SOLAR ENERGY PROGRESS-

Solar energy technology has made great strides in the past decade: Long-range space-craft are using increasingly large arrays of solar batteries; new solar still designs are moving in the direction of lightweight packaged units; in places like Australia, solar water heaters are on the increase; research continues in the area of solar air-conditioning both here and abroad; and, since larger and larger power sources are becoming necessary for the space program, interest is again turning to large solar concentrators.

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THERE are two fundamental values on which most solar radiation calculations are based: (1) the average earth-sun distance, known as the "astronomical unit," and (2) the "solar constant," which is the unit intensity of solar radiation on a surface normal to the sun's rays, outside the earth's atmosphere, at the mean earth-sun distance. The most recent determination of the astronomical unit, made by J. H. Lieske of the Yale University Observatory, gave a value of 92,957,200 ± 50 miles [1].[1] Previously quoted values were 92.6×10^6 miles [2] and 92,976,200 ± 250 miles [3]; the Encyclopaedia Brittanica gives 93×10^6 miles. The differences are small but by no means insignificant in space work.

The latest and probably the most accurate determinations of the solar constant were made during 1966 and 1967 by a series of pyrheliometer measurements from aircraft flying nearly 10 miles above the earth. As reported by Drummond and Hickey [4], the most probable value of the solar constant is 136.1 mw/sq cm, which is equivalent to 1.946 langleys per min or 430.5 *Btu*.[2] The value which has been in wide use during the past several decades had been 442 *Btu* (2.00 ly/min or 140.3 mw/sq cm) derived by Johnson [5] from a compilation of data taken from a number of sources, including rocket-borne spectrographs which reached elevations of 38 miles. The Eppley-JPL value agrees closely with Dr. Abbot's best Smithsonian estimate [6], 1.940 ly/min or 429.3 *Btu*, and it is likely to remain unchallenged until an astronaut standing on the moon has an opportunity to make an unhurried measurement with a high-precision solar radiometer.

The spectral distribution of the sun's radiant energy in outer space is as important to satellite designers as is the exact value of the solar constant. Until that moon-based astronaut has an opportunity to make direct spectrographic measurements, the curve derived by Johnson in 1954 [5] stands as the most reliable estimate of the solar spectrum. On the surface of the earth the curves devised by Parry Moon in 1940 [7] have been the engineering standard. Moon based his work on the Smithsonian solar constant, and it now seems that he was very close to the best attainable value. More recently, Gates [8] has made new estimates of the spectral distribution for air masses from 1.0 to 10.0, and his results are given in terms of both wavelength and wave number, the reciprocal of wavelength. He has also considered various concentrations of aerosols and water vapor, basing his calculations on the Johnson solar constant.

A useful set of probable solar radiation intensity data for clear days is to be found in the 1967 ASHRAE Handbook of Fundamentals [9]. These values were obtained by a computer program set up by D. G. Stephenson [10] of the Division of Building Research, National Research Council of Canada, using direct solar radiation data compiled by Threlkeld and Jordan [11] and an empirical formula developed by Threlkeld [12] for the diffuse radiation. The ASHRAE tables cover latitudes from 24 to 56 deg north by 8-deg increments. Similar data are given by Stephenson [13] by 2-deg increments for latitudes from 43 to 55 deg north. These tables give the solar altitude and azimuth (measured from the south) at hourly intervals, in addition to the intensity of the direct solar beam for the 21st day of each month. Data are also given for "solar heat gain factors" [9] which can readily be converted into the

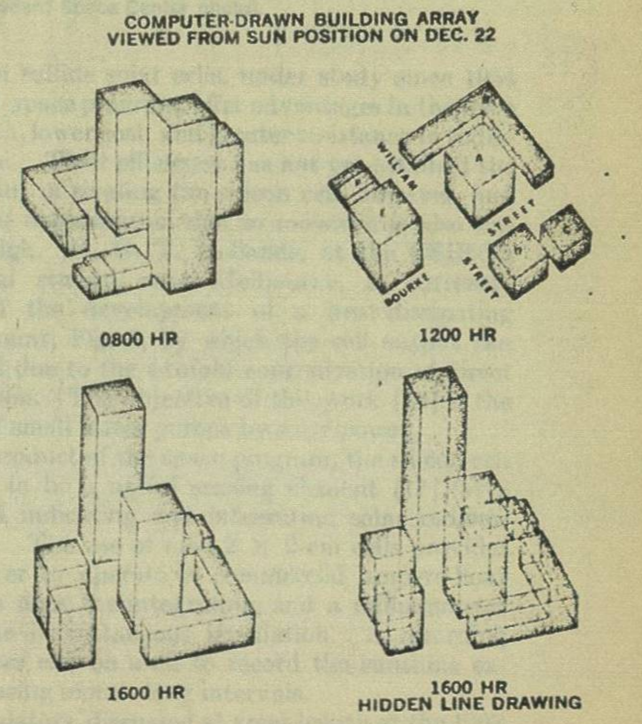

Fig. 1 Isometric views of Australian building complex as seen by the sun at 0800, 1200, and 1600 hr local solar time (CSIRO photo).

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[1] Numbers in brackets designate References at end of article.
[2] *Btu* = Btu/hr/sq ft.

A WORLD PICTURE

intensity of the total radiation incident upon horizontal surfaces and on vertical surfaces facing in each of the eight principal directions. Equations are also given by which the intensity of the radiation falling on tilted surfaces can be estimated.

The Australians have made great strides during the past decade in many aspects of solar energy technology, due in part to the fact that an economic incentive exists because of the lack of natural gas in that continent and in part to the fact that a team of ingenious and dedicated engineers has been set up under the leadership of Roger Morse in the Mechanical Engineering Division of the Commonwealth Scientific and Industrial Research Organization at Melbourne. Among their achievements is the development of a computer program (appropriately designated SHADE) by which isometric projections of building arrays can be drawn as they would be viewed from the sun's position. Fig. 1 shows a building complex now under construction in Melbourne as the sun would see it at 0800, 1200, and 1600 hr.

Solar Batteries

The silicon cell, now some 15 years of age, has proven to be a superbly reliable means for the direct conversion of solar radiation into electricity. Invented in 1954 by the team of Bell Laboratories scientists who also invented the transistor, the silicon cell has now been developed to the point where all of the permanent satellites and most of the long-range spacecraft launched by Russia and the U. S. during the first decade of the space age have used increasing large arrays of solar batteries. Originally used in the P-on-N version (the positive surface faced the sun), the first generation of solar cells was found to be susceptible to rapid deterioration from destructive solar radiation. Research conducted both in Russia and the U. S. showed that reversing the cell, thus placing the negative element in the sun-facing position, produced greatly superior radiation resistance. All of the cells being produced today are N-on-P type, although large numbers of P-on-N cells are still available from space-surplus dealers.

The current status of photovoltaic power technology was described in detail by Smith [14], who pointed out that high-quality cells (10–12 percent initial conversion efficiency) are now being manufactured in large numbers by three suppliers in the U. S. Cherry and Statler [15], in their paper on radiation resistance, list three more U. S. manufacturers and three in Europe.

Most of today's cells are 2 × 2 cm in area, with a thickness as low as 0.004 in. In full sunlight (using the Johnson solar constant of 140 mw/sq cm), a typical 2 × 2-cm cell will give a short circuit current of about 125 ma, an open-circuit voltage of 0.50 v (at 60 C), and a maximum power of some 42 mw. Deterioration due to electron bombardment is a serious problem for cells which are to be used on spacecraft which are traveling toward the sun.

The generation of significant amounts of power requires series-parallel connections of extremely large numbers of individual cells, with as many as 350,000 individual cells for the Saturn I workshop, and twice this number for future space stations. A major effort is now being made to produce larger individual cells, thus reducing the number of connections which must be made and improving efficiency by reducing the area occupied by those connections. Important reductions in assembly costs can also be accomplished. Fig. 2 shows an experimental array of 2 × 8-cm cells which will reduce by a factor of four the number of junctions which must be made, as compared with the conventional 2 × 2-cm cell which is currently in use.

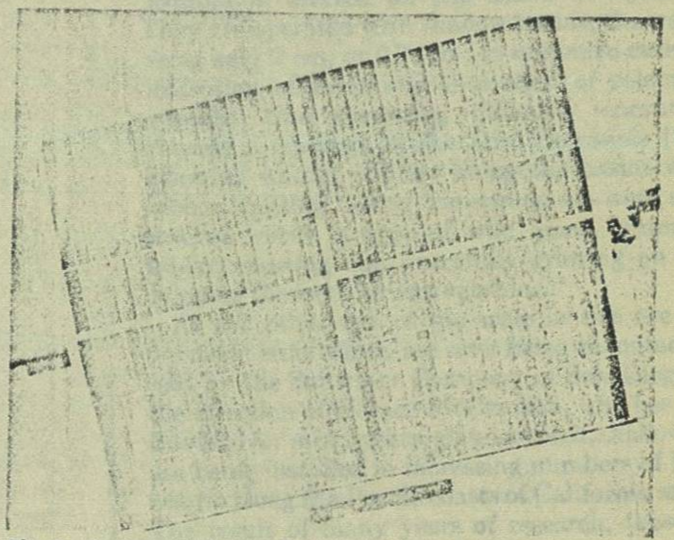

Fig. 2 Experimental solar "paddle," covered with 2 x 8-cm silicon cells (Goddard Space Center photo).

Cadmium sulfide solar cells, under study since 1954 for the U. S. space program, offer advantages in the form of larger area, lower cost, and greater resistance to radiation damage. Their efficiency has not yet attained the halfway point in rivaling the silicon cell, however, and their rate of deterioration due to moisture is also undesirably high. K. G. T. Hollands, at the CSIRO's experimental station near Melbourne, is currently working on the development of a heat-dissipating reflector mount, Fig. 3, by which the cell output can be increased due to the twofold concentration of direct solar radiation. The objective of this work [16] is the operation of small water pumps by solar power.

As a by-product of the space program, the silicon cell has proven to be a useful sensing element [17] for a self-powered indicating and integrating solar radiometer, Fig. 4. The use of nine 2 × 2-cm cells provides enough power to operate a commercial ampere-hour meter which does the integrating, and a milliammeter indicates the instantaneous irradiation. A recording millivoltmeter can be used to record the sunshine experienced during month-long intervals.

Solar simulators, discussed at great length at the 1962 ASME Annual Meeting, have now come of age with the

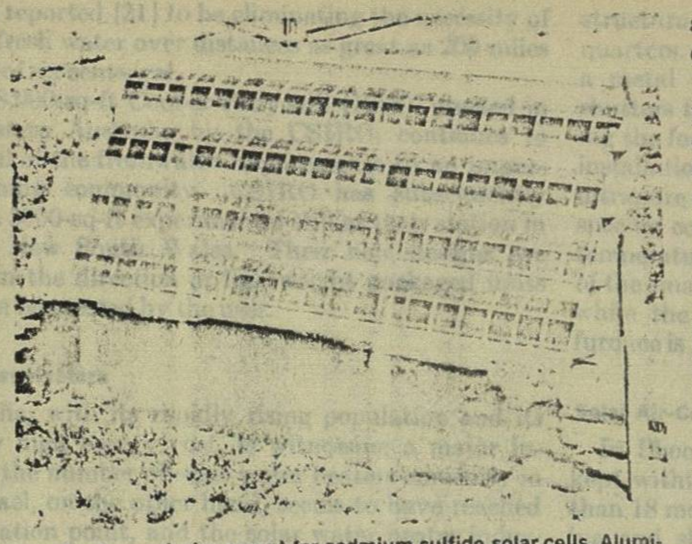

Fig. 3 Concentrator mount for cadmium sulfide solar cells. Aluminum wings double cell irradiation and help to dissipate heat (CSIRO photo).

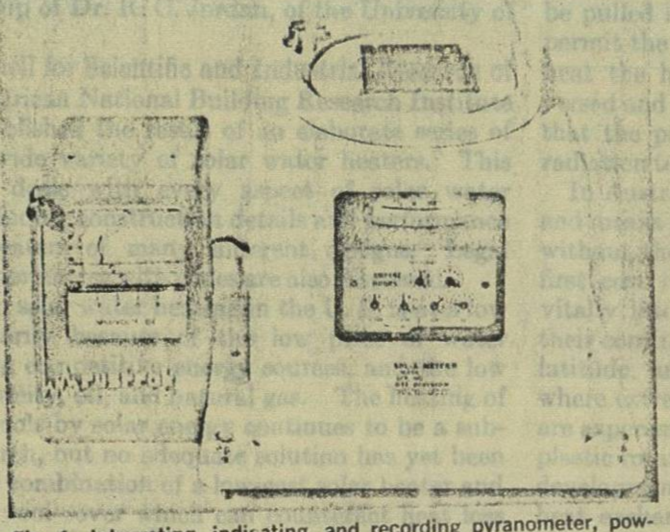

Fig. 4 Integrating, indicating, and recording pyranometer, powered by nine 2 x 2-cm silicon solar cells (Talley Industries photo).

construction of a gigantic vacuum chamber in which a full-scale space vehicle can be uniformly irradiated with simulated solar radiation from a battery of filtered xenon lamps. More compact versions of the same concept are available for terrestrial testing of solar cells and other components of space power systems.

Solar Stills

The production of potable water from salt or brackish supplies is the oldest application of solar energy to a technological process. In fact, the world's first solar still, and for nearly a century its largest, was built in Chile in 1872. Its area was 51,000 sq ft and this size was not exceeded until the 93,500-sq-ft, glass-covered seawater still was erected on the Greek island of Patmos in 1967. The design parameters of solar stills have been studied with great care by investigators in Australia, Greece, Israel, Russia, and the U. S. Battelle Memorial Institute [18] is currently preparing a detailed report for the U. S. Office of Saline Water covering all aspects of the design of solar stills. The report is expected to be made available this year.

The details of the Patmos installation have been reported by A. and E. Delyannis [19], who have pointed out in an earlier publication [20] that glass is to be preferred over plastic films as the covering material of large solar stills. Among the reasons given are the lower total cost of glass as compared with wettable fluorocarbon films, the greater resistance of glass to damage by wind and storm, its freedom from vapor permeation, pinhole leaks, and the electrostatic properties of plastic films which cause dust to adhere tightly, requiring frequent washing with precious distillate.

The total cost of the Patmos still is reported as $1.49 per sq ft of distillation area and its average output is nearly 7000 gal of fresh water per day. The 21,700-sq-ft still erected in 1969 on Nissyros cost $2.11 per sq ft. The Greek stills now embody the results of the experience gained from their first large still, the 28,600-sq-ft installation erected on the island of Symi in 1964. They are operated with shallow basins, the water depth being only 2 cm, or 0.78 in., to minimize excessive concentration of brine and formation of calcium sulfide crystals. One surprising difficulty encountered at Patmos is reported by the Drs. Delyannis [19] in the following words: "After lining the basins with butyl rubber sheeting during the spring, we were amazed to observe weeds, a type of wild grass, perforating the rubber sheeting and peacefully growing on top of it, enjoying the fresh air and sunshine."

At the other end of the scale in size are the small domestic stills which are now being manufactured and sold by the Sunwater Company of San Diego. Under the direction of Horace McCracken, who has labored in this field for many years, glass-covered, shallow-pan stills are being installed in increasing numbers of homes and resorts along the Pacific coasts of California and Mexico. The result of many years of research, these stills are provided with automatic water-feeding devices, Fig. 5, which will keep them supplied with the proper amount of seawater. With outputs from 2 to 200 gal/day, these

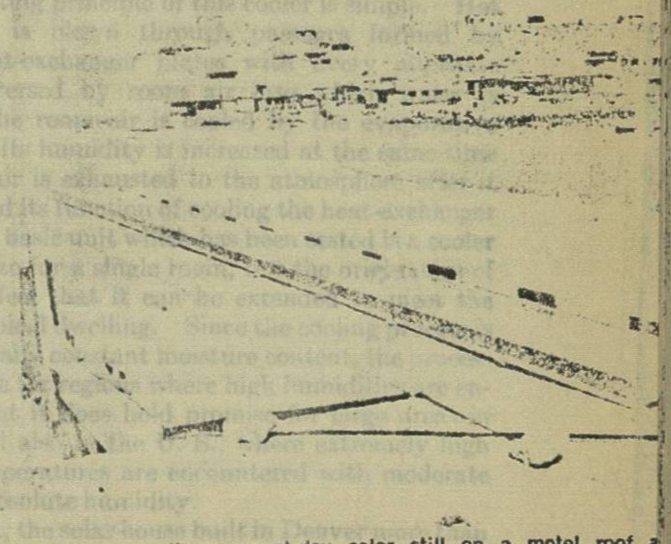

Fig. 5 Ten-gallon present-day solar still on a motel roof at Puertecitos, Baja California, Mexico. Prior to this installation, all fresh water used here had to be hauled 200 miles by land, sea or air (SEAWATER photo).

stills are reported [21] to be eliminating the necessity of hauling fresh water over distances as great as 200 miles at a cost of six cents/gal.

The 38,000-sq-ft Coober Pedy still (1966), erected in northwestern Australia by the CSIRO, continues to supply all of the freshwater requirements to an important mining community. CSIRO has subsequently erected a 5000-sq-ft experimental still at their station in Griffith New South Wales. Their new designs are moving in the direction of lightweight packaged units which can be erected by the user.

Solar Water Heaters

Australia, with its rapidly rising population and its relatively high energy cost, is witnessing a major increase in the number of solar water heaters currently in use. Israel, on the other hand, seems to have reached the saturation point, and the solar water heater industry there is on the decline. Several definitive publications have appeared in recent years on the technology of heating domestic water supplies by solar radiation. The first of these [22] was prepared by the ASHRAE Technical Committee on Solar Energy Utilization under the leadership of Dr. R. C. Jordan, of the University of Minnesota.

The Council for Scientific and Industrial Research of the South African National Building Research Institute [23] has published the result of an elaborate series of tests of a wide variety of solar water heaters. This publication deals with every aspect of solar water heating, including construction details and performance of water heaters of many different designs. Legal details for compliance with codes are also discussed.

Interest in solar water heating in the U. S. is at a low point, primarily because of the low price of water heaters using competitive energy sources, and the low cost of electricity, oil, and natural gas. The heating of swimming pools by solar energy continues to be a subject of research, but no adequate solution has yet been found to the combination of a low-cost solar heater and an effective pool cover which can counteract heat loss by evaporation and radiation to the sky.

Solar Furnaces

The first scientific use of a solar furnace is reportedly that of Lavoisier in Paris in 1774, who used "a glass lens as tall as a man for carrying out chemical studies at high temperatures." Nearly two centuries later, the first large solar furnace of modern times was erected under the direction of Dr. Felix Trombe at Montlouis in the Western Pyrenees. This furnace used a heliostat 30 ft square to reflect the sun's rays onto a concentrator made of 3500 individual plane glass mirrors which were mechanically deformed to create a paraboloid. The successful operation of this furnace has led to the construction of a vastly larger unit on a mountainside between the adjacent villages of Font Romeu and Odeillo. This location is reported [24] to be the sunniest place in France, averaging 250 clear days per yr.

Sixty-three heliostats are used, each containing 180 plane mirrors, 50 cm square, giving a total of 2835 sq m of reflecting surface. The concentrator consists of 9000 small plane mirrors, arranged to form a paraboloidal surface of 2500 sq m. It is supported by a 10-story structure which also houses the laboratory headquarters. The focal area of the furnace is contained in a metal enclosure which is fitted with stainless-steel shutters to control the amount of solar radiation reaching the focal zone. The principal objectives of the new installation are reported to be [25] production of large, ultrapure crystals by zone melting, preparation of highly specific compounds, and production of extremely high temperature refractory materials. The thermal power of the smaller French furnace is 50 equivalent kilowatts, while the rated power of the new and much larger furnace is 1000 equivalent kilowatts.

Solar Air-Conditioning

In Phoenix, Arizona, a prototype building has been kept within the comfort zone during a period of more than 18 months by the operation of a unique solar heating and sky-cooling system (ME, January 1970, pp. 19–25). The structure uses shallow ponds of water which are in thermal contact with the metal ceiling of the room to provide both thermal storage and temperature modulation. Horizontal plastic panels above the ponds constitute the roof of the building, and these can be pulled away from the ponds during winter days to permit the rays of the sun to warm the ponds and thus heat the house. In the summer the situation is reversed and the insulating panels are removed at night so that the ponds can be cooled by evaporation and by radiation to the sky [26].

In Australia much effort has been expended on ways and means to produce cooling by other natural processes without the use of refrigeration, which is expensive in first cost and in running cost. The Australians are vitally interested in natural air-conditioning, because their continent lies mainly between 10 and 35 deg south latitude, and it is characterized by vast desert areas where extremely high temperatures and low humidities are experienced. Experiments with rock piles and with plastic rotary regenerators are reported [27], and a new development of a unit air cooler, employing a plastic heat exchanger with evaporatively cooled plates, was reported recently.

The operating principle of this cooler is simple. Hot outdoor air is blown through passages formed by dimpled heat-exchanger plates with every alternate passage traversed by room air into which water is sprayed. The room air is cooled by the evaporative process, but its humidity is increased at the same time and so this air is exhausted to the atmosphere after it has performed its function of cooling the heat-exchanger plates. The basic unit which has been tested is a cooler suitable in size for a single room, but the originators of this system feel that it can be extended to meet the needs of a typical dwelling. Since the cooling process is one of essentially constant moisture content, the process is not suitable for regions where high humidities are encountered, but it does hold promise for large areas in Australia and also in the U. S., where extremely high dry-bulb temperatures are encountered with moderate or even low absolute humidity.

In the U. S., the solar house built in Denver more than a decade ago by Dr. George Löf continues to operate satisfactorily, with most of its winter heat requirements being supplied by the sun. Similar results are reported