water yield of about 0.6 lb/$ft^2$ during the winter months (or about 0.07 gal/$ft^2$), with a peak output approaching 1.0 lb/$ft^2$. Preheating of the batch feedwater each morning was also tried as a means of increasing the length of the distilling day.

During the early 1950's, several different organizations and individuals began developing solar stills. These included the University of California, the University of Wisconsin, Battelle Memorial Institute, CSIRO (Australia), George Lof (Denver, Colorado), Cyril Gomella (Algeria), Georgio Nebbia (Italy), Bjorksten Laboratories, and R. Fitzmaurice (Cyprus).

University of California. The University of California has been studying solar stills since January, 1952. Professor Everett Howe has published many articles describing this work (Howe, 230-250). The main emphasis has been on small family-size solar stills, and various models have been installed on about a dozen South Pacific islands. Over 25 kits of a 6 x 8-ft solar still have been furnished to the South Pacific Commision. These small solar stills produce a maximum of about 5 gallons of fresh water per day. A wooden framework is used together with a "Vee"-shaped glass cover, a black polyethylene bottom, aluminum "tee" sections for glass supports, and galvanized sheet metal for distillate troughs.

A substantial amount of work has also been conducted on inclined-tray solar stills, which began in March, 1959 (McCracken, 327, 328). By 1965, approximately 65 different stills had been constructed and tested in an effort to increase serviceability and durability and reduce cost. This inclined-tray development began at the University of California, but was continued independently by Horace McCracken after 1962.

The University has also published a pamphelt "How to Build a Solar Still" (Edson, et al., 160).

A recent master's thesis at the University reports on the solar transmissivity of selected glasses and plastics (Grange, 191).

University of Wisconsin. Research work on solar stills began at Madison, Wisconsin, around 1952 (Herlihy, 209, 210; Daniels and Duffie, 117). This early work investigated a solar still comprised of two horizontal eccentric plastic (Kel-F) tubes. The inner tube was nearly filled with saline water blackened with dye, and the inflated outer tube was used to reduce heat losses. Air was blown along the top of the water in the inner tube to carry the water vapor to a condenser tube surrounded by incoming cold water. Later work on this type of solar still tested three different plastic materials, Mylar, Kel-F, and 100-X Teflon, and the effect of two enclosing tubes and lower air flow rates (Salam and Daniels, 405). Data were also obtained on the infrared-absorption spectra of these plastic films. Experiments were also tried with solar-heated chimneys to create air flow through the still. Similar double-tube stills were built by Battelle at Daytona Beach, Florida, in 1960, wherein the inner tube was made of a black porous plastic film filled with water. Water vapor but not liquid could pass through the porous plastic and condense on the inside of the outer tube.

Daniels has designed several plastic-covered solar stills for use on the South Pacific Islands and elsewhere (Daniels, 118-121). Various designs and materials have been tested periodically in Wisconsin, Florida, Arizona, and on the South Pacific island of Rangiroa from about 1963 to 1966. A typical construction had a 12-ft-long by 2 to 5-ft-wide basin made of concrete or lined with butyl rubber, wooden or concrete distillate troughs, and a wooden framework and ridge-pole covered with weatherable Mylar or Tedlar held in place with long plastic sandbags. One design was proposed using a concrete basin and curbs with a single-sloped 23-degree Mylar cover held in place with tubular sandbags (Daniels, 119).

In 1966, the University published a study of the distribution of solar radiation around the world (Lof, Duffie, and Smith, 313, 314). The 12 world maps in the report show isolines of the average daily solar radiation (direct and diffuse) incident on a horizontal surface for each month of the year. Data from over 1,000 stations around the world were compiled to produce these charts.

Battelle-Columbus. In 1953, Battelle Memorial Institute, Columbus, Ohio, conducted an investigation for the OSW on multiple-effect evaporation of saline waters, using solar energy to generate steam (Battelle, 51). Preliminary design data and estimated costs were developed for several different types of distillation plants employing parabolic-cylindrical solar collectors for generating low-pressure steam usable in multiple-effect evaporators.

From 1958 to 1965, Battelle operated a solar distillation research station at Daytona Beach, Florida, for the Office of Saline Water. Several types of solar stills were constructed and operated in pilot-plant sizes to obtain realistic data on their construction, performance, and maintenance (Battelle, 52-55). Some of the stills were developed by Battelle engineers and others were designed by various other organizations contributing to the Office of Saline Water program.

Table 2 lists the types and sizes of stills investigated at Daytona Beach. The glass-covered basin stills were the most satisfactory of all those evaluated, considering all factors, i.e., construction methods, first cost, performance, and maintenance.

TABLE 2. SOLAR STILLS EVALUATED AT DAYTONA BEACH, FLORIDA

| Type of Still | Designer | Number of Stills Constructed | Basin Area per Still, sq ft |
|---|---|---|---|
| Glass-Covered, original | Löf – Battelle | 1 | 2450 |
| Glass-Covered, second | Battelle – Löf | 1 | 2650 |
| Inflated Cover, Unit 1 | DuPont (Edlin) | 1 | 500 |
| Inflated Cover, Unit 2 | DuPont (Edlin) | 1 | 2330 |
| Inflated Cover, Unit 3 | CWS(a) (Edlin) | 1 | 1600 |
| Tilted Wick, Unit 1 | Curtiss-Wright (Telkes) | 20 | 25 |
| Tilted Wick, Unit 2 | Battelle | 1 | 45 |
| Tilted Tray | Battelle | 1 | 10 |
| Vertical Envelope | Bjorksten | 4 | 150 |
| Materials Evaluation Stills | Battelle | 4 | 80 |
| Inflated Plastic Tube | Battelle | 4 | ~33 |
| Plastic Film Pails(b) | Battelle | 40 | < 1 |

(a) Church World Service.
(b) For exposure testing of plastic films. No distilled water produced.

The first unit, constructed in 1958, was a 12-in.-deep basin-type still designed originally by Dr. Lof (U.S. Bur. Reclamation, 464; Lof, 302, 303). This still had a basin area of about 2,450 ft$^2$, and had double-sloped glass covers at 15 degrees. Later, another deep-basin still was constructed using improved methods and materials. This still had 10-degree covers and one large basin of 2,650 ft$^2$, rather than several pairs of interconnected bays.

Two inflated, plastic-covered stills were built during the winter of 1958-1959 using designs and materials supplied by DuPont (146). The smaller 500-ft$^2$ unit had a Teslar film (later renamed Tedlar) cover, and the larger 2,330-ft$^2$ unit had a Mylar film. Both had shallow basins and were insulated from the ground. After hurricane Donna damaged these stills in September, 1960, DuPont continued work on this design at its own station near Miami, Florida. Later, another inflated plastic still was constructed at Daytona Beach by Church World Service. This design used two 8-ft-wide bays, 100 ft long giving a total basin area of 1,600 ft$^2$. The basin was insulated with a 1-in. layer of sawdust, and the brine depth was 1 in. The original basin liner of black polyethylene film was "burned out" twice because of dry spots occurring with the shallow water layer. The linings were therefore replaced by 30-mil butyl rubber sheets. The air-inflated cover was wettable Tedlar film. When intact and operated properly, the performance was excellent. Heavy rains occasionally collapsed the covers, and high winds sometimes tore the plastic. This inflated, plastic-covered still was a forerunner of the 29,000-ft$^2$ solar still installed on the island of Symi, Greece, by Church World Service in October, 1964.

The first tilted-wick stills were designed by Dr. Maria Telkes and manufactured by the Curtiss-Wright Corporation. Twenty units, each 25 $ft^2$, were set up in September, 1960. Glass covers were used on 12 units, Weatherable Mylar on 4 units, and Tedlar on 4 units. One glass cover had a special coating to reflect the infrared radiation. Several black wick materials tried included cotton terry cloth, cotton sail cloth, and glass fibers pressed into a black plastic film. After a few months of operation, the wick materials faded and within 6 months became weak and brittle. Productivity was outstanding (about 50 percent higher than the deep-basin stills), because of the tilt toward the sun and the low thermal mass of the still. The second tilted-wick design was built directly on ground that had been graded to an angle of 30 degrees facing south. A black polypropylene felt wick was placed over a layer of polyethylene film, and the unit was covered with glass.

Four vertical-envelope stills with a total area of 600 $ft^2$ were also installed at Daytona Beach. These had been designed and fabricated by Bjorksten Laboratories (73, 74). The vertical wick of black terry cloth material was suspended between two transparent Griffolyn plastic films on two of the units. Corrugated aluminum panels were used on the back side of the other two units instead of the plastic. Unfortunately, these stills were damaged by winds so often that useful data were never obtained.

Four small stills of 80 $ft^2$ each were constructed to evaluate basin liners and other construction materials. Two had 12-in.-deep basins, and the other two had 2-in.-deep basins. A floating wick, made of black polypropylene felt, was tried in one of these stills. The productivity of the latter increased about 10 to 20 percent, which was not enough to justify the added cost and maintenance associated with the wick.

Several inflated plastic-tube solar stills were also built and tested. These were 20-ft long and 1-1/2-ft diam. cylinders of Tedlar plastic with distillate channels heat sealed to the inside about halfway up each side. The units were laid horizontally on a black plastic sheet and partially filled with sea water. This type of still could be used in "expedient" or survival-type applications.

Many plastic materials were also evaluated over a period of about 7 years by exposing them to conditions similar to those found in solar stills. In some instances the films were stretched across the top of 5-gallon paint cans which were nearly filled with water. The cans were lined with black polyethylene and tilted southward 30 degrees. A similar technique was used previously by Bjorksten Laboratories (74). Altogether, 40 samples of plastic films were tested. The most durable films, Tedlar, Weatherable Mylar, and Aclar, lasted about 4 years under these exposure conditions, which are considered less severe than those of actual solar-still operation because of lower temperatures and lesser wind effects.

In addition to the construction and operation of solar stills at the Daytona Beach station, supporting work consisting of computer studies and the operation of a laboratory still were carried out at Battelle's Columbus Laboratories (Lof, et al., 310; Bloemer, et al., 86). The laboratory still was heated electrically in such a way as to simulate solar-still operation. The still was so constructed that design and operating parameters could be varied independently. These included basin depth, cover slope, cover-to-brine distance, outside air temperature, outside wind speed, energy input rate, and thermal insulation beneath the basin. Some trials were conducted under steady-state conditions and others were conducted with variable energy input to simulate solar heating. The results indicated that, aside from energy input, the only factors significantly affecting solar-still output are brine depth and the amount of insulation beneath the basin. The performance of the laboratory still closely matched that of the Florida deep-basin stills under the same conditions, showing that the laboratory still was a good simulation of a solar still.

Two other types of solar stills were evaluated by Battelle in Columbus. One was a double-tube still somewhat similar to those developed at the University of Wisconsin (Herlihy, 209, 210; Salam, 405). The outer transparent plastic tube was kept inflated. The inner tube was made of a porous, opaque plastic film and was filled with saline water. The porous film would allow water vapor, but not liquid, to pass through and condense on the inside of the outer tube. The other still was a floating still design and was also an inflated-plastic design. The cover was made of transparent plastic and the bottom of black porous plastic which would be in contact with the body of water. The sides or perimeter of the still were weighted internally to provide distillate troughs and counteract the tendency of the plastic cover and bottom to form a cylinder because of the inflation pressure. As the black, porous plastic was warmed and heated the water beneath it, the water which evaporated passed through the porous film and into the still where it condensed on the transparent cover.

In 1967, Battelle-Columbus conducted a brief study for OSW on the use of extremely low-cost plastic films (polyethylene and vinyl for example) for the cover and basin liner of solar stills (Irwin and Fischer, 255). The intent was to determine whether cheap films, costing one cent per $ft^2$ or less, could be used in a practical still, recognizing that they may have to be replaced every several months. The study concluded that a still built of low-cost short-lived plastics would not produce water at a lower cost than a glass-covered solar still. In late 1968, Battelle began the present study for OSW to compile a comprehensive manual on the state of the art of solar distillation, and to review and summarize the many separate activities around the world.

George O. G. Löf. In 1953, Dr. George Lof, a consultant in Denver, Colorado, also began analyzing solar stills. As a consultant to OSW, he investigated various proposed methods for solar distillation and presented efficiencies and costs for about 30 different methods, including survival stills, basin-type stills, tilted-type stills, solar evaporators with external condensors, multiple-effect stills with membranes or plates, and focusing-type solar collectors for steam generation (Lof, 300). In 1954, OSW asked Dr. Lof to analyze and evaluate the data obtained on the small solar still tested in the Virgin Islands during 1948 and 1949, which was described above (Lof, 301).

Dr. Lof later developed a design for a glass-covered, 12-in.-deep, basin-type solar still having interconnected bays with a total area of about 5,000 $ft^2$ (50 ft by 100 ft). This design is described in detail in several References (U.S. Bureau of Reclamation, 464; Lof, 302, 303). Originally designed to be built at a site near San Diego, California, a smaller unit of about 2,450 $ft^2$ was eventually built at Battelle's Daytona Beach facility under OSW sponsorship in 1958 (Battelle, 52). The basin liner was a 1/2-in.-thick asphalt mat, mopped with hot asphalt for water tightness and increased radiation absorption. The walls and supports were concrete block and the perimeter of the still was insulated with 2-in.-thick Foamglass. At a radiation level of 2,000 Btu/$ft^2$-day, the average productivity was around 0.08 gal/$ft^2$-day, or 200 gpd.

A second deep-basin still was built in 1960 to test a more economical design with greater durability (Battelle, 54). This 2,650-$ft^2$ still was designed with one large continuous deep basin rather than individual adjacent bays. Concrete beams were substituted for timber framing, and asphaltic putty was used instead of neoprene extrusions. Thus, the total cost was reduced to about \$2.00/$ft^2$ compared to \$7.50/$ft^2$ for the first unit. The productivity per square foot was essentially the same for both stills. The first detailed theoretical analysis of conventional solar stills was made by Lof, Eibling, and Bloemer in 1960 (310) and extended in 1961 for presentation at the U.N. Conference (309).

Dr. Lof also acted as a consultant with OSW and Battelle-Columbus during the construction and evaluation of other types of solar stills at the Daytona Beach facility. These included Telkes' tilted-wick type, Bjorksten's vertical-envelope still, and Edlin's inflated-plastic design for Church World Service. In 1963, Lof assisted the OECD in evaluating solar desalting research and proposals in Spain, and in 1965, OSW engaged Lof to participate in a cooperative program for building a solar still at Las Marinas, Spain (Lof, 318; Blanco, et al., 76, 77). The basic design is similar to the improved basin-type still evaluated at Daytona Beach. The basin area is about 9,500 $ft^2$, and is asphalt-lined and glass-covered. Departures from the Daytona Beach design involved using a more shallow basin (approximately 4 in. of salt water), and condensate troughs which were moulded into the precast concrete beams. The completed still produced about 0.08 gal/$ft^2$-day at a solar radiation intensity of 2,000 Btu/$ft^2$-day, which was about the same as the basin-type stills at Daytona Beach and elsewhere. Summer output averaged between 0.085 and 0.090 gal/$ft^2$-day (about 800 gpd total), and the winter output averaged about 20 to 30 percent of the maximum summer production. The Las Marinas still was designed to supply the total potable water requirements of a small village of about 300 inhabitants. However, the villagers use mostly brackish well water because it is so much cheaper than the distillate from the solar still.

In 1966, Lof, Duffie, and Smith published extensive data on solar-radiation intensities gathered from more than 1,000 stations around the world (Lof, et al., 313, 314). These documents furnish important solar-radiation data necessary for designing a solar still to achieve desired production rates for any or all months of the year. Reference 313 contains four world maps showing isolines of total solar radiation for the months of March, June, September, and December. Reference 314 contains a complete set of 12 world maps giving solar radiation isolines for each of the 12 months.

Australia. In 1953 the CSIRO (Commonwealth Scientific and Industrial Research Organization) in Melbourne, Australia, started investigating solar stills as a simple and low-cost method for de-salting underground brackish water at remote places in the interior of Australia (Wilson, 491). Early tests were made on a small 5-$ft^2$ Telkes-type still. In 1956 an automotive company sponsored the installation of a 40-$ft^2$ unit at a service station. This still had a double-sloped glass cover at 45 degrees supported by a framework of aluminum, copper troughs, black PVC basin liner, and rock-wool insulation. The emphasis then shifted to the development of a low-cost unit similar to the type developed by Gomella in Algeria (Gomella, 182). These units consisted of an asbestos-cement (Transite) tray measuring about 4 x 6 ft with a glass cover sloped at 10 degrees and they were insulated on the bottom. Fiber-glass reinforced plastic was also used to construct trays but the cost was higher. A still was also designed for Antarctica conditions where the sun's altitude angle never exceeds 45 degrees. This unit consisted of a double-glazed cubical structure containing a stack of black plastic trays (Wilson, 491).

In 1963 CSIRO developed a bay-type, glass-covered solar still with each bay being about 3-1/2 ft wide by 128 ft long. The bottom was lined with black polythene (polyethylene) sheet, 8 mils thick. The length of the solar still was divided into a series of dams or weirs to produce shallow pools of saline water.

Table 3 lists the glass-covered still built by the CSIRO in Australia.

TABLE 3. SOLAR STILLS IN AUSTRALIA

| Location | Date Built | Basin Evaporating Area, $ft^2$ | Projected Glass Area, $ft^2$ |
|---|---|---|---|
| Muresk I | Dec. 1963 | 4,000 | 4,500 |
| Northam | 1964 | 4,000 | 4,500 |
| Perth | 1966 | ? | 5,400 |
| Muresk II | Nov. 1966 | 4,000 | 4,500 |
| Coober Pedy | Nov. 1966 | 34,000 | 38,000 |
| Caiguna | Dec. 1966 | 4,000 | 4,000 |
| Hamelin Pool | Dec. 1966 | 6,000 | 6,800 |
| Griffith | Aug. 1967 | 4,450 | 5,000 |

The first full-size prototype was built at Muresk in December, 1963, and had a total glass area of about 4500 $ft^2$, and an evaporating area of about 4,000 $ft^2$. It produced a total of 87,700 U. S. gallons per year for an average of 240 gpd. The peak daily output was 480 gpd while the averages for typical summer and winter months were 430 and 120 gpd, respectively. This still was replaced in November, 1966, with an improved design designated Mark II. The basic design and size were the same but a greater degree of vapor tightness was achieved by using silicone rubber as a sealant between sheets of glass. In addition, galvanized iron sheet-metal troughs were used as walk-ways between bays and were formed in such a way as to support the glass covers and provide distillate troughs. These improvements increased the overall productivity somewhat.

In November, 1966, a 38,000-$ft^2$ solar still was constructed at Coober Pedy. The design was similar to the Mark II prototype. Its peak capacity is about 4,000 gpd with a yearly average around 2,000 gpd. Provision was made for ultimately enlarging the Coober Pedy still to 100,000 $ft^2$. Similar stills have also been constructed at Caiguna, Hamelin Pool, and Griffith. Improvements tested on the Griffith still have included concrete curbs, aluminum or stainless steel distillate troughs, silicone sealant for all joints, butyl rubber liner, increased slope along the length, and polystyrene insulation.

The University of Western Australia at Perth has reported on two small tray-type solar stills that were investigated for an Honours thesis (Whinnen, 487; Appleyard, 39). One had a double-sloped glass cover with a steep slope, and the other was a plastic-covered, diamond-shaped still with condensing surfaces above and below the suspended black polyethylene tray. A three-effect, tilted-wick solar still was also constructed and tested (Cooper and Appleyard, 109). More recently, a 450-$ft^2$ solar still has been built on the campus to supplement the digital computer simulations of the transient processes occurring in a solar still of the CSIRO design (Cooper, 110).

Algeria. In 1953, Cyril Gomella began developing various tray-type solar stills in Algeria (Gomella, 179-183). Twenty stills of ten different designs were tested throughout the country, and a small unit consisting of a molded asbestos-cement tray, set on insulation and covered with glass, has been put into wide use. The tray area was 33 $ft^2$ and the glass covers were inclined at only 10 degrees to the horizontal. These have been sold commercially throughout the northern part of Africa, including Algeria, Morocco, various parts of the Sahara, Senegal, and Tchad. This design was also studied at CSIRO in Australia and made available commercially. Gomella later began investigating the various factors involved with building larger solar stills (Gomella, 186, 187). Beginning in 1965, Gomella acted as the scientific director for the installation of the 9,350-$ft^2$ solar still at Las Marinas, Spain. This solar still has been operating since March, 1966, and its construction details and performance are described in several references (Blanco, Gomella, and Barasoain, 76, 77, 79; Lof, 318).

Lejeune and Savornin were also investigating various other still designs at the University of Algiers beginning in 1954 (295, 296, 297, 407). Five types were studied, including three horizontal trays, one tilted tray with rows of horizontal channels, and one tilted wick. The evaporating areas were between 1.0 and 6.3 $ft^2$. The designs attempted to improve convection movements within the still, or shade the condensing surface from the sun. Only the tilted wick produced better than the control still which had a single-sloped glass roof.

Italy. Development work on solar stills also began in Italy during 1953 under the direction of Dr. Giorgio Nebbia at the University of Bari (368 to 371). Most of the stills have been small shallow-basin, tray-type designs with a roof inclination of about 45 degrees. The earliest still was made entirely of acrylic plastic (plexiglas). Others have used glass covers with wood, sheet metal, or concrete trays and frames. One type was specifically designed to be used on the flat roofs of houses. An interesting "vertical" solar still was built in 1958 which had four horizontal trays spaced above one another and enclosed in a glass "box". All of the glass walls acted as condensing surfaces, and the water yield was high per unit of ground area occupied. This design is primarily for temperate zones where better insolation of the four trays is possible. It was reported that the productivity was good even during winter months. An enlarged version of this vertical still has also been built. More recently, Nebbia has experimented with glass-covered, inclined-tray solar stills which he states are the most satisfactory of all those tested (Nebbia, 374).

Bjorksten Laboratories. Beginning in 1954, Bjorksten Laboratories constructed several types of plastic-covered solar stills for OSW in an effort to develop a design that would be applicable to large-scale distillation plants. Several tubular designs were also tested (Bjorksten, 73, 74). A vertical-wick solar still was later developed at Bjorksten and evaluated at Battelle's Daytona Beach facility during 1960 and 1961. This design was termed a "suspended – or vertical-envelope" solar still. A black wick material was suspended vertically between front and back sheets of transparent Griffolyn (polyester) plastic film, and acted as the radiation absorber and brine evaporator. Some models used corrugated aluminum sheets as the back panel. Unfortunately, no useful data were obtained because of wind damage and poor wettability of the wick material. Rather extensive weathering tests of many plastic film materials were also conducted at Bjorksten Laboratories by subjecting the plastics to artificial solar-still conditions, both outdoors and indoors (Bjorksten, 74).

South Africa. As early as 1954, the South African C.S.I.R. reported work on solar stills (P.W.D., Union of So. Africa, 391; Cillie, 105). Special attention is currently being given to investigate the use of solar stills on farms and in small communities. Small-scale pilot plants have been constructed to evaluate existing designs. Standardized modules with prefabricated concrete parts, glass covers, and butyl rubber liners are being planned for use on farms in Southwest Africa (Odendaal, 376).

Cyprus. In the summers of 1954 and 1955, Fitzmaurice and Seligman conducted some experiments on the north coast of Cyprus with various small solar stills (166). The two 1954 models were typical tray-type stills with 45-degree glass covers and insulated 16.5-ft$^2$ basins. The 1955 model had the 2.7-ft$^2$ brine tray completely enclosed with glass, using 45-degree covers on the top and bottom. Thus the condensing area was essentially double that of a standard design. An increase in productivity was obtained because the new design was completely sealed to prevent vapor leakage. The larger condensing surface was used to lower the vapor pressure within the still in an effort to minimize leakage problems and permit complete sealing. A fixed reflector was also used to further increase the yield of this small solar still.

Chile. Since about 1955, research work at the Universidad Técnica Federico Santa Maria, Valparaiso, Chile, has been devoted to the possibility of using solar energy for both the distillation of water and the generation of electric power. In 1958, Victor A. Bocic wrote a thesis on a pilot-plant design, under the direction of Julio Hirschmann (Bocic, 91). Hirschmann has published several articles describing the design of this pilot plant for using solar energy to produce both fresh water and electricity (Hirschmann, 212-215). The earlier reports assumed that an inclined solar-heat collector made with copper tubes would be used to heat the saline water to a temperature of 158 F. However, because the solar collector represented 89 percent of the total plant investment, the latest report describes the use of solar ponds with concentration gradients to produce heated saline water for the system. The heated water passes through a vacuum evaporator and the steam then drives a turbine to produce electricity. The steam is finally condensed to provide distilled water. Reference 212 describes a plant sized to produce 2,500 gpd of distilled water and 50 kw of useful electricity, and Reference 215 reports corresponding values of 7,400 gpd and 253 kw. The size availability of turbines necessitated the larger plant design. Further work depends on the availability of funds.

In 1968, a 1,076-ft$^2$, double-sloped, glass-covered solar still was built in the small village of Quillagua, near the harbor of Tocopilla, Chile. The all-cement base and sides are frequently cracked by earthquakes, so another solar still is planned with a single-sloped glass cover and asbestos cement trays. A pilot plant similar to the CSIRO solar stills in Australia is also planned for this same village (Hirschmann, 216).

U.S.S.R. In addition to the earlier work in the U.S.S.R. by Trofimov and Tekuchev referred to above, during 1956 the Solar Energy Laboratory at the Krzhizhanovsky Power Institute in Moscow began investigating solar stills as a means of supplying water to arid and semiarid regions of Russia. The first design had high side walls and consequently obtained a low efficiency (Brdlik, 98). The heat- and mass-transfer processes in solar stills have been studied by Baum and Bairamov (61, 62). The air-circulation patterns were studied by means of a small laboratory apparatus and an interferometer. They observed that only the boundary layers circulated and contributed to the process of heat and mass transfer. The remaining volume was relatively stagnant. Formulas were also developed for calculating the heat-transfer coefficient for the conditions of evaporation from the brine surface and condensation on the inclined cover.

In 1962, a solar still was designed and tested at the Lenin Tashkent State University which operated with an external condenser and a chimney for creating a draft (Sharafi, 410). External air entered the still through a slit, passed through a soaked gauze, over the surface of the water, into the external condenser which was cooled with flowing or evaporating water, and finally up the chimney. A damper was located in the vertical pipe for regulating the draft. However, appreciable condensation also occurred on the glass cover.

Studies have also been conducted by Dzhubalieva (147) on the aerodynamic pressure distributions over the surface of single- and double-sloped still covers to investigate the effect of leaky joints on performance. The amount of vapor leakage caused by the natural thermal head only, with no wind, was also investigated (Dzhubalieva, 148). In the period from 1961 to 1965, five experimental stills were tested at the experimental station of the Physics and Engineering Institute of Turkemenian S.S.R. Academy of Sciences (Baum and Bairamov, 63) to determine an optimum design for the arid regions of Turkmenia. The stills were each about 11 ft$^2$ in area, and constructed of plywood and glass, with sawdust insulation. The most efficient design tested had a single-sloped glass cover with an angle of 30 degrees.

Based on this work, construction of a large solar still began in Ashkhabad, Turkmenia, in the spring of 1969. The final size is to be about 25,800 ft$^2$. The first 6,400 ft$^2$ was to begin operating in April, 1969 (Baum, 69). The average yearly production is expected to be about 24.5 gal/ft$^2$-year, or 0.067 gal/ft$^2$-day. Rainfall will also be collected. This installation will supply drinking water for a herd of 7,000 caracule sheep. The distillate may also be blended with well water to increase the total output. Electricity for pumping the well water will be supplied by a 300 to 400-watt solar photoelectric generator. Thus this experimental installation will be powered completely by solar energy (Baum, 66).

France. Beginning in 1956, the Laboratory of Solar Energy, National Commission for Scientific Research, Montlouis, France, combined the functions of a solar still with those of a hothouse to provide water, and the proper climate, for growing plants (Trombe and Foex, 452, 453). A hothouse, 20 ft long by 10 ft wide by 10 ft high, was built with insulated walls and a glass roof. Trays for containing brackish water were mounted horizontally beneath the glass roof and about 7 ft above the ground. The distilled water which condensed on the glass roof provided water for the vegetables. The size and arrangement of the trays provided the proper shade, and the bottoms of the tanks were partially shielded to limit the radiative heat transfer and prevent overheating of the plants. A much larger installation was planned for the Sahara, but it is not known if this was ever constructed.

Senegal, West Africa. In 1956, experiments were being conducted in Dakar, French West Africa (now Senegal) with a small solar still being mass produced by the Radiasol Company (Masson, 334). The approximately square 10-$ft^2$ still was made of sheet steel, insulated on the bottom and sides, and covered with double-sloped glass covers. The tray was lined with black plastic, the distillate troughs were made of a plastic material, and the joints were sealed with rubber strips.

During the early 1960's work at the University of Dakar, Dakar, Senegal, shifted from simple solar stills to solar-energy systems producing electric power and fresh water (Masson, 336). These are vapor-generating plants using solar energy to heat water which vaporizes a secondary heat-transfer fluid to drive a turbogenerator. The power generated is used to pump fresh water from a well, some of which is used to condense the heat-transfer fluid. The overall efficiency is below 1 percent.

Masson has also published an article relating the duration (hours) of sunlight to the total radiation energy received (Masson, 335).

India. Work on tray-type solar stills began in 1957 at the National Physical Laboratory, New Delhi, India. Five small tray-type stills were constructed to assess the performance of various materials and glass cover designs (Khanna, 269 to 273, 276). The trays were elevated above ground for ease of inspection and to protect the wooden frames from termites and mildew. Various metals used for tray material included galvanized iron, copper, and mild steel; and the basin bottoms were blackened with bituminous paint. Sawdust and rockwool were used for insulation, and the glass joints were sealed with putty made from chalk and double-boiled linseed oil mixed to the right consistency (Khanna, 277). Khanna also reported that in the arid region of Rajasthan, experimental solar stills were installed and operated by the Defense Laboratory for troops, but no performance data were available. A design has been formulated for a 4,000-$ft^2$ still to be installed in a remote Rajasthan village, using wood frames, glass covers, and stabilized soil for the basin, but funds have not become available.

The Central Salt and Marine Chemicals Research Institute (CSMCRI), Bhavnagar, India, has also reported a considerable amount of work on solar stills (Gomkale, et al., 188, 190; Datta, et al., 123; Ahmed, et al., 35). Several experimental solar stills, similar in some respects to the basin stills at Daytona Beach, Florida, were installed as a pilot plant in 1965. Twelve bays having symmetrical and unsymmetrical glass covers were tried and basin depths varied from 2 to 12 in. Various materials were used for the bottoms of the basins, including concrete (painted black), a tar-gravel mixture, and a stabilized soil made by adding 3 percent lime and 3 percent cement. The vapor tightness of most of the bays was also measured. In 1968, a small glass-covered, bay-type still was installed at the Navinar lighthouse. Its average output is around 30 gpd (Datta, 124).

Five articles by Garg, et al., (170 to 174) describe work on a humidification-dehumidification technique similar to that developed by Hodges at the University of Arizona and later built at Puerto Peñasco, Sonora, Mexico (Hodges, 219 to 225). This type of distillation originally used solar energy to preheat the saline water to about 150 F in concrete troughs covered with plastic, but it has been found more economical to use the waste heat from an existing diesel engine for this purpose (Hodges, 225, 226; Garg and Datta, 172, 174; Gomkale, 189).

Iran. In 1957, Tim DeJong tested three very small glass-covered, basin-type solar stills in Tehran, Iran (DeJong, 126). Double- and single-sloped glass covers were used, and one design had a segmented semicircular glass cover over the east, south, and west sides. Water-cooled copper coils were installed inside two of the units to serve as the condensing surface instead of the glass or galvanized tin panels.

Georgia Institute of Technology. From 1958 to 1961, the Georgia Institute of Technology under contract with the OSW, studied both natural-convection and forced-convection solar still designs (Grune, et al., 192 to 197). The four natural-convection stills were standard tray-type stills using either glass or plastic covers and shallow or deep basins, and were used as control units (i.e., standards for comparison). The six forced-convection solar stills were similar to the natural-convection stills except that air was blown through the stills to transport the water vapor to an external, water-cooled condenser. Depending on the design and operating conditions, the productivities of the forced-convection stills were approximately double those of the standard, natural-convection stills. Some of the externally condensing stills also had internal distillate troughs. Various ideas were tried to increase evaporation rates: Orlon wicks, brine-spray nozzles, elevated perforated brine trays, double covers, storage of the condenser cooling water for use at night in the basin, and multiple-depth trays within a single unit.

Spain. During 1958, two small (20 $ft^2$) experimental solar stills were constructed in Spain (Barasoain, 49). These were similar to Gomella's fiber-cement, tray-type still. Then in 1960 the investigation was expanded to include 10 different types of solar stills (Fontan, 167; Suarez, 422). These included studies of various glass angles and construction techniques, as well as combinations of tilted and horizontal sections under the same cover. It was found that the conventional glass-covered still with a shallow basin and a low-inclination cover was the most efficient design.

In November, 1963, Las Marinas was selected as the site of the first large-scale solar distillation plant in Spain, partly because that location had a supply of brackish water from the wells used for irrigation of that region (Blanco, 76; Lof, 318, Aguilar, 34). The installation was designed to provide the village of about 300 persons with water of higher quality. The project was a cooperative effort, involving the Government of Spain and the Organization for Economic Cooperation and Development (Paris). The principal persons involved in this project were Prof. Blanco, Ing. Gomella, and Dr. Barasoain. The OSW cooperated with this project through an exchange arrangement with Dr. Lof. The 9,350-$ft^2$ still was completed in March, 1966. The design of the Las Marinas still was somewhat similar to the deep-basin stills tested at Daytona Beach. The maximum distillate output approaches 1,000 gpd, and rainwater is also collected. The water is sterilized and slightly mineralized before drinking. However, the brackish well water is used directly by many of the villagers because it is much cheaper than the solar-distilled water. Therefore, not all of the water produced by the still is used (Aguilar, 34).

It has been reported for some time that another large solar still may be constructed on the Island of Tabarca, near the coastal city of Alicante, Spain. It will also be a glass-covered shallow-basin still with an area of about 27,000 $ft^2$ (Blanco, 81).

Franklin Institute. In November, 1958, work was begun at the Franklin Institute for the Office of Saline Water to study means for producing permanently hydrophylic surfaces on plastic films for use as solar-still covers (Erb, 164). Methods of vacuum deposition of silicon monoxide and chemical deposition of titanium dioxide by the hydrolysis of tetralkyl orthotitanates were investigated. A continuous dip-coating technique was developed for applying the titanium dioxide coating, and samples were run with cellulose acetate, Mylar, and Teslar (Tedlar). DuPont has more recently developed a technique for making one surface of Tedlar film wettable by simply passing the film through heated calendar rolls (Edlin, 511). A satisfactory embossing pattern consists of parallel 60-degree grooves at a frequency of 1400 lines per in. and having a depth of about 0.66 mil.

In June, 1960, the Franklin Institute began investigating coatings for plastic films which would selectively reflect infrared radiation in solar stills (Erb, 165). The basic purpose was to reflect the infrared energy rather than absorb it in the cover or allow it to pass through. However, it was found that the thin film of water inside a still cover would absorb practically all of the infrared radiation before it could reach the reflective surface coating. Therefore, only solar stills using external condensing systems (like those developed at the Georgia Institute of Technology) were considered candidates for infrared-reflecting coatings. The thin-metal-film approach was judged technically not feasible, and the interference-film approach, both single- and multiple-film systems, was judged technically, but not economically, feasible.

Sunwater Company. In late 1959, Horace McCracken began selling solar stills commercially (McCracken, 327, 330). These were step-inclined-tray stills using a porcelain-enameled-steel tray and a glass cover. The available sizes ranged from 1/2 to 3 gpd. McCracken began development work on this type of still at the University of California in March, 1959 (McCracken, 328). In March, 1966, McCracken developed a horizontal tray-type solar still, having an insulated silicone coated aluminum tray and a 6-degree single-sloped glass cover (McCracken, 330). In July, 1959, McCracken started the Sunagua Company (later renamed Sunwater) in San Diego, California, and is currently marketing these horizontal tray-type stills in various sizes. Portable, residential, and commercial types are now available and modules can be grouped to obtain the desired output. Units of various sizes, ranging from 1/2 gpd to 100 gpd, have been installed at various locations in the southwestern United States, Mexico, and the Caribbean (McCracken, 330).

Egypt. During 1960, several small solar stills were tested by the National Research Centre, Cairo, Egypt (Hafez and Elnesr, 199). The first still constructed had a wooden frame and a single glass pane sloped at 25 degrees. The 5.5-$ft^2$ basin was covered with a black cloth material with its ends immersed in a saline-water reservoir. A method of preheating the saline water was tried using an insulated reservoir covered with two layers of glass. Water evaporation in the preheater was prevented by a thin layer of oil on the water. The slight increase in yield did not justify its high cost. Next, a portable tray-type still was built using an aluminum tray and a foldable, double-sloped glass cover. Later designs were constructed of concrete to lower costs and increase life expectancy. Two 215-$ft^2$ stills were operated for about a year in a desert area near Cairo. The two 6.5 by 33-ft concrete basins were waterproofed and blackened with asphalt, and a metal framework was used to support the 30-degree double-sloped glass covers. In early 1961, a small concrete base still, 4 ft wide by 3.3 ft long, was developed to allow factory production of modules. Aluminum framework was used to support the 30-degree double-sloped glass, insulation was used beneath the base, and the concrete base and curbs were supported with bricks.

In 1966, a 3-ft-diam, plastic-covered still was developed at the National Research Centre and tested on the Red Sea coast and at Cairo for a year (Sakr, 403, 404). The galvanized iron tray was blackened and well insulated, and the Mylar cover was elevated at the center to form a 30-degree angle around the edge of the still. To avoid fogging of the plastic, caused by dropwise condensation, a small hummer (vibrator) was attached to the plastic cover. An empirical equation was derived relating productivity to the intensity of solar radiation.

Richard Hummel. In 1960, a design for a large-scale solar still producing 10 million gpd of fresh water was described by Hummel and Rudd (251). The same design was also discussed in later publications (Hummel, 252 to 254). The design consisted of two layers of wire-reinforced plastic covers. The lower condensing covers were air inflated and covered bays 50 to 100 ft wide by 1 mile long. The elevated upper cover was stretched flat and extended over the entire area, about 1 square mile. However, drainage of rainwater from the flat upper cover may present problems, as might high winds. Hummel also discussed means for adapting this solar-still design to multiple-effect and power-generation systems.

University of Arizona. The University of Arizona, Tucson, Arizona, in the spring of 1961, began developing a distillation system using solar energy to preheat the saline water for a humidification-dehumidification cycle (Hodges, et al., 219-226). This work was supported by OSW and the University. In this system, the basic functions of heating the saline water, evaporating a portion of it, and condensing the vapor are performed in three separate components. Therefore, it is not a conventional simple solar still. In the early experimental plants built at the University of Arizona, and at the pilot plant constructed at Puerto Peñasco, Sonora, Mexico, in 1963-64 in collaboration with the University of Sonora, solar energy was used to warm the saline water to a final temperature of 150 F before it was circulated through an evaporation chamber. The five solar absorbers at Puerto Peñasco were shallow troughs (2 in. deep) lined with black plastic or butyl rubber and covered with two layers of clear plastic films of PVC or PVF. The inside plastic film rested on the surface of the water, and the outer film was inflated to provide an insulating effect. The total area of the solar absorbers was 10,400 $ft^2$ and the pilot plant in Mexico has produced over 5,000 gpd. In 1965, the Puerto Peñasco plant was modified so that it could operate from the waste heat of the 60 kw diesel-electric set rather than the solar collectors. Both jacket-water and exhaust-gas heat is utilized, and the overall plant production increased to 6,000 gpd using only waste heat.

Harold R. Hay. Please refer to write-up on page 22.

McGill University. Since 1961, the Brace Research Institute (BRI) of McGill University in Macdonald College, Quebec, has been developing solar stills on several West Indies islands in the Caribbean Sea (Lawand, 290). The first still was built during the winter of 1961 at the Brace Experiment Station in St. James on the island of Barbados (Lawand, 281). It was a glass-covered still with a wooden framework supporting the galvanized steel tray. The tray size was 2.8 by 17.9 ft (50 $ft^2$), and was insulated with wood shavings and painted with black epoxy resin paint.

In 1963, BRI reported on measurements of solar transmittance for Tedlar, Mylar, and glass (Whillier, 486). The total solar transmittance of 4-mil Tedlar was 92 percent at normal incidence, and the infrared transmittance was about 30 percent. Heat-loss coefficients and solar transmittances were calculated for collectors with multiple glazings, including combinations of glass and Tedlar.

Also in 1963, Selcuk (408) designed and tested a small multiple-effect, tilted solar still at the Experiment Station. Two glass covers and two effects were used. Brine evaporator troughs were attached to the back sides of the solar-heat-collector plate and the condenser plate of the first effect. Both indoor and outdoor tests were conducted with electrical and solar heating, respectively.

From September 1965 to December 1968, a prototype of the Petit St. Vincent still (described below) was operated at the Barbados Experiment Station. It had an area of 400 $ft^2$ (Lawand, 293).

Early in 1967, BRI cooperated with Petit St. Vincent, Ltd. to install a large-scale solar still to provide fresh water for a hotel development project on the remote, previously uninhabited island of Petit St. Vincent (Lawand, 290). This is an inflated, plastic-covered still comprised of 15 concrete bays, each approximately 8.6 ft wide by 150 ft long (19,300 $ft^2$). Weirs, or cascades, were located at intervals of about 5 ft by mounding the earth beneath the butyl rubber liner. Provisions were made for collecting rainwater from the still covers.

In September, 1968, BRI constructed a glass-covered solar still on the island of Anguilla in the West Indies. This is a bay-type still of 280 $ft^2$, built of concrete and glass. The double-sloped glass cover was sealed with silicone rubber cement. A second glass-covered still was built in Haiti and put into operation during the Summer of 1969 (Lawand, 292, 293). This design utilizes single-sloped glass covers facing southward with an angle of 15 degrees, concrete curbs, and butyl rubber basin liners. The 15 bays are about 2.2 ft wide by 73 ft long (2,400 $ft^2$). Weirs and insulation are also used beneath the basin.

Brace Research Institute has also published reports with step-by-step instructions for building small plastic or glass-covered solar stills (Brace, 94; Lawand, 286).

Taiwan. In 1961, Taiwan Normal University reported that research work was being conducted on several small tray-type solar stills (Wang, 482). These units had roof-type glass covers sloped at about 45 degrees, and the trays were 3 by 6 ft or 3 by 3 ft. These types have been manufactured for use on the surrounding islands by fishermen and troops. The larger stills could produce 18 to 20 lbs of water daily (approximately 2.3 gpd).

Japan. A somewhat different type of solar still was developed in Japan during 1961 (Kobayashi, 278). Termed an "earth-water collector", it is essentially a conventional solar still without a brine basin. Water vapor is thus extracted from the soil and condensed on the cover. Wooden frames, together with single-sloped glass covers or double-sloped plastic covers, were used. Tests were conducted at Tokyo, Mt. Mihara, Mt. Fuji, and on a desert in Pakistan to study the productivity of various types of soils. Distillation continued during the night at a reduced rate, and the peak productions occurred following rain. The average productivity in Tokyo was about one-fifth that of a conventional solar still. It was stated that this study originated during World War II.

Tunisia. Since 1962, the Solar Energy Group of the Tunisian Atomic Energy Commission has been actively studying solar distillation (454). More than a dozen still designs were tested, and beginning in 1967, three larger solar distillation stations have been built in Tunisia at Chakmou, Chibou, and Mahdia (Tunisian AEC brochures, 455). These designs consist of bays with single-sloped glass covers facing southward and inclined at 10 degrees. The curbs are constructed of concrete and bricks, and the bottom is concrete coated with bitumen (asphalt). Provisions are made for collecting rainwater, and the distillate is mixed with brackish well water for drinking purposes. The following tabulation gives the basin sizes and the number of persons supplied by these stills.

| Station | Evaporation Area, $ft^2$ | No. Persons |
|---|---|---|
| Chakmou | 4,700 | 500 |
| Chibou | 430 | 40 |
| Mahdia | 14,000 | 2,000 |

Designs have also been developed for family-size solar stills to supply 2, 5, or 10 persons and enable Tunisians to install these in their own homes. Additional solar-still installations are planned for several islands around Tunisia. The following tabulation lists the anticipated locations and sizes:

| Tunisian Island | Evaporating Area, ft$^2$ |
|---|---|
| Djerba | 10,800 |
| " | 10,800 |
| Kerkennah | 10,800 |
| " | 5,400 |
| Kuriates | 5,400 |
| Zembra | 5,400 |

One benefit Tunisia hopes to realize by providing fresh water with solar-still stations is increased vigor in the people. The usually available drinking water is high in salt content (6,000 ppm or more) and they feel that the energy required by the liver and kidneys to remove the salt consumes what strength is gained from eating rather poor food.

Leslie Salt Co. In late 1962, the Leslie Salt Company of San Francisco, California, studied the technical and economic feasibility of constructing a solar still over their existing solar salt-concentrating ponds (Leslie Salt Co., 298). This study was partly sponsored by the OSW. Many designs were considered, but the study was narrowed down to variations of the deep-basin type still used at Daytona Beach. Cost estimates were made for a deep-basin still, using wood or concrete pilings, and a Leslie design for a floating still using styrofoam blocks and double-sloped glass covers. On the basis of estimated costs, the floating still would be the most economical. A visit to the Leslie plant in 1968 indicated that no further work has been done on this concept, although the company is still interested in its potential.

Aqua-Sol, Inc. In 1963, Reynold Eckstrom founded the Aqua-Sol consulting engineering firm, and was responsible for building the prototype of the Symi still at Battelle's Daytona Beach facility in 1963 for Church World Service. In 1964, he supervised the building of the Symi still (Eckstrom, 149), and during 1965, he built large plastic-covered stills on the Greek Islands of Aegina and Salamis, and on the Cape Verde Island of Santa Maria do Sal (Eckstrom, 150, 151). Currently, he is developing a small portable solar still to produce between 3 to 5 gpd. A new semirigid plastic material has been developed for the cover (Eckstrom, 152).

Greece. Beginning in 1964, the construction of the first of several solar stills for the Greek Islands began on Symi (Delyannis, 129; Eckstrom, 149). Church World Service (CWS), New York City, sponsored the plastic-covered solar stills on the islands of Symi, Aegina, and Salamis. The Greek government sponsored the glass-covered solar stills on the islands of Patmos, Kimolos, and Nisiros (Delyannis, 130).

Table 4 lists the various locations and sizes of solar stills built on several of the Greek islands.

TABLE 4. SOLAR STILLS BUILT ON GREEK ISLANDS

| Island | Designer | Starting Date | Evaporating Basin Area, $ft^2$ |
|---|---|---|---|
| Symi | DuPont (Frank Edlin) | Oct. 1964 | 29,000 |
| Aegina | Ditto | Oct. 1965 | 16,000 |
| Salamis | " | Oct. 1965 | 4,200 |
| Patmos | Technical University, Athens (Anthony Delyannis) | June 1967 | 93,000 |
| Kimolos | Ditto | 1968 | 27,000 |
| Nisiros | " | 1969 | 22,000 |

The plastic-covered stills have been redesigned several times because of cover damage suffered from wind and rain. The original design, developed by Frank Edlin at DuPont, had an inflated air-supported plastic cover. DuPont had tested earlier inflated designs at Daytona Beach, Florida, during 1959-1960 (Battelle, 52), and Aqua-Sol, Inc. (St. Paul, Minn.), constructed a prototype of the Symi still at the Daytona Beach OSW facility in 1963 for CWS (Battelle, 55). Reynold Eckstrom of Aqua-Sol, Incorporated, was the consulting engineer in charge of building the Florida prototype and the first solar still at Symi, Greece. The Symi still consisted of 14 bays, each with a width of 10 ft and of different lengths, varying between 117 ft and 265 ft because of the shape of the land available (Eckstrom, 149). A second plastic-covered still was built for CWS on the island of Aegina. A V-shaped cover was used with pipes acting as weights to maintain the V-shape and the distillate troughs were located under the "V" in the center of the basins. Two bays of the Symi still had used this V-cover design, and another still was built on the island of Salamis using this design. Problems were encountered when dirt and rain collected too rapidly in the "V", and movement of the pipe abraided the plastic film (Eckstrom, 151, 152). Therefore, a third plastic-cover design was developed by Edlin in 1968 which had a tightly stretched Tedlar cover with a single inclination of only 5 degrees. Cracking of the plastic film has occurred, and it appears that the plastic-covered solar stills in Greece may be abandoned (Radway, 392). CWS recently purchased a 7,500 gpd vapor-compression still which will be installed on the island of Symi (Desalting Digest, 31).

The design of the glass-covered stills in Greece was developed by Anthony and Emmy Delyannis at the Technical University of Athens, Greece. They had tested several designs at an Experimental Station on the island of Symi before installing the larger units (Delyannis, 130, 133). They have experimented with such things as aluminum supporting structure, black Orlon matting in the basin, and internal condensing coils which preheat the feedwater and produce a cyclic shallow-to-deep basin during each day. The glass-covered stills on the islands consist of individual bays about 10 ft wide by 65 to 130 ft long. The glass cover is unsymmetrical, with the long slope of about 10 degrees facing southward, and the short slope of 80 degrees on the north side (Delyannis, 137, 138). The still on Patmos suffered extensive damage during the winter of 1967, evidently because it was left unused during the rainy season and the ground and structure shifted, but has now been completely rebuilt (Delyannis, 140). Solar distillation plants of the same basic design have recently been built on the islands of Kimolos and Nisiros.

The Greek AEC has also reported work on step-inclined-tray and roof-type stills for seawater desalination and the concentration of radioactive waste liquors (Hatzikakidis, 203). Solar energy was also to be used for preheating the saline water before introduction to the stills.

Cape Verde Islands. In 1965, an inflated plastic-covered still similar to the one built on the island of Symi, Greece, was built on the island of Santa Maria do Sal in the Cape Verde Islands. Reynold Eckstrom of Aqua-Sol, Inc., built this still to supply water for a hotel. It consists of 6 bays, each 9.5 ft wide by 149 ft long, for a total evaporating area of about 8,000 $ft^2$. The operator reported recently to Eckstrom that the stills were functioning very well, and that he finds it necessary to operate the blowers for inflation only once each evening for a few minutes (Eckstrom, 152).

Ethiopia. A 1965 report describes the design of a small solar still developed in Ethiopia at the Haile Sellassie I University (Hobbs, 218). A single-sloped glass cover at 12 degrees was mounted over an insulated metal tray painted dull black. Construction details and a breakdown of materials and costs were given for a 2 by 6 ft tray size.

U.S. Water Conservation Laboratory. The U.S. Water Conservation Laboratory in Phoenix, Arizona, developed a simple desert-survival still in 1965 (Jackson and Van Bavel, 256, 257). This small still uses solar energy to distill water from desert soils and desert plants. The still is made by digging a shallow hole in the ground about 3 ft in diameter, and covering it with a plastic film weighted in the center to form a conical shape. A container is placed below the center weight to catch the condensate water dripping from the plastic film to increase the amount of water obtained from the soil itself. Yields averaged about 0.4 gpd with pieces of cactus, with fresh plant material required after 5 days. In 1966, materials for the desert survival still were available in kit form.

Harold R. Hay. In 1961, Harold Hay developed the use of weighted V-covers for plastic-covered stills (Hay, 204, 516). Although his experiments were on small models, the large still on the island of Aegina was also of this type. In this design, some of the problems of the inflated plastic cover can be overcome, but the valleys of the V-covers tend to collect rainwater and debris, and the plastic may be damaged by movement of the pipes that are used as weights. According to Hay (207), these problems can be overcome with proper design.

Hay has also reported on an elaborate solar-still concept, including weighted-V covers, and has obtained a patent on the same (Hay, 204,516). It is comprised of a plastic cover draped over ridge beams and weighted in the valleys, moveable and stationary brine trays, and a distillate reservoir built beneath the brine trays. The moveable brine trays float on the distillate in the reservoir; thus they are perfectly horizontal and can be moved about to avoid being shaded by the elevated fixed trays. Variations of this design were also described, including the use of heat-storage chemicals. Hay has also designed an Equifeed system for solar stills which feeds saline water at a variable rate, depending on the solar intensity (Hay, 207).

Pakistan. Since about 1967, the Atomic Energy Commission of Pakistan has been investigating the feasibility of using solar stills to provide water for the arid Makran Coastal regions (Kamel, 263). The possibility of combining salt production with seawater desalting may also benefit the fisheries industry. The site chosen for what may become the world's largest solar distillation plant is Gwadar (Niaz, 375; Delyannis, 137). Initial plans show that the general layout would be very similar to the Greek stills on the islands of Patmos, Kimilos, and Nisiros. The intended capacity of the proposed plant is 18,000 gpd. The physical plant would consist of 296 bays, each about 9.8 ft wide by 65.6 ft long, for a total evaporating area of 191,000 $ft^2$. When funds become available, building of the Gwadar still should begin (Delyannis, 140).

Solar Sunstill, Inc. In 1969, a kit-type, plastic-covered solar still was marketed commercially by Solar Sunstill, Inc., Setauket, Long Island, New York (Raseman, 394). The unit consists of a square basin, 64 $ft^2$ in area. The plastic cover is pyramid shaped, supported in the center by a slender fiberglass mast. The inside of the cover is treated with Sunclear, a special hydrophilic coating, to produce a wettable surface. All the parts are made of plastic, except for an aluminum alloy framework which supports the distillate trough around the perimeter of the cover.

It has been reported that solar stills have also been built in the following countries:

Libya (La Parola, 280)
Kenya (Ramsay, 393)
Morocco (Ambroggi, 38).

Regrettably, attempts to obtain information on these stills were unsuccessful.

# SECTION 3. EXAMPLES OF LARGE BASIN-TYPE SOLAR STILLS

This section contains photographs, sketches, and detailed descriptions of 27 large basin-type solar stills. Of these, 20 are believed to be currently in use, with a total area of over 284,000 ft$^2$ and an average productivity of about 20,000 gpd. The term "large" has been applied arbitrarily to stills having a basin area exceeding about 1,000 ft$^2$. Nearly all of these stills were built directly on the ground, with only a layer of sand used as insulation beneath the basins. Smaller solar stills are described similarly in Section 9. Naturally, some of the smaller designs shown could be adapted for use in larger installations.

Table 5 is a list of the solar stills described in this section. The country and location are given, together with the basin size (evaporating area) and the approximate year-around average daily productivity.

TABLE 5. LARGE BASIN-TYPE SOLAR STILLS

| Country | Location | Date Built | Basin Size, ft$^2$ | Productivity, gpd | Figure Number |
|---|---|---|---|---|---|
| Australia | Muresk I[a] | Dec., 1963 | 4,000 | 220 | 1 |
| | Muresk II | Nov., 1966 | 4,000 | 220 | 1 |
| | Coober Pedy | Nov., 1966 | 34,000 | 1,680 | 2 |
| | Caiguna | Dec., 1966 | 4,000 | 205 | -- |
| | Hamelin Pool | Dec., 1966 | 6,000 | 320[b] | -- |
| | Griffith | Aug., 1967 | 4,450 | 240 | 2 |
| Cape Verde Islands | Santa Maria do Sal | 1965 | 8,000 | 560[b] | -- |
| Chile | Las Salinas[a] | ~1872 | 48,000 | 3,900[b] | 3 |
| | Quillagua | 1968 | 1,076 | 106 | 4 |
| Greece | Symi[a] | July, 1964 | 28,920 | 2,000[b] | 5 |
| | Aegina | Oct., 1965 | 16,040 | 1,120[b] | 6 |
| | Salamis | Oct., 1965 | 4,180 | 290[b] | 6 |
| | Patmos | July, 1967 | 93,000 | 6,900 | 7 |
| | Kimolos | 1968 | 27,000 | 2,000 | -- |
| | Nisiros | 1969 | 22,000 | 1,600 | 7 |
| India | Bhavnagar | Oct., 1965 | 4,060 | 220 | 8 |
| Mexico | Natividad Island, Baja California | Mar., 1969 | 1,024 | 100[c] | 9 |
| Spain | Las Marinas | Mar., 1966 | 9,350 | 680 | 10 |
| Tunisia | Chakmou | 1967 | 4,730 | 140 | 11 |
| | Mahdia | 1968 | 14,000 | 1,100 | 12 |
| U.S.A. | Daytona Beach, Fla.[a] | | | | |
| | Original Deep Basin | Jan., 1959 | 2,450 | 140[b] | 13 |
| | Second Deep Basin | Apr., 1961 | 2,650 | 150[b] | 14 |
| | Large Inflated Plastic | Jan., 1959 | 2,330 | 100[b] | 15 |
| | Church World Service | July, 1963 | 1,600 | 160[b] | 16 |
| U.S.S.R. | Bakharden, Turkmenia | Apr., 1969 | 6,450 | 430[c] | 17 |
| West Indies | Petit St. Vincent | Feb., 1967 | 18,400 | 1,300 | 18 |
| | Haiti | June, 1969 | 2,400 | 200[c] | 19 |

(a) No longer operating. (b) Estimated productivity. (c) Anticipated productivity.

6900 x 3,78 = 26,08 m³/day

93.000 ft² = 8640 m² =

## STILLS AT MURESK, WESTERN AUSTRALIA (C. S. I. R. O.)*

**Internal size:** 10 bays, each 3-1/2 ft wide x 128 ft long, 4,000 $ft^2$ basin area, 4,500 $ft^2$ projected glass.

**External size:** Approx. 45 ft wide x 130 ft long; 5,800 $ft^2$ overall.

**Brine depth:** Varies from about 1 to 1.7 in. between weirs.

**Cover:** Horticultural-grade glass, 18 x 33 in., 15-degree slope, wire tie-downs at intervals.

**Vapor seals:** (Muresk I) Rubber-lined metal strips and butyl-rubber strips. (Muresk II) Silicone-rubber sealant, butyl-rubber strips, soft mastic.

**Distillate troughs:** Formed from sheet metal, basin liner is extended to also line the distillate channels, 1:40 slope (maximum).

**Basin liner:** 8-mil black polyethylene sheet placed – (I) inside tray, (II) directly on ground; 1:40 slope (maximum).

**Walls and curbs:** Preformed galvanized sheet metal for – (I) tray, (II) walkways.

**Other features:** Continuous feedwater from brackish river water (1,700 ppm winter to 14,000 ppm summer), 1-3/4-in.-high weirs at 4-ft intervals, ground sprayed with insecticide and weedicide, fence around stills, feedwater treatment for algae, about 10 to 60 man-hrs/1000 $ft^2$-yr maintenance required for unattended still.

**Productivity:** (I) Annual average about 0.062 gal/$ft^2$-day, or 22.6 gal/$ft^2$-yr. (II) 0.084 gal/$ft^2$-day. (Note: Output of still II later reported about equal to still I).

**Problems:** Lightweight construction susceptible to lifting by wind vortexes, excessive vapor leakage in Muresk I, shifting of clay soils if sand layer not used, algae feedwater treatment required, gradual decline in output owing to brine and distillate leaks, cleaning of basins.

**Dates:** (I) December, 1963, to November, 1966; (II) November, 1966, to present.

**Note:** Photographs of Muresk II, showing construction details, are in Section 8.

**References:** Morse, 344-347.

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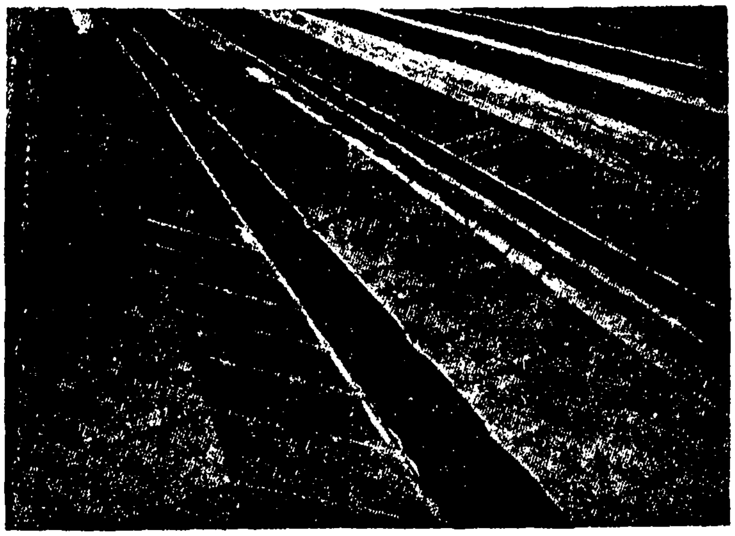
*Commonwealth Scientific and Industrial Research Organization.

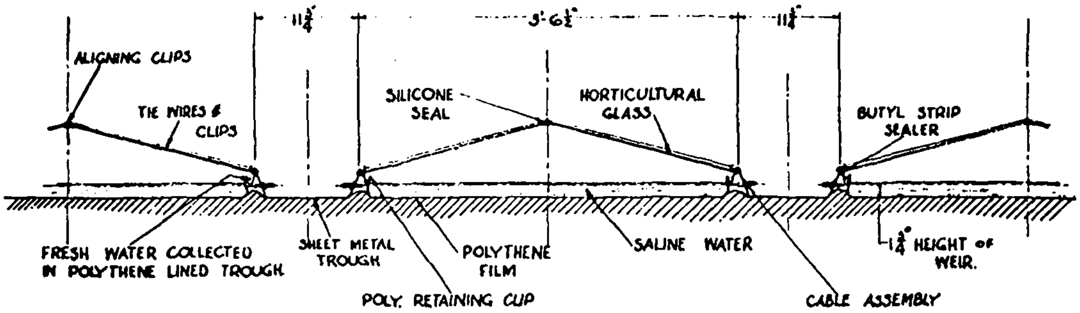
$0{,}062 \text{ gal}/ft^2 \cdot d = 0{,}062 \times 3{,}78 \times \frac{1}{0{,}0929}$

$= 2{,}52 \; l/m^2/\text{day}$

a. Muresk I Still (Photo from Sun at Work, Fourth Quarter, 1965)



b. Muresk II Still (Photo from Ref. 345)



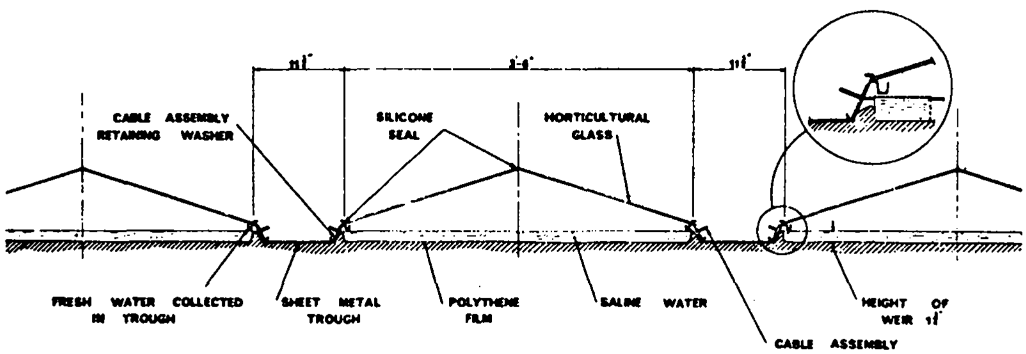

c. Muresk II and Coober Pedy Design

FIGURE 1. STILLS AT MURESK, WESTERN AUSTRALIA

## STILL AT COOBER PEDY, SOUTH AUSTRALIA (C.S.I.R.O.)

| | |
|---|---|
| Internal size: | 76 bays, each 3 ft 6 in. wide x 143 ft long; 34,000-$ft^2$ basin area, 38,000-$ft^2$ projected glass area (future expansion to 100,000 $ft^2$ planned). |
| External size: | Two groups, one 225 ft x 145 ft, one 117 ft x 145 ft; total area 49,000 $ft^2$. |
| Brine depth: | Varies from about 1 to 1.7 in. between weirs. |
| Cover: | Horticultural-grade glass (20 oz/$ft^2$), 18-degree slope, wire tie-downs at intervals. |
| Vapor seals: | Silicone-rubber sealant, butyl-rubber strips, soft mastic. |
| Distillate troughs: | Black polyethylene basin liner extends over groove in galvanized sheet metal troughs, between 1:50 and 1:120 slope. |
| Basin liner: | 8-mil black polyethylene directly on ground. |
| Walls and curbs: | Preformed galvanized sheet metal walkways. |
| Other features: | Brackish wellwater feed (24,000 ppm), continuous feedwater supply through plastic restrictor tubes (0.1 lb/hr-$ft^2$), 1-3/4-in. high weirs at 4-ft intervals, about 10 to 60 man-hrs/1000 $ft^2$-yr maintenance required for unattended still, earth mounds 18 in. high around still for windbreak, fence around area, insecticide sprayed on ground. |
| Productivity: | 4,800-gpd peak (0.126 gal/$ft^2$-day), 2,020 gpd yearly average (0.053 gal/$ft^2$-day, 19.3 gal/$ft^2$-yr). |
| Problems: | Lightweight construction susceptible to lifting by wind vortexes, soil movement of clay soils requires layer of sand, pinholes in basin liner caused brine leaks, shifting of walkways caused distillate spillover, floating film of salt. |
| Dates: | November, 1966, to present. |
| Note: | Solar stills at Caiguna (4,000-$ft^2$ basin, 5,000-$ft^2$ proj. glass) Hamelin Pool (6,000-$ft^2$ basin, 6,800-$ft^2$ proj. glass), and Griffith (4,450-$ft^2$ basin, 5,000-$ft^2$ proj. glass) are of similar designs. Improvements tried at Griffith include concrete curbs, aluminum or stainless steel distillate troughs, silicone sealant for all joints, butyl rubber liner, increased slope along length, polystyrene insulation. |
| References: | Morse, 344, 346, 347, 349, 350, and personal communication. |

a. Coober Pedy Solar Still, Australia

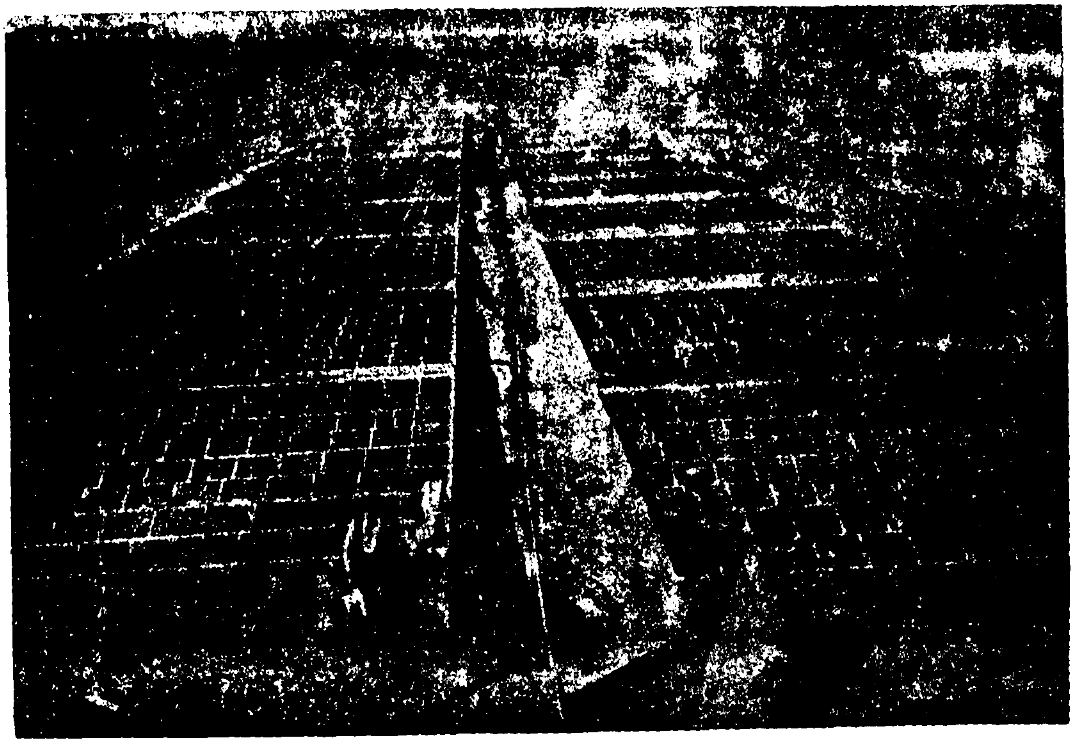



b. Mark III Design (Griffith, N.S.W., Australia, Ref. 350)

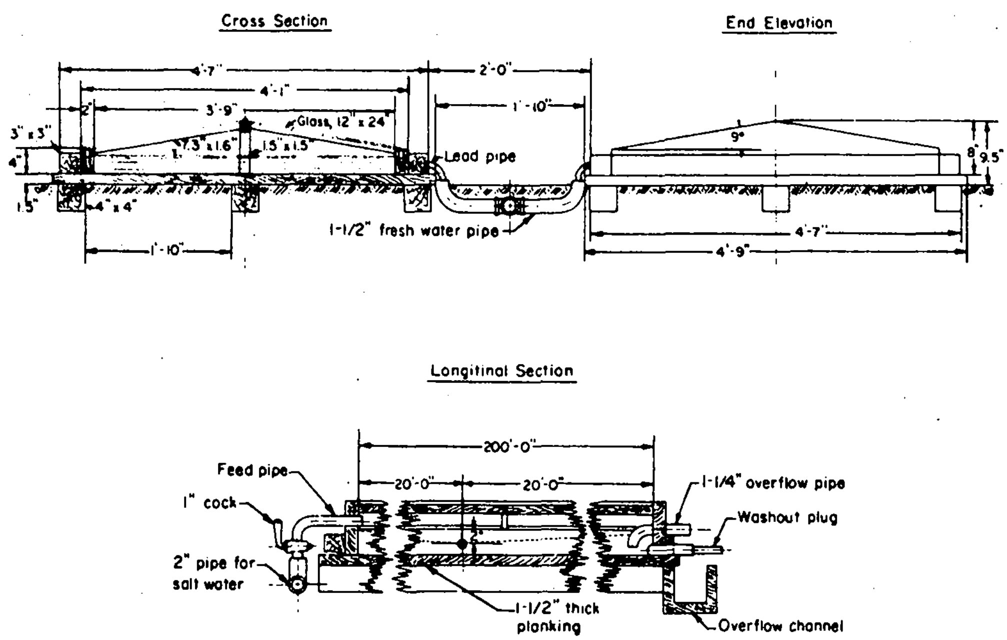
FIGURE 2. STILL AT COOBER PEDY, SOUTH AUSTRALIA

## STILL AT LAS SALINAS, CHILE

| | |
|---|---|
| Internal size: | Originally 64 bays, each 3 ft 9 in. wide x 200 ft long, 48,000-$ft^2$ basin area; later photo indicates each bay around 30 ft long, and approximately 1/2 original area. |
| External size: | Originally 51,200-$ft^2$ glass area, each bay occupied a space 6 ft 7 in. wide x 202 ft long, total of 85,000-$ft^2$ land area; later photo shows still about one-half original size. |
| Brine depth: | 2 to 3 in. (1-in. slope in 200 ft). |
| Cover: | Glass panes 2 x 2 ft, sloped 9 degrees 13 minutes. |
| Vapor seals: | Putty. |
| Distillate troughs: | Grooves cut in wooden (pine) sides, 0.1 in./ft slope. |
| Basin liner: | Wooden planks, waterproofed with putty and blackened with logwood and alum. |
| Walls and curbs: | Wooden structure throughout. |
| Other features: | Salt water reservoir for 4 day's supply, windmill pump, preheating of feedwater tests, distillation occurred between 10 a.m. and 10 p.m., salinity of feedwater 14 percent, basins flushed out every 2 days, peak radiation intensity about 3,000 Btu/$ft^2$-day. |
| Productivity: | Peak output of 6,000 gpd when new, or 0.12 gal/$ft^2$-day. |
| Problems: | Much maintenance required, crystal deposits in basin, glass breakage due to frequent whirlwinds, brine and distillate leakage through cracks in wood planking and troughs. |
| Dates: | About 1872 to 1908. |
| References: | Harding, 202; Telkes, 434. |



a. 1908 Photograph (Ref. 434)



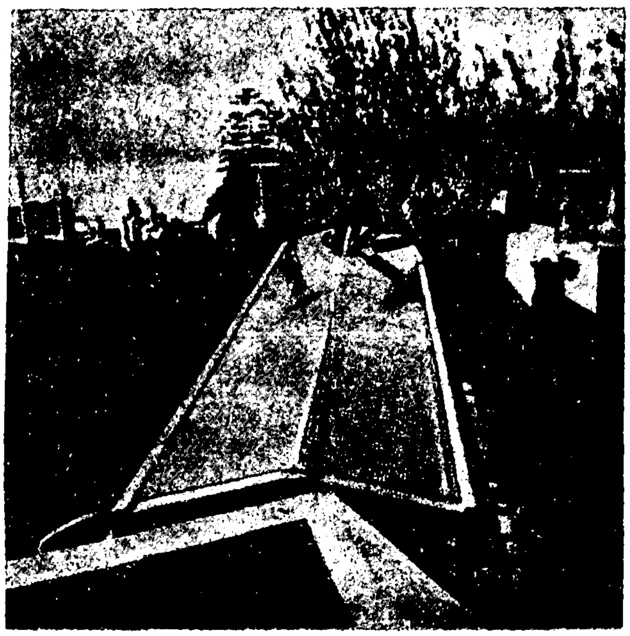

b. 1872 Design of Carlos Wilson (Ref. 202)

FIGURE 3. STILL AT LAS SALINAS, CHILE

## STILL AT QUILLAGUA, CHILE

| | |
|---|---|
| Internal size: | Approximately 1,076 $ft^2$. |
| External size: | Not reported. |
| Brine depth: | Not reported. |
| Cover: | Glass. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Concrete. |
| Walls and curbs: | Concrete. |
| Other features: | None reported. |
| Productivity: | Approximately 106 gpd (0.10 gal/$ft^2$-day). |
| Problems: | Frequent earthquakes produce cracks in concrete basins which must be sealed periodically. |
| Dates: | Early 1968 to present. |
| Note: | Second pilot plant to be built using asbestos-cement trays. |
| References: | Hirschmann, 216. |

a. Pilot Plant Under Construction



b. Prototype, Still No. USM-6

FIGURE 4. STILL AT QUILLAGUA, CHILE

## STILL ON THE ISLAND OF SYMI, GREECE (CHURCH WORLD SERVICE)

| | |
|---|---|
| **Internal size:** | 14 bays, each 9 ft 6 in. wide x 112 to 262 ft long; 28,920-$ft^2$ evaporating-surface area. |
| **External size:** | Approximately 32,000 $ft^2$; long dimension East-West oriented. |
| **Brine depth:** | Approximately 2 in. |
| **Cover:** | 12 bays inflated, 2 bays V-shaped, Tedlar (wettable); approximately 1/4-in.-water inflation pressure used for inflated design. |
| **Vapor seals:** | Neoprene gaskets (adhesive coated) clamped between cover and liner. |
| **Distillate troughs:** | Originally aluminum, later concrete lined with basin liner. |
| **Basin liner:** | Black butyl rubber sheet; sand insulated basin. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | Designed for feedwater preheating by using waste heat from nearby power-plant (use discontinued), diesel-driven feed and fresh water pumps, rainfall collection, black acrylic fiber batting used in basin to absorb solar energy, sea water fed batchwise early every morning, sea water tank holds 4-day supply, copper sulphate and chlorine feedwater treatment. |
| **Productivity:** | Both cover designs, about 0.10 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day, about 0.040 gal/$ft^2$-day at 1,000 Btu/$ft^2$-day; maximum output about 0.15 gal/$ft^2$-day. |
| **Problems:** | Delivery of materials on schedule, accurate leveling of ground, deterioration of aluminum distillate troughs, collapse of covers due to rain, covers susceptible to wind damage (covers deflated and flooded to prevent damage), dust adherence to plastic covers, electric power failures in storms allowed deflation, cover life of approx. 2 years (partly due to misuse by villagers), floating Orlon mats removed because of scale and sediment collection, air leaks, surrounding hills limit sunlight hours. |
| **Dates:** | July, 1964, to 1969. |
| **Note:** | A similar inflated, plastic-covered still was built in 1965 on Santa Maria do Sal, Cape Verde Islands by Aqua-Sol, Inc.; 6 bays, each 9 ft 6 in. wide x 149 ft long; about 8,000-$ft^2$ evaporating area. |
| **References:** | Eckstrom, 149, 150, 152; Delyannis, 129, 138; Lawand, 289; Lof, 316; Edlin, 511; Anon., 25. See also CWS still at Daytona Beach, Florida. |

(Photo From Sun at Work, First Quarter, 1965)

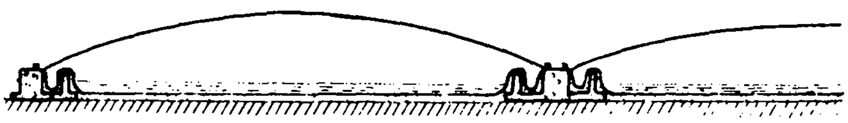
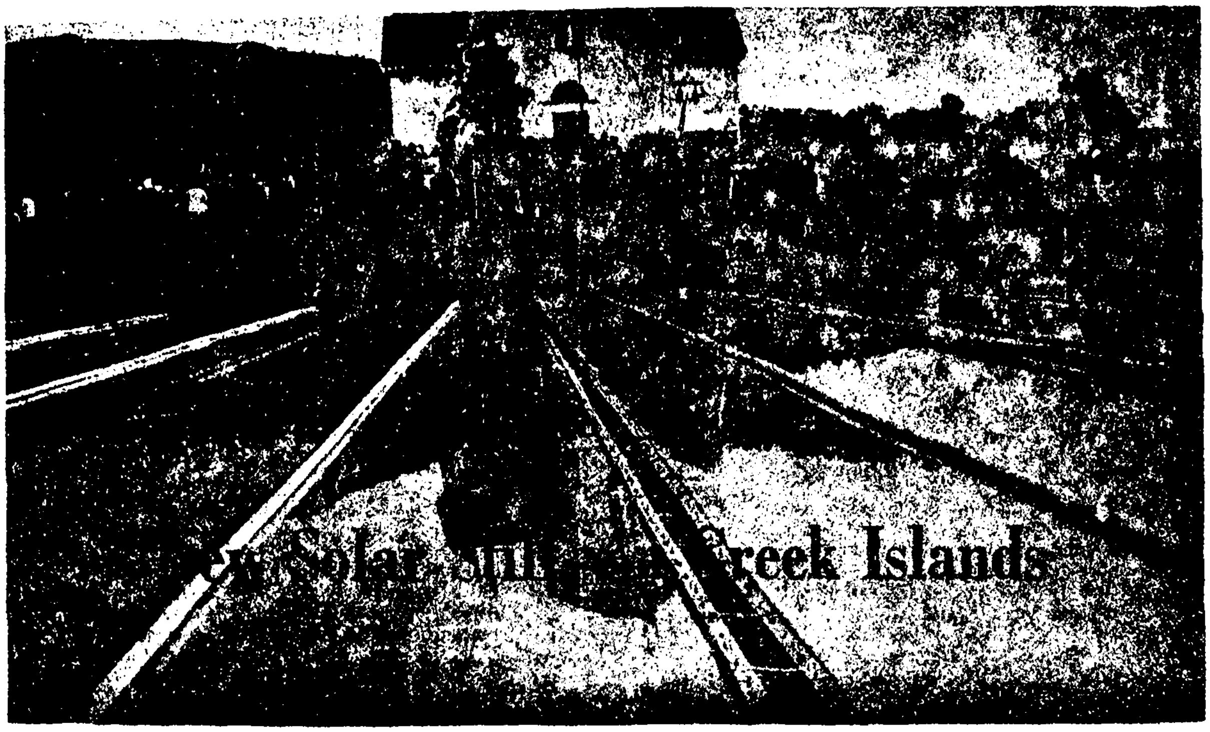


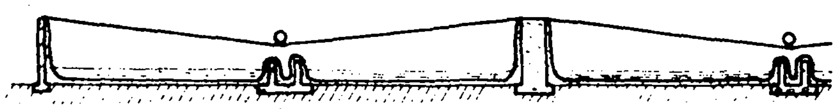
FIGURE 5. STILL ON THE ISLAND OF SYMI, GREECE

## STILL ON THE ISLAND OF AEGINA, GREECE

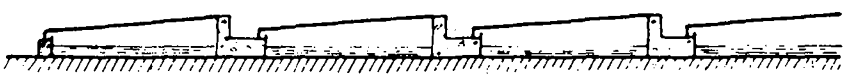
| | |
|---|---|
| **Internal size:** | 12 bays, each 9 ft 6 in. wide x 149 ft long; 16,038-$ft^2$ evaporating surface area. |
| **External size:** | Approximately 130 ft wide x 160 ft long; 20,400 $ft^2$ overall. |
| **Brine depth:** | Approximately 2 in. |
| **Cover:** | Originally V-cover of Tedlar, later stretched-cover of Tedlar with 5 degree slope (single-slope design), with 12,300-$ft^2$ evaporating area. |
| **Vapor seals:** | Not reported. |
| **Distillate troughs:** | Moulded concrete. |
| **Basin liner:** | Black butyl rubber sheet, sand-insulated basin. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | 19,000-gal settling tank for feedwater, 10,000-gal tank for fresh water, 10,000-gal tank for rainwater. |
| **Productivity:** | About 0.15 gal/$ft^2$-day (maximum output anticipated for V-cover). |
| **Problems:** | Dirt and debris collecting in valley of V-shaped cover required frequent cleaning, rainwater collecting at low points along valley caused sagging and tearing of film, movement of pipe weight wears film, susceptible to wind damage, V-cover life of less than 1 year because of severe winter wind storms, cracks developed in stretched-cover design. |
| **Dates:** | (V-cover) October, 1965; (Stretched-cover) December, 1967, to 1969. |
| **Note:** | A similar solar still with V-cover was constructed on the island of Salamis on a YMCA dining hall roof in October, 1965; 6 bays, each 9.5 ft wide x 75 ft long; 4,180-$ft^2$ evaporating area. |
| **References:** | Eckstrom, 150, 151; Delyannis, 138; Anon., 25. |



a. Aegina I Still (Photo From Ref. 151)



b. Aegina I and Salamis

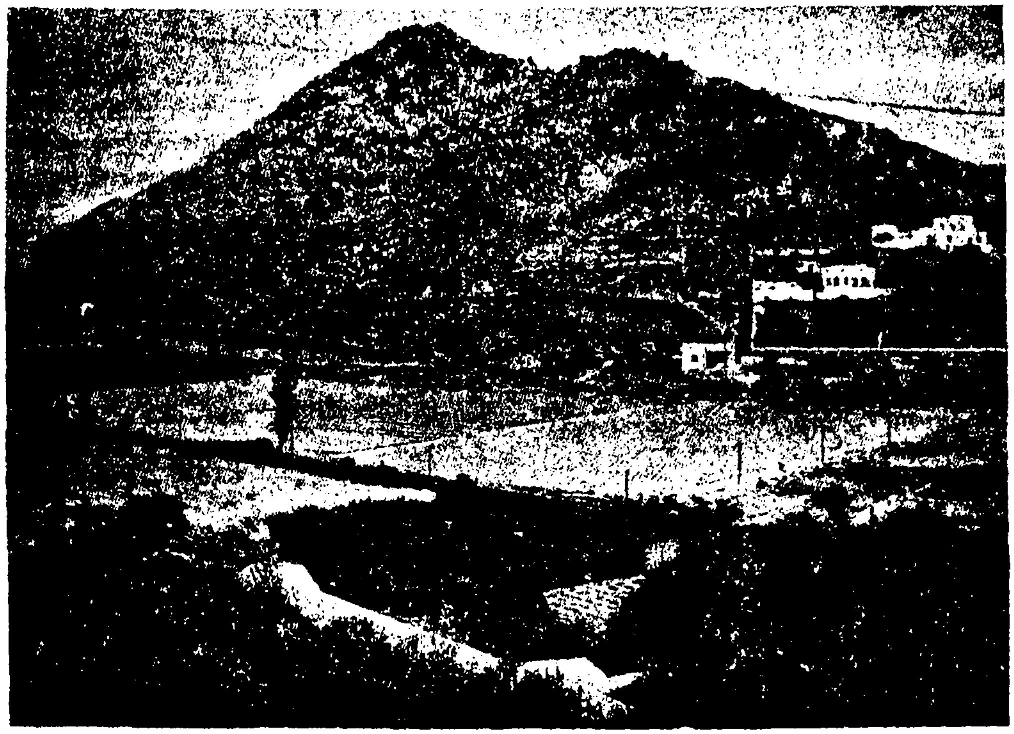


c. Aegina II

FIGURE 6. STILL ON THE ISLAND OF AEGINA, GREECE

## STILL ON THE ISLAND OF PATMOS, GREECE

| | |
|---|---|
| Internal size: | 71 double bays, each 10 ft wide x 131 ft long; 93,000-$ft^2$ evaporating area. |
| External size: | Three groups, each approx. 328 ft wide x 132 ft long; 130,000 $ft^2$ overall. |
| Brine depth: | Approx. 0.8 in. |
| Cover: | Glass, 0.10 to 0.12 in. thick, 12 degree southward-facing slope, aluminum alloy supporting structure. |
| Vapor seals: | Plastic putty. |
| Distillate troughs: | Extruded aluminum, 1:1000 slope. |
| Basin liner: | 1/32-in.-thick black butyl rubber sheet. |
| Walls and curbs: | Concrete beams. |
| Other features: | PVC piping, valves, and fittings; polypropylene fittings inside still, rain collection (approx. 24 in./year), precut aluminum pieces, units completely emptied and refilled every 2 days in summer, and once a week in winter, settling tank and gravel filter for seawater. |
| Productivity: | Yearly average of 0.074 gal/$ft^2$-day predicted on basis of small experimental prototypes built on the island of Symi during 1965-1966. |
| Problems: | Weeds punctured butyl rubber liner, extensive damage caused by shifting of structures due to winter rains and non-use of still. |
| Dates: | July, 1967, to present (Rebuilt in 1969). |
| Note: | Similar designs on Islands of Kimolos (27,000-$ft^2$ evaporating area) and Nisiros (22,000-$ft^2$ evaporating area). A somewhat modified design is planned for Gwadar, Pakistan with an evaporating surface area of 191,000 $ft^2$ and an average output of 18,000 gpd (Delyannis, 137). |
| References: | Delyannis, 132, 133, 135, 136, 138; Anon., 27. |



a. Patmos (Ref. 135)

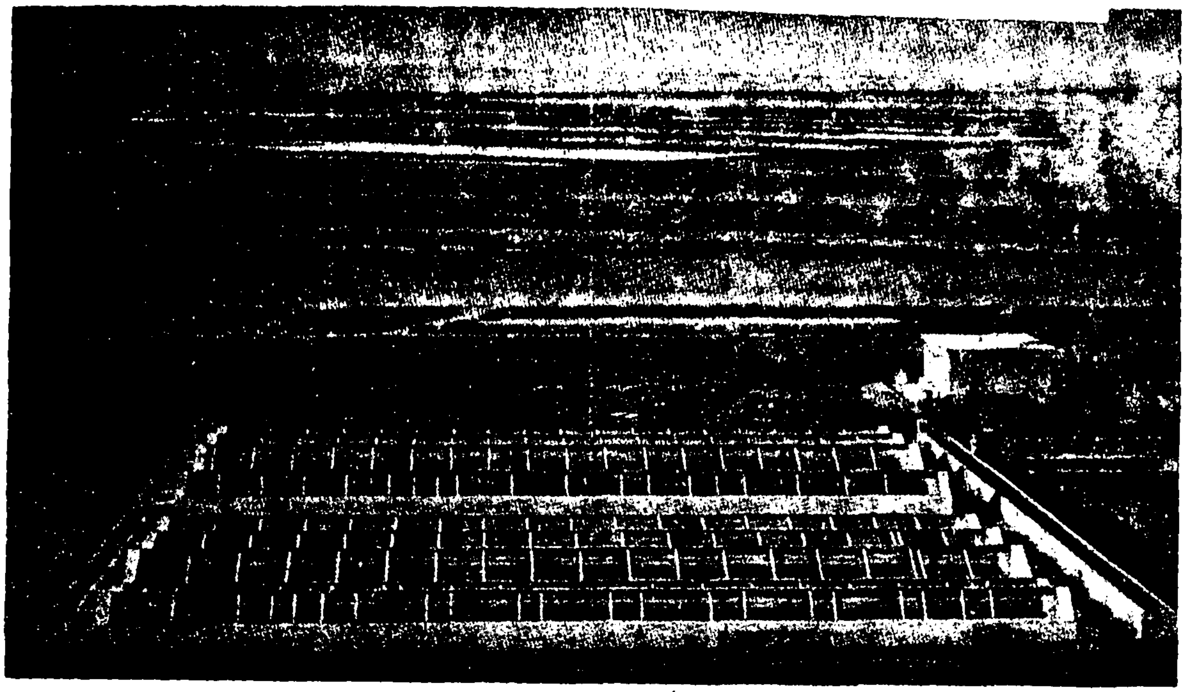
b. Nisiros

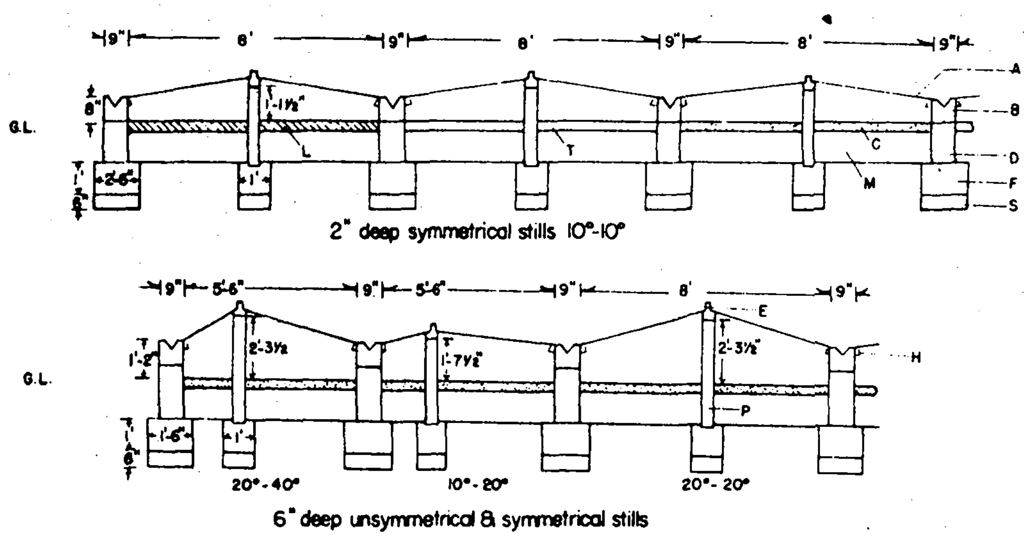
c. Design of Stills

FIGURE 7. STILLS ON ISLANDS OF PATMOS AND NISIROS, GREECE

## STILLS AT CENTRAL SALT AND MARINE CHEMICALS RESEARCH INST. (BHAVNAGAR, INDIA)

| | |
|---|---|
| Internal size: | 12 bays, 5 ft 6 in. or 8 ft wide x 55 ft long (two about 15 ft long); evaporating surface areas from 110 to 530 $ft^2$; approximately 4,060-$ft^2$ total evaporating surface area. |
| External size: | Not given, long dimensions East-West. |
| Brine depth: | 2-, 6-, and 12-in.-deep bays. |
| Cover: | Glass, 0.12-in. thick x 3 ft x 4 ft; symmetrical and unsymmetrical double-slopes, 10 to 40-degree slopes. |
| Vapor seals: | Sealing putty (Tarplastic), and a cotton adhesive tape. |
| Distillate troughs: | Aluminum. |
| Basin liner: | Concrete painted with black anticorrosive mastic paint (Tank Mastic), tar-gravel mixture, and stabilized-soil bottoms. |
| Walls and curbs: | Concrete, precast concrete beams and pillars. |
| Other features: | Rainwater troughs, continuous- or batch-feed technique, vapor tightness measured, feedwater treatment with copper sulfate and alum dosing, settling tank for sea water. |
| Productivity: | Average of 10 original bays 0.060 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day (Range 0.056 to 0.064 gal/$ft^2$-day), yearly average 0.054 gal/$ft^2$-day (220 gpd). |
| Problems: | Lower production of stabilized soil still, vapor leaks (vapor tightness 50 to 80 percent), distillate leaks, glass sagging with 10-degree cover slope, silt deposits, algae growth (Phormidium), deterioration of cotton adhesive tape in 1 year, stabilized soils swelled up and percolation occurred. |
| Dates: | October, 1965, to present. |
| References: | Datta, et al., 123, 124; Ahmed, et al., 35. |






A Glass sheet 1/8" thick
B Precast RCC channel
C Cement concrete painted black
D Brick masonary
E Precast R.C.C. beam
F Cement concrete
H Aluminum channel
L Stabilized soil
M Murram (Gravel)
P Precast RCC pillar
S Sand
T Tar gravel mixture

FIGURE 8. STILLS AT C. S. M. C. R. I. (BHAVNAGAR, INDIA)

## STILL AT NATIVIDAD, MEXICO* (SUNWATER COMPANY)

| | |
|---|---|
| Internal size: | Four trays, each 26 in. wide x 120 ft long; 1,040-$ft^2$ evaporating area. |
| External size: | Each tray approximately 2 ft 4 in. wide x 120 ft long. |
| Brine depth: | Approximately 1 in.; baffles (weirs) every 10 ft. |
| Cover: | Glass; 6-degree slope facing southward; vapor side of glass initially cleaned with fine sandpaper, scouring powder, wetting agent and ammonia. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Preformed grooves in aluminum tray, coated with silicone rubber. |
| Basin liner: | Silicone rubber coating on aluminum tray, black bottom; 1-1/2 inches of rock wool insulation. |
| Walls and curbs: | Prefabricated aluminum tray, supported and protected by concrete blocks. |
| Other features: | Prefabrication of tray, lightweight construction, 20-yr life estimated, gasoline engine drives pump for sea water, still can be allowed to go dry, back wall of tray reflects sunlight, auxilliaries sized to allow still expansion to 400 gal/day, batch fed each night. |
| Productivity: | Presently rated at 100 gal/day (0.10-gal/$ft^2$-day yearly average). |
| Problems: | Wind interfered with spreading of rock wool insulation, light weight trays susceptible to lifting by wind. |
| Dates: | March, 1969, to present. |
| References: | McCracken, 329, 330. |

*Village on island in Pacific, off the central coast of Baja California, Mexico.

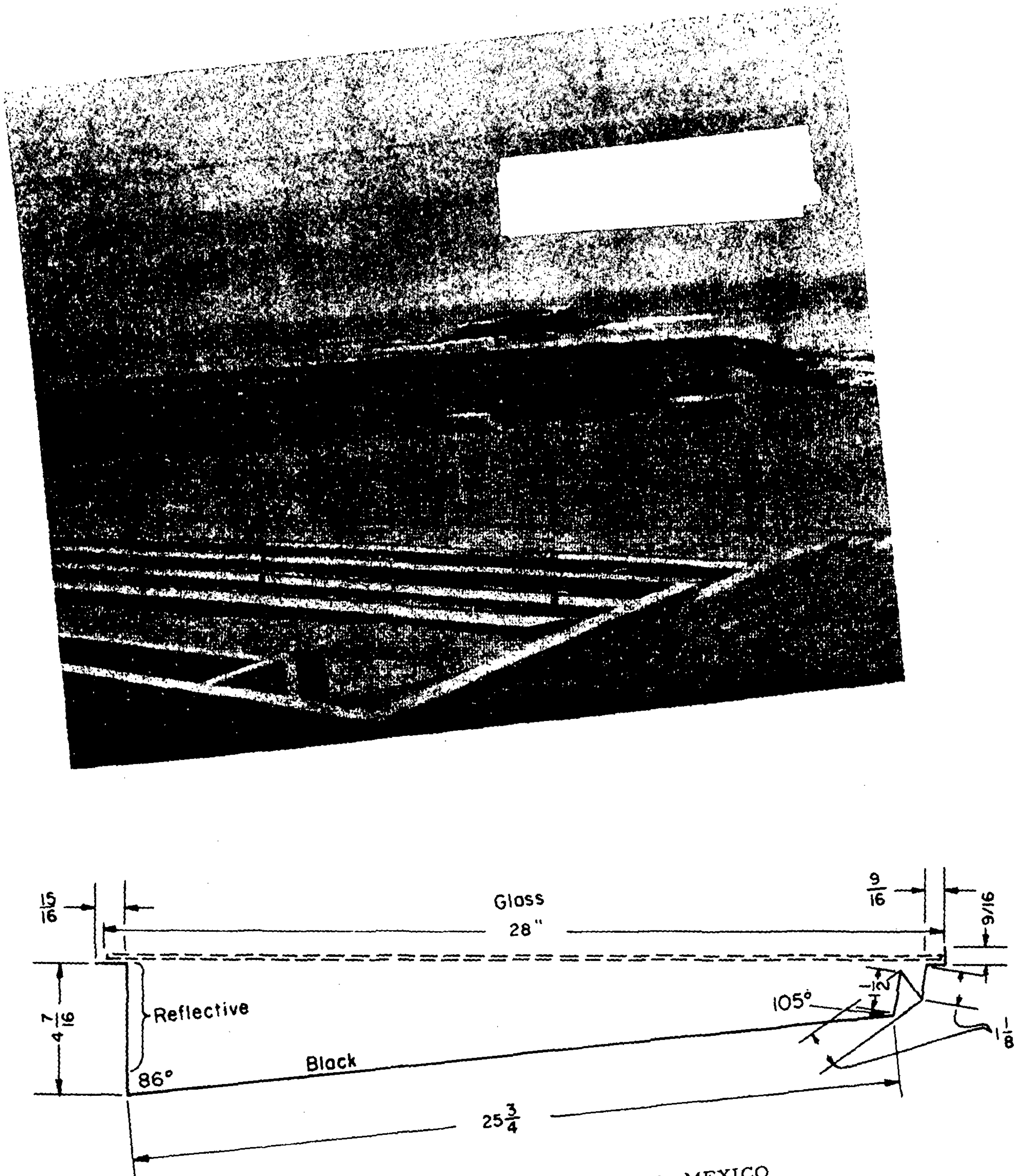
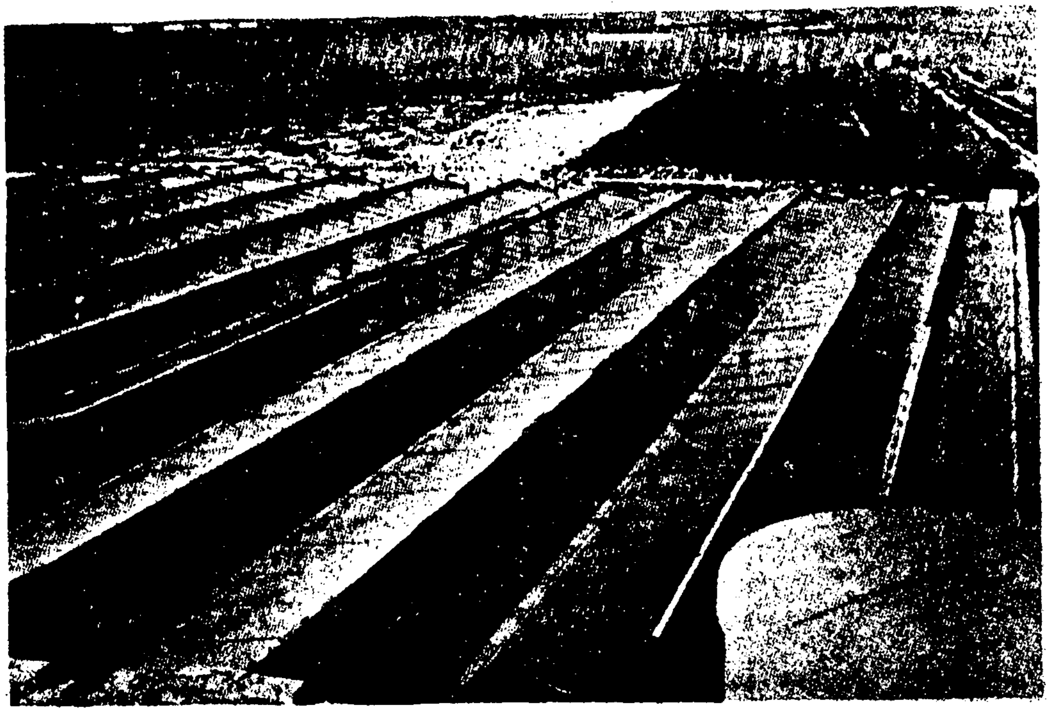



FIGURE 9. STILL AT NATIVIDAD, MEXICO

## STILL AT LAS MARINAS, SPAIN

| | |
|---|---|
| Internal size: | Approximately 92 ft wide x 102 ft long; 9,350-$ft^2$ basin area. |
| External size: | Approximately 95 ft wide x 105 ft long; 10,000 $ft^2$ overall. (Long dimension East-West). |
| Brine depth: | Approximately 4 inches average over basin. |
| Cover: | Glass sheets, 1/8 x 31 x 50 in., 10-degree slope, supported by plastic pieces in the valleys, overlapped "fish-scale" and side-by-side arrangements. |
| Vapor seals: | Asphaltic mastic caulking material, aluminum strips over valley spaces. |
| Distillate troughs: | Moulded concrete valley beams lined with various materials, including thin stainless steel, aluminum foil, black polyethylene, painted coatings, etc. |
| Basin liner: | Asphalt sheets 1/8 in. thick (heat sealed). |
| Walls and curbs: | Earth banks, concrete beams, hollow concrete blocks. |
| Other features: | Rainwater collection, distilled water is purified and mineralized, various materials tested, intermittent- or continuous-feed provisions, feedwater treatment with copper sulfate, 300 villagers served. |
| Productivity: | "Adjusted" output was 0.10 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day (Assuming all bays produced as the two best.). During first year of operation, actual production was 20.0 gal/$ft^2$-yr (0.055 gal/$ft^2$-day) and 2.92 gal/$ft^2$-yr of rainwater was collected. |
| Problems: | Distillate trough leakage with all materials except stainless steel and black polyethylene, glass breakage with overlapped panes due to use of only one support, vapor-seal joint failures between side-by-side panes, reevaporation of condensate, growth of algae before feedwater treatment began, rainwater leakage into condensate troughs, villagers inclined to use the brackish well water because it is much cheaper. |
| Dates: | March, 1966, to present. |
| Note: | Design improvements and modifications are discussed by Lof in Reference 318. |
| References: | Blanco, 76, 80; Lof, 318; Aguilar, 34. |





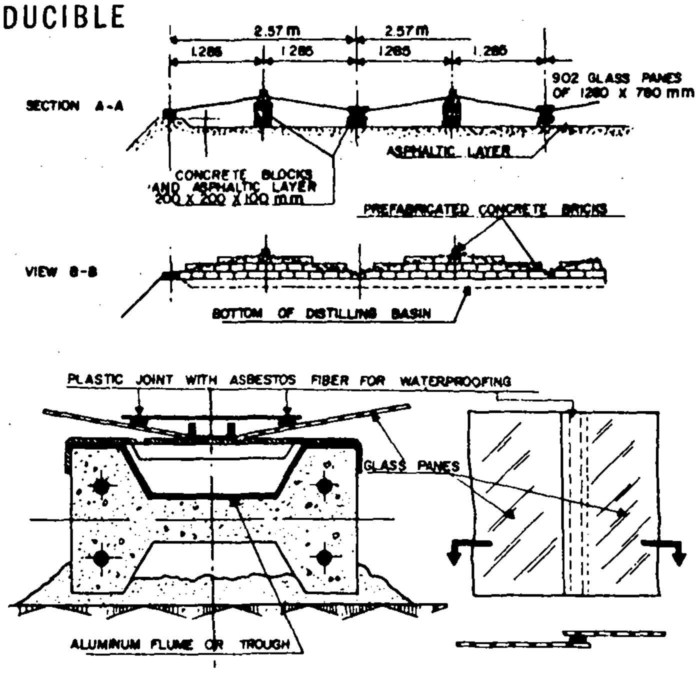
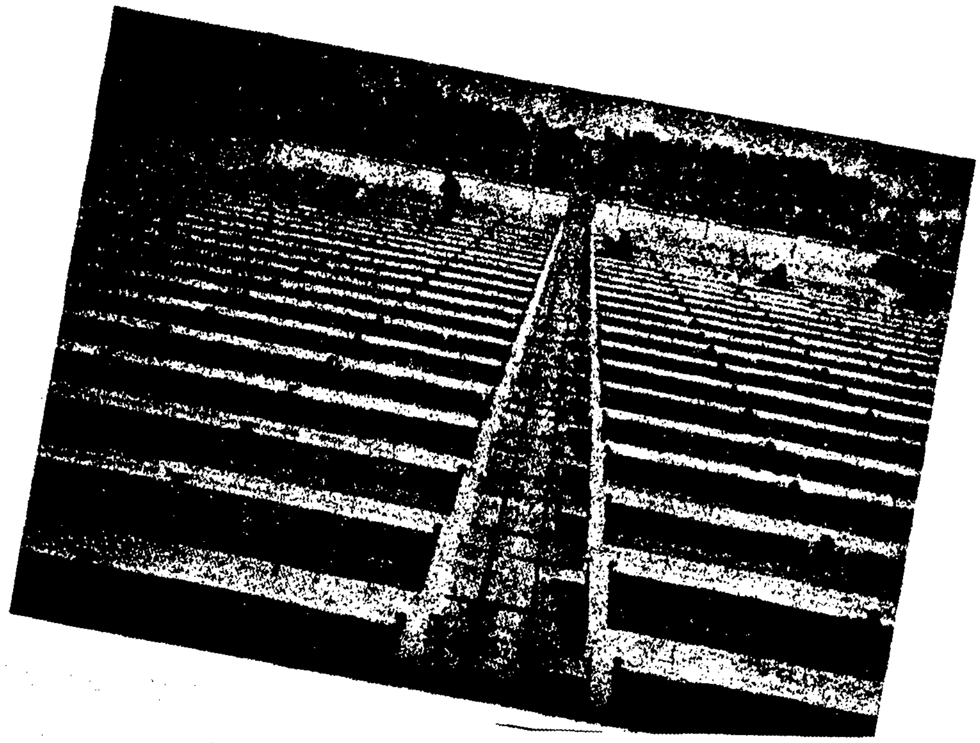



FIGURE 10. STILL AT LAS MARINAS, SPAIN

## STILL AT CHAKMOU, TUNISIA (TUNISIAN AEC)

| | |
|---|---|
| Internal size: | Approximately 50 bays, 4,730-$ft^2$ total evaporating area. |
| External size: | 6,450-$ft^2$ overall area. |
| Brine depth: | Approximately 1 in. |
| Cover: | Glass, 10-degree slope facing southward. |
| Vapor seals: | Rubber strips, plaster, and mastic. |
| Distillate troughs: | Moulded concrete curb. |
| Basin liner: | Concrete bottom, asphalt coated. |
| Walls and curbs: | Bricks and concrete. |
| Other features: | Provides drinking water for 500 persons, rainwater collected off still's concrete platform, brackish feedwater has 6 g/$\ell$ of salt, two parts of distilled water mixed with one part brackish water for drinking, 1/2 hr maintenance daily. |
| Productivity: | Varies between 53 and 210 gal/day (about 0.01 to 0.04 gal/$ft^2$-day). |
| Problems: | Cracks in base and walls leak brine and vapor (performance should be tripled after repairs are made), clogging of feedwater pipes, dust must be cleaned from glass after dust storms, every 2 weeks calcium sulfate deposits and a floating carbonate film must be cleaned from bays. |
| Dates: | Early 1967 to present. |
| Note: | The construction of many similar stills is planned. |
| References: | Tunisian AEC, 454, 455. |



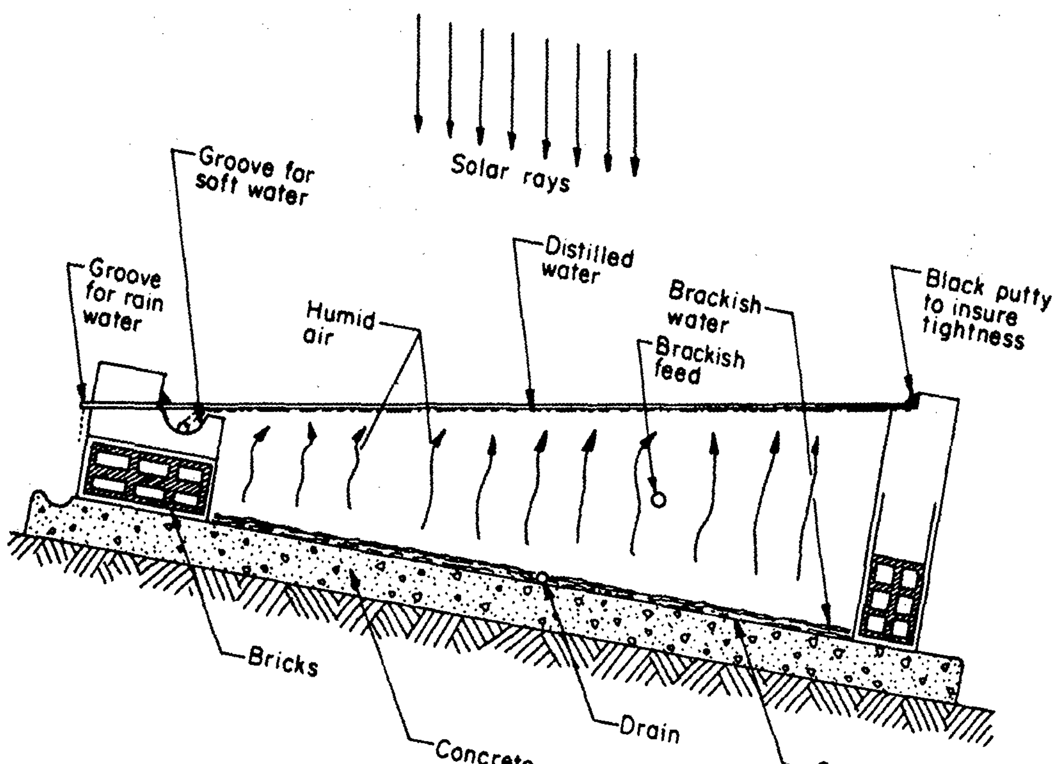



FIGURE 11. STILL AT CHAKMOU, TUNISIA

## STILL AT MAHDIA (ESSAAD), TUNISIA (TUNISIAN AEC)

| | |
|---|---|
| Internal size: | Individual bays; 14,000-$ft^2$ total evaporating surface area. |
| External size: | 30,000-$ft^2$ overall. |
| Brine depth: | Approximately 1 in. |
| Cover: | Glass, 10-degree slope facing southward. |
| Vapor seals: | Black putty (mastic) or black plastic sealant ("Igass"). |
| Distillate troughs: | Moulded in concrete curb. |
| Basin liner: | Concrete, asphalt coated. |
| Walls and curbs: | Bricks and concrete. |
| Other features: | Provides drinking water for 2,000 persons, brackish water preheated, salinity of feedwater 9 g/ℓ, distillate can be mixed with brackish water to increase amount of potable water. |
| Productivity: | Up to about 0.12 gal/$ft^2$-day in summer, approximately 0.04 gal/$ft^2$-day in winter. |
| Problems: | None reported. |
| Dates: | Early 1968 to present. |
| Note: | The construction of many similar stills is planned. |
| References: | Tunisian AEC, 454, 455. |

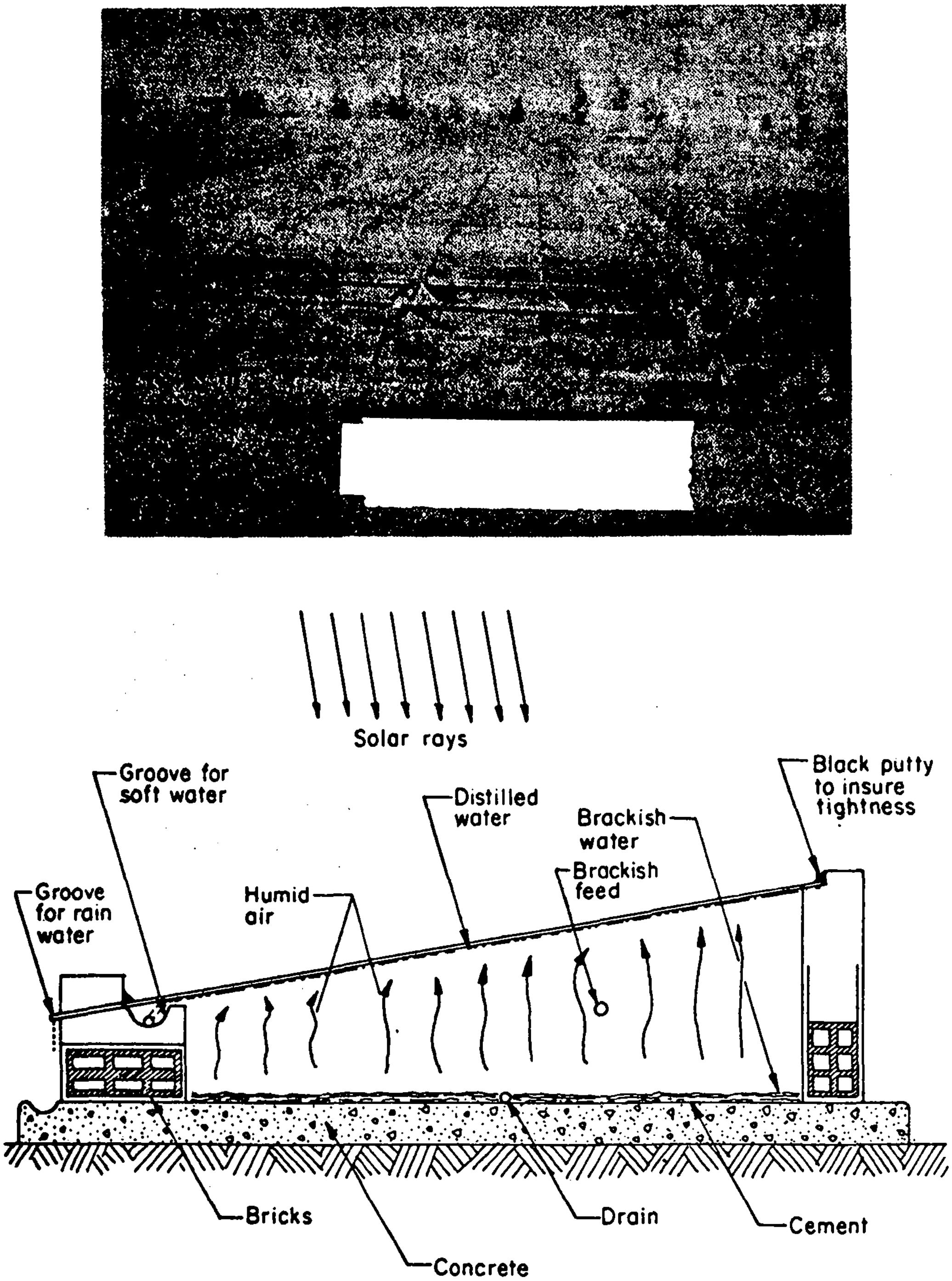
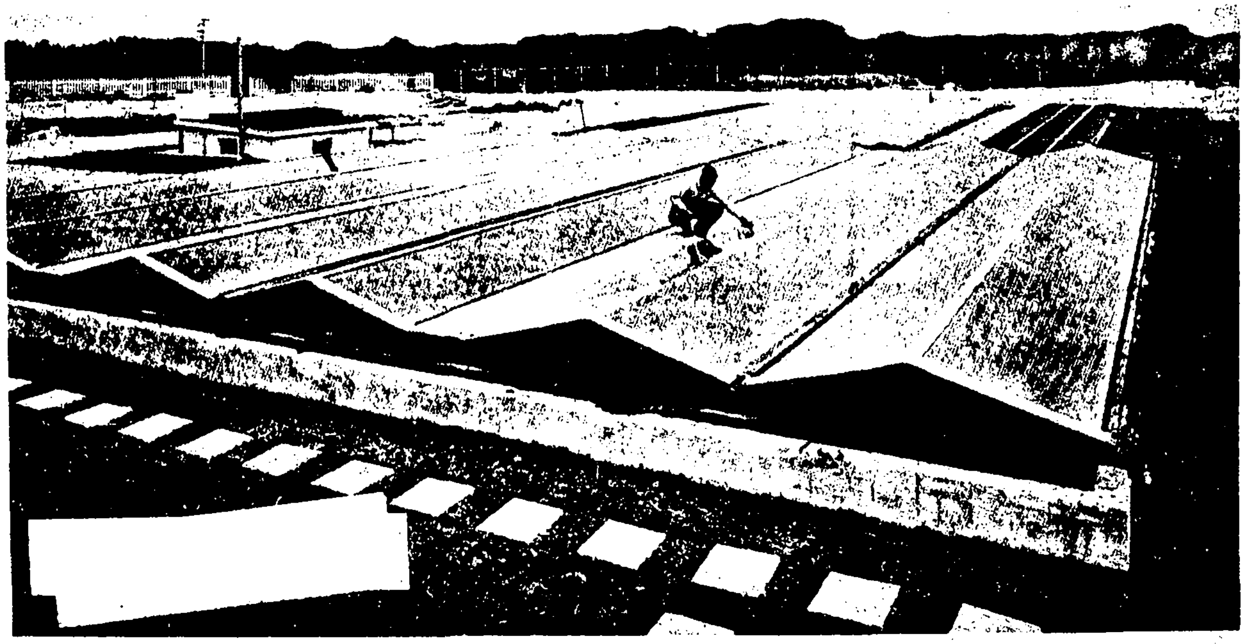



FIGURE 12. STILL AT MAHDIA, TUNISIA

## ORIGINAL DEEP-BASIN STILL AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| Internal size: | 6 bays, each 7 ft 10 in. x 52 ft; 2,450-ft$^2$ basin area. |
| External size: | 55 x 56 ft; 3,070-ft$^2$ overall. |
| Brine depth: | 7 to 12 in. |
| Cover: | Glass panes, 3/16 and 1/8-in. thick x 4 ft x 4 ft, 15-degree slope. |
| Vapor seals: | Extruded-neoprene channels and pressure-sensitive tape. |
| Distillate troughs: | Aluminum initially, then copper; 0.028 in./ft slope. |
| Basin liner: | Asphalt mats (1/2 in. thick), mopped with hot asphalt; not insulated. |
| Walls and curbs: | Concrete blocks, precast concrete beams, redwood framing. |
| Other features: | Perimeter insulation, feedwater heat exchanger using distillate and brine, soil sterilized with weed killer, peak output at 6 p.m., copper sulfate feedwater treatment for algae, three pairs of interconnected bays. |
| Productivity: | 0.08 gal/ft$^2$-day at 2,000 Btu/ft$^2$-day. |
| Problems: | Leaks developed in basin, aluminum troughs, and neoprene seals; algae and bacterial slime grew in basins. |
| Dates: | January, 1959, to June, 1965. |
| References: | Battelle, 52. |



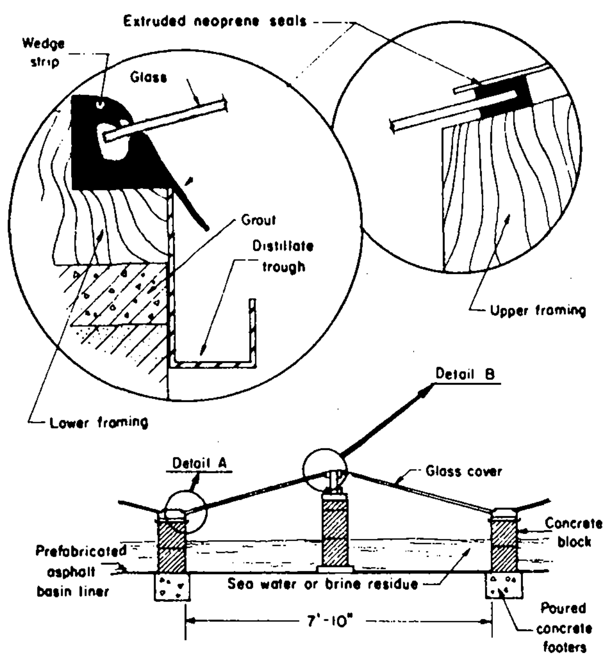



FIGURE 13. ORIGINAL DEEP-BASIN STILL AT DAYTONA BEACH, FLORIDA

## SECOND DEEP-BASIN STILL AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| Internal size: | One large basin, 47.0 ft x 56.5 ft; 2,650-$ft^2$ basin area. |
| External size: | 56 ft wide x 64 ft long, 3,580 $ft^2$ overall. |
| Brine depth: | 2 to 12 in. |
| Cover: | Glass panes, 1/8 in. and 1/10 in. x 4 ft x 4 ft, 10-degree slope. |
| Vapor seals: | Asphaltic cement and butyl rubber caulking. |
| Distillate troughs: | Originally copper strips (0.005 in. thick), later stainless steel (0.004 in. thick). |
| Basin liner: | Prefabricated asphalt mats (1/4 in. thick), hot-mopped asphalt, not insulated. |
| Walls and curbs: | Earth dikes, concrete blocks, precast concrete beams. |
| Other features: | Filter for feedwater, soil sterilized with weed killer. |
| Productivity: | 0.08 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| Problems: | Distillate leaks, algae and bacterial slime growth, shifting of concrete pedestals. |
| Dates: | April, 1961, to May, 1965. |
| References: | Battelle, 54, 55. |

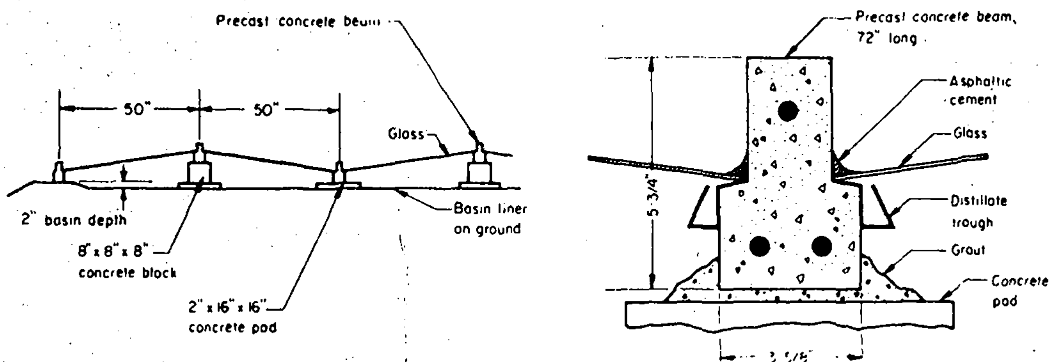



FIGURE 14. SECOND DEEP-BASIN STILL AT DAYTONA BEACH, FLORIDA

## LARGE INFLATED, PLASTIC STILL AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| Internal size: | 15 bays, each 2 ft 6 in. wide x 62 ft 4 in.; 2,330-$ft^2$ basin area. |
| External size: | 49 ft 9 in. wide x 63 ft 5 in. long; 3,160 $ft^2$ overall. |
| Brine depth: | 1-1/2 to 4 in. |
| Cover: | 5-mil Weatherable Mylar film (nonwettable), 1/4-in.-water inflation pressure. |
| Vapor seals: | Extruded neoprene grommets. |
| Distillate troughs: | Contoured curbs, Mylar lined, 0.095 in./ft slope. |
| Basin liner: | 4-mil polyethylene ground sheet, 8-mil black polyethylene pan sheet, 2-in. bottom and 1/2-in. side insulation. |
| Walls and curbs: | Concrete. |
| Other features: | Floating black Orlon wick, blower required, soil sterilized with weed killer, peak output at 1 p.m. |
| Productivity: | 0.06 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day (one nonleaking bay had 0.08 gal/$ft^2$-day). |
| Problems: | Distillate leaks, loss of electric power during hurricane resulted in extensive damage, rain sometimes collapsed covers, burnout of pan sheet at dry spots. |
| Dates: | January, 1959, to September, 1960. |
| Note: | Design shown is a modification of an original design by DuPont. |
| References: | Battelle, 52, 54. |

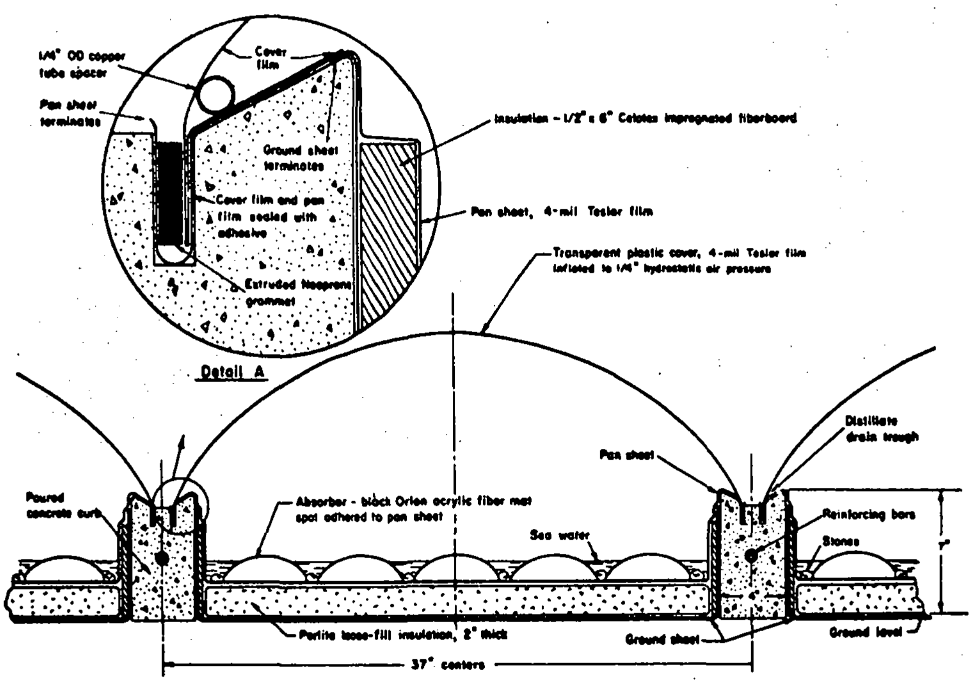



FIGURE 15. LARGE INFLATED, PLASTIC STILL AT DAYTONA BEACH, FLORIDA

## CHURCH WORLD SERVICE STILL AT DAYTONA BEACH, FLORIDA (AQUA-SOL, INC.)

| | |
|---|---|
| Internal size: | 2 bays, each 8 ft wide x 100 ft long; 1,600-$ft^2$ basin. |
| External size: | Approximately 17 ft wide x 101 ft long; 1,720 $ft^2$ overall. |
| Brine depth: | 1 in. |
| Cover: | Inflated Tedlar (wettable), held in place by aluminum angles nailed through the film to the curbs. |
| Vapor seals: | Heat-sealed seams, gummed-rubber strips along edges. |
| Distillate troughs: | Galvanized steel. |
| Basin liner: | Originally black polyethylene, then 30-mil butyl rubber; 1-in. layer of sawdust insulation. |
| Walls and curbs: | Wood beams. |
| Other features: | Blower required for inflation. |
| Productivity: | 0.13 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| Problems: | Burnout of original polyethylene pan sheets, collapse of covers by heavy rains, tearing and pulling loose of covers by high winds. |
| Dates: | July, 1963, to September, 1964. |
| Note: | This installation was a prototype of the still built on the Greek island of Symi. |
| References: | Battelle, 55. |

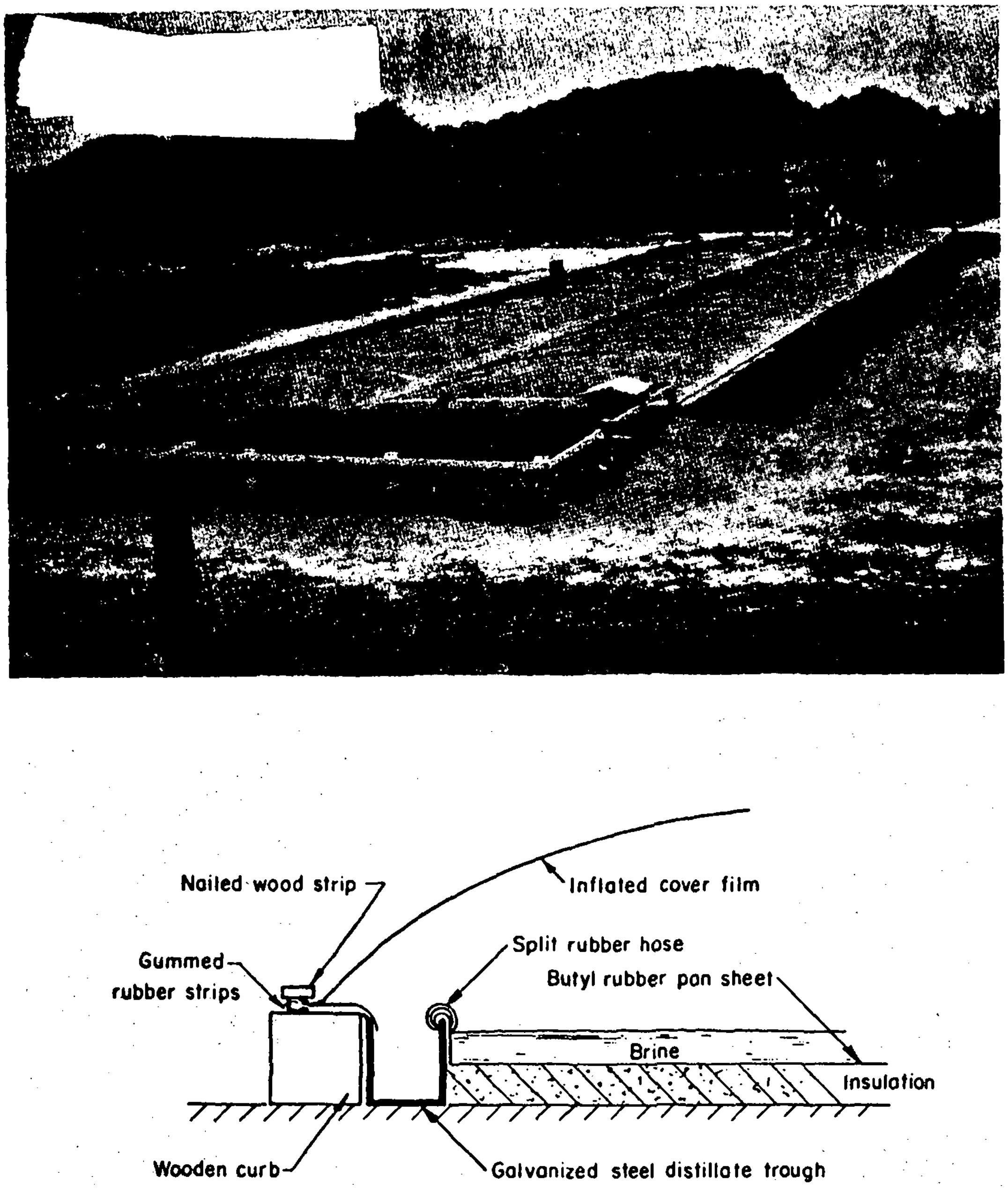
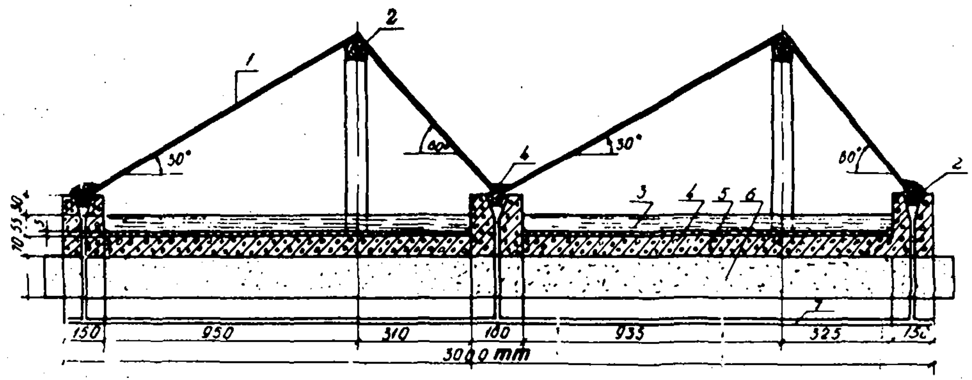



FIGURE 16. CHURCH WORLD SERVICE STILL AT DAYTONA BEACH, FLORIDA

## STILL AT BAKHARDEN, TURKMENIA, U.S.S.R.

| | |
|---|---|
| Internal size: | Approx. 28 bays, 49.7 in. wide x 55 ft long; 6,450-$ft^2$ total basin area. (To be enlarged to 25,800 $ft^2$ after detailed study). |
| External size: | Internal size plus curbs and about 2-ft walkways between bays. |
| Brine depth: | Approximately 2 in. |
| Cover: | Glass, 0.12 in. (3mm) thick, 30-degree slope on south side, 60-degree on north side, wooden ridge pole. |
| Vapor seals: | Waterproof mastic (experimental stills used an adhesive prepared by mixing natural drying oil and Portland cement). |
| Distillate troughs: | Grooves moulded in concrete curbs. |
| Basin liner: | Reinforced concrete and waterproof mastic, sand layer underneath. |
| Walls and curbs: | Reinforced concrete. |
| Other features: | Rainfall collected (4-5 in./yr), auxilliaries sized for 25,800-$ft^2$ still, distillate mixed with brackish water for watering sheep, electrical pumping power provided by solar cells, two wells, two distillate reservoirs, one mixed-water reservoir. |
| Productivity: | 0.067 gal/$ft^2$-day (yearly average anticipated); (0.117 gal/$ft^2$-day in June, 0.017 gal/$ft^2$-day in December). |
| Problems: | Low winter production, salt deposits on basin liners of experimental stills. |
| Dates: | April, 1969, to present. |
| Note: | This design resulted from tests during 1961-1964 with five 11-$ft^2$ stills at the experimental station of the Physics and Engineering Institute of Turkemenian S.S.R. Academy of Sciences. |
| References: | Baum, 63, 69; Bairamov, 45. |

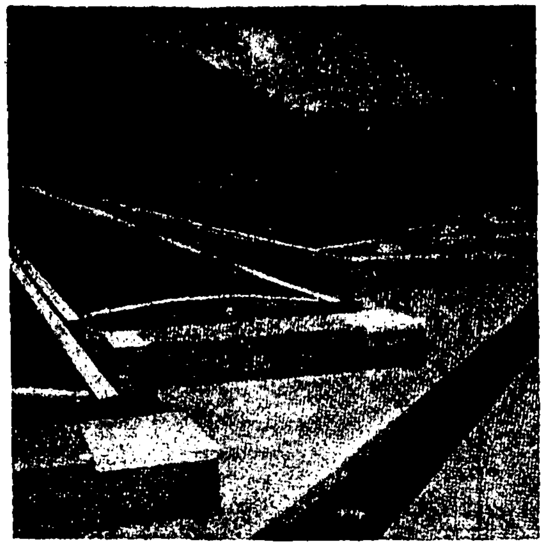


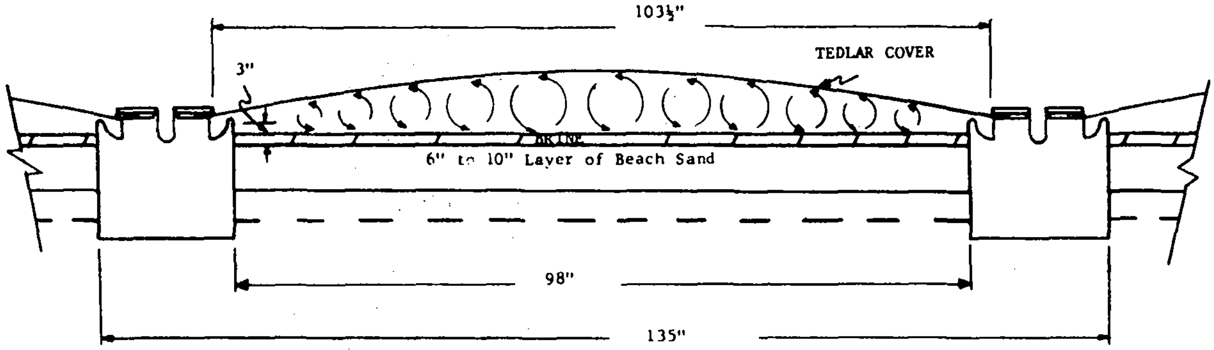

1. Glass, 3 mm
2. Light wooden beam
3. Salt water
4. Waterproof mastic "TSZOL"
5. Reinforced concrete
6. Sand layer
7. Piped for condensate collection
8. Water supply
9. Discharge of brine
10. Reinforced concrete pillars (posts).

FIGURE 17. STILL AT BAKHARDEN, TURKMENIA

## STILL ON PETIT ST. VINCENT ISLAND, WEST INDIES (BRACE EXPERIMENT STATION, MCGILL UNIV.)

| | |
|---|---|
| Internal size: | 15 bays, each 8 ft 2 in. wide x 150 ft long; approx. 18,400-$ft^2$ evaporating area (19,300-$ft^2$ projected cover area). |
| External size: | Each bay about 10 ft x 150 ft; each bay offset 8 ft at each end; long axis North-South. |
| Brine depth: | Approximately 2 in.; weirs at 4 to 7-ft intervals; about 29-in. drop in 150 ft. |
| Cover: | Inflated 4-mil "mettabraided" Tedlar (wettable), 0.25-in.-water inflation pressure. |
| Vapor seals: | Plastic electrical conduits clamped between hold-down strips and concrete curbs, with Tedlar and butyl rubber films between; butyl rubber adhesive tape. |
| Distillate troughs: | Grooves in concrete curbs lined with basin liner; approximately 1 in./5 ft slope. |
| Basin liner: | 30-mil black butyl rubber sheet; sand layer (6 to 10 in.); polyethylene ground sheet used on several bays to protect against ground water; some bays insulated; floating black Orlon wick. |
| Walls and curbs: | Concrete (not reinforced). |
| Other features: | Originally windmill-generated electric power to charge 12-volt batteries to run blowers (now a-c and d-c operation provided), floating Orlon mats used, polyethylene ground sheet under sand base layer on several bays, rainfall collection (35 to 45 in./year), water output used for hotel, soil treated with weed killer, perforated plastic pipe for feedwater inlet, plastic pipe for distillate drain, batch feed every 2 days, still located on leeward side of island. |
| Productivity: | About 0.07 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day (about 0.08 gal/$ft^2$-day for best bay); yearly average about 0.07 gal/$ft^2$-day (1968). |
| Problems: | Low blower output occasionally with battery power, scale encrustation on floating mats, sediment on basin liner, heavy rains collapsed covers before design modification provided adequate drainage, some vapor and air leaks, clamping system difficulties, chlorination of water in storage reservoirs deemed necessary because of rainwater collection. |
| Dates: | February, 1967, to present. |
| References: | Lawand, 290. |





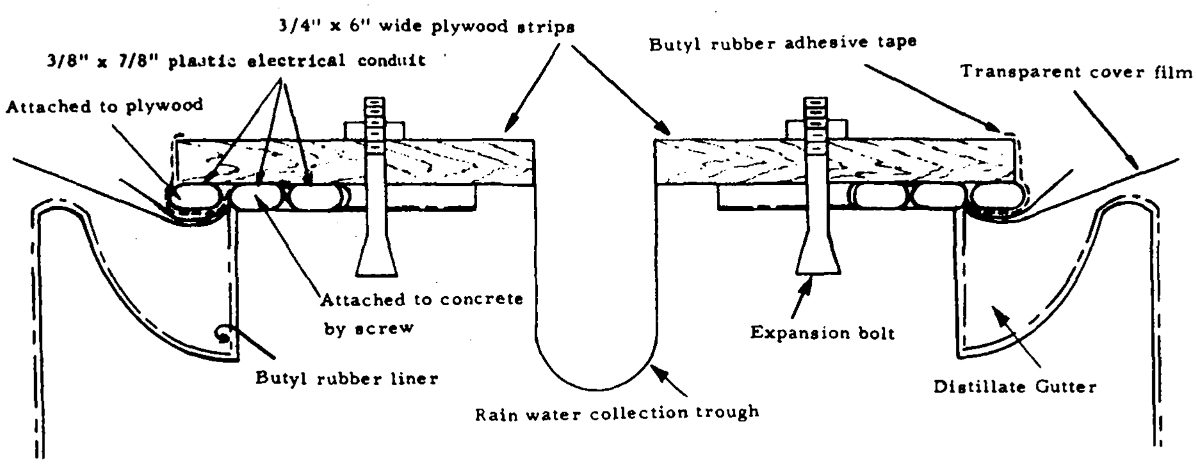
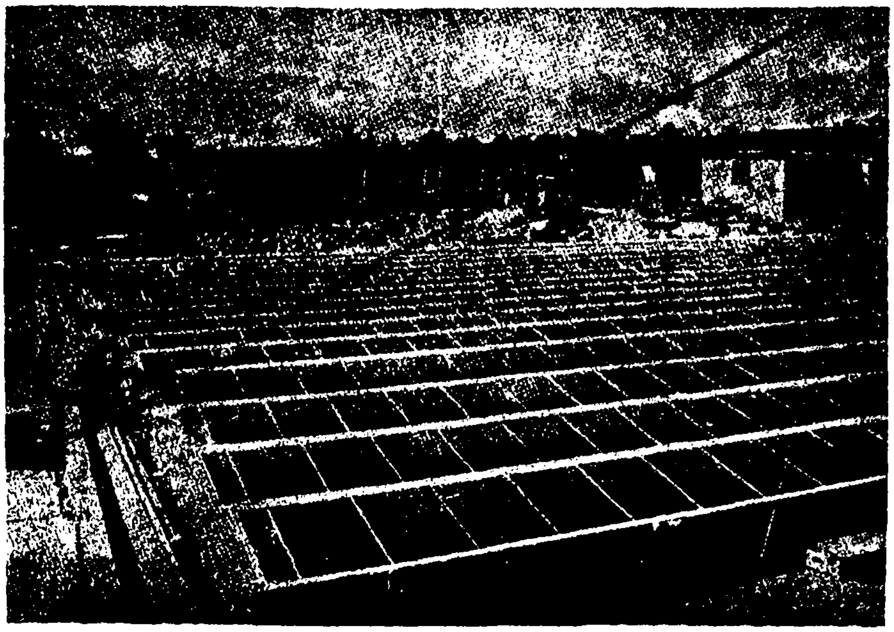




FIGURE 18. STILL ON PETIT ST. VINCENT ISLAND

## STILL ON THE ISLAND OF HAITI, WEST INDIES (BRACE EXPERIMENT STATION, MCGILL UNIV.)

| | |
|---|---|
| **Internal size:** | 15 bays, 2 ft 2 in. wide x 73 ft long; 2,400-$ft^2$ evaporating surface area. |
| **External size:** | Approximately 48 ft wide x 76 ft long. |
| **Brine depth:** | 1-1/2 to 2 in. between weirs, located 6 ft apart. |
| **Cover:** | Designed for glass panes, 18 x 30 in. (single strength, 18 oz) 15-degree slope, facing southward. |
| **Vapor seals:** | Silicone rubber sealant with epoxy paint under glass on curb walls for a bonding surface. |
| **Distillate troughs:** | Grooves in concrete curbs, coated with a waterproof layer of plaster; 1:75 slope. |
| **Basin liner:** | Butyl rubber. |
| **Walls and curbs:** | Reinforced concrete curbs, concrete blocks. |
| **Other features:** | Windpowered Savonius rotor for pumping sea water or brackish well water, rain and brine gutters, separate rainwater and distillate tanks (14 to 20 in. rain per year), ground treated with herbicide and sea water, inside of north wall painted to reflect sunlight, observation ports at both ends of each bay (left open if bays are dry or severe storms threaten), bays filled and flushed early each morning, solar still will supplement existing rainfall-collection system, PVC pipe for sea water, ABS pipe for distillate and brine. |
| **Productivity:** | Plant rated for 200-gpd annual average (0.083 gal/$ft^2$-day). |
| **Problems:** | Original order of glass panes broken during shipment. |
| **Dates:** | Approx. June, 1969, to present. |
| **References:** | Lawand, 291, 292. |



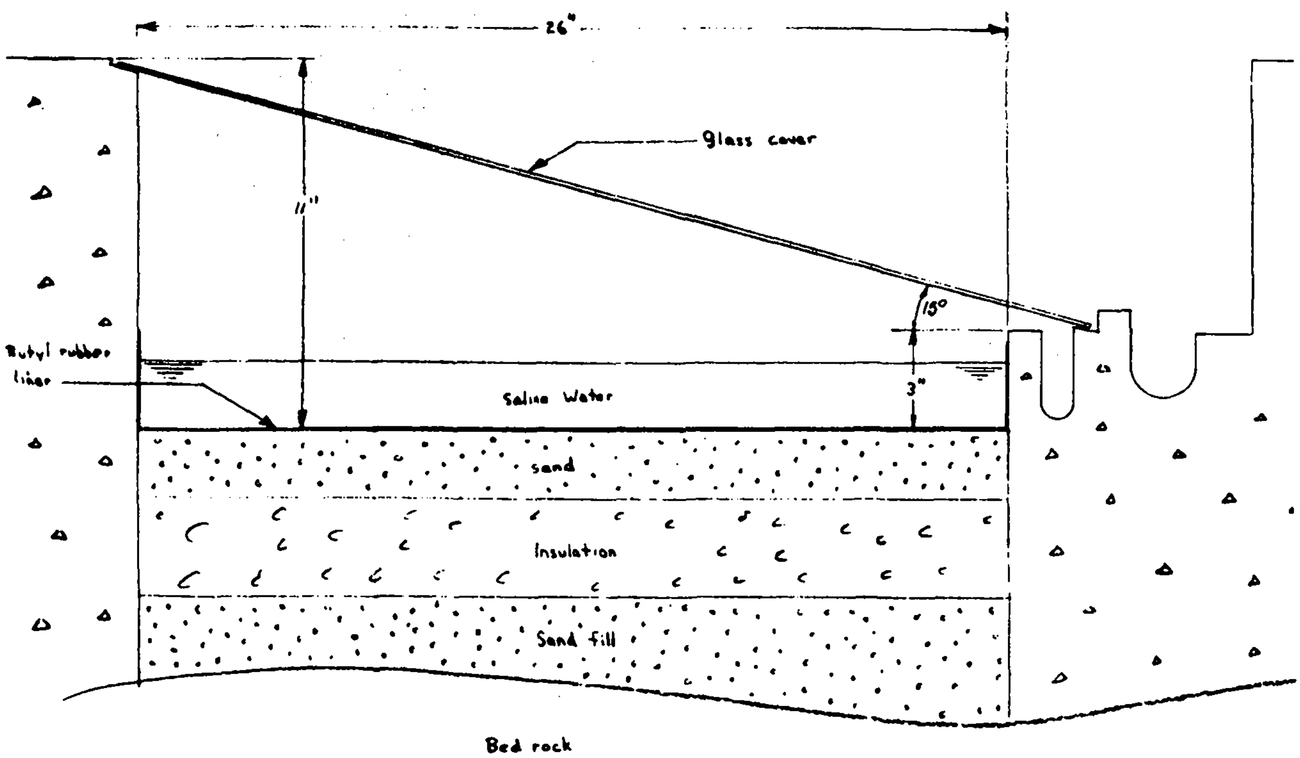



FIGURE 19. STILL ON THE ISLAND OF HAITI

## SECTION 4. SOLAR DISTILLATION TECHNOLOGY

A simple basin-type solar still consists essentially of a shallow basin of saline water covered with a transparent roof. The basin is lined with a black, water-impervious material such as butyl rubber. All joints in the cover and sides of the still should be reasonably well sealed to prevent vapor leakage. The cover must have a proper slope to allow the condensed vapor on the underside of the cover to drain into suitably arranged troughs to collect the distillate.

The solar radiation that penetrates through the cover and brine layer to the bottom of the blackened basin and is absorbed provides the energy to heat the saline water. When the brine reaches a temperature 20 to 30 F above atmospheric temperature, evaporation will proceed at a usable rate. The resulting mixture of water vapor and air circulates inside the enclosure, and condensation occurs as the vapor comes into contact with the cooler cover. The heat of condensation is given up to the cover and is dissipated to the atmosphere by radiation and convection. The condensate flows to the troughs and drains to a storage reservoir.

The brine in the basin can be maintained at a relatively constant level by either continuous or batch addition of saline water and withdrawal of brine. The amount of distilled water produced in a typical well-designed still is nominally 0.1 gpd for each $ft^2$ of basin area when the solar radiation level is about 2000 $Btu/ft^2$ - day.

The feedwater may require treatment to prevent the growth of algae or slime in the basin. The basin may also require cleaning periodically if substantial mineral deposits occur on the basin liner. The distillate can be treated or blended with feedwater to improve its taste.

### Fundamental Studies

Several thermodynamic analyses of solar stills have been reported which further the basic understanding of solar-still technology. The resulting knowledge of the effects of many variables, together with the availability of data from recent experimental investigations, has enabled the design of improved stills. Today only a few aspects lack detailed data, the most notable of which are vapor leakage and heat-transfer losses around the edges of solar stills.

The various fundamental studies are discussed below under the subjects listed. In chronological order, the principal investigators whose analyses have been presented in the literature are as follows:

Telkes (427, 430, 432, 435, 436).
Lof (301, 302, 304, 309, 310).
Brdlik (98).
Bloemer, et al. (52, 54, 55, 85, 86, 90).
Grune, et al. (192, 194, 197).
Howe and MacLeod (240).
Garrett and Farber (175).
Gomella (185).
Baum (60, 62, 65).
Dunkle (144).
MacLeod and McCracken (324).
Bairamov (45).
Sharafi (410).
Dzhubalieva (147, 148).
Datta, et al. (123).
Martens (333).
Masson (335).
Morse and Read (345, 346, 350).
Lawand (290, 294).
Cooper (110, 111).

## Energy and Mass Balances

Figure 20 shows the major energy transfer paths in a basin-type still.

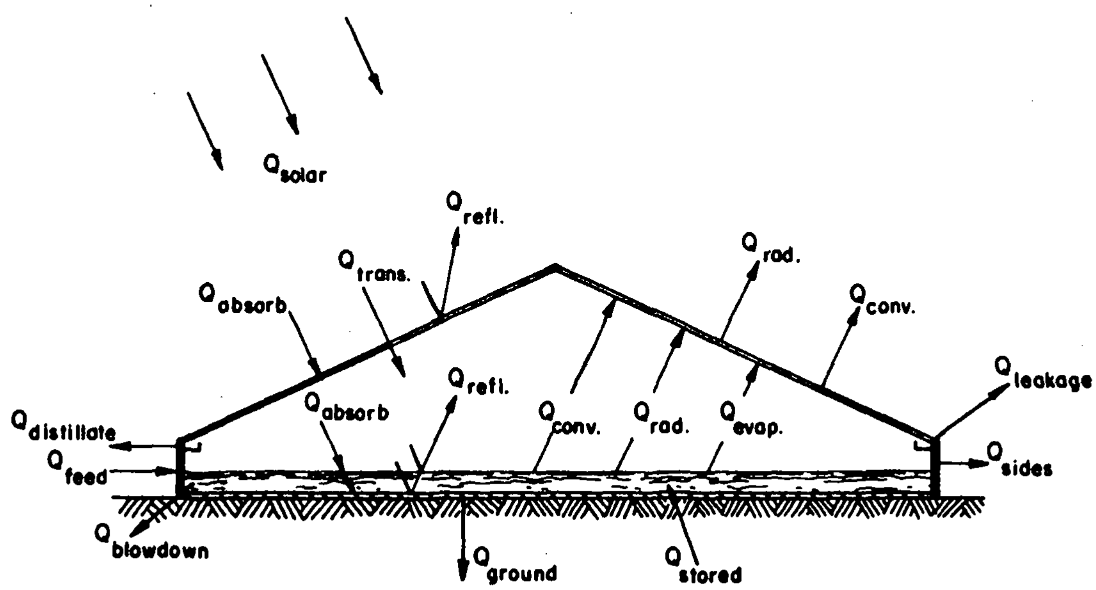



FIGURE 20. MAJOR ENERGY-TRANSFER PATHS IN A BASIN-TYPE SOLAR STILL

As depicted, small portions of the direct and diffuse solar radiation reaching the still are reflected and absorbed by the cover. A smaller portion of it is reflected from the water surface and basin bottom. Also, part of it (the longest wavelength portion) is absorbed in the water. The rest is absorbed on the basin bottom. Most of the radiation incident on the basin bottom is transferred to the saline water, while small portions may be lost by conduction to the ground and through the sides of the distiller. The heated saline water then loses energy by several processes. Infrared radiation from the water surface is either absorbed or partly transmitted by the cover depending on the properties of the cover. Glass, for example, is opaque to longwave radiation and completely absorbs that emitted from the water surface. Plastic films are more transparent to infrared radiation but the thin film of condensate absorbs most of the radiation emitted from brine (Erb, 165; Lawand, 290). Energy is also transferred from the water to the cover by convection currents within the still and by alternate vaporization and condensation of water. It is this last energy transfer, the latent heat of the water vapor transferred from the basin to the cover, that is essential for the system to produce fresh water.

The energy transferred to the cover is conducted through it and dissipated to the atmosphere by radiation and convection. There may also be some sensible heat supplied to the still in the feedwater and some sensible heat lost in the condensate and brine blowdown. Any leakage of vapor or liquid from the still involves additional thermal loss. Finally, because solar-radiation intensity and other factors are varying over even short time intervals, there is a continual change in the enthalpy of the still and its contents.

Mass-flows balances for solar stills entail accounting for the quantity of feedwater fed into the stills and the quantity of water leaving the still which includes brine blowdown, brine leakage, distillate collected, distillate leakage, and water-vapor loss. Internal mass-flow balances may also include any refluxing of distillate from the cover to the basin and re-evaporation or spillage of distillate from the collection troughs.

The investigators listed earlier in this Section have analyzed the energy and mass-transfer balances for several types of solar stills: namely, glass-covered trays (Telkes, Brdlik, Howe, Baum, Dunkle, MacLeod, Bairamov), basins (Lof, Bloemer, Datta), and bays (Baum, Morse, Cooper); plastic-covered bay (Lawand); tilted wick (Telkes); and external condensation stills (Grune, Sharafi).

Computers have also been used to assist in determining the effect of many design and operating variables on productivity (Lof, 309, 310; Baum, 60, 65; Bloemer, et al., 55, 85, 86; Morse, 346, 350; Cooper, 110, 111). These variables include solar-radiation intensity, wind velocity, ambient temperature, brine depth, basin insulation, and cover slope and transmissivity.

Some investigators constructed laboratory stills to study the effects of variables under carefully controlled conditions using electric heating beneath the basin liner to simulate the absorption of solar energy (Telkes, 430; Grune, 197; Bloemer, 55, 85, 90; Baum, 62). One laboratory still used a wind tunnel and models to investigate the pressure distribution around solar stills and the effect this would have on leaking joints (Dzhubalieva, 147).

The assumptions usually made when calculating energy balances in a solar still are that there are no temperature gradients in the cover or in the basin and that there is no vapor leakage. This latter assumption may be correct for small units but is not usually true for large installations operated for any length of time. Vapor leakage is discussed more fully under the subject of wind velocity.

## Energy Distributions

Table 6 gives a breakdown of most of the energy distributions measured within various basin-type stills and reported in the literature. Although percentages of the energy of evaporation (i.e., the operating efficiency) shows general agreement, there are sometimes quite wide differences in the distribution of the other energy quantities. Often this is caused when different authors assign some of the miscellaneous losses to different categories such as unaccounted for, reflected, or ground losses. Some of these differences are produced by the features of the various designs. For example, the ratio of still perimeter to evaporating area will affect the amount of edge losses (compare Bloemer and Lof with Morse and Cooper). Also, the plastic-covered still with a floating wick (Lawand) would be expected to have different amounts of reflected energy from the cover and brine surfaces. All of the efficiencies greater than 50 percent were obtained with relatively high constant heat input rates. All lower values represent daily average efficiencies.

Usually the energy required for preheating of the saline supply to its evaporating temperature (typically between 110 and 150 F) is included in the quantity of energy assumed for evaporation. For example, to heat seawater (specific heat = 0.94 Btu/lb-F) from 75 to around 130 F requires approximately 50 Btu/lb, and to evaporate it at that temperature requires approximately 1020 Btu/lb. Thus, the usual amount of energy assumed for evaporation is 1070 Btu/lb.

TABLE 6. PERCENT ENERGY DISTRIBUTIONS IN BASIN-TYPE SOLAR STILLS

| Energy | Investigator (Reference Number): Telkes (430) | Telkes (433) | Telkes (436) | Lof (301) | Lof (302) | Lof (310) | Bloemer (52, 83) | Howe (240) | Baum (60) | Grune (197) | Datta (123) | Morse (345, 346) | Lawand (290) | Cooper (110) | Nominal Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Evaporation | 41 | 68 | 69 | 34 | 47 | 40.5 | 32 | 30 | 61 | 41.2 | 29.6 | 32.5 | 35.6 | 26.9 | 40 |
| Radiation reflected by cover | 8 | 8 | 15 | 15 | 13 | 11.8 | 12 | 41 | 17 | 14.2 | 43.6 | 8.1 | 6.5 | -- | 10 |
| Radiation absorbed by cover | | | | | -- | 4.4 | 10 | | | 6.7 | | 9.9 | -- | -- | 5 |
| Radiation reflected by liner | 4 | 4 | | 10 | 5 | -- | -- | | | 2.5 | -- | -- | 6.6[c] | -- | 5 |
| Energy radiated from glass | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | (60.8) | 35.1 | 22.0 | (70) |
| Energy convected from glass | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | | | 23.0 | |
| Brine preheating | -- | -- | -- | 10 | -- | -- | -- | 2 | -- | 3.2[b] | -- | -- | 1.6[b] | -- | --[d] |
| Radiation from brine | 10 | 10 | 8 | 10 | 23 | 16.9 | 25 | 12 | 13 | 12.2 | 15.2 | 18.3 | -- | 12.6 | 15 |
| Internal convection | 4 | 4 | 2 | 5 | 11 | 8.4 | 6 | 3 | 2 | 7.5 | 5.9 | | -- | 4.1 | 5 |
| Edge losses | 33 | 6 | 6 | -- | -- | 3.5 | 2 | 3 | -- | 6.3 | 2.4 | 22.4 | 11.8 | 6.3 | 5 |
| Ground losses | | | | 6 | -- | | | 9 | 7 | | -- | | | 5.1 | 5 |
| Vapor leakage | -- | -- | -- | 8[a] | 1 | -- | 0 | -- | -- | -- | 0 | -- | -- | -- | 5 |
| Unaccounted | -- | -- | -- | 2 | -- | 14.5 | 13 | -- | -- | 6.2 | 3.3 | 8.8 | 2.8 | -- | 5 |
| Solar radiation, Btu/ft$^2$-day (hour) | ? | (300) | (300) | 2,000 | 1,890 | 2,318 | 1,400 | ? | (258) | 1,996 | 2,070 | 2,554 | 2,227 | 2,250 | 2,000 |

(a) Energy loss from condensation on glass ends.
(b) Increase in enthalpy of still.
(c) Floating wick.
(d) Included in evaporation energy.

Efficiency calculations for solar stills are usually based on this amount of energy. Feedwater temperatures often range between 55 and 100 F and the evaporation temperatures fluctuate between 110 and 150 F. Within these temperature ranges the total energy required for preheating and evaporation can vary between 1040 and 1100 Btu/lb, with 1070 Btu/lb being a good average value. It should be noted, however, that somewhat more heat than this quantity would actually be required because more salt water must be supplied than is evaporated. If the ratio of distillate to blowdown is 1:1 (neglecting vapor leakage), an additional 50 Btu/lb would be required to preheat the feed. The 1070 Btu/lb value may nevertheless be considered the amount of heat required for preheating and evaporation, provided that the sensible heat in the excess feedwater is accounted for in the effluent blowdown.

The energy percentages are based on the total amount of direct and diffuse solar radiation received on a horizontal surface. This is the quantity of solar radiation measured by instruments such as the Eppley, Kipp, and Robitzsch pyrheliometers.

The conditions chosen for experiments and calculations by the various investigators were so different from each other that the results cannot be directly compared. However, the column of typical averages in Table 6 represents estimates of nominal values that might be expected for basin-type stills consisting of either one large pond or multiple individual bays.

## Performance Correlations

Efficiency. The performance of a solar still is often given in terms of operating efficiency. An expression which can be used for calculating efficiency was given by Bloemer, et al. (Battelle, 52) as:

$$\text{Efficiency, percent} = \frac{(\text{Production, gal/ft}^2\text{-day})(8,913 \text{ Btu/gal})(100)}{(\text{Solar Radiation, Btu/ft}^2\text{-day})} \quad (1)$$

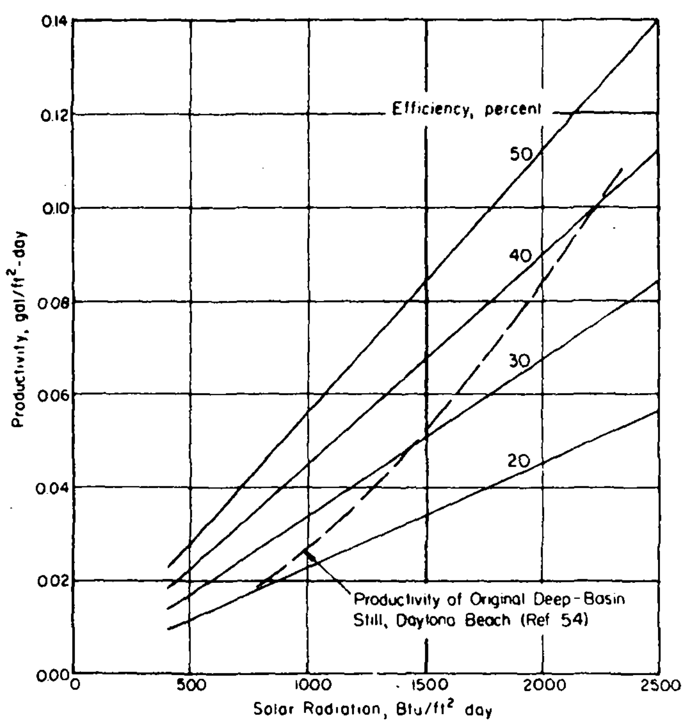



FIGURE 21. EFFICIENCY AND PRODUCTIVITY OF SOLAR STILLS

The constant in this equation was based on 1070 Btu required for preheating and evaporating each pound of distillate, and a distillate weight of 8.33 lb/gal. For example, if the productivity of a solar still were 0.09 gal/ft$^2$-day, with a solar radiation input of 2000 Btu/ft$^2$-day, then the efficiency calculated by Equation (1) would be around 40 percent.

The operating efficiency of a solar still increases as the brine temperature increases with higher solar-radiation inputs owing to the fact that the evaporation rate increases exponentially with brine temperature. However, this increase in evaporation rate is accompanied by exponential increases in thermal-radiation losses from the brine and the cover at higher temperatures, as well as by increased vapor losses. In a typical basin still, the efficiency may be 25 percent at a solar radiation input of 1000 Btu/ft$^2$-day and may increase to 40 percent at 2000 Btu/ft$^2$-day.

Figure 21 is a plot of Equation (1) with the production curve of the original deep-basin still at Daytona Beach superimposed for a typical example (Battelle, 54).

Grune (197) divided the overall efficiency into three components expressed by the following equations:

$$\text{Collector Efficiency} = \frac{\text{Solar radiation trapped by still}}{\text{Solar radiation}} \tag{2}$$

$$\text{Insulation Efficiency} = \frac{\text{Solar radiation trapped-insulation losses}}{\text{Solar radiation trapped}} \tag{3}$$

$$\text{Internal Efficiency} = \frac{\text{Latent heat transferred to cover by water vapor}}{\text{Solar radiation trapped} - \text{Insulation losses}} \tag{4}$$

The overall efficiency is then equal to the product of these three efficiencies. Typical component efficiencies for a natural convection solar still with a 15-degree single-sloped glass cover at a radiation level of 1,996 Btu/ft$^2$-day were 76.6 percent, 91.8 percent, and 58.6 percent in the order listed above. The product of these three efficiencies gave an overall efficiency of 41.2 percent.

Productivity. The amount of distilled water produced by a solar still is a function of the brine-surface temperature and the temperature difference between the brine surface and the cover. However, many factors affect the temperatures of the brine and cover such as solar-radiation intensity, still design, wind velocity, and ambient air temperature. The following correlations are all based on experimental data, and therefore are empirical equations.

Bloemer, et al. (52, 90) correlated data obtained with an electrically heated laboratory "solar" still, with the following equation:

$$P_1 = \left[ 9.33 + 2.32 \times 10^{-10} (T_s)^{5.23} \right] \Delta T / 10^4, \text{ lb/ft}^2\text{-hr} \quad , \tag{5}$$

$T_s$ = surface-water temperature, F

$\Delta T$ = water surface-to-cover temperature difference, F.

Figure 22 is a plot of Equation (5). These data were taken with an 8 percent NaCl solution in the still. The brine temperature was measured at the surface with the bead of a 40-gage thermocouple.

Figure 23 shows that the effect of salinity on the productivity of a laboratory still is relatively small over a reasonable concentration range. The normal variation in a batch-fed, basin-type solar still using seawater would range between 3.5 and 8 percent. A continuously fed still will have less fluctuation, although concentration gradients may exist, especially in long, narrow bays with weirs.

The actual productivity of the deep-basin still at Daytona Beach was correlated with an empirical equation involving only the brine temperature (Battelle, 55).

$$P_1 = 3.1 \times 10^{-17} (T_w)^{7.1} + 0.008, \text{ lb/ft}^2\text{-hr} \quad , \tag{6}$$

$T_w$ = water (brine) temperature, F.

Although this equation fitted the data reasonably well, it is difficult to justify on theoretical grounds. Equation 5 shows $\Delta T$ to be a factor also, but apparently under most natural conditions of operation in a deep-basin still of high thermal inertia, $\Delta T$ and $T_w$ are closely related.

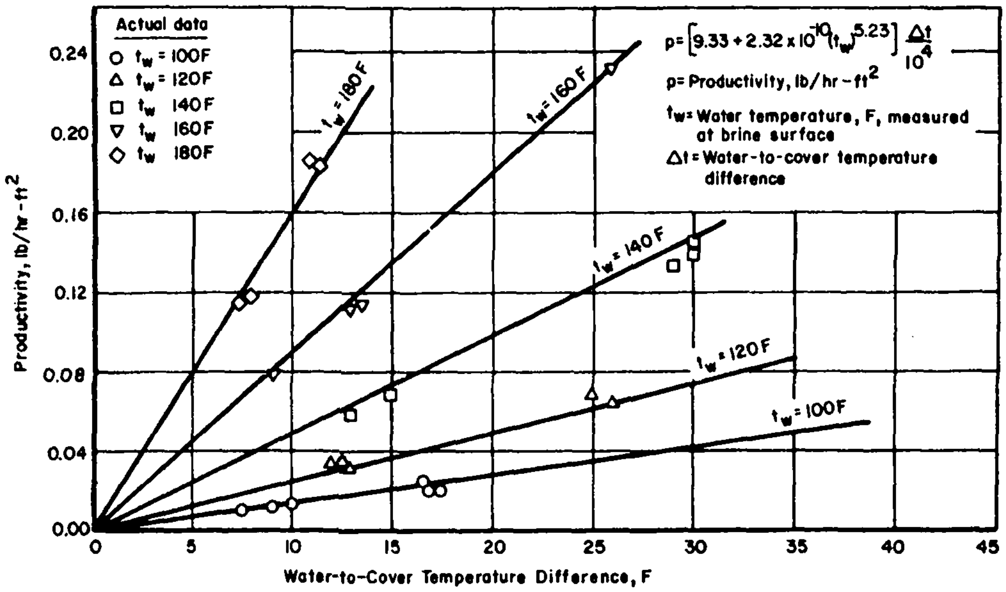



FIGURE 22. PRODUCTIVITY OF BATTELLE LABORATORY STILL

(Eight percent NaCl solution in still, water temperature measured at surface)

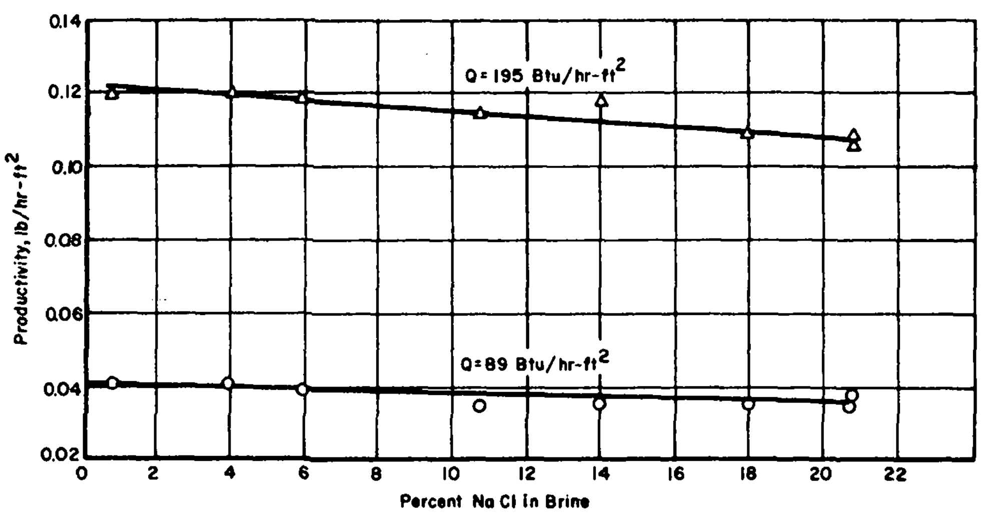



FIGURE 23. EFFECT OF SALT CONCENTRATION OF BRINE ON PRODUCTIVITY OF BATTELLE LABORATORY STILL

An equation relating productivity to solar radiation for the original deep-basin still at Daytona Beach shows the following exponential relationship:

$$P = 3.24 \times 10^{-7} (R)^{1.64}, \text{ gal/ft}^2\text{-day} \qquad (7)$$

R = solar radiation, Btu/ft$^2$-day.

Expressed in a more convenient form, this can be written as

$$P = 6.17 \times 10^{-4} (R/100)^{1.64}, \text{ gal/ft}^2\text{-day} \qquad (8)$$

Grune developed linear-regression equations for glass- and plastic-covered stills (natural-convection type) which assume a linear relationship between productivity and solar radiation (Grune, 194). A typical equation for a glass cover with a 30-degree slope was

$$P_2 = 2.28 \times 10^{-4}(R) + 0.044, \text{ lb/ft}^2\text{-day} \qquad (9)$$

In terms of gallons this becomes

$$P = 2.74 \times 10^{-5}(R) + 0.0053, \text{ gal/ft}^2\text{-day} \qquad (10)$$

Grune also presented the following equation for the productivity of a forced-convection still using a constant air-flow rate, a spray system, and distillate troughs in addition to an external water-cooled condenser (Grune 197):

$$P = 0.00288\sqrt{R}\ , \text{ gal/ft}^2\text{-day}\ . \qquad (11)$$

Lawand (290) has developed similar regression-line equations relating solar-still productivity to solar radiation for several bays of the plastic-covered still on Petit St. Vincent Island. The nine equations have slightly different constants but one typical straight-line relationship is:

$$P = 2.04 \times 10^{-4} (I) - 0.041, \text{ gal/ft}^2\text{-day}\ , \qquad (12)$$

I = solar insolation, Langleys/day.

Expressed in terms of radiation in Btu/ft$^2$-day this equation becomes:

$$P = 5.53 \times 10^{-5} (R) - 0.041, \text{ gal/ft}^2\text{-day}\ , \qquad (13)$$

R = solar radiation, Btu/ft$^2$-day.

The above equations, (10) and (13), assume that a linear relationship exists between solar ratiation and productivity. This is not usually the case because, normally, the efficiency of a solar still increases with the operating temperature, which in turn is dependent on the amount of solar radiation.

Baum (60, 66) developed the following equation relating hourly productivity to efficiency and solar radiation:

$$P_3 \cong \eta\, I/600, \text{ kg/m}^2\text{-hr}\ , \qquad (14)$$

where $\eta$ = efficiency of still, percent

I = solar radiation, kgcal/m$^2$-hr

Expressing radiation as Btu/ft$^2$-hr, this equation becomes:

$$P_4 \cong 2.28 \times 10^{-5}\, \eta\, R, \text{ gal/ft}^2\text{-hr}\ . \qquad (15)$$

Baum stated that for approximate calculations on a well-built still, an efficiency of 50 to 60 percent could be used for the warm months and 30 to 50 percent for the cool months. He also recommended reducing the solar-radiation term by 5 to 15 percent for low sun angles to compensate for a larger percent of the incident radiation being lost. This same expression has been used by Dzhubalieva (147) in an analysis of the effects of vapor leakage on productivity, with the efficiency being calculated in terms of several leakage parameters. It was found that wind can markedly lower productivity, depending on the aerodynamic coefficients and the size of cracks.

Figure 24 is a plot of three of the above empirical equations which relate productivity to solar radiation on a daily basis for typical basin-type solar stills. Each equation shown is based on data taken for a particular design and a specific equation.

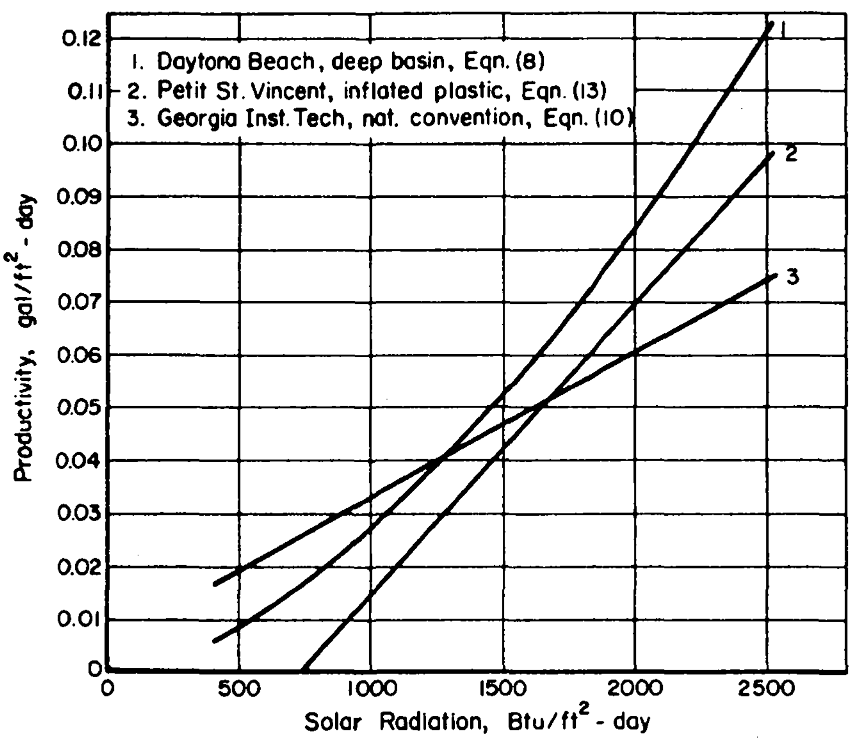



FIGURE 24. PLOT OF EMPIRICAL PRODUCTIVITY EQUATIONS

Heat Transfer. The following empirical equations were developed by Baum and Bairamov (62) describing the heat-transfer coefficients at the evaporating and condensing surfaces of a laboratory "solar" still.

$$Nu_{evap} = 39.8 \times \epsilon_{evap} (Gr \times Pr)^{0.17}_{evap} \qquad (16)$$

for $(2.17 \times 10^6) \leq (Gr \times Pr)_{evap} \leq (1.78 \times 10^7)$

and $$Nu_{cond} = 1.413 \times 10^4 \times \epsilon_{cond} (Gr \times Pr)_{cond} \quad , \tag{17}$$

for $(2.35 \times 10^6) \leq (Gr \times Pr)_{cond} \leq (2.51 \times 10^7)$ ,

where

Nu = Nusselt number

Gr = Grashof number

Pr = Prandtl number

$\epsilon$ = volumetric steam content near the surface.

This laboratory model consisted of an electrically heated, insulated chamber, 1 ft by 1 ft, by 6 in. high, with a single-sloped, water-cooled cover. Therefore, use of the above equations is probably limited to stills of similar design.

Figure 25 is a characteristic chart developed by Morse and Read (344 to 347, 350) relating heat transfer by evaporation to the temperature of the cover as a function of several variables. These variables include brine temperature, wind speed, and internal heat transfer between brine and cover by radiation and convection. This chart may be used to predict the instantaneous output (productivity) of a solar still similar to their design under prescribed conditions. Also, the daily output can be obtained by using this graphical technique in a stepwise progression at hourly intervals for a 24-hour period. The use of this characteristic chart is explained by an example problem in reference 346 (Morse and Read), and a table of calculated values for 24 one-hour periods is presented. The definitions of the symbols on the chart are as follows:

$T_g$ = glass temperature, F

$T_w$ = water temperature, F

$T_a$ = air temperature, F

$q_e$ = heat transfer by evaporation from brine to cover, Btu/hr-ft$^2$

$q_{ga}$ = heat transfer from cover to air, Btu/hr-ft$^2$

$q_r$ = heat transfer by radiation from brine to cover, Btu/hr-ft$^2$

$q_c$ = heat transfer by convection from brine to cover, Btu/hr-ft$^2$

$q_b$ = heat loss through base of still, Btu/hr-ft$^2$

$H_s$ = solar radiation on horizontal surface, Btu/hr-ft$^2$.

Mass Balance. The amount of liquid and vapor leakages from a solar still can be expressed in terms of a "degree of tightness" defined by Baum (63):

$$\text{Degree of Tightness} = \frac{\text{Amount of distillate + blowdown}}{\text{Amount of feedwater}} \tag{18}$$

Productivity tests with a small experimental single-slope still yielded an output of 0.128 gal/ft$^2$-day with a 0.9 degree of tightness, and only 0.074 gal/ft$^2$-day at a tightness of 0.7.

Degree of tightness measurements were also made on the CSMCRI stills at Bhavnagar, India by measuring the distillate output and the corresponding decrease in brine level (Ahmed, 35). Values ranged between 0.51 and 0.79.

Liquid and vapor leakage from large commercial basin stills have not been measured, and it appears that data on this factor are much needed.

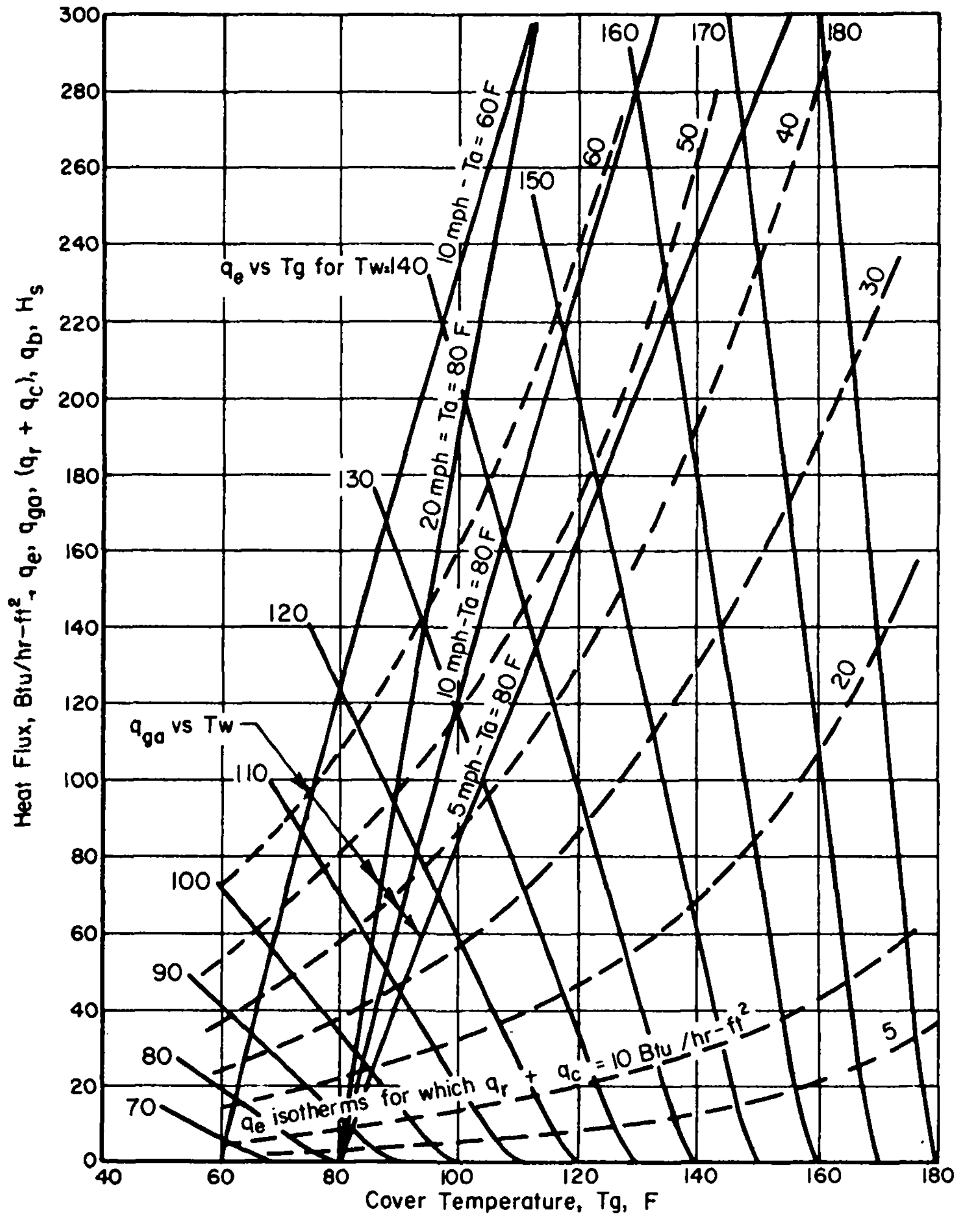



FIGURE 25. CHARACTERISTIC CHART FOR THERMAL PERFORMANCE OF A CSIRO SOLAR STILL

## Effects of Atmospheric Variables

Solar Radiation. The radiation received from the sun provides the energy necessary to evaporate the water from the basin of a solar still. It is the most important variable affecting productivity. Design of the still cover and basin affects the fraction of incident radiation absorbed by the layer of water and used for evaporation.

The productivity of a solar still is usually plotted as a function of the amount of total solar radiation received on a horizontal surface expressed in Btu/ft$^2$-day or cal/cm$^2$-day (Langleys/day). The total solar-radiation energy (direct and diffuse components) is the quantity measured by an Eppley pyrheliometer. The productivity of a typical basin-type still usually increases exponentially with solar radiation because the overall operating efficiency increases as the temperature of the brine (and still components) increases.

Most of the productivity curves reported in the literature are based on data taken during all types of sky conditions, including rainy, partly cloudy, and clear days. The productivity data obtained on any given solar still will usually correlate reasonably well when plotted as a function of the total amount of solar radiation received each day. Cooper (110, 111) has included an intermittency factor in a computer analysis of CSIRO solar stills to account for the variability in solar radiation caused by partly cloudy skies.

The direction and intensity of solar radiation impinging on a still varies throughout each day. Experience and calculations have shown that for a still to produce the most fresh water it should be designed to achieve high brine temperatures with minimum thermal lag. For example, a shallow brine layer will reach a higher operating temperature than a deep layer, other things being equal.

The solar radiation incident on a still is composed of both direct and diffuse components. The diffuse radiation is that portion of the direct solar beam that is scattered by atmospheric dust, smoke, water vapor, etc. Approximately 10 to 40 percent of the total solar radiation consists of diffuse radiation on clear or partly cloudy days (Telkes, 430; Lawand, 290). The apparent effective angle of incidence for this diffuse radiation on a horizontal surface is about 60 degrees (Hottel and Woertz, 229; Parmelee, 377).

Wind Velocity. As the wind speed increases over a solar still more heat will be removed from the cover by convection. This will lower the cover (condenser) temperature. This by itself would increase the rate of condensation inside the still. However, as the cover temperature decreases the rate of heat transfer from the brine to the cover by means of radiation and convection also increases. The brine temperature is thereby decreased until a new thermal balance is reached at lower temperatures throughout the still. Because the rate of evaporation decreases exponentially with the temperature of the brine, the net effect of increased wind speed is a slight decrease in productivity. The effect of wind velocity has been studied by several investigators.

Telkes experimented with an electrically heated laboratory still and reported that wind velocity did not have an appreciable influence on productivity provided the condensing surface had more area than the evaporating surface (Telkes, 430).

Lof (309, 310) reported on a digital-computer-program study made at Battelle to examine the effect of design and operating variables, and predicted that productivity would decrease about 29 percent with an increase in external convection coefficient from 1.5 to 10 Btu/hr-ft$^2$-F, corresponding to wind velocities of approximately 5 to 50 mph. This conclusion was later modified by an analog-computer study conducted by Bloemer, et al. (86) which predicted a decrease of about 13 percent in productivity as the external-convection coefficient increased from 1.5 to 6 Btu/hr-ft$^2$-F. In a later study with a laboratory still, Bloemer, et al. (55, 90) reported a 6 percent decrease in output for an increase in external convection coefficient from about 0.5 to 7 Btu/hr/ft$^2$/$^\circ$F.

Morse has reported the results of a computer study in which wind effects were studied and concluded that the effect of wind on still output was unimportant since the output decreased only 3 percent as the wind velocity increased from 5 to 20 mph (Morse, 350). A more recent computer study related to CSIRO stills indicated an increase in still output of 11.5 percent as the wind increased from 0 to 4.8 mph, and a further increase of 1.5 percent as the velocity increased to 19.7 mph (Cooper, 110). This result has been disputed by Lof, however (Lof, 322).

All things considered, with emphasis placed on the closely controlled laboratory work of Bloemer, the best conclusion seems to be that an increase in wind velocity has a relatively small negative effect on productivity if a still is well sealed to prevent vapor leakage. However, when poorly sealed joints exist in the still cover, increased wind velocity can increase the vapor leakage considerably and thereby further reduce the productivity. The magnitude of this effect has been studied by Dzhubalieva (147, 148). For one example problem given, the productivity of a leaky still was 21 percent less than an airtight still with no wind, 22.5 percent less at a wind speed of 9 mph, and the productivity approached zero at wind speeds greater than 34 mph. This effect has also been noted by Delyannis (138).

Ambient Air Temperature. There is general agreement that the productivity of a solar still increases as the ambient air temperature increases. The magnitude of the reported increases averages about 5 percent for each 10 F rise in ambient temperature.

Telkes reported (430) that her laboratory still had a slightly higher efficiency when the ambient air temperature increased, and that this was confirmed by field tests.

Lof (309, 310) presented computer results which indicated that productivity increased about 40 percent as the ambient air temperature increased from 50 to 110 F, even though the temperature difference between the brine and glass cover decreased as the brine temperature went from 120 to 160 F.

Baum's computer analysis (60) predicted an increase in output of approximately 35 percent with an ambient temperature change from 32 to 122 F.

Bloemer, et al. (86) predicted an increase in productivity of about 35 percent as the air temperature increased from 50 to 90 F. In a later study with a laboratory still, Bloemer found (90) that productivity was not affected noticeably by changes in room temperature between 62 and 86 F.

Morse reported (350) a predicted output increase of about 25 percent as the ambient air temperature went from 60 to 100 F. He also compared the effects of a constant ambient temperature with one which was continually changing but had the same daily mean and found a negligible difference in productivity. It was also reported that the effect of ambient air temperature was more pronounced if edge- and ground-loss coefficients were higher.

Cooper (110) showed a graph which indicated that output increased about 13 percent as the average ambient temperature increased from 60 to 80 F.

Rainfall. Obviously, a solar still is not effective during heavily overcast or rainy conditions. However, the covers of basin-type solar stills can provide a large catchment area for rainfall collection. It is necessary only to provide a suitable collection system. Both glass and inflated, plastic stills have been used successfully to collect rainfall. The exact percentage of rainfall that can be collected and retained in any given area is difficult to predict because of the influence of local conditions such as the rate of rainfall, wind speed, and size of drainage pipes. For example, Howe (247) assumed that only 80 percent of the rainfall could be collected, and that a maximum of 2-1/2 in. of rain could be collected in any one day.

Tests undertaken by Lawand (209) on Petit St. Vincent Island showed a collection efficiency of 90 to 100 percent from the solar-still covers during short-duration rainfalls. However, during periods of driving rain there was no direct correlation between rainfall and water collected.

Also, very little water was collected during drizzles or showers of less than 0.05 in. Therefore, Lawand used an anverage annual rainfall collection efficiency of 80 percent. If the annual rainfall is 35 in. per year as on Petit St. Vincent, this represents a collection of 17.5 gal/ft$^2$-yr from the cover of a still and surrounding walkways, etc.

Morse (345) allowed for a 70 percent runoff efficiency and used a total catchment area 1.28 times larger than the projected glass area of the stills. This includes the walkways between each bay which can be easily used for rain gutters. Morse also reported that allowing for rain catchment supplementing the stills'output, solar distillation was more economical than only rain catchments in regions having less than 10 in. of rain per year, but that rain catchments were cheaper where rainfalls exceed 18 in. per year. At Coober Pedy, Australia, where the rainfall is only about 6 in. or less per year, a rainfall-collection system was not included because the water was being used for human consumption, and contamination might be a problem (Morse, 344).

Datta (124) reports that 80 to 90 percent of the rainfall is collected from the CSMCRI stills at Bhavnagar, India.

Figure 26 shows the quantity of water that can be gained by rainfall collection for various collection efficiencies. This quantity can be collected to supplement the annual output of a solar still using the still covers and surrounding walkways as rain catchment areas. The most common estimate used for collection efficiency is 80 percent. For comparison purposes, an annual average solar-still production of 0.07 gal/ft$^2$-day is equivalent to about 25.5 gal/ft$^2$-yr, referred to the evaporating area. Therefore, if a particular solar still has a rain-catchment area equal to its basin area, and a collection efficiency equal to 80 percent, an annual production of 25.5 gal/ft$^2$-yr is "equivalent" to an annual rainfall of 51 in. However, the output of the still itself is equal to about 41 in. of rain at 100 percent collection efficiency. Alternatively, 80 percent collection of 15 in. of precipitation would augment the 25.5 gallons of solar distilled water by about 7.5 gallons per year, equivalent to almost a 30 percent increase.

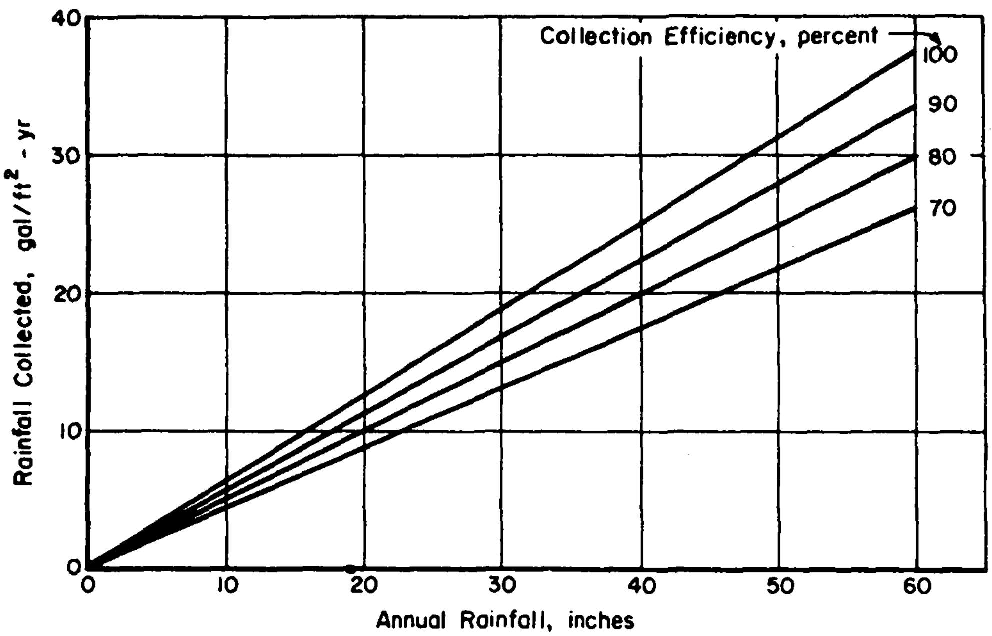



FIGURE 26. AMOUNT OF RAINFALL COLLECTED

Effects of Design Factors

Various design factors can affect the daily and annual productivity of a solar still, but only four are important. These are: brine depth, vapor tightness, distillate leakage, and insulation for the bottom and sides.

Brine Depth. It has been demonstrated in laboratory experiments (Telkes, 430; Bloemer, 85; Battelle, 55) and theoretical calculations (Löf, 309; Morse and Read, 346) that the shallower the layer of brine in a basin-type still, the higher the total daily productivity, other things being equal. As explained earlier, this results from the fact that shallow layers will reach higher temperatures during the hours of peak sunshine and because the evaporation rate increases exponentially with an increase in brine temperature. Thus, a greater percentage of the available solar energy will be used for evaporation and a smaller percentage will become heat losses from the basin.

A shallow layer of water will achieve higher temperatures during the day than a deep layer because of the lower thermal capacity. For example, a typical uninsulated basin-type still with a 1-inch depth of brine may reach a maximum temperature around 160 F at about 2 p.m. solar time, whereas a 12-inch depth would reach 140 F at about 4 p.m. (Battelle, 55). When the deep basin was insulated with 2 inches of Foamglas, the maximum brine temperature was essentially unchanged, but the maximum temperature for a 1-inch depth increased to about 175 F at the same net radiation input of 2200 Btu/ft$^2$-day.

Figure 27 shows the effect of brine depth and insulation on the productivity of an electrically heated laboratory "solar" still (Battelle, 55). Two inches of Foamglas (k = 0.036 Btu/hr-ft-F) were used for the insulated basin experiments, and 30 inches of sand for the uninsulated tests. It is interesting to note that for an uninsulated still, the productivity increases very little as brine depth is decreased, particularly at higher radiation levels.

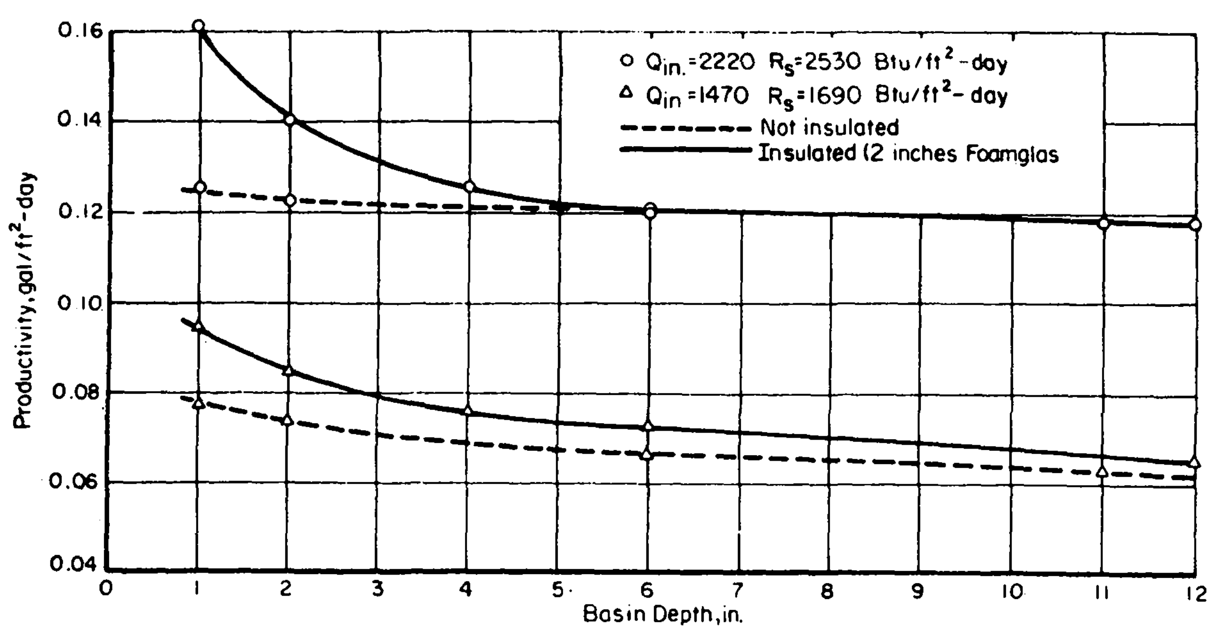



FIGURE 27. EFFECT OF BASIN DEPTH ON PRODUCTIVITY OF BATTELLE LABORATORY STILL

It has been the experience of several engineers in charge of building large basins for solar stills that a 2-inch depth of brine is a realistic practical minimum in order to prevent dry spots from occurring on the basin liner as a result of inaccuracies in leveling the ground. Somewhat more shallow brine layers are achieved in the CSIRO design used in Australia by sloping the still along its length and using weirs at about 4-ft intervals. These form shallow pools of brine, about 1 inch deep at the shallow ends and 1-3/4 inches deep at the weirs.

It should be noted that despite wide variation in brine depth among the numerous large solar stills which have been built, differences in productivity have been relatively small. Deep-basin stills have, in some instances, out-performed shallow-basin stills. This is because the small differences due to basin depth are masked by larger performance differences caused by a combination of other factors such as vapor leakage, bottom or side losses, and climate.

As a matter of general interest, an evaporation rate of 0.10 gal/$ft^2$-day corresponds to a water depth change of 0.16 inch/day. Therefore, if a still is to be fed intermittently, say every 2 days in summer, then this change of water depth may a consideration in designing for a shallow basin.

Vapor Tightness. All solar stills should be designed to be completely vapor tight. In practice, however, cracks and holes are found in new stills, especially at junctions of different materials, and these may become larger as a still ages.

On glass-covered stills, nonhardening caulking compounds or sealants are recommended. Asphaltic mastics have been employed with good results in several large basin stills. One particularly satisfactory type of sealant recently used is silicone rubber. This has been used extensively on the newer Australian stills for glass-to-glass, and glass-to-metal or glass-to-concrete joints (Morse, personal communication, January 21, 1969). A primer is used for joints other than glass-to-glass.

Plastic-covered stills usually have heat-sealed seams (if necessary) and some type of clamped gaskets around the periphery. The plastic-covered stills in Greece had double-sided adhesive weather stripping (Eckstrom, 152). The inflated, plastic-covered still on Petit St. Vincent used three flexible plastic electrical conduits side by side, over and under which were placed the Tedlar cover and the Butyl rubber basin liner. This assembly was then clamped against the concrete curbs. The basin liner was also glued to the concrete curb and butyl rubber adhesive tape was also employed (Lawand, 290). Some permeability exists in the plastic films, and Lawand estimated this leakage as about 1 lb of water vapor and 1/2 lb of air per hour per still (1,285 $ft^2$).

Unfortunately, very few investigators have measured the amount of vapor leakage occurring in solar stills. Some experiments were conducted on the original deep-basin still at Daytona Beach to determine the effect of leaving 1/8-inch gaps between all glass panes. The resulting vapor-leakage area reduced the productivity about 20 percent (Battelle, 54). Research workers in Bhavnagar, India, at the central Salt and Marine Chemicals Research Inst. (CSMCRI) have investigated the amount of vapor leakage from small stills by comparing the drop in brine level with the amount of distillate collected. They have reported that the amount of water lost by vapor leakage in 10 experimental solar stills varied from about 21 percent to 49 percent (Ahmed, 35). The efficiencies ranged between 20 and 30 percent at a radiation level of 1,440 Btu/$ft^2$-day, but they did not necessarily correspond to the leakage rates because other design differences existed. They mentioned that one of the problems was glass sagging on the stills with 10-degree cover slopes. Another was that the cotton adhesive tape used for joints between glass panes was satisfactory for only about a year. Also, some distillate leaks were reported where the aluminum troughs passed through the end walls.

Morse and Read reported a significant increase in productivity for the Muresk II still over Muresk I, primarily because silicone rubber was used as a joint sealant along the ridge rather than a rubber-gasketed clamp (Morse and Read, 345). However, this report was later negated when it was found that summer production rates were essentially equal (Morse, et al, 349).

Two theoretical studies have been conducted by Dzhubalieva (147, 148) to calculate the amount of vapor leakage caused either by wind-velocity coefficients or the natural thermal head. However, the sizes and locations of the cracks must be known or estimated to use these procedures.

Distillate Leakage. Even very small holes or cracks in distillate collection channels severly reduce distiller output because the flow rate in a single channel is so small that the entire stream can easily be lost (externally or by return to the brine) if the trough is imperfect. Only completely corrosion-resistant, one-piece channels have been found satisfactory. Thin stainless steel troughs and polyethylene films have been successfully used, whereas copper, aluminum, concrete, various coatings, and jointed heavy plastic have failed. The troughs must be deep enough to prevent running over the top if uneven settling or other obstruction occurs, and narrow enough, or shaded, to minimize re-evaporation by the sun. Probably the largest factor in decline of distiller output with time has been distillate trough leakage.

In many stills, distillate troughs are 100 to 250 ft long in which instances distillate drainage or re-evaporation from the troughs can be a problem. With the saw-tooth cover used by Howe, the troughs run perpendicular to the long dimension of the still (Howe, 247 – 249). Because each trough is less than 6 ft long, this design is reported to be less subject to re-evaporation and dislocation (Howe, personal communication, Jan. 30, 1969).

Several trough materials were tried in the deep basin stills at Daytona Beach, including jointed split plastic pipe, and thin one-piece strips of aluminum, copper, and stainless steel. The only completely satisfactory material was stainless steel (Battelle, 55). It was concluded that joints in condensate troughs must be avoided if leakage is to be prevented. Joints eventually fail due to thermal expansion and contraction, and condensate leaks back into the brine.

At Las Marinas, Spain, the troughs were moulded in the concrete curbs and then lined with six different test materials, including thin aluminum and various paints. Only two trough-lining materials were satisfactory: thin stainless steel and a double thickness of black polyethylene film (Lof, 318). The others developed leaks in a few weeks to a few months.

In some still designs, the basin liner (polyethylene or butyl rubber) is extended over the side of the curb and is used to line the distillate trough as well as the basin.

Any re-evaporation of distillate from the troughs or spillage back into the basin reduces the output of a still. Therefore, the troughs are often shaded from direct sunlight and built narrow and deep. Steeper slopes also provide more rapid drainage of the distillate after it drains from the cover into the trough.

A slight shifting of the ground after the Coober Pedy still was built caused distillate spillage within many bays (Morse, et al., 349). It was discovered that 40 out of 152 bays were not producing any water for this reason. These distillate troughs were integrally formed in the sheet-metal walkways and were 143 ft long. The troughs are rather small and the slope was between 1 in 50 and 1 in 120 (Morse, 344, 347).

Insulation. The bottom and sides of solar stills can be insulated to increase productivity by raising brine temperatures and reducing heat losses. Refer to Figure 27, in which the productivity curves show that the advantage of insulating the bottom of a basin still is greater at shallower brine depths. Similar results were reported graphically by Cooper (110). At a 2-inch brine depth, Figure 27 indicates that the average increase in the two productivity curves obtained by insulating the bottom is about 14 percent. This indicates that to economically justify insulating large-basin stills built on a sand base, the cost of insulation (including installation labor) should be below about 14 percent of the capital cost of the still. Often, a layer of dry sand 2 or more inches thick beneath the basin liner is adequate if proper drainage is provided.

It should be understood that insulation beneath the basin of a solar still may be beneficial, or may have practically no benefit at all. The two functions of bottom insulation are to decrease the net heat-conduction losses from the bottom and to decrease the effective heat-storage capacity (or thermal inertia) of the distiller. Insulation will have a large effect in reducing the heat loss from a still having a shallow tray of water supported above the ground. Its effect on net conduction loss from the bottom is minimal, however, if the still is built directly on dry ground and covers a large area. This is because the earth acts as a semi-infinite solid, through which there is no net conduction, and because heat losses around the perimeter are a very small fraction of the total solar energy absorbed. Heat conducted into the ground as brine temperature rises is almost completely returned to the brine by conduction upward as the brine cools (at night, for example). Finally, if the ground-based distiller has a relatively deep brine pond (several inches of salt water), the thermal capacity is already large, so the absence of insulation would have only a minor influence on the maximum temperatures achieved.

Needless to say, if insulation is used beneath a solar still basin, it must be kept dry or its insulating effect will diminish drastically. Some insulating materials, such as a sawdust, will physically deteriorate if excessive moisture is present. Insulation can become wet from ground water or from leaks occuring in the basin liner.

<u>Cover Material</u>. The most common solar-still-cover material is glass - either single strength (0.10 in. thick) or double strength (0.125 in. thick). If the inside glass surface is clean, the condensate will form a thin film which will not reduce the transmission of sunlight. The daily average portion of the incident solar radiation (direct and diffuse) transmitted through ordinary window glass is approximately 85 percent; roughly 10 percent is reflected and 5 percent absorbed. Glass is essentially opaque to the long-wavelength radiation emitted by the brine. If properly supported, the life of glass covers on a solar still is virtually unlimited. However, improper installation may result in breakage, and the broken glass may damage the liner also.

Several plastic-covered stills have been built using a 4-mil-thick (0.004 inch) polyvinyl fluoride film (Tedlar). The life of a well designed and maintained inflated cover may be as long as 5 years (Lawand, 290), but the inflated cover on the Symi still lasted less than 3 years. V-shaped and stretched-cover designs have not been evaluated as extensively as the inflated type, but experience to date has indicated shorter lifetimes. In the Greek installations, the V-covers were damaged by wind and rainfall, and the stretched covers developed cracks after a short time.

Plastic films should be treated for wettability to prevent dropwise condensation which would reduce the amount of sunlight transmitted and add to the possibility of distillate dripping back into the brine. Tedlar is made wettable on one side by calender rolling or embossing to mechanically "scratch" or indent the side used for condensing. Currently, Tedlar film treated for wettability costs more than glass on a unit area basis.

Tedlar, 4 mils thick, will transmit about 92 percent of the direct solar radiation, with about 4 percent reflected and 4 percent absorbed, at angles of incidence between 0 and 45 degrees (DuPont, 145; Lawand, 290). The transmissivity to the diffuse solar radiation component is about 84 percent. Thus, the overall transmissivity is roughly 90 percent. Approximately 5 percent of the infrared energy radiated from the brine layer will be transmitted through a wetted Tedlar cover (Lawand, 290).

Many types of plastic films have been life tested under conditions simulating the solar-still environment (Bjorksten, 74; Battelle, 54, 55). These included various types of Tedlar, Mylar, PVC, Kel-F, Teflon, Nylon, Aclar, and polyethylene, to name only a few. The outdoor exposure equipment consisted of 5-gallon paint cans nearly filled with water and covered with the plastic films. These test conditions are not believed to be as severe as those existing in a full-size solar still, because of lower temperatures and stresses. The only materials lasting approximately 5 years were 5-mil Teflon, 4-mil Tedlar, and 5-mil weatherable Mylar.

Cover Slope and Shape. As the cover slope increases, the productivity evidently declines slightly because the operating temperatures of the still components are lowered. The lower temperatures result from more condenser area being available to transfer heat to the atmosphere. The cover temperature will be lower for a given heat input rate, and this will, in turn, produce a lower brine temperature. However, since both the brine temperature and the temperature difference between brine and cover affect the productivity, it is not immediately obvious what might happen to productivity. Nevertheless, decreases in still productivity with an increase in glass area have been reported by Lof, et al. (309, 310), Baum (60), Bloemer (54, 90), Morse (348), and Cooper (110). However, it appears that the effect of cover slope on productivity is quite small. Other factors related to slope are more important.

The slopes of glass covers usually range between 10 and 30 degrees. However, slopes as low as 6 degrees have been used successfully (McCracken, 330), although extensive cleaning and scouring procedures are used to obtain good wettability, and the span is only about 28 inches. When single-strength glass (0.10 in. thick) is used at angles of around 10 degrees for unsupported spans of about 4 ft, the deflection may cause sealing problems at joints.

The two deep-basin stills built for OSW at Daytona Beach used 15 and 10 degree covers, in that order, and the similar design at Las Marinas, Spain also used 10 degree covers. CSIRO increased the slope of their glass covers from 15 to 18 degrees for improved structural stability because no supports other than the glass itself, were used (Morse and Read, 345). This change lowered productivity about 3 percent (Morse, personal communication, October, 1968). After experimenting with cover slopes of 10, 15, 20, and 40 degrees at CSMCRI in Bhavnager, India, they (Ahmed, et al., 35) selected the 20 degree slope as the most suitable for further developmental work. Baum and Bairamov (63) selected a 30 degree slope after investigating stills with 30, 35, and 40 degree slopes.

It appears that glass slopes between 10 and 20 degrees should be the most practical for large solar still installations. The method by which the cover is supported will probably determine the minimum practical angle. For a given horizontal area to be covered by a 10 degree sloped cover, approximately 5 percent more glass would be required for a 20 degree slope, 14 percent more at 30, 39 percent more at 45, and 97 percent more at 60 degrees.

The shape of a glass cover will have some effect on the amount of solar radiation entering the still. However, the effect appears to be negligible for large still installations. For smaller units, shadowing caused by end walls and curbs may have a relatively larger influence. The three most common shapes for glass covers are: (1) symmetrical double-sloped cover, (2) non-symmetrical double-sloped cover, and (3) single-sloped cover. Only Number (1) is relatively free of compass-orientation requirements, whereas (2) and (3) must be oriented with their long axis East-to-West.

Another experimental design consisted of a transparent south-sloping glass cover and an opaque internally reflective North-sloping cover (the reverse in the Southern Hemisphere) for use in the temperate zones (Telkes, 430; Khanna, 270, 271). This type of cover will increase the productivity at low sun angles. Telkes stated that the North reflecting surface should be tilted southward at an angle which is equal to the solar altitude at noon on June 21.

The effect of spacing between cover and brine was examined experimentally on a laboratory still by Bloemer (55, 85, 90). Increasing the average spacing from 6 to 16 in. had no noticeable effect on the productivity. It was estimated that spacings would have to be less than 1 or 2 in. before any change in internal-convection rate would occur. Naturally, in an actual solar still, the side walls should be kept as low as possible to minimize shadowing of the bottom of the basin.

The slope of the covers and the shape of the internal volume probably have an influence on the circulation patterns within a still. Baum (60) suggested that only two large circulation patterns exist in stills with symmetrical 45 degree sloped covers, whereas several smaller circulation cells are likely with lower cover angles. The restriction of circulation within a solar still may have some influence on the slight productivity increase as the cover angle is decreased. However, Telkes used a blower inside a tilted-wick still to circulate the air, and reported no change in productivity (Telkes, 437).

Two layers of glass have been tried as solar-still covers in an attempt to improve productivity by means of increasing the operating temperatures (Grune, 197; Battelle, 54). Contrarily, substantial decreases in productivity were observed, evidently caused by increased solar reflection and absorption losses from the additional glass surfaces, which more than offset their insulating effect. Bloemer (54) measured a decrease in productivity of around 40 percent when a double-glass cover, with an air space of 1/2 in., was installed on one bay of the original deep-basin still at Daytona Beach.

Several cover shapes were studied theoretically by Martens (333) to determine the amount of solar radiation entering a solar still. The four shapes studied were a hemisphere, a cone, a tent with a square base, and a tent with a rectangular base. The tent-shaped covers admitted the most flux, with the rectangular base better than the square base. This study considered only the direct component of the incident solar radiation.

The optimum shape of inflated-plastic-covered stills has been studied by Edlin (511). The optimum arc-to-chord ratios were given for stills with bay widths from 3 to 15 ft. A ratio below 1.01 caused refluxing of the distillate, while a ratio higher than 1.2 formed an undesirable air foil which could result in damage to the film. The optimum arc-to-chord ratio given was 1.110 for a bay 3 ft wide, 1.020 for 9 ft, and 1.012 for a 15-ft width.

Compass Orientation. Solar stills usually have been oriented with their long axes either East-West or North-South. The orientation of stills with symmetrical glass covers at reasonably low slopes does not appear to influence productivity. However, glass-covered stills with nonsymmetrical covers or single-sloped covers should be oriented with their long axes East-West with the low-sloped cover or single cover "facing" the Equator.

Khanna reported (270) that an East-West still with 15-degree symmetrical glass covers produced slightly more water than an identical still oriented North-South, under normal conditions. However, when the windspeed exceeded 5 mph in a direction normal to the glass covers of the North-South still, its output increased while that of the East-West still decreased. These were small, insulated, tray-type stills (4ft 2 in. by 3 ft 8 in.) elevated above ground. Naturally, differences in size and location of vapor leaks could have influenced these results.

Morse has stated that productivity of stills of the CSIRO design is independent of compass orientation (Morse, personal communication, Oct., 1968).

The inflated plastic-covered stills on Symi were oriented with their long axes East-West, while the similar design on Petit St. Vincent is North-South. These covers are all so nearly flat, and the bays so wide, that compass orientation could not be expected to influence output.

Liner Material and Color. The bottom of the basin should absorb the maximum amount of solar radiation impinging upon it and be impervious to saline water. Such materials as black butyl rubber, black asphalt mats, black asphalt paving, black asphalt paint over concrete, black polyethylene film, and blackened stabilized soils have been used for basin bottoms.

The most successful and trouble-free material is commercial black butyl rubber sheeting with a thickness of about 30 mils (about 1/32 in.). "Vulcanized" or adhesive-sealed, leak-proof joints can be prefabricated or made on site. The material is not affected by sunlight or by high temperatures associated with dry spots on the bottom or the edges above the brine surface. Butyl rubber canal linings and pond bottoms have been extensively tested and used for years.

"Prefabricated" asphalt mats about 1/4 inch thick, joined by asphalt-sealed overlapping strips of the same material, have also given trouble-free service in large basin-type stills in Florida and in Spain. For this (and the butyl rubber) material, a useful life of 20 years may be realized.

Black polyethylene film, 8 mils thick, has been successfully used in Australia for the narrow-bay CSIRO design. It is expected that replacement will be required about every 10 years.

Asphaltic concrete ("black top") and Portland cement concrete have not been found sufficiently water-tight to eliminate the need for a heavy application of roofing-type asphalt or pitch on the surface. Cost then becomes too high. Earthquakes have also caused cracks in concrete stills in Chile (Hirschmann, 216).

Stabilized soils have been tried at the CSMCRI in Bhavnagar, India, but water leakage and heat losses are quite high (Ahmed, 35).

Floating Wicks. Several investigators have tried floating porous pads of fabric-type materials on the surface of the brine to increase productivity. The purpose is to produce higher evaporating temperatures by absorbing the sunlight at the upper surface of the brine, and by increasing the evaporating-surface area of the brine.

Tests were conducted at Daytona Beach with a floating wick of black polypropylene felt (Battelle, 55). Results indicated that the productivity of an uninsulated basin-type still could be increased by 10 to 20 percent. This increase was not enough to justify the added cost of the wick.

Delayannis has also experimented with a floating wick of black Orlon mat (Delyannis, 140). It was found that calcium sulfate crystals formed on the lower side and that there was no significant gain in productivity.

A floating Orlon wick was also used in several bays of the Petit St. Vincent still (Lawand, 290). This still has weirs along its length, and the Orlon matting caused a slow but continual syphoning from one level to the next, so that a small but continuous stream of brine flowed out of the overflow at the lowest level. Here also, it has been concluded that if there is any gain in output, it is too small to justify the added cost of the floating wick.

## Effects of Operational Techniques

Feedwater Preheating. Various techniques have been used to preheat the saline water before supplying it to the still basin. These include heat exchangers to recover heat from the outgoing distillate and blowdown, internal condenser coils, and solar-heated feedwater storage tanks.

As discussed earlier, only about 50 Btu/lb are required for preheating, and around 1,020 Btu/lb are required for evaporation. Therefore, preheating represents less than 5 percent of the total heat input required. Another way of considering this is to say that less than 5 ft of a 100 ft still is used for preheating. Since the still itself is about the cheapest type of heat exchanger available, other preheating devices cannot be economically justified.

If waste heat from engines or other sources were readily available, it might be advantageous to use the solar still as the secondary cooling loop to dissipate the heat while simultaneously obtaining additional distillation. Such a system would continue to produce fresh water when no solar energy was available, as at night or during cloudy periods.

Blowdown Ratio and Flushing. Two methods are used to replenish the brine in a solar still.

(1) The technique most often used is the batch-type operation, wherein general flushing and filling are performed either late at night or early in the morning when the brine is the coolest. This method wastes the least amount of heat because the heat content of the waste brine is at a minimum. A schedule which involved flushing when the brine temperature was higher would be accompanied by lower water yields.

The flushing and filling operation is performed at intervals ranging from daily to weekly, depending on the distillation rate and depth of brine. Flushing is necessary to avoid the build up of salt concentration to a level where deposits would occur, usually between 7 and 8 percent for sea water. This represents a concentration ratio of about 2. Usually, about twice as much makeup is added as was distilled during the previous time interval to accomplish both replenishing and some flushing simultaneously. However, some stagnant areas may remain unchanged. Therefore, some stills are completely drained and then refilled at regular intervals. This procedure avoids the buildup of algae or scale (Delyannis, 136 to 138). It is usually desirable to automate these functions to reduce operating labor costs.

(2) The other method of feedwater control uses a continuous supply of salt water. The CSIRO stills in Australia operate this way, as they were designed to be placed in remote areas and not require continual attention. The saline water is fed at a constant rate of 0.1 lb/ft$^2$-hr, which is equivalent to about 0.28 gal/ft$^2$-day (Morse, et al., 349). Because this flow rate is almost three times higher than the maximum distillate rate, some heat will be lost in the continuous overflow of brine from the still. Experiments were conducted at feed rates of 0.1, 0.2, and 0.5 lb/ft$^2$-hr, and a 5 percent decrease in output was noted for each 0.1 lb/ft$^2$-hr increase (Morse, personal communication, October 1968). Unfortunately, lower flow rates were not tried. The continuous-feed method has the advantage of being completely automatic, but at a slight penalty in thermal efficiency.

Feedwater Treatment. If sedimentation occurs on the basin liner, or if algae and bacteria are permitted to grow within a still, the productivity will begin to decline because of increased solar reflection from the basin (Battelle, 54). Therefore, it is sometimes advisable to filter and chemically treat the feedwater. The extent of filtering or chemical treatment required depends on the quality of the raw water. Usually brackish well water does not require treatment, but it may produce deposits on the liner or thin films of calcium carbonate or calcium sulfate on the surface of the brine (Morse, 349).

Sea water can be partially filtered by drawing it through a gravel bed or screens. In addition, the feedwater storage reservoir is often used as a settling tank to remove suspended matter (Battelle, 54).

Algae and bacteria growth may become a problem, particularly if contaminated feedwater is used, as at Daytona Beach, Florida; Muresk, Australia; and Bhavnagar, India. This problem was solved at Muresk by adding to the raw feedwater a mixture of 1 ppm copper sulphate, 2 ppm copper citrate, and 10 ppm calcium hypochlorite (Morse and Read, 345). Delyannis has reported that no treatment for algae has been necessary, as he completely drains the still at regular intervals before refilling (Delyannis, 140). However, some calcium carbonate and calcium sulfate deposits have occurred. Eckstrom reported that copper sulphate and chlorine were added to the CWS stills in Greece to kill blue-green algae and microbes (Eckstrom, 150). Algae growth was encountered in the distillate troughs of the Las Marinas, Spain still (Lof, 318), and was probably a result of impurities entering the still through leaky joints in the glass covers.

A fairly detailed study of algae and slime growth in the solar stills at Daytona Beach has been reported (Battelle, 54).

Cleaning of Covers and Basins. The productivity of solar stills will diminish if the covers become coated with dust, soot, debris, or salt deposits. Long-term operation of many glass-covered stills has indicated that ordinarily they will not require cleaning. The glass covers on the stills at Daytona Beach did not require cleaning. Morse reported (350) that only after exceptionally severe dust storms did cleaning of the covers appear to be advisable. However, in Boston, Telkes found it necessary to clean glass covers frequently because of the soot generated by a nearby powerplant (Telkes, 435).

Plastic-film covers have an electrostatic property which attracts dust, and experience with plastic-covered stills has shown that they should be washed periodically to maintain satisfactory productivity. To further add to this disadvantage, distillate must be used to clean the covers because salt deposits would remain if salt water were used (Delyannis, 132, 133).

Basin liners sometimes develop a coating of silt, scale, or algae, which may or may not decrease the absorptivity of the liner. If productivity decreases significantly, it will be necessary to schedule periodic cleanings. The experience in Australia has been that cleaning should be scheduled at yearly intervals (Morse, et al., 349). In the glass-covered stills in Greece, the problem of algae or scale buildup has been avoided by completely draining the basin before refilling every few days (Delyannis, 136, 138). The stills at Bhavnagar, India have experienced a deposited layer of silt on the bottoms, but no appreciable difference in productivity has been observed (Datta, 124).

Usually, a portion of the cover must be removed for a person to enter the still to clean or perform other maintenance work. Interestingly, two of the stills built at the CSMCRI in Bhavnagar, India, contained manholes in the end walls for this purpose (Ahmed, et al., 35).

## Principles of Operation for Other Types of Solar Stills

### Improvements by Tilting

Several designs of tilted, or inclined, solar stills have been used to increase the productivity above that achieved in horizontal basin-type stills. There are two primary reasons for this improvement:

(1) Tilted evaporator surfaces intercept more energy per square foot of solar collector area, and the covers reflect less sunlight because of a more direct angle of incidence,

(2) Porous wicks or shallow steps provide stills with low thermal capacity; consequently, higher evaporator (brine) temperatures are achieved which, in turn, yield higher evaporation rates.

The principal investigators of tilted stills have been Trofimov (451), Telkes (432, 435 – 440), Savornin (406), MacLeod and McCracken (324), Howe (239, 244, 249), McCracken (327, 328), Bloemer (52, 54, 55), Bjorksten (73, 74), Daniels (119), Bairamov (45), and the

Tunisian AEC (454). The Bjorksten stills had a vertical porous wick, while the others all used tilted wicks or trays with "steps". The angle of inclination depended either on the design or the latitude.

Tilted-wick or inclined-tray stills also have the characteristic of giving relatively high productivity during the winter months, whereas in basin-type stills productivity is considerably lower in the winter. Representative annual productivity averages may be around 0.07 gal/ft$^2$-day for a basin-type still, whereas they may be around 0.10 gal/ft$^2$-day for a tilted-wick type. The area in each case is the area of the evaporating surface.

Aside from the fact that wick materials that are both durable and easily wettable have not yet been developed, there is doubt that the higher productivity of the various tilted designs compensates for their increased cost of construction.

## Improvements by Forced Convection with External Condensation

Various investigators have studied the merits of blowing air through a solar still and into an external, water-cooled condenser. The most extensive tests on this type of still were conducted at the Georgia Institute of Technology for the OSW (Grune, et al., 192-197). Other studies were conducted by Herlihy (209, 210), Salam (405), Sharafi (410), and the Tunisian AEC (454).

Although productivities as high as 0.22 gal/ft$^2$-day were obtained by Grune, it can be concluded that the higher costs resulting from the additional equipment required for this type of solar still more than offset the gain in yield. In some stills of this type, the reported productivities were no better than those for standard natural-convection types of solar stills.

## Improvements by Multiple-Effect Operation

A multiple-effect solar still uses sunlight to provide the heat of evaporation in the first effect. Then the heat of condensation from the first effect is used to provide the heat of evaporation in the second effect, and so on. The condenser of the last effect can be cooled with water or air. The principal investigators have been Telkes (435-438), Dunkle (144), and Selcuk (408).

The advantage of conventional multiple-effect over simple distillation is the reduction in fuel requirements. Capital costs per unit of production capacity are actually somewhat higher. Since solar energy costs nothing, and capital investment is the main expense for solar distillers, there is no advantage in multiple-effect solar distillation unless the costs associated with each succeeding effect are less than the cost of an equivalent area of a simple solar still.

As in other design modifications of simple basin-type solar stills, the increased output obtainable from multiple-effect solar stills per square foot of solar collecting surface does not justify the added costs. In some designs a solar absorber is advocated for providing hot water to supply heat to the first effect. However, Morse has stated that basin-type solar stills are cheaper to build than solar absorbers (Morse, personal communication, October, 1968).

The humidification-dehumidification stills developed at the University of Arizona (Hodges, et al., 219-225) have sometimes been referred to as multiple-effect solar stills. However, they are not true solar stills as defined in this manual, because solar energy was used only to preheat the saline water in solar absorbers. These absorbers have now been replaced with heat exchangers which utilize waste heat from a diesel engine's jacket water and exhaust gases (Hodges, et al., 225, 226). The engine was required to generate electricity to operate the blowers, pumps, etc. Experiments with this type of still have also been done in Bhavnagar, India (Garg, et al., 172, 174).

## Miscellaneous Influences on Productivity

Deterioration of Solar Stills. Several investigators have reported that the productivity of their solar stills decreased gradually with time. This may be caused partly by a gradual build-up of scale deposits which increases the reflection loss. However, a more logical explanation appears to be that a combination of the following effects tends to increase the leakage of vapor, brine, and/or distillate:

(1) Gradual deterioration of materials

(2) Movement associated with thermal expansion and contraction

(3) Shifting of the ground or structural components.

A steady decline in productivity of about 10 percent per year has been experienced in the CSIRO stills (Morse, et al., 349). This has not been fully explained. At first it was thought to be caused by white salt and clay deposits on the black polyethylene basin liner. However, the production remained unchanged after cleaning several bays. It was later believed to be caused by a combination of factors, including pinhole leaks in the basin liner, distortion of distillate troughs caused by slight changes in grade, increase of ground moisture under still, and increased vapor leakage.

Figure 28 shows the decline of productivity experienced on solar still Number 16 at the University of California (Tleimat, 447). This still has an evaporating area of 411 $ft^2$, and a 29-degree double-sloped glass cover. This still was reconditioned and painted in 1960 after operating from 1957 to 1960.

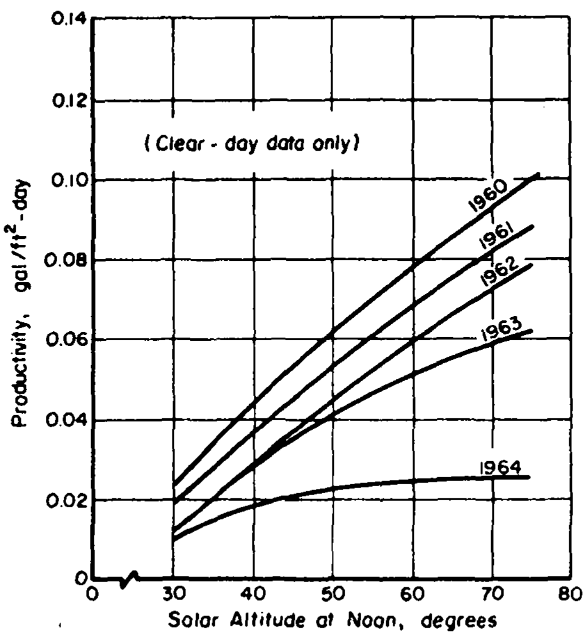



FIGURE 28. PRODUCTIVITY DECLINE OF STILL NUMBER 16 (UNIVERSITY OF CALIFORNIA)

In 1961, leakage occurred with a noticeable drop in production. Then in 1962 the tray was covered with a sheet of 4-mil black polyethylene film. Productivity was immediately improved to the 1960 level, but after a few weeks, cracks developed in the liner and leaks again occurred. Water then seeped under the film and leaked through the wooden tray. By 1964, the seawater caused parts of the film to rise and float on the surface, thus increasing leakage and further decreasing productivity. This gradual decrease of productivity represents the progressively declining condition of the still. A solar altitude of 50 degrees at Richmond, California, represents a solar radiation level of about 2000 Btu/ft$^2$-day (Howe, 240).

Figure 29 shows the decline in productivity observed for solar still Number 55 at the University of California (Tleimat, 447). This still was of the sawtooth design with the valleys of the glass covers, and the distillate troughs, positioned perpendicular to the long dimension. In the spring of 1967, a layer of algae began to grow on the seawater surface. This growth was allowed to continue to study its effect on productivity. Early in 1968, the caulking compound showed some cracks and vapor leakage was noticed. In the fall of 1968, when the still was opened for cleaning and rebuilding, it was observed that the galvanized iron distillate trough had corroded somewhat, and that sand had collected in the troughs after sifting through cracks in the caulking joints.

These significant decreases in still productivity emphasize the importance of careful design and construction, together with a proper choice of materials and adequate maintenance. It is believed that decreases in yield can be successfully minimized by taking such precautions, and that relatively constant yields over periods of 20 years should be obtainable. No noticeable decrease in productivity was observed in the deep-basin stills at Daytona Beach over a period of about 6 years.

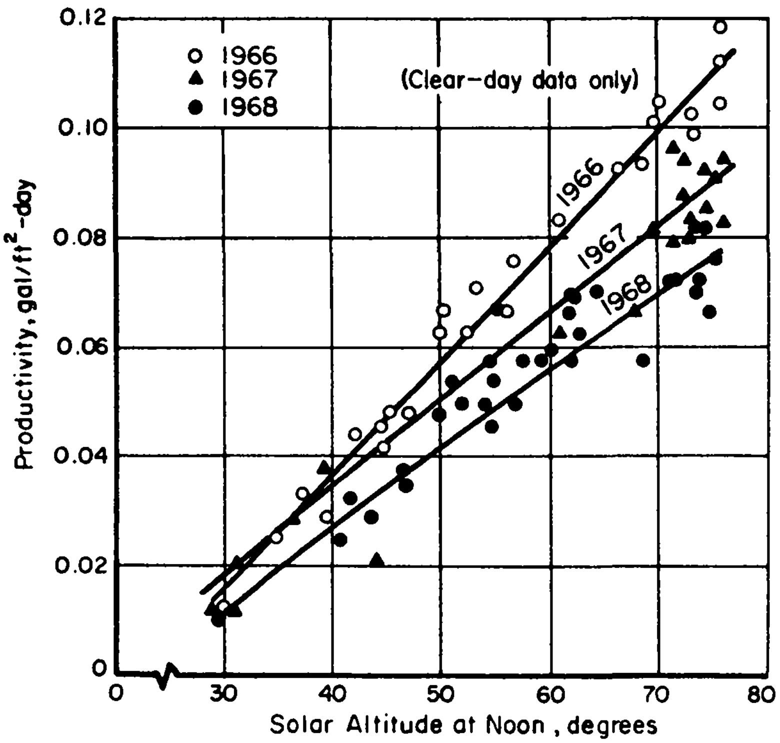



FIGURE 29. PRODUCTIVITY DECLINE OF STILL NUMBER 55 (UNIVERSITY OF CALIFORNIA)

Accidents. The area around a solar still should usually be enclosed with a fence to prevent animals or people from damaging the covers of the still.

Severe winds can lift panes of glass or tear plastic film, so the design must protect against such contingencies. The stills in Australia are surrounded by a mound of earth approximately 18 in. high which acts as a windbreak. This prevents lifting of glass panes on the nearest bay, and subsequent damage due to flying glass. Often, clips or tie downs are used to prevent lifting in regions subject to extreme wind storms. An idea proposed for the bay-type Haiti still was to design one glass pane so that it would swing free if the pressure became excessive (Lawand, 292). Observation ports have also been designed for each end of the bays in the Haiti still, and during any threatened storm these are supposed to be opened to equalize pressures.

If a solar still is built directly on the ground using a basin-liner, it is advisable to first spray the ground with an insecticide and a weed killer. The basin liner can be punctured by weeds growing beneath the liner, or by boring insects. Burrowing animals may also cause problems in some areas. If the site is near the sea, the area can be covered with beach sand and then sprayed thoroughly with seawater to render it sterile.

The basin of a solar still should be kept covered with water to prevent excessive temperatures from occurring within a still. Normally the basin is filled with water before the cover is installed. With some basin-liner materials, such as black polyethylene, the stills cannot be allowed to become dry or the liner will melt. This may also happen if dry spots occur. Some types of materials outgas at high temperatures and coat the inside of the cover. Materials such as butyl rubber and silicone rubber will withstand these higher temperatures, but other difficulties such as thermal expansion may occur. In the Haiti still mentioned above, the observation ports were to be opened at both ends of a bay if for any reason there was no water in that bay.

Experience has also shown that a solar still should be operated continuously year-round. If a solar still is not in use, rain water may soak into the soil underneath the basin and cause ground shifting. By operating continuously, the high basin temperatures will tend to keep the ground dry. If not all of the distillate can be used, and storage is not provided, then the excess can be diverted back into the basin so that normal operating conditions are maintained. Some feedwater can be added as needed to make up for any vapor leakage.

The productivity of solar stills is dependent primarily upon the amount of solar radiation available. Other variables, such as atmospheric conditions and design differences, are of considerably less importance. Therefore, the performance of solar stills is best correlated by plotting the daily water output per unit area of basin as a function of the daily amount of solar energy received per unit area of horizontal surface (e.g., gal/ft$^2$-day versus Btu/ft$^2$-day).

When rainfall is collected from the covers and walkways of a solar still, the yearly output of potable water can be increased. The subject of rainfall collection is discussed in Section 4, together with a graph depicting the amount of rainwater obtained for various collection efficiencies.

Questions often arise as to the relative effectiveness of plastic films versus window glass for covers of solar stills. In an attempt to answer these questions, two inclined-tray stills were constructed at the University of California (Howe, 249; Tleimat, 446). The stills were identical except that one was covered with 1/8-inch-thick window glass, and the other with Type-40 clear Tedlar, 0.002 inch thick, mechanically treated to produce a wettable surface.

Figure 30 compares the performance of the identical glass and plastic-covered, inclined-tray stills (Howe, 249; Tleimat, 446). These data were collected over a 2-year period, beginning in March, 1964. The total production of the plastic-covered still was 82 percent of the total for the glass-covered still. A description of these stills is contained in Section 9, Figure 123.

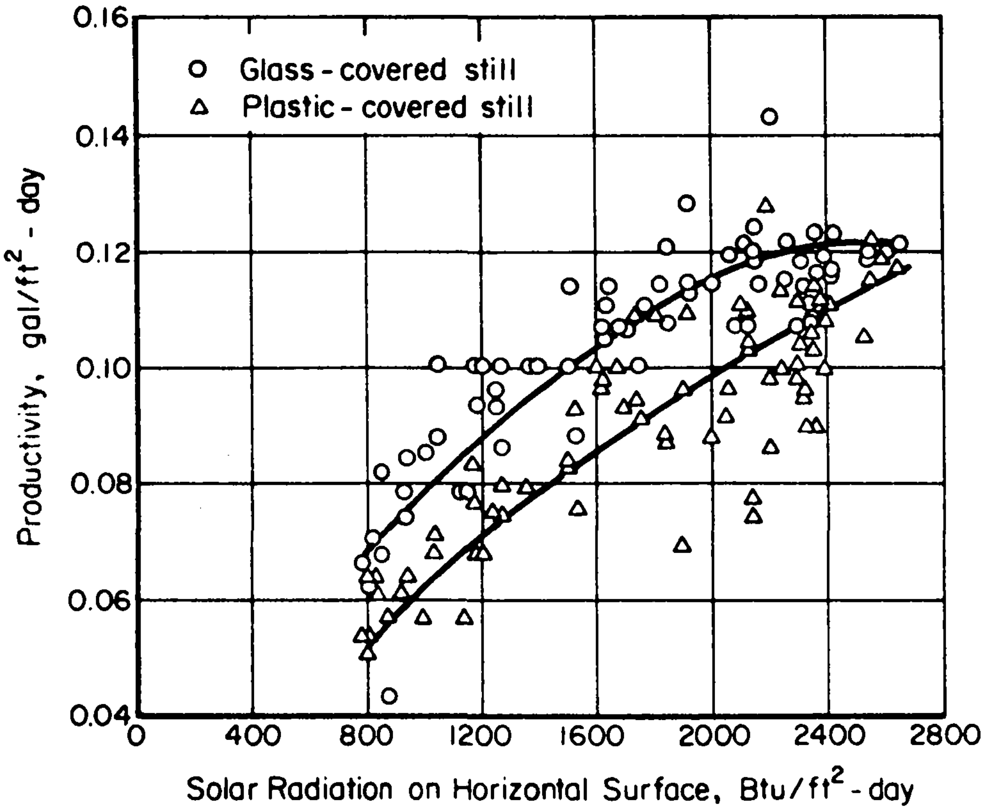



FIGURE 30. COMPARISON OF PERFORMANCE OF GLASS-COVERED AND PLASTIC-COVERED, INCLINED-TRAY STILLS

Figure 31 is a plot of the productivity of several relatively large basin-type solar stills as a function of solar radiation. These curves represent several different still designs and sizes at a number of locations. They are not all directly comparable, however, because of many differences in the conditions under which the data were obtained. Such factors as experimental adjustments during operation, design differences in portions of the same installations, degree of attention to maintenance, etc., render these results only roughly comparable. Superiority of any particular design cannot be inferred from these curves. Indeed, the data show much similarity in performance for considerably different designs and highly variable conditions.

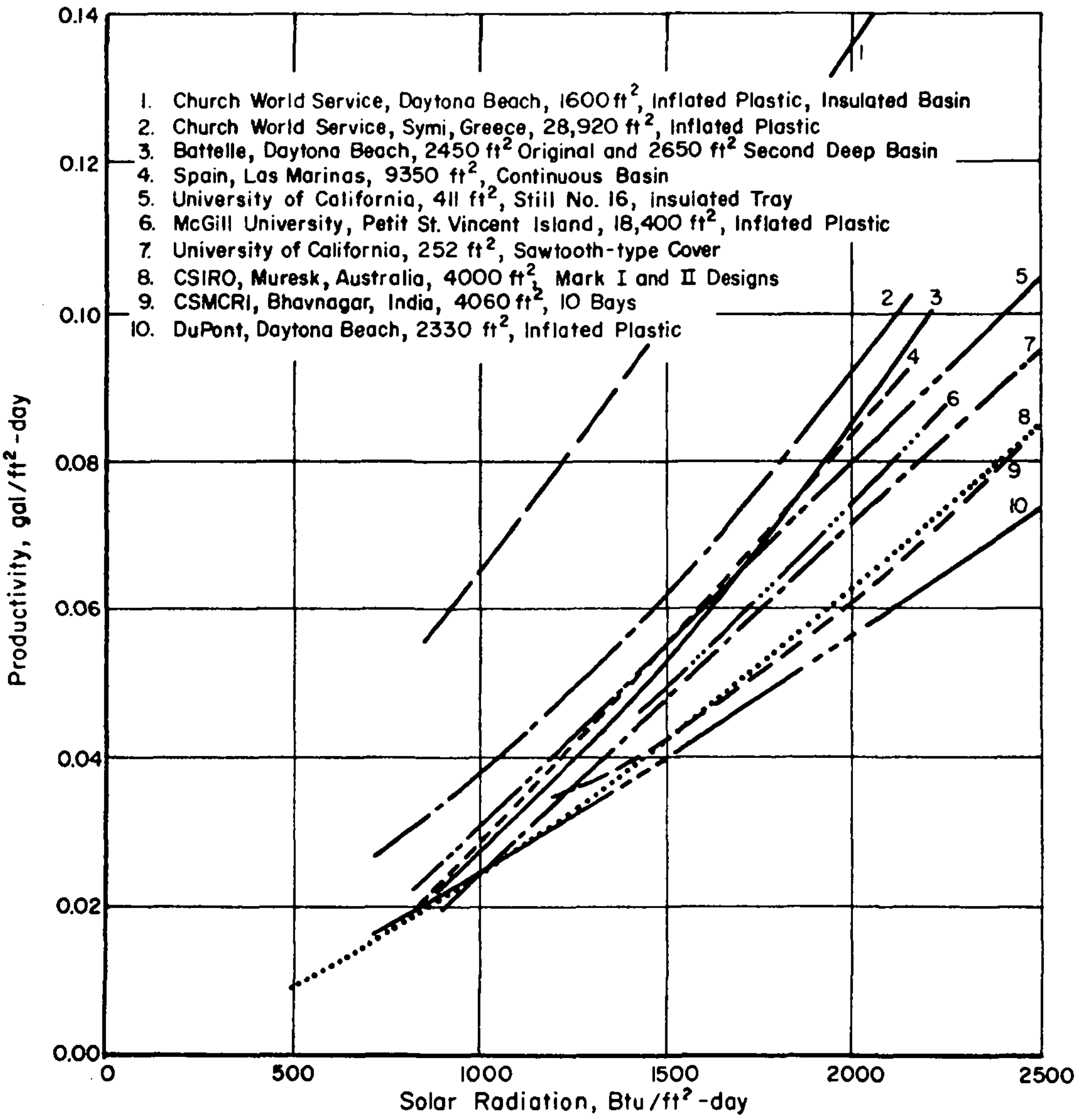



FIGURE 31. PRODUCTIVITY OF LARGE BASIN-TYPE SOLAR STILLS

Considerable scatter exists in the actual data points for each still and these plots represent the average or best-fit curves. The curve for the CWS still in Daytona Beach is based on a limited amount of data. Two possible reasons for the high output of the CWS still are that a 1-in. layer of sawdust was used as insulation beneath the basin liner, and only a 1-in. depth of brine was maintained.

As discussed in Section 4, curve number 3 for the deep-basin still was represented by Equation (8), which is

$$P = 6.17 \times 10^{-4} (R/100)^{1.64}, \text{ gal/ft}^2\text{-day} ,$$

where

$$R = \text{solar radiation, Btu/ft}^2\text{-day} .$$

The average productivity of all the curves, except the highest one, is represented quite well by the following equation:

$$P = 1.10 \times 10^{-3} (R/100)^{1.40}, \text{ gal/ft}^2\text{-day} . \tag{19}$$

The variation from this average at a radiation level of 2,000 Btu/ft$^2$-day is approximately ±25 percent.

## Small Basin-Type Stills

The productivity of small stills is quite comparable to that shown above for large stills. A small still usually will be better sealed, have more insulation under the basin and around the sides, and be better maintained than will a large one built for commercial use. These effects will tend to increase the productivity of a small still at a given solar-radiation level. However, the edge effects of heat losses and shadowing are usually greater in a small still, because the ratio of perimeter to basin area is larger. The combined effects tend to be offsetting, such that the output of small and large stills is roughly comparable.

## Inclined-Tray and Tilted-Wick Stills

The productivity of inclined, or tilted, stills can be considerably higher than basin-type stills, especially during the winter months when the sun's angle of inclination is lower. This increase in productivity is due mainly to the greater amount of radiation received per unit area of evaporating surface, and partly due to higher evaporator temperatures being achieved because of the low thermal mass of the brine.

Figure 32 shows the productivity of three inclined-tray stills (Numbers 21, 34, and 41) and one horizontal-tray, basin-type still (Number 16) tested at the University of California (Howe, 241; Tleimat, 447). Stills 21, 34, and 41 were inclined at 38, 25, and 20 degrees, respectively, from the horizontal. The curve for Still 16 was superimposed for comparison purposes. It must be emphasized that these curves are based on data taken only on clear days, as they are plotted as a function of solar altitude at noon. The approximate radiation levels are included for comparison purposes.

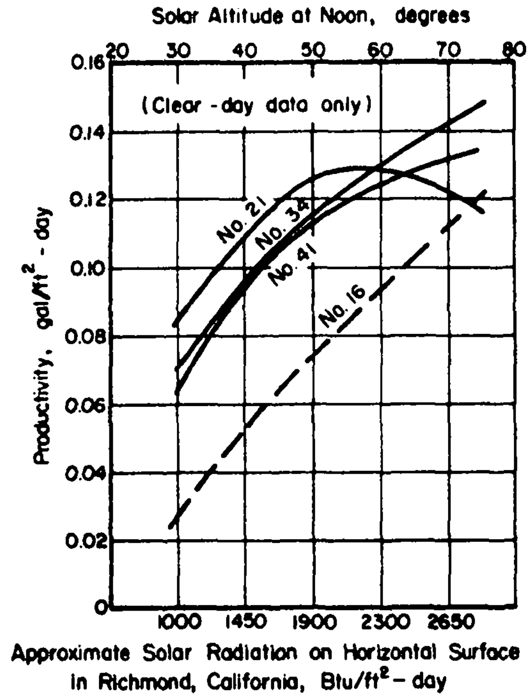



FIGURE 32. PRODUCTIVITY OF INCLINED-TRAY STILLS (UNIVERSITY OF CALIFORNIA)

Figure 33 is a plot of the productivity obtained with an inclined-tray still at the University of Bari, Italy (Nebbia, 374). Models of this general design have been termed Number 8 and are described in Section 9. These are inclined at approximately 20 degrees from the horizontal.

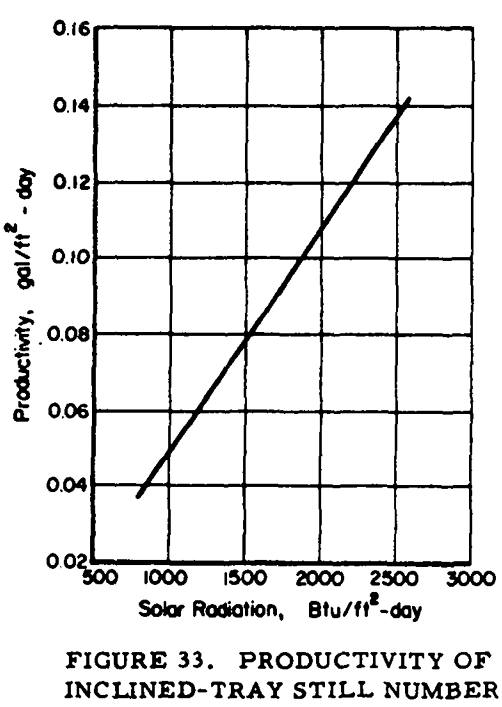



FIGURE 33. PRODUCTIVITY OF INCLINED-TRAY STILL NUMBER 8 (UNIVERSITY OF BARI, ITALY)

Figure 34 gives the productivity of a Telkes' designed tilted-wick still tested at Daytona Beach (Battelle, 54). The radiation measured on a fixed inclined plane cannot easily be related to that received on a horizontal plane because it depends on the inclination of the sun and on the proportion of diffuse radiation. The Eppley pyrheliometer was therefore mounted to measure the solar radiation received in the plane of the still which was tilted 30 degrees from horizontal.

Figure 35 is a replot of the data in the previous figure, but related to the radiation received on a horizontal plane (Battelle, 54). The two curves show the extremes of summer and winter performance. Since the angle of incidence for sunlight on the South-facing tilted stills was much more favorable in winter than in summer, performance was higher in winter at the same horizontal radiation value. The upper extremes of the two curves show the still's productivity under the best conditions (i.e. – on clear days), so such performances can be compared with the clear-day data shown for the inclined-tray stills at the University of California. It is seen that very nearly the same output is obtained at the same solar-radiation levels, indicating approximately equal performance of inclined-tray and tilted-wick stills.

Figure 36 shows several regression lines computed from daily performance data obtained with vertical and nearly vertical wick-type stills (Bjorksten, 73). The effective Btu/ft$^2$-day represents a calculated value of radiation received by the evaporator wick using the measured radiation on a horizontal surface, correcting for the angle of tilt, and assuming the average sun declination occurred at ±30 degrees from the meridian. Still Number 1 was vertical but the others were inclined 15 degrees from the vertical to receive more radiation. Experiments were conducted during the short period between July 13 and September 8, 1955, and cloudy days provided the majority of variation in the amount of solar radiation received. On clear days the radiation on a horizontal plane varied between 2,563 Btu/ft$^2$-day on July 13 to 1,927 Btu/ft$^2$-day on September 6. These values were calculated to represent an effective radiation on the wick of 871 and 1,368 Btu/ft$^2$-day, respectively, for the vertical still and 1,512 and 1,831 Btu/ft$^2$-day, respectively, for the stills inclined 15 degrees from the vertical. The results show that per square foot of evaporator surface, the productivity of the best two stills of this type would exceed that of the horizontal-basin type in winter, but would be considerably poorer in summer. The glass-covered unit appeared to be superior to the plastic-film units. In most latitudes, the annual productivity of vertical, or nearly vertical stills, would be less than that of horizontal basins.

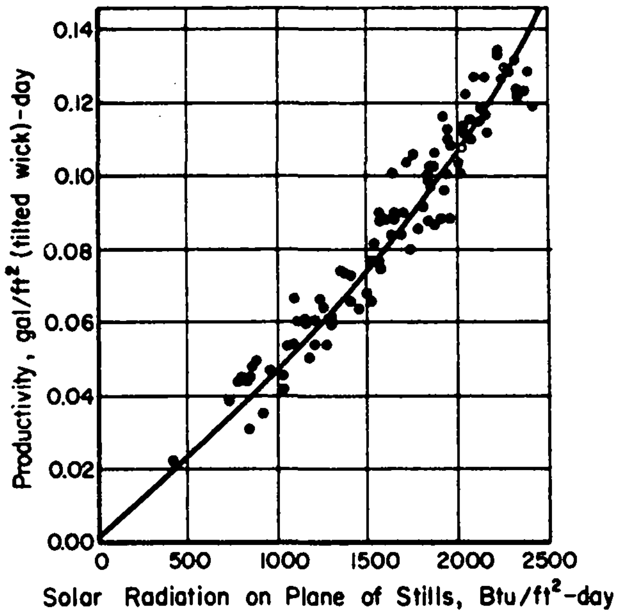



FIGURE 34. PRODUCTIVITY OF TILTED-WICK STILLS (DAYTONA BEACH)

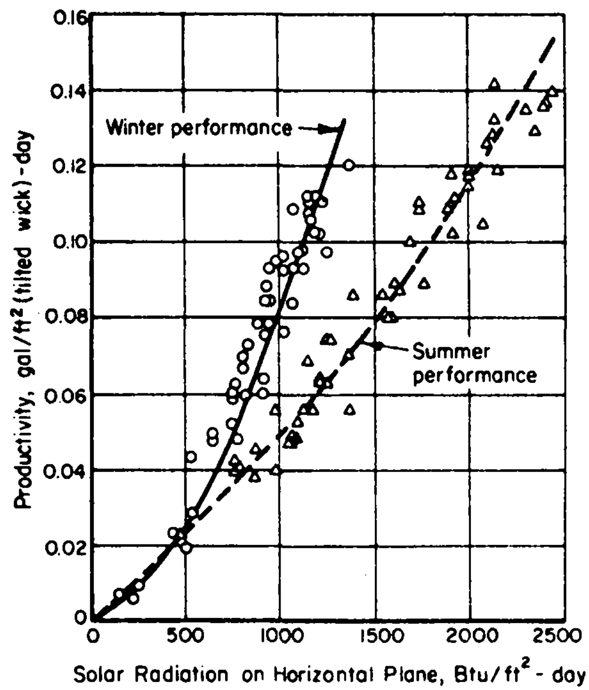



FIGURE 35. PRODUCTIVITY OF TILTED-WICK STILLS, SUMMER AND WINTER

## Miscellaneous Types of Stills

Forced Convection with External Condensation. A detailed study of conventional basin-type solar stills used in conjunction with an external condenser was conducted at the Georgia Institute of

Technology (Grune, et al., 197). It was found that the productivity of a forced-convection still with an external water-cooled condenser could range from below to about twice that of a well-designed conventional solar still which used only the transparent cover as the condenser. At an optimum air-flow rate, an efficiency between 50 and 60 percent was attained.

Figures 37 and 38 show the productivities obtained with two forced-convection, external-condenser-type solar stills (Grune, 197). The average increases in productivity over that of a typical basin-type solar still are about 25 and 60 percent, respectively, for Stills $II_b$ and IV.

Vertical Multiple-Tray Type. A solar still having four small horizontal trays spaced one above the other was tested at the University of Bari in Italy (Nebbia, 367). The trays were completely enclosed with glass.

Figure 39 shows the productivity of this still, based on the combined area of the four trays (Nebbia, 367). On this basis, the productivity is very similar to basin-type stills. However, less ground area is occupied by this means, but if many such stills were required they would have to be spaced far apart to avoid shadows. Therefore, the ground area for an entire facility would probably be comparable to that required by the basin-type still.

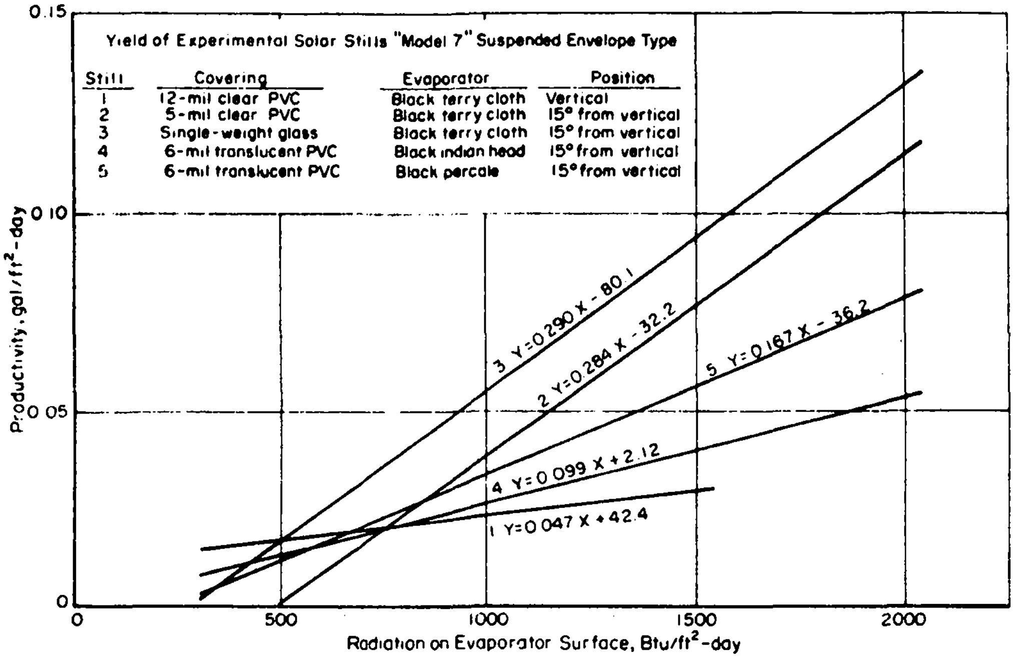



FIGURE 36. PRODUCTIVITY OF SUSPENDED-ENVELOPE STILLS (BJORKSTEN LABORATORIES)

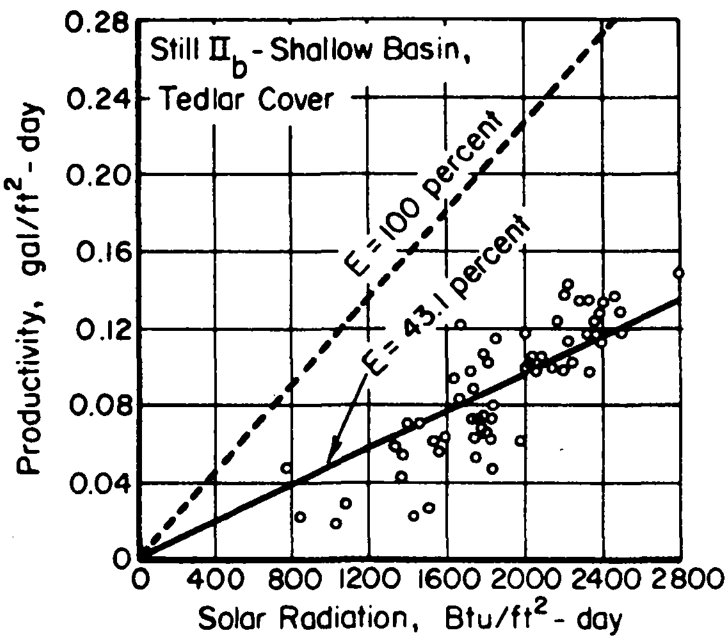



FIGURE 37. PRODUCTIVITY OF FORCED-CONVECTION STILL

Number II (Georgia Inst. Tech.)

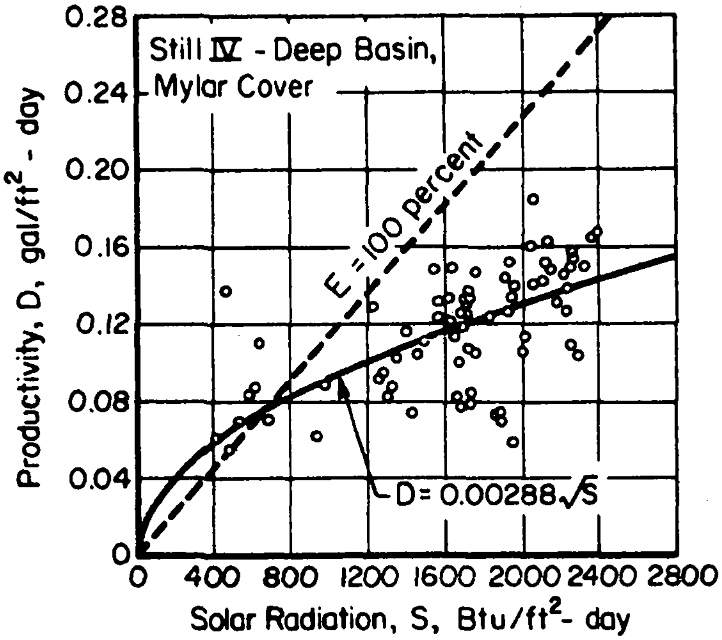



FIGURE 38. PRODUCTIVITY OF FORCED-CONVECTION STILL

Number IV (Georgia Inst. Tech.)

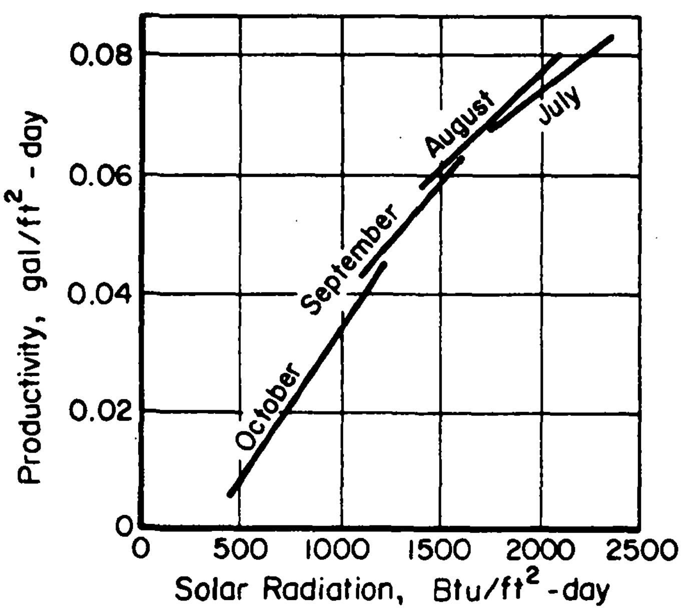



FIGURE 39. PRODUCTIVITY OF VERTICAL TRAY-TYPE STILL (UNIVERSITY OF BARI, ITALY)

# SECTION 6. ECONOMICS OF SOLAR DISTILLATION

The cost of water produced in a solar still depends on (1) the total capital investment in the plant, (2) the costs of operation, maintenance, and repair of the facility, and (3) the water output from the plant. Related factors which can affect the total water costs are the cost of storing water to compensate for the seasonal variations in still productivity, and the quantity and cost of rain water collected from the surface of the still.

Since the solar-distillation process produces a commodity which can be obtained in other ways and which can be supplied from other sources, decisions on the use of the process in particular circumstances must depend also on the alternatives. In this context, two alternatives may be considered. The first is, of course, natural fresh water. The cost of such a supply, in the quantity required, and delivered at the place or places where needed, must be known or determined before prudent decisions can be made. The second alternative is the production of desalted water by some other, nonsolar process such as by multiple-effect distillation, vapor-compression distillation, reverse osmosis, electrodialysis, or some other process. The cost of water obtained by one of these methods must also be estimated so that the delivered cost of water so obtained may be compared with the cost of solar-distilled water.

In the following discussion, cost considerations are limited to those involving solar-distilled water, inasmuch as ample information is available elsewhere on natural-freshwater costs and the costs of desalted water produced by other, more-conventional processes. It is shown that the interrelationship of cost and production factors is such that, (1) the costs of desalted sea water and brackish ground water may be lower than natural-freshwater costs in arid regions where freshwater supplies would have to be transported long distances by means of expensive systems, and (2) water produced in solar stills may be cheaper than any other desalted-water supply if the climate is favorable and if relatively small water outputs (possibly up to 50,000 gpd) are required.

In most desalting processes the cost of energy is a large, if not the largest, item of expense. Capital costs (interest, amortization, etc.) are usually the next largest item. In solar distillation, however, the energy costs nothing, and more than 90 percent of the water cost results from charges on capital investment. Thus, efforts to reduce the cost of solar-distilled water are directed primarily at maximizing the water output per unit of annual fixed costs. There is no value in making more efficient use of the energy input unless, by so doing, water yield per unit of annual fixed costs is enhanced. With the more conventional desalting processes, however, where energy is a primary factor in the total cost, efforts to increase water output per unit of energy supplied are obviously desirable, even at the expense of additional investment in facilities.

As in any capital intensive operation, it is important to operate the plant at the highest possible load factor to minimize costs. In other words, idle equipment, if that equipment represents the main cost of production, increases the cost of the product per unit of output. Full use of the water produced by a solar still is therefore essential for economical design.

It must not be assumed, however, that simply minimizing the first cost of a solar still will result in the cheapest solar-distilled water. For if by so doing, the useful life of the facility is decreased and the investment has to be amortized over a shorter period, the cost per thousand gallons of output may be increased. Consequently, it is important to recognize that the capital cost per total water output over the life of the plant is the important criterion. In other words, the annual cost of the investment (including interest, amortization of principal, taxes, insurance, and any other factors directly related to capital investment) divided by the annual water production should be minimized.

As will be demonstrated, the costs of operating and maintaining a solar still may be, and certainly should be, a very small item in the total cost of water production. With suitable design, a solar still may be made virtually self-operating, requiring only occasional inspection and servicing. Similarly, routine maintenance and repair can be reduced to a satisfactory minimum by proper design. In the sizes where solar distillation appears useful, it is essential that both of these expense items be small or else they will probably be entirely too large to tolerate. For example, a full-time operator would require an outlay of several dollars per thousand gallons produced from a small still (below 10,000 gpd capacity) simply in his wages. This would, of course, be true for any desalting process where continuous operating labor would be required. In the solar-distillation process, however, experience shows that operating and maintenance personnel can be minimized by suitable design.

Finally, the cost of water produced from a solar still, typically \$3 to \$4 per 1,000 gallons, decreases only slightly as plant size increases. This is because the method of constructing the solar still, once capacities of a thousand gallons or more per day are involved, does not significantly change as plant size is increased. Thus, the cost of construction per square foot of distiller area does not decrease markedly in sizes above this level. Quite the contrary is the case with other desalting processes. As size increases, the capital cost per unit of capacity decreases substantially. Moreover, advantage can be taken in the larger sizes of energy economies and the additional cost of so doing is more than offset by the fuel savings.

Just as the costs of conventional desalting processes decrease with larger plant sizes, the costs rise sharply as plant sizes are reduced. At capacities as low as 50,000 gpd, multiple-effect evaporation, for example, is prohibitively costly – many dollars per thousand gallons. All items of expense increase – capital investment per unit of output, energy costs (due to decreased efficiency in smaller sizes), and particularly, costs of operating labor per unit of output. Thus, where water demands are modest and where the climate is favorable, solar distillation appears to have a substantial advantage over the more conventional processes.

## Capital Costs

The cost of fabricating a large solar still is affected by numerous factors. Among these are the size of the unit, the design employed, the type of materials used, the cost of skilled and unskilled labor, and various local conditions. Investment per unit of annual distillate output is also dependent on the climate (primarily solar radiation) and on operating efficiency. Although several large solar stills have been built, capital costs are still subject to some uncertainty because of the experimental nature of all the installations to date. Even though the distilled water produced in most of these units has been utilized, novelty in design, auxiliary equipment for experimental testing, and design and fabrication mistakes have artifically increased construction cost.

The rather limited production of small, family-size stills likewise limits the usefulness of cost estimates based on these figures. Economies could certainly be realized in larger scale manufacture.

In spite of the limitations cited above, there is sufficient experience with construction of solar stills to permit (1) completely reliable capital costs for several of the distillers, as actually incurred, and (2) reasonably reliable projections (say within 10 to 20 percent error) of construction costs which would be expected if all of the novel and experimental features were eliminated and if the facilities were built on the basis of existing, tested designs. Finally, a fair degree of reliability can be ascribed to estimates of capital cost based on designs involving other materials and methods which might be employed in the future.

Experience with building solar stills in the USA, notably with the programs of the Office of Saline Water, has shown that the division of construction costs between labor and materials is on the order of about 35 to 40 percent for labor, with the balance for materials. This fraction of course will vary with the design, the extent of prefabrication of components, the use of machinery in construction and assembly, and the prevailing wage rates. In countries where labor rates are much lower, only 15 to 20 percent of the total cost of the installation may be in construction labor. Also, the over-all capital costs are expected to be lower in the less-developed regions of the world, even though there might be slight increases in the cost of materials due to transport problems, import requirements and the like. However, since most of the solar-still designs involve the use of materials commonly available in almost all countries, this factor would generally be of little significance.

Nearly all of the cost of a large solar-distillation plant is associated with the still itself (i.e. – ground preparation, curbs, basin liner, cover supports, cover and condensate channels). This portion of the total capital cost is almost directly proportional to the area of the distillation basin. There are some other costs, however, which are relatively independent of basin area, or, if dependent, only to a small extent. There are the reservoirs for salt water and distilled-water products, rain-water reservoir (if any), salt-water supply pump and distilled-water product pump, piping external to the still, valves, controls, and miscellaneous items. In a large installation, the total of all these items is only a few percent of the entire capital cost. For example, a 100,000-$ft^2$ still requiring an investment of about \$100,000, would probably have no more than \$5,000 worth of these supporting facilities. If, however, the distiller were only 10,000 $ft^2$, the supporting facilities may cost as much as \$3,000 to \$4,000, resulting in a substantially larger total investment per unit of productivity. It is clear from these considerations that larger plants can be somewhat cheaper per unit of capacity than smaller plants, and that the total cost per square foot of solar still is generally the most important consideration in solar distillation economics.

On the basis of experience in the construction of nearly a dozen large solar stills, the range of capital cost which has been experienced is about 65¢ to \$2/$ft^2$ of basin area. From these experienced costs, estimates of anticipated cost of stills employing the same general designs but with the use of larger sizes, construction economies of various types, and other savings, investment requirements of about \$1/$ft^2$ down to approximately 60¢ have been made. There is little doubt that future solar stills of durable designs can be built at costs in this range.

A final general point on capital investment requirements is the cost of land on which the solar still is constructed. Although solar distillation requires far more land than any other desalting process, there would rarely be a situation where this would be a significant cost factor. In a rather extreme example, a solar still might be built on commercial or residential land in or near a small community which is valued at \$1000 per acre. This is equivalent to about 2¢/$ft^2$ – an insignificant item in the typical \$1/$ft^2$ plant cost. Ordinarily, land should be available at prices well below this figure, so its cost is of little consequence.

## Daytona Beach Stills

The first glass-covered deep-basin solar still constructed at Daytona Beach was an experiment directed toward establishing the validity of the principle that a massive, deep-basin distiller constructed directly on the ground, without insulation, would operate with good efficiency and minimum maintenance expense. The design was not intended as a production prototype, and therefore the materials and methods of construction were not concerned with economical objectives. Therefore, its final cost of more than \$5/$ft^2$ has no relevance to the economics of practical solar stills.

Table 7 shows the actual costs of construction (materials and labor) for the second deep-basin still built at Daytona Beach (Battelle, 54). This still was built largely on the experience obtained with the first unit, but was designed and built with economy as a principal objective.

The construction labor was figured at $4 per man-hour. It is seen that the largest items are the purchase and installation of the asphalt mat liner, 45¢/ft², and the glass cover, also 45¢/ft². The next largest item is the concrete precast beams, 35¢/ft², followed by the land preparation, 32¢/ft². The total cost, $2.04/ft², includes miscellaneous contractor's costs and profits.

TABLE 7. CONSTRUCTION COST BREAKDOWN OF SECOND DEEP-BASIN STILL (DAYTONA BEACH)

| Item | 2650-Ft² Still, actual cost per ft², $ | | | 1,000,000-Ft² Still, estimated cost per ft², $ | | |
|---|---|---|---|---|---|---|
| | Material | Labor | Total | Material | Labor | Total |
| Layout, grading, compacting | 0.04 | 0.28 | 0.32 | 0.01 | 0.09 | 0.10 |
| Asphalt mat liner | 0.28 | 0.17 | 0.45 | 0.15 | 0.10 | 0.25 |
| Concrete blocks | 0.06 | 0.04 | 0.10 | 0.06 | 0.04 | 0.10 |
| Lintels | 0.22 | 0.13 | 0.35 | 0.19 | 0.10 | 0.29 |
| Glass | 0.33 | 0.12 | 0.45 | 0.25 | 0.10 | 0.35 |
| Miscellaneous piping | 0.03 | 0.01 | 0.04 | 0.03 | 0.01 | 0.04 |
| Distillate trough | 0.03 | 0.02 | 0.05 | 0.03 | 0.02 | 0.05 |
| | 0.99 | 0.77 | 1.76 | 0.72 | 0.46 | 1.18 |
| Contractor's fee(a) | | | 0.28 | | | 0.12 |
| Total | | | 2.04 | | | 1.30 |

(a) Taken as 16 percent for small still and 10 percent for large still.

Also shown in the table are estimates for a one million-ft² solar still of identical design. Such a still would have an average annual capacity of about 70,000 to 80,000 gpd in a sunny climate. It is seen that economies of scale, even without design change, permit a reduction in total cost to about $1.30/ft². Again the glass, liner, and concrete beams are the largest items. Although these costs are based on an extremely large still, almost exactly the same figures would be obtained for a size only one-fifth as large, or 200,000 ft². This is because the methods of construction and the large-volume purchase of materials would permit the same price and cost structure.

Table 8 contains capital costs which are a projection on the basis of further improvements in distiller design and the substitution of some materials which have been found (subsequent to the preparation of the initial estimates) to be more satisfactory and more economical (Battelle, 54).

TABLE 8. CAPITAL COST ESTIMATES FOR IMPROVED DEEP-BASIN STILLS

| Plant Capacity(a), gpd | 330 | 100,000 |
|---|---|---|
| Basic Materials(b), $/ft² | $0.90 | $0.60 |
| Labor, Site Preparation, Assembly(b), $/ft² | 0.70 | 0.30 |
| Contractor's Fee(c), $/ft² | 0.26 | 0.09 |
| Total Cost, $/ft² | $1.86 | $0.99 |

(a) Average productivity assumed to be 40 gal/ft²-yr (distillate and rainwater collection).
(b) Land acquisition and property taxes not considered. Materials and labor costs appropriate to eastern seacoast of United States, with labor costs of $4/man-hour.
(c) Contractor's fee taken as 16 percent for small still and 10 percent for large still.

Table 9 shows a breakdown of costs in the U. S. for the latest variation of the OSW deep-basin Daytona Beach design (Battelle, 55; Bloemer, 87). The table shows the construction labor in terms of man-hours, rather than dollars, in order that they can be used in regions where labor costs are quite different from those in the United States. The approximate plant size on which these figures are based would be in the range of 50,000 $ft^2$ and above. It is seen that if a labor rate of $4/hour is assumed, the total cost is approximately $1.25/$ft^2$. If, however, the labor wage rate comparable to that in some of the less-developed areas were used, say 50¢/man-hour, the cost is only about 80¢/$ft^2$.

TABLE 9. TYPICAL BASIN-TYPE STILL COSTS WITHIN THE UNITED STATES

| Item | Material, $/1,000 $ft^2$ of Basin Area | Labor, Man-Hours/ 1,000 $ft^2$ of Basin Area |
|---|---|---|
| Layout, grading, compacting, and soil sterilization | 10 | 20 |
| Asphalt-mat liner | 80 | 40 |
| Concrete blocks | 60 | 10 |
| Precast-concrete beams | 190 | 25 |
| Glass and asphaltic cement | 210 | 25 |
| Distillate-trough materials | 50 | 5 |
| Miscellaneous piping and pumps | 70 | 5 |
| Storage tank | 50 | 5 |
| Total | 720 | 135 |

Table 10 shows the estimated capital costs of a large-basin still constructed in a developing country having a 50¢ hourly wage rate (Battelle, 55; Bloemer, 87). The total investment of about 90¢/$ft^2$ and an annual productivity of about 25 gallons of distilled water and 8 gallons of rain-water per square foot would be equivalent to $10 per average daily gallon production capacity. In a plant of this size, this level of cost should be readily attainable. Developments which have occurred since the above estimate was reported may actually reduce the costs below those estimated.

TABLE 10. BASIN-TYPE SOLAR STILL CAPITAL COSTS

50,000-gpd Capacity; 550,000 $Ft^2$[(a)]

| | |
|---|---|
| Basic Still Materials, $0.72/$ft^2$ | $396,000 |
| Erection and Assembly, $0.50/man-hour | 39,600 |
| Instruments | 5,000 |
| Feedwater Supply | 500 |
| Contingencies | 20,000 |
| Engineering | 4,000 |
| Construction Interest | 25,600 |
| Site | 1,500 |
| Total Plant Investment | $492,200 |

(a) Distillate plus rainwater = 33 gal/$ft^2$-yr.

## Australian Stills (CSIRO Designs)

Capital costs of the several models of the CSIRO stills have not been published in detail. Most of the stills have involved a certain amount of experimental design, so actual costs would be somewhat misleading unless adjustments were made. In discussions with the designers, however, it has been stated that the latest design (Mark IV) involves a total material cost of 35 to 45¢/$ft^2$ and that the total cost of the installation lies between $1 and $1.50/$ft^2$. It has also been reported (Morse, 344, 347) that one of the stills (Muresk II, Western Australia) was built for approximately 60¢/$ft^2$, total cost. However, the horticultural glass used in the Australian still is available for less than 10¢/$ft^2$ (Morse, 344, 345) and the polyethylene film for the bottom of the distiller should be available at costs not exceeding 2 to 3¢/$ft^2$. Information on costs of the other components should be available in the near future.

In summarizing the CSIRO conclusions on capital cost, it has been suggested that under Australian conditions, the installed cost of a solar still should range from 70¢ to $1.30/$ft^2$ of glass area. At an average annual productivity of 25 gal/$ft^2$-yr, corresponding to 0.0685 gal/$ft^2$-day, the capital investment becomes approximately $10 to $20 per average daily gallon of capacity.

## Greek Stills

Two concurrent solar distillation developments in Greece have been indicated. Three plants employing the design developed at the Technical University of Athens by Delyannis have been constructed on the islands of Patmos, Kimolos, and Nisiros. This design is essentially a series of long, narrow bays lined with Butyl rubber sheet and covered by an arrangement of glass panes supported on an aluminum-framework. The parallel development, sponsored by Church World Service, has involved the construction of plastic-covered stills on the islands of Symi, Aegina, and Salamis. Three variations have been used, all based on long, narrow, plastic-covered bays. These variations have comprised air-inflated covers, weighted-V covers, and stretched covers sloped in a single direction with tightness being maintained by tension-loaded side rails.

Glass-Covered Stills (Technical University of Athens Design). Actual costs of the three distillers employing this design have not been published. Estimates prior to construction, however, placed the investment cost at about $10/$m^2$ or slightly less than $1/$ft^2$ (Delyannis, 132). Also prior to construction it was stated (Delyannis, 140), that material costs per square foot would be: Butyl liner 22¢, aluminum extrusions for frames 26-1/2¢, and glass 21¢ (conversion, 30 drachmas = $1.00). These items total approximately 70¢/$ft^2$.

Table 11 gives an approximate distribution of investment costs of the 93,000-$ft^2$ Patmos still that has been made available (Read, 396).

It is seen that the actual costs of glass, aluminum, and butyl exceeded the estimates by only small factors, but the costs of numerous other items and of labor place the total investment at a relatively high level.

The Kimolos still, of the same design but only 27,000-$ft^2$ area, was built for about $61,000, of which 24 percent was for 135 man-months of labor, 49 percent was for materials, 8 percent was for shipping, and 19 percent was for a special 4-in. concrete slab on which the butyl lining and the rest of the still were installed (Read, 396). It is seen that the unit cost of this still was somewhat higher than that of the Patmos installation, primarily because of the concrete slab considered desirable, and to some extent because of the smaller size. Deducting the cost of the slab, the cost of about $50,000 for a 27,000-$ft^2$ still is equivalent to approximately $1.85/$ft^2$, about 12 percent above the unit cost of the Patmos plant.

TABLE 11. CAPITAL-COST DISTRIBUTION FOR PATMOS STILL

| Item | Cost/Ft$^2$ | Item | Cost/Ft$^2$ |
|---|---|---|---|
| Glass | \$0.248 | Electric Supplies and Pump | \$0.051 |
| Aluminum Frames | 0.300 | Transport Costs | 0.074 |
| Butyl Liner | 0.288 | Insurance | 0.026 |
| Cement | 0.048 | Concrete Tanks for Salt-Water Supply, Distillate, and Brine | 0.055 |
| Sand and Gravel | 0.054 | | |
| PVC Pipe and Valves | 0.065 | Auxiliaries (fence, canal, etc.) | 0.122 |
| Subtotal | \$1.003 | Subtotal | \$0.328 |
| | Total Materials Cost | \$1.331/ft$^2$ | |
| | Total Labor Cost, semiskilled at \$3.56 to \$4.46/day, technician at \$6.25/day | 0.306 | |
| | Totals Installed Cost of Plant | \$1.637/ft$^2$ | |

Plastic-Covered Stills (Church World Service Sponsored). There is no published information on the capital cost of any of the Greek plastic-covered stills. A personal communication with Eckstrom in November, 1965 indicated a capital requirement for the V-cover Aegina still of about \$30,000 for the 16,000-ft$^2$ installation. The investment included the cost of site preparation, salt-water reservoir, a fresh-water tank, and the pump house, as well as the still itself. The latter item involved an expenditure of \$20,100. The total investment in the distiller and auxiliaries was therefore approximately \$1.75/ft$^2$.

An estimate of the construction cost of a small section of an inflated plastic still was based on a 1600-ft$^2$ pilot installation at Daytona Beach (Battelle, 55). Based on the actual labor of construction, approximately 30¢/ft$^2$ was involved for construction labor at \$4/man-hour. With an estimated materials cost of 50¢/ft$^2$, the total investment required would be 80¢/ft$^2$. This design, however, was found to require modifications prior to full-scale construction, so the estimated investment would have to be considered to be lower than that involved in the Symi installation.

No cost data on the mechanically tensioned plastic-film design, built on full scale as a replacement unit on the island of Aegina, have been published. This new design was employed in order to improve the effectiveness and durability of the distiller rather than to lower its cost. Consideration of its design features indicates that construction cost would not be less than that of the V-cover still, and possibly somewhat more. It might therefore be estimated that the investment requirements in this new design would lie somewhere between \$1 and \$2/ft$^2$.

Some partial cost data on the rebuilt Aegina still employing mechanically tensioned plastic film have become available (Read, 396). For materials only, the following investments are involved: Tedlar film – 27.6¢/ft$^2$, butyl liner – 22¢, aluminum extrusions – 13.4¢, concrete in place – \$13.40/yd$^3$, equivalent to an estimated (by authors) 13¢/ft$^2$. These items total 76¢/ft$^2$. If insulation, site preparation, tanks, piping, and labor costs are included, it is seen that the total investment will be in the \$1 to \$2 range, and probably near the \$1.75/ft$^2$ cost of the original V-cover still at that same site.

Spanish Still (Las Marinas)

The 9,350-ft$^2$ solar still at Las Marinas was built at a cost equal to 71,430 French francs, equivalent to approximately \$14,600. The capital cost was thus \$1.56/ft$^2$. Various special items such as dual salt-water sources, special instrumentation, and other auxiliaries would not be required in a plant having no experimental features. Eliminating the cost of these special items results in an adjusted total capital investment of 48,200 francs, or \$9,850 – approximately \$1.05/ft$^2$.

Table 12 shows an itemized expense for the Las Marinas installation (Lof, 318). It is seen that the basin lining and glass covers constitute almost half the investment requirement and that the concrete beams represent another 20 percent. The lower cost for land preparation than in the similar Daytona Beach installation is due mainly to the lower price of labor in the Spanish location.

TABLE 12. CAPITAL COST OF SOLAR STILL AT LAS MARINAS[a]

| | Actual Cost, \$ | Adjusted Cost, \$ | Actual Cost, \$/ft$^2$ water surface | Adjusted Cost, \$/ft$^2$ water surface | Distribution of Adjusted Costs, percent |
|---|---|---|---|---|---|
| Land Preparation | 242 | 242 | .026 | .026 | 2.5 |
| Concrete Beams | 1,968 | 1,968 | .211 | .211 | 20.0 |
| Masonry | 584 | 584 | .063 | .063 | 6.0 |
| Basin Lining, Glass Covers | 4,695 | 4,695 | .502 | .502 | 47.5 |
| Piping, Channels | 1,752 | 944 | .188 | .101 | 9.6 |
| Miscel. Equip. | 2,300 | 961 | .246 | .103 | 9.9 |
| Electrical | 1,660 | 0 | .178 | .000 | 0.0 |
| Special Works | 1,362 | 442 | .146 | .047 | 4.5 |
| Totals | 14,563 | 9,836 | 1.560 | 1.053 | 100.0 |

(a) Basin area (area within outer edge of salt-water surface) = 9,350 ft$^2$.

The Spanish Research and Development Group believes that further cost reductions are possible, perhaps as much as 30 percent, by additional development and improvement. Savings in cost of glass covers, concrete beams, and the basin lining are believed possible. A projected total cost of 70¢ to 80¢/ft$^2$ has been envisaged for future installations of this design.

## Petit St. Vincent Island Still

Fifteen bays with inflated plastic film (polyvinlyfluoride "Tedlar") covers, each with a projected cover area of 1285 ft$^2$, were installed between March, 1967, and March, 1968.

Table 13 gives a breakdown of capital costs for the Petit St. Vincent still, based on one bay of 1,285 ft$^2$ (Lawand, 290).

The costs shown are those directly associated with an individual unit. They do not include the salt-water-supply system, product water collection and storage, piping, pumps, air blower, and general plant requirements. It has been reported that the total cost of the entire 19,300-ft$^2$ plant (projected cover area), including all facilities, is about \$3.13/ft$^2$ (Lawand, 290).

TABLE 13. CAPITAL COSTS OF INFLATED PLASTIC STILLS, PETIT ST. VINCENT

| Materials[a] | Cost, $ (US) | Labor Time, hr | Labor Cost at 29¢ to 59¢/Hr (in Brit. West Indies), $ (US) | Percent of Total |
|---|---|---|---|---|
| Plastic film cover (4 mil) | 570 | 40 | 20 | 25 |
| Butyl liner (30 mil) | 400 | 75 | 38 | 22 |
| Floating mat | 100 | -- | -- | 0[b] |
| Clamping system | 363 | 208 | 104 | 19 |
| Foundation and concrete curbs | 185 | 1325 | 363 | 23 |
| Fittings | 70 | 48 | 24 | |
| Supervision (20 percent) | | 340 | 170 | 11 |
| Subtotal | | | 719 | |
| Administration (20 percent of materials) | | | 337 | |
| Totals | 1688 | 2036 | 1056 | 100 |
| Costs/ft$^2$ | 1.31 | | 0.82 | |
| Total cost | | 2.13/ft$^2$ | | |

(a) Based on one bay with projected cover area of 1,285 ft$^2$.
(b) Negligible because of probable deletion in future units.

Indian Stills (CSMCRI, Bhavnagar)

There are 12 glass-covered stills at this location ranging in size from about 110 ft$^2$ to 530 ft$^2$, totalling 4060-ft$^2$ basin area.

Table 14 gives a breakdown of the capital costs for this installation. Including labor and materials, the total cost was approximately 80¢/ft$^2$ (Ahmed, et al., 35):

TABLE 14. CAPITAL COST OF CSMCRI STILLS

| | Cost, ¢/ft$^2$[a] | Percent |
|---|---|---|
| Site Preparations | 0.7 | 0.9 |
| Foundation Work | 1.3 | 1.6 |
| Murran (gravel) Filling | 3.3 | 4.1 |
| Bottom Concrete Work and Plastering | 11.3 | 14.1 |
| Brick Masonry and Plastering | 8.7 | 10.9 |
| Precast Items | 5.3 | 6.6 |
| Rain-Water Collection Including Gutters and Piping | 2.7 | 3.4 |
| Painting | 1.3 | 1.6 |
| Feeding Channel, Piping, Distillate-Collection Channels and Man-Holes | 9.4 | 11.8 |
| Glass Fixing | 18.0 | 22.5 |
| Tanks, Pumps, etc. | 18.0 | 22.5 |
| | 80.0 | 100.0 |

(a) Conversion: 7.50 Rupees = $1.00.

There appears to be some doubt that a concrete bottom is sufficiently leak-proof, so the cost would rise appreciably if butyl rubber or even preformed asphalt sheets were used. The

Indian workers visualize the possibility, however, that costs can be reduced by various means, including a continuous-basin or pond-type design rather than separated long, narrow bays, and possibly by use of soil sealants rather than more expensive linings. They have recently reported that for installations having an area of 10,000 $ft^2$ or larger, a cost saving of 10 to 20 percent is expected for pond-type construction as compared to bay-type construction (Datta, 124). A construction cost as low as 63¢/$ft^2$ is thought possible by use of these measures. It must be recognized, however, that these estimates are subject to the limitations imposed by the rather small scale of the pilot plant on which they are based.

## Tunisian AEC Stills

Three glass and masonry stills in Tunisia, of 430-$ft^2$, 4730-$ft^2$, and 14,000-$ft^2$ evaporating area, have been supplying distilled water to communities of various sizes (40, 500, and 2000 persons). The brackish ground-water supply ranges from 0.6 to 1.8 percent salinity. No cost breakdowns have been published, but it has been reported (Tunisian AEC, 455) that the total cost of these stills is between 5 and 7 dinars/$m^2$, equivalent to \$0.88 to \$1.24/$ft^2$. It is thus evident that in respect to plant investment, this design, under these North African conditions, requires an investment comparable to those realized in Spain, India, Australia, and projected in the United States.

## Russian Still in Turkmenia

The estimated costs for the 25,800-$ft^2$ solar still under construction in the Bakharden District of Turkmenia have been reported by Baum and Bairamov (63). Table 1 in that paper indicates a capital cost for a particular installation capable of supplying water to 7,000 sheep, equivalent to 24.46 rubles/$m^3$ of water produced per year. On the basis of the reported productivity of test distillers in this area of approximately 1.04/$m^3$ of water/$m^2$ of distiller per year, equivalent to 26.5 gal/$ft^2$-yr (Baum, 66), the equivalent capital cost (one ruble = \$1.11) is \$2.64/$ft^2$. In a projection of the design to a subsequent installation capable of watering 5,000 sheep, presumably with certain economies introduced, a capital cost factor of 9.11 rubles/$m^3$-yr of water was estimated. This is equivalent to a capital cost of 98¢/$ft^2$ of distiller area.

Baum, et al., have also reported computations on investment costs for their basin-type solar still (Baum, 65). They show a capital cost variation from 22.52 to 23.61 rubles/$m^2$ as the salinity varies from 40,000 ppm to 10,000 ppm. Using an average of 23 rubles/$m^2$, the capital investment becomes \$2.35/$ft^2$. This cost is apparently based on a somewhat simplified design of the original 2400-$m^2$ (25,800 $ft^2$) still, but not so extensively modified as in the basis for the foregoing 98¢/$ft^2$ estimate.

# Operating Costs

Reliable information on the costs of operating solar stills is even more scarce than the data on capital costs discussed above. This is due not only to the fairly limited number of solar stills in practical operation (thereby limiting the amount of available information), but also and more significantly to the fact that none of the stills has been in operation long enough to permit reliable appraisal of a depreciation rate, the most important factor in the cost of operation. A third difficulty is the uncertainty and lack of information on the cost of distiller repair.

In spite of the above problems, and some others discussed below, some estimates of solar-distiller operating costs have been made, and the results of these estimates now appear to be reasonably useful in comparing solar distillation with other desalting methods and with the costs of providing natural fresh water to a community. These estimates have been based partially on experience with actual installations and partially on engineering and economic principles as they relate to such equipment. Operating costs so estimated are the aggregate of investment amortization, interest charges, taxes, insurance, repair supplies and labor, operating and supervisory labor, and raw materials and energy.

Amortization, interest, taxes, and insurance may be considered fixed charges, allocated as certain percentages of the total capital investment. Maintenance expense and operating labor costs, not usually considered proportional to investment, are estimated on the basis of specific data on comparable facilities. Raw materials and energy costs are proportional to the output of the plant. In the following subsections, these fixed cost distributions are analyzed.

## Amortization of Investment

The investment of capital in a commercial or industrial facility is commonly recovered during the expected useful life of the facility by charging a portion each year as part of operating costs. Various methods and schedules employed involve equal, increasing, or decreasing payments each year. If the components of the plant have different lifetimes, depreciation of each may be separately estimated and totalled. The rate of amortization of the investment in a solar still involves consideration not only of the useful service life but also the rate of obsolescence. The amortization period must usually be taken as the shorter of the depreciation or obsolescence intervals.

For purposes of appraising amortization rates, large solar stills may be conveniently divided into two main types and the small stills may be considered separately. One group of the large installations has been constructed of materials commonly used in buildings, such as glass, concrete, and asphalt; the other type has been built of less durable materials such as thin plastic films and wood. Some installations have involved both types of materials. Since the life of these components is quite different, the two types of large solar stills are best considered separately.

Considering first the useful service life of the group of stills employing ordinary building materials, it may be expected that the components will serve as long as they ordinarily do in conventional buildings. A minimum life of 20 years should be obtained, possibly ranging up to 50 years depending upon the quality of maintenance. These lives would of course not be achieved in circumstances involving natural disasters such as floods, earthquakes, and hurricanes. However, one of these designs has survived hurricane winds exceeding 100 mph.

The rate of obsolescence of a particular design or even of any desalting installation is a highly speculative question. The development of improved designs, perhaps involving less expensive, more durable, or more efficient systems, might indicate that the investment in an existing, partially depreciated plant should have been amortized more rapidly. Increased water requirements by a community, through population growth or industrial development, might require such a large expansion in a solar-distillation plant that other desalting processes could be employed less expensively. It is even possible that population growth might justify long-distance transport of fresh water and complete discard of desalting facilities. In comparison with other desalting processes, solar distillation is particularly vulnerable to premature obsolescence because of its capital-intensive characteristics.

At the present stage of development, it would be imprudent to anticipate more than a 20-year useful economic life for a solar-distillation plant. In some locations, even this life might be too long for realistic amortization. Thus, it appears that the durability of the materials in this type of solar still is sufficiently great that the limiting factor will be obsolescence. A 5 percent annual amortization of the investment thus seems to be reasonable. A corollary to this argument is that it appears unnecessary to develop or use materials in a solar still having lives substantially greater than about 20 years. Quite clearly, if additional life involves appreciably higher cost, it does not appear warranted.

The durability of solar distillers covered with plastic films is much more doubtful than the foregoing. Controlled tests with polyvinyl fluoride films have indicated about a 4-year life in sunny climates. However, in actual solar stills, wind, rain, and other factors have limited the useful life to less than 4 years. The so-called "weatherable" forms of polyester, polyvinyl chloride, and polyethylene films have even shorter lifetimes in these applications. Other components can be expected to have longer lives, depending upon their basic characteristics. Depreciation of the complete stills might therefore be considered as comprising two principal items; one involving slow depreciation of the more durable components and one involving rapid depreciation of the plastic films and any expendable or replaceable items directly associated with them. In expectation of some improvements in plastic films and their use in solar stills, the depreciation rate on the transparent plastic covers might be based on an optimistic life of about 5 years, involving therefore an annual depreciation rate of 20 percent of the first cost of these components and their installation. If, say, one-fourth of the distiller capital cost is associated with the replaceable covers and the labor for their replacement, and three-fourths with components having 20-year life, the mean effective annual depreciation rate would be about 9 percent.

Although considerably more detailed depreciation and/or amortization schedules might be employed, there is little justification because of the doubtful factors involved. For durable stills, obsolescence at a rate which at present is speculative appears to be the controlling factor. Ultimate useful lifetimes of plastic covers have not been established, so only the roughest estimate can now be made. The figures suggested above are believed to be in the range which should be employed for design purposes at the present time.

The rate of depreciation on small, family-size stills must be dependent on the materials of construction and the design type. An "expendable" still, by its very nature, is expected to be fully depreciated in a very short time, possibly less than 1 year. Thus, the full capital cost of the still would be written off in a year or less. The nonexpendable, more durable family-size stills should be expected to have useful lives of at least several years, but as yet, experience is not sufficient to permit close estimates of this factor. A guarantee of 1 year is provided by one manufacturer, and a 3-year guarantee has been quoted (McCracken, 330). If an ultimate service life of 20 years appears possible, then a 5 percent annual depreciation charge would be justified.

## Interest Charges

The interest paid on capital borrowed by the owner of a solar still (or the earnings foregone if the owner uses his own funds for construction) is another item of expense directly related to capital investment. This cost may vary greatly from place to place and from time to time, depending upon the "money market" and the degree of financial risk involved.

Governmental divisions and subdivisions are usually able to borrow money at lower interest rates than private organizations. It is probable that most community water supplies would be provided by municipal or federal authorities, so interest charges may logically be assumed to be at the lowest level existing in the region. In the industrialized countries, prime interest rates are now in the 7 to 9 percent per annum range, with high-quality commercial credit 1 to 2 percent higher. In the less industrialized countries, rates may be still higher, up to 15 percent or more. Interest rates have of course averaged considerably less than these values, over the years.

It is assumed in this analysis that a portion of the investment in a solar still is amortized each year, so there will be a steadily decreasing principal on which interest is charged annually. If the amortization schedule is one which provides for equal annual payments of principal plus interest (conventional mortgage retirement plan), the average unamortized balance over the life of the installation will be a little over half the original investment, so the approximate annual interest cost will be on the order of half the prevailing interest rate times the first cost.

A more exact treatment involves combining the amortization and interest charges into a single "mortgage-retirement charge" or "capital-recovery factor", by use of interest tables or the following equation,

$$\overline{AP} = r \left[ 1 + \frac{1}{(1 + \frac{r}{100})^n - 1} \right] \tag{20}$$

where $\overline{AP}$ is the constant annual payment of principal plus interst expressed as percentage of the capital investment, n is the years of life, and r is the annual percentage interest rate. For example, if n is 20 years and r is 8 percent, the total annual payment, $\overline{AP}$, of principal and interest is 10.185 percent of the original investment. In other situations, and with other types of financing and amortization policies, the cost of capital for plant construction would have to be determined as required in each specific circumstance.

## Taxes and Insurance

If a solar still is publicly owned, there would usually be no tax charge against the investment, and insurance might be considered unnecessary. It should be pointed out, however, that even if no insurance is provided for, the risks of accidental damage from natural or human causes and the risk of personal injury to workers and passers-by would have to be assumed by the owner of the installation. In effect, this risk is an insurance cost. So either if insurance is purchased or if it is simply assumed by the owning authority, this cost should be provided for in the analysis. Experience is lacking, but as an approximation, 1 percent of the unamortized capital investment may be assumed as an annual premium.

Since governmental ownership of large solar stills would ordinarily be expected, just as water supply systems are public utilities, taxes will usually not be an item of cost. If privately owned water supply units are involved, an annual tax cost of about 1 percent of unamortized investment could be taken as representative.

Since the investment in a solar distiller will be amortized over the expected life of the installation, about one-half the above percentage rates for taxes and insurance may be applied to the original capital investment for average annual costs. On an annual basis, the effective insurance rate calculated on the original investment should therefore be approximately 1/2 percent.

## Total Fixed Charges

The sum of typical charges for depreciation and interest, plus taxes and insurance, may now be determined as a percentage of original distiller investment. For the durable type still, the above items may be taken as, respectively, 10.2 and 0.5, for a total of 10.7 percent per annum. For a permanent installation which includes, however, a short-lived component such as a transparent plastic-film cover having a 5-year life (and assuming the cover to represent one-fourth of the investment), the respective rates would be 13.8 and 0.5, for a total of 14.3 percent per annum.

The annual fixed charges on a small, family-size solar distiller should probably be considered somewhat higher due to more rapid write off, higher interest costs, and somewhat higher insurance risks. If a 10-year amortization period is assumed, together with a 10 percent interest rate and a 1 percent insurance cost, an annual rate of 17.3 percent is obtained.

### Maintenance and Repairs

Although not strictly a fixed charge, it would be expected that the cost of maintenance and repairs on a large solar still would be nearly proportional to the size of the installation, and hence to the total investment. There is not yet enough experience with the operation of large solar stills to permit reliable appraisal of this item, but some estimates are possible.

In estimating maintenance costs, it must be assumed that the solar stills have been designed to be essentially maintenance free. If this is not the case, the cost of this item becomes prohibitive. This may be illustrated by an example. Assuming that a design required annual replacement of caulking, and that patching and cleaning would be necessary at least once a year, the area which a workman could maintain in a day would probably not exceed 400 $ft^2$. This is equivalent to the maintenance of about 100, 000 $ft^2$ of distiller by one man, on an annual basis. In an industrialized country, this labor and necessary materials would cost possibly $5, 000, so if the distiller had a nominal production rate of 25 gal/$ft^2$-yr, the maintenance cost alone would be about $2. 00 per thousand gallons of water produced. This expense illustrates the necessity of acieving a virtually maintenance-free design.

With the durable type of solar still, employing typical building materials and a design which involves an absolute minimum of repairs, an annual charge of 1 to 2 percent of investment is considered realistic. Thus, a 100, 000-$ft^2$ still, requiring a $100, 000 investment, could be expected to require repairs costing $1, 000 to $2, 000 per year. Since this represents only a few weeks of one man's time in an industrialized country, the still would have to be designed for trouble-free service. Repair requirements should be only those to deal with damage or deterioration resulting from unusual conditions occasionally encountered. In comparison with costs of other desalting processes, this is a very low maintenance cost and one which can be borne even in small solar plants. The repair of complex machinery, which is characteristic of other processes, is completely avoided.

For the less-durable-type solar stills, employing plastic-film covers and bottoms, a greater allowance should probably be made for repairs and maintenance. This allowance should not, of course, include replacement of covers at regular intervals, because that cost has been included in the depreciation-amortization item. But the patching of small holes, washing of covers, occasional deflation (if the inflated design is used) to avoid wind and rain damage, subsequent rainwater removal, and re-inflation would be required. Again, there is not sufficient experience with these designs to assess this item, but for the present, possibly 2 to 4 percent of the total investment would be a conservative estimate.

It is reasonable to expect that a distiller of a particular type, if doubled in size, would require roughly twice the investment and twice the cost of repair and maintenance. Certain equipment, such as pumps, valves, and piping would not require maintenance in proportion to their size (and cost), but these are relatively small items in the total outlay for the plant.

In regions where wage rates are much lower than in the industrialized countries, annual maintenance labor costs for a durable still would be lower than the 1 to 2 percent of investment ($1, 000 to $2, 000 for a 100, 000-$ft^2$ still). Such sums would be sufficient for maintenance of a 200, 000 to 400, 000-$ft^2$ still in countries where ordinary labor is available at $2/man-day. To some extent, the lower labor cost may be offset by higher repair-materials costs, particularly if there are transportation problems. It thus appears that 1/2 percent of investment should amply cover repairs and maintenance in the developing countries.

These figures are reasonably consistent with the low end of a range based on experience in Australia, where 10 to 60 man-hours per year are considered necessary per 1000 $ft^2$ of distiller (Morse, 349). Maintenance of a 100, 000-$ft^2$ still at $3 per man-hour would thus cost a minimum of $3, 000 per year, and at $2 per man-day, would cost $250. The upper end of the range, more representative of requirements in the developmental stage of new distiller designs, involves costs several times as high. With fully commercial, well-proven designs, maintenance costs will be at the low end of this scale, i.e., 1 to 2 percent of investment in high-wage areas and less than 1/2 percent in low-wage areas.

## Operating Labor and Supervision

The cost of labor for operating and supervising a solar still appears to be the only item which is relatively independent of the total investment in the facility. This work involves the routine tasks of providing for supply and delivery of salt water, brine, and distilled water; the addition of treating agents to the raw water and product; the maintenance of records; collection of revenue from the water users; and the ordering of maintenance services as required. Somewhat uncertain at this time is the need for occasional cleaning of the salt-water basin.

The solar-distillation process is virtually self-regulating. The only manual tasks are the switching of pumps for feed- and product-water handling and occasional addition of liquid or solid chemicals to these streams. Even if these tasks are manually performed (rather than automatically), and if the paper work mentioned above is included, only a few hours per week of a man's time is required. Practical solar stills involved in community water supply would therefore normally be operated by a person who had other duties and who could conveniently combine these tasks. Only a portion of his wages should therefore be chargeable to distiller operation.

If salt water is supplied to the still intermittently, and if the distilled water pump (employed to deliver distilled water from the primary receiver to a storage tank) is automatically controlled by means of a float switch in the primary receiving tank, an operator would be required for possibly an hour, on a schedule varying from once a day to once a week, depending upon the average depth of water maintained in the solar still. The supply of salt water to the solar still can also be made as automatic as the delivery of product to storage. Level controllers can be incorporated which would supply salt water either continuously or on a preset intermittent schedule. Addition of chemicals could also be entirely automatic. Operating labor would not be necessary, and only occasional surveillance of the installation would be required. There are solar stills now in operation which are virtually unattended, and plans for completely self-operated units have been made.

The costs of these services would depend on the extent to which they are used and the prevailing wage scales. From nominal supervision only, and zero cost (the supervisor being employed for other basic duties in a municipality), to an hour per day at $3 per hour, operating labor could cost from nothing to about $1,000 per year. In the developing countries, the maximum labor cost should be well below the upper end of this scale. The cost per thousand gallons of water produced would then depend on the size of the installation. At an average daily rate (averaged over the entire year) of 10,000 gallons, operating labor at the upper extreme cited here would cost approximately 27¢ per thousand gallons; at only 1,000 gallons daily average, operating labor on this same basis would be a prohibitive $2.70 per thousand gallons.

If it might be impractical to employ an operator on a part-time basis, the entire salary of an individual would have to be paid by the solar-distillation plant. This might involve costs four or five times as great as the above figures. Such a situation would certainly justify the installation of automatic facilities which would make it possible to operate the distiller by someone employed for periodic inspection of the operation when off duty from his regular work. Thus, operating labor and supervision should not exceed a maximum of $1,000 per year, and it certainly could be much less. This amount is a relatively small item in the cost of water from a large plant (say above 20,000 gpd), but in a small installation, this might be excessive. It may be concluded that except in regions where unskilled labor is very cheap, operating labor should be minimized or actually eliminated by use of automatic controls. Where labor is available at a few dollars per day, automatic operation might not represent significant savings.

## Raw Materials and Energy Costs

Saline water is practically the only raw material utilized in a solar-desalting plant (other than possibly some chemical additives for biological control). At the seashore, salt water costs nothing, so the only expense associated with raw feedwater supply is its transport to the solar still. If brackish ground water is the source, the cost of this supply is the amortized cost of the well and the cost of pumping.

The cost of transporting saline water to the distiller is dependent on the distance and the height to which the water must be delivered. Using a typical power requirement of 1/2 kilowatt-hour per thousand gallons of water per 100 feet of lift, energy costs for pumping may be estimated. A seaside solar still might be expected to require something on the order of a 20-foot lift (including pipe friction), so if 2 gallons of salt water are supplied per gallon of product, about 0.2 kilowatt-hour would be required per 1000 gallons of distillate. If brackish well water were being used, the lift more likely would average about 100 feet, thus requiring about 1.0 kilowatt-hour per 1000 gallons of distillate. Small electrical loads in communities having limited power supplies might average 5 cents per kilowatt-hour, equivalent in these two illustrations to pumping costs of 1 cent to 5 cents per thousand gallons of distilled water.

To the energy cost for pumping must be added the fixed costs of amortizing and maintaining the salt-water-supply piping and the pumping equipment. Here again, considerable variability would have to be expected. As an illustration, an electric pump installation with several hundred feet of piping, sufficient in size to supply 20,000 gpd of salt water, may require an investment in the $500 to $1000 range. If the annual fixed cost on these facilities is taken as 15 percent, 2 to 4 cents per thousand gallons of product would cover this item.

An additional supplementary cost of a brackish well would have to be included if that source is involved. For example, a 100-foot well, drilled at a cost of $10 per foot and supplying 20,000 gpd of salt water, at an annual fixed cost of 10 percent would add about 3 cents per thousand gallons of product.

Summarizing the cost of supplying raw salt water, it can be seen that the cost depends on the circumstances, and that for sea water it might be expected to range from about 3 cents to possibly 10 cents per 1,000 gallons of distilled water. If brackish well water is required, additional pumping and well costs might add 4 to 7 cents to the above figures.

It should be pointed out that wind-driven pumps may be easily employed for supplying salt water to solar stills. A sufficient reserve supply of salt water should be maintained in a feed tank to allow for wind variability. Direct drive to the pump may be employed, thereby eliminating electric motors and dependence on electricity supply. In many situations, this type of installation would permit reductions in cost of supplying salt water to the solar still. However, since only a few cents per thousand gallons are involved, the saving would be modest.

The solar energy required in this operation is available at no cost and the auxiliary energy needed for pumping has been included above. Therefore, no additional energy costs are incurred. Any energy requirements for pumping the product water would normally be considered part of distribution costs and not associated with production.

Since most of the cost of solar-distilled water is related to investment, which is in turn dependent on the size and capacity of the installation, it is necessary to correlate the size and cost of the installation with the water-production rate. Cost figures, largely on an annual basis, have been summarized above. Distiller productivity, in relation to size and investment, must now be established.

## Rate of Water Production

The capital cost of solar distillers, described above, has been correlated with the area of the installation, as dollars invested per square foot of solar distiller. The amount of water produced per unit of time by 1 $ft^2$ of still depends on numerous factors, including principally the solar radiation intensity and certain design features. These points have been discussed in an earlier section, so it is now appropriate to establish some sort of typical figures on which water costs can be based.

As shown in Figure 31, most of the community-size solar stills have shown similar water-production rates at comparable solar-radiation levels. These yields have been in the vicinity of 0.09 gal/$ft^2$-day in the summer at radiation levels of 2,000 to 2,200 Btu/$ft^2$-day. Winter performance has been approximately 0.02 gal/$ft^2$-day at a radiation level of 800 Btu/$ft^2$-day. It is obvious that stills in more sunny climates will produce more water than installations in less favorable situations. However, the economics of solar distillation are such that good solar climates are practically essential to economic feasibility, and in fact, all of the sizable installations are in such areas.

If typical average daily radiation levels in each month are found, and typical water yields at these radiation levels are obtained from performance graphs and totalled for the year, annual yields of approximately 25 gal/$ft^2$ are obtained. Lower figures, down to the 20-gal range, are obtained in less sunny climates and with less efficient stills, whereas hot, desert regions show slightly higher annual outputs. Without specifying particular locations and specific solar-distiller designs a more precise figure is not possible. Accordingly, a 25-gal/$ft^2$-yr output will be used in the subsequent estimates of water production costs.

It is evident from the above discussion that the yield of a solar distiller is highly variable, seasonally as well as daily. A small amount of water storage can, of course, smooth out the day-to-day variations in output, thereby providing a relatively constant supply for community needs. However, the winter productivity of only one-half to one-fifth of that in summer represents a much more difficult problem. Water for drinking and cooking use is required by a community throughout the year at a somewhat more constant level, perhaps between a factor of one to two. Somewhat higher potable-water requirements would be expected in the summer months, but certainly not by a factor of four or five as in distiller output. Hence, consideration must be given to the cost of providing water as required rather than as available.

The investment in a solar still is too high to justify designing the still sufficiently large for the winter demand and to waste the excess summer production. A more economical alternative is to design the still to meet the demand in the summer, and to provide some supplementary source of water to make up winter deficiencies. The choice of this alternative would of course depend upon the cost of the auxiliary supply. If this cost were much in excess of the cost of solar distillation, a third alternative would undoubtedly be the most economical. This would involve providing sufficient storage to accumulate excess summer production for use during the following winter and spring when solar-distiller output is insufficient.

The storage alternative would usually be the most practical because the cost of storage-tank capacity is considerably less than the cost of additional solar distiller to make up deficits in production. The example shown in the footnote* illustrates the use of storage capacity to compensate for variable productivity during the year. For the extreme case of completely uniform water demand throughout the year (ordinarily, the demand would follow to some extent the variable productivity of the solar still), and with high variability in production of fivefold, and with no "natural" storage available (steel tankage assumed), about a one-fourth increase in total plant cost would be necessitated by the tank installation. This would be equivalent to approximately $1 additional cost per thousand gallons of water, bringing the water cost to $5.09 per 1000 gallons in this illustration. By comparison, the cost of a solar distiller to carry the entire demand in the winter months would be approximately three times the estimated $87,500 or approximately $250,000, and the water cost, based on only that portion which could be used, would be $11.40 per 1000 gallons. Obviously, provision of storage is the most economical solution unless a good-quality auxiliary supply is available at a cost less than about a dollar higher than the solar distillation cost.

An additional factor in solar-distiller productivity and variability is rainfall. There is at least some rainfall in most locations, and its collection on the large solar distiller cover is possible and practical. Virtually no additional cost is involved in the collection of rainwater, except possibly for an additional temporary storage sump and chlorination facilities. Even in semiarid regions, an annual rainfall of 10 to 15 inches is common. At an assumed annual rainfall of 12 inches, a square foot of solar still would deliver an additional 6 gal/ft$^2$-yr, if 80 percent collection efficiency were achieved. On the basis of a 25-gal/ft$^2$-yr distillation rate, this precipitation would thus represent an additional yield of 24 percent. If the distribution of the 12 inches of precipitation throughout the year is such that 80 percent can be collected, stored, and used, this additional quantity (525,000 gallons) would result in a 19 percent reduction in the cost of water per thousand gallons delivered, or $4.11 versus $5.09 per 1000 gallons. (This assumes no additional cost would be incurred by providing for rain water collection and chlorination).

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*Assume constant water demand of 6000 gpd, and an average productivity of 25 gal/ft$^2$-yr. Assume average daily water production of a solar still having annual average output of 6000 gpd is as follows (no rainwater included):

| | | | |
|---|---|---|---|
| Nov., Dec., Jan. | 2000 gpd | May, June, July | 10000 gpd |
| Feb. | 4000 | Aug. | 8000 |
| Mar. | 6000 | Sept. | 6000 |
| Apr. | 8000 | Oct. | 4000 |

Compute storage tank size needed to provide uniform delivery and no water waste. Starting in April, and until Sept., a total excess of 30 [2000 + (3 x 4000) + 2000] = 480,000 gallons is produced, which requires storage.

Storage is therefore $\frac{480,000}{6,000}$ = 80 times daily average production.

Distiller area required = 6000 x $\frac{365}{25}$ = 87,500 ft$^2$, at cost $\cong$ $87,500.

Horizontal steel tank of 480,000-gal size costs approx. 5¢ per gallon = $24,000. Therefore, storage requires a 27.5 percent increase in total distiller-plant cost.

Annual fixed costs without storage, at 10 percent = $8,750.

Annual fixed costs with storage, at 10 percent = $11,150.

Annual water production, 6000 x 365 = 2,190,000 gal.

Approximate water cost without storage, <u>if all could be used as produced</u> = $4.00/1000 gal.

Approximate water cost with storage = $5.09/1000 gal.

Approximate water cost without storage, if excess summer production (above 6000 gpd) is wasted = $\frac{\text{8750 + total cost of auxiliary water used in winter}}{2,190,000}$.

If auxiliary supply is $6/1000 gal, and 480,000 gallons are purchased,

Water cost = $\frac{8750 + 480 \times 6}{2,190,000}$ = $5.30/1000 gal.

It is clear that if rainfall is at all significant, its collection will be an economic advantage in a solar-distillation operation. The size of the benefit depends on the amount of rainfall and on whether it is received at rates and at times when it can be used. If the precipitation is so heavy and intermittent that storage tanks are not adequate for its retention, it will be of small advantage. In many situations, however, a large fraction of the annual rainfall occurs during months when solar radiation is low (due partially to the clouds which result in precipitation), and this additional yield can offset lower distillation rates during those times. This is not always the case, however, so prudent design would generally involve the assumption that only a portion of the annual rainfall could be beneficially used. The portion would, in turn, depend upon the time of year in which precipitation usually occurred, the distribution during this time (whether reasonably uniform over extended periods or heavy during short periods), the demand for water during these periods, and the availability of storage. A rough analysis of these factors would show that there could be an increase of 15 to 40 percent in the useful water supply from a typical solar still if provisions were made for collecting and storing a rainfall of 10 to 15 inches per year with collection efficiencies ranging between 70 to 100 percent.

If rainwater is stored in the same tank used for distilled water, the tank volume (and solar-still area) can be reduced if a certain minimum precipitation can be depended upon during the winter months of low productivity. Or if a separate tank is used for sanitary reasons, the size of the distilled-water tank can be decreased. For example, if the equivalent of 2 inches of rainfall were collected (0.624 gal/ft$^2$ per inch of rain collected) in each month of December, January, and February, the amount of rainwater would amount to about 330,000 gallons, and thus the total annual water delivery from the 87,500-ft$^2$ plant would be increased from 2,190,000 gallons to 2,520,000 gallons. This would provide an average of about 6,900 gpd, and, if demand were constant, would reduce the required storage of distilled water to 345,000 gallons (30[1100 + (3 x 3100)+1100]) during the five summer months. Assuming, however, a constant daily demand of 6,000 gallons, as in the footnote example, the size of this particular solar collector could be reduced to 76,300 ft$^2$ (2,190,000 gal ÷ 28.74 gal/ft$^2$) and the storage to 300,000 gallons. At a plant cost of \$1/ft$^2$ of still area and 5¢/gal of storage, the total investment of \$91,300 would be about 18 percent less than the \$111,500 required if this moderate amount of winter rainfall were not collected and stored for use. Hence, the 15 percent increase in water delivery per square foot of distiller would permit a 18 percent reduction in total plant costs.

## Cost Per Thousand Gallons

The cost of water production is dependent on four principal factors; the annual fixed or capital costs, operating costs, the cost of salt-water supply, and the annual productivity of the system. These factors have been discussed and quantitatively appraised in the foregoing paragraphs. It now is appropriate to express these elements in the form of a working equation from which the cost of producing a thousand gallons of distilled water can be computed.

The following equation relates the cost of water production to the above factors:

$$C = \frac{10\,I\,[\overline{AP} + \overline{MR} + \overline{TI}] + 1000\,Lw}{(Y_D + Y_R)\,(A)} + S \quad , \tag{21}$$

where

C = cost of water, \$/1000 gal

I = total capital investment, \$

$\overline{AP}$ = annual payment* = $r\left[1 + \dfrac{1}{(1 + \frac{r}{100})^n - 1}\right]$, percent of investment/year

r = annual percentage interest rate, percent/year

*Based on constant annual payments of principal plus interest.

$n$ = pay-out period, years

$\overline{MR}$ = annual maintenance and repair (labor and materials), percent of investment/year

$\overline{TI}$ = effective annual tax and insurance charges, percent of investment/year

$L$ = annual operating labor, man-hours/year

$w$ = operating labor wage, \$/man-hour

$Y_D$ = annual unit yield of distilled water, gal/$ft^2$-year

$Y_R$ = annual unit yield of collected rainwater, gal/$ft^2$-year

$A$ = area of distiller on which yields are based, $ft^2$

$S$ = total cost (fixed and operating) of salt-water supply, \$/1000 gal of product.

An illustration of the use of this equation can be based on the typical figures previously discussed. For this example, a durable type solar still of 100,000 $ft^2$ may be selected, which, in a favorable climate, should have a maximum productivity of about 10,000 gpd of distilled water and an average annual productivity of about 25 gal/$ft^2$. If it is assumed that 12 inches of rain can be collected and used per year, the total annual productivity would increase to about 33 gal/$ft^2$.

For the purpose of this illustration, the assumed investment in the distillation plant is \$100,000 and the investment will be amortized over a 20-year period. Interest on the unamortized balance at an annual rate of 8 percent is assumed, and equal annual payments of principal plus interest is selected as the amortization schedule. Annual taxes and insurance assumed at 1 percent of current value, are equivalent to approximately 1/2 percent of original investment. Maintenance and repair are assumed at 1 percent of investment. From tables of loan retirement over 20 years at 8 percent interest, it is found that 10.185 percent of investment must be repaid as principal and interest, which, with taxes, insurance, maintenance, and repair, make a total annual fixed charge of 11.685 percent of investment.

The item for operating cost, Lw, for an automatic plant is estimated at \$1000 per year. The cost of salt-water supply, S, from a nearby sea water source may be taken as 5 cents per thousand gallons of product.

Substituting the above figures into the equation yields a total water-production cost of \$3.86 per thousand gallons. This figure would be expected to vary considerably from place to place, from one plant size to another, and with numerous other factors. However, it may be considered representative of the cost which could be expected in the case of a new plant of approximately the size indicated.

Some of the items in the above equation depend on gross distiller area and some do not, so an actual water cost must be based on a specific plant size. However, the major portion of the total is the fixed cost based on capital investment. Since capital investment is nearly proportional to distiller area (assuming a large installation for which the relatively constant costs of pumps, piping, and accessories are a small fraction of the costs proportional to area), most of the water cost in sizable plants (say with average annual capacities of 10,000 gpd or more) can be determined without defining a particular size. So if the total annual fixed costs are 11.685 percent of a plant investment of \$1/$ft^2$ (including storage and auxiliaries), and if the annual productivity is 33 gal/$ft^2$, the resulting fixed cost of \$3.54 per 1,000 gallons represents about 92 percent of the total cost of water produced. To this can be added a few cents for the cost of supplying the necessary salt water to the still either from the sea or from a brackish well. Operating labor cost depends on the size of the installation when reduced to the basis of a thousand gallons of product. It is an appreciable item if the solar distiller is small (capacities of hundreds of gpd). Finally, the computed cost would be higher if any part of the total output of the distiller could not be used unless additional facilities were provided. These cost estimates are also affected by the amount of rainwater collection. For example, each additional 12 inches of precipitation collected and stored for use would result in a water cost reduction of about \$1 per thousand gallons, if costs of additional storage, if needed, are not included.

## Reported Water Costs for Large Solar Stills

The criteria for determination of water costs differ so greatly among the organizations and individuals involved in solar-distiller operation throughout the world, that reported water costs in actual solar-distiller plants really are not comparable one with another. In addition to large differences in construction costs (due to differences in size, materials of construction, labor wage rates, etc.), various amortization rates have been used, interest charges have differed substantially, and the amount and cost of operation and maintenance have varied greatly.

Nevertheless, it is believed that the water costs reported by several authorities for specific solar stills should be quoted here. The reader is simply advised to refer to the original publications to gain insight into the assumptions and criteria employed for each cost estimate and to be judicious in comparing figures reported by different investigators.

Daytona Beach Stills. The stills at Daytona Beach were not used as water-supply facilities, so the costs of water reported are based on hypothetical extrapolation of experienced costs to larger scale and to practical use.

Table 15 indicates projected water costs for two improved, glass-covered deep-basin stills, having 50-year amortization periods, basin areas of 3000 and 910,000 $ft^2$, and yearly average daily water outputs of 330 gallons and 100,000 gallons, respectively, corresponding to distilled water and rainwater collection of 40 $gal/ft^2$-yr. (Battelle, 54). These costs of $3.06 and $1.43 per 1000 gallons are now regarded as overly optimistic, primarily because of the 50-year amortization schedule, and to some extent because of higher than ordinary water yield. Furthermore, the interest rates of 6 and 4 percent used in the analyses are too low for present conditions. If these two units are amortized in 20 years with interest rates of 9 and 7 percent, respectively, the capital charges would be $609 and $85,000, resulting in water costs of $5.20 and $2.63 per thousand gallons.

TABLE 15. PROJECTED WATER COSTS FOR IMPROVED DEEP-BASIN STILLS

| Plant Capacity[a], gal/day | 330 | 100,000 |
|---|---|---|
| Capital Costs[b], $/$ft^2$ | $1.86 | $0.99 |
| Operating Costs, $/yr | | |
| Labor[c] | Nil | 6,000 |
| Materials | 10 | 3,000 |
| Electric Power[d] | Nil | 610 |
| Capital Charges[e] | 354 | 41,900 |
| Total, $/yr | $364 | $51,510 |
| Water Cost[f], $/1000 gal | $3.06 | $1.43 |

(a) Productivity assumed to be 40 $gal/ft^2$-yr (distillate plus rainwater collection).
(b) Breakdown shown previously in Table 8.
(c) One full-time maintenance man on large still, including necessary supervision.
(d) Raw water, brine, and distillate pumped against 10-ft head. Brine concentration 4:1. Pumping efficiency 10 percent. Electric power 2¢/kwhr.
(e) Determined on equal yearly payment basis, 50-year life, interest of 6 percent on small still and 4 percent on large still.
(f) Operating 360 days per year.

Table 16 gives a breakdown of operating costs for a basin-type still (Bloemer, 87; Battelle, 55). A 20-year amortization at 4 percent interest was assumed (again, interest rate too low for present rates) in a typical newly developing region having \$0.50/hr labor. Some savings in operating labor (by automatic control) and in the taxes and insurance item might be expected to offset part of a higher interest expense at current rates. At 8 percent interest, the amortization item would be \$137 rather than \$110 per day, and the total cost per 1000 gallons would be \$3.72. This figure is considered realistic for the improved Daytona Beach design under typical present conditions.

TABLE 16. DAILY OPERATING COSTS FOR A BASIN-TYPE STILL

50,000-gpd Capacity

| | | |
|---|---|---|
| Power | \$ 1.35 | |
| Supplies and Maintenance Materials | 7.00 | |
| Operating Labor (\$0.50 per Man-Hour) | 8.00 | |
| Payroll Extras | 1.30 | |
| General and Administrative Overhead | 2.30 | |
| Amortization (20 years at 4 percent interest) | 110.00 | → 70% |
| Taxes and Insurance | 28.00 | |
| Interest on Working Capital | 1.10 | |
| Total Daily Cost | \$159.05 | |
| Cost per 1,000 Gallons = 3,78 m³ | \$3.18 | = € 1 /m³ |

<u>Glass-Covered Stills in Greece</u>. Operating experience is rather limited on the three glass-covered stills in Greece, on the islands of Patmos, Kimolos, and Nisiros. Some design problems and weather damage shortly after construction have delayed data on Patmos, and the other stills have been completed only recently.

There has been reported, however, one water-cost figure applicable to the Patmos installation. On an estimate of 23 gal/ft$^2$-yr, a water-production cost equivalent to \$4.20 per 1000 gallons has been estimated. This figure is based on a capital cost of \$1.35/ft$^2$ and depreciation on a 30-year basis.

No cost data are yet reported for the glass-covered stills on the islands of Kimolos and Nisiros.

<u>CSIRO Stills in Australia</u>. The CSIRO design involving glass covers and a polyethylene plastic-film basin liner is reported to have cost approximately 50¢/ft$^2$ at Muresk (Morse and Read, 345). At an annual output of 16.2 Imperial gal/ft$^2$ (19.5 U.S. gal/ft$^2$), and a total annual charge including depreciation, interest, maintenance, and operation of 12.1 percent, a water cost of \$A3.75 per 1000 Imperial gallons was estimated (\$US3.45 per 1000 U.S. gallons) (Morse, personal communication, Jan. 21, 1969). It should be pointed out that this cost is based on a rather low water productivity and, also, a lower than usual construction cost for a solar still. No rainwater was considered in the calculation. A more recent estimate (Morse, 350) is a capital cost range of 66 cents to \$1.32/ft$^2$, in Australia, representing something like \$13 to \$26 per <u>average</u> daily gallon capacity throughout the year. These costs are based on a production of 18.2 Imperial gal/ft$^2$-yr (21.9 U.S. gallons). At a production rate of 25 U.S. gal/ft$^2$-yr, typical of the continuous-basin still, and possibly achievable in the CSIRO design with some improvements, these capital costs would drop to about \$9.50 to \$19 per average daily gallon capacity. At a 12.1 percent annual total cost rate, these figures would be equivalent to about \$3.15 to \$6.30 per 1000 gallons.

Las Marinas Still in Spain. The solar still at Las Marinas is reported to produce water at a cost of $1 per 1000 gallons, not including fixed charges on the investment. If fixed charges are included and amortization is based on 30 years, the price of the water is estimated at $4 per 1000 gallons.

Estimates on an improved design in a larger project at Nueva Tabarca, Spain, involved operating costs of 42 cents per 1000 gallons and total cost, including 30-year amortization, of $2.55 per 1000 gallons.

Estimates based on the same original data but involving slightly different assumptions are $4.30 per 1000 gallons actually obtained and $3.40 per 1000 gallons if certain adjustments and repairs were made in the distiller, primarily required because of some experiments conducted along with the water-production function. These estimates all include the recovery of approximately 10 inches of rainwater per year.

Still in Turkmenia, USSR (Projected Cost Estimates). The estimated cost of water which will be produced in the 25,000-$ft^2$ solar still ranges from $1 to $3/$m^3$, corresponding to about $3.80 to $11.00 per 1000 gallons. From the information available, it appears that the materials and costs for construction of this installation are considerably higher than others of the glass-covered type.

Plastic-Covered Stills on Greek Islands. It is not possible to present a meaningful figure for water-production cost from plastic-covered solar stills in Greece. The reason for this is that the designs and materials used to date have not survived long enough to permit a realistic appraisal of a depreciation rate. If the actual life of these installations is used in a calculation, the cost per 1000 gallons actually produced would be an order of magnitude above most of the costs reported above. Fixed charges of 30 to 100 percent per annum, based on capital investment comparable with the glass-covered stills would have to be assumed applicable. Therefore, at this time it can only be said that the water-production costs realized in the several plastic-covered stills in Greece are not sufficiently realistic to be meaningful.

Plastic-Covered Still on Petit St. Vincent. Detailed information on capital costs of the inflated, plastic stills at Petit St. Vincent is available and has been summarized earlier in this section. However, this installation is relatively new, and therefore determination of realistic depreciation and operating costs is not yet possible. The experimental nature of the installation and uncertain useful life of various components make water-cost estimates speculative. An estimate based on limited experience (Lawand, 290) places the cost of solar-distilled water at the very high level of $30.50 per thousand gallons, and at about $20 if 18 inches of rainfall are also collected. Unless major cost reductions can be achieved, this system cannot be expected to compete with glass-covered solar stills or with other desalting processes.

Small, Family-Size Stills (Sunwater Company). Small glass-covered, prefabricated stills marketed for family use range in price from about $60 per daily gallon capacity in the smaller sizes (less than 1/2 gpd) down to about $40 per daily gallon in larger sizes (several gpd). On the basis of estimates of installation costs, these larger units cost about $90 per daily gallon, installed. The cost of water produced in these various stills has not been reported as such, but if it is estimated that an annual fixed cost of about 17.3 percent would cover depreciation, interest, and insurance (as discussed previously in the subsection, "Total Fixed Charges"), the water would cost about $28 per 1000 gallons for the smaller units (excluding installation costs, if any), $19 per 1000 gallons for a 3-gpd unit itself, and about $43 per 1000 gallons for the 3-gpd unit installed. These water costs should of course not be compared directly with those for larger plants because of the very large difference in capacity and the naturally larger expense of producing relatively small amounts of water. On the other hand, it should be recognized that operating and repair costs have not been included, it being assumed that the owner or householder would provide these services himself.

A custom-built unit of this same design, having a capacity of several hundred gpd, has been installed in Mexico for a cost of approximately \$60 per daily gallon, of which about \$30 is the cost for the still itself. Assuming this commercial-size plant has a life expectancy of 20 years and fixed costs of 10.7 percent per annum, then the corresponding cost for water would be approximately \$18 per 1000 gallons.

Small, Family-Size Still (Solar Sunstill, Inc.). A plastic-covered still designed for individual family use sells in kit form for \$240, New York. The 64-ft$^2$ basin area will produce about 6 gpd during the summer months. Thus these stills cost about \$40 per daily gallon maximum capacity, or about \$60 per daily gallon average annual capacity in a typical climate. The installation and any auxiliaries are to be provided by the purchaser. The life of the plastic cover is estimated to be about 3 to 5 years, and the anticipated life of the plastic basin liner and other components is 10 years or longer. Assuming a 3.3-year cover life, a 10-year amortization period, a 10 percent interest rate, a 1 percent insurance cost, and that a replacement cover costs 1/6 of the initial investment, the annual fixed cost would be 20.8 percent. With a capital investment cost of around \$60 per daily gallon, the water cost would be about \$34 per 1000 gallons. The initial cost and relatively short lifetimes of these plastic components results in the high water cost, which does not include the costs of installation or auxiliaries, if any. It is also assumed that the operating and repair costs would be negligible, as they would be provided by the owner.

Other Solar-Still Installations. A number of other solar stills, small and large, have been planned and/or built, but there is not sufficient information on them to permit meaningful determination of water production costs.

### Projected Costs

It appears from the foregoing discussion, that the durable-type, glass-covered solar stills will produce water on a consistent, dependable basis for a cost between \$3 and \$4 per 1000 gallons, in most situations. This range is based on the best of current technology and designs, including some storage to average out the variable productivity of the solar still throughout the year and including some rainwater collection. Variations above this figure may of course be expected when conditions are not so favorable. It is possible that improved designs and cheaper materials may reduce the costs somewhat below this range. However, in summary, it is believed that this range represents the best estimates for planning purposes, at least for the next several years.

## Feasibility Considerations

When consideration is being given to methods for supplying potable water in a particular location, one of several circumstances may be involved. First, there may have been no use of potable water at all because no people are living in the area. The problem is then that of providing a water supply where none previously existed. Second, if people are living in a community, there is obviously potable water available, but it may be of poor quality, insufficient quantity for desired use, or of excessive cost. Finally, there may be a situation where the present supply is satisfactory but it is expected that because of population growth, quality deterioration, or other factors, the available water will not meet future demands. Any one or more of the foregoing factors may be the cause of concern for providing new or better supplies of water.

### Alternative Sources of Water Supply

Broadly speaking, an existing or a projected community has three possible sources of water: natural fresh water, water which has already been used and is being recycled (usually with some purification), and mineralized water from which part of the dissolved salts must be removed. It is not within the scope of this Manual to detail the economics of various fresh water sources nor of water reuse systems; abundant information on these subjects is available in the published literature. Roughly speaking, however, it may be said that if fresh water of satisfactory quality for human consumption is available within "reasonable" distance of the community, with sufficient dependability that a year-round supply can be assured, possibly requiring substantial storage facilities, this source should be the cheapest of all the possibilities. Flow through open channels or closed piping, with or without pumping, can be provided at costs of a fraction of a cent to a few cents per mile of transport. Ground water of good quality can be pumped from depths of many hundreds of feet for a few cents per 1000 gallons. Rainwater can be collected on roof tops and other impervious areas and stored in cisterns through reasonably prolonged dry seasons for costs well below $1 per 1000 gallons. In extreme cases, however, such as those requiring transport of water over considerable distances by tank truck, ocean tanker, or by very long distance piping involving relatively small volumes of flow, costs often increase sharply into the range of several dollars per 1000 gallons. In such circumstances, water planners should then consider alternatives which would include water reuse and salt-water purification.

Reuse of municipal water is in its infancy, but certain factors governing the economics of this practice are already clear. The most important of these are first, that the system requires a well developed network of water supplied piping and sewage collection, and second that the volumes of water handled must be large — many millions of gallons per day. If these conditions are not both met, the cost of sewage treatment and reuse would generally be prohibitively high per unit of water supply. For small communities, it therefore cannot be expected that this technique will soon find application.

Consideration of desalting as a water-supply alternative necessitates first, of course, the availability of abundant salt-water supplies, either as brackish ground water or as sea water. Extensive technical and economic studies of desalting of sea water by various distillation processes have shown that costs of about $1 per 1000 gallons can be achieved with production capacities of about 1 million gpd. With plants 10 to 100 times this size, costs may decrease toward about half this level. Below 1 million gpd, however, distillation plant costs rise steeply per unit of water produced, moving into the range of several dollars per 1000 gallons as capacities below 0.1 million gpd are involved.

If brackish water is the source, other processes such as electrodialysis and reverse osmosis may be competitive with distillation, and costs in this same range and possibly somewhat lower may be achieved at similar plant capacities.

It may, therefore, be generally stated that in situations where unusually high fresh water costs are involved, and where water reuse is considered impractical for various reasons, desalting may be considered a potential source. In such circumstances, it then becomes necessary to appraise the potential of alternative desalting processes.

## Applicability of Solar Distillation

It has been shown that, under favorable conditions, solar-distilled water, whether from sea water or brackish ground water, can be produced for about $3 to $4 per 1000 gallons at capacities above about 1000 gpd. The necessary conditions for achieving costs in this range are first, ample solar radiation and second, moderate rainfall during seasons of low solar availability. Studies of the distribution of solar energy and rainfall show that most locations in the Tropic and Temperate Zones meet the requirements for solar-distiller productivities in the range of 25 to 35 gal/ft$^2$-yr, thus making possible production at the above costs. In some locations, however, the distribution of solar energy and of rainfall throughout the year is such that substantial amounts of water storage would have to be provided to avoid waste in some seasons and deficiencies in others. Such storage might increase overall water cost by 50¢ to $1 per 1000 gallons, in the most extreme circumstances.

In comparing the costs of solar distillation in the above range with the costs of water by other desalting processes, some general observations may first be made. The economies of scale operate much more intensively in all of the other desalting processes. Thus, as plant size is reduced from, say 100,000 gpd, the cost of solar distillation per unit of output remains practically constant down to a very low production rate, whereas the cost of water produced in conventional distillation and membrane processes increases exponentially.

Figure 40 shows typical comparisons of distilled-water costs for several processes in these lower capacity ranges (Bloemer, 87, 89; Battelle, 55). These curves indicate that at daily outputs of something less than 50,000 gallons, solar distillation is the most economical desalting process. In calculating the costs for solar stills the following assumptions were made: (1) the average solar-radiation intensity was 2,000 Btu/ft$^2$-day, (2) the corresponding average productivity was 0.085 gal/ft$^2$-day, or 31 gal/ft$^2$-yr, (3) an uninsulated, 2-in.-deep, basin-type still was used, (4) local labor costs were $0.50 per man-hour, and (5) a 20-year amortization period at 4 percent interest rate was assumed for all types of plants. Although labor costs and interest are now higher, and the relative positions of the various curves would be shifted upward somewhat, it appears that solar stills can be economically advantageous in sizes below about 50,000 gpd.

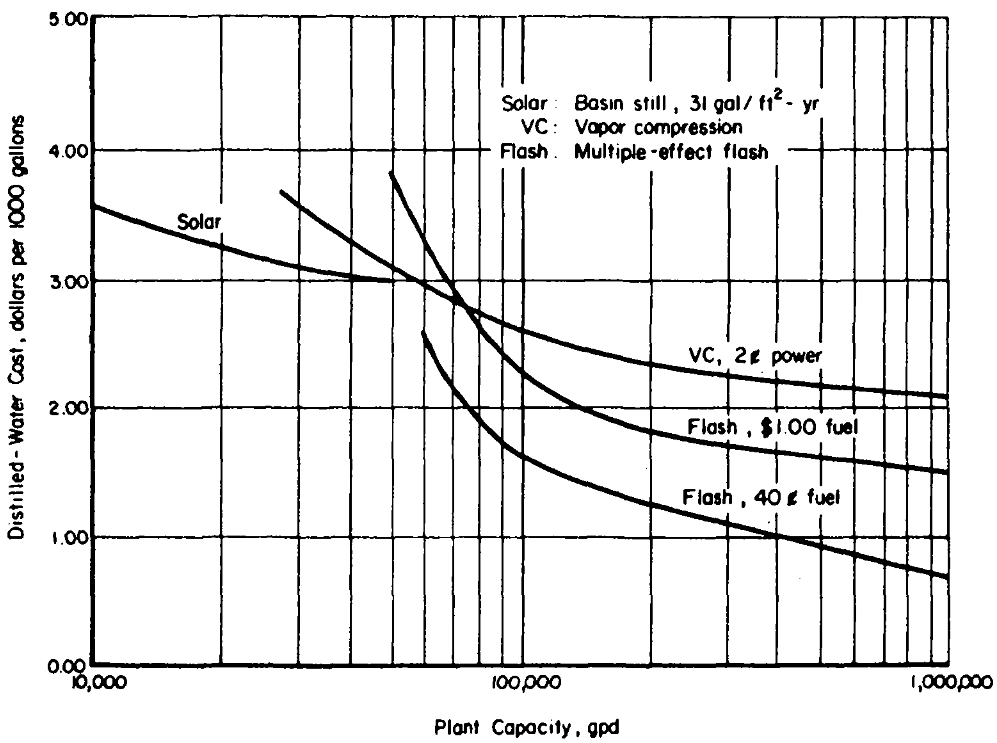



FIGURE 40. DISTILLED-WATER COST COMPARISONS

It is pertinent to examine the situations, therefore, where desalting plants of less than 50,000-gpd capacity may be useful. At the usage in a typical American household, a 50,000-gpd water supply would provide the total needs of a community having a population of 500 to 1000 persons. In the size range of clear superiority of the solar process, say 20,000 gpd, such a plant could supply a community of only 200 to 400 people. It is clear that the number of locations in the United States where a water supply of this size would be needed is extremely limited.

If, however, only the potable requirements are considered, a 20,000-gpd plant could meet the needs of a community of about 10,000 people. In such a situation, dual water supplies would have to be provided, one for the potable requirements, and the other low quality supply for sanitary and general use. A few such systems exist in the United States, but the applicability is obviously limited.

In numerous countries throughout the world, there are many communities where potable water is not distributed to individual households by piping, but instead, the potable supply is transported from central points to dwellings by tank truck, cart, and by individuals. Particularly in the newly developing countries, and in the smaller communities of a few hundred to a few thousand persons, this system is commonly used. And in a substantial number of communities, even the central supply is expensive water transported by larger container sometimes from a long distance. Costs of several dollars per 1000 gallons are not uncommon in such situations. Most of the solar stills now operating are located in communities in which these circumstances exist.

Summarizing, the situations where solar distillation appears to be one of the better possibilities for fresh water supply contain the following conditions:

(1) Expensive fresh water source,

(2) Adequate solar energy,

(3) Potable-water requirement generally below 50,000 gpd,

(4) Source of low quality water for nonpotable uses.

The following items contribute to, but are not absolute requirements for, the competitive advantage of solar distillation over other desalting processes:

(1) Expensive electricity and fuel,

(2) Isolated community,

(3) Limited technical manpower for operation and repair of chemical-process equipment,

(4) Absence of distribution piping systems,

(5) Availability of low-cost construction labor.

## Evaluation Procedure

Although no single description of an evaluation procedure applicable to all situations can be presented, the following discussion illustrates the manner in which a water planner may make a preliminary assessment of the potential of solar distillation in a community which requires a new or additional potable-water supply. First, the cost of developing (or augmenting) a new (or existing) fresh-water supply should be evaluated. This need not be a detailed engineering estimate, but rather a preliminary approximation based on relatively standard approximation methods. If the apparent cost of the new supply is something above \$1 per 1000 gallons, desalting may be considered a potential method for meeting the demand. After evaluating the question of a single supply for all uses as compared with dual potable and nonpotable supplies (including the availability of a nonpotable supply and its cost), an estimate of the required capacity of the desalting installation should then be made.

If the capacity of the desalting installation must be substantially above 50,000 gpd, present economic indications would make solar distillation a dubious prospect. If, however, the requirements are generally below this level, more-detailed cost estimates of the solar distillation process in comparison with the alternative desalting processes using distillation or membranes and fuel or power should then be made. Data such as presented in Figure 40 should be weighed. Consideration should of course be given to the future water requirements of the community as well as those now existing so that selection of a process to meet current requirements might not lead to an uneconomic situation some years hence.

If these considerations show that solar distillation may be competitive or better than competitive with other methods of providing fresh water to the community in question, it then becomes necessary to make rather close engineering estimates of construction costs and operating expenses of a solar-distillation plant. Final comparison with cost estimates for other processes might then also be required before making a decision to proceed.

In the overall view, it appears probable that the situations where solar distillation will be increasingly used involve villages and small communities in newly developing regions of the world where water is scarce, expensive, and not well distributed, where salt water is available either from the sea or from brackish ground supplies, and where solar energy is abundant and dependable.

# SECTION 7. APPRAISAL OF SOLAR DISTILLATION

This section of the Manual is intended to bring into proper perspective several often-neglected aspects of solar distillation. These include the relative merits of various types and designs of solar stills, the comparison of solar distillation with other means of obtaining potable water, the potential uses for solar stills, and the sociological factors to be considered.

## Solar-Still Types and Design Features

The most proven and economical type of solar still is the glass-covered, ground-based solar still, comprised of either a group of long, narrow bays or large, nearly square basins.

With the individual-bay design, the length of each bay is usually between 75 and 150 ft, whereas its width depends on the size of glass panes available and the particular cover design. Bay widths vary between about 2 and 10 ft for glass-covered designs. Examples of larger installations using the bay-type construction with glass covers include the Battelle original deep-basin still in Daytona Beach, the CSIRO stills in Australia, the University of California stills on several islands in the South Pacific, the Greek government stills on several islands in the Aegean Sea, the installations of the Tunisian AEC, the still in Turkmenia, the CSMCRI stills in Bhavnagar, India, and the McGill University still in Haiti. Of these, the CSIRO design has received the most developmental effort.

For the stills using one large pond of saline water, the basin is usually designed to be approximately square, with dimensions ranging up to 100 ft in length and width. The glass cover is, of necessity, designed with peaks and valleys, so the outside appearance resembles the bay-type construction except that no walkways are present between the valleys. Examples of larger single-basin or pond-type stills include the second deep-basin still built at Daytona Beach, the still at Las Marinas, the still at the Navinar lighthouse in India, and the still planned for Nueva Tabarca Island off the coast of Spain. Of these, the Daytona Beach design was probably the most reliable, although some changes were recommended.

Two basic approaches may be used to achieve shallow brine depth. The approach used with large, open basins or ponds, and with some individual-bay designs, is to accurately grade the entire length and width of the basin or bays. Average brine depths of about 2 inches are considered to be practical minimum for large installations using this method. The other technique, used with bay-type construction, is to slope each bay along its length, and then provide weirs or dams at frequent intervals to create shallow pools of brine. The bottom of the bays can be leveled between weirs to provide a constant depth of brine in each pool, or the bottom can remain sloped such that the depth of brine will vary between weirs. For example, if a slope of 1 in 50 is used along the length of a bay and weirs are placed at 4-ft intervals, the water depth will vary about 1 inch between weirs. Three advantages of using a sloped still with weirs are: (1) shallower brine layers are obtained, (2) grading requirements are less severe, and (3) distillate drainage along the length of the still is improved. A disadvantage is the increased difficulty in cleaning the basin liner, if this should be required. Either of these designs, one large basin or individual bays, should give satisfactory performance.

Satisfactory cover designs consist of either symmetrical double-sloped glass or single-sloped glass. Some stills use a combination of these two basic designs, and have an unsymmetrical glass cover with the low sloping glass facing the Equator. The advantages of a symmetrical double-sloped cover are: (1) the compass orientation of its axis can be either East-West or North-South with no difference in productivity, (2) wider bays or spans are covered, which means that fewer curbs, distillate troughs, etc., are required, (3) the glass can furnish its own structural support, as in the CSIRO design, and (4) shadowing of adajacent bays is kept to a minimum. Advantages of a single-sloped cover are: (1) in some designs, relatively simpler construction and sealing techniques can be used, and (2) some shadowing of distillate troughs can be obtained to prevent re-evaporation. There do not appear to be any clear-cut advantages with an unsymmetrically sloped cover, as: (1) cutting of glass may be required, (2) additional support framework will usually be needed for the glass, and (3) uneven forces will be acting on the curbs, tending to shift or overturn them.

The recommended slope for glass covers lies between 10 and 20 degrees from the horizontal. The minimum angle will depend on the thickness of the glass and the distance between supports. A practical minimum to provide good drainage for the condensate is 10 degrees, although 6 degrees is being used by one manufacturer of commercial stills. Single strength glass (0.10 in. thick) will exhibit noticeable sagging at angles of 10 degrees and spans of about 4 ft. This factor may tend to shorten the effective life of vapor-tight seals. Therefore, at low angles and long spans, double-strength glass (0.125 in. thick) is recommended. However, when it is desired to use a single-strength glass the angles should be increased to 15 or 20 degrees, unless the span is less than about 3 ft. Even in windy or stormy locations, single-strength glass should normally be adequate.

Where a temporary or semipermanent installation (up to a maximum of 5 years) is envisaged, or in isolated locations where transportation of glass would be difficult, plastic covers warrant consideration. They should be treated for wettability to prevent dropwise condensation, and special attention should be given to prevent wind damage and to provide for rain drainage. The various plastic-covered stills utilize either blower-inflated or mechanically-supported designs. The most durable type of plastic film developed thus far for solar stills has been 4-mil wettable polyvinylfluoride (Tedlar). Currently, its price exceeds that of glass and its expected lifetime is no longer than 5 years.

Even very small holes or cracks in condensate-collection channels severely reduce distiller output because the flow rate in a single channel is so small that the entire stream can easily be lost (externally or by return to the brine) if the trough is imperfect. Only completely corrosion-resistant, one-piece channels have been found satisfactory. Thin stainless steel troughs and polyethylene films have been used successfully, whereas copper, aluminum, concrete, various coatings, and jointed split plastic pipe have failed. The troughs must be deep enough to prevent spillage or overflow should uneven settling or obstructions occur, and must be narrow enough to minimize re-evaporation by the sun. Probably the greatest single reason for the gradual decline of distiller output has been leakage of condensate from troughs.

Solar stills should be designed so that air and vapor leakage can be kept at a practical minimum. To meet this requirement, sealants are needed that will withstand the extreme rigors of the solar-still environment. Nearly every major solar still built has shown some deterioration in productivity, a part of which is believed to be due to vapor leakage. Thus designers have yet to solve the sealant problem completely, although the silicone-rubber cement used in the newer Australian stills offers much promise.

In general, it can be stated that only the most-durable materials should be used in a solar still designed for a permanent water supply. It can be argued that tradeoffs may occur between material costs and durability, but if maintenance problems develop during the projected lifetime, the cost of the water produced increases significantly. Therefore, careful consideration should be given to designing a solar still as free from maintenance and continual attention as possible. For these same reasons, automatic operation is desirable for such functions as draining, refilling, or flushing.

Long-term testing of the better materials now being used in solar stills is needed because long life with minimum maintenance of various combinations of materials has not yet been demonstrated. No one yet can say with authority that a solar still can be built to last 20 years without extensive and costly maintenance, although this lifetime appears quite feasible with a combination of the better materials now available. The economics of solar distillation is such that long life with mimimum maintenance is essential if the cost of fresh water by this means is to be within the acceptable range of \$3 to \$4 per 1000 gallons. Hopefully, most of the large solar stills now in operation will be adequately maintained and allowed to operate long enough to gain this needed information.

## Solar Distillation Versus Other Desalting Processes

The economics of solar distillation was discussed and evaluated in Section 6. In comparing the economics of solar stills with other desalting processes, it has been projected that solar stills may be the most economical desalting process in sizes up to possibly 50,000 gpd (Battelle, 55; Morse, 344, 345). Unfortunately, this has not yet been confirmed by direct experience with large commercial solar stills. The largest solar still built thus far is the 93,000-ft$^2$ installation on the Greek island of Patmos, which has an average productivity of around 7,000 gpd.

The estimated cost of water obtained from solar stills was shown in Figure 40 in comparison with several other desalting processes. The cost of solar-distilled water is relatively independent of plant size, and runs between \$3.00 and \$4.00 per 1000 gallons. The cost of water produced in other desalting processes increases sharply as plant size decreases, due to relatively higher capital investment and increased energy and labor expense. As their capacity moves below the 50,000-gpd range water costs rise substantially above the \$3 to \$4 levels. Therefore, it appears that solar stills have an economic advantage in sizes below 50,000 gpd.

One of the main reasons more solar stills have not been constructed in many parts of the world is the high initial investment requirement - higher than any other practical process. For example, the first cost of large basin-type solar stills is in the range of \$10 to \$20 per daily gallon capacity, and this is about twice as high as that for other types of desalting equipment in similar sizes. Ideally, maintenance costs on solar stills should be very low, and solar energy is essentially "free". By contrast, operating, maintenance, and energy costs for other types of desalting processes are considerable, whereas the initial capital costs are lower, on a gpd basis. In countries where investment capital is limited, solar distillation is at a disadvantage, even though the long-term cost picture is more favorable for the smaller sizes.

For a given-capacity desalination plant, a solar still will require much more land area than the other types. Even so, the land cost is a small item in solar distillation. As a rough estimate, on a year-round basis, a solar still will require about 14 ft$^2$ of basin area for each gpd of capacity. Even at a high land value of \$1000/acre, which is 2.3 cents/ft$^2$, the proportionate land cost in the total water cost represents only a few cents/1000 gallons.

Several other economic characteristics of solar stills which differ from other desalting processes are (1) the still can be constructed on site using local materials and workers, (2) operation and maintenance can be handled by local people with little technical training, and (3) the solar still is usually a modular-type design; so the capacity of an existing still can be increased as the need arises with practically no cost penalty (Battelle, 55).

In areas where the above characteristics are important considerations, and where there is a reasonable intensity of solar radiation, together with a need for relatively small quantities of fresh water, solar stills should definitely be considered as a means for desalting saline water.

Potable water for most communities is obtained from natural fresh water supplies such as lakes, rivers, or wells. However, seasonal variations and uncertainties in rainfall can seriously affect the availability of fresh water from these natural supplies. Also, in some areas of the world, the water obtained from wells is too brackish to drink. Therefore alternatives must be considered, such as building large rain catchments and reservoirs, hauling or transporting of potable water from more-distant sources of supply, or providing means for desalting brackish water or sea water.

Solar stills can replace or complement rain catchments in many areas of the world. A solar still will produce fresh water throughout the year at a fairly predictable daily rate, whereas rainfall is often seasonal and unpredictable. Therefore, larger storage cisterns will be required if only rainfall is collected. It is also worth noting that the output of a solar still tends to follow the normal seasonal variations in demand for fresh water.

As discussed in Section 4, a solar still will produce the equivalent of about 41 inches of rainfall per year, assuming an annual average productivity of 0.07 gal/ft$^2$-day (25.5 gal/ft$^2$-yr). Since rain catchments cost considerably less to build than solar stills, on a square foot basis, there will exist an annual rainfall where the costs of water produced by rain catchment and storage will equal the costs of water from a solar still. This break-even point will of course be influenced by local labor and material costs, but will depend primarily on the amount of rainfall and the solar-radiation intensity for each locality. When the cover of a still is also used for rain catchment, then there will exist a different break-even point between using only a rain catchment and storage facility or a solar still which has provision for collecting rain.

These break-even points have been considered in detail by Morse and Read for Australian conditions (Morse, 345). They reported that, when allowing for rain supplementing the still's output without additional storage, it was probable that a solar still was a better proposition than rain catchment for localities where the rainfall was less than 10 inches per year, but not as likely to be economically attractive if rainfall exceeds 18 inches per year. In other words, their cost analysis showed that rain catchment areas and storage reservoirs could produce fresh water more economically than solar stills when the annual rainfall was 18 inches or more, even when the cover and walkways of the still were used also for rain catchment. These cost figures were determined by assuming that bituminous-sealed catchments and open earth reservoirs were used for rain catchment and storage. Allowance was also made for evaporation from the open storage tank, but a cost estimate for covered tanks showed that the lower catchment-area cost was offset by the more expensive tank.

With rainfall-collection systems, there is always danger of contamination if the water is to be used for human consumption. Therefore, chlorination and monitoring of water quality may be necessary. This problem does not exist for distillate collected from solar stills, unless rain water is collected from the covers and mixed with the distillate. The solar still built at Coober Pedy, Australia, was not designed to collect rainfall because of this contamination problem, coupled with the fact that the average rainfall is only 5 to 6 inches per year at that location, and also unpredictable (Morse, 344, 345, 347).

In areas where the annual rainfall exceeds about 35 inches, there is general agreement that rain-catchment areas and storage cisterns produce water more cheaply than solar stills (Howe, 247; Lawand, 290). However, other considerations may make solar stills more desirable, such as purity of water, regularity and dependability of supply, etc.

Many locations now obtain their potable water by hauling or transporting it over considerable distances. This is especially true in seasons of drought. Naturally the costs of such water depends on many factors. Therefore, each individual locality should carefully analyze and compare these various methods, or combination of methods described, before deciding on the most economical and advantageous water supply.

## Potential Uses of Solar Stills

Solar stills are well suited for supplying domestic water to a small community or village. If it is assumed that 5 gpd is required for each person, and that solar stills as large as 50,000 gpd are economically feasible, then a solar still could supply potable water for villages containing up to 10,000 people.

Another logical use for solar stills is to provide drinking water for livestock. The Australians and Russians have designed solar stills for watering cattle and sheep. Factors which must be taken into account for such stills include: (1) annual grazing density, (2) proximity of the animal to the watering spot, and (3) water requirement for each animal. These considerations will determine how many animals can be watered by each solar still, what its capacity should be, and how far apart they should be spaced. Estimates made by CSIRO personnel for Australian conditions report that Merino sheep drink about 1 gpd in the summer (Ref. - "Rural Research in CSIRO", March, 1967), and beef cattle about 5 gpd (Morse, personal communication, October, 1968). For these cases they estimate the size of the respective solar stills to water a flock of 350 sheep and 100 cattle. It was also reported that their reduced winter demand coincides with the lower productivity of a solar still.

In Turkmenia, USSR, it has been reported that to provide water for a flock of 1,000 Caracule sheep, the annual need would be about 528,000 gal/yr, or an average of 1,450 gpd (Baum, 66). The first experimental still built recently on the pastures of the Bakharden state farm in Turkmenia, has an area of 6,450 $ft^2$. It is planned to enlarge this to 25,800 $ft^2$ after the initial study is completed. The anticipated average productivity is 0.067 gal/$ft^2$-day, which represents around 1,730 gpd.

The salt content of drinking water can be higher for livestock than for human consumption; therefore, in some cases, it may be worthwhile to mix the distillate with some raw saline water to obtain a greater yield. However, it has also been determined that sheep require more water as their drinking water becomes progressively more salty (Ref. - "Rural Research in CSIRO", March, 1967). In one specific case, a 100 percent increase in drinking water with a salt content of 1 percent watered only 40 percent more Merino sheep than salt-free water. This was because of the salt-induced thirst of the sheep. Nevertheless, it represents a significant gain. The amount by which the gross output of a solar still can be increased by blending with raw feedwater will depend on the salinity of the feedwater, and on the tolerance of the livestock.

Table 17 lists the suitable salinity levels for various water uses as reported in the Reference "Rural Research in CSIRO", March, 1967.

TABLE 17. SUITABLE SALINITY LEVELS

| Purpose | Upper Limits for Safety, ppm (total dissolved solids) | Maximum Desirable Levels, ppm (if mostly NaCl) |
|---|---|---|
| Irrigation | 500-1,000 | 300-400 |
| Domestic | 2,000 | 1,000 |
| Beef cattle | 10,000 | 4,000 |
| Sheep | 15,000 | 8,000 |

Another use for solar stills could be to provide very pure water to industries or laboratories requiring such a supply. The water obtained from a well-designed solar still is essentially pure distilled water. There will usually be no dissolved solids in the product water if the distillate troughs are constructed of a durable material and if the still and collection system are well sealed to prevent outside contaminants from finding their way into the distillate.

Solar stills may also be used in areas where the present supply of water is of low quality and needs upgrading. They can also augment or replace present water supplies which may be expensive or inadequate. Or they could provide a fresh-water supply where none now exists, and thus open up new territories for habitation or grazing.

## Sociological Factors

If a solar still is to provide a constant and reliable supply of potable water for inhabitants of a village or community, it must be well received and respected. This aspect will be enhanced if the installation is reliable and relatively maintenance free. Nevertheless, the fact remains that it is usually very difficult to replace old traditions with new technology.

One advantage of many solar-still designs is that the materials, as well as the construction and maintenance labor, can be furnished largely by the local community. This is desirable from the standpoint of benefiting the local economy, and for "esprit de corps".

The availability of a good fresh-water supply can of itself improve the general well-being and foster economic development of a community. The Tunisian AEC has reported that people who regularly drink water containing too much salt are weak, lazy, and apparently exhausted (Tunisian AEC, 454). They attribute this to the fact that the liver and kidneys must expend more energy to assimilate the water. Also, this problem is compounded by the fact that their food is low in energy value. Therefore, they believe that if the children have an opportunity to drink good water, they will become progressively more active and will begin to change the region through their increased ability to work and think.

There are many areas of the world where a suitable supply of fresh water would open up undeveloped land areas for use by local citizens or for the establishment of a tourist trade. The solar still built on the island of Petit St. Vincent is an example of the development of a resort area on what was before a remote, uninhabited island.

## Salient Features of Solar Stills

The following list summarizes several of the more important advantages of solar stills.

(1) Solar stills can provide fresh water at a lower cost than other desalting systems when the demand is less than about 50,000 gpd.

(2) The materials for construction are often available locally.

(3) The labor for construction, operation, and maintenance can be provided by unskilled or semiskilled workers from the local community.

(4) The operating and maintenance costs are low.

(5) Because of modular-type construction, solar stills can be enlarged easily to meet a future demand.

(6) Solar stills provide a more continuous and a purer supply of fresh water than a rain-catchment system.

Disadvantages under certain conditions are:

(1) The productivity per square foot of basin area is low; consequently sizeable land areas are required.

(2) The initial capital costs are high – a factor of particular importance in the financing of a solar-distillation plant by a small community.

# SECTION 8. DESIGN AND CONSTRUCTION PROCEDURES

## Sizing Solar Stills and Storage Reservoirs

This section presents a step-by-step approach for determining the size of a solar still and storage reservoir needed to meet a given water demand in any area of the world. An example problem is given to illustrate the techniques involved. These calculations are based on average-productivity curves, general solar-radiation maps, and typical rainfall patterns. If better data are available for any particular location, these should be relied upon rather than mean annual distribution maps of radiation and rainfall.

Figures 41, 42, 43, and 44 are world maps showing the average distribution of total solar radiation for the months of March, June, September, and December, respectively (Lof, et al, 313). A complete set of 12 radiation maps is contained in Reference 314. However, four maps are sufficient for the purposes of estimating seasonal and annual averages. These maps give the monthly averages of total (direct and diffuse) solar radiation incident on a horizontal surface area in langleys per day. (One langley is equivalent to 1 cal per $cm^2$, or 3.69 Btu per $ft^2$).

Figures 45 and 46 are world maps showing average annual rainfall lines and the seasons of maximum rainfall (Encyclopedia Britannica, World Atlas, 163). A more complete set of seasonal rainfall maps is available in the literature, which reports the average monthly rainfall for most areas of the world for the four months of January, April, July, and October, together with mean annual maps (Kendrew, 267). The Britannica World Atlas (163) also has plots of climatic graphs, showing mean monthly rainfall and temperature for 27 principal cities around the world.

The following equation will be used to calculate the productivity of a typical basin-type solar still.

$$P = 1.10 \times 10^{-3} (R/100)^{1.40}, \text{ gal/ft}^2\text{-day} \quad ,$$

where

R = total solar radiation, $\text{Btu/ft}^2$-day.

This equation was presented and discussed in Section 5. It represents the average performance of nine large solar stills. As previously shown, it is expected that current and future improvements in distiller design will result in higher yields, and modification of the equation can then be made to account for better performance.

For an example problem, to illustrate a design technique which can be used to size a solar still for a given location and purpose, the following assumptions will be made:

(1) The solar still is to be located in Tunisia, near Tunis (approximately 10° East Longitude and 36° North Latitude).

(2) The demand for fresh water is approximately constant at 6,000 gpd.

(3) Distillate and rainwater storage is sufficient for accumulating excess production in any part of the year.

Table 18 lists the solar radiation levels as read from the maps, and the corresponding productivities calculated from the productivity equation.

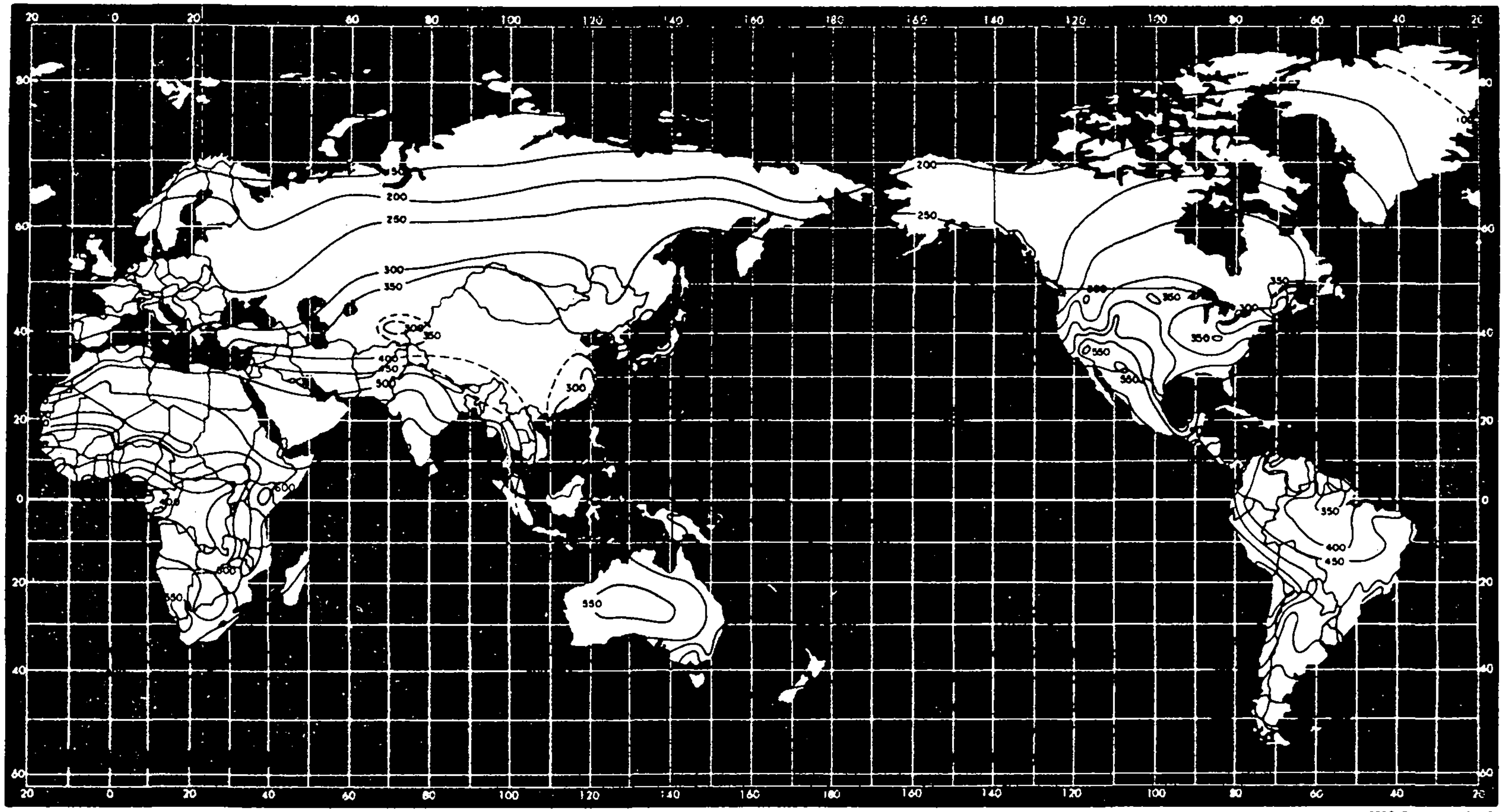



FIGURE 41. AVERAGE SOLAR-RADIATION DISTRIBUTION FOR MARCH

Note: Lof SE 10, 1 (1966)

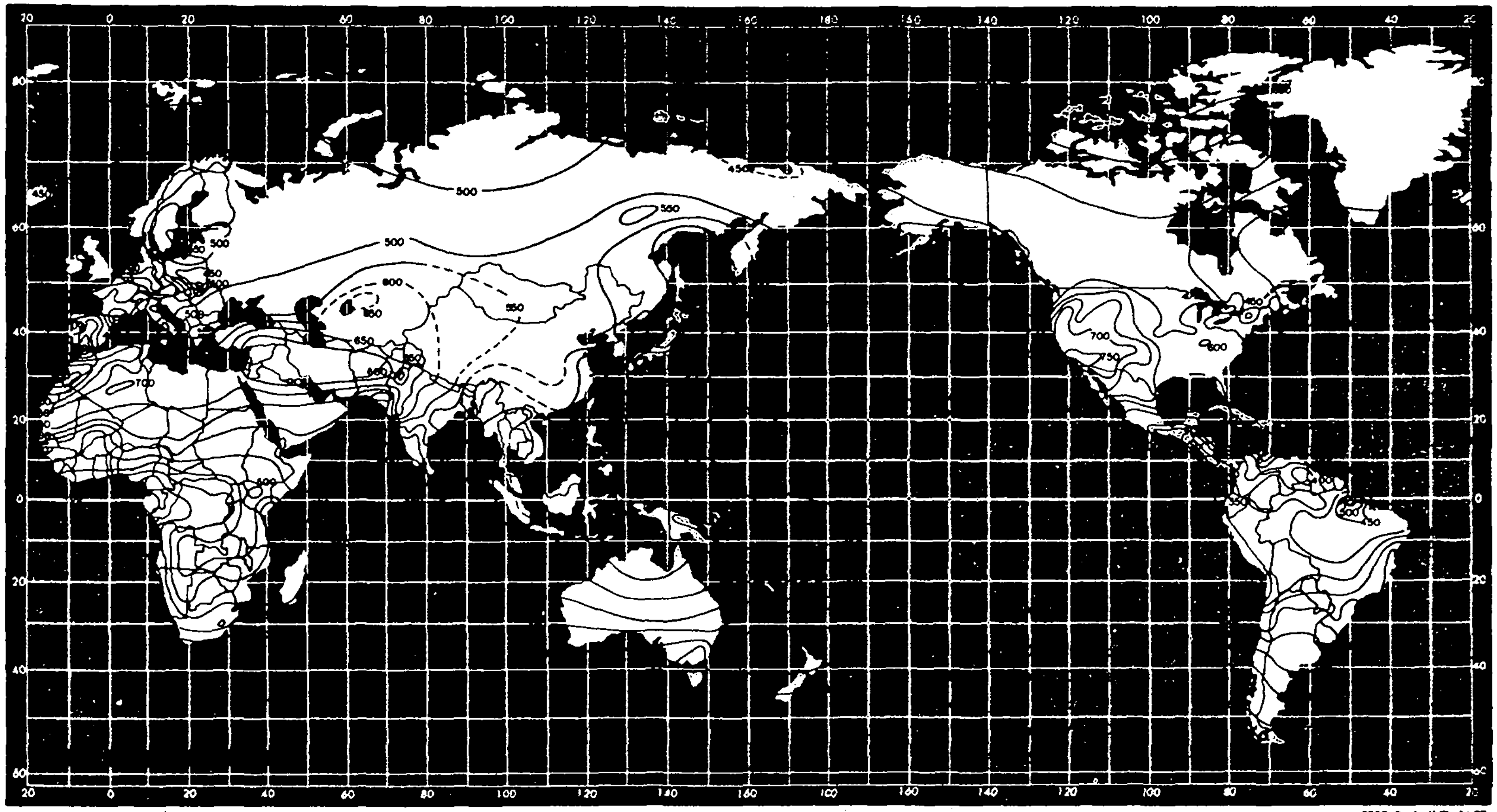


FIGURE 42. AVERAGE SOLAR-RADIATION DISTRIBUTION FOR JUNE

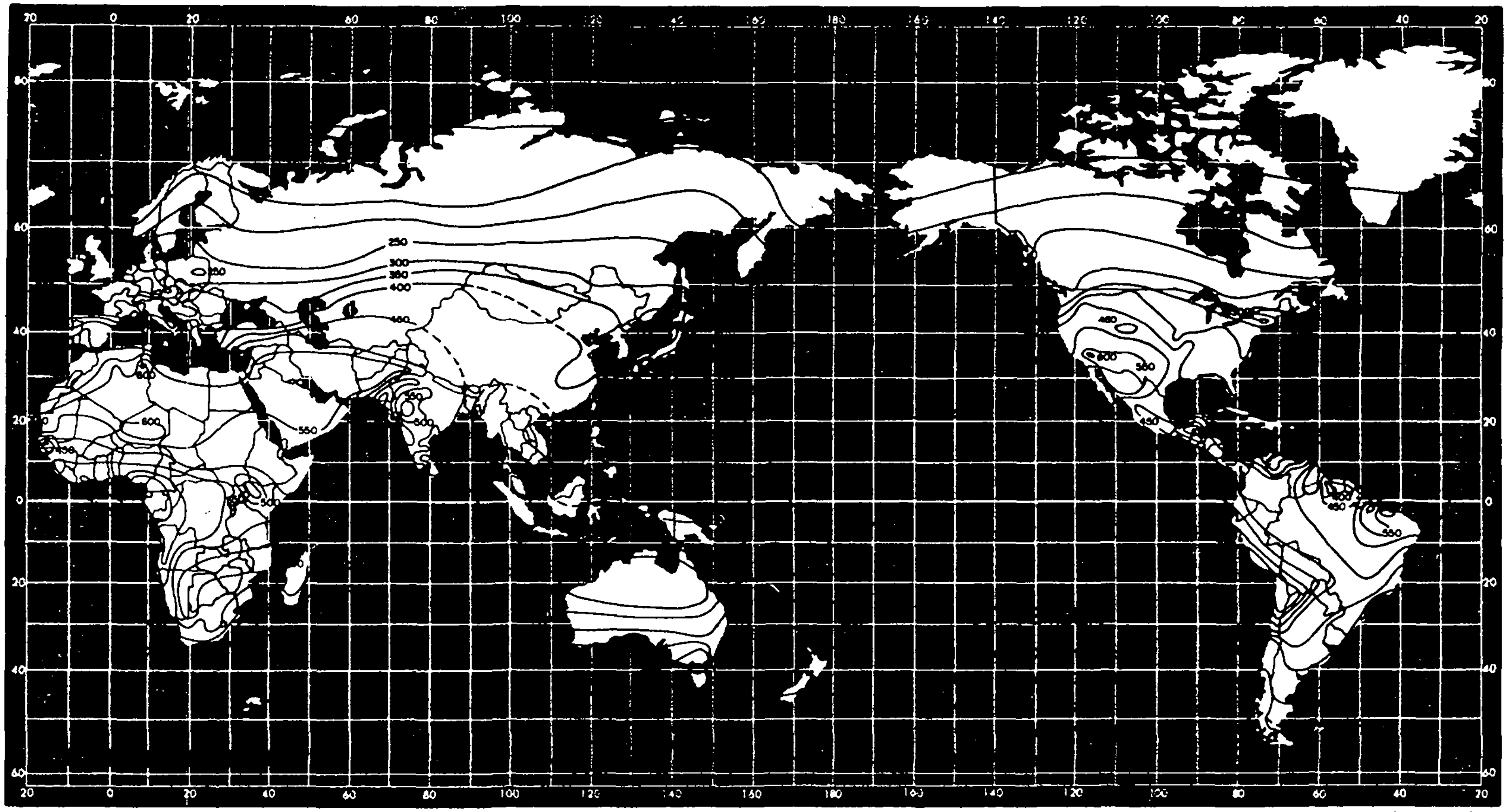



FIGURE 43. AVERAGE SOLAR-RADIATION DISTRIBUTION FOR SEPTEMBER

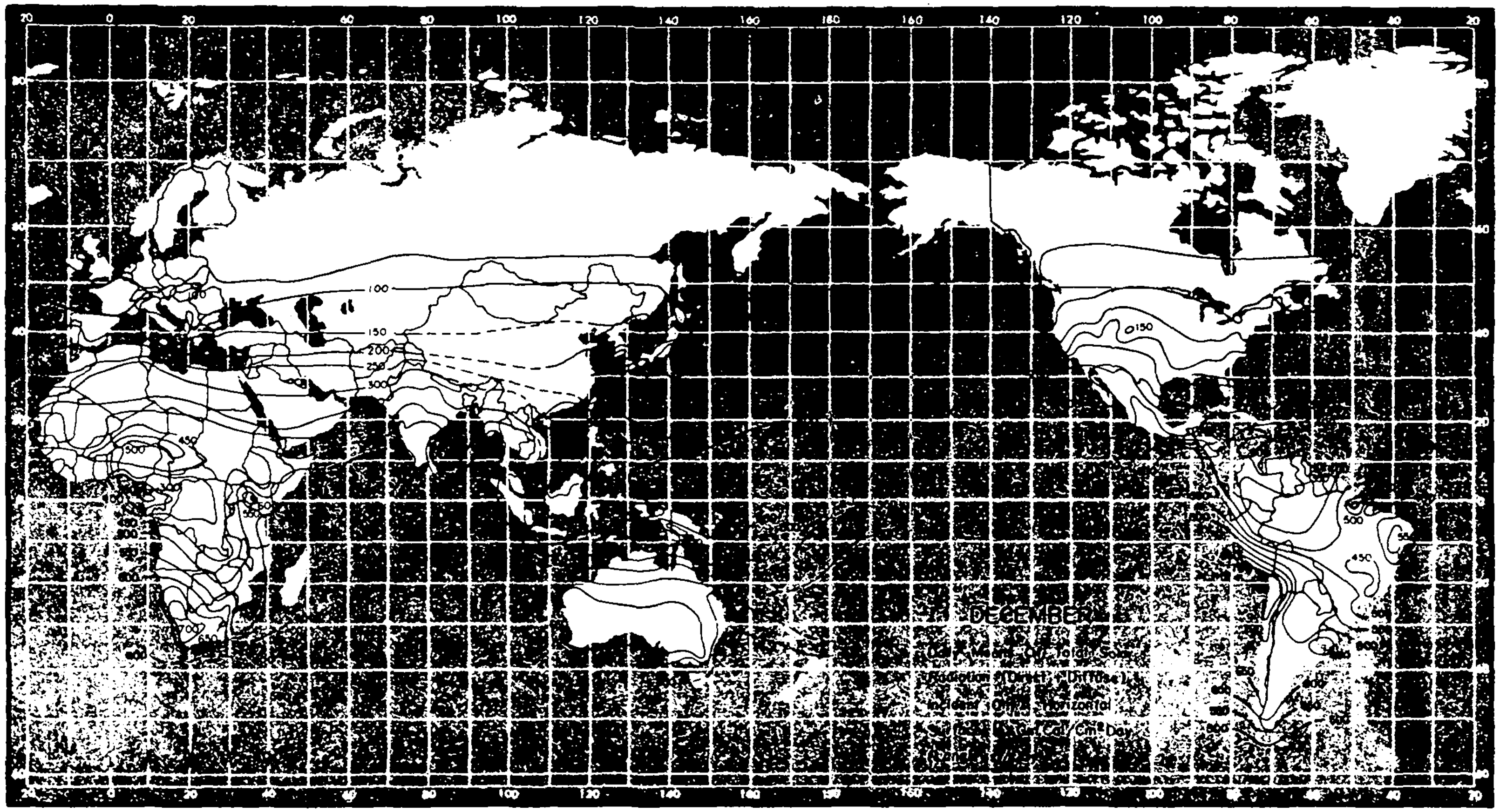



FIGURE 44. AVERAGE SOLAR-RADIATION DISTRIBUTION FOR DECEMBER

NOT REPRODUCIBLE

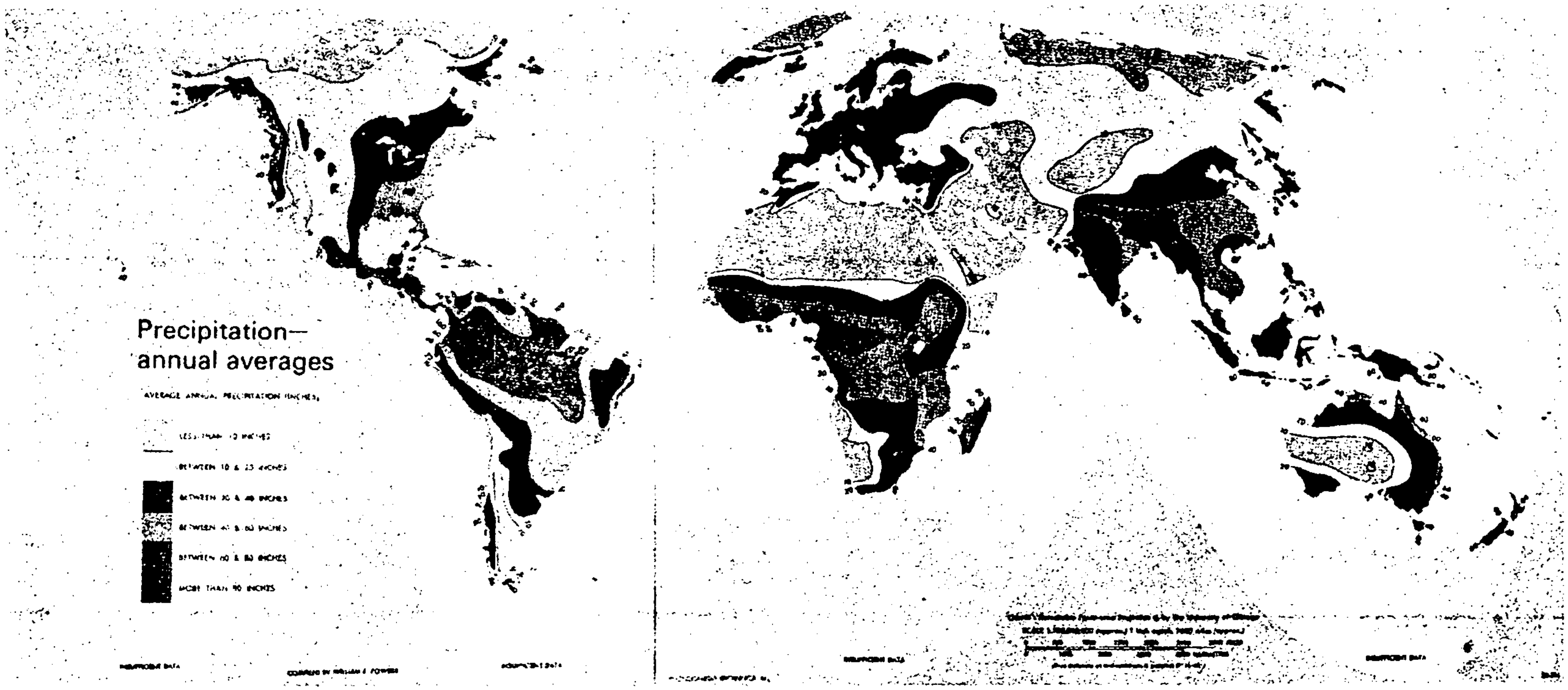



FIGURE 45. AVERAGE ANNUAL RAINFALL PATTERNS

Ref. Britannica World Atlas 1966


FIGURE 46. SEASONAL RAINFALL PATTERNS

Ref. Britannica World Atlas 1966

TABLE 18. CHARACTERISTICS OF A TYPICAL SOLAR STILL NEAR TUNIS, TUNISIA

| Month | Average Radiation (Langley/day) | Average Radiation ($Btu/ft^2$-day) | Productivity ($gal/ft^2$-day) |
|---|---|---|---|
| March | 400 | 1,480 | 0.048 |
| June | 650 | 2,400 | 0.094 |
| September | 450 | 1,660 | 0.056 |
| December | 210 | 780 | 0.019 |
| Approximate Yearly Averages | 428 | 1,580 | 0.054[a] |

(a) Equals 19.7 $gal/ft^2$-yr.

## Still Area Required

If no rainfall were collected, and if storage volume is sufficient to accumulate the excess summer production for winter use, the solar still would need an evaporating area of about 110,000 $ft^2$ (6000 gpd/0.054 $gal/ft^2$-day) to produce a yearly average of 6000 gpd. The maximum summer productivity in this location would be about five times higher than the minimum winter productivity. These magnitudes of productivity correspond very nearly to the example shown in Section 6 as a footnote.

The average annual rainfall for this location appears to be around 16 inches per year (Figure 45). If it is further assumed that only 80 percent of the rainfall will be collected from the surface of the still, then approximately 8.0 $gal/ft^2$-yr of rainwater will be obtained. (See Figure 26). Thus, the total output of the still will be about 27.7 $gal/ft^2$-yr (19.7 + 8.0). The surface area required if the solar still is to average 6,000 gpd ($2.19 \times 10^6$ gal/yr) is now reduced to about 79,000 $ft^2$. By collecting the rainwater the "equivalent" productivity of the solar still has been increased 40 percent and the size of the still reduced accordingly. Again, storage of all collected rainwater until needed is assumed.

## Storage Volume Required

If it is assumed that a constant demand of about 6000 gpd is required throughout the year, then the seasonal variations in solar distillation and rainfall collection would have to be taken into account to properly size a storage reservoir of sufficient capacity to allow this type of usage. The size of the still itself would remain approximately 79,000 $ft^2$.

Table 19 shows calculated distributions of distillate production and rainwater collection to illustrate a method which can be used to determine the approximate size of a storage reservoir required for the above solar still. The monthly distribution of rainfall was obtained by using information contained in Figure 46, and balancing the monthly values to arrive at a total of 16 inches for the year.

TABLE 19. RESERVOIR CAPACITY WITH RAINWATER COLLECTION

| Months | Distillate Produced(a) GPD | Distillate Produced(a) Gallons | Rainfall, inches | Rainwater Collected(b), gallons | Total Fresh Water Collected Gallons | Total Fresh Water Collected GPD | Storage Required(c), gallons |
|---|---|---|---|---|---|---|---|
| Nov, Dec, Jan | 1,500 | 138,000 | 8 | 315,200 | 453,200 | 4,926 | 0 |
| Feb | 2,500 | 70,000 | 2 | 78,800 | 148,800 | 5,314 | 0 |
| Mar | 3,800 | 117,800 | 1 | 39,400 | 157,200 | 5,071 | 0 |
| Apr | 5,000 | 150,000 | 1 | 39,400 | 189,400 | 6,313 | 7,470 |
| May, June, July | 7,400 | 680,800 | 0 | 0 | 680,800 | 7,400 | 122,912 |
| Aug | 6,500 | 201,500 | 1 | 39,400 | 240,900 | 7,771 | 52,917 |
| Sept | 4,400 | 132,000 | 1 | 39,400 | 171,400 | 5,713 | 0 |
| Oct | 3,000 | 93,000 | 2 | 78,800 | 171,800 | 5,542 | 0 |
| Totals | 4,337(d) | 1,583,100 | 16 | 630,400 | 2,213,500 | 6,064(d) | 183,299 |

(a) Calculated and interpolated from productivities given in previous table, using a still area of 79,000 ft$^2$.

(b) Rainwater collection efficiency of 80 percent assumed for collection area of 79,000 ft$^2$.

(c) Excess over average production of 6,064 gpd.

(d) Averages calculated from total gallons produced or collected.

The above calculations indicate that a solar still with a basin area of 79,000 ft$^2$, a rainwater collection system, and a storage reservoir capacity of 183,000 gallons, should meet the assumed requirement of providing a constant supply of about 6,000 gpd of fresh water. Naturally, if more exact data on solar radiation and rainfall are available for each of the 12 months for a particular location, more reliable estimates should be made before building an actual solar still. This example merely indicates the method of sizing the still and reservoir.

If rainwater were not collected in the above example, then the required still size would have to be approximately 110,000 ft$^2$, and the reservoir capacity would also have to be increased considerably to provide a constant supply.

Table 20 shows the storage capacity required when no rainwater is collected. These values are very similar to the example problem given previously in Section 6 when determining the costs of water with storage included.

For the solar still in this example to produce a constant daily supply of 6,000 gpd without rainwater collection, its basin area should be about 110,000 ft$^2$, and the storage reservoir should have a capacity of about 515,000 gallons.

Table 21 gives a summary of the above calculations, and indicates the advantages which can usually be gained by including a rainfall-collection system when designing a solar still.

TABLE 20. RESERVOIR CAPACITY WITHOUT RAINWATER COLLECTION

| Months | Distillate Produced[a] GPD | Distillate Produced[a] Gallons | Storage Required[b], gallons |
|---|---|---|---|
| Nov, Dec, Jan | 2,100 | 193,200 | 0 |
| Feb | 3,500 | 98,000 | 0 |
| Mar | 5,300 | 164,300 | 0 |
| Apr | 7,000 | 210,000 | 28,500 |
| May, June, July | 10,300 | 947,600 | 391,000 |
| Aug | 9,000 | 279,000 | 91,450 |
| Sept | 6,200 | 186,000 | 4,500 |
| Oct | 4,200 | 130,200 | 0 |
| Totals | 6,050[c] | 2,208,300 | 515,450 |

(a) Values from previous table multiplied by 110,000/79,000.
(b) Excess over average production of 6,050 gpd.
(c) Average daily productivity (2,208,300/365).

TABLE 21. COMPARISON OF SOLAR STILLS DESIGNED FOR 6,000 GPD

| | Still Size, $ft^2$ | Reservoir Capacity, gallons |
|---|---|---|
| With Rainwater Collection | 79,000 | 183,300 |
| Without Rainwater Collection | 110,000 | 515,400 |

The procedures presented above are typical, and could be modified easily for other areas of the world and for different potable-water requirements. The above illustrations assumed that the potable-water requirement was constant throughout the year. However, the same procedures could be followed for a varying demand, with adequate storage provided for the excess water produced during some months, so that the supply would be sufficient for the entire year. The distiller area in this case would be determined by totaling the daily demands for the entire year and dividing this total by the annual water output per square foot of distiller area.

Another important feature shown by the above numbers is that the daily production fluctuates much less when rainfall collection is included, if the rainy season coincides with the months of low distillation rate. The fluctuation in total daily output was between 4,926 and 7,771 gpd with rain catchment included, and between 2,100 and 10,300 gpd without rain catchment.

## Materials of Construction

Since the building of the first large commercial solar still in Las Salinas, Chile, around 1872, the most significant gains in solar still technology have come by way of improved materials of construction. The productivity has not been increased much, but the maintenance and operating expenses have been reduced appreciably. For example, the 48,000-$ft^2$ still at Las Salinas was constructed of wood, glass, and putty, and its operation required a clerk, a glazier, two full-time laborers, and occasionally a carpenter. By contrast, some recently built stills require only one full-time attendant and a few are designed to operate unattended for long periods of time. Glass, concrete, and asphalt materials appear to require only a minimum of maintenance.

Indigenous materials are usually preferred. However, in selecting materials, the overall economics must be carefully considered, including maintenance and rebuilding intervals as well as initial capital cost. The present trend is toward materials that will last 20 years with minimum upkeep. Such materials include concrete, glass, butyl rubber, and stainless steel.

Table 22 lists still-component materials that have proved to be reasonably satisfactory in actual use around the world. For each component, the materials are listed in order of preference from the standpoint of durability. The actual materials used in specific solar-still installations around the world are described in Sections 3 and 9, together with problems encountered. When a solar still is to be built directly on the ground using a basin liner, it is advisable to first use an insecticide and a weed killer to reduce the possibility of punctures.

TABLE 22. MATERIALS FOR CONSTRUCTION OF SOLAR STILLS

| Component | Materials |
|---|---|
| Basin Liner | Butyl rubber (0.015 to 0.030 inch thick). Asphalt mats (0.12 to 0.25 inch thick). Black polyethylene (0.008 inch thick). Roofing asphalt (over concrete, etc.). |
| Cover | Window glass (0.10 or 0.12 inch thick). Wettable Tedlar plastic[a] (0.004 inch thick). |
| Support Structure | Concrete. Concrete block. Aluminum. Galvanized metal. Redwood.[a] |
| Distillate Trough | Stainless steel. Butyl rubber (lining). Black polyethylene (lining). |
| Sealant | Silicone rubber. Asphalt caulking compound. Butyl-rubber extrusions. |
| Piping and Valves | PVC (polyvinylchloride). Asbestos cement (for saline water). ABS (acrylonitrile-butadiene-styrene). |
| Water Storage Reservoirs | Concrete. Masonry. |

(a) Relatively short lifetimes.

## Examples of Construction

Examples of the building sequences used in the construction of two types of glass-covered solar stills are shown in two series of photographs. One type consists of a single basin, or pond, for a shallow brine layer. The other type uses long, narrow individual bays for the basin, with walkways between each bay. The bottom of the bay-type stills can be either nearly level or sloped with weirs spaced at intervals along its length to create shallow pools of brine.

Figures 47 through 55 are a sequence of photographs and descriptions showing the second deep-basin still being built at Daytona Beach, Florida, in early 1961. Complete sets of photographs are given in References 53 and 54. Although this particular basin was designed to use a brine depth of up to 12 inches for experimental purposes, the same construction techniques are applicable for shallower basin designs.

Figures 56 through 63 are a series of pictures showing the second (Mark II) CSIRO still being constructed at Muresk, Australia, in late 1966. This particular bay-type design uses cables stretched across the bay at frequent intervals underneath the basin liner to create a series of shallow pools of brine.

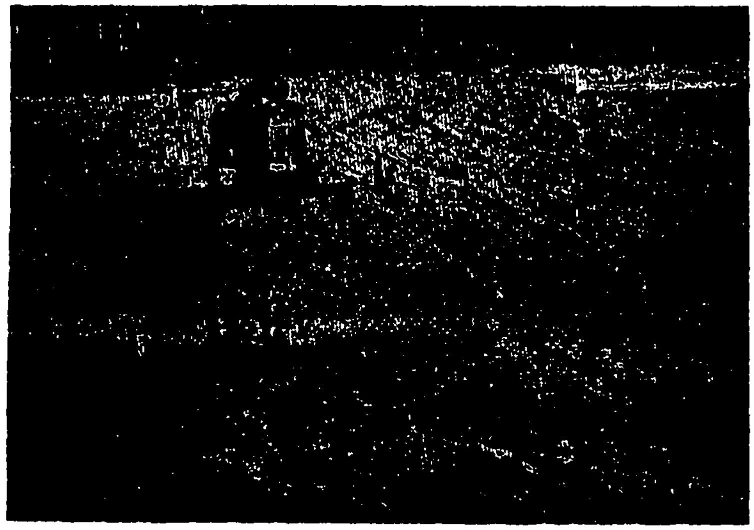


FIGURE 47. ROUGH GRADING OF BASIN AND DIKE (SECOND DEEP-BASIN STILL)

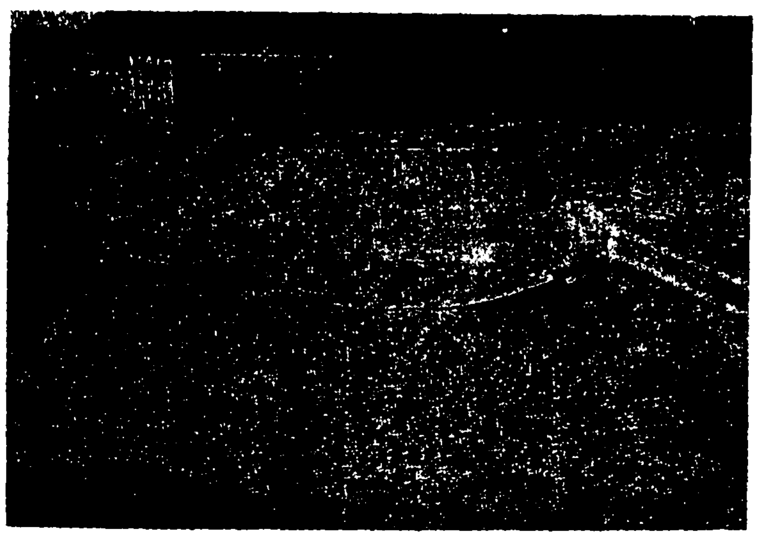


FIGURE 48. LAYING OF PREFABRICATED ASPHALT MATS

FIGURE 49. SEALING LINER JOINTS WITH GUSSET STRIPS AND HOT-MOPPED ASPHALT

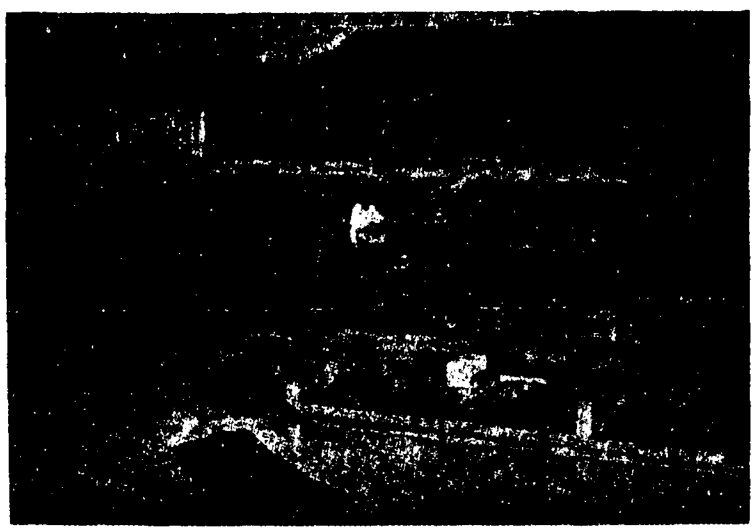


FIGURE 50. THE COMPLETED WATER-TIGHT BASIN

FIGURE 51. PLACING PRECAST CONCRETE BEAMS ON CONCRETE-BLOCK PEDESTALS

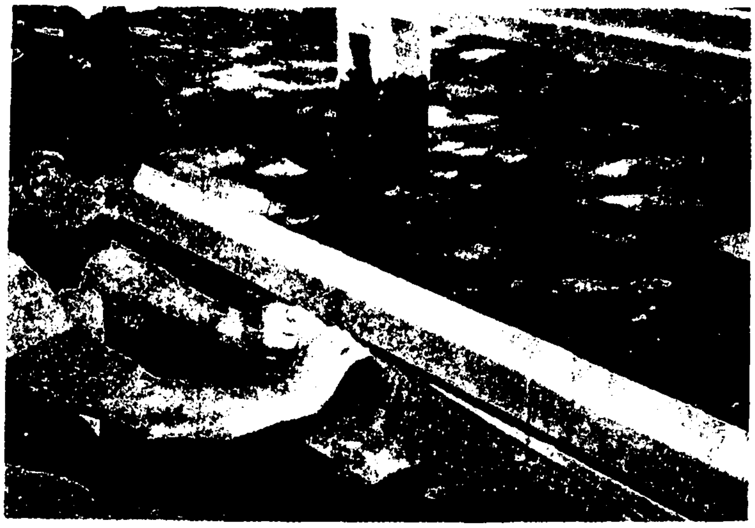


FIGURE 52. INSTALLING DISTILLATE TROUGH IN GROOVE OF LOWER BEAM

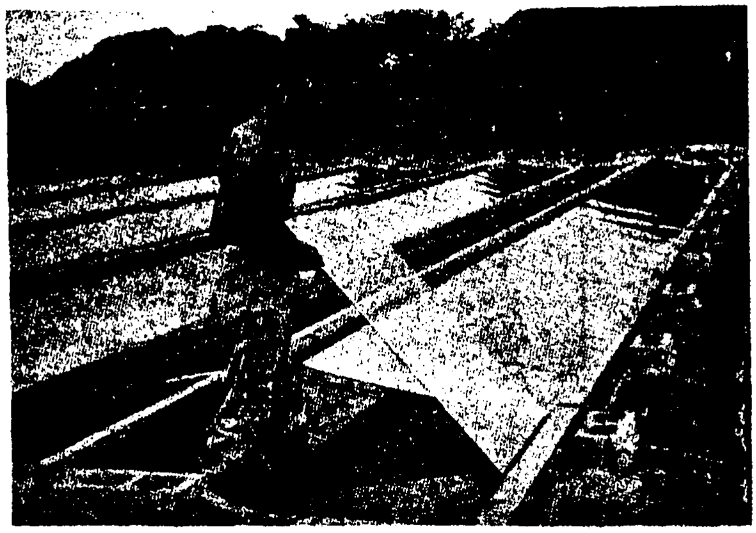


FIGURE 53. LAYING GLASS PANES IN PLACE

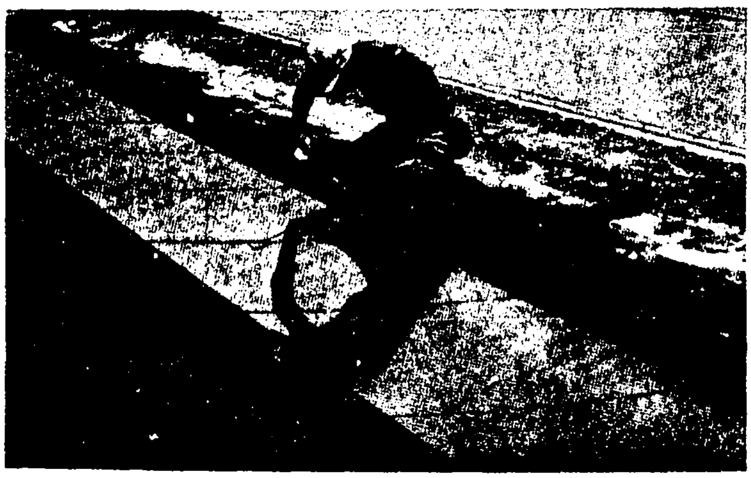


FIGURE 54. SEALING GLASS COVER WITH ASPHALTIC CEMENT

FIGURE 55. THE COMPLETED SECOND DEEP-BASIN STILL

FIGURE 56. JOINING SHEET-METAL TROUGHS (MURESK MARK II STILL)

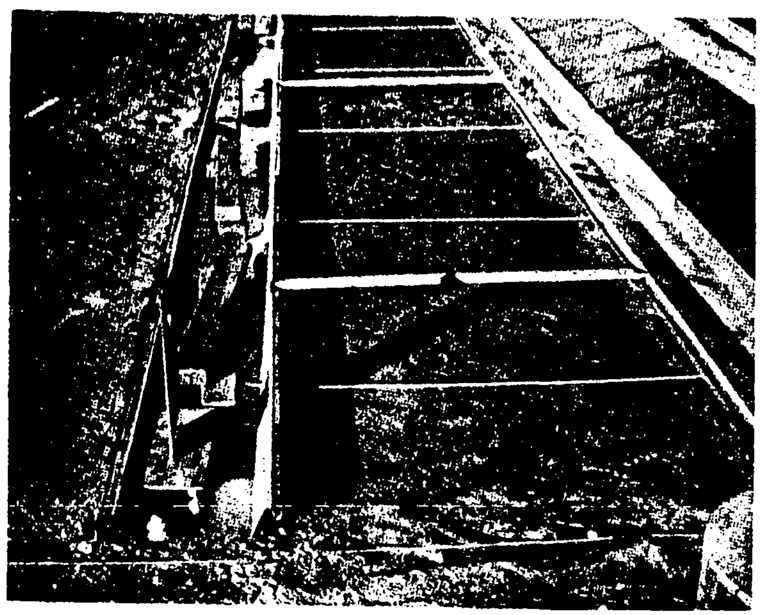


FIGURE 57. ALIGNING TROUGHS AND LOCATING WEIR CABLES

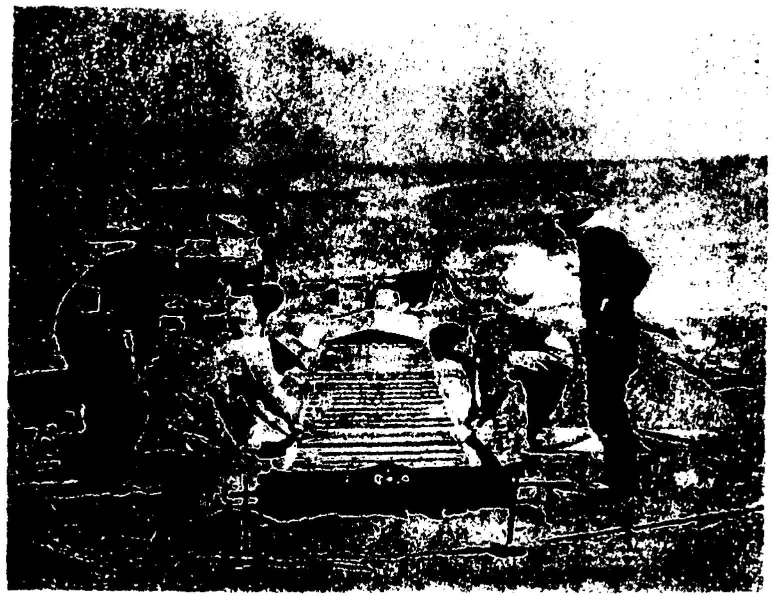


FIGURE 58. LAYING POLYETHYLENE LINER

FIGURE 59. JOINING GLASS PANES WITH SILICONE RUBBER IN WOODEN JIGS

FIGURE 60. INSTALLING GLASS COVER

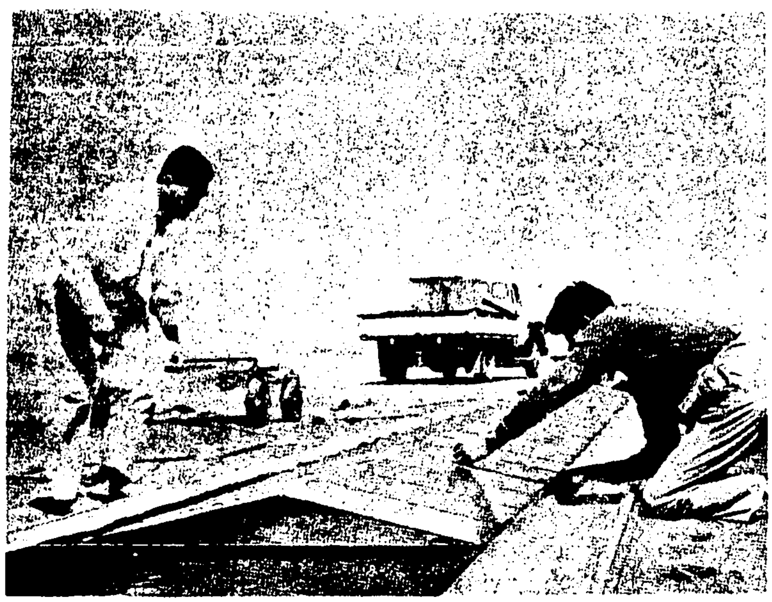


FIGURE 61. ATTACHING TIE-DOWN WIRES OVER GLASS

FIGURE 62. GENERAL VIEW OF OPERATIONS

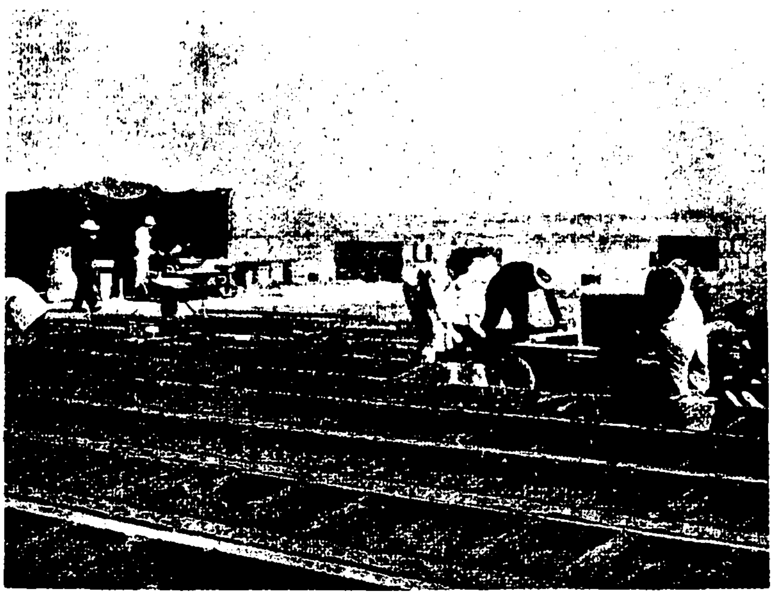


FIGURE 63. GENERAL VIEW OF ASSEMBLY OF SECOND MURESK STILL

## SECTION 9. DESCRIPTIONS OF SMALL SOLAR STILLS

This section is similar in format to Section 3 where examples of 27 large basin-type stills were given. In this section, photographs, drawings, and descriptions of more than 130 small solar stills are presented. There are probably a few solar stills which are not included in this group, either because the information was not readily available, or because they did not come to the attention of the authors in their search. However, those included are believed to be representative of the many design variations which have been tried, and those missed have not had any significant impact on solar distiller development. This information is presented for completeness, and to apprise the reader of the many experiments which have been conducted on solar stills. It is hoped that these descriptions will stimulate new ideas, as well as prevent redundancy of research efforts in the future.

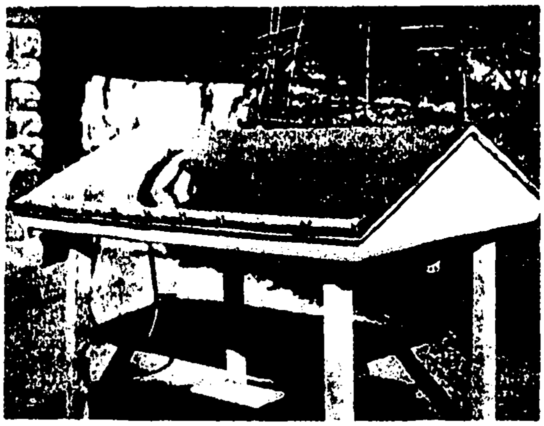
Table 23 is a list of the solar stills described in this section. The descriptions are arranged in alphabetical order by country under each of the three subdivisions and are keyed to figure numbers. Where more than one location or investigator is involved, the various stills are listed in chronological order.

TABLE 23. SMALL SOLAR STILLS, VARIOUS TYPES

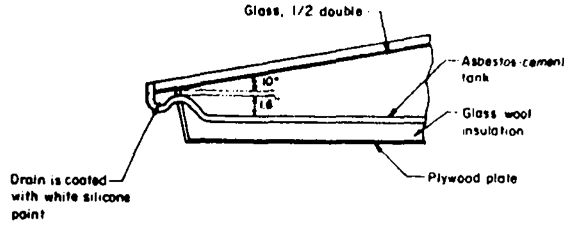
| Country | Location | Investigator | Figure Number |
|---|---|---|---|
| | | Small Basin or Tray Types | |
| Algeria | Algiers | S. E. T. U. D. E. (Gomella) | 64 |
| Australia | Mildura | C. S. I. R. O. (Wilson) | 65 |
| | Melbourne | C. S. I. R. O. (Dunkle) | 66 |
| | Perth | Univ. of Western Australia (Appleyard) | 67 |
| Chile | Valparaiso | Univ. Tecnica Federico Santa Maria (Hirschmann) | 68 |
| Cyprus | Kyrenia | (Fitzmaurice and Seligman) | 69 |
| Egypt | Cairo | National Research Center (Hafez) | 70 |
| Ethiopia | Dire Dawa | Haile Sellassie I Univ. (Hobbs) | 71 |
| India | New Delhi | National Physical Lab. (Khanna) | 72 |
| India | Navinar Lighthouse | C. S. M. C. R. I. (Bhavnagar, India) | 73 |
| Iran | Tehran | Consulting Engr. Firm (DeJong) | 74 |
| Italy | Bari | Universities of Bologna and Bari (Nebbia) | 75 |
| Mexico | Puertecitos, Baja California | Sunwater Company (McCracken) | 76 |
| Pakistan | Lahore | C. S. I. R. (Kahn) | 77 |
| Senegal | Dakar | Univ. of Dakar (Masson) | 78 |
| South Pacific Islands | Rangiroa | Univ. of Wisconsin (Daniels) | 79 |
| South Pacific Islands | Fiji, etc. | Univ. of California (Howe) | 80 |
| Spain | Las Rozas and Madrid | Nat'l Commission of Special Energy Sources (Fontan) | 81, 82 |
| Taiwan | Taipeh | Taiwan Normal Univ. (Wang) | 83 |
| Tunisia | Tunis | Tunisian AEC | 84 |
| | Chibou | Tunisian AEC | 85 |
| Union of South Africa | Pretoria | C. S. I. R. (Cillie) | 86, 87 |
| U. S. A. | Cohasset, Massachusetts | Massachusetts Inst. Tech. (Telkes) | 88 |
| | Cambridge, Massachusetts | Massachusetts Inst. Tech. (Telkes) | 89 |
| | Richmond, California | Univ. of California (Howe) | 90 to 95 |
| | Madison, Wisconsin | Bjorksten Research Labs (Bjorksten and Lappala) | 96 to 101 |
| | Daytona Beach, Florida and Columbus, Ohio | Battelle Memorial Institute (Bloemer, et al.) | 102 to 106 |
| | Daytona Beach, Florida Tempe, Arizona Madison, Wisconsin | Univ. of Wisconsin (Daniels) | 107 to 110 |
| | Ballarat, California | Sunwater Company (McCracken) | 111 |
| | Setauket, Long Island, New York | Solar Sunstill, Inc. (Delano and Raseman) | 112 |
| U. S. S. R. | Ashkhabad | Turkmenian Academy of Sciences (Bairamov and Baum) | 113 |
| West Indies | Virgin Islands | U. S. Federal Works Agency (Rounds and Lof) | 114 |
| | Barbados | McGill University (Lawand) | 115, 116 |
| | Anguilla | McGill University (Thierstein) | 117 |

TABLE 23. (Continued)

| Country | Location | Investigator | Figure Number |
|---|---|---|---|
| | | Inclined-Tray and Tilted-Wick Types | |
| France | Marseilles | Heliotechnique Laboratory (Touchais) | 118 |
| Italy | Bari | Univ. of Bari (Nebbia) | 119 |
| Tunisia | Tunis | Tunisian AEC | 120 |
| U.S.A. | New York, New York, and Princeton, New Jersey | New York Univ. and Curtis-Wright Corp. (Telkes) | 121 |
| | Madison, Wisconsin | Bjorksten Research Labs (Bjorksten and Lappala) | 122 |
| | Richmond, California | Univ. of California (Howe and McCracken) | 123 |
| | Daytona Beach, Florida | Battelle Memorial Institute (Bloemer, et al.) | 124 to 126 |
| | San Diego, California | Sunwater Co. (McCracken) | 127 |
| | New York, New York | D. S. Halacy, Jr. | 128 |
| | Madison, Wisconsin | Univ. of Wisconsin (Daniels) | 129 |
| | Phoenix, Arizona | Questlab (Rhodes) | 130 |
| U.S.S.R. | Ashkhabad | Turkmenian Acad. of Sciences (Bairamov) | 131 |
| West Indies | Virgin Gorda Island, Virgin Islands | Tippetts-Abbett-McCarthy-Stratton (Engineers and Architects, NYC) | 132 |
| | | Miscellaneous and Combination Types | |
| Australia | Melbourne | C.S.I.R.O. (Dunkle) | 133 |
| France | Paris | Univ. of Paris (Trombe and Foex) | 134 |
| Japan | Tokyo | Masatsugu Kobayashi | 135 |
| Mexico | Puerto Penasco, Sonora | Universities of Arizona and Sonora (Hodges) | 136 |
| Tunisia | Tunis | Tunisian AEC | 137 |
| U.S.A. | Cambridge, Massachusetts | Massachusetts Inst. Tech. (Telkes) | 138 |
| | Madison, Wisconsin | Univ. of Wisconsin (Daniels) | 139 |
| | New York, New York | New York Univ. (Telkes) | 140 |
| | Madison, Wisconsin | Bjorksten Research Labs | 141 |
| | Atlanta, Georgia | Georgia Inst. Tech. (Grune) | 142 |
| | Columbus, Ohio | Battelle Memorial Institute (Bloemer, et al.) | 143 |
| | Daytona Beach, Florida | Battelle Memorial Institute (Bloemer, et al.) | 144 |
| | San Francisco, California | Leslie Salt Co. | 145 |
| | Phoenix, Arizona | U. S. Dept. of Agriculture (Jackson and Van Bavel) | 146 |
| | Houston, Texas | NASA (Melpar, Inc.) | 147 |
| | Wyandanch, Long Island, New York | Lunn Laminates, Inc. (Delano) | 148 |
| | Washington, D. C. | A.I.D. (Cadwallader) | 149 |
| U.S.S.R. | Tashkent | Lenin Tashkent State Univ. (Sharafi) | 150 |
| | Moscow | Krzhizhanovsky Power Inst. (Baum) | 151 |
| West Indies | St. James, Barbados | McGill Univ. (Selcuk) | 152 |



a. Polyester-Resin-and-Fiber-Glass Tray with Plexiglass Cover




b. Section of Asbestos-Cement Tray with Glass Cover

FIGURE 64. ASBESTOS-CEMENT TRAY STILL (S. E. T. U. D. E.*, ALGERIA)

| | |
|---|---|
| Internal size: | Approximately 3.1 ft wide x 4.1 ft long; 12.6-$ft^2$ evaporating surface; long dimension East-West. |
| Brine depth: | Approximately 1 in. |
| Cover: | Glass, 10-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Moulded into tray, coated with white silicone paint. |
| Basin liner: | Asbestos-cement (Transite) tray, blackened, rock wool insulation underneath. |
| Walls and curbs: | Moulded asbestos-cement (Transite) tray. |
| Other features: | Pretreatment of raw brackish water, charcoal filter or limestone gravel used to improve taste of distilled water, reservoirs needed to balance peak winter demand, reflectors useful in winter, over 150 units distributed before 1960 (Barasoain, 49). |
| Productivity: | Approximately 0.15 gal/$ft^2$-day (June), approximately 0.03 gal/$ft^2$-day (January); annual average approximately 0.11 gal/$ft^2$-day. |
| Problems: | Lime, magnesium, and salt crystal deposits; floating white film on brine surface; frost on glass covers in morning, low output during peak demand in winter, heavy and fragile tray (fiberglass trays tried, but porosity developed). |
| Dates: | 1955 to present. |
| References: | Gomella, 179-183. |

*Societe d'etudes pour le traitement et l'utilisation des eaux (Water Treatment and Utilization Research Company).

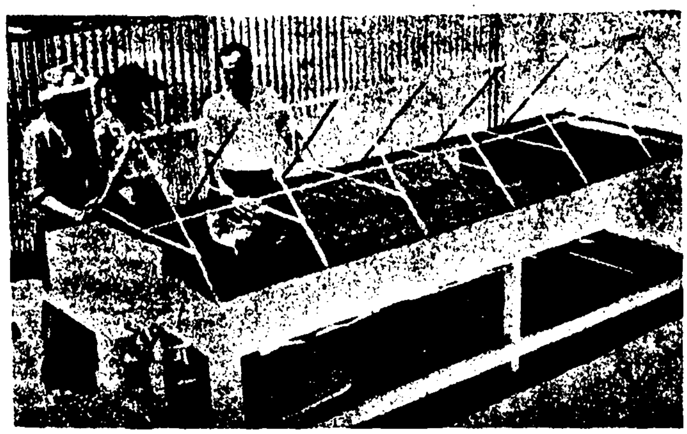


FIGURE 65. STILL AT MILDURA, AUSTRALIA (C. S. I. R. O. )*

| | |
|---|---|
| Internal size: | 40-$ft^2$ evaporating surface; external dimensions 4 ft x 12.3 ft. |
| Brine depth: | Not reported. |
| Cover: | Glass, 45-degree slope, aluminum framework with lateral and longitudinal braces, glass ends. |
| Vapor seals: | Nonhardening caulking compound. |
| Distillate troughs: | Copper. |
| Basin liner: | Black PVC sheet glued to Masonite, mineral wool insulation. |
| Walls and curbs: | Heavy wooden bench. |
| Other features: | Operated by service station for distilled water for batteries, river water used, produced more water than needed so smaller unit was designed and constructed. |
| Productivity: | (Avg. for one week, February, 1956) Approximately 0.20 gal/$ft^2$-day at approximately 2,400 Btu/$ft^2$-day. |
| Problems: | Distillate drainage from shallow gutters, difficult to maintain shallow brine layer, high cost caused shift of interest to smaller units which could be mass produced (see fiber-cement tray still). |
| Dates: | January - April, 1956. |
| References: | Anon., 10; Wilson, 491. |

*Commonwealth Scientific and Industrial Research Organization.

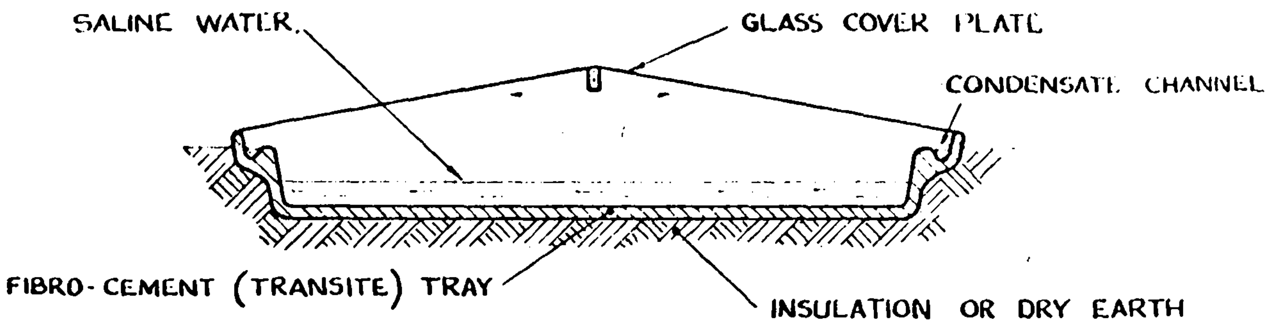
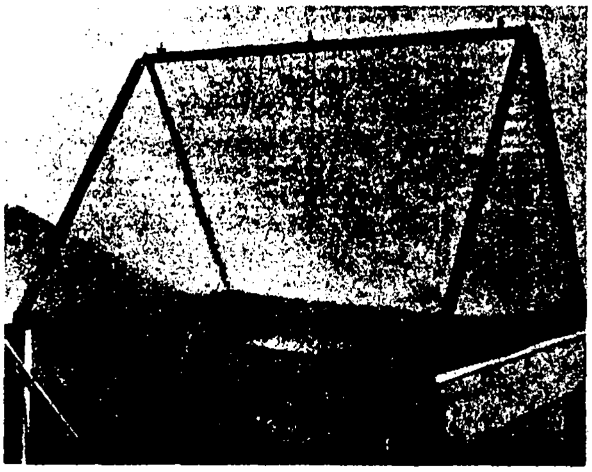


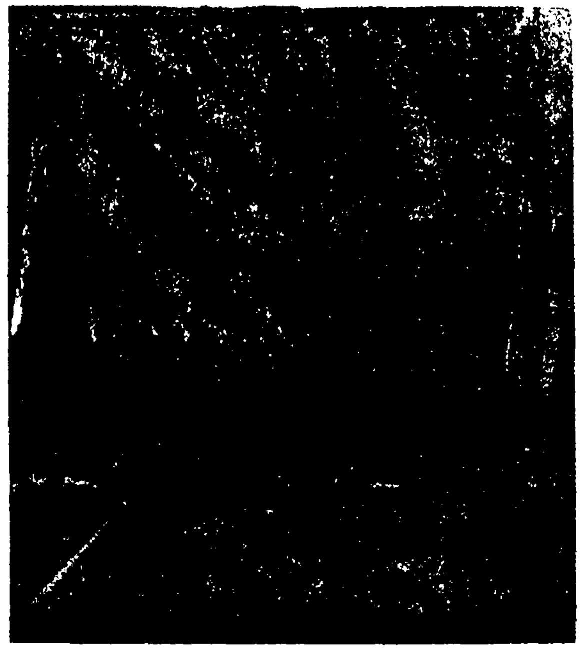

FIGURE 66. FIBER-CEMENT TRAY STILL (C.S.I.R.O.,* AUSTRALIA)

| | |
|---|---|
| Internal size: | Approximately 3.5 ft x 6 ft; approximately 20-$ft^2$ evaporating area. |
| Brine depth: | Between 0.4 and 1.5 in. |
| Cover: | Overlapped glass panes, 24 in. x 24 in., 20 oz/$ft^2$, 10-degree slope, aluminum T-bar ridge support. |
| Vapor seals: | Nonhardening caulking compound. |
| Distillate troughs: | Moulded in tray, 1/4-in. slope in 6 ft. |
| Basin liner: | 3 coats of black paint, 2-in.-thick insulation beneath tray. |
| Walls and curbs: | Fiber-cement (Transite) tray 0.35 in. thick, or fiber glass reinforced plastic tray 0.09 in. thick. |
| Other features: | Small unit size, prefabrication possible, addition of lime or sodium carbonate recommended to improve taste of distilled water, blue-black ink added to brine, do-it-yourself instructions provided. |
| Productivity: | Summer = 2 gal/day, Winter = 1 to 2 pints/day for a 20-$ft^2$ unit. |
| Problems: | 0.24-in.-thick fiber-cement tray was too thin; 0.35 in. recommended. |
| Dates: | Work began in 1956 (Trays now available commercially). |
| References: | Dunkle, 144; C.S.I.R.O., 113. |

*Commonwealth Scientific and Industrial Research Organization.



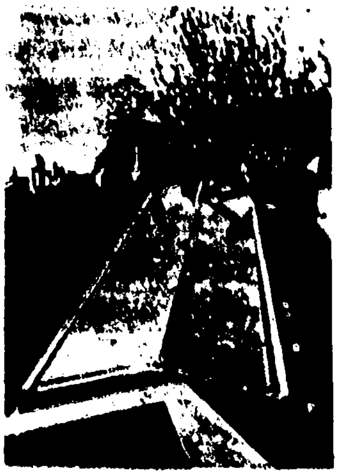
a. Glass-Covered Still



b. Diamond-Shaped Plastic Still

FIGURE 67. STILLS AT THE UNIVERSITY OF WESTERN AUSTRALIA

| | |
|---|---|
| Size: | Not given. Plastic-covered still had diamond-shaped cross section. |
| Brine depth: | 0.32 to 0.70 in. |
| Cover: | One of glass, the other of 12-mil PVC. |
| Vapor seals: | Not described. |
| Distillate troughs: | Not described. |
| Basin liner: | Black polyethylene tray used in diamond-shaped plastic-covered still. |
| Walls and curbs: | Wood framework (glass), metal framework (plastic). |
| Other features: | Steep slope for glass and plastic covers. |
| Productivity: | Efficiencies of 60 percent (glass) and 54 percent (plastic) claimed. |
| Problems: | Faulty sealing of the glass still, nonwetting of PVC cover, tested over a radiation range of only 300 to 1200 Btu/ft$^2$-day. |
| Dates: | Latter half of 1964. |
| References: | Appleyard, 39. |



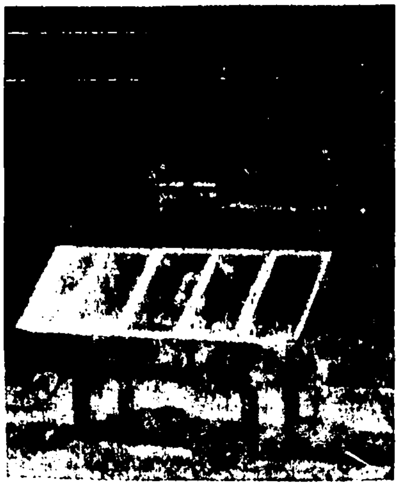
a. Still USM-6

b. Still USM-7

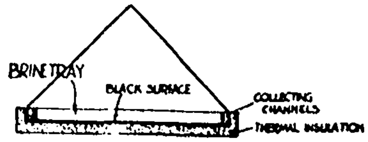
c. Still USM-8

FIGURE 68. STILLS AT THE UNIVERSIDAD TECNICA FEDERICO SANTA MARIA (VALPARAISO, CHILE)

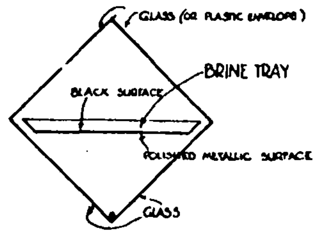
| | |
|---|---|
| Internal Size: | Not reported. |
| Brine depth: | Not reported. |
| Cover: | Glass. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Moulded in curbs. |
| Basin liner: | (Still No. USM-6) Concrete, (USM-7) asbestos cement, (USM-8) probably black polyethylene film. |
| Walls and curbs: | (Still No. USM-6) concrete, (USM-7) asbestos-cement basin, (USM-8) Australian CSIRO type. |
| Other features: | None reported. |
| Productivity: | All approximately 0.10 gal/$ft^2$-day. |
| Problems: | Earthquakes damage concrete stills if built on ground. |
| Dates: | Around 1967. |
| Note: | Stills USM-1 through USM-5 were experimental stills using evaporating wicks. |
| References: | Hirschmann, 216. |



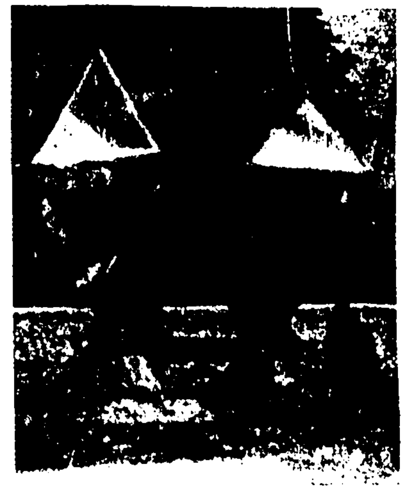
a. 1954 Type




b. Cross Section 1954 Type



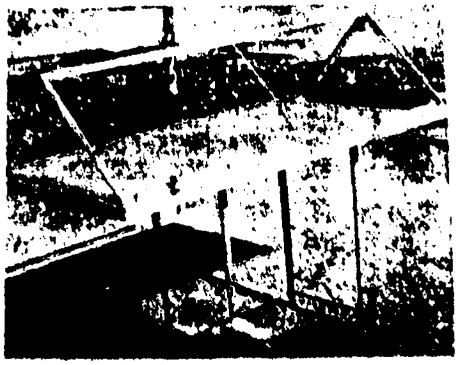

c. Cross Section 1955 Type



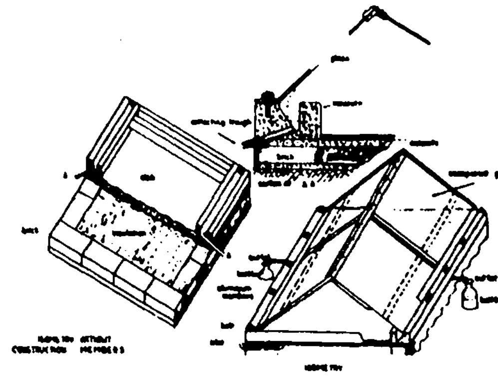
d. 1955 Type

FIGURE 69. STILLS ON ISLAND OF CYPRUS

| | |
|---|---|
| Internal size: | (Two 1954 stills), each tray 34 x 70 in., 16.5 $ft^2$; (two 1955 stills) larger one approx. 14 x 28 in., 2.69 $ft^2$. |
| Brine depth: | Not reported. |
| Cover: | Glass, 0.09 in. thick, 45-degree slope; type of plastic not reported (nonwettable). |
| Vapor seals: | One-inch strips of fiberglas tape and cold setting polyester resin. |
| Distillate troughs: | Same as tray materials, coated with white-pigmented polyester resin. |
| Basin liner: | (1954 stills) one of laminated polyester resin and one of galvanized steel, both with a layer of black pigmented polyester, insulated with 1/2 in. fiberboard plus 1 in. fiberglas; (1955 stills) tray suspended inside still, black top, polished bottom. |
| Walls and curbs: | Wooden framework. |
| Other features: | 1954 stills provided water for two orange trees and four lemon trees, sea water used, stills flushed with fresh sea water soon after sunrise each day, completely sealed units attempted; 1955 stills had larger condensing areas to reduce internal vapor pressure, solar reflector added to glass unit. |
| Productivity: | (1954 stills) Average of 0.12 gal/$ft^2$-day in June and 0.10 gal/$ft^2$-day in Sept., resin tray 20 percent lower output; (1955 stills) glass unit had 0.14 gal/$ft^2$-day in Aug. and 0.21 gal/$ft^2$-day with reflector, plastic unit had 0.08 gal/$ft^2$-day in early Sept. |
| Problems: | (1954) Sealing strips loosened occasionally and allowed glass panes to fall into still so wooden ridge poles were added, complete sealing of 1954 stills not possible, some brine leaked and wetted insulation; (1955) plastic cover was nonwetting. |
| Dates: | June - September, 1954, and August - September, 1955. |
| References: | Fitzmaurice and Seligman, 166. |



a. Foldable Aluminum-Tray Still



b. Concrete-Base Still

FIGURE 70. STILLS AT THE NATIONAL RESEARCH CENTER (CAIRO, EGYPT)

| | |
|---|---|
| Internal size: | (Aluminum still) not reported; (Concrete still - Type 1) two units, each 6.5-ft-wide x 33-ft-long, 215-$ft^2$ basins; (Concrete - Type 2) one unit 4-ft-wide x 3.3-ft-long, 13-$ft^2$ basin; (Plastic-covered still) 3.3 ft diameter. |
| Brine depth: | (Aluminum and Concrete stills) not reported; (Plastic still) 0.4 in. |
| Cover: | (Aluminum) Glass, ~45-degree slope, aluminum framework; (Concrete) Glass, 30-degree slope, aluminum framework; (Plastic) 20-mil Mylar, 30-degree slope, 88 percent transmissivity, center rod support with spherical head. |
| Vapor seals: | (Aluminum and Concrete) not reported; (Plastic) double metal ring used to fasten the plastic around the distillate channels. |
| Distillate troughs: | (Aluminum and Plastic) not reported; (Concrete), No. 1 - separate channels attached to walls, No. 2 – moulded in concrete walls. |
| Basin liner: | (Aluminum) aluminum tray; (Concrete) concrete waterproofed and blackened with a thin layer of asphalt, insulated basin; (Plastic) galvanized iron tray, blackened and insulated. |
| Walls and curbs: | (Aluminum and Plastic) not reported; (Concrete) concrete. |
| Other features: | (Aluminum) small reservoir provides constant level of brine, roof is foldable for easy transportation, glass ends; (Concrete) Type 2 still erected to improve first concrete-base model and obtain cost estimates; (Plastic) Brine flushed every day after sunset, an electric vibrator attached to plastic cover to promote flow of condensate drops. |
| Productivity: | (Aluminum) 0.135 gal/$ft^2$-day (July-August average); (Concrete) No. 1 – about 0.086 gal/$ft^2$-day in summer (~2,200 Btu/$ft^2$-day) and 0.025 gal/$ft^2$-day in winter (~1,300 Btu/$ft^2$-day), No. 2 – approx. 0.12 gal/$ft^2$-day estimated for yearly average; (Plastic) empirical equation derived, $Y = (E/832)-2.25$, where Y is yield in L/$m^2$-day, E is radiation in Kcal/$m^2$-day, which gives approx. 0.105 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| Problems: | (Aluminum) none reported; (Concrete) No. 1 – cracks in distillate channels, bad insulation underneath basin, longer inclined glass distance produced higher glass temperature as water film temperature increased; (Plastic) dropwise condensation on cover, dust adherance to cover required frequent cleaning, decrease in transmissivity of cover after operating for 1 year. |
| Dates: | (Aluminum) July-August, 1960; (Concrete) 1960-1961; (Plastic) around 1966. |
| References: | Hafez and Elnesr, 199; Sakr, 403, 404. |

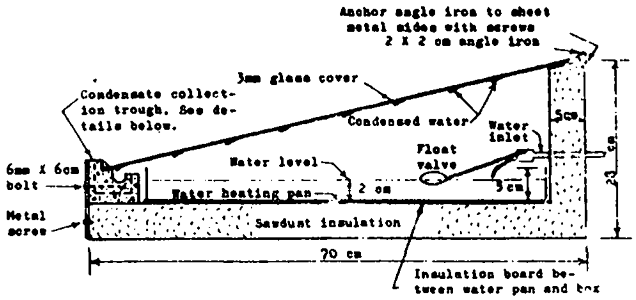
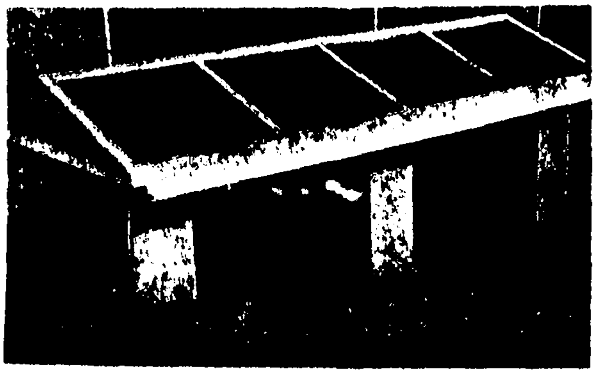
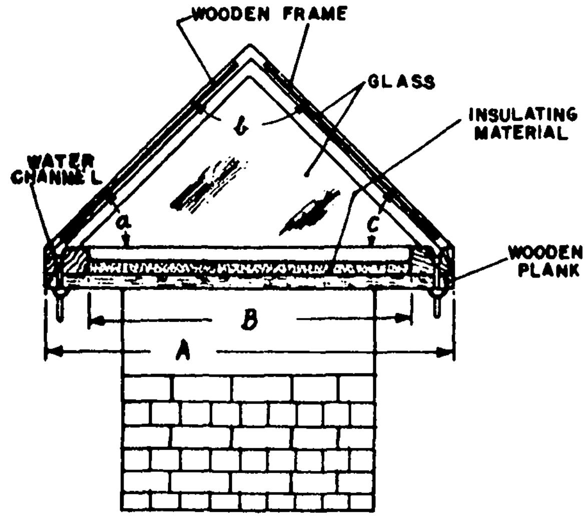



FIGURE 71. STILL AT THE HAILE SELLASSIE I UNIVERSITY (DIRE DAWA, ETHIOPIA)

| | |
|---|---|
| Internal size: | Tray, 2 in. deep x 22 in. wide x 74 in. long; 11.3-$ft^2$ evaporating area. |
| Brine depth: | 0.8 in. |
| Cover: | Glass panes, 0.12 in. (3mm) thick x 27.5 x 39.4 in., 12-degree slope. |
| Vapor seals: | Window glass putty. |
| Distillate troughs: | Moulded in concrete curb. |
| Basin liner: | Galvanized sheet metal painted dull black, insulation board and sawdust underneath. |
| Walls and curbs: | Galvanized sheet metal box, reinforced concrete curb. |
| Other features: | Float valve for level control, one end removable. |
| Productivity: | 0.12 to 0.15 gal/$ft^2$-day during dry months October-June; approximately 1/3 as much during rainy months July-September. |
| Problems: | None reported. |
| Dates: | Around 1964 – 1965. |
| References: | Hobbs, 218. |



a. Still B (Stills C, D, E similar)




b. Side View, Still B
A = 4 ft. 2 in., B = 3 ft. 8 in.,
a = c = 15° and b = 150°.

FIGURE 72. STILLS AT NATIONAL PHYSICAL LABORATORY (NEW DELHI, INDIA)

| | |
|---|---|
| Internal size: | 5 units; one tray (Still A) 2 ft 10 in. wide (48.0 $ft^2$), four trays (Stills B-E) 3 ft 8 in. wide (29.1 $ft^2$ each); both East-West and North-South orientations tried. |
| Brine depth: | Approximately 1 in. |
| Cover: | Glass panes, 1/8 in. x 2 ft x 2 ft (Still A-3 ft x 2 ft), supported by wood frames; 15-degree slope. (Still A had a 43-degree glass cover and a 73-degree insulated aluminum cover). |
| Vapor seals: | Putty, made from chalk and double-boiled linseed oil. |
| Distillate troughs: | Galvanized iron or zinc sheet originally, later polythene hot pressed into channels. |
| Basin liner: | Galvanized iron or copper trays, painted black with bituminous paint, insulated with 2 in. of sawdust or rock wool. |
| Walls and curbs: | Wood planking and side rails, elevated above ground on masonry platforms. |
| Other features: | Brackish well-water feed, outside of stills painted white, various materials tested. |
| Productivity: | 0.061 gal/$ft^2$-day (Sept.), 0.028 gal/$ft^2$-day (Jan.). |
| Problems: | Improvements in still construction needed to meet Indian Standards Specifications for total dissolved solids in distilled water, trays elevated above ground to avoid termites, mildew, etc., galvanized iron eventually rusts, sawdust deteriorates if it becomes damp. |
| Dates: | 1957 to present. |
| References: | Khanna, 269-271, 276, 277. |

FIGURE 73. STILL AT NAVINAR LIGHTHOUSE (C.S.M.C.R.I.,* INDIA)

| | |
|---|---|
| Internal Size: | One large pond, 615-$ft^2$ evaporating area. |
| Brine depth: | Approx. 4 in. |
| Cover: | Glass, approx. 20-degree slope. |
| Vapor seals: | Tarplastic. |
| Distillate troughs: | Not reported. |
| Basin liner: | Concrete, painted black. |
| Walls and curbs: | Concrete. |
| Other features: | Rainwater collection, batchwise feed. |
| Productivity: | 30 gpd (annual average) |
| Problems: | Vapor leakage due to improper sealing of glass-to-glass joints before Tarplastic sealant used. |
| Dates: | September, 1968, to present. |
| References: | Datta, 124. |

*Central Salt and Marine Chemicals Research Institute.

a. Still 1

b. Stills 2 (in background) and 3

FIGURE 74. STILLS IN TEHRAN, IRAN

| | |
|---|---|
| Internal size: | (Still 1) 16 in. x 28 in., 3.10 $ft^2$, (Still 2) 2.50-$ft^2$ tray, (Still 3) 18.5 in. x 25 in., 3.20 $ft^2$. |
| Brine depth: | 0.3 in. or less. |
| Cover: | (1) Glass, 68-degree slope, (2) Glass on 3 sides, 41-degree slope, galvanized tin on north side, (3) Glass, 34-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Galvanized tin. |
| Basin liner: | Galvanized tin trays, painted dull black. |
| Walls and curbs: | Tin or wood. |
| Other features: | Stills operated inside a greenhouse during winter months, (1) ends of tin, reflecting aluminum advantageous for North cover, (2) North cover of galvanized tin, 14 ft of water-cooled copper tubing inside with 1.17-$ft^2$ surface, (3) back and ends of wood, 21 ft of copper tubing inside with 2.30-$ft^2$ surface. |
| Productivity: | (1) Approx. 0.01 gal/$ft^2$-day during April, about 0.03 gal/$ft^2$-day during summer months, and 0.06 gal/$ft^2$-day estimated with reflecting north cover. |
| Problems: | Shadows from end walls on Stills 1 and 3, low brine temperatures (120 F maximum reported). |
| Dates: | During 1957. |
| References: | DeJong, 126. |

STILLS AT THE UNIVERSITIES OF BOLOGNA AND BARI (ITALY)

| Model | Date Built | Construction Mat'l. Tray | Construction Mat'l. Cover | Insulating Material | Tray Area, $ft^2$ | Max. Productivity, gal/$ft^2$-day |
|---|---|---|---|---|---|---|
| 1 | 1953 | Plexiglas | Plexiglas | None | 1.7 | -- |
| 2 | 1953 | Wood | Glass | Cork | 27 | 0.07 |
| 3 | 1953 | Plexiglas | Glass | Cork | 2.7 | 0.10 |
| 4 | 1954 (3 units) | Iron | Glass | Compressed cellulose fibers | 16 and 32 | 0.07 |
| 5 | 1955 | Concrete | Glass | Pumice | 108 | 0.06 |
| 6 | 1957 | Aluminum | Plexiglas | Inside air | 3.5 | 0.10 |
| 7 | 1958 | Aluminum | Glass | Inside air | 11.6 (4 trays) | 0.09 |
| 7A | ~1962 | Aluminum | Glass | Inside air | 38.7 (5 trays) | 0.06[a] |

(a) At a radiation level of approximately 1,850 Btu/$ft^2$-day.

Covers: Slope of about 45 degrees used on all models except 7A.

Other features: Trays refilled every two or three days; Still 7 had good productivity in winter, Still 5 was built on the flat roof of a house, aluminum trays blackened electrolytically; Still 7A is enlarged version of No. 7.

Problems: Dropwise condensation on plexiglas covers (Stills 1 and 6), re-evaporation of distillate (Still 5).

Dates: 1953 to present.

References: Nebbia, 363-370.

1

2

3

4

5

6

7

7A

FIGURE 75. STILLS AT THE UNIVERSITIES OF BOLOGNA AND BARI (ITALY)

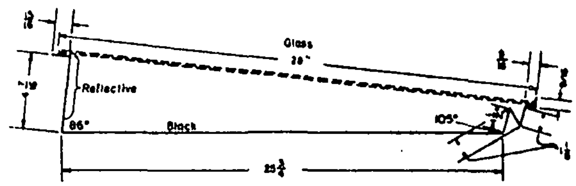



FIGURE 76. STILL AT PUERTECITOS, BAJA, CALIFORNIA, MEXICO (SUNWATER CO.)

| | |
|---|---|
| Internal size: | One tray, 26 in. wide x 45 ft long; approx. 100-$ft^2$ basin area. |
| Brine depth: | Approx. 1 in. |
| Cover: | Glass; 6-degree slope facing southward. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Preformed grooves in tray. |
| Basin liner: | Silicone-rubber-coated aluminum, black bottom, insulated. |
| Walls and curbs: | Prefabricated aluminum tray. |
| Other features: | Mounted on roof of resort motel, tie-downs used to prevent movement or lifting of stills by wind, modular construction, prefabrication of tray, taste of distillate can be improved by flowing over bed of limestone or marble chips. |
| Productivity: | Rated at 10 gal/day as yearly average (0.10 gal/$ft^2$-day). |
| Problems: | None reported (peak demand probably in winter). |
| Dates: | Approx. 1967 to present. |
| Note: | Small stills of this type have also been installed at private residences throughout the Southwestern United States, Mexico, and the Caribbean in sizes down to 1/2 gpd. |
| References: | Anon., 29; McCracken, 329. |

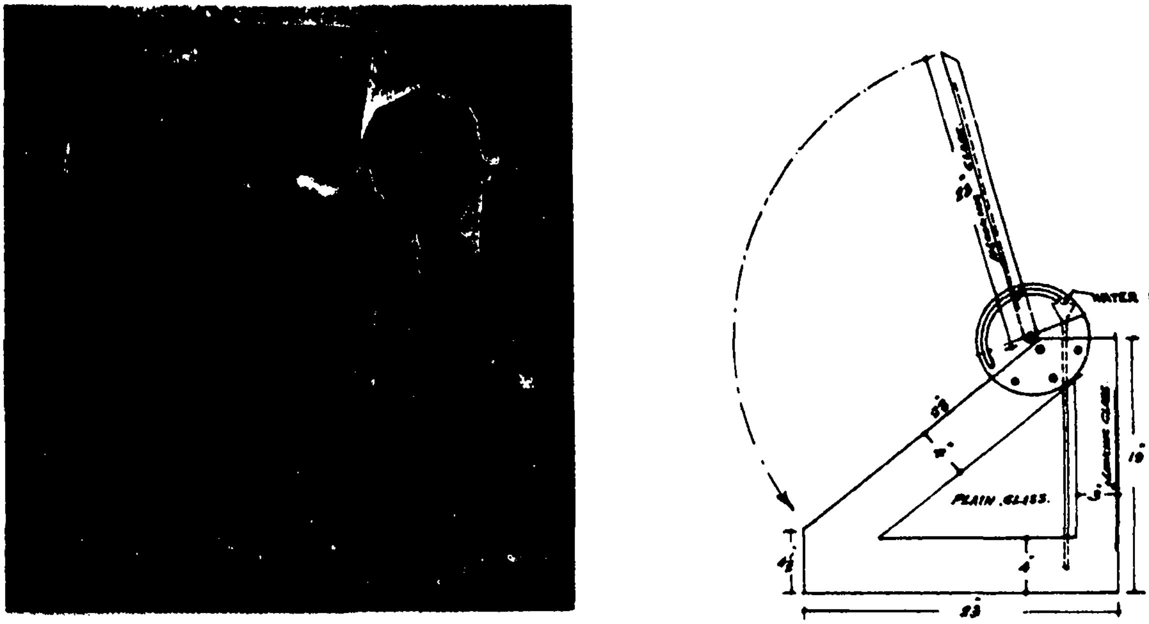



FIGURE 77. STILL WITH REFLECTING SURFACES (PCSIR*, LAHORE, WEST PAKISTAN)

| | |
|---|---|
| External size: | 23 in. wide, 19 in. high, length not reported. |
| Brine depth: | 1/4 to 2 in. |
| Cover: | Glass, approx. 40-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Material not reported, but channels surround tray. |
| Basin liner: | Copper tray. |
| Walls and curbs: | Not reported. |
| Other features: | Adjustable mirror to reflect additional sunlight, mirror on inside back wall. |
| Productivity: | At ambient temperatures between 86 and 90 F; (1/4-in. water depth) 0.121 gal/$ft^2$-day, (1 in.) 0.115 gal/$ft^2$-day, (2 in.) 0.086 gal/$ft^2$-day. |
| Problems: | None reported. |
| Dates: | Around 1963. |
| References: | Khan, 268. |

*Pakistan Council of Scientific and Industrial Research.

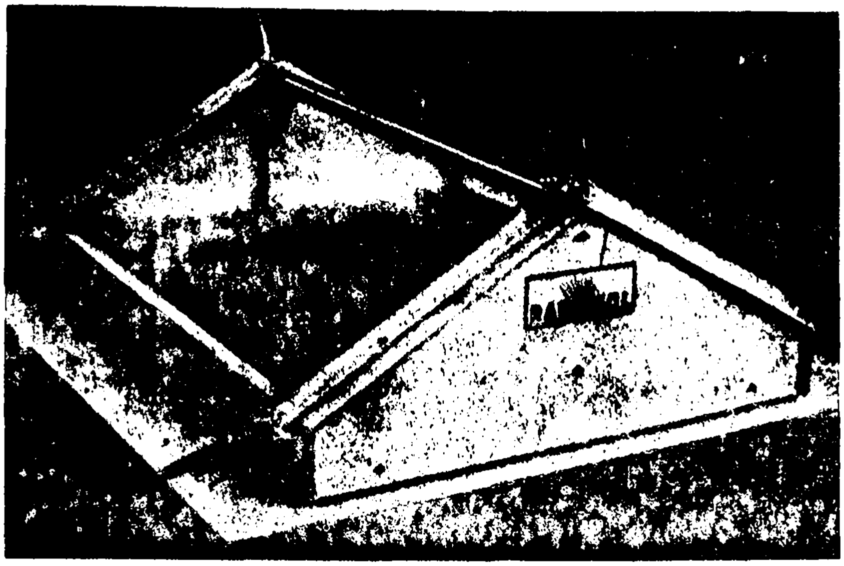
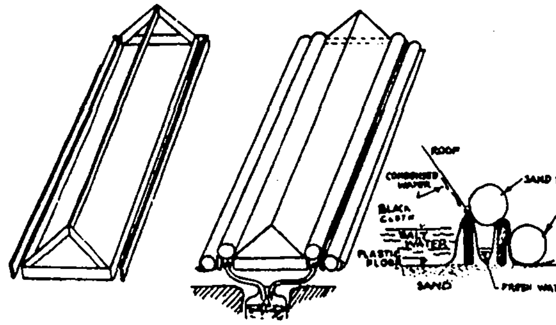


FIGURE 78. THE RADIASOL STILL (SENEGAL, WEST AFRICA)

| | |
|---|---|
| Internal size: | Not reported. |
| Brine depth: | Not reported. |
| Cover: | Glass, approx. 30-degree slope. |
| Vapor seals: | Rubber gaskets at all joints. |
| Distillate troughs: | Plastic material. |
| Basin liner: | Black plastic; bottom, sides, and ends insulated with fiberglass. |
| Walls and curbs: | Sheet steel. |
| Other features: | Black plastic, liner easily removable for cleaning or replacing, double tube provided for filling and emptying. |
| Productivity: | Not reported. |
| Problems: | Shadows cast by end walls, crystalline deposits when calcareous or magnesian well water is used. |
| Dates: | Around 1956. |
| References: | Masson, 334. |

a. Plastic Stills at Rangiroa, South Pacific




b. Design of Plastic Still with Sandbags

FIGURE 79. PLASTIC STILLS AT RANGIROA, SOUTH PACIFIC (UNIV. OF WISCONSIN)

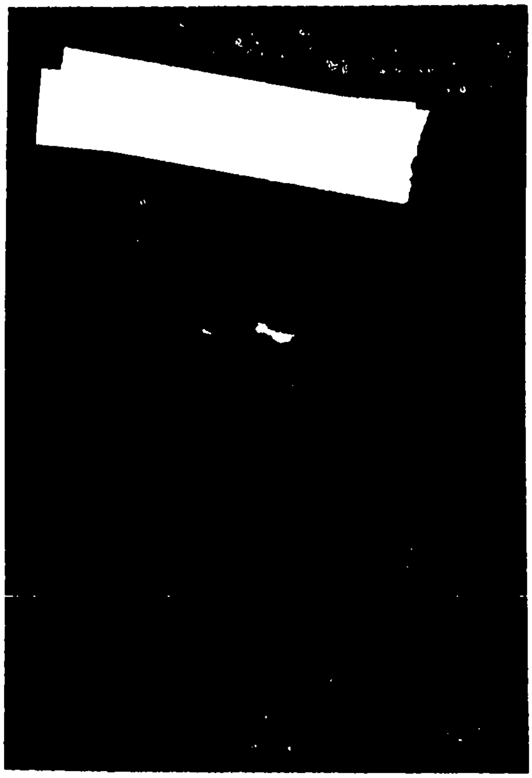
| | |
|---|---|
| Internal size: | 4 stills, each 2 ft wide x 12 ft long. |
| Brine depth: | Approx. 1 in. |
| Cover: | Transparent polyethylene, approx. 40-degree slope, bamboo ridge pole. |
| Vapor seals: | Cylindrical plastic sandbags used as weights. |
| Distillate troughs: | Wood, sandbags, or concrete; lined with basin liner. |
| Basin liner: | 6-mil transparent polyethylene sheet, floating black cloth, fine coral sand layer underneath. |
| Walls and curbs: | Wood walls for two stills, sandbags for one, and concrete for one. |
| Other features: | Polyethylene bags used to collect distilled water. |
| Productivity: | Approx. 0.04 gal/$ft^2$-day on February 17, 1963 (2100 Btu/$ft^2$-day). |
| Problems: | Difficulty with black polyethylene basin liners overheating where not covered with water, dropwise condensation on cover, frequent adjustments of sandbags required. |
| Dates: | Two weeks of operation in February, 1963. |
| References: | Daniels, 118. |

a. Still at Lautoka, Fiji


b. Cross Section

FIGURE 80. SAWTOOTH-TYPE STILLS ON SOUTH PACIFIC ISLANDS (UNIV. OF CALIFORNIA)

| | |
|---|---|
| Internal size: | 6 ft x 84 ft, 288-$ft^2$ basin area. (8 modules, 6 ft x 6 ft each). |
| Brine depth: | (Lautoka) 3/4 in. (Rangiroa) 1-1/2 in. |
| Cover: | Glass panes, 18 x 36 in., 10-degree slope, aluminum tee-section supports. |
| Vapor seals: | Rubber strips in valleys, galvanized iron strips cover peaks. |
| Distillate troughs: | Metal trough hung below valleys from framework (galvanized iron or brass strips). |
| Basin liner: | Black polyethylene, laminated. |
| Walls and curbs: | Precast concrete structures at Lautoka, Fiji, and plywood side rails at Rangiroa. |
| Other features: | Ridges and valleys run across narrow width of still so distillate troughs are less than 6 ft long, modular construction, batch filled daily (shallow basins) or weekly (deeper basins), rainfall collected, area fenced. |
| Productivity: | Average of 0.08 gal/$ft^2$-day used to size stills (max. productivity about 30 gpd). |
| Problems: | Leaks in valleys allow rainwater and dirt to enter distillate trough, basin liner pierced by grass. |
| Dates: | 1965 to 1966 (Both large stills). |
| Note: | Many similar but smaller stills built on other islands. Over 25 built from kits of 6 x 8-ft modules. |
| References: | Howe, 247-250, personal communication, Jan. and Feb., 1969. |



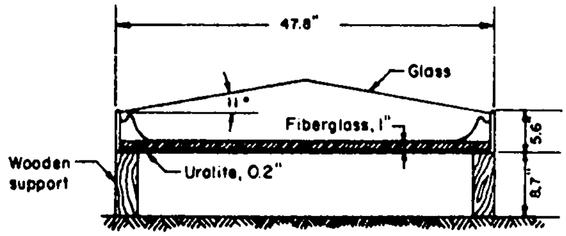
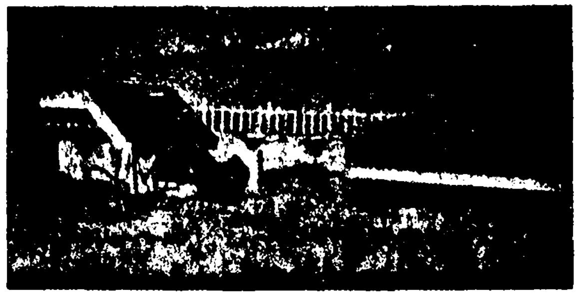



FIGURE 81. STILLS AT LAS ROZAS, SPAIN

| | |
|---|---|
| Internal size: | Two stills, each with approx. 21-$ft^2$ basin area. |
| Brine depth: | Not reported (approx. 2 to 3 in.). |
| Cover: | One still with glass 0.12 in. (3 mm) thick, the other with Mylar (treated for wettability), both had 10.8-degree slope, aluminum framework support. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Moulded in fiber-cement curbs. |
| Basin liner: | Tray of zinc sheet with wooden framework and glass-fiber insulation underneath. |
| Walls and curbs: | Fiber-cement tray and curbs supported by four wooden posts. |
| Other features: | Constant brine level maintained, brine blackened with dye (aniline). |
| Productivity: | (Glass cover) approx. 0.10 gal/$ft^2$-day at approx. 2000 Btu/$ft^2$-day; (Plastic cover) low yield, not reported. |
| Problems: | Slope of plastic cover insufficient to prevent refluxing of distillate drops, aniline (dye) had to be added occasionally. |
| Dates: | August - October, 1958. |
| References: | Barasoain and Fontan, 49. |

a. Stills 1, 2, and 3



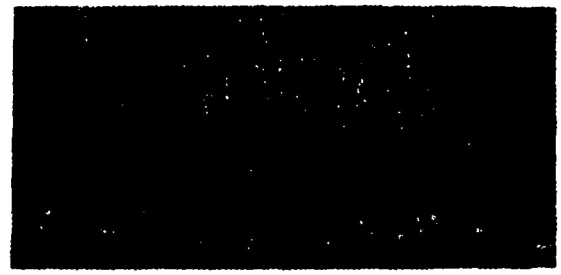
b. Stills 4 and 5

FIGURE 82. SIX STILLS AT LAS ROZAS, SPAIN (NATIONAL COMMISSION OF SPECIAL ENERGY SOURCES)

| Still | Cover Mat'l. | Slope, degrees | Evaporation Area, $ft^2$ | Outside Dimensions, ft. Width | Length | Orientation of Length |
|---|---|---|---|---|---|---|
| 1 | Glass | 10 | 21.5 | 4.1 | 6.0 | N-S |
| 2 | Glass | 40 | 21.0 | 4.1 | 6.0 | N-S |
| 3 | Plastic | 40 | 23.2 | 4.1 | 6.4 | N-S |
| 4 | Glass | 40 | 8.4 | 5.7 | 3.1 | E-W |
| 5 | Glass | 10 & 40 | 5.4 | 3.7 | 3.4 | E-W |
| 6 | Glass | 15 & 35 | 7.1 | 3.8 | 3.5 | E-W |

| | |
|---|---|
| Brine depth: | (Stills 1-3) approx. 3 to 4 in. |
| Cover: | (Stills 1, 2, 4-6) Glass, 0.12 in. (3 mm) thick; (Still 3) 5-mil Mylar. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Usually lined with basin-liner material. |
| Basin liner: | Zinc sheet, 0.08 in. (2 mm) or 0.05 in. (1.2 mm) thick. |
| Walls and curbs: | Wooden box frames, stills supported above ground. |
| Other features: | Ten different types of stills tested, constant brine level maintained, aniline dye added to brine. |
| Productivity: | (1) approx. 0.10 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day, (2) approx. 0.08 gal/$ft^2$-day, (3) approx. 0.07 gal/$ft^2$-day, (4-6) data were not ready for publication. |
| Problems: | None reported. |
| Dates: | 1958 to 1961+. |
| References: | Fontan and Barasoain, 167. |

a. Solar Still Equipment for Research Purposes



b. Solar Stills Ready for Shipping to the Satellite Islands for Fishermen and Troops

FIGURE 83. STILLS AT TAIWAN NORMAL UNIVERSITY (TAIPEH, TAIWAN)

| | |
|---|---|
| Internal size: | Three stills 3 ft x 6 ft, three stills 3 ft x 3 ft; 81 $ft^2$ total basin area. |
| Brine depth: | Not reported. |
| Cover: | Glass, approx. 45-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Not reported. |
| Walls and curbs: | Not reported. |
| Other features: | Smaller size designed and produced for use on islands by fishermen and military troops, ends of glass, stills on lab roof withstood typhoon. |
| Productivity: | Maximum of approx. 0.13 gal/$ft^2$-day. |
| Problems: | None reported. |
| Dates: | Around 1960-1961. |
| References: | Wang, 482. |

a. Single-Slope Still, DA or D1

b. Double-Slope Still, DC or D6

FIGURE 84. SINGLE- AND DOUBLE-SLOPED STILLS (TUNISIAN AEC)

| | |
|---|---|
| Internal size: | (Single sloped) DA – 38-$ft^2$ evaporating area, D1 – 59 $ft^2$; (Double sloped) DC and D6 – 22 $ft^2$. |
| Brine depth: | Not reported. |
| Cover: | Glass, approx. 10-degree slope; (DA, D1) 0.20 in. thick, (DC, D6) 0.24 in. thick. |
| Vapor seals: | (DA, D6) Mastic, (D1) Rubber and plaster, (DC) Dull black paint. |
| Distillate troughs: | (DA, D1) Moulded in curb, (DC, D6) Not reported. |
| Basin liner: | (DA) 5-in.-thick asphalt (D1) Initially black tiles, then cement, (DC) Zinc plate, (D6) Cement. |
| Walls and curbs: | (DA, D1, D6) Masonry, (DC) Wood. |
| Other features: | (D1, D6) anticipated lifetime of 20 years. |
| Productivity: | Summer: (DA) 0.11 gal/$ft^2$-day (D1) 0.06 (DC) 0.07 (D6) 0.12; Winter: (DA) 0.04 (D1, DC) 0.01 (D6) 0.05. |
| Problems: | Black tiles not advantageous from the standpoint of distilled water cost, water has had unpleasant taste due to organic materials used for sealing and solar absorptance, incrustation of basins. |
| Dates: | (D1, D6) Built February, 1967. |
| Note: | Still D1 was the prototype for the larger installations at Chakmou, Chibou, and Mahdia (Tunisia), with more planned. Ten small stills of various designs tested, and construction plans made for family-size stills for 2, 5, or 10 persons. |
| References: | Tunisian AEC, 454. |

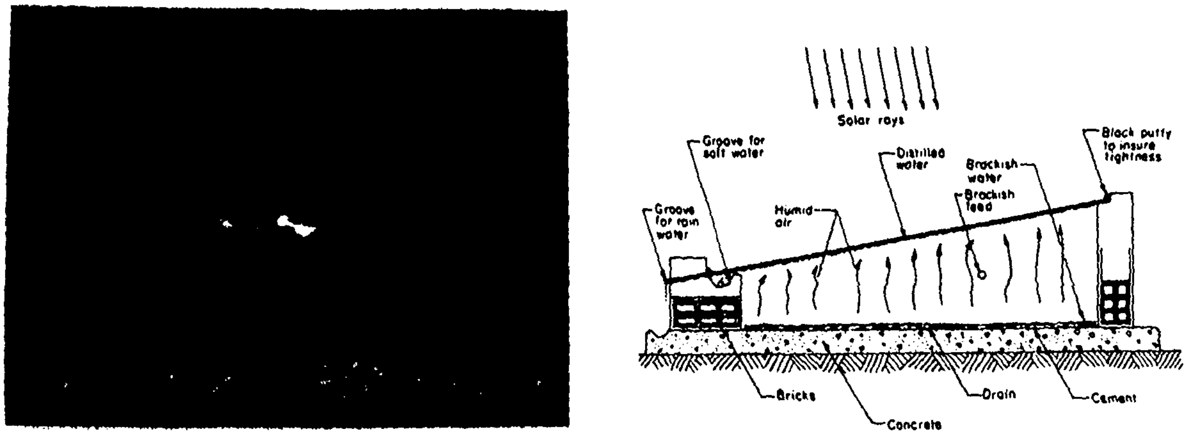



FIGURE 85. STILL AT CHIBOU, TUNISIA

| | |
|---|---|
| **Internal size:** | 10 bays; 430-$ft^2$ evaporating area (overall area 1100 $ft^2$). |
| **Brine depth:** | Approx. 1 in. |
| **Cover:** | Glass; 10-degree slope facing southward. |
| **Vapor seals:** | Black plastic sealant ("Igass"). |
| **Distillate troughs:** | Moulded in concrete curb. |
| **Basin liner:** | Cement bottom. |
| **Walls and curbs:** | Bricks and concrete. |
| **Other features:** | Provides drinking water for 40 persons, feedwater contains 9 g/l of salt, three parts distilled water mixed with one part brackish water for drinking, raised platform for stills 3 ft above ground to keep dust off the covers. |
| **Productivity:** | Varies between 21 and 37 gpd (0.05-0.08 gal/$ft^2$-day), mixed to give 53 gpd of potable water. |
| **Problems:** | Some salt in distilled water (0.02 g/l), four to five times larger station would be desirable for the region. |
| **Dates:** | July, 1967, to present. |
| **Note:** | The construction of many similar stills is planned. (See descriptions of Chakmou and Mahdia stills in Section 3.) |
| **References:** | Tunisian AEC, 454, 455. |

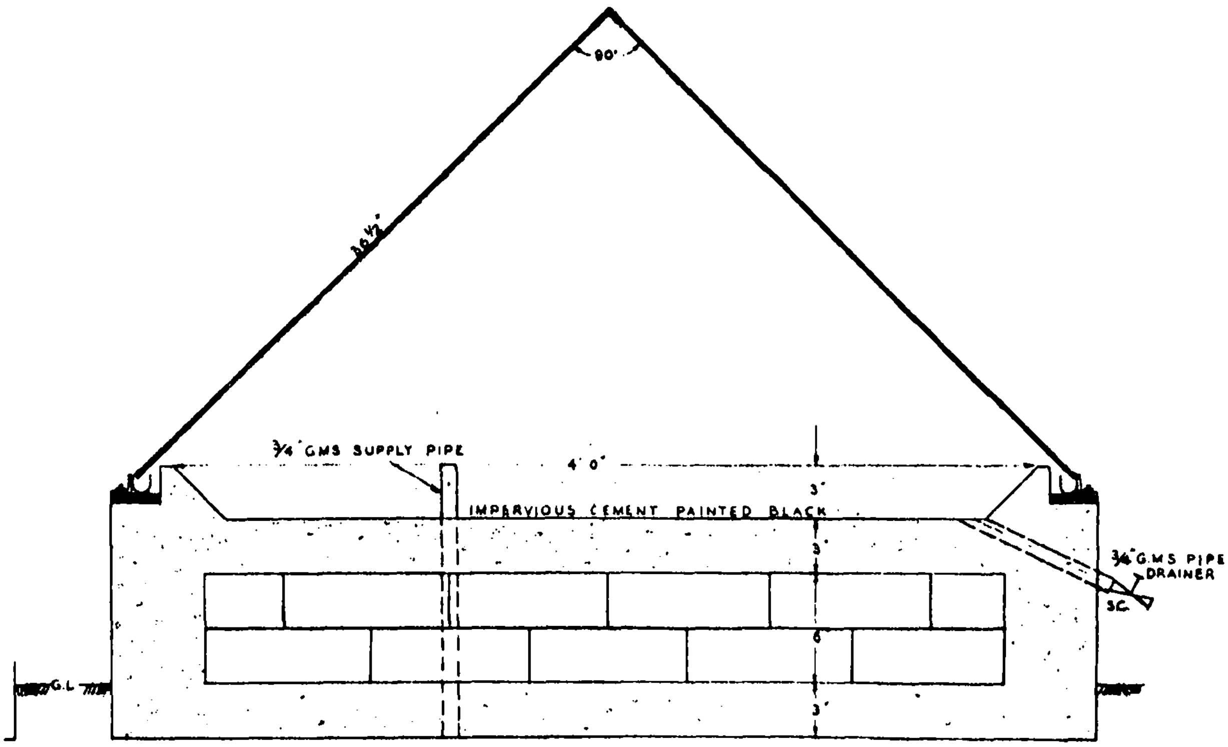



FIGURE 86. STILL DESIGN OF C.S.I.R.* (PRETORIA, SOUTH AFRICA)

| | |
|---|---|
| **Internal size:** | Each separate module, 4 ft wide x 8 ft long; 32-$ft^2$ basin area. |
| **Brine depth:** | Approx. 2 in. |
| **Cover:** | Glass panes, 3/16-in. thick x 33-1/4 in. wide x 36-1/2 in. long, 45-degree slope, supported by angle-iron and T-iron framework. |
| **Vapor seals:** | 1/2-in.-thick rubber gasket between angle-iron frame and concrete base; all glass puttied in. |
| **Distillate troughs:** | 1/16-in.-thick aluminum sheet, around four sides. |
| **Basin liner:** | Impervious concrete, painted black; 6-in. layer of insulating brick underneath. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | Ends of glass, standardized modular construction. (Present design uses pre-fabricated concrete parts and butyl rubber basin liner, stills to be used on farms in South West Africa.) |
| **Productivity:** | Not reported. |
| **Problems:** | None reported. |
| **Dates:** | Around 1954. |
| **References:** | P. W. D. Union of South Africa, 391; Odondaal, 376. |

*Council for Scientific and Industrial Research.

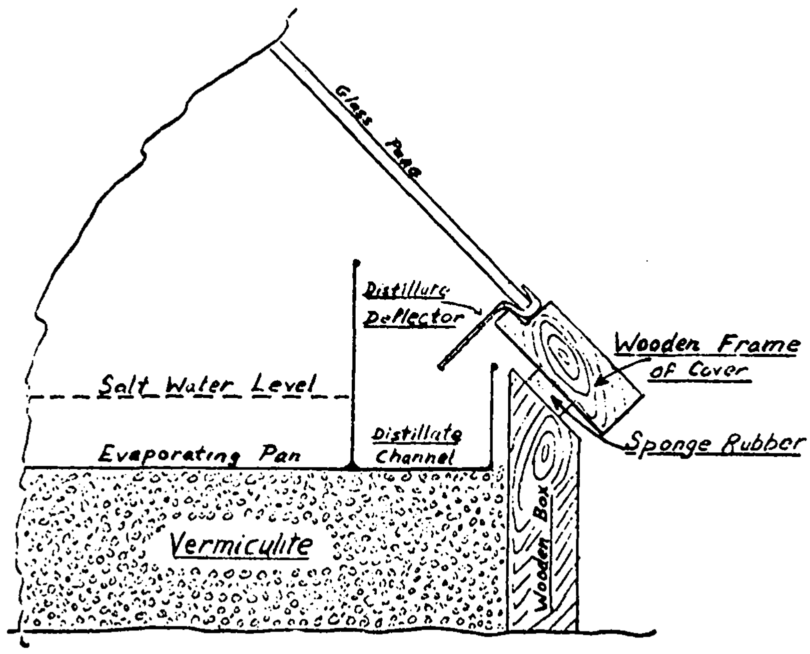



FIGURE 87. STILL AT THE UNIV. OF THE WITWATERSRAND (C.S.I.R.,* SOUTH AFRICA)

| | |
|---|---|
| Internal size: | 4 ft x 4 ft x 3 in. deep; 16-$ft^2$ basin area; E-W orientation. |
| Brine depth: | 1.2 in. |
| Cover: | Glass, 3/16 in. thick, 45-degree slope; glass ends, wooden framework. |
| Vapor seals: | Sponge rubber strips added later. |
| Distillate troughs: | Wooden channels, painted flat white, distillate deflectors used. |
| Basin liner: | Wooden base, painted black with bitumenous paint, and later plastic paint; 6-in. layer of Vermiculite for insulation. |
| Walls and curbs: | Wood, with concrete slab for base. |
| Other features: | Artificial sea water used, constant level in basin maintained, distillate returned to basin with distilled water added for vapor losses, vertical mirror (2 x 4 ft) used to reflect additional radiation onto basin (after July 1954), water cooling of glass covers tried. |
| Productivity: | Approx. 0.07 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day, the vertical mirror increased yield 8 percent, and the cooled covers 23 percent. |
| Problems: | Cleaning of glass cover required every day, leakage of condensate before metal deflectors added, warpage of wooden frame allowed vapor to escape between cover and base, failure of bitumenous paint, wetting of insulation because of leaks. |
| Dates: | May, 1952, to December, 1954. |
| References: | Cillie, 105. |

*Council for Scientific and Industrial Research.

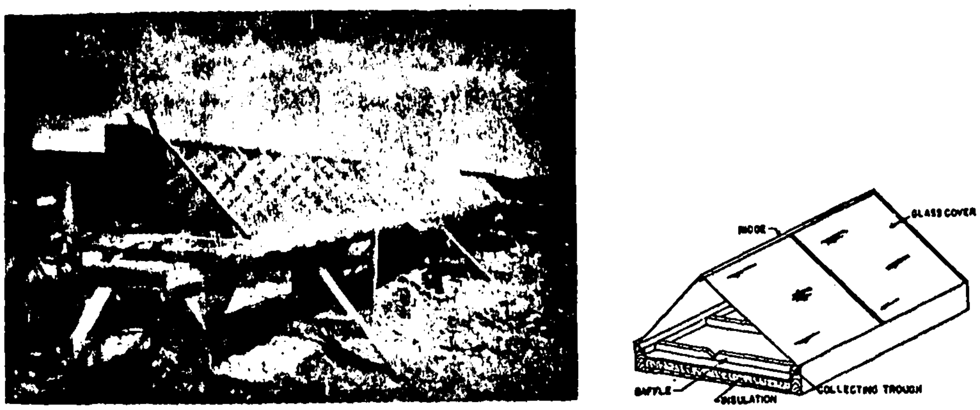
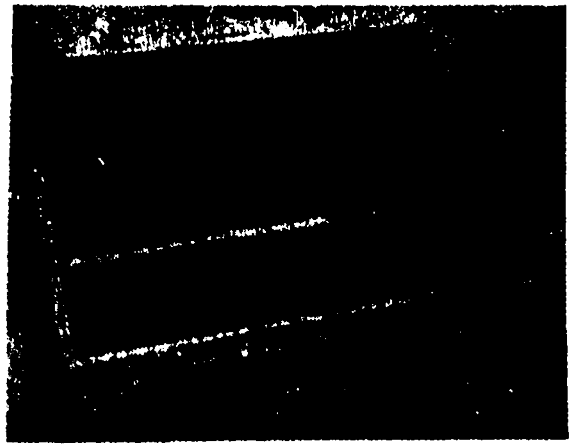



FIGURE 88. ROOF-TYPE STILL AT COHASSET, MASSACHUSETTS

| | |
|---|---|
| Internal size: | Approx. 4 ft wide x 50 ft long! 200-$ft^2$ basin area. |
| Brine depth: | Approx. 1 in., weirs spaced at intervals along tray. |
| Cover: | Glass, 45-degree slope. |
| Vapor seals: | Not known. |
| Distillate troughs: | Grooves cut in redwood side rails. |
| Basin liner: | Wooden bottom, painted black, 1-in.-thick insulation. |
| Walls and curbs: | Wooden base and redwood side rails. |
| Productivity: | 1.2 lb/$ft^2$-day (0.14 gal/$ft^2$-day) maximum. |
| Problems: | None mentioned, evidently operated only a few months during one summer. |
| Dates: | Summer, 1961. |
| References: | Telkes, 432-434, 436. |

a. Still for Tropic Zones



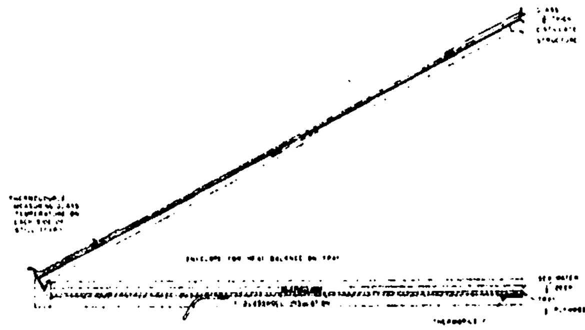
b. Still for Temperate Zones

FIGURE 89. TRAY-TYPE STILLS FOR TROPIC AND TEMPERATE ZONES (M.I.T.)*

| | |
|---|---|
| Internal size: | Various stills, 2 to 32-$ft^2$ tray area. |
| Brine depth: | Approx. 1/4 to 1 in. |
| Cover: | Glass, approx. 45-degree slope, redwood supports, long dimensions East-West. |
| Vapor seals: | Not reported. (Tight sealing advocated.) |
| Distillate troughs: | Grooves in redwood side rails. |
| Basin liner: | Black plastic sheet, 1-in.-thick insulation. |
| Walls and curbs: | Redwood supports and side channels. |
| Other features: | Double-sloped glass cover recommended for tropics, single-sloped glass with reflecting North side recommended for temperate zones, insulated basins. |
| Productivity: | Approx. 0.20 gal/$ft^2$-day maximum. |
| Problems: | Vapor-tight sealing and basin insulation found to be important. |
| Dates: | Approx. 1952 to approx. 1955. |
| Note: | An electrically-heated, 4-$ft^3$, tray-type still was also operated to study the effect of various parameters on productivity. |
| References: | Telkes, 430, 432-435. |

*Massachusetts Institute of Technology.

a. General View



b. Cross-Sectional View of Solar Still 16

FIGURE 90. ROOF-TYPE STILLS AT THE UNIVERSITY OF CALIFORNIA

| | |
|---|---|
| Internal size: | Five stills, each 47 in. wide x 51 ft long; one still 8 ft wide x 52 ft long; 1,410-$ft^2$ total basin area; long dimensions E-W oriented; experimental units, each somewhat different. |
| Brine depth: | Originally 1 in. (200 gal storage with 1 in. weirs every 8 ft), later 1/4 in. (50 gal storage with 1/4 in. weirs every 2 ft). |
| Cover: | (Five small units) glass panes, 18 in. x 36 in., ~45 degree slope; (one large unit) glass panes, 3/16 x 28 x 56 in., 29-degree slope, wooden ridge poles. |
| Vapor seals: | Not mentioned. |
| Distillate troughs: | Redwood side rails with groove for distillate. |
| Basin liner: | Marine plywood bottom, painted black, 1-in.-thick insulation underneath; 4-mil black polyethylene also used as basin liners. |
| Walls and curbs: | Wooden frames built approx. 3 ft above ground. |
| Other features: | Units tried with batch, intermittent, and continuous feed operation, weirs (dams) along tray, storage of warm water and nightime operation tried, air and water circulation inside stills studied, one 4 x 8 ft still constructed with a vertical mirror on north side. |
| Productivity: | Between 0.06 and 0.10 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| Problems: | Shadows cast by glass support structure, leaks in brine trays and redwood side rails, vapor leaks, low transmissivity of glass, deterioration of black paints used on basins, cracking of black polyethylene over weirs allowed brine to leak under liner. |
| Dates: | February 1952 to 1964. |
| Note: | Reference 447 contains a table describing approximately 40 other solar stills built and tested at the University of California. Do-it-yourself plans are available for a 44 x 96 in. tray-type still (Figure 92). |
| References: | Howe, 235, 240, 241, 243; Tleimat, 447. |

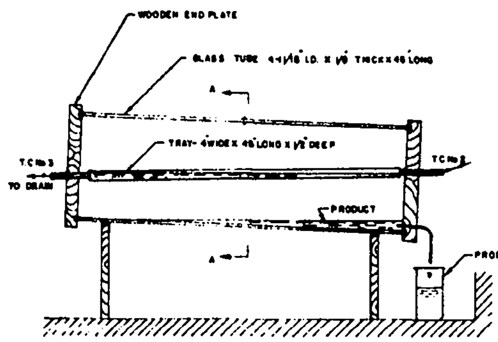
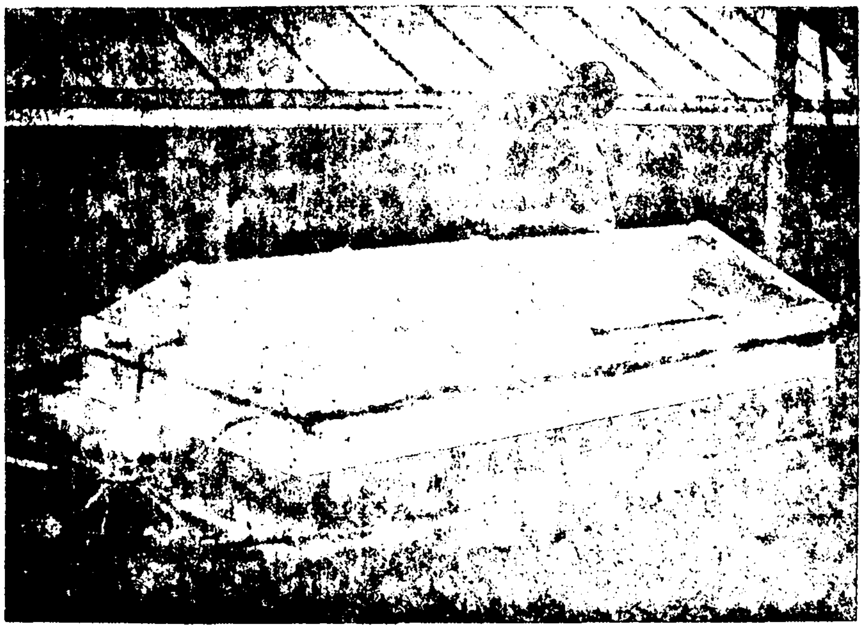



FIGURE 91. TUBULAR-TRAY-TYPE STILL (UNIVERSITY OF CALIFORNIA)

| | |
|---|---|
| Internal size: | One glass unit, approx. 5 in. diam. x 4 ft long; one plastic unit (diamond shaped), 4 ft wide x 51 ft long. |
| Brine depth: | Suspended trays, approx. 1/2-in. deep. |
| Cover: | Small unit was a glass tube, large unit was covered with 3-mil cellulose acetate. |
| Vapor seals: | Ends of glass tube sealed with gasketed wooden ends and tie rods. |
| Distillate troughs: | Inside of glass or plastic tubes acted as condenser and distillate trough. |
| Basin liner: | Metal trays, painted black, centrally supported. |
| Walls and curbs: | Wooden frame for plastic-covered still (diamond-shaped cross section). |
| Other features: | Approximately same production as 4 x 50-ft glass covered stills, no insulation used, nocturnal production studied in the glass unit by using city water preheated in a hot water heater (simulating waste heat or stored energy). |
| Productivity: | About 0.10 gal/ft$^2$-day maximum. (With preheated feed water and nocturnal operation, the glass unit produced about 0.20 gal/ft$^2$-day with a temperature difference of 50 F between inlet water temperature and minimum ambient air temperature). |
| Problems: | First plastic cover destroyed by wind. |
| Dates: | Late 1952 to approx. 1956. |
| References: | Howe, 235, 241, 243; Tleimat & Howe, 445. |



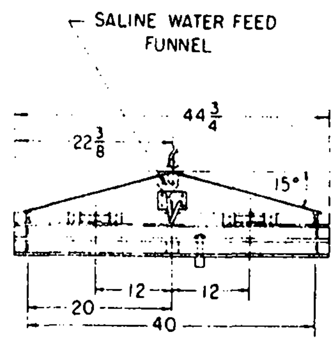



FIGURE 92. "DO-IT-YOURSELF" STILL (UNIVERSITY OF CALIFORNIA)

| | |
|---|---|
| Internal size: | Approx. 40 in. wide x 92 in. long; 25-$ft^2$ basin area, long dimension E-W oriented. |
| Brine depth: | Approx. 1 to 2 in. |
| Cover: | Glass, double-strength, 15-degree slope, redwood ridge pole. |
| Vapor seals: | Rubber tubing gasket between cover frame and bottom frame, vinyl tape, and caulking compound. |
| Distillate troughs: | Galvanized steel strips. |
| Basin liner: | Early versions used epoxy paint or black polyethylene sheet over marine plywood, later versions use 2-mil-thick Mylar or Tedlar film. |
| Walls and curbs: | Redwood frames, marine plywood bottom. |
| Other features: | Designed for "do-it-yourself" building, bottom insulated with 1-1/2 in. of glass wool, unit is hand filled and flushed. |
| Productivity: | (At Richmond, California) approx. 3.0 gpd in June, and 0.5 gpd in December (0.12 and 0.02 gal/$ft^2$-day). |
| Problems: | Difficulty with vapor seals, epoxy paint, and black polyethylene. |
| Dates: | 1959 through 1966. |
| Reference: | Edson, et al., 160. |

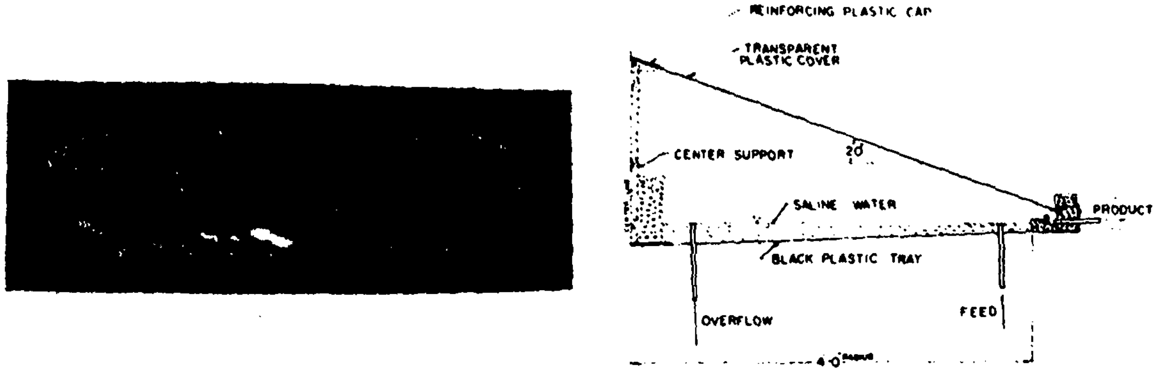
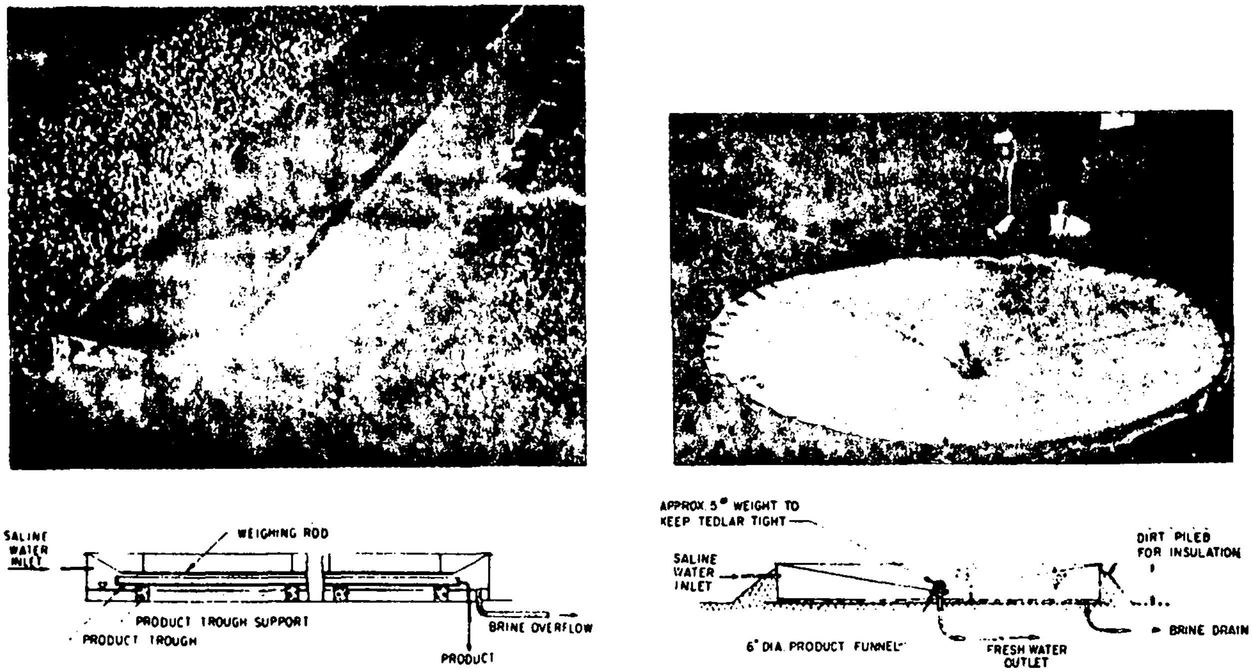



FIGURE 93. CIRCULAR PLASTIC-COVERED STILL (UNIVERSITY OF CALIFORNIA)

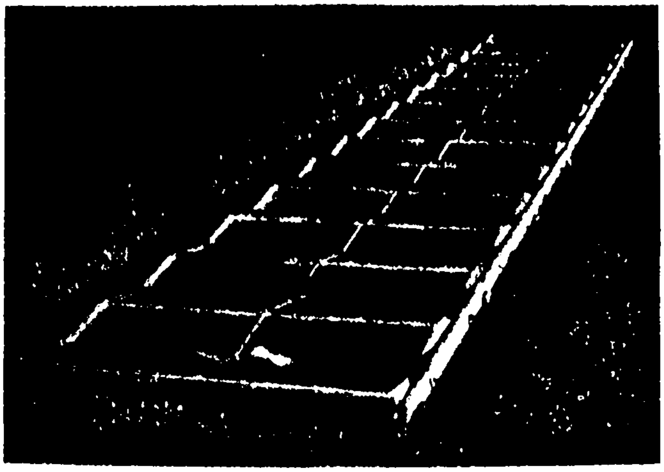
| | |
|---|---|
| Internal size: | 8-ft diam.; 50-$ft^2$ basin area. |
| Brine depth: | Approx. 2 in. |
| Cover: | Originally 7.5-mil cellulose-acetate film supported by nylon cords, later 2-mil Tedlar film supported by wires and made wettable by sandpapering, 20-degree slope. |
| Vapor seals: | Not mentioned, cover secured by weight of concrete segments. |
| Distillate troughs: | Groove in concrete covered with basin liner material. |
| Basin liner: | Initially 6-mil black polyethylene film, replaced by reinforced black Griffolyn plastic film. |
| Walls and curbs: | Circular segments of concrete beams. |
| Other features: | Rainwater collected, prefabrication of curbs possible. |
| Productivity: | 0.12 gal/$ft^2$-day (maximum for both covers). |
| Problems: | Cellulose-acetate cover lasted about 6 months and Tedlar about 1 year, both fatigued by wind-loading and fluttering, nylon cords rotted, weight of rainwater pulled cover loose, black polyethylene deteriorated. |
| Dates: | Summer, 1963, to 1965. |
| Note: | This still (or a similar unit) was built at Lautoka on the South Pacific Island of Fiji. |
| References: | Howe, 248, 249. |

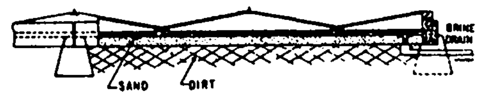



a. Rectangular Still b. Circular Still

FIGURE 94. INVERTED PLASTIC-COVERED STILLS (UNIVERSITY OF CALIFORNIA)

| | |
|---|---|
| Internal size: | (Rectangular) 2 ft 10 in. wide x 17 ft 2 in. long; 49-$ft^2$ basin, (Circular) 7 ft 8 in. diameter; 46-$ft^2$ basin. |
| Brine depth: | (Rectangular) approx. 2 in., (Circular) approx. 1 in. |
| Cover: | 2-mil Type 40 wettable Tedlar, 10-degree slope toward center, rectangular cover weighted by steel reinforcing rod 3/8-in. diam. (wrapped and tied), circular cover had 5-lb weight at center. |
| Vapor seals: | None mentioned. |
| Distillate troughs: | (Rectangular) 0.016-in.-thick brass vee supported by small concrete blocks, (Circular) brass funnel. |
| Basin liner: | Type 65 black Griffolyn plastic film. |
| Walls and curbs: | 20-gage galvanized steel sheet, preformed. |
| Other features: | Reduced wind loading on covers, holes punched in vee to allow drainage of rainwater. |
| Productivity: | 0.12 gal/$ft^2$-day (maximum output after cleaning distillate trough). |
| Problems: | Rain washed dust and sand into product line which caused occasional plugging, circular cover lasted about 1 year, rectangular cover about 3 years. |
| Dates: | July, 1964, to December, 1967. |
| References: | Howe, 249. |






Modular Unit

FIGURE 95. SAWTOOTH-TYPE STILL (UNIVERSITY OF CALIFORNIA)

| | |
|---|---|
| Internal size: | 6 ft wide x 6 or 8 ft long modules (depending on glass size); typically 48-ft$^2$ basin area. (Three units as large as 6 ft x 48 ft – 288-ft$^2$ basins – have been built, one in Richmond, California, and two on South Pacific Islands.) |
| Brine depth: | 3/4 to 1-1/2 in. |
| Cover: | Glass panes, 1/8-in. thick (25 oz/ft$^2$) x 18 x 36 in., 24 x 36 in., or 18 x 22 in., approx. 10-degree slope, originally galvanized sheet metal support structure, later aluminum tee-sections. |
| Vapor seals: | Initially "DAP" caulking compound or mastic on outer joints, black vinyl electrician tape and vinyl adhesive tape along glass-to-glass joints; later a butyl-based caulking compound used. |
| Distillate troughs: | V-shaped galvanized iron or brass strips resting on concrete blocks or supported with wires from aluminum tee-sections along valleys. |
| Basin liner: | Black polyethylene in U.S., usually black Griffolyn in South Pacific installations, layer of sand underneath. |
| Walls and curbs: | Plywood or concrete framework. |
| Other features: | Distillate troughs less than 6 ft long facilitate drainage, sized for family use (approx. 5 gpd output), modular construction, kits developed, batch-type feed early in morning at daily or weekly intervals depending on brine depth and evaporation rate, rain collection, approx. 25 units installed on South Pacific Atolls. |
| Productivity: | 0.10 to 0.12 gal/ft$^2$-day (maximum output), average of 0.08 gal/ft$^2$-day used to size stills for South Pacific. |
| Problems: | Basin liner pierced by grass on Fiji, fences required, leakage of rainwater into distillate troughs, algae growth on surface of seawater, cracks in original caulking compound, corrosion of galvanized iron distillate troughs. |
| Dates: | July, 1965, to the present (both in Richmond, California, and on South Pacific Islands). |
| Note: | This type of still installed on many of the South Pacific Islands. Many of these assembled from kits (6 x 8 ft modules). |
| References: | Howe, 247-250, personal communication February, 1969; Tleimat and Howe, 446. |

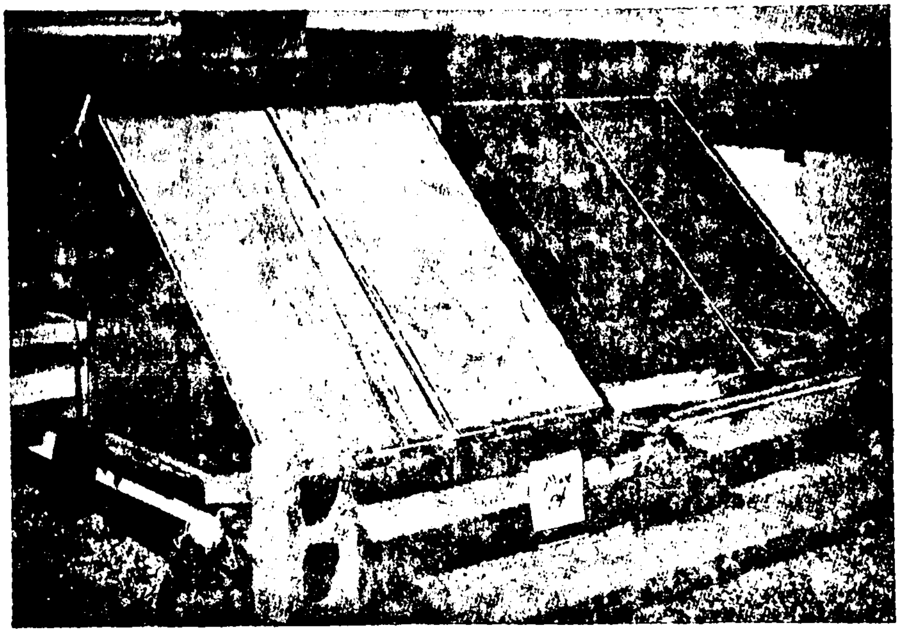


FIGURE 96. TRIANGULAR STILLS (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| **Internal size:** | Two stills, size not reported. |
| **Brine depth:** | Not reported. |
| **Cover:** | One still glass-covered (double strength), one still plastic-covered; semirigid plastic sheet materials and plastic films evaluated, approx. 45-degree slope southward. |
| **Vapor seals:** | Nonhardening caulking compound on glass-covered still, not reported for plastic-covered still with removable frames. |
| **Distillate troughs:** | Not reported. |
| **Basin liner:** | Wood coated with asphalt paint. |
| **Walls and curbs:** | Redwood frames. |
| **Other features:** | Plastic-covered still had removable cover frames to evaluate various cover materials, inside back surface of stills covered with aluminized Mylar to reflect sunlight onto basin. |
| **Productivity:** | (Glass) 0.103 gal/ft$^2$-day at 2,150 Btu/ft$^2$-day, (Plastic, PVC untreated) 0.062 gal/ft$^2$-day (Plastic, PVC treated for weltability) 0.092 gal/ft$^2$-day. |
| **Problems:** | Flutter of plastic covers in wind caused refluxing of condensate, dropwise condensation on the plastic materials unless treated, difficulty in anchoring against high winds and cleaning evaporating pans. |
| **Dates:** | 1954. |
| **References:** | Lappala and Bjorksten, 279; Bjorksten, 73. |

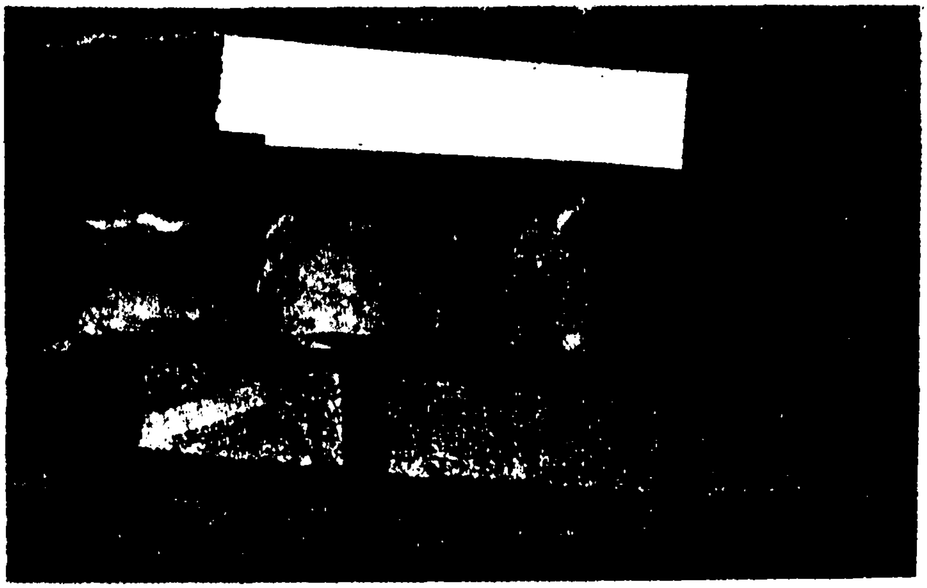


FIGURE 97. TUBULAR PLASTIC STILLS (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| Internal size: | Several small stills, size not reported. |
| Brine depth: | Not reported. |
| Cover: | Semirigid plastics: treated and untreated cellulose acetate butyráte, cellulose acetate, polyethylene, and polyvinyl chloride evaluated. |
| Vapor seals: | Plexiglass tension hoops around ends. |
| Distillate troughs: | Bottom of plastic cylinders. |
| Basin liner: | Evaporating pans initially of either cellulose acetate, cellulose acetate butyrate, or 10-mil black vinyl sheet; replaced by galvanized sheet metal painted with asphaltum paint and insulated underneath. |
| Walls and curbs: | Wooden framework support stand. |
| Other features: | Ends made of polyethylene. |
| Productivity: | Not reported (Low yield). |
| Problems: | Original evaporating pans sagged or deformed badly at operating temperatures, condensate dripped back into pan from top of cylinders, difficult to anchor, semi-rigid plastics more costly than plastic films and yields lower. |
| Dates: | 1954. |
| References: | Bjorksten, 73. |

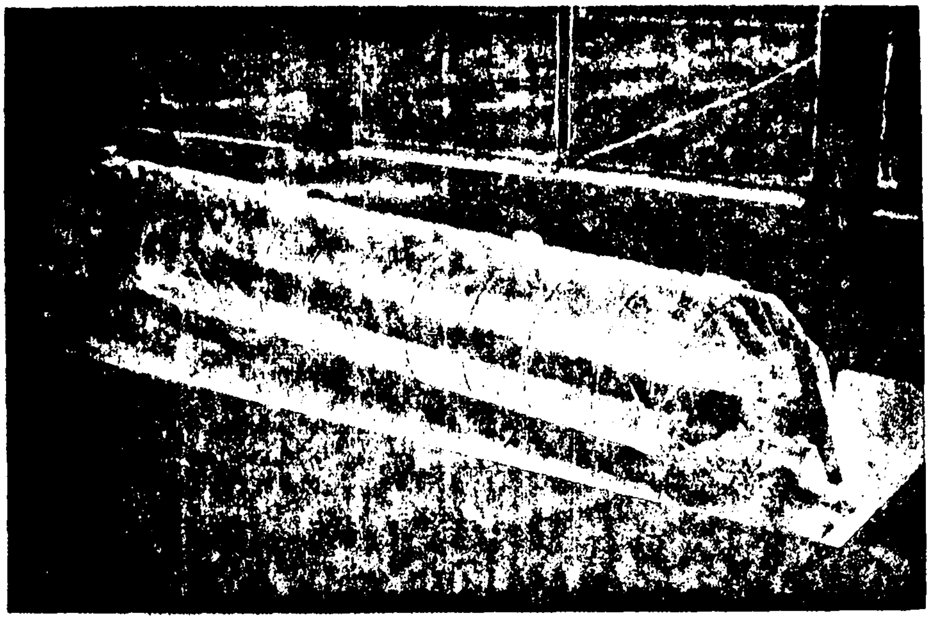
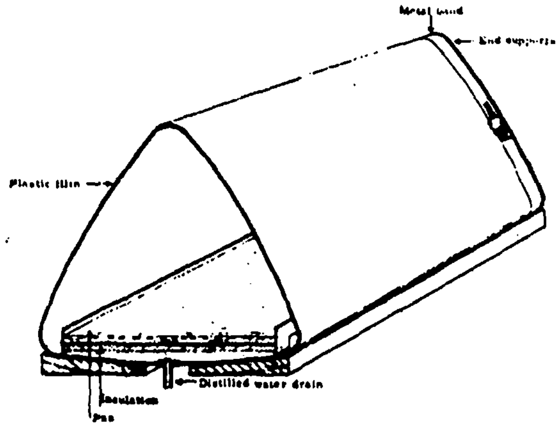


FIGURE 98. TUBULAR SPIRAL-SUPPORTED STILL (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| **Internal size:** | Approx. 12-in. diam., about 10 ft long. |
| **Brine depth:** | Not reported. |
| **Cover:** | Polyethylene, supported with spiral-wound galvanized iron wire 0.062 in. in diameter. |
| **Vapor seals:** | Heat-sealed seams. |
| **Distillate troughs:** | Bottom of tube. |
| **Basin liner:** | Evaporating pan made of black semirigid vinyl acetate. |
| **Walls and curbs:** | None required. |
| **Other features:** | 8-in.-wide roll of plastic film formed into tube by heat sealing overlapped edges around galvanized iron wire. |
| **Productivity:** | Not reported. |
| **Problems:** | Film did not heat seal where surface had been treated for wettability so edges were masked before spraying, high winds damaged stills, condensate dripped back into evaporating pans with all circular designs, difficulty of anchoring, tubular designs abandoned. |
| **Dates:** | 1954. |
| **References:** | Bjorksten, 73. |

a. Three Plastic Stills




b. Design of Plastic Stills

FIGURE 99. GLASS AND PLASTIC EVALUATION STILLS (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| Internal size: | Ten stills, each had a 2-$ft^2$ evaporating surface area, and a 5.65-$ft^2$ condensing surface area. |
| Brine depth: | About 0.38 in. |
| Cover: | Still (1) Glass, (2, 4, 5, 7) 4-mil polyvinyl chloride (thin surface coating, thick coating, two untreated), (3) 0.5-mil Mylar, (6) polyethylene, (8) Mylar – polyethylene laminate, (9) Cellulose acetate butyrate, (10) Nylon mesh reinforced cellulose acetate; ridge poles required, 60-degree slope found most efficient. |
| Vapor seals: | Metal clamping band around each end wall. |
| Distillate troughs: | Bottom and lower corners of triangular cross section. |
| Basin liner: | Metal pan. |
| Walls and curbs: | Wooden framework support, redwood ends. |
| Other features: | Cover 2 recommended over Cover 3 because of ease of fabrication and wettability treatment, anchoring required, artificial light sources used for indoor tests. |
| Productivity: | (At 2,150 Btu/$ft^2$-day), Still (1) 0.103 gal/$ft^2$-day, (2), 0.092, (3) 0.085, (4) 0.081, (5) 0.074, (6) 0.069, (7) 0.068, (8) 0.064, (9) 0.057, (10) uncertain. |
| Problems: | Cover life not evaluated, for larger stills a wire-supported design recommended. |
| Dates: | 1954 to 1955. |
| References: | Bjorksten, 73. |

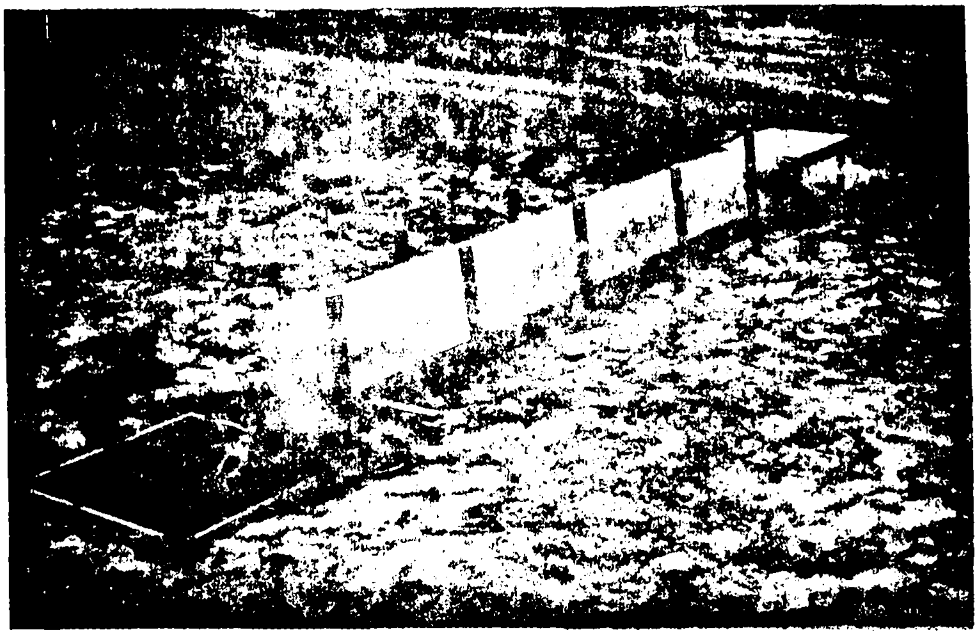


FIGURE 100. AIR-INFLATED STILL (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| **Internal size:** | Plastic cylinder, 12-in. diameter, approx. 8 ft long. |
| **Brine depth:** | Not reported. |
| **Cover:** | Polyethylene. |
| **Vapor seals:** | Heat-sealed seams. |
| **Distillate troughs:** | Bottom of polyethylene tube. |
| **Basin liner:** | Rigid black polyvinyl acetate evaporating pan. |
| **Walls and curbs:** | Wood posts for anchoring. |
| **Other features:** | Small squirrel-cage blower used for inflation. |
| **Productivity:** | Very low. |
| **Problems:** | Evaporating pan buckled and warped, slow movement of condensate on tube walls, some condensate dripped back into pan. |
| **Dates:** | 1954. |
| **References:** | Bjorksten, 73. |

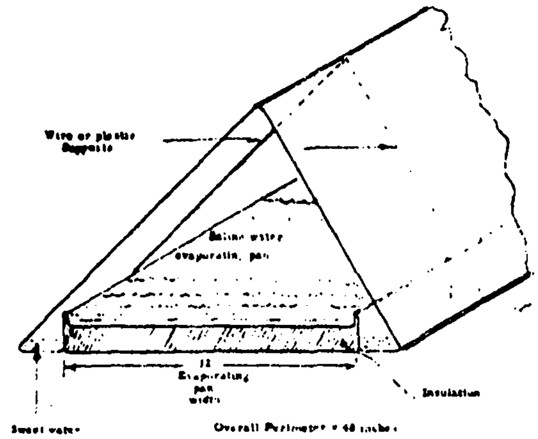



FIGURE 101. TRIANGULAR WIRE-SUPPORTED STILLS (BJORKSTEN RESEARCH LABS)

| | |
|---|---|
| Internal size: | Four stills, each evaporating tray 1 ft wide x 10 ft long. |
| Brine depth: | Less than 1 in. |
| Cover: | 3-mil polyvinyl chloride, supported with spirally wound 14-gage galvanized wire heat sealed between overlapped edges of the 12-in. -wide plastic film. |
| Vapor seals: | Heat-sealed seams. |
| Distillate troughs: | Formed by bending the wire supports, 2 in. wide on each side of basin. |
| Basin liner: | Two stills with glass fiber-polyester pans, and two with integral basins shaped from the wire supports; black pigment in molded pans, black cloth in integral basins. |
| Walls and curbs: | Wooden plank support. |
| Other features: | Tested near Del Ray Beach, Florida, stills placed on wooden planks insulated from the ground; anchoring required. |
| Productivity: | No data on yields obtained. |
| Problems: | Exposure to sunlight and winds produced leaks along the heat-sealed seams, migration of tar from insulation covering paper into the plastic film, two modified stills built with triangular cross sections having a single-sloped cover at 55 degrees and heavier wire and vinyl film but 85-mph winds badly damaged stills. |
| Dates: | March, 1955. |
| References: | Bjorksten, 73. |

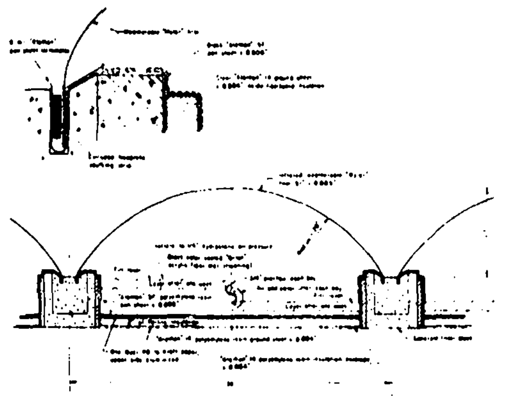


FIGURE 102. SMALL INFLATED PLASTIC STILL AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| **Internal size:** | 5 bays, each 2 ft 8 in. wide x 37 ft 2 in. long; 500-ft$^2$ basin area. |
| **Brine depth:** | 1-1/2 to 4 in. |
| **Cover:** | 3-mil Teslar* (nonwettable), 1/4-in.-water inflation pressure. |
| **Vapor seals:** | Extruded neoprene grommets. |
| **Distillate troughs:** | Contoured curbs, Teslar lined, 0.072 in./ft slope. |
| **Basin liner:** | 4-mil polyethylene ground sheet, 8-mil black polyethylene pan sheet, 2-in.-bottom and 1/2-in.-side insulation. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | Floating black Orlin wick, rainwater collection, blower required, soil sterilized. |
| **Productivity:** | Not reported. |
| **Problems:** | Dropwise condensation, distillate spillover and leaks, collapse of covers by rain, burnout of pan sheet at dry spots, torn covers. |
| **Dates:** | December, 1958, to September, 1959. |
| **Note:** | Design shown is a modification of an original Du Pont design. Description of large inflated plastic still, 2,300-ft$^2$ basin, is given in Section 3. |
| **References:** | Battelle, 52. |

*Later named Tedlar.

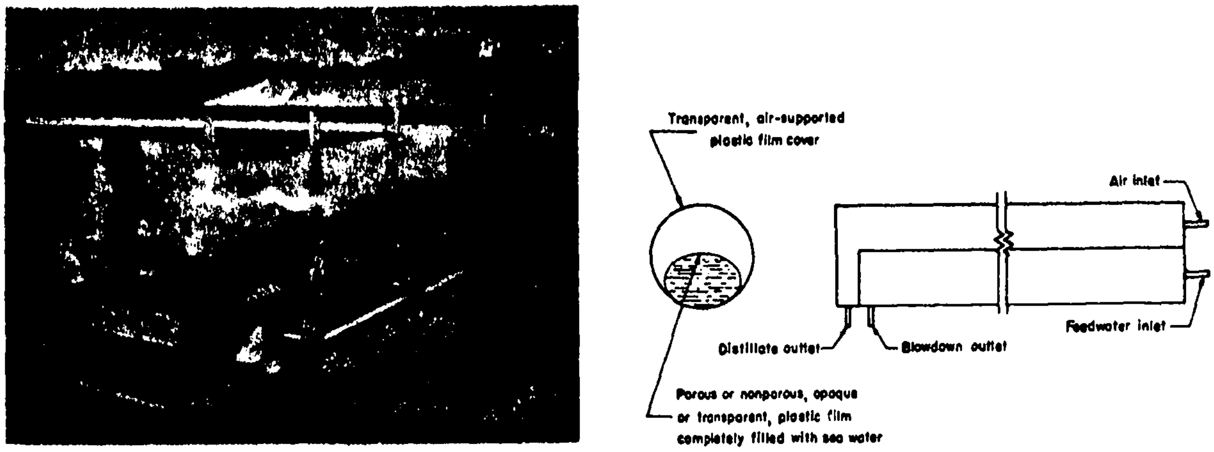




FIGURE 103. DOUBLE-TUBE STILL (BATTELLE-COLUMBUS)

| | |
|---|---|
| Internal size: | Inner tube 6-in. diam. x 9 ft long; outer tube 18-in. diam. x 10 ft long. |
| Brine depth: | Inner tube of black porous polyethylene film filled with brine. |
| Cover: | Outer tube of 4-mil Tedlar, air supported. |
| Vapor seals: | Heat-sealed seams. |
| Distillate troughs: | Bottom of outer tube acted as distillate trough. |
| Basin liner: | Inner tube, 10-mil Porothene (polyethylene). |
| Walls and curbs: | Tie-downs required. |
| Other features: | Prefabrication possible, good portability. |
| Productivity: | No reliable data obtained. |
| Problems: | Leaks along heat-sealed seams of the weak porous-plastic inner tube, distillate re-evaporation. |
| Dates: | Approx. August, 1960, to approx. October, 1960. |
| References: | Battelle, 52. |

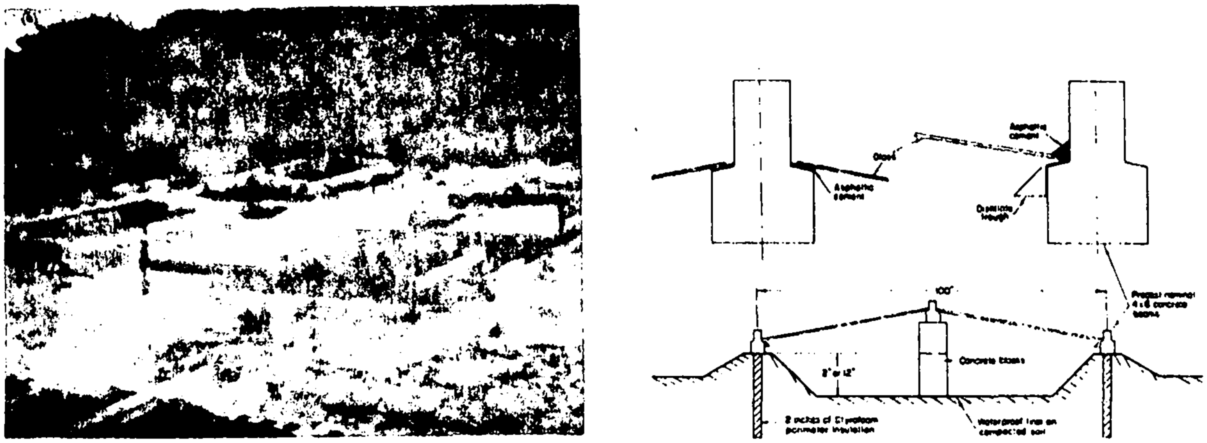



FIGURE 104. MATERIAL-EVALUATION STILLS AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| Internal size: | Four stills, each approx. 8 ft x 10 ft; approx. 80-$ft^2$ basins. |
| Brine depth: | Two stills approx. 12 in., two approx. 2 in. |
| Cover: | Glass (single and double strength). |
| Vapor seals: | Asphaltic cement, overlapped glass, butyl rubber caulking. |
| Distillate troughs: | Aluminum and stainless steel. |
| Basin liner: | One each with butyl rubber sheet, asphalt paving, asphalt mat with PVC core, and asphalt-impregnated jute. |
| Walls and curbs: | Concrete beams and blocks, mounded earth. |
| Other features: | Floating black polypropylene felt wick tried on one still, single-strength glass satisfactory. |
| Productivity: | Not reported (primarily materials study). |
| Problems: | Asphalt paving leaked excessively, jute liner deteriorated after approx. 1 year. |
| Dates: | Approx. June, 1962, to approx. May, 1965. |
| References: | Battelle, 54, 55. |

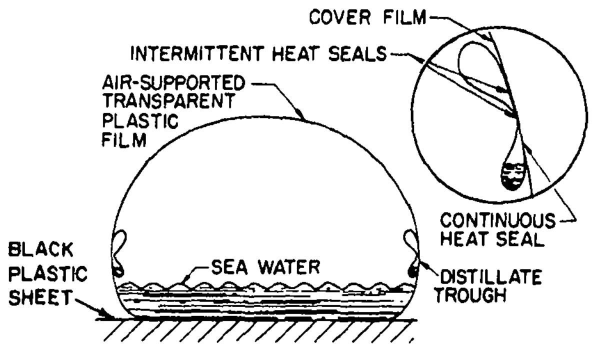



FIGURE 105. INFLATED PLASTIC TUBE STILLS AT DAYTONA BEACH, FLORIDA (BATTELLE)

| | |
|---|---|
| **Internal size:** | Four tubes, 1-1/2-ft diam. x 20 ft long; each basin approx. 33 $ft^2$. |
| **Brine depth:** | Approximately 2 to 3 in. |
| **Cover:** | Tube material was 4-mil Tedlar (nonwettable). |
| **Vapor seals:** | Heat-sealed seams. |
| **Distillate troughs:** | Plastic-film troughs heat sealed to tube wall. |
| **Basin liner:** | Ground sheet of black polyethylene film under tubes used for solar absorber. |
| **Walls and curbs:** | Stakes and tie-downs required. |
| **Other features:** | Designed as an "expedient" or temporary still, inflation required, floating black terrycloth wick tried, tubes placed on sheet of black polyethylene. |
| **Productivity:** | Approximately 0.06 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| **Problems:** | Accurate leveling required for proper distillate drainage, tie-downs necessary in strong winds, distillate leakage at connections. |
| **Dates:** | November, 1962, to approx. July, 1963. |
| **References:** | Battelle, 54, 55. |

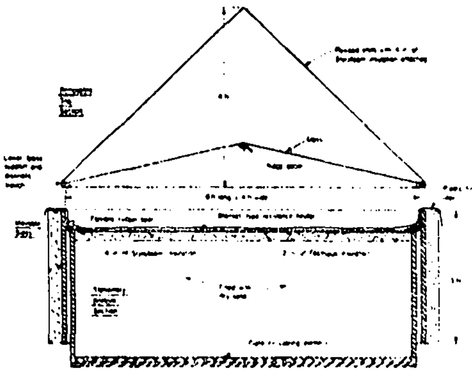


FIGURE 106. LABORATORY STILL (BATTELLE-COLUMBUS)

| | |
|---|---|
| Internal size: | 8 ft wide x 4 ft long; 32-ft$^2$ basin. |
| Brine depth: | Variable, 0 to 14 in. |
| Cover: | Glass, 1/8 in. thick, slope variable 0 to 45 degrees, cover height above brine variable 1 to 18 in. |
| Vapor seals: | Tape. |
| Distillate troughs: | Copper. |
| Basin liner: | 6-mil polyethylene film, blanket-type electric heater, 2-in.-thick bottom insulation (when used). |
| Walls and curbs: | Plywood, redwood. |
| Other features: | Electrically heated liner, transient and steady-state conditions imposed, variable brine depth, variable cover angle, perimeter insulation, external fan cooling, still located in constant-temperature room. |
| Productivity: | Output depended on variables, 0 to 0.24 lb/hr-ft$^2$ (steady-state tests), 0 to 0.16 gal/ft$^2$-day (transient tests). |
| Problems: | Difficulty in obtaining productivity equal to actual still outputs in Daytona Beach, Florida. |
| Dates: | Approx. November, 1962, to June, 1965. |
| References: | Battelle, 55. |

Stills G Through K

FIGURE 107. PLASTIC-COVERED STILLS AT DAYTONA BEACH, FLORIDA (UNIVERSITY OF WISCONSIN)

| | |
|---|---|
| **Internal size:** | (Still G) 3 ft x 12 ft, (H) 2 ft x 12 ft, (I) 2.5 ft x 11.25 ft, (J) 2 ft x 12 ft, (K) 2 ft x 12 ft; long axes East-West. |
| **Brine depth:** | Not reported. |
| **Cover:** | (G) 4-mil polyethylene, burlap on ends, 40-degree slope; (H) 2-mil Tedlar, BPE (black polyethylene ends), 34 degrees; (I) 5-mil Weatherable Mylar, BPE, 28 degrees (J) 2-mil Tedlar, BPE and back, approximately 30 degrees; (K) 3-mil Mylar, BPE, approximately 30 degrees. |
| **Vapor seals:** | Cylindrical plastic sandbags used as weights. |
| **Distillate troughs:** | Lined with basin liner. |
| **Basin liner:** | 6-mil black polyethylene. |
| **Walls and curbs:** | Wooden framework. |
| **Other features:** | Built on leveled sand. |
| **Productivity:** | Not reported. |
| **Problems:** | None reported. |
| **Dates:** | Winter, 1962. |
| **References:** | Battelle photographs; (designed by F. Daniels). |

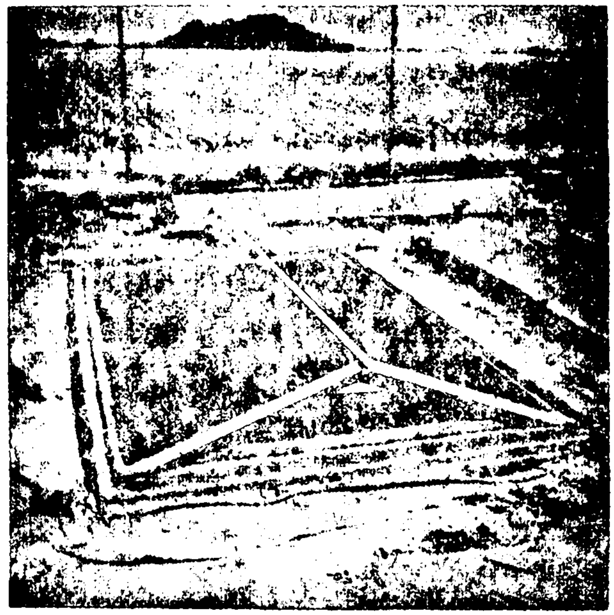


FIGURE 108. PLASTIC-COVERED STILLS AT TEMPE, ARIZONA (UNIVERSITY OF WISCONSIN)

| | |
|---|---|
| **Internal size:** | 2.5 to 5 ft wide x 12 ft long. |
| **Brine depth:** | Approximately 1 to 2 in. |
| **Cover:** | Polyvinyl chloride or Weatherable Mylar supported by wooden framework. |
| **Vapor seals:** | Cylindrical plastic sandbags used as weights for covers. |
| **Distillate troughs:** | Moulded in concrete curbs. |
| **Basin liner:** | Concrete or butyl rubber with sawdust insulation. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | Units were manually drained and filled each day, plastic covers sandpapered for wettability, crushed charcoal briquettes tried on basin for solar absorption. |
| **Productivity:** | Maximum approximately 0.08 gal/ft$^2$-day (efficiency approximately 40 percent in summer and 25 percent in winter). |
| **Problems:** | Short life of PVC cover (approximately 1 year), frequent cleaning of basin required, vapor-tight seals. |
| **Dates:** | Around 1963 and 1964. |
| **Reference:** | Cadwallader, 103; (designed by F. Daniels). |

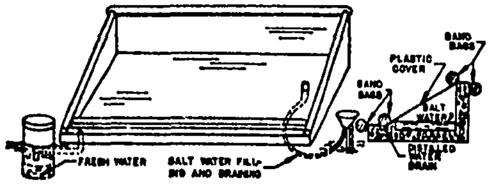



FIGURE 109. PLASTIC-COVERED CONCRETE STILL (UNIVERSITY OF WISCONSIN)

| | |
|---|---|
| Internal size: | 36 in. wide, length not reported. |
| Brine depth: | Not reported. |
| Cover: | Mylar (sandpapered for wettability), 23-degree slope. |
| Vapor seals: | Cylindrical plastic sandbags for weights. |
| Distillate troughs: | Moulded in concrete curb. |
| Basin liner: | Concrete painted black with asphalt. |
| Walls and curbs: | Concrete, 1 to 2 in. thick. |
| Other features: | Black plastic sandbags are painted with white rubber latex to prevent overheating, basin and wall insulation helpful, an internal reflector for the back wall was mentioned. |
| Productivity: | Over 40 percent efficiencies obtained. |
| Problems: | Cover must be pulled tight occasionally. |
| Dates: | Around 1964. |
| Reference: | Daniels, 119. |

FIGURE 110. PLASTIC-COVERED STILL (UNIVERSITY OF WISCONSIN)

| | |
|---|---|
| **Internal size:** | Approximately 2 ft wide x 12 ft long; 25-$ft^2$ basin. |
| **Brine depth:** | Approximately 1 in. |
| **Cover:** | Several transparent plastics tried (cellulose acetate, Mylar, Tedlar, and polyethylene), approximately 30-degree slope. |
| **Vapor seals:** | Cylindrical, plastic sandbags for weights. |
| **Distillate troughs:** | Moulded in concrete curbs. |
| **Basin liner:** | Concrete. |
| **Walls and curbs:** | Concrete. |
| **Other features:** | Distillate troughs also around triangular ends, heavy winds withstood, cost about $20, built in 1 day. |
| **Productivity:** | 30 to 40-percent efficiency with wettable covers, 20 to 30 percent with nonwettable covers. |
| **Problems:** | Cellulose acetate cover tore easily. |
| **Dates:** | Around 1964. |
| **Reference:** | Daniels, 119. |

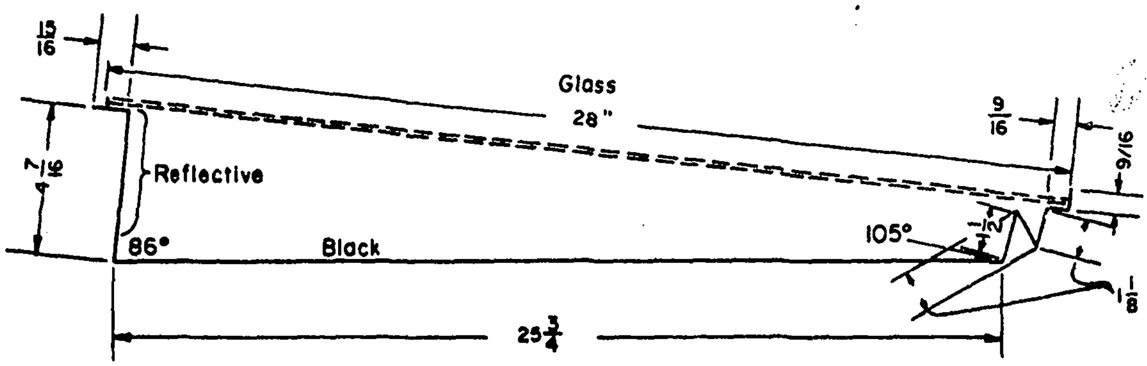



FIGURE 111. SUNWATER STILL AT BALLARAT, CALIFORNIA (SUNWATER COMPANY)

| | |
|---|---|
| Internal size: | Six trays; approximately 210-$ft^2$ basin area. |
| Brine depth: | Approximately 1 in. |
| Cover: | Glass; 6-degree slope facing southward. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Preformed grooves in tray. |
| Basin liner: | Silicone-rubber-coated aluminum, black bottom, insulated. |
| Walls and curbs: | Prefabricated aluminum tray. |
| Other features: | Supplies drinking water for trailer resort, generous space between each row to avoid shadows, tie-downs used to prevent movement of stills in wind. |
| Productivity: | Rated at 20 gpd as yearly average output (0.10 gal/$ft^2$-day). |
| Problems: | Peak water demand in winter. |
| Dates: | Approximately 1966 to present. |
| Note: | Small stills of this type have also been installed at private residences throughout the Southwestern U.S., Mexico, and the Caribbean in sizes down to 1/2 gpd. |
| References: | McCracken, 329, 330. |

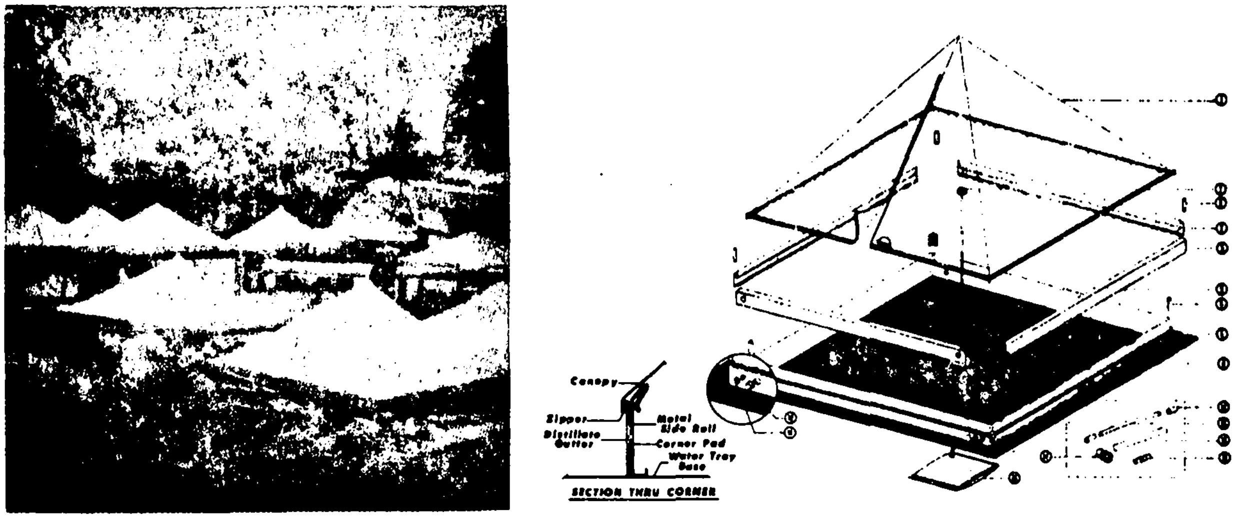
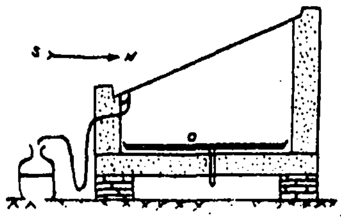


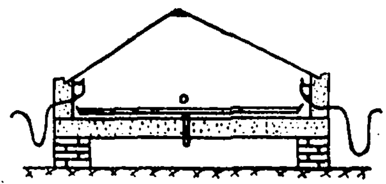

FIGURE 112. SOLAR SUNSTILL (SETAUKET, LONG ISLAND, NEW YORK)

| | |
|---|---|
| Internal Size: | Pyramid shaped, 8 ft x 8 ft base, approx. 40 in. height at center; 64 $ft^2$ basin area. |
| Brine depth: | Approx. 2 in. |
| Cover: | Pyramid-shaped, 8-mil transparent plastic, hydrophilic coating of Sun Clear* on inside, center mast support. |
| Vapor seals: | Zippered seams around base and up one side of cover. |
| Distillate troughs: | Green PVC, located around the perimeter, sealed to basin liner and supported by aluminum side rails. |
| Basin liner: | Black PVC sheet, 8 mils thick. |
| Walls and curbs: | Aluminum-alloy side-rail framework to form curbs and support distillate troughs. |
| Other features: | One side of cover has zipper for access to basin, fiberglass support mast, shipping weight about 50 lb, modules can be connected, life of cover expected to be 5 years. |
| Productivity: | Maximum of about 6.5 gpd (approx. 0.10 gal/$ft^2$ day). |
| Problems: | Some covers torn by animals. |
| Dates: | Became commercially available mid-1969. |
| References: | Raseman, 394; Solar Sunstill, Inc., 412. |

*Product of Solar Sunstill, Inc.




a. Still 1



b. Stills 2, 3, and 5

FIGURE 113. EXPERIMENTAL STILLS AT THE TURKMENIAN ACADEMY OF SCIENCES (U.S.S.R.)

| | |
|---|---|
| Internal size: | All 4 stills approximately 49 in. x 31 in.; 10.7-ft$^2$ basins. |
| Brine depth: | Approximately 1/2 in. |
| Cover: | Glass, 0.08 in. thick (2 mm). Slopes: Still (1) 30 degrees; (2) 45; (3) 40; (4) 30; (5) 30. Wooden ridge poles. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Galvanized iron trays, usually painted black. |
| Walls and curbs: | Double plywood with sawdust insulating layer between. |
| Other features: | Still 2 had glass at both ends, distillate drain tube positioned to provide water trap. |
| Productivity: | Still 1 had approximately 0.12 gal/ft$^2$-day maximum, others relative to Still 1 produced (2) 68.3 percent, (3) 51.8 percent, (5) 70.4 percent; annual average approximately 0.06 gal/ft$^2$-day. |
| Problems: | None reported. |
| Dates: | 1960 to 1962. |
| Note: | Still 4 described in next section (Tilted-Wick type). |
| Reference: | Bairamov, 45. |

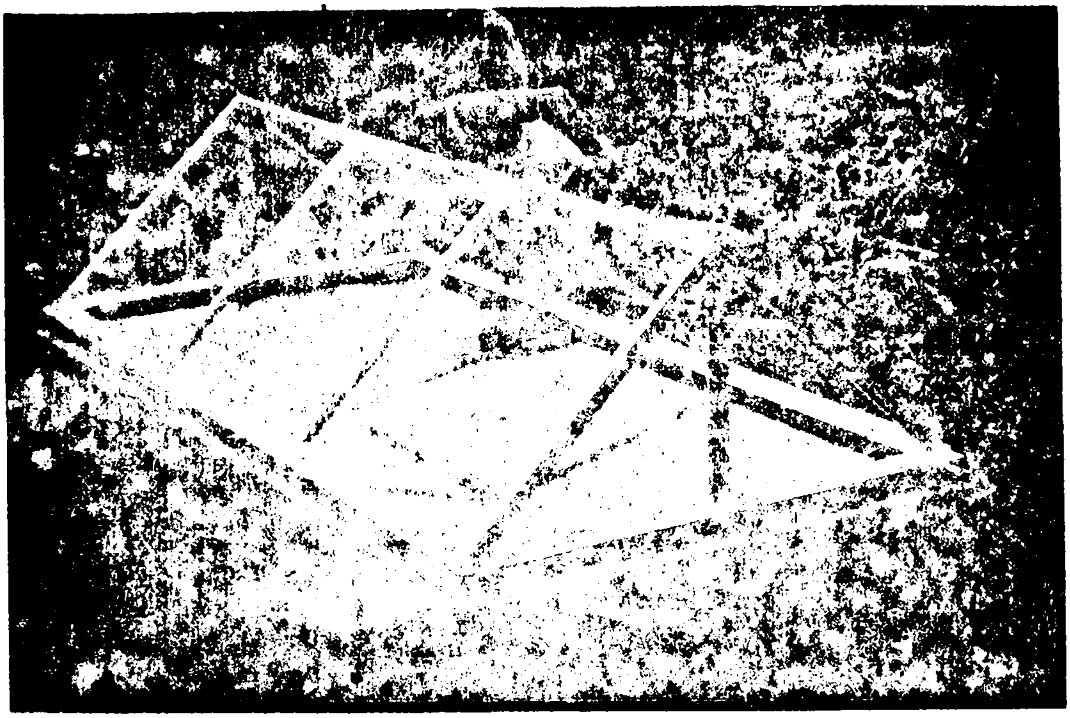
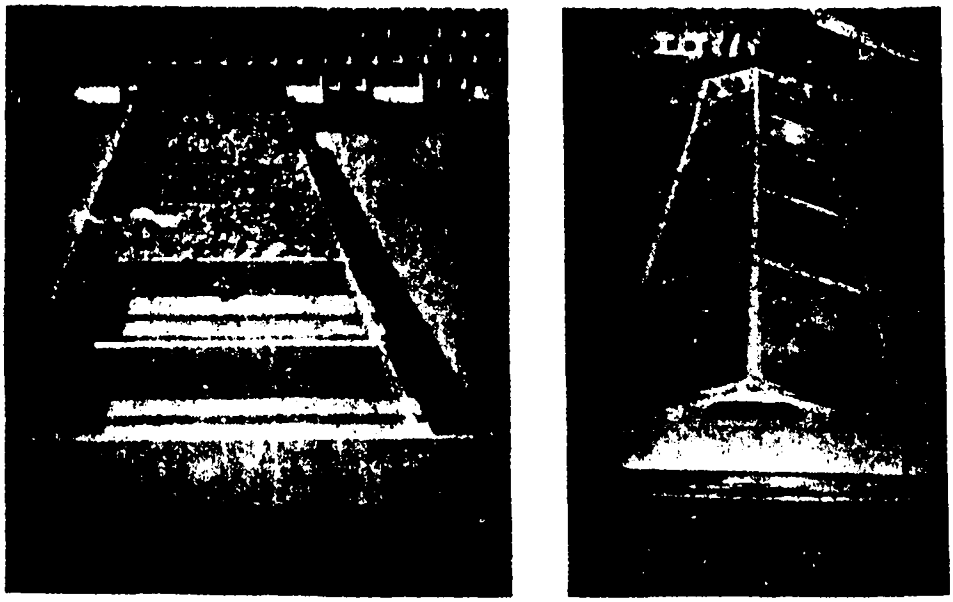


FIGURE 114. TRAY-TYPE STILL (VIRGIN ISLANDS)

| | |
|---|---|
| Internal size: | Basin size, 4 ft wide x 9 ft long, 3 in. deep; 36-$ft^2$ evaporating area; long axis East-West. |
| Brine depth: | Between 0.5 and 2.0 in. |
| Cover: | Glass (single-strength), 45-degree slope; ends also glass; 58-$ft^2$ glass area. |
| Vapor seals: | Nonhardening caulking compound. |
| Distillate troughs: | Grooves in wooden side rails (?). |
| Basin liner: | 2-in.-thick "Foamglas" insulation blocks, waterproofed with a black asphalt paint. |
| Walls and curbs: | Wood frame and supports. |
| Other features: | Preheating of feedwater experiments, basin hand-filled with seawater early each morning, excessive distillate storage not needed in this area. |
| Productivity: | Between 0.07 and 0.12 gal/$ft^2$-day (November, 1948, to April, 1949), approx. 0.08 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day. |
| Problems: | Occasional cleaning of basin required because of accumulation of algae, salt crusts, etc. |
| Dates: | November, 1948, to April, 1949. |
| References: | Lof, 301; Strobel, 418. |



a. Still Under Construction b. Still 4-1/2 Years Later

FIGURE 115. DEMINERALIZATION STILL NO. 1 (BRACE EXPERIMENT STATION, ST. JAMES, BARBADOS)

| | |
|---|---|
| Internal size: | Approximately 2.8 ft wide x 17.9 ft long; 50-$ft^2$ basin area. |
| Brine depth: | Approximately 1 in. |
| Cover: | 12 glass panes, double-strength (24 $oz/ft^2$), 18 x 36 in., 15-degree slope, metal frame supports. |
| Vapor seals: | Tropical metal putty and tropical wood putty. |
| Distillate troughs: | Grooves cut in side framework for distillate and rainwater, two coats of epoxy resin paint for waterproofing. |
| Basin liner: | 26-gage galvanized steel tray, 2 coats of black epoxy resin paint, 2 in. of insulation. |
| Walls and curbs: | Wooden framework, treated with antitermite and antifungus compound. |
| Other features: | Wood shavings for insulation (sprayed with antitermite solution), small door opening in each end for cleaning, filling, etc., polyethylene hoses, tray filled and emptied by syphoning, rainwater collected. |
| Productivity: | Not reported. |
| Problems: | Large amount of time spent in priming and painting lumber and tray. |
| Dates: | January, 1962, to 1966 +. |
| Note: | Plans and instructions for building a 2 x 4-ft still of similar characteristics for service stations has been published (Lawand, 286). Average output approx. 0.8 gpd (0.12 $gal/ft^2$-day). |
| Reference: | Lawand, 281. |

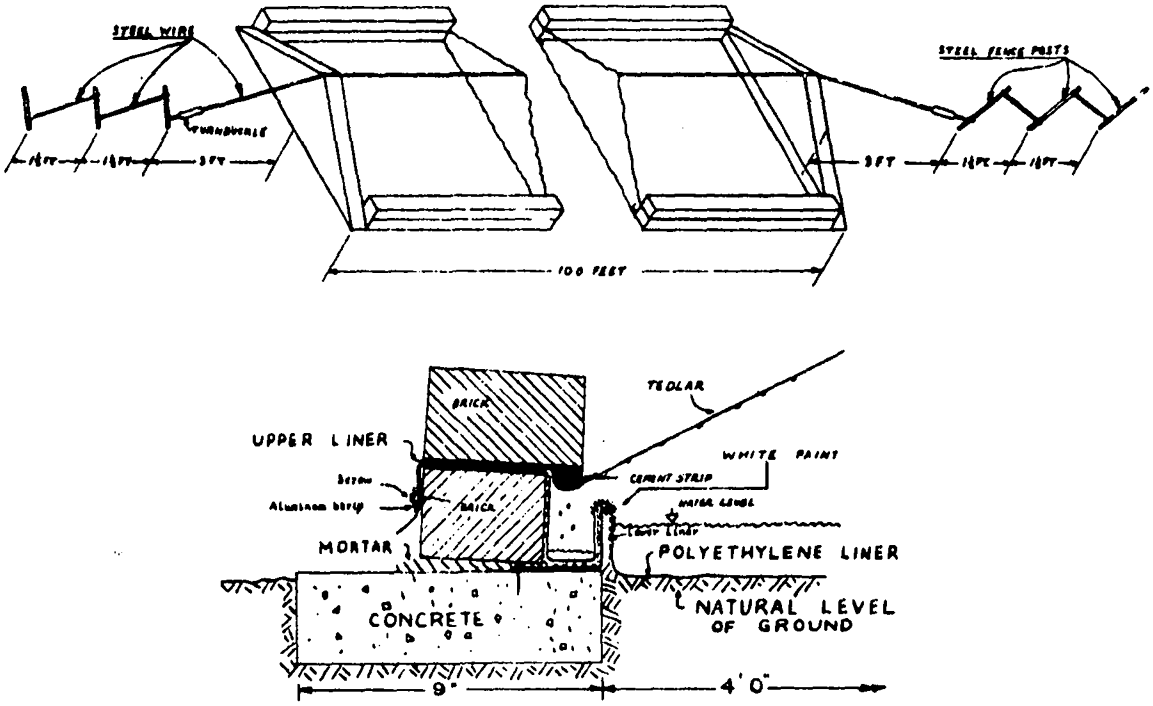



FIGURE 116. PLASTIC-COVERED STILL (BRACE RESEARCH INSTITUTE, McGILL UNIVERSITY)

**Internal size:** One bay, 4 ft wide x 100 ft long; 400-ft$^2$ evaporating area.

**Brine depth:** 1/4 to 1 in., weirs.

**Cover:** 4-mil Tedlar, suspended over a tightly stretched, plastic-covered steel wire; approx. 30-degree slope.

**Vapor seals:** Cover weighted between layers of black polyethylene.

**Distillate troughs:** Sheet metal, double-lined with black polyethylene (including basin liner).

**Basin liner:** 10-mil black polyethylene film, sand base.

**Walls and curbs:** Concrete foundations and concrete bricks.

**Other features:** Ground sprayed with insecticide and weed killer, fences and windbreaks advocated, batch or continuous feed suggested, top row of bricks lined with black polyethylene to avoid puncturing Tedlar cover.

**Productivity:** Between approx. 0.06 and 0.09 gal/ft$^2$-day in Barbados.

**Problems:** Acid treatment of feedwater sometimes necessary to avoid scale formation, wind and rain may loosen or damage plastic cover.

**Dates:** Do-it-yourself leaflet published in January, 1965.

**Reference:** Brace Research Institute, 94.

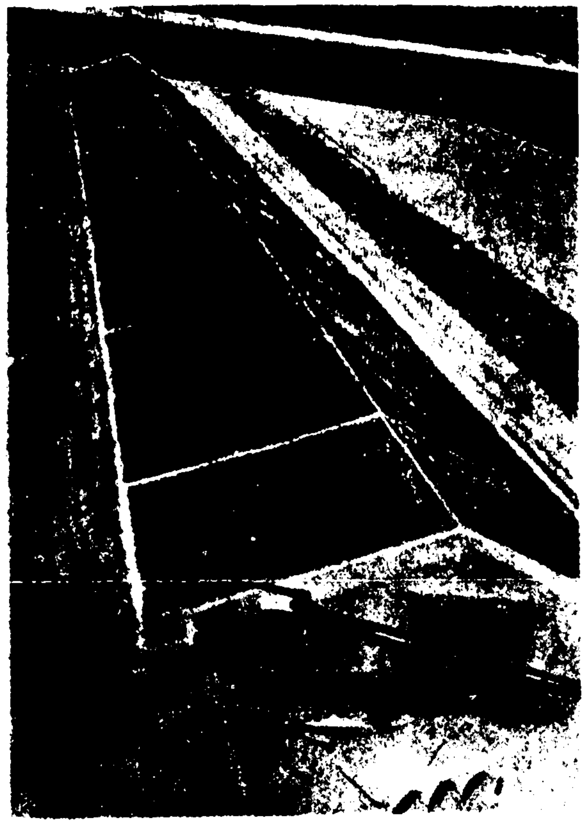
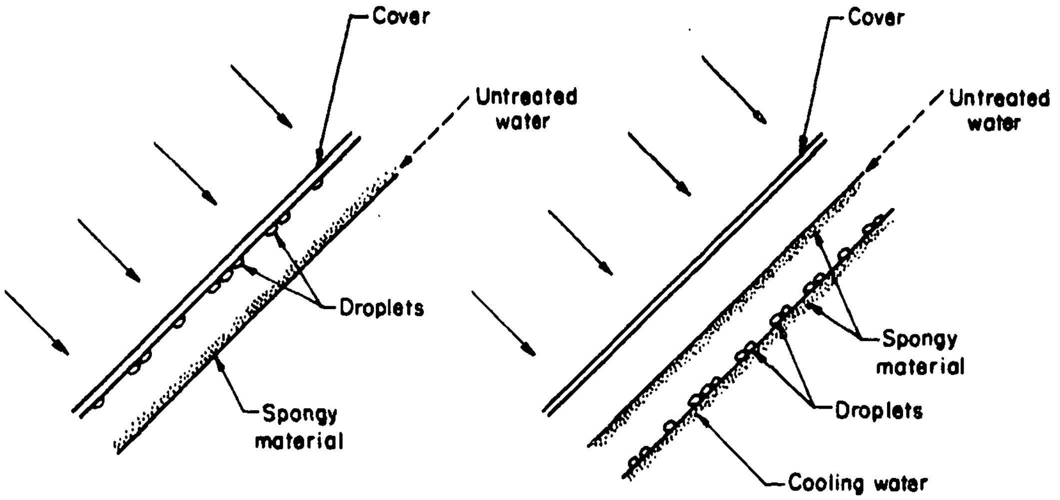


FIGURE 117. STILL ON ANGUILLA, WEST INDIES (BRACE RESEARCH INSTITUTE McGILL UNIVERSITY)

| | |
|---|---|
| **Internal size:** | 4 ft 11 in. wide x 53 ft long; 261-ft$^2$ evaporating area (282-ft$^2$ projected cover area). |
| **Brine depth:** | 1/4 to 2-1/2 in. |
| **Cover:** | Glass panes, 1/8 in. x 3 ft x 3 ft; 20-degree slope; wire tie-downs on each section of glass. |
| **Vapor seals:** | White silicone rubber sealant. |
| **Distillate troughs:** | Moulded in concrete curbs, painted with basin liner paint; 1:800 slope. |
| **Basin liner:** | Concrete, painted with a chemical- and acid-resistent black concrete paint. |
| **Walls and curbs:** | Concrete, outside of still painted white. |
| **Other features:** | Built on roof of house, rainwater collection, float valve in still to prevent overfilling, access door in each end of still, brackish and seawater feed available, brine completely flushed at weekly intervals, plastic pipe. |
| **Productivity:** | Not reported. |
| **Problems:** | Imported materials delayed, minor leaks initially. |
| **Dates:** | September, 1968, to present. |
| **Reference:** | Thierstein, 442. |




a. Conventional Type b. Design of Mr. Jean Mary

FIGURE 118. THE JEAN MARY STILL (MARSEILLES, FRANCE)

| | |
|---|---|
| **Internal size:** | Not reported. |
| **Brine depth:** | Thickness of sponge material (wick). |
| **Cover:** | Glass, tilted. |
| **Vapor seals:** | Not reported. |
| **Distillate troughs:** | Not reported. |
| **Basin liner:** | Spongy material (wick) bonded to blackened aluminum sheet. |
| **Walls and curbs:** | Not reported. |
| **Other features:** | Back condensing panel is cooled with evaporation of water from spongy material, multiple-effect solar still anticipated, condensation occurs only on back panel. |
| **Productivity:** | Not reported. |
| **Problems:** | It was reported that adjustments and improvements were being made. |
| **Dates:** | Around 1967. |
| **Reference:** | Touchais, 448. |

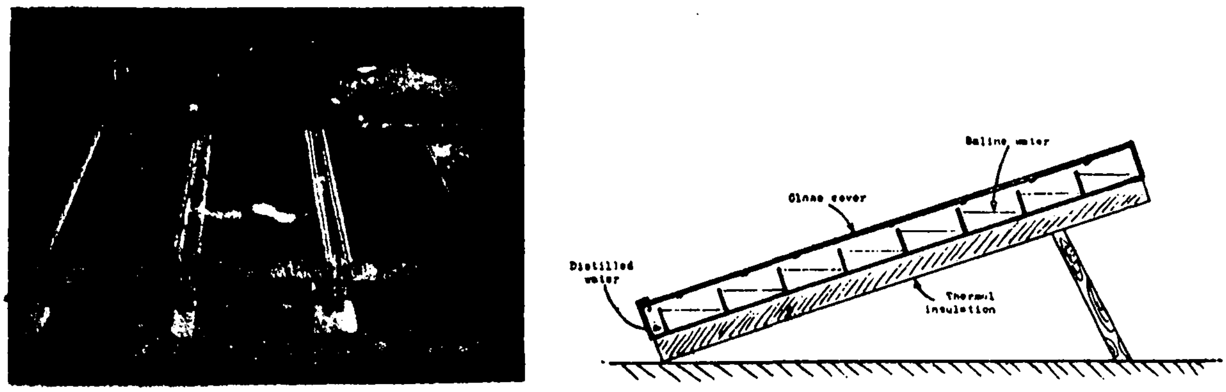



FIGURE 119. INCLINED-TRAY STILL, NO. 8 (UNIVERSITY OF BARI, ITALY)

| | |
|---|---|
| Internal size: | 16.1-$ft^2$ tray area. |
| Brine depth: | Shallow pools between baffles. |
| Cover: | Glass, unit inclined about 20 degrees. |
| Vapor seals: | Medical adhesive tape used for glass-to-metal seals. |
| Distillate troughs: | Not reported. |
| Basin liner: | Metal painted black, insulated. |
| Walls and curbs: | Metal and wooden framework. |
| Other features: | Various materials and sizes tested, one unit built with double-glass covers through which feedwater was continuously circulated. |
| Productivity: | 0.11 gal/$ft^2$-day at 2000 Btu/$ft^2$-day (Maximum of 0.14 gal/$ft^2$-day). |
| Problems: | Maintenance and scaling problems because house owners did not supply feedwater at regular intervals, units damaged when run empty, adhesive tape lasts only a few months. |
| Dates: | Approximately 1962 to the present. |
| References: | Nebbia, 371, 373, 374. |

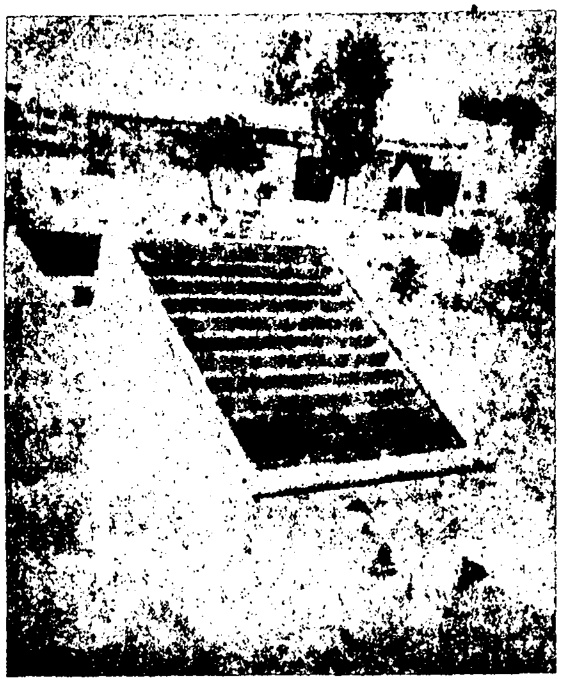
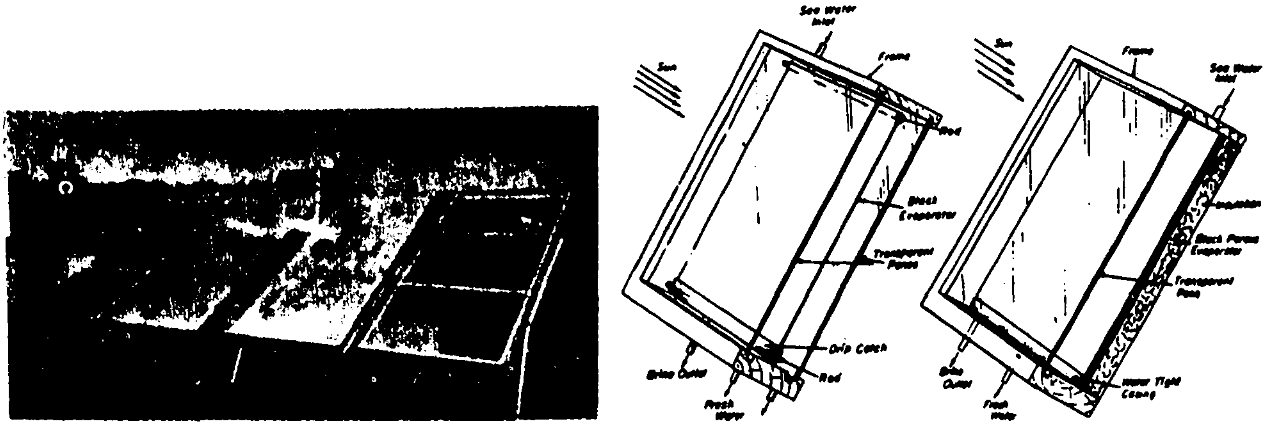


FIGURE 120. STEPPED STILL, DB (TUNISIAN AEC)

| | |
|---|---|
| Internal size: | 11-$ft^2$ evaporating area. |
| Brine depth: | Not reported. |
| Cover: | Glass, 0.12 in. thick, approx. 30-degree slope. |
| Vapor seals: | Mastic, plaster. |
| Distillate troughs: | Not reported. |
| Basin liner: | Blackened with coal. |
| Walls and curbs: | Eternit (asbestos shingles? ). |
| Other features: | Anticipated lifetime of 15 years. |
| Productivity: | Summer – 0.11 gal/$ft^2$-day; winter – 0.04 gal/$ft^2$-day. |
| Problems: | None reported. |
| Dates: | Built February, 1964. |
| Reference: | Tunisian AEC, 454. |




| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Cover: | Glass | W-Mylar | Teslar-20 | Glass |

a. Four Solar-Still Modules Assembled on Supporting Stands, Total Evaporator Area 100 $Ft^2$

b. Still With Two Glass Panes

c. Still With Insulated Back

FIGURE 121. TILTED-WICK TYPE STILLS (NEW YORK UNIVERSITY AND CURTISS-WRIGHT)

| | |
|---|---|
| Internal size: | Many sizes, from approx. 4-$ft^2$ to 25-$ft^2$ units. |
| Brine depth: | Thickness of soaked wick (black terry cloth, corduroy cloth, acetate, Orlon, etc.), equivalent to approx. 1/32-in. water layer. |
| Cover: | Single-strength glass or plastic used (Mylar and Tedlar), units tilted 30 degrees. |
| Vapor seals: | Pressure-sensitive mylar tape over glass joints, synthetic rubber-resin base adhesive. |
| Distillate troughs: | Sheet aluminum or inside bottom corner of still (depending on design). |
| Basin liner: | Waterproof supporting film or structure (5-mil Mylar, etc.), back insulated. |
| Walls and curbs: | Wooden framework lined inside with 2-mil Mylar, metal structural supports. |
| Other features: | Tilted to give more uniform output throughout the year, modular construction, 20 to 50 percent greater output than horizontal-tray still, Tygon tubing feed conduit, sea water strainer, glass-tube capillaries regulated continuous feed, feed water preheated in brine-discharge channel, self-cleaning wick. |
| Productivity: | Approx. 0.16 gal/$ft^2$-day maximum, approx. 0.11 gal/$ft^2$-day yearly average (predicted). |
| Problems: | Complete wetting of wicks, fading of wicks, deterioration of wick materials, soot deposits on covers (in New York City), nonwettability of plastic covers, overfeeding of wick on cloudy days, stills running dry. |
| Dates: | 1955 to 1961. |
| Note: | See also description of tilted-wick stills at Daytona Beach, Florida. |
| References: | Telkes, 431, 432, 435-440; Battelle, 54. |

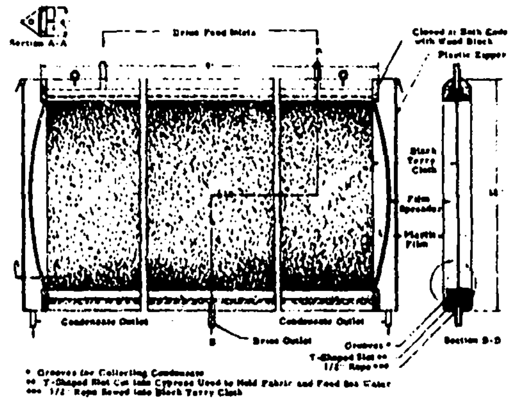



FIGURE 122. SUSPENDED-ENVELOPE, VERTICAL-WICK STILLS (BJORKSTEN RESEARCH LABS)

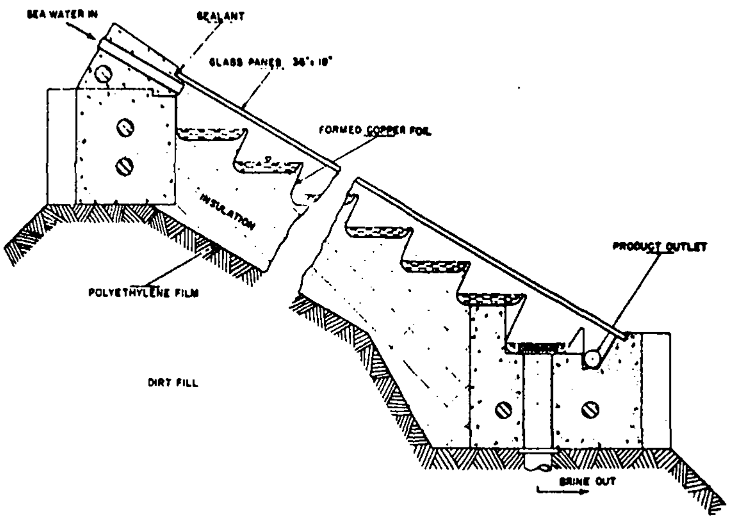
| | |
|---|---|
| Internal size: | Two stills, 31 in. high x 9 ft long, 23.2-$ft^2$ evaporating area; two stills 31 in. high x approx. 4 ft long. |
| Brine depth: | Thickness of cloth wick. |
| Cover: | One glass-covered still, several plastic-covered stills (5- and 12-mil clear PVC, and 6-mil translucent PVC). |
| Vapor seals: | Electronically welded plastic seams, and multiple folds with clips or extruded plastic zippers. |
| Distiilate troughs: | Grooves cut in cyprus-wood bottom piece. |
| Basin liner: | Black percale, black Indian head, and black terry cloth wicks (spreader bar used to maintain tension). |
| Walls and curbs: | Cyprus wood (top and bottom pieces). |
| Other features: | Stills supported and suspended by 0.25-in. wire cables stretched between steel fence posts, bottom of stills anchored, vertical and slightly tilted (15 degrees from vertical) orientations used, the rate of continuous brine flow adjusted to provide minimum drainage during maximum sunlight. |
| Productivity: | 0.12 gal/$ft^2$-day at 2,150 Btu/$ft^2$-day of effective radiation on vertical or nearly vertical surface (both glass and plastic-covered stills). |
| Problems: | Incomplete wetting of wicks until a perforated feed tube was incorporated, wind caused some covers to contact wick if spacing was less than about 2 in., black terry cloth most satisfactory but faded after 2 to 3 weeks of exposure. |
| Dates: | Summer, 1955. |
| Note: | Later models tested at Madison, Wisconsin (June, 1958) and at Daytona Beach, Florida (Fall, 1960 to Spring, 1961, see Figure 125). |
| References: | Bjorksten, 73, 74. |

a. Still 21
Size 4 x 8 Ft, Slope 38 Degrees

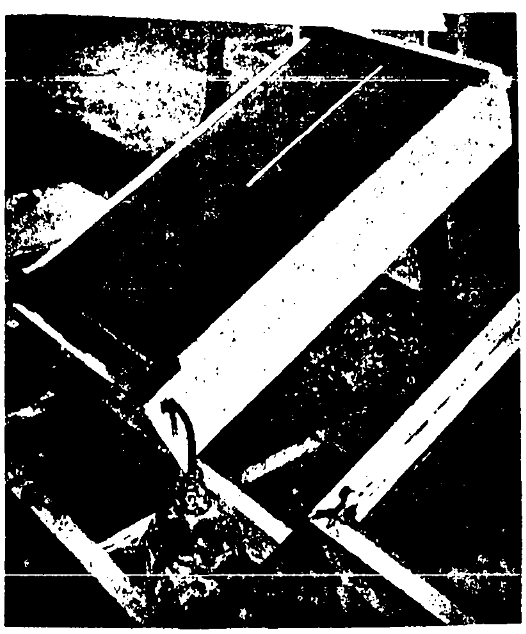
b. Still 34
Size 2 x 8 Ft, Slope 25 Degrees

FIGURE 123. INCLINED-TRAY STILLS (UNIVERSITY OF CALIFORNIA)

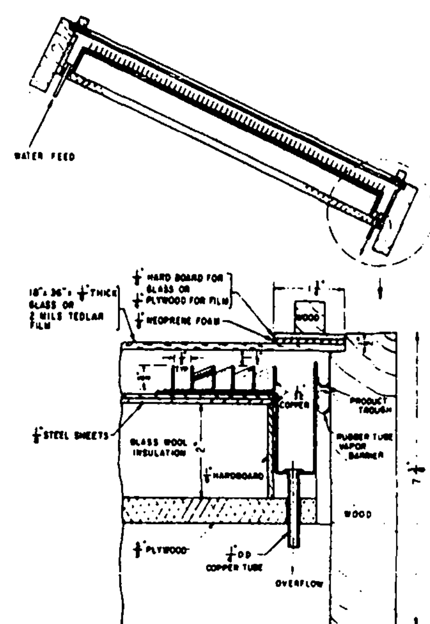
| | |
|---|---|
| Internal size: | Various unit sizes, 4 x 8 ft, 2 x 8 ft, 1.5 x 3 ft, etc. |
| Brine depth: | Series of shallow pools formed by longitudinal (horizontal) baffles. |
| Cover: | Usually glass, 2-mil Tedlar used for comparison, trays inclined at various angles (38, 25, and 20 degrees, etc.) |
| Vapor seals: | Rubber tubing, neoprene gaskets, etc. |
| Distillate troughs: | Not reported. |
| Basin liner: | Various tray materials (wood, metals, plastics), longitudinal baffles, epoxy-base black paint, 2-in.-thick insulation. |
| Walls and curbs: | Wooden framework. |
| Other features: | Higher production rates than horizontal trays, better year around average due to inclination, modular construction, two identical stills built to compare glass and plastic covers. |
| Productivity: | Approx. 0.13 gal/$ft^2$-day at approx. 2,000 Btu/$ft^2$-day (horizontal surface radiation). The total output of Tedlar-covered still was 82 percent of the glass-covered unit over a 2-year period. |
| Problems: | Cost of construction, durability of materials, taste and odor of distilled water due to paints, etc., small holes in plastic cover, blistering of black epoxy paint. |
| Dates: | March, 1959, to present. |
| Note: | The inclined tray development was begun at the University of California by Horace McCracken, and also continued independently by him (McCracken, 327, 328, 330). |
| References: | Howe, 241, 249; Tleimat, 445-447; McCracken, 328. |




c. Still 41
Size 3 x 12 Ft, Slope 30 Degrees



d. Stills for Comparing Glass and Plastic Covers
Size 18 x 36 In., Slope 25 Degrees




e. Design of Comparison Stills

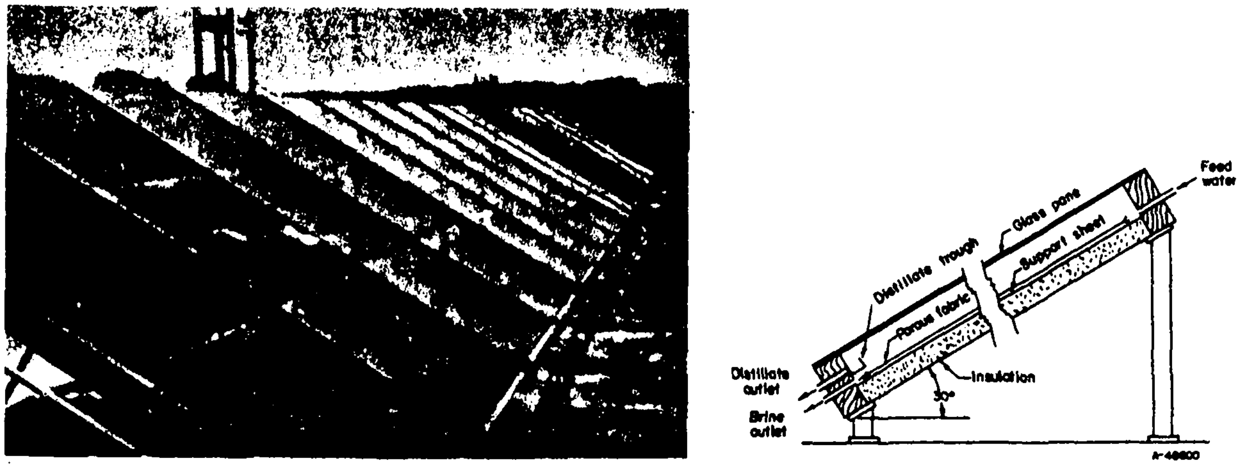



FIGURE 124. TELKES' TILTED-WICK STILLS (DAYTONA BEACH, FLORIDA)

| | |
|---|---|
| Internal size: | 20 units, each 39 in. wide x 7 ft 10 in. long, 500-$ft^2$ total wick area. |
| Brine depth: | Soaked wick of black terrycloth initially, later sailcloth, and glass fibers pressed into black plastic. |
| Cover: | 12 units glass, 4 units Weatherable Mylar, 4 units Tedlar, 2-1/2-in. spacing between cover and wick. |
| Vapor seals: | Neoprene washers and a synthetic rubber-resin base adhesive. |
| Distillate troughs: | Aluminum sheet. |
| Basin liner: | Wick-support sheets of various plastic films, insulation 1 in. thick. |
| Walls and curbs: | Redwood framework, angle-iron supports. |
| Other features: | Southward facing, tilted 30 degrees from horizontal, more radiation received in winter, chlorination feedwater treatment. |
| Productivity: | 0.11 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day on the 30-degree inclined surface. |
| Problems: | Deterioration of wooden components, nonuniform wetting of wick, wick materials faded and became weak and brittle, capillary flow-control tubes clogged with algae before chlorination. |
| Dates: | September, 1960, to June, 1963. |
| References: | Battelle, 52, 54. |

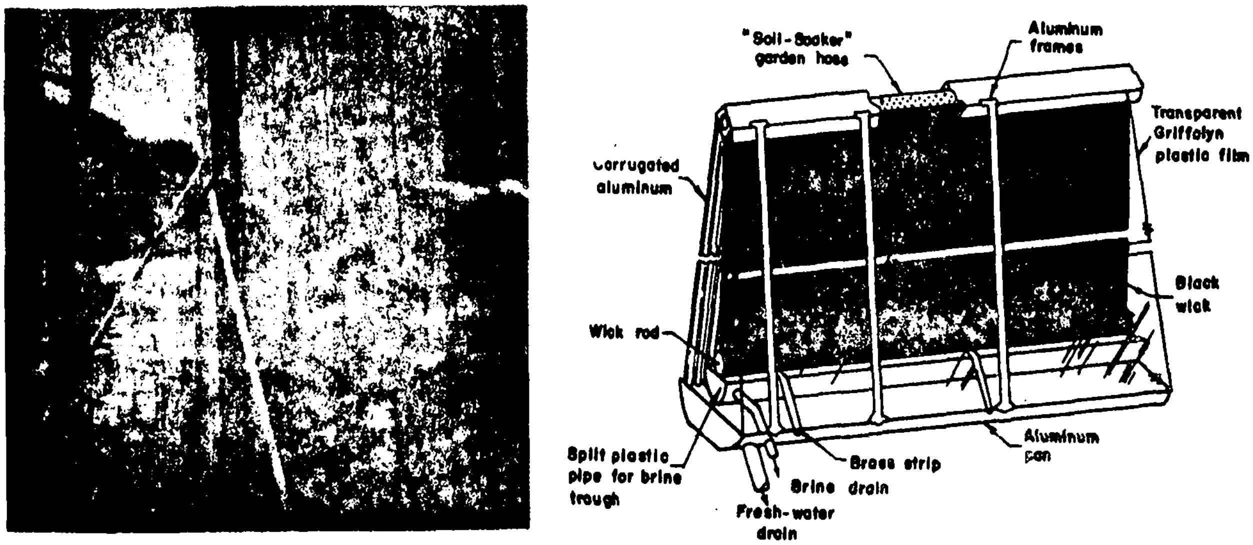



FIGURE 125. BJORKSTEN VERTICAL-ENVELOPE STILL (DAYTONA BEACH, FLORIDA)

| | |
|---|---|
| Internal size: | Four units, each approx. 6 ft high x 12 ft long; 600-$ft^2$ wick area (both sides). |
| Brine depth: | Saturated wick of black terry cloth. |
| Cover: | Mylar front covers, back panels were Mylar on two units and corrugated aluminum on the other two. |
| Vapor seals: | Heat sealing and adhesives. |
| Distillate troughs: | Aluminum bottom pan. |
| Basin liner: | None required. |
| Walls and curbs: | Aluminum framework, fiberglass piping. |
| Other features: | Vertical position gives better winter output, can be tilted about 15 degrees from vertical. |
| Productivity: | No useful data obtained in Florida. (See description for Bjorksten Research Laboratories, Figure 122). |
| Problems: | Susceptible to wind damage, nonuniform wetting of wicks, plastic-cover films blown against wicks until supports added, brine spillage into distillate. |
| Dates: | Approx. September, 1960, to approx. May, 1961. |
| References: | Battelle, 52, 54. |

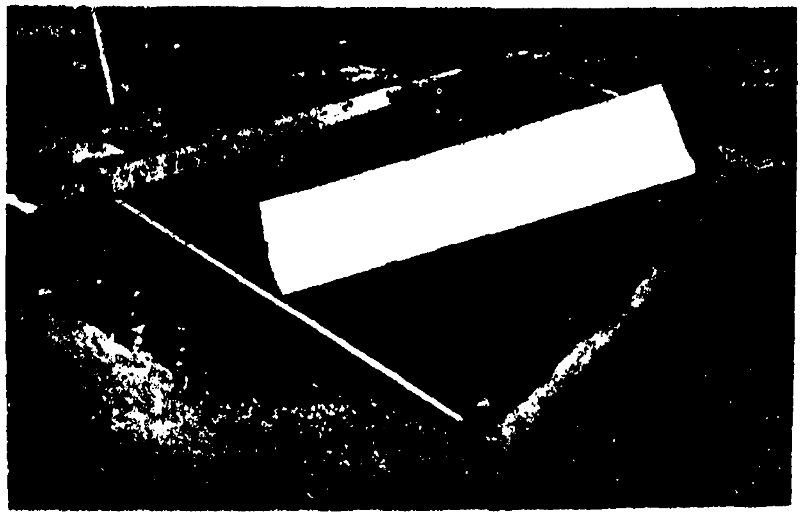


FIGURE 126. SECOND TILTED-WICK STILL (DAYTONA BEACH, FLORIDA)

| | |
|---|---|
| **Internal size:** | Approx. 4 ft wide x 12 ft long; 50-$ft^2$ wick area. |
| **Brine depth:** | Soaked wick of black polyethylene felt, also black terry cloth wick. |
| **Cover:** | Glass, tilted 30 degrees from horizontal, facing southward. |
| **Vapor seals:** | Asphaltic cement. |
| **Distillate troughs:** | Stainless steel. |
| **Basin liner:** | Polyethylene plastic ground sheet. |
| **Walls and curbs:** | Concrete beams. |
| **Other features:** | Tilted to receive more sunlight, built directly on sloped ground. |
| **Productivity:** | No useful data because of incomplete wetting of wick. |
| **Problems:** | Uneven distribution of feedwater, incomplete wetting of wick. |
| **Dates:** | Around March, 1964. |
| **Reference:** | Battelle, 55. |

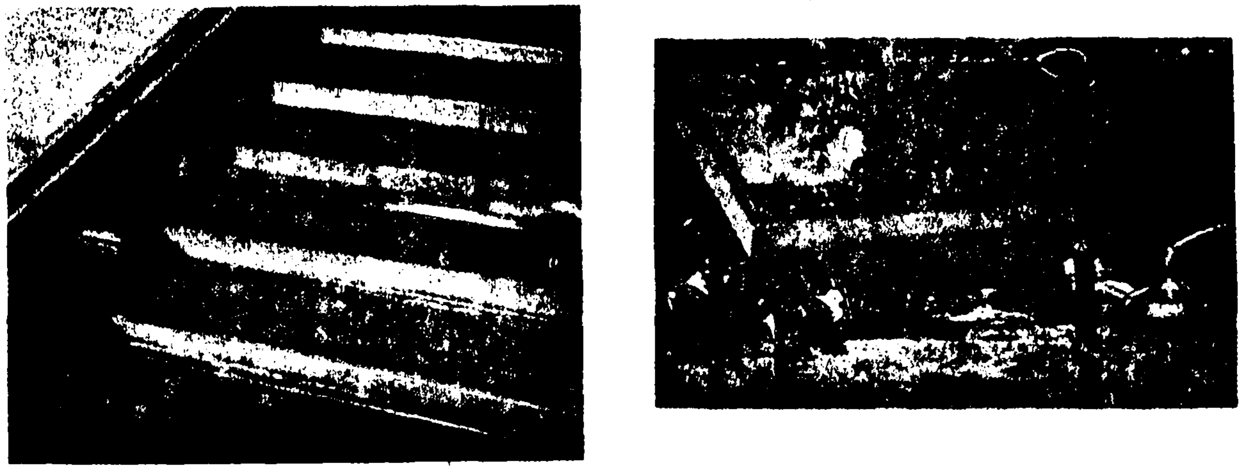
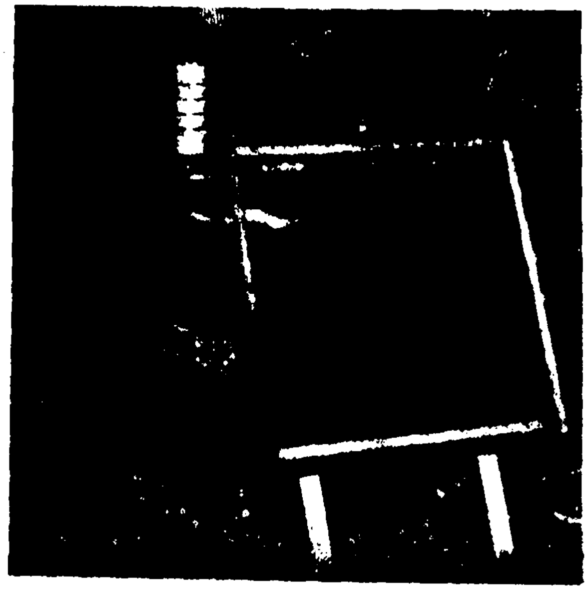


FIGURE 127. INCLINED-TRAY STILL (SUNAGUA COMPANY*)

| | |
|---|---|
| Internal size: | 10.6-$ft^2$ tray area. |
| Brine depth: | Series of shallow horizontal trays, each about 5 in. wide and 1 in. deep. |
| Cover: | Glass, approx. 30-degree slope for cover and tray. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Final tilted-tray design had porcelain-enameled steel trays with two coats of enamel, any pinholes were sealed with silicone rubber sealant, insulated tray. |
| Walls and curbs: | Not reported. |
| Other features: | Good winter productivity relative to summer, some units sold commercially with 3-year warranty, designed so that stills could become dry without damage, approx. 65 different tilted-tray stills constructed and tested by McCracken. |
| Productivity: | 0.10 gal/$ft^2$-day yearly average. |
| Problems: | Many designs and materials evaluated to avoid high cost, bad taste in distillate, warpage, brine leaks, etc.; tilted-tray abandoned in favor of horizontal tray. |
| Dates: | 1962 to approx. 1965. |
| References: | McCracken, 327, 328. |

*Now Sunwater Company.



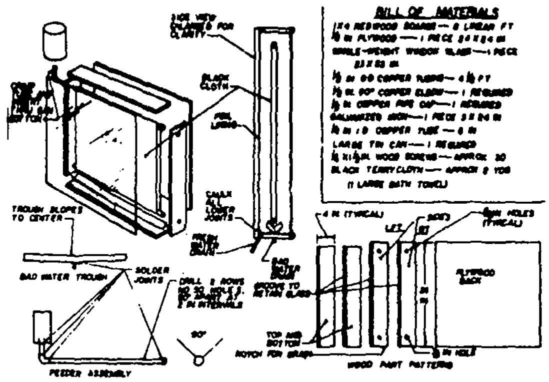



FIGURE 128. HOME-MADE STILL

| | |
|---|---|
| Internal size: | Approx. 23 x 23 in. |
| Brine depth: | Double layer of wick material. |
| Cover: | Glass, 23 x 23 in. (single strength), unit tilted approx. 15 degrees from vertical. |
| Vapor seals: | Caulking. |
| Distillate troughs: | Bottom corner of box. |
| Basin liner: | Black terrycloth wick, galvanized iron brine trough. |
| Walls and curbs: | Redwood sides, plywood back. |
| Other features: | Plans given for do-it-yourself construction, copper feed tube drilled at 2-in. intervals with two rows of holes. |
| Productivity: | Not reported. |
| Problems: | Wick material fades quickly. |
| Dates: | Around 1963. |
| References: | Anon., 21; Halacy, 200. |

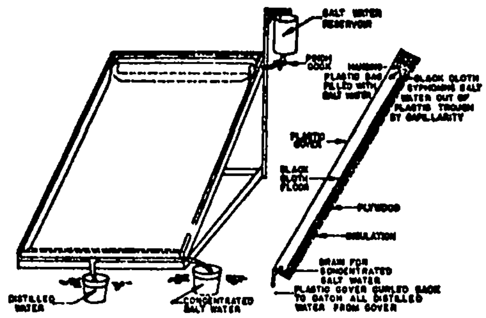



FIGURE 129. PLASTIC-COVERED TILTED STILL (UNIVERSITY OF WISCONSIN)

| | |
|---|---|
| **Internal size:** | Not reported. |
| **Brine depth:** | Black cloth wick. |
| **Cover:** | Clear plastic, slope 20 degrees or more. |
| **Vapor seals:** | Adhesive plastic tape. |
| **Distillate troughs:** | Formed from plastic-cover material. |
| **Basin liner:** | Thick black cloth wick over a sheet of Mylar. |
| **Walls and curbs:** | Wooden framework, insulated plywood bottom. |
| **Other features:** | Plastic trough at top for feedwater. |
| **Productivity:** | Fair efficiency reported. |
| **Problems:** | Insulated bottom required for better efficiency, steeper slope required if nonwettable plastic cover used. |
| **Dates:** | Around 1964. |
| **Reference:** | Daniels, 119. |

Built by William Rhodes at Questlab

FIGURE 130. TILTED-WICK STILL AT PHOENIX, ARIZONA (QUESTLAB)

| | |
|---|---|
| **External size:** | 40 x 40 x 6-in.-deep box. |
| **Brine depth:** | Thickness of cloth wick. |
| **Cover:** | Glass, tilted approx. 30 degrees. |
| **Vapor seals:** | Not reported. |
| **Distillate troughs:** | Not reported. |
| **Basin liner:** | Dark terrycloth wick suspended inside by means of glass rods in hems and nylon cords. |
| **Walls and curbs:** | Stainless steel box, angle iron support frame. |
| **Other features:** | Water used in laboratory, water-pressure regulator feeds water into funnel, stainless steel tube manifold with slit along top to feed water to wick, cover and back act as condensing surfaces. |
| **Productivity:** | About 2 gpd (1 gpd before cleaning glass cover). |
| **Problems:** | Dropwise condensation on glass until cleaned with concentrated nitric acid, costly materials. |
| **Dates:** | Built during 1966. |
| **Reference:** | Anon., 11. |

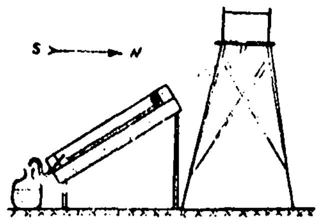



FIGURE 131. EXPERIMENTAL TILTED-WICK STILL NO. 4 (TURKMENIAN ACADEMY OF SCIENCES, U.S.S.R.)

| | |
|---|---|
| Internal size: | Still 4, approx. 31 x 49 in., 10.7-$ft^2$ wick. |
| Brine depth: | Thickness of wick. |
| Cover: | Glass, 0.08 in. thick, 30-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Black cloth wick. |
| Walls and curbs: | Double plywood with sawdust insulating layer between. |
| Other features: | Distillate drain tube positioned to provide water trap. |
| Productivity: | Maximum of about 0.10 gal/$ft^2$-day. |
| Problems: | Several failures. |
| Dates: | 1960 to 1962. |
| Note: | Stills 1 to 3, and 5 described previously (tray types). |
| References: | Bairamov, 45. |

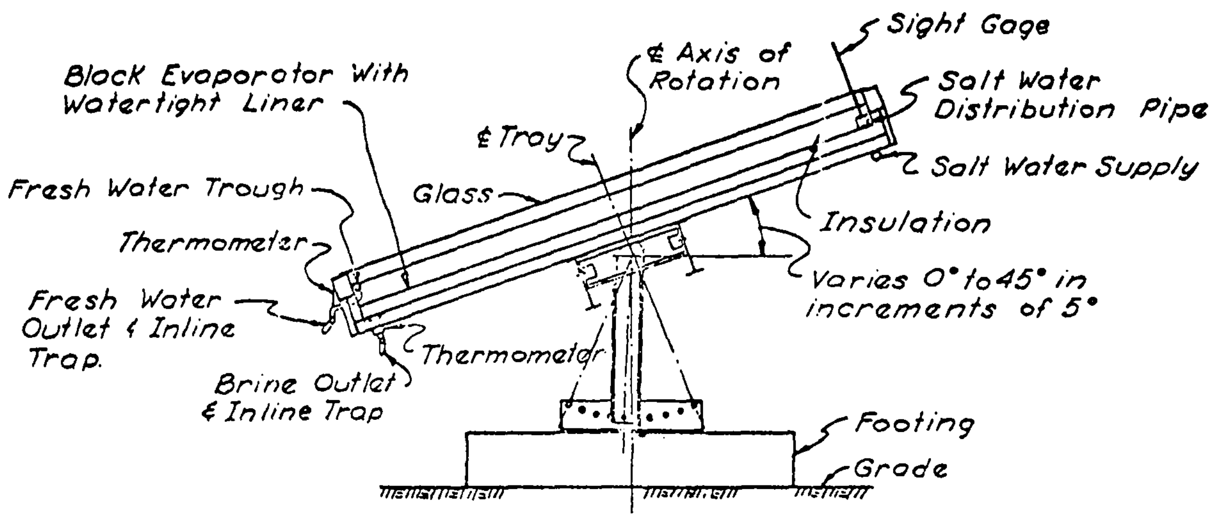



FIGURE 132. EXPERIMENTAL TILTABLE STILL (VIRGIN GORDA ISLAND, VIRGIN ISLANDS)

| | |
|---|---|
| **Internal size:** | Two units, tiltable trays each 9 ft 11 in. long by 24 ft wide; 240-$ft^2$ evaporating area per unit; axis oriented East-West. |
| **Brine depth:** | Thickness of wick. |
| **Cover:** | Glass, 0.19 in. thick, steel framework; tiltable from 0 to 45 degrees in 5-degree increments. |
| **Vapor seals:** | Caulking, rubber gaskets, butene tape. |
| **Distillate troughs:** | Metal trough. |
| **Basin liner:** | Black evaporator wick over black polyethylene film, insulation. |
| **Walls and curbs:** | Wood and concrete. |
| **Other features:** | PVC piping and valves, salt water feed rate of 60 to 70 gpd, variable tilt possible. |
| **Productivity:** | Approx. 15 to 20 gpd during April, 1962, with feed rate of 60 to 70 gpd. (Approx. 0.08 gal/$ft^2$-day). |
| **Problems:** | Leakage from tray before polyethylene sheet installed, pipe leakage before PVC used. |
| **Dates:** | May, 1960, to June, 1962. |
| **Note:** | Stills donated to Brace Research Inst., St. James, Barbados, West Indies after termination of experiment. |
| **Reference:** | Tippetts, et al., 444. |

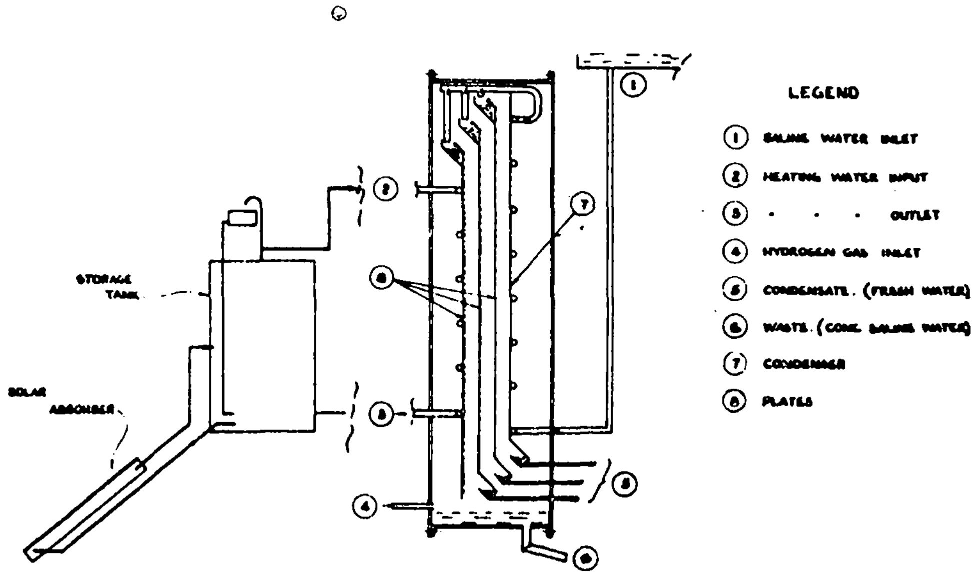



FIGURE 133. MULTIPLE-EFFECT, DIFFUSION STILL (C. S. I. R. O. *, AUSTRALIA)

| | |
|---|---|
| Internal size: | 5-effect laboratory model, plates 24 in. wide, height not reported. |
| Brine depth: | Wick thickness not reported. |
| Cover: | None used. (Hot water used to heat first plate.) |
| Vapor seals: | Not reported. |
| Distillate troughs: | Formed at bottom of plates. |
| Basin liner: | Vertical plates covered with a porous wick such as fiber-glass cloth or nylon felt, spaced 1/8 to 1/2-in. apart. |
| Walls and curbs: | Not reported. |
| Other features: | Solar absorber used to provide hot water to heat the first effect's evaporator plate, incoming brine is preheated by cooling the condenser of the last effect, narrow spacings and hydrogen gas increase diffusion rates, storage tank used to allow 24-hr operation. |
| Productivity: | (Air, 3/8-in. plate spacing) 2.77 lb/hr with overall temperature difference 161 F to 90 F, or 4.16-psi vapor-pressure differential; at 2-psi differential (air, 1/4-in.) 1.2 lb/hr, (air, 1/8-in.) 2.3 lb/hr (hydrogen, 1/8-in.) 6.4 lb/hr. |
| Problems: | Uniform distribution of the water film over bare plates, clogging of wick when sea water used, closed spacing of plates caused contamination of product until spacers added. |
| Dates: | Around 1961. |
| Reference: | Dunkle, 144. |

*Commonwealth Scientific and Industrial Research Organization.

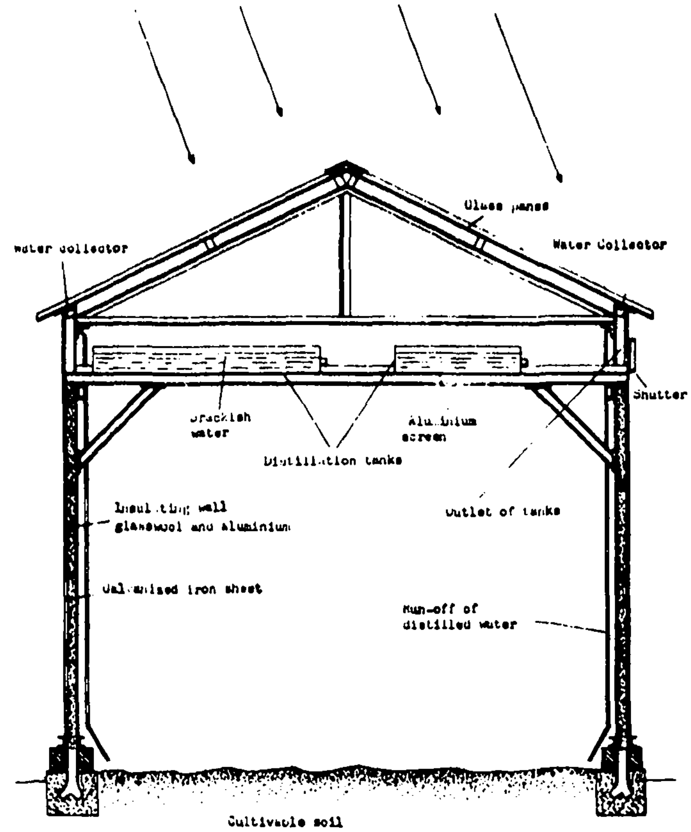
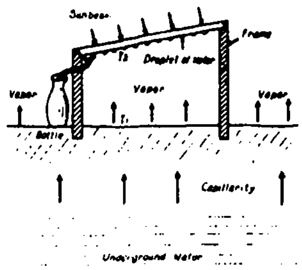


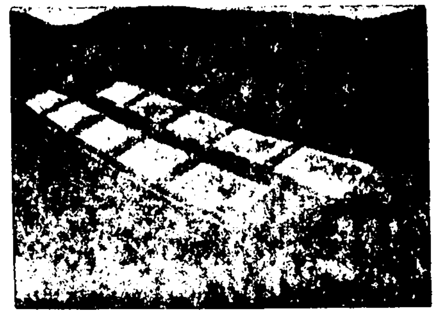

FIGURE 134. COMBINATION STILL AND GREENHOUSE (UNIVERSITY OF PARIS, FRANCE)

| | |
|---|---|
| Internal size: | Small greenhouse, 3 ft wide and 6.2 ft long, tray area of 11.8 $ft^2$; large greenhouse, 10 ft wide x 20 ft long x 10 ft high (6.6 ft under brine trays), tray area not reported; long dimension oriented East-West. |
| Brine depth: | Not reported. |
| Cover: | Glass roof, approx. 25-degree slope. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Metal channels. |
| Basin liner: | Not reported. |
| Walls and curbs: | Galvanized sheet metal walls (insulated) and concrete foundation curbs. |
| Other features: | (Smaller unit) approx. 75 percent relative humidity inside, hybrid French beans grown during two summer months; (larger unit) brine trays shilded from plants by aluminum screens, mention made of increasing $CO_2$ content in greenhouse, approx. 80 percent of sunlight for brine trays and 20 percent for plants directly. |
| Productivity: | (Smaller unit) 0.11 to 0.13 gal/$ft^2$-day tray area, (larger unit) 0.10 to 0.12 gal/$ft^2$-day of tray area. |
| Problems: | None reported. |
| Dates: | Smaller unit 1956-1957; larger unit 1961 +. |
| References: | Trombe and Foex, 452, 453. |

a. Experiment in Suburbs of Tokyo




b. Principle of Operation

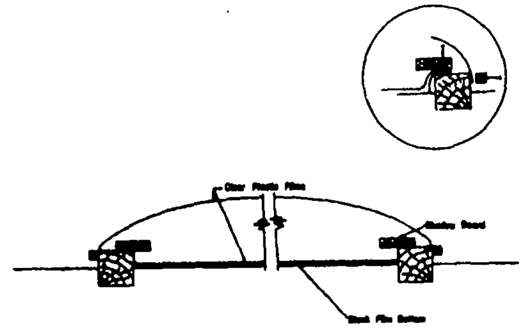


c. Collectors Using Plastic Covers

FIGURE 135. EARTH-WATER COLLECTOR (TOKYO, JAPAN)

| | |
|---|---|
| Internal size: | Not reported. |
| Brine depth: | No brine layer (water contained in surface soil). |
| Cover: | Glass or plastic, single and double sloped, wooden frame support. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | None used. (Water evaporated from the soil.) |
| Walls and curbs: | Still rests on top of soil. |
| Other features: | Experiments conducted in Tokyo, Mt. Mihara, Mt. Fuji, and the Quetta Desert of Pakistan; condensation continued at night especially in the desert area, radioactive contaminated soils will produce potable water by this means. |
| Productivity: | (In Tokyo) approx. 0.012 gal/ft$^2$-day average for November to March; peak outputs followed rain. |
| Problems: | In desert area still did not produce any water during the daytime, productivity depends on type of soil. |
| Dates: | Summers of 1961-1963. |
| Reference: | Kobayashi, 278. |

a. Pilot Plant



b. Solar Collector Design

FIGURE 136. HUMIDIFICATION-DEHUMIDIFICATION PLANT AT PUERTO PENASCO, SONORA, MEXICO (UNIVERSITIES OF ARIZONA AND SONORA)

| | |
|---|---|
| Internal size: | 5 bays for solar water heaters, 6 to 8 ft wide x 300 ft long; 10,400-ft$^2$ total collector area. |
| Brine depth: | Approx. 2 in. after level-control weirs installed (burn-out of some basin liners occurred with more shallow layers). |
| Cover: | Two plastic covers; one floating on surface of brine, the other inflated. |
| Vapor seals: | Not reported. |
| Distillate troughs: | None used, evaporation prevented. |
| Basin liner: | Black butyl rubber or black polyethylene; PVC or PVF films floated on brine surface. |
| Walls and curbs: | Redwood curbs pinned to the ground. |
| Other features: | Shadow boards used to protect black plastic film from sunlight where not submerged; collectors flushed in the morning to remove cold water and in the evening to remove hot water, storage reservoirs used to permit 24-hour operation of plant, solar collectors later replaced by using waste heat from the diesel engine's water jacket and exhaust system. |
| Productivity: | Heated water obtained (May, 1964), 8.55 lb/ft$^2$-hr (180 gpm) flow rate heated an average of 13.4 F between 9:00 a.m. to 5:00 p.m.; plant designed to produce about 5,000 gal. of distilled water per day during summer. |
| Problems: | Burnout of basin liners with shallow layers of water, Tedlar film on water surface lasted only 18 months, inflated Tedlar covers destroyed by a heavy hail storm after 31 months, a light-stabilized polyethylene film on the water surface failed after 19 days, and a PVC film failed in 80 days, algae growth in collectors. |
| Dates: | Fall, 1963, to present. |
| Note: | This is a solar collector for heating sea water and not a solar still. A similar unit was built at the Central Salt and Marine Chemicals Research Inst. in Bhavnagar, India (Garg, et al., 170-174). Their solar collector consisted of two bays, each 3 ft wide x 16 ft long (96-ft$^2$ total area) and 2 in. deep, with a single cover of PVC film. Unit produced about 20 gpd. A pilot plant for 1,200 gpd was designed to gather data for scale-up purposes. A simple solar still was recommended for plant capacities below about 24,000 gpd. |
| References: | Hodges, 222-225. |

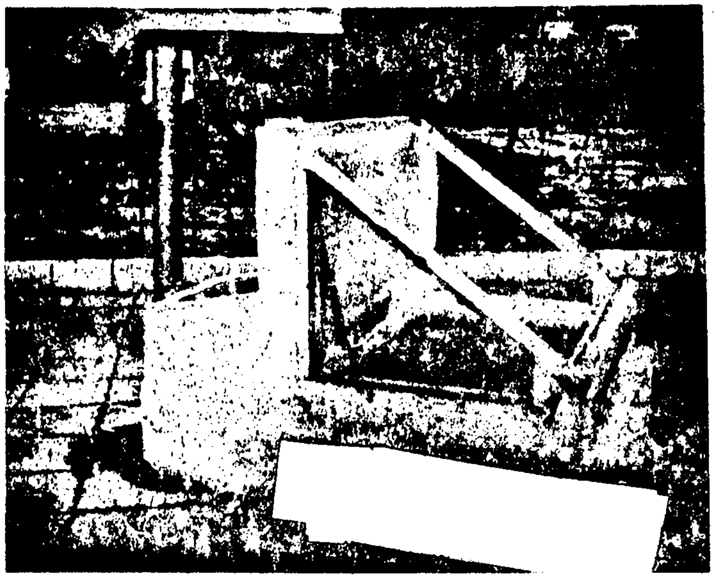


FIGURE 137. SEPARATE EVAPORATOR AND CONDENSER STILL, D2 (TUNISIAN AEC)

| | |
|---|---|
| **Internal size:** | 11-$ft^2$ evaporating area. |
| **Brine depth:** | Not reported. |
| **Cover:** | Glass, 0.16 in. thick, approx. 30-degree slope. |
| **Vapor seals:** | Mastic. |
| **Distillate troughs:** | Not reported. |
| **Basin liner:** | Black tiles. |
| **Walls and curbs:** | Masonry. |
| **Other features:** | Chimney used for natural-draft circulation, anticipated lifetime of 15 years. |
| **Productivity:** | Summer - 0.15 gal/$ft^2$-day, winter - 0.04 gal/$ft^2$-day. |
| **Problems:** | Black tiles did not improve production enough to warrant the higher cost. |
| **Dates:** | Built May, 1966. |
| **Reference:** | Tunisian AEC, 454. |

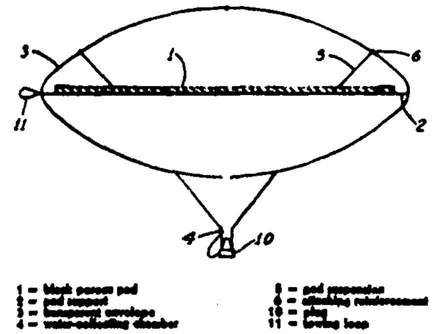



FIGURE 138. LIFE RAFT STILLS (M. I. T.)

| | |
|---|---|
| Internal size: | Approx. 2-ft$^2$ absorber-evaporator wick; open – approx. 20-in. diam. x approx. 15 in. high (circular model); folded – 80 cu in., 1-lb weight. |
| Brine depth: | Saturated black cellulose sponge, 1/4 in. thick. |
| Cover: | Transparent Vinylite, treated for wettability. |
| Vapor seals: | Heat-sealed seams. |
| Distillate troughs: | Cone-shaped bottom. |
| Basin liner: | None used. (Black absorbent pad). |
| Walls and curbs: | Device floats, tied to life rafts. |
| Other features: | Compact, portable, inflatable, floating, part of survival kits, horizontal sponge holds larger quantity of sea water than tilted sponge, units were used as standard equipment by the Air Force for life rafts. |
| Productivity: | Approx. 1 quart maximum output per day. |
| Problems: | Unpleasant taste of distillate from Vinylite, wettability treatment of plastic cover, some seawater may drip into distilled water, stills had to be weighted for stability on rough water, cemented seams unsatisfactory, sponge must be resoaked at intervals and salt deposits flushed away. |
| Dates: | 1943 - 1945+. |
| References: | Telkes, 427, 430, 433, 441. |

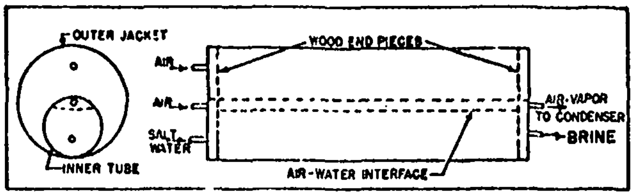
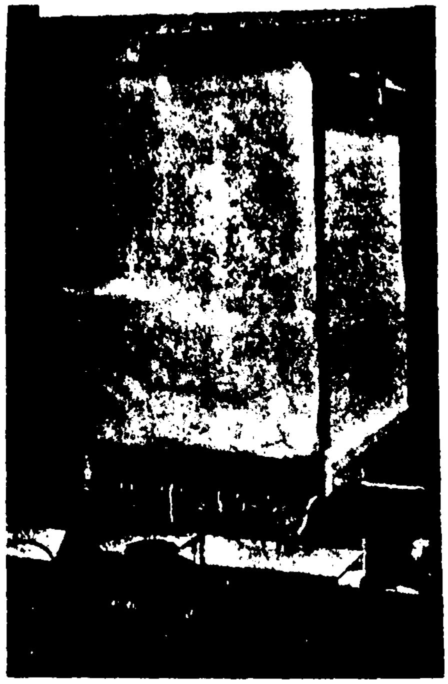
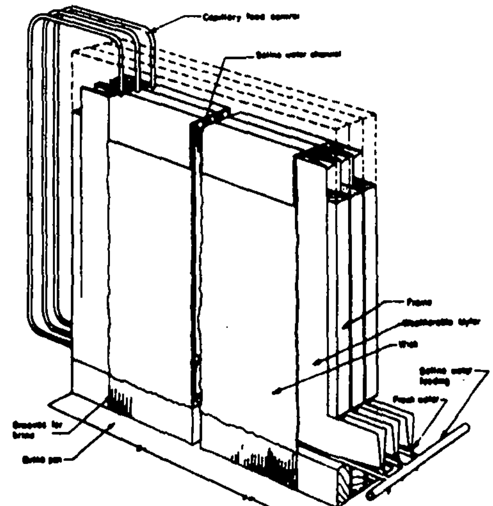



FIGURE 139. DOUBLE-TUBE PLASTIC STILL WITH EXTERNAL CONDENSER (UNIVERSITY OF WISCONSIN)

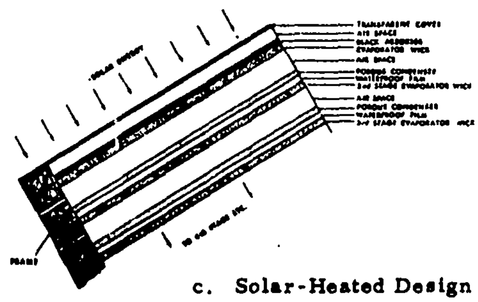
| | |
|---|---|
| **Internal size:** | (1953-1955) Double plastic tubes, inner tube 3.8-in. diam., outer tube 6.4-in. diam.; 4.30-$ft^2$ exposed water surface. (1957) Inner tube 1.9-in. diam. x 10 ft long, outer tube 3.8-in. diam.; 1.78-$ft^2$ evaporating surface area. |
| **Brine depth:** | Inner tube nearly or partially filled with brine. |
| **Cover:** | Tubes of Trithene, Kel-F, Weatherable Mylar, and 100-X Teflon tried. |
| **Vapor seals:** | Not reported. |
| **Distillate troughs:** | External condenser of copper tubing. (Exit air circulated through tubing surrounded by incoming brine.). |
| **Basin liner:** | Inner plastic tube. |
| **Walls and curbs:** | Circular wooden ends, stills placed on wooden tables. |
| **Other features:** | Outer tube inflated, air circulated through inner tube and an external condenser cooled by the incoming salt water, black dye added to brine, data taken only for 1 hour each day during steady-state conditions, fixed air flow for all experiments, solar-heated chimneys 3 ft high tested for air circulating technique. |
| **Productivity:** | (1953) About 25 percent efficiency reported; (1959) 20 to 40 percent based on experiments of 1-hour duration (100-X Teflon produced the highest efficiency). |
| **Problems:** | Occasional droplets of water condensed on inner plastic tube. |
| **Dates:** | Around 1953 and July, 1957 to June, 1958. |
| **References:** | Herlihy, 209, 210; Salam and Daniels, 405. |



a. Ten-Stage Multiple-Effect Still, Electrically Heated



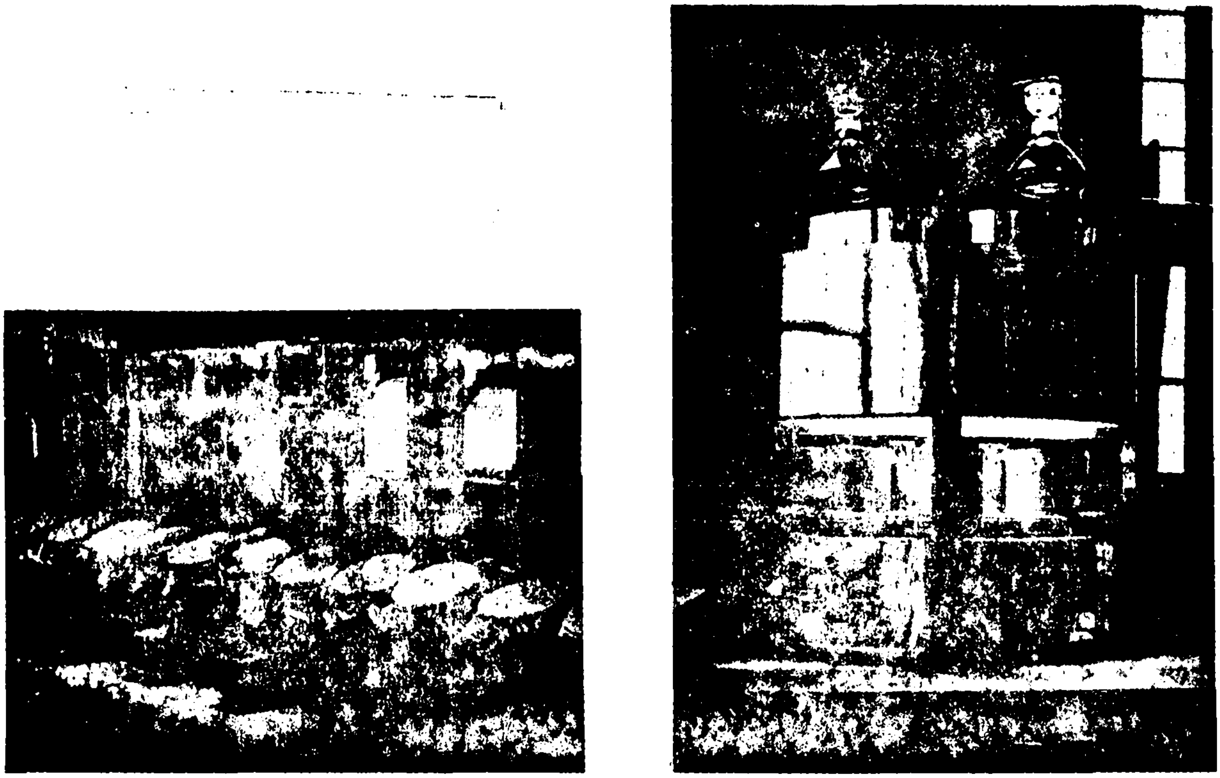
b. Ten-Stage Design



c. Solar-Heated Design

FIGURE 140. MULTIPLE-EFFECT STILLS (NEW YORK UNIVERSITY)

| | |
|---|---|
| Internal size: | One 1 to 5-effect still with 1-ft$^2$ frames, one 10-effect still with 2.25-ft$^2$ frames, and one 4-effect still with 7.9-ft$^2$ frames. |
| Brine depth: | Thin layers of vertical porous wicks (filter paper, cotton cloth, flannel, or nylon felt) bonded to separating sheets (Mylar or aluminum). |
| Cover: | All three units electrically heated, the 4-effect unit was also solar heated through a glass cover. |
| Vapor seals: | Mylar plastic films separated stages and covered the periphery, adhesives used for plastic to wood joints. |
| Distillate troughs: | Mylar film or aluminum. |
| Basin liner: | Mylar or mylar-lined brine troughs. |
| Walls and curbs: | Wood frames, fiberglass insulation. |
| Other features: | Capillary feed control, electrically heated for lab tests, air or evaporative cooled condenser side. |
| Productivity: | (10-effect still) 1 gal/hr heated with 2000 Btu/hr, a tilted 10-effect solar still estimated to produce six times that of a single effect solar still of equal heated area. |
| Problems: | A solar-heat collector and a heat exchanger would be required to supply the heat input to the center of a symmetrical multiple-effect still, porous condenser layer required on nonwettable plastic films, complete and uniform wetting of wicks. |
| Dates: | Approx. 1956 to approx. 1958. |
| References: | Telkes, 435-438; Battelle, 52. |



a. Outdoor Tests    b. Indoor Apparatus for Accelerated Exposure

FIGURE 141. PLASTIC-FILM EXPOSURE APPARATUS (BJORKSTEN RESEARCH LABS)

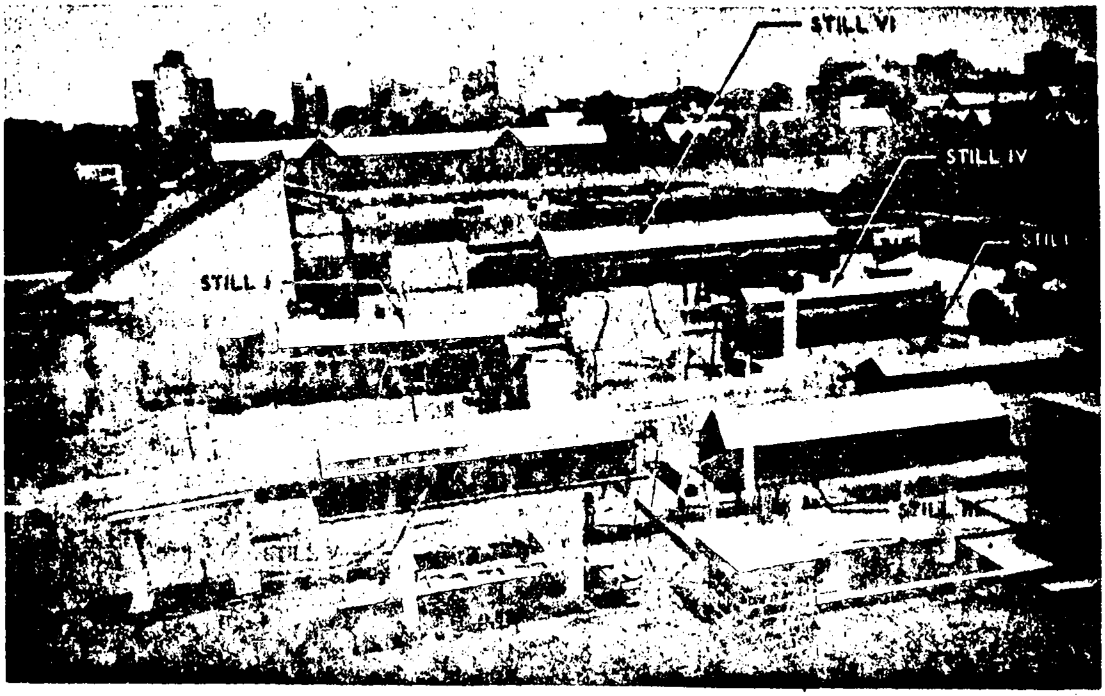
| | |
|---|---|
| Internal size: | 5-gal paint cans, 12-in. diam. |
| Brine depth: | Sand in bottom third of cans saturated with water. |
| Cover: | Many plastic film materials life-tested, including Teflon, Mylar, Teslar (Tedlar), and Kel-F; cans tilted 15 degrees southward. |
| Vapor seals: | Spring-loaded band of plastic tubing. |
| Distillate troughs: | None used (distillate recirculated internally). |
| Basin liner: | Sand used in bottom one-third of cans, black dye added to water. |
| Walls and curbs: | Paint cans. |
| Other features: | Laboratory tests also conducted with heat lamps to accelerate failures, black dye added to water in cans, 21 samples tested, several polyfluoroethylene films showed best durability. |
| Productivity: | None planned. |
| Problems: | Accelerated lab tests could not be correlated with outdoor exposure tests, only 16.5 months of outdoor testing. |
| Dates: | March, 1957, to August, 1958. |
| Reference: | Bjorksten, 74. |

STILLS AT GEORGIA INSTITUTE OF TECHNOLOGY (ATLANTA, GEORGIA)

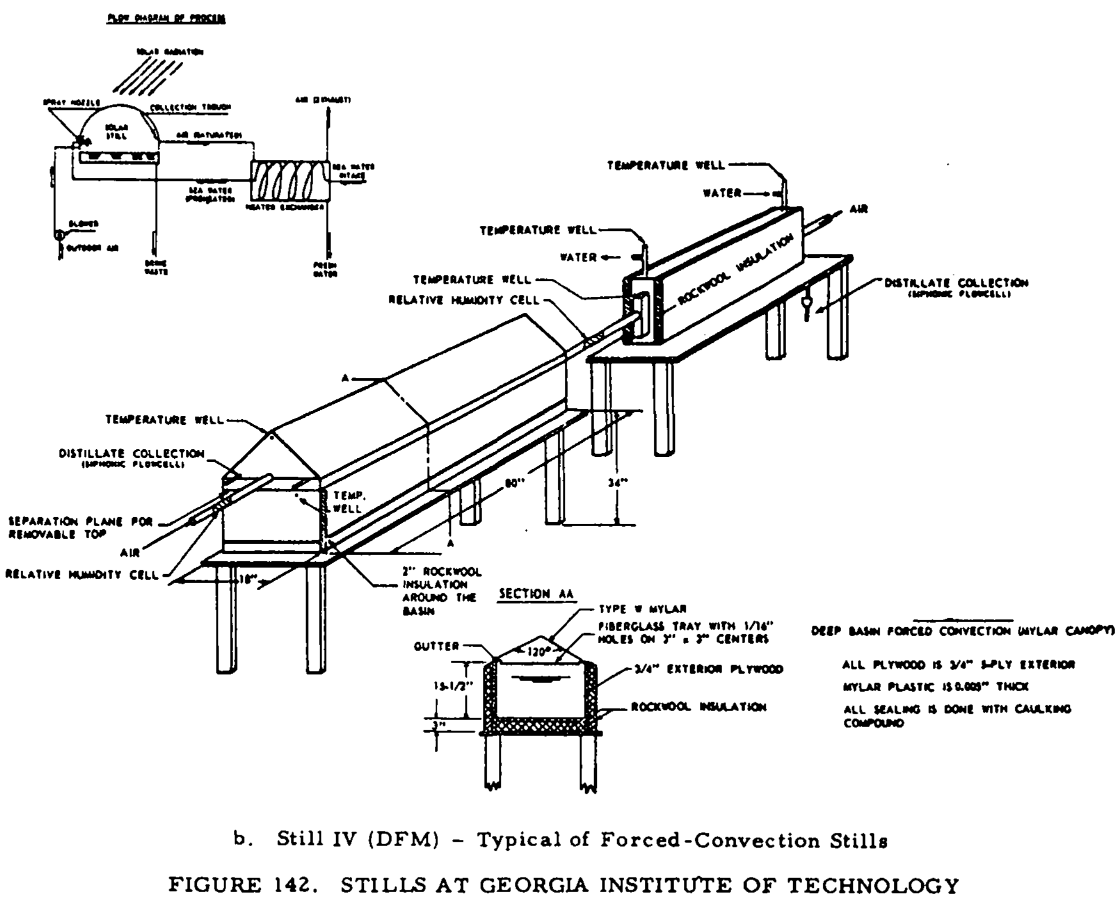
| Still[a] | Designation[b] | Cover Material | Cover Slope, degrees | Net Effective Area, $ft^2$ | Brine Depth, in. | Still Orientation | Mass of Water, lb | Mean Efficiency, % |
|---|---|---|---|---|---|---|---|---|
| I | DNM | Mylar | 45 | 9.08 | 10 | N-S | 573 | 19.2 |
| I | DNM | Mylar | 30 | 9.08 | 10 | N-S | 573 | 13.9 |
| II | SFM | Mylar | 30 | 8.95 | 2 | N-S | 83 | -- |
| $II_b$ | SFT | Tedlar (2 layers) | 0 (flat) | 8.54 | 2 | N-S | -- | -- |
| III | SNT | Tedlar | 45 | 8.95 | 1/8 | N-S | ~4.5 | 32.1 |
| III | SNM | Mylar | 30 | 8.95 | 2 | N-S | 71 | 24.7 |
| IV | DFM | Mylar | 30 | 8.95 | 12 | N-S | 661 | -- |
| V | SNG | Glass (7/32 in.) | 45 | 8.95 | 2 | N-S | 71 | 23.7 |
| V | SNG | Ditto | 30 | 8.95 | 2 | N-S | 71 | 29.2 |
| V | SNG | " | 30 | 8.95 | 1/8 | N-S | ~4.5 | 34.1 |
| $V_b$ | SNG | Glass (1/8-in.) (double layer) | 15 (single slope) | 8.95 | 0.13 (Orlon wick) | E-W | -- | 28.8 |
| $V_b$ | SNG | Glass (1/8 in.) | 15 (single slope) | 8.95 | 0.13 (Orlon wick) | E-W | -- | 38.2 |
| VI | DFT | Tedlar | 30 | 61.1 | 12 | N-S | 3,133 | -- |
| $VI_b$ | MFT | Tedlar (2 layers) | 0 (flat) | 58.4 | 0.25 - 7.5 (8 basins) | -- | -- | -- |
| VII | SFG | Glass (7/32 in., ≤4 layers) | 0 (flat) | 5.94 | 3 | Indoors | -- | -- |

(a) Subscript "b" denotes 1961 modifications to 1960 stills.
(b) D = deep basin, S = shallow basin, M = multiple depth basin; N = natural convection, F = forced convection; M = 5-mil Mylar type W, T = 1.5-mil Tedlar type 20A, G = glass.

| | |
|---|---|
| Vapor seals: | Caulking compound, and felt weather stripping. |
| Distillate troughs: | Galvanized sheet metal, painted black (used only in natural convection stills and IV and VI). |
| Basin liner: | (I-VI) 3/4-in. 5-ply exterior plywood, lined with 1.5-oz. fiberglas mat saturated with black-pigmented polyester resin, (VII) 1/8-in.-thick copper, electrically heated. |
| Walls and curbs: | Usually exterior plywood, 3/4 inch thick, insulated with 2-in.-thick styrofoam sheets with aluminum foil on exterior surface, sealed with 2-in.-wide tape. |
| Other features: | Constant-level tanks with float valves controlled depth of (tap) water in basins, black dye sometimes added to water in basins, external condensers water cooled with provision for storing heated water for use in basins at night, still IV had a perforated fiberglas tray through which brine was circulated to increase mass-transfer area, still $VI_b$ had two air passages below basins for preheating and partially condensing and brine spray nozzles over the deepest of the eight basins, still VII was an electrically heated laboratory model. |
| Productivity: | (Best natural convection still-$V_b$ with single cover) approx. 0.09 gal/$ft^2$-day at 2,000 Btu/$ft^2$-day; (Forced convection still IV with distillate troughs) approx. 0.13 gal/$ft^2$-day; (Forced convection still $II_b$ without troughs) approx. 0.10 gal/$ft^2$-day; (Still $VI_b$-MFT) approx. 0.23 gal/$ft^2$-day. |
| Problems: | Dropwise condensation on nonwettable plastic covers. |
| Dates: | 1958 to 1961. |
| References: | Grune, et al., 192-197. |




a. 1960 Stills




b. Still IV (DFM) – Typical of Forced-Convection Stills

FIGURE 142. STILLS AT GEORGIA INSTITUTE OF TECHNOLOGY (ATLANTA, GEORGIA)

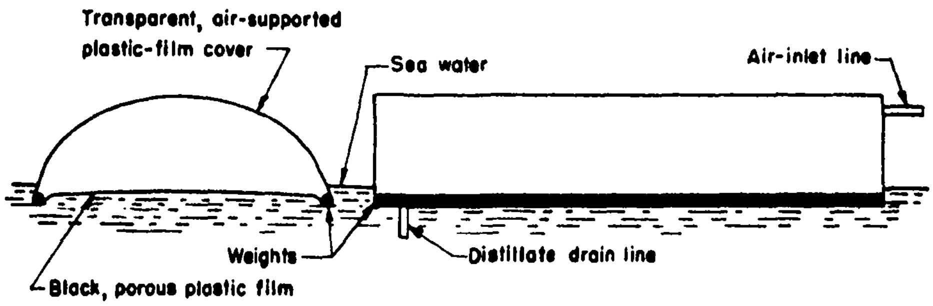



FIGURE 143. FLOATING-TYPE STILL (BATTELLE-COLUMBUS)

| | |
|---|---|
| **Internal size:** | 1 ft wide x 5 ft long, 5-$ft^2$ area. |
| **Brine depth:** | No brine inside still. |
| **Cover:** | Transparent polyethylene, inflated. |
| **Vapor seals:** | Heat-sealed seams. |
| **Distillate troughs:** | Edges of still weighted to form troughs. |
| **Basin liner:** | Black porous polyethylene (Porothene) bottom. |
| **Walls and curbs:** | Anchoring required. |
| **Other features:** | Portable, lightweight, weights required to give desired cross section, inflation pressure necessary. |
| **Productivity:** | None reported. |
| **Problems:** | Difficult to weight edges properly and remove distillate. |
| **Dates:** | Around September, 1959. |
| **Reference:** | Battelle, 52. |

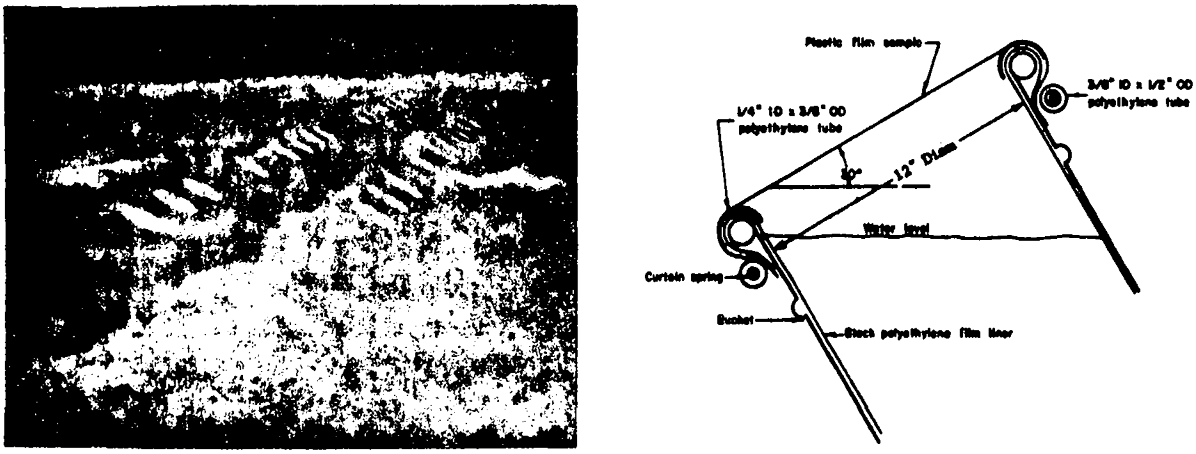



FIGURE 144. PLASTIC-FILM EXPOSURE PAILS (DAYTONA BEACH, FLORIDA)

| | |
|---|---|
| Internal size: | Approx. 40 5-gal paint cans, 12-in. diam. |
| Brine depth: | Approx. 12 in. |
| Cover: | Various plastic films evaluated. |
| Vapor seals: | Spring-loaded band of polyethylene tubing. |
| Distillate troughs: | None used. |
| Basin liner: | Black polyethylene film. |
| Walls and curbs: | Wooden framework used to tilt pails 30 degrees southward. |
| Other features: | No distillate output; easy method of exposing plastic films to solar still conditions, but less severe than actual stills because of lower wind stresses and lower operating temperatures achieved. |
| Productivity: | No output. |
| Problems: | Weatherable Mylar, Tedlar, and Aclar lasted the longest, about 4 years. |
| Dates: | September, 1959, to June, 1965. |
| References: | Battelle, 52, 54, 55. |

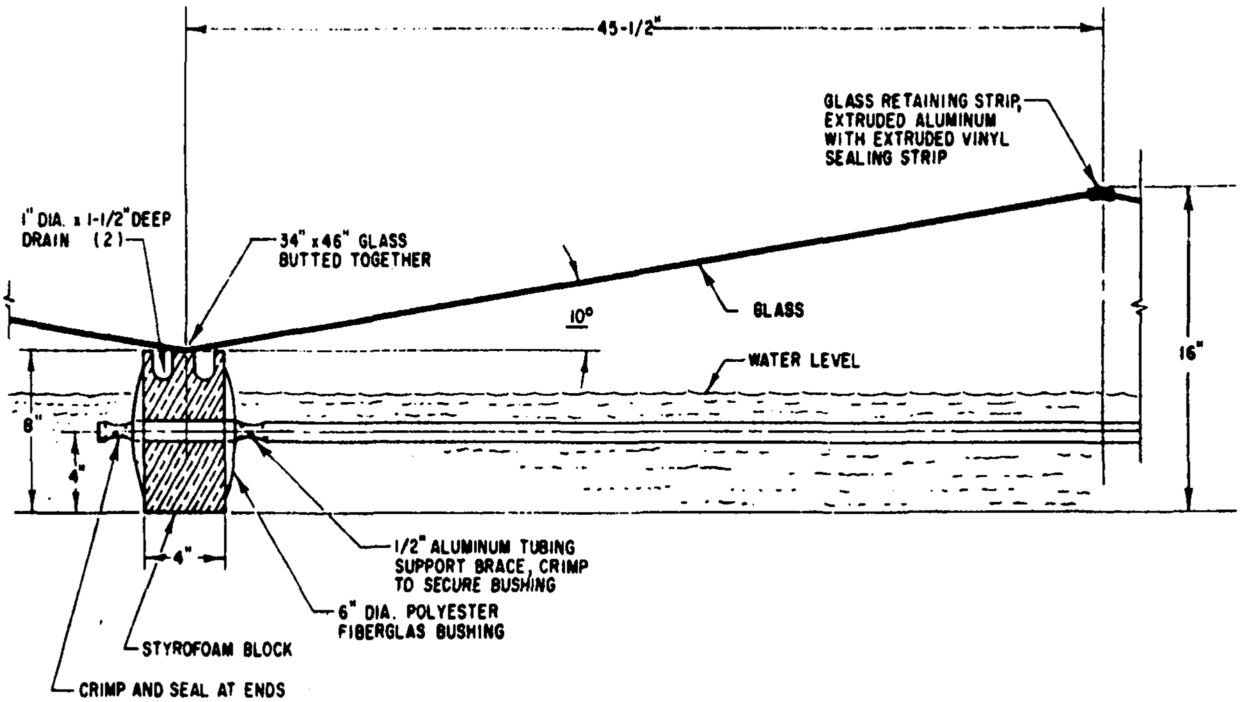



FIGURE 145. FLOATING-STILL DESIGN (LESLIE SALT CO., SAN FRANCISCO, CALIFORNIA)

| | |
|---|---|
| Internal size: | (Each bay) 7.25 ft wide x 42.5 ft long; 308-$ft^2$ evaporating area per bay. |
| Brine depth: | Depth of pond. |
| Cover: | Glass panes, 0.10 in. thick x 34 in. x 46 in., 10-degree slope. |
| Vapor seals: | Extruded-vinyl sealing strips. |
| Distillate troughs: | Grooves in styrofoam curbs. |
| Basin liner: | Bottom of pond. |
| Walls and curbs: | Floating styrofoam blocks with tubular aluminum tie rods. |
| Other features: | ABS plastic pipe for distillate, rainfall collection, designed to be built over existing salt-concentrating ponds, floating still design cheapest of several evaluated. |
| Productivity: | (Estimate only.) 0.07 gal/$ft^2$-day plus 17 in./yr rainfall collection. |
| Problems: | Still not actually built. |
| Dates: | Late 1962. |
| Reference: | Leslie Salt Co., 298. |

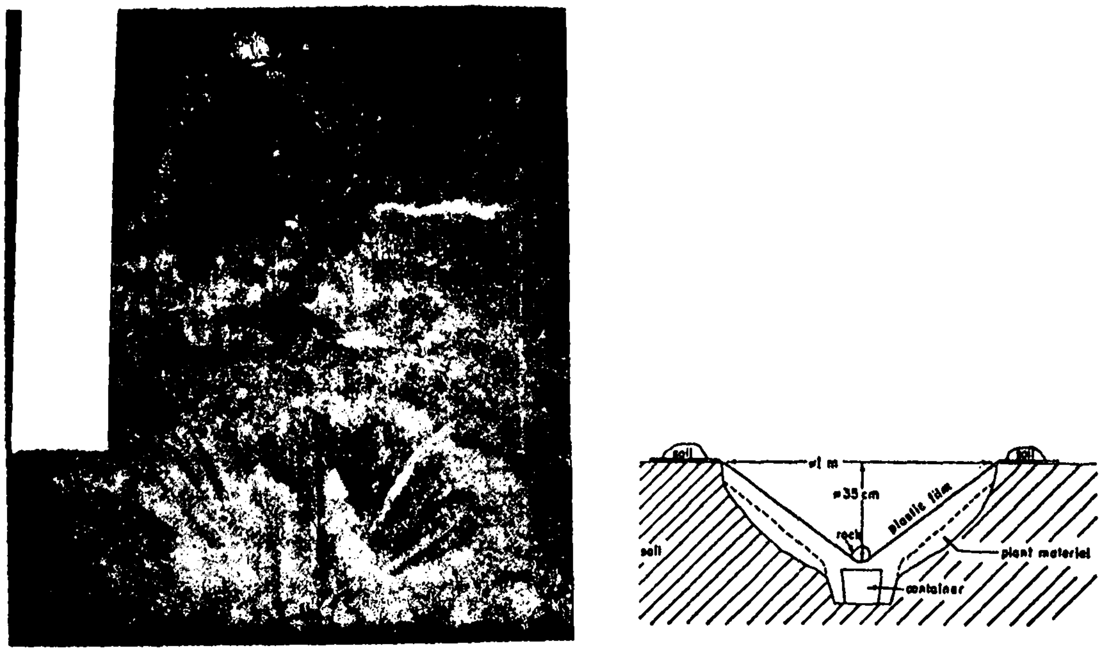



FIGURE 146. DESERT SURVIVAL STILL (U.S. DEPT. OF AGRICULTURE, PHOENIX, ARIZONA)

| | |
|---|---|
| **Internal size:** | Approx. 3-ft diam., 1.5 ft deep. |
| **Brine depth:** | Cut-up plant material used as raw-water supply. |
| **Cover:** | Plastic film (1-mil adherable Tedlar recommended), 25 to 40-degree slope, weighted in center. |
| **Vapor seals:** | Soil used to hold plastic cover in place. |
| **Distillate troughs:** | Water container below cone-shaped plastic cover, small plastic tube can be used to suck water from container. |
| **Basin liner:** | None used. |
| **Walls and curbs:** | Hole dug in ground. |
| **Other features:** | Designed as simple kit for a survival still, five stills tested with various types of soils, six stills tested with various plant materials added. |
| **Productivity:** | Approx. 0.2 gpd with soil base only, approx. 0.4 gpd with cut-up plant materials added. |
| **Problems:** | Output decreases in proportion to the reciprocal of the square root of time after installation for a still not using plant materials, dropwise condensation on most plastic materials unless made wettable by scratching. |
| **Dates:** | Spring, 1965. |
| **Reference:** | Jackson and Van Bavel, 257. |

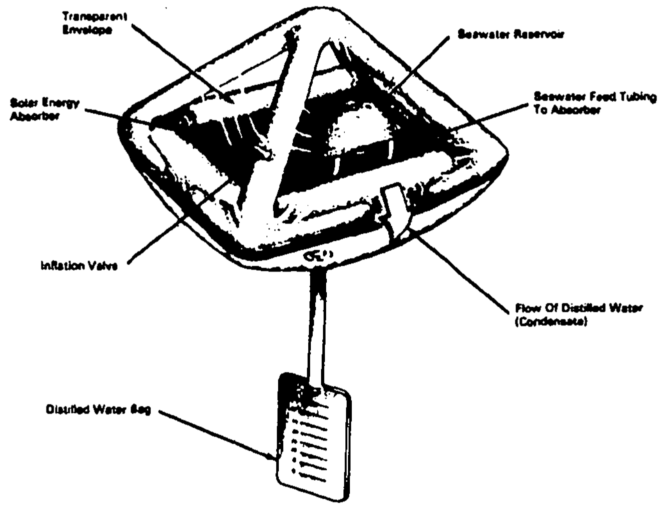



FIGURE 147. NASA EMERGENCY STILL (HOUSTON, TEXAS)

| | |
|---|---|
| **Internal size:** | Not reported. |
| **Brine depth:** | Thickness of wick material. |
| **Cover:** | PVC treated for wettability, pyramid shaped, supported by inflatable framework. |
| **Vapor seals:** | Edge-sealed seams. |
| **Distillate troughs:** | Bottom of still and distilled-water storage bag (weighted to remain submerged). |
| **Basin liner:** | Black-taffeta wick, horizontally supported by an integral air mattress. |
| **Walls and curbs:** | None required. (Unit towed from life raft, etc.). |
| **Other features:** | Still is collapsible and portable, weighs 1 lb and occupies 40 in.$^3$, inflated to float on sea or rest on land, originally developed for the Apollo program but not used, produced for NASA by Melpar, Inc. |
| **Productivity:** | About 2 pints/day. |
| **Problems:** | Designed for short lifetime. |
| **Dates:** | Around 1965. |
| **References:** | Anon., 26; NASA, 355; Smith, et al., 523. |

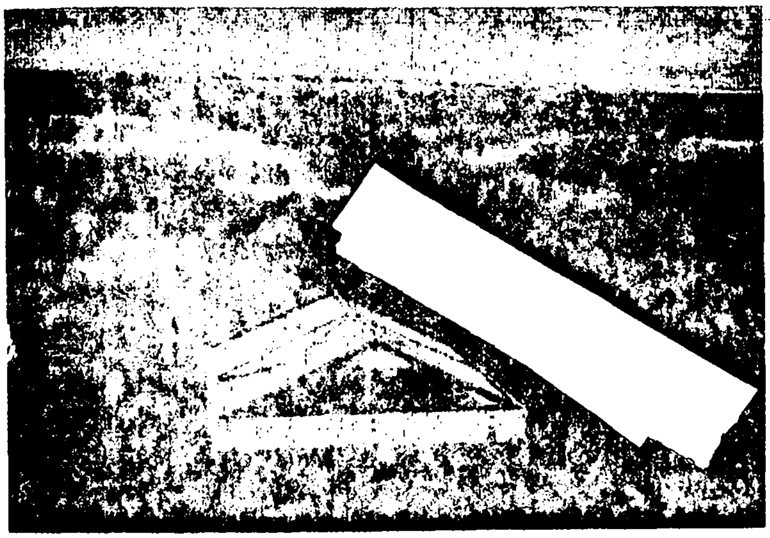


FIGURE 148. THE DELANQ FLOATING STILL (LUNN LAMINATES, INC., WYANDANCH, LONG ISLAND, NEW YORK)

| | |
|---|---|
| **Internal size:** | Approx. 10 ft x 10 ft; 100 $ft^2$. |
| **Brine depth:** | Floating wick on pond surface. |
| **Cover:** | Plastic film. |
| **Vapor seals:** | Not reported. |
| **Distillate troughs:** | Not reported. |
| **Basin liner:** | Wick floats on surface of water. |
| **Walls and curbs:** | Unit floats on water surface. |
| **Other features:** | Might be used on marshes, rice paddies, etc.; weighs 85 lbs, distilled-water tank submerged. |
| **Productivity:** | Approx. 10 gpd (approx. 0.10 gal/$ft^2$-day). |
| **Problems:** | None reported. |
| **Dates:** | Before 1967 (tested for several years). |
| **Reference:** | Cadwallader, 103. |

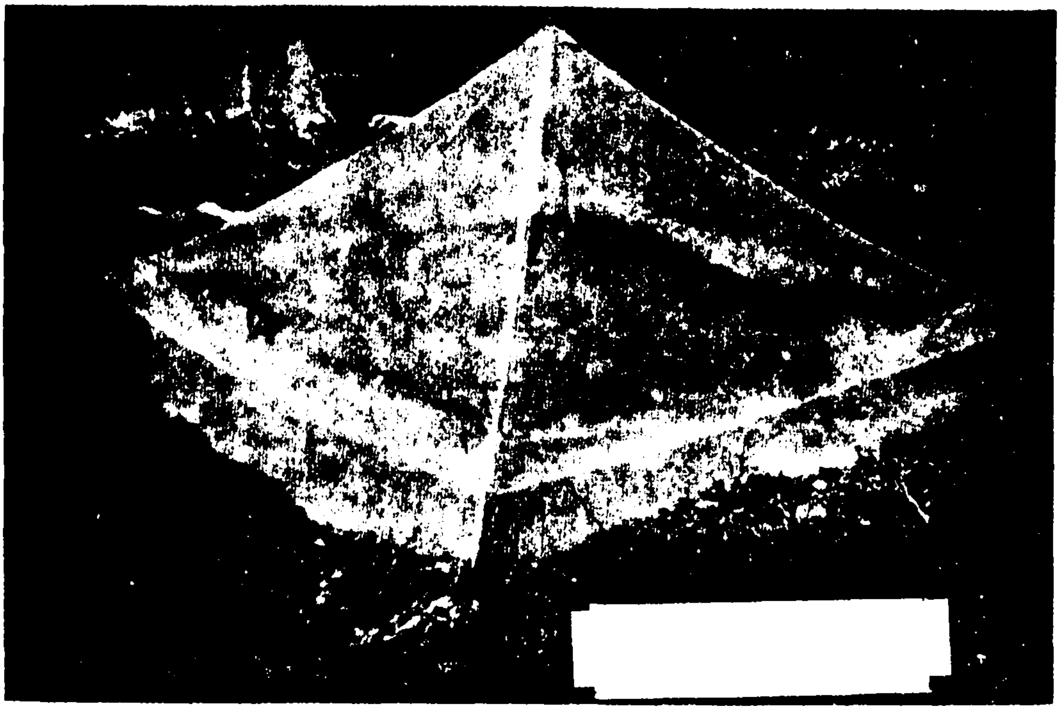


FIGURE 149. PLASTIC TENT STILL (AGENCY FOR INTERNATIONAL DEVELOPMENT)

| | |
|---|---|
| Internal size: | Not reported. |
| Brine depth: | No brine layer (collects ground moisture.). |
| Cover: | Plastic film, tent shaped. |
| Vapor seals: | Sealed seams, and soil covered around bottom edges. |
| Distillate troughs: | Plastic trough formed by a flap around the base of the cover. |
| Basin liner: | Surface of the soil. |
| Walls and curbs: | Anchored into soil. |
| Other features: | A ground-water or dew collector, available from a foreign manufacturer for $16 each, tested by some of the A. I. D. bureaus, emergency type of still. |
| Productivity: | Maximum of a few pints/day. |
| Problems: | Proper sealing of seams, distillate trough adhered to sides of cover, rodents would burrow into unit, only small amounts of water produced. |
| Dates: | Before 1967. |
| Reference: | Cadwallader, 103. |

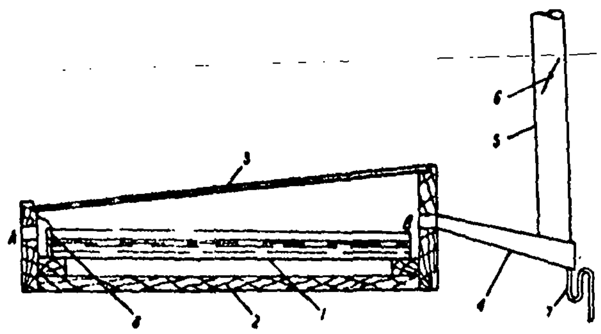


FIGURE 150. AIR-CIRCULATING, EXTERNAL-CONDENSING STILL (LENIN TASHKENT STATE UNIV., U.S.S.R.)

| | |
|---|---|
| Internal size: | Evaporating pan area 3.0 $ft^2$; condenser area 0.75 $ft^2$; chimney 2-in. diam. x 5 ft long. |
| Brine depth: | Approx. 3/4 in. |
| Cover: | Glass. |
| Vapor seals: | Unit not sealed (air circulation through still). |
| Distillate troughs: | None used (external condenser made of galvanized iron with internal fins). |
| Basin liner: | Metal pan (not painted black). |
| Walls and curbs: | Wooden box of 1-in.-thick boards. |
| Other features: | Incoming air passed through a wick of gauze, chimney painted black, condenser externally cooled by evaporation from wet gauze. |
| Productivity: | 0.05 gal/$ft^2$-day (June 7, 1962). |
| Problems: | Condensate also formed on glass cover (an output 1.5 times greater than simple solar still predicted if condensate from glass cover were also collected). |
| Dates: | Approx. June, 1962. |
| Reference: | Sharafi, 410. |

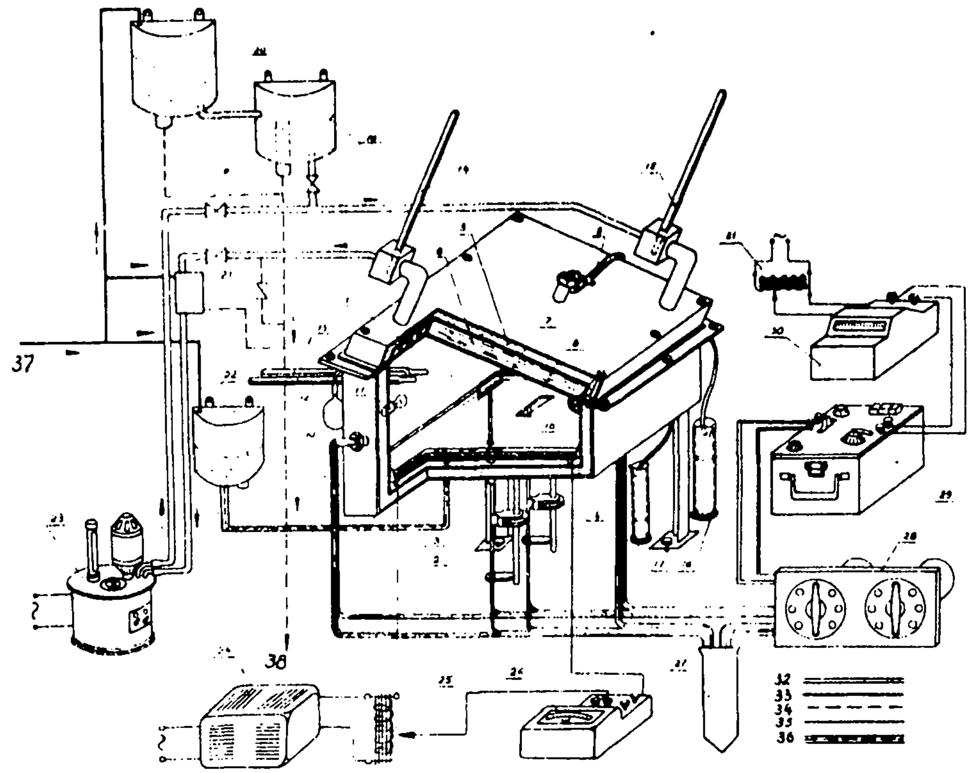
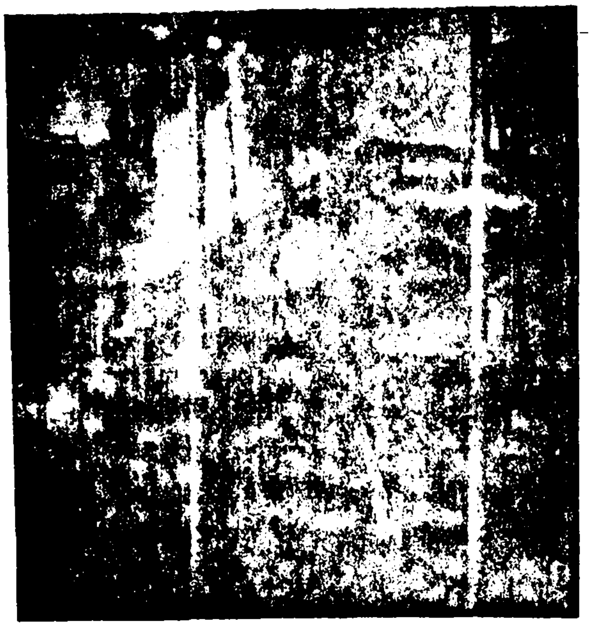
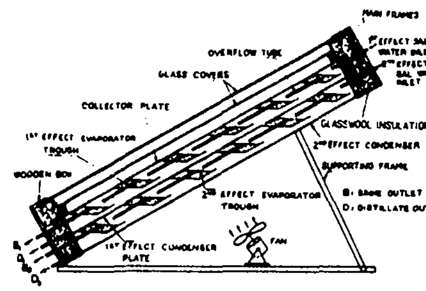



FIGURE 151. LABORATORY STILL AT KRZHIZHANOVSKY POWER INST. (MOSCOW, U.S.S.R.)

| | |
|---|---|
| Internal size: | Approx. 1 ft x 1 ft x 6 in. high. |
| Brine depth: | Shallow layer, heated electrically. |
| Cover: | Sloped brass (water-cooled heat exchanger). |
| Vapor seals: | Not reported. |
| Distillate troughs: | Not reported. |
| Basin liner: | Insulation and electric heater under water pan. |
| Walls and curbs: | Metal box, insulated. |
| Other features: | Condensate collected from top surface and side walls, water temperature varied from 74 to 207 F and condensing temperature from 61 to 192 F, interferometer studies of convection patterns, empirical equations derived for evaporation and condensation heat transfer coefficients (see Section 4, subheading Heat Transfer). |
| Productivity: | Not reported (designed for study of internal-convection coefficients). |
| Problems: | None reported. |
| Dates: | During 1963. |
| Reference: | Baum, 62. |



a. Indoor Test Set-Up




b. Outdoor Test Set-Up

FIGURE 152. TILTED MULTIPLE-EFFECT STILL (BRACE EXPERIMENT STATION, ST. JAMES, BARBADOS)

| | |
|---|---|
| Internal size: | Approx. 40 x 40 in.; 10.2-$ft^2$ absorber area. |
| Brine depth: | Approx. 0.75-in. in evaporator troughs. |
| Cover: | Two layers of glass, 31.5-degree tilt. |
| Vapor seals: | Not reported. |
| Distillate troughs: | Lower corners of assembly. |
| Basin liner: | Cascaded evaporator troughs made of steel and welded to steel plates, back faces of troughs insulated with a plastic-sponge mat. |
| Walls and curbs: | Channel-iron framework, wooden external box. |
| Other features: | Also operated indoors with electric heating, fan sometimes used on condenser side, absorber surface blackened, ends and sides insulated. |
| Productivity: | Outdoor tests with 2-effect unit, 0.083 gal/$ft^2$-day at 1,800 Btu/$ft^2$-day with natural convection, 0.103 gal/$ft^2$-day at 1,850 Btu/$ft^2$-day with fan cooling. |
| Problems: | Relatively high cost and weight. |
| Dates: | Early 1963. |
| Note: | This design similar to U. S. Patent 3,167,488 by J. M. Malek (January 26, 1965), filed August 4, 1960. |
| Reference: | Selcuk, 408. |

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