

SMITHSONIAN MISCELLANEOUS COLLECTIONS

VOLUME 98, NUMBER 5

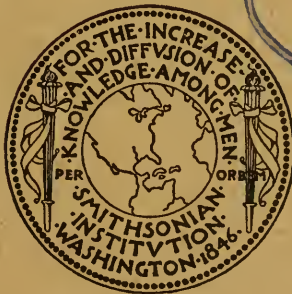
UTILIZING HEAT FROM THE SUN

(WITH FOUR PLATES)

BY

C. G. ABBOT

Secretary, Smithsonian Institution



(PUBLICATION 3530)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
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The Lord Baltimore Press
BALTIMORE, MD., U. S. A.

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In large regions lying in the low latitudes desert conditions prevail. Day after day the sun glares down, occasionally dimmed a little by cirrus clouds, or perhaps by a few heaping cumuli. In such regions 80 percent or even more of the hours of daylight would be useful for furnishing solar heating.

QUANTITY OF SOLAR ENERGY

The quantity of energy available from solar radiation under such conditions as I have pictured is immense. As I shall show in what follows, we may count on the possibility of converting 15 percent of the energy of such solar rays as are intercepted by our devices into mechanical work. Assuming that to avoid appreciable losses through shading one unit by another, and to allow plenty of room for other purposes, only one-tenth of the area available is actually covered by heat collectors, and further allowing for night and cloudy weather, still the State of New Mexico could supply from solar radiation over ten trillion horsepower-hours per year of mechanical power, which compares with the power possibilities of all coal, oil, and water at present used annually for heat, light, and power combined in the United States.

INTERMITTENCE AND STORAGE OF SOLAR POWER

Like hydroelectric power, solar power demands no continuing expense other than for care and interest on the investment. Unfortunately, however, solar power is subject to the drawback that it ceases during night hours, and when the beam is intercepted by clouds. There are certain uses, such as pumping water for irrigation for instance, where this intermittence is no serious objection. But for most purposes power must be available at all times. Hence to become a great industrial factor solar power demands the association of storage of energy, either as heat, or in chemical, electrical, or

mechanical forms. As efficient production of solar power must nevertheless be the first step, I shall postpone considerations of storage for the present.

WATER DISTILLING AND COOKING BY SOLAR HEATING

There are other uses for solar heating which do not so much involve storage. Among them are the distillation of water and the cooking of food. It is stated that in Bermuda the past year was so deficient in rainfall that fresh water was imported from New York, although the Atlantic ocean is all around. In some of our western States the water in many parts is too alkaline for drinking or for storage batteries. In Florida the water in some localities stinks with hydrogen sulphide. Under such conditions as these the solar distilling device should be useful. As for cooking, though not practical in cloudy regions, it is easy to provide heat storage for 24 hours, and with a solar cooking device the ovens may be kept at baking temperatures for weeks and months continuously in the more cloudless parts of our country.

RECENT COMMERCIAL PRODUCTS A BOON TO SOLAR DEVICES

The cheap production of efficient solar heat devices has awaited the commercial development of aluminum products, now so plentifully used in the industries, and the common use of vacuum devices, which came with the incandescent lamp and radio industries. Formerly, inventors relied on glass mirrors which were heavy, costly, and not durable. It is now possible to purchase the so-called "Alcoa" in thin sheets, which readily take the curvature of a suitable cradle form without previous shaping. This material reflects over 80 percent of solar radiation, and may be used for years without dimming. As the loss of heat in the boiler at the focus of a solar-radiation appliance is the great obstacle to be provided against, the possibility of making cheap glass jackets enclosing high vacua like thermos bottles is the other great improvement which has become practicable in recent times.

MECHANISM FOR FOLLOWING THE SUN

The daily march of the sun through the sky, and its yearly march from north to south, must be considered. If one uses a spherical boiler and a circular mirror, he must allow for both of these apparent motions as Eneas did at the ostrich farm, Pasadena, about 1905. If, however, one uses a tubular boiler parallel to the axis of the earth,

the yearly adjustment is unnecessary and the daily motion can be allowed for by merely rotating the parabolic cylindrical ray-concentrating mirror about an axis coincident with that of the boiler tube at the rate of 15° per hour. In this arrangement the boiler tube may be firmly fixed. This, with the simplicity of the mechanical driving of the mirror, renders this arrangement preferable to all others for most purposes. The mirror may be driven by clockwork, or, if electric facilities are available, still better by a 60-cycle synchronous motor through a worm and wheel.

I have used both types of driving. Our solar cooker on Mount Wilson, having been built long ago, is cumbersome. It has a heavy mirror, 8 feet wide by 12 feet long. I attached to the mirror a grooved wheel 30 inches in diameter coaxial with the lower trunnion of the mirror. A steel wire in the groove of the wheel supported a weight of about 200 pounds, sufficient to rotate the mirror toward the west. Through a second steel wire wound in the groove in the opposite sense, the weight also drove a clockwork. This clockwork train ended in a flyvane. A long hand rotated with the central shaft and once in each revolution was stopped by a displaceable pin. The long hand would make a full rotation in about 3 minutes. A common alarm clock was provided with a wheel of 12 pins on the back of its hour shaft, and these pins, acting through a lever escapement displaced the stop-pin once each 5 minutes. Hence the mirror moved intermittently as governed by the alarm clock, and was never more than 1 minute from its proper position to focus sun rays upon the heater tube. Still simpler clockwork contrivances may be used to drive smaller mirrors for solar heating devices.

DOMESTIC WATER HEATERS

Those who have visited Florida or southern California may know of the roof water heaters which are used considerably for providing hot water for bath and other household purposes. A shallow depression is let into the south roof exposure, and lined with blackened sheet metal. Therein is supported a blackened grid of pipes like a steam radiator. The boxlike depression is covered tightly with glass windows. Water circulates through the piping, and thence to a reservoir at a higher level within the house. Such a system acts by gravity like the water heater system of a cook stove. If the reservoir is well insulated from heat losses and the location is relatively cloudless and never freezing, such a system is found to be very useful for furnishing hot water both day and night, without maintenance

cost or attention. While on Mount Wilson, several years ago, I bought 200 feet of black garden hose. I coiled 150 feet of it in a flat coil upon a wooden X, and carried it up the ladder to the south side of the cottage roof. The other 50 feet I connected to the water hydrant in the yard and to a spigot in the bathtub. By this simple arrangement we could draw 5 gallons of very hot water each half hour on every sunny day.

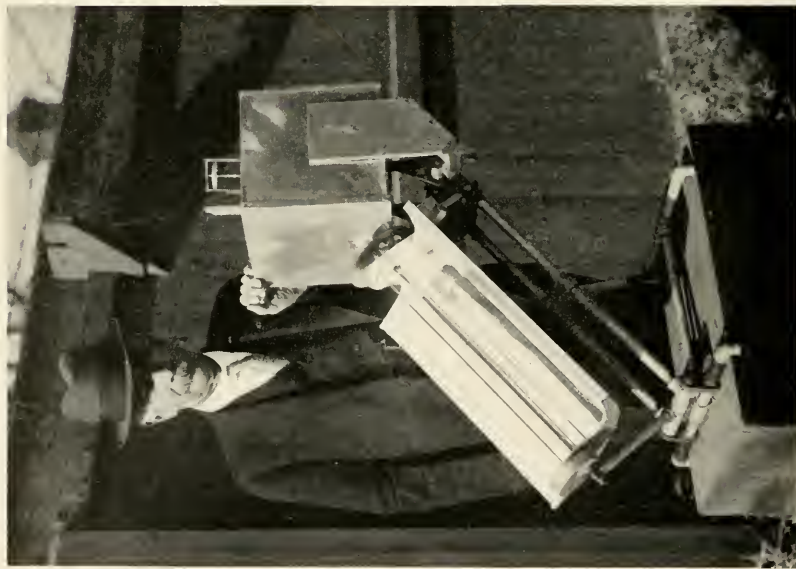
SOLAR COOKERS

When we attempt cooking by sun heating we require temperatures far above the boiling point of water. Hence some other liquid of a much higher boiling point is desirable as a heat conveyor, otherwise high pressures and evaporation would be met with. In our cooker on Mount Wilson I used engine cylinder oil within a blackened metal tube in the focus of the mirror. About 60 gallons of this oil were employed in the system, so that there was a large capacity for heat, and cooking could be done by night as well as by day. However, it required about 2 days of sun to get the system heated initially, for owing to nearby trees there were only 7 hours per day of sunshine. In recent installations I have preferred to use "Arochlor," a nearly black liquid product of the Monsanto Chemical Company. I have made this liquid almost completely absorptive of sun-rays by adding a small amount of lampblack in suspension therein. While engine cylinder oil chars somewhat, and evaporates considerably at 210° C., "Arochlor" does not boil below 350° C., and evaporates scarcely any at lower temperatures. This liquid, being highly absorptive, may be used directly in the vacuum-jacketed glass focus tube. Circulation may be provided by bringing back from the oven sheath a small metal or glass tube within the focus tube to near its lower end. Such a focus tube passes freely through the hollow trunnion at the upper end of the mirror, and is sealed by a well-designed stuffing box to the metal sheath which encloses the oven. According as one wishes for a quickly heating oven, or on the other hand for one to remain hot through temporary cloudiness and the night hours, the oven sheath contains little or much of the liquid. This part of the system may be surrounded by a thick layer of glass wool for insulation, leaving, of course, means for reaching the oven door.

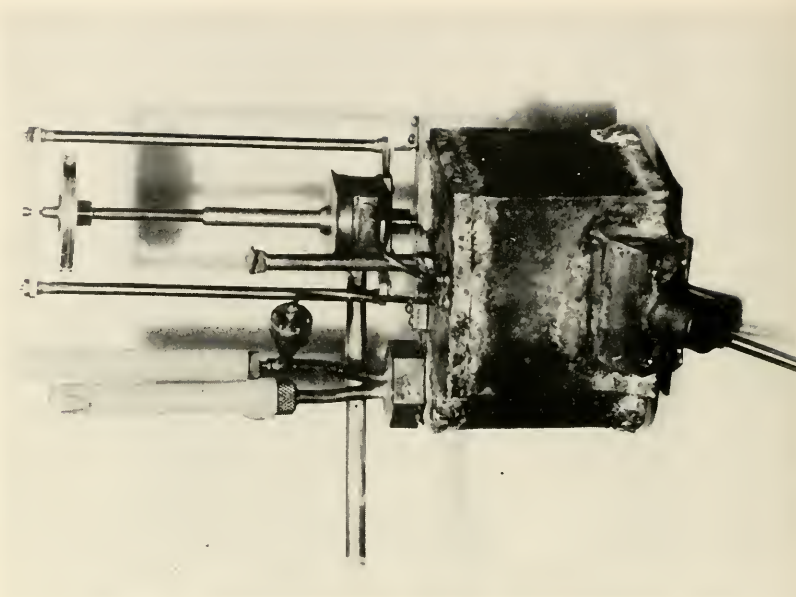
In another embodiment of the cooking device, I have sealed the glass vacuum-jacketed focus tube to a vertical cylindrical glass jar to contain the liquid. Within the liquid is an inner glass jar used as the oven. The oven is approached from above with food to be cooked.



SOLAR COOKER. MOUNT WILSON, CALIF.



1. TOY SOLAR COOKER



2. OVEN AND ENGINE OF TOY SOLAR COOKER

In this embodiment the outer of these two glass cylinders may be itself surrounded by evacuated space. This makes a very beautiful and highly efficient, quickly heated oven of small capacity. For a large installation it is better not to use the liquid directly as the absorbing medium, but to contain it in a blackened copper tube, itself surrounded by a vacuum jacket of glass. This arrangement lends itself to a more robust connection of the heater tube to the oven jacket. Liquid may then be supplied to give a large capacity for heat and to heat a plurality of ovens.

To fix approximately our ideas of the size of an outfit for solar cooking, I give the following figures. In clear sky conditions one may depend on from 1.2 to 1.4 calories per square centimeter per minute of energy in the solar beam. Using the lower of these figures we have still to encounter the following losses. Mirror reflection 82 percent, vacuum jacket transmission, if direct to liquid, about 89 percent, if through a blackened metal tube to liquid about 80 percent. Hence there remains about 0.79 to 0.87 calory per square centimeter per minute. The maximum temperature which a mirror will maintain in an oven depends on the rate of loss of heat. The time required to approach that temperature depends on the capacity of the oven and its surroundings for heat. These variables I cannot, of course, predict without specifications. But it may safely be said that, with good design, a mirror of 4×8 feet surface will keep two ovens of ordinary size hot enough to bake biscuits well, by night as well as by day, in any fairly cloudless regions in the temperate zones.

TOY SOLAR COOKER

I have constructed a toy cooker with a mirror surface of 15×20 inches to warm an oven $3\frac{1}{4}$ inches square, $2\frac{1}{2}$ inches high, and insulated by 3 inches in thickness of glass wool. It requires about an hour to heat the oven to about 130° C. above surrounding temperatures, and the oven bakes cakes 3 inches square very nicely in a half hour.

SOLAR WATER DISTILLING

Distillation of water may be very efficiently done with solar heating. The arrangement of the mirror is similar to that just described for cooking purposes. In this case, however, the elongated vacuum jacket, like a thermos tube except that it is not silvered within, is supported in the focus of the mirror with its open end at the bottom, and its closed end extending a foot or more above the top of the mirror, which rotates on rollers bearing the hollow trunnions of the

mirror. In the case of the cooker, and also of the power flash boiler, soon to be described, the absorber of rays is made as small in diameter as possible in order to reduce heat losses, so that the temperature may run high. In the solar water distiller, however, the temperature cannot exceed the boiling point of water. With a vacuum jacket surrounding the focus tube, heat losses at that temperature are small per unit area. Hence the focus tube is made much larger in diameter in order to provide freer escape for steam. This requires a larger vacuum jacket than in the devices for cooking and for power.

I pour the water to be distilled into a vessel supported behind the mirror and nearly at the level of the upper end of the mirror. A long snout runs from the bottom of the water vessel down behind and parallel to the mirror, and, bending at right angles, comes up to join the focus tube of copper, which is blackened outside to absorb solar rays. Thus the water flows by gravity from the vessel to an equal height within the focus tube. Within this snout and focus tube is a smaller tube for steam. It extends from above the level of the water in the vessel to above the level of the mirror in the focus tube. It is open to the atmosphere above the vessel, and open to steam above the water in the focus tube. A branch leaves the steam tube at its lowest point, and passes sealed through the wall of the snout, so that distilled water may drop from the steam tube into a receptacle underneath.

Only one difficulty is met with in this device. The steam must be caused to escape by such a protected orifice that the surging, boiling water within the focus tube does not ever reach that orifice to mingle with the condensed steam. This is accomplished by a series of umbrella diaphragms along the upper part of the steam tube, and by using a diminished orifice, well shielded by a cap.

The efficiency of the device is very high. The steam being condensed by flowing through the entering water, that water reaches the lower end of the boiler tube at almost boiling temperature. Thus it is only the latent heat of steam that must be provided by solar radiation, and not the heat required to raise water to boiling. In experiments made in Florida in March 1938, the stinking water of Arcadia was distilled to perfect purity and odorlessness. Distillation commenced within 5 minutes after the sun came out of a cloud. A mirror of 11 square feet of surface distilled between 2 and 3 gallons of water, entirely automatically in one cloudless day.

THE SOLAR FLASH BOILER FOR POWER

Since cumulus clouds are apt to obscure the sun occasionally in regions suited to solar power production, the flash boiler, rather than the boiler of large heat capacity, is indicated. For if it takes an hour or more to raise the desired steam pressure, many days will be wasted when the sky about the sun is clear one half of the time. Accordingly my efforts in recent months have been directed toward the develop-

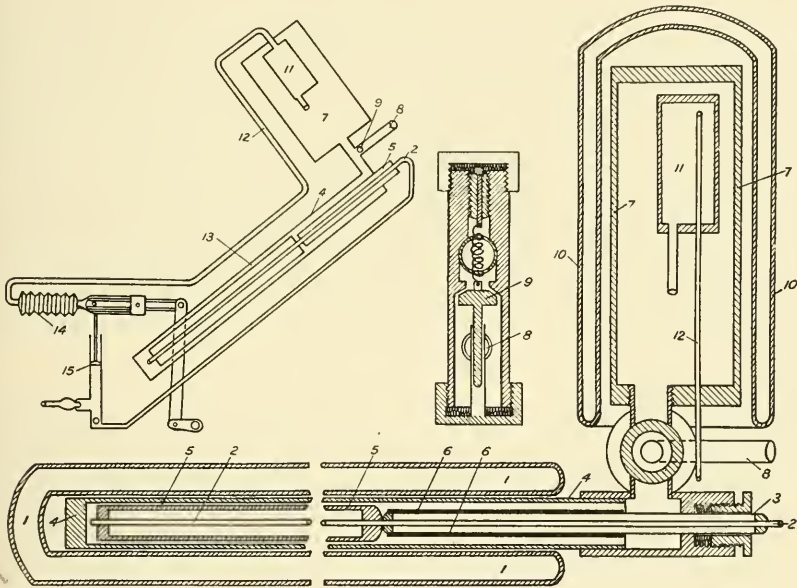


FIG. 1.—Diagram of solar flash boiler showing water injection governed directly by steam pressure. In a later model the water injection is governed by the temperature expansion of the boiler tube.

ment of the automatic flash-boiler solar engine. That is, an engine of a single tube boiler protected from heat losses by an elongated glass vacuum jacket, and fed by a current of water automatically graduated in flow by the temperature of the boiler. The device is intended to raise full steam pressure within 5 minutes after solar exposure. Should the sun enter a cloud, the water supply is immediately cut off. Should the steam pressure rise above the desired maximum, the water supply is increased. Thus the boiler is fully automatic, and it takes advantage of all the clear sky which comes between clouds.

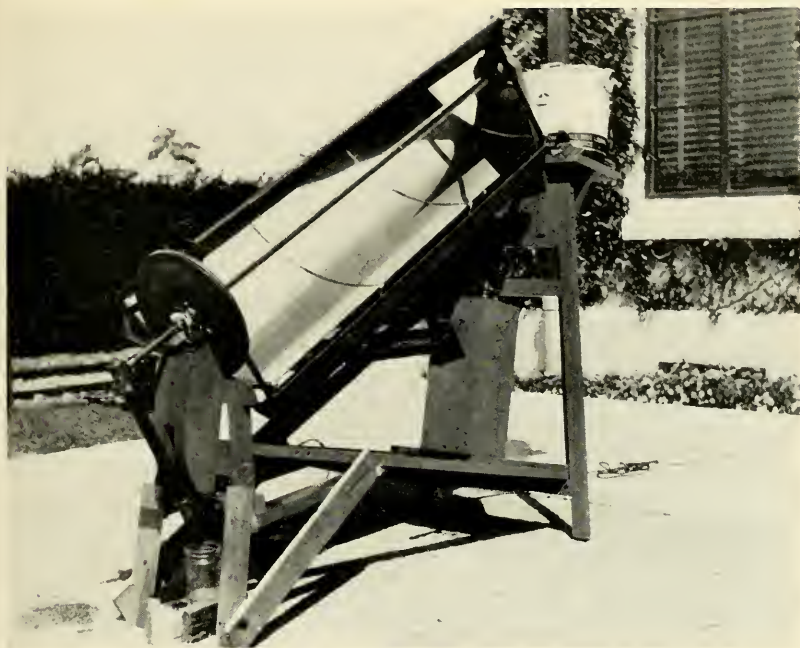
FLASH-BOILER DEVICES

It would be convenient if it were practicable to have the glass vacuum jacket open at both ends so that water could flow in at the bottom and go out as steam at the top. But the unequal linear expansion of the inner and outer tubes of the glass jacket is difficult to allow for in a permanent sealage. Accordingly, I have preferred to make the vacuum jacket, surrounding the boiler tube, like an elongated thermos bottle with open end up. This requires the water tube entering at the top to pass through the steam to the lower end of the boiler. I introduce two metallic tubes sealed upon the water tube within the boiler, called, respectively, the spreader tube and the vacuum jacket tube. The spreader tube encloses the water tube in the lower two-thirds of the length of the boiler tube, and forces the water to circulate in a thin layer against the inner wall of the boiler tube, so as to be most favorably situated to burst into steam. The vacuum jacket tube is sealed upon the water tube in the upper one-third of the length of the boiler tube, so as to reduce the tendency of the entering water to cool the superheated steam in the upper part of the boiler tube.

AUTOMATIC REGULATION OF FLOW OF BOILER WATER

I accomplish automatic regulation of the water supply as follows: A pump is provided whose stroke is continuously adjustable between the limits zero and the greatest required. The essence of this regulation consists in an eccentric pin forming part of a shaft driven by the same small synchronous motor that rotates the mirror. One end of the pin is coaxial with the shaft bearings, but the other end revolves in a small orbit. The shaft carrying the pin is mounted in a carriage, displaceable longitudinally, so that according to its longitudinal position the pin gives more or less throw to the pitman that works the pump.

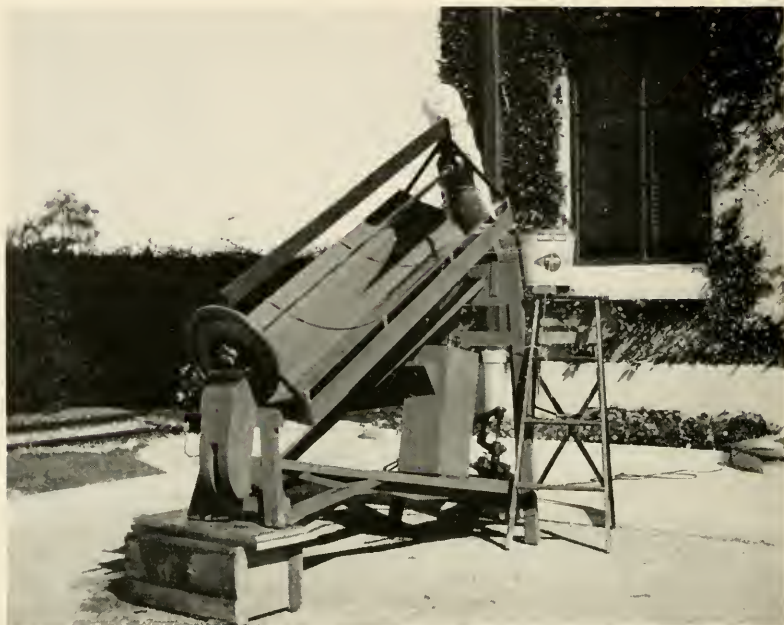
To govern the position of the carriage I impart motion by a screw, driven by a tiny direct-current motor operated by dry cells. The operation of this motor forward or backward is governed by a suitable multiple contact switch. The switch is operated by a lever system worked by the differential expansion between the boiler tube and an invar tape attached to the lower end of the boiler tube. Hence the temperature of the boiler, which is the index of the prevailing steam pressure, governs the position of the carriage. There is mounted upon this carriage the uniformly rotating eccentric pin, and this in turn governs the stroke of the pump which forces water into the boiler.



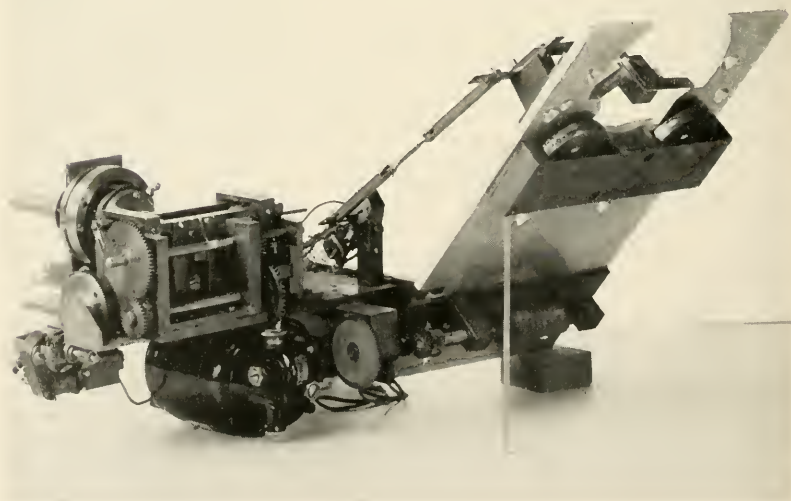
1. SOLAR WATER DISTILLER AS USED IN FLORIDA 1938



2. SOLAR BOILER FOR $\frac{1}{2}$ HORSEPOWER ENGINE AS EXHIBITED TO INTERNATIONAL POWER CONGRESS AT WASHINGTON 1936



1. SOLAR FLASH BOILER $\frac{1}{5}$ HORSEPOWER CAPACITY AS USED IN FLORIDA 1938



2. DRIVING MECHANISM FOR THE MIRROR AND WATER INJECTOR FOR THE SOLAR FLASH BOILER

EFFICIENCY OF SOLAR FLASH BOILER

Regarding the efficiency of conversion of solar energy into mechanical power by the flash boiler, the following computations are pertinent :

Efficiency of Solar Flash Boiler

- A. Efficiency of the boiler, assumed temperature 190° C.:
 - Mirror reflection82 percent
 - Transmission by vacuum jacket.....85 “
 - Absorption by boiler tube.....95 “
 - Loss of heat through the jacket.....10 “
 - Boiler efficiency $0.82 \times 0.85 \times 0.95 \times 0.90 =$60 “
- B. Thermodynamic factor for perfect engine :
 - Assumed temperature of condenser.....30° C.
 - Efficiency factor $\frac{190^{\circ} - 30^{\circ}}{190^{\circ} + 273^{\circ}}$34.5 percent
- C. Mechanical efficiency of engine is assumed to be 75 percent.
- D. Final result. Efficiency of conversion of solar to mechanical energy :
 - Factor = $0.60 \times 0.345 \times 0.75 =$ 15.5 percent

COMPETITION OF SOLAR POWER AGAINST COAL, OIL, AND WATER POWER

In the experiments of most earlier inventors, the protection of the boiler tube by a vacuum jacket was not practicable, the cheap but accurate construction of the mirror to give high reflection with permanency was not feasible, and the simplest arrangement to follow the sun was not generally made use of. Consequently, the cost was up and the efficiency was down. Hence these earlier devices were quite unable to compete with power from coal or water under most conditions. With the high efficiency and great simplicity of the present flash boiler scheme, I compute that power can be had from the sun at not exceeding 0.5 cent per horsepower-hour, and still give a good return on the investment.

WILLSIE AND BOYLE EXPERIMENTS

I wish, however, to refer to one of the earlier inventions in which efficiency was sacrificed for cheapness. It was that of Willsie and Boyle who installed a solar power plant at Needles, Ariz., about 1910. Their scheme comprised a large, shallow black-bottomed pond wherein the water attained temperatures considerably below the boiling point. This heat they used to drive a sulphur dioxide engine, cooled by the evaporation of water. They claimed that their device was able to compete with coal in that locality, although both its boiler efficiency and its thermodynamic efficiency were low. It appears not to have come into much commercial use, however.

STORAGE OF SOLAR HEAT OR POWER

I will now consider briefly some suggestions relating to the storage of heat or of power from the sun. As everyone knows, heat is prone to dissipate itself. There are no insulators against heat conduction comparable in efficiency to those which prevent the flow of electricity. My friend Dr. Cottrell, however, proposed to me a scheme which may be worth a trial. He suggests a silo-shaped, cement-lined pit in the ground, filled nearly to the top with dry coarse sand, and roofed over. Above the sand lies a layer of perhaps 10 feet of glass wool, such as is used for roof insulation. A pipe leading from the solar heater to the center of the upper surface of the sand has an appropriate network of branch pipes covering the surface. A similar network at the bottom of the pile leads to an outlet pipe, and thence back to the heater. An automatic pump which runs only while the focus tube is hot, draws hot air through the solar heater into the top of the sand. Owing to the notoriously bad conductivity of dry sand, and the high degree of protection from upward convection and conduction offered by the thick layer of glass wool, the sand pile receives the heat, and keeps it in a horizontal layer. The heated layer gradually works down, till, if the storage operation is very long-continued, the whole sand pile becomes of nearly as high temperature as the air in the focus tube itself. With a sand silo of sufficient capacity, Dr. Cottrell thinks the efficiency would be so high that when the heat was drawn away, perhaps months later, by reversing the circulation of air, the air would come away from the top of the sand very nearly as hot as it formerly entered. No one has tried this interesting scheme, but it would be desirable to do so. Should it succeed, it might show the way to use the heat of summer to warm one's house in winter.

Electric storage batteries are so well known that it is unnecessary to point out that solar power may be conserved thereby for night use. It is the cost which shades this proposal.

Chemical storage might be done by electrolyzing water, and saving the hydrogen to be burned in air with boilers to generate steam. This involves the problem of successful use of hydrogen as a steaming fuel.

Mechanical storage could be accomplished by pumping water to a high level reservoir, to be used in a hydroelectric plant later. This also looks costly, and difficult except in hilly country.

Possibly best of all would be a heat storage within a pressure tank filled with water, and surrounded by a thick envelope of glass wool. The water, heated far above the boiling point, would supply steam for hours of cloudiness or night.

COMMERCIAL USE AND COST OF SOLAR HEATING

It is probable that so long as coal is cheap and abundant there will be no extensive use of solar power. However, small installations, in 2- to 5-horsepower units, may become profitable under favorable conditions. Solar heat has already been used successfully for refrigeration, and possibly might be combined with a heating system for conditioning the air in ranch propositions in cloudless regions. The classic use of solar power is, of course, for irrigation, and here, as remarked above, the problem of storage is not important. It is conceivable that great reservoirs might be pumped full of water from rivers or lakes by solar power in dry years to irrigate land when rains fail.

As remarked above, both solar cooking and solar distilling of non-potable water are practical and efficient propositions, which it is likely will be in common use before very long if the necessary outfits can be produced at attractive prices. The cost of solar devices, as of all other products, depends greatly on the volume of sales. These devices, however, as compared with automobiles are extremely simple. Though it might cost prohibitively to produce them singly, I think not if produced in thousands.