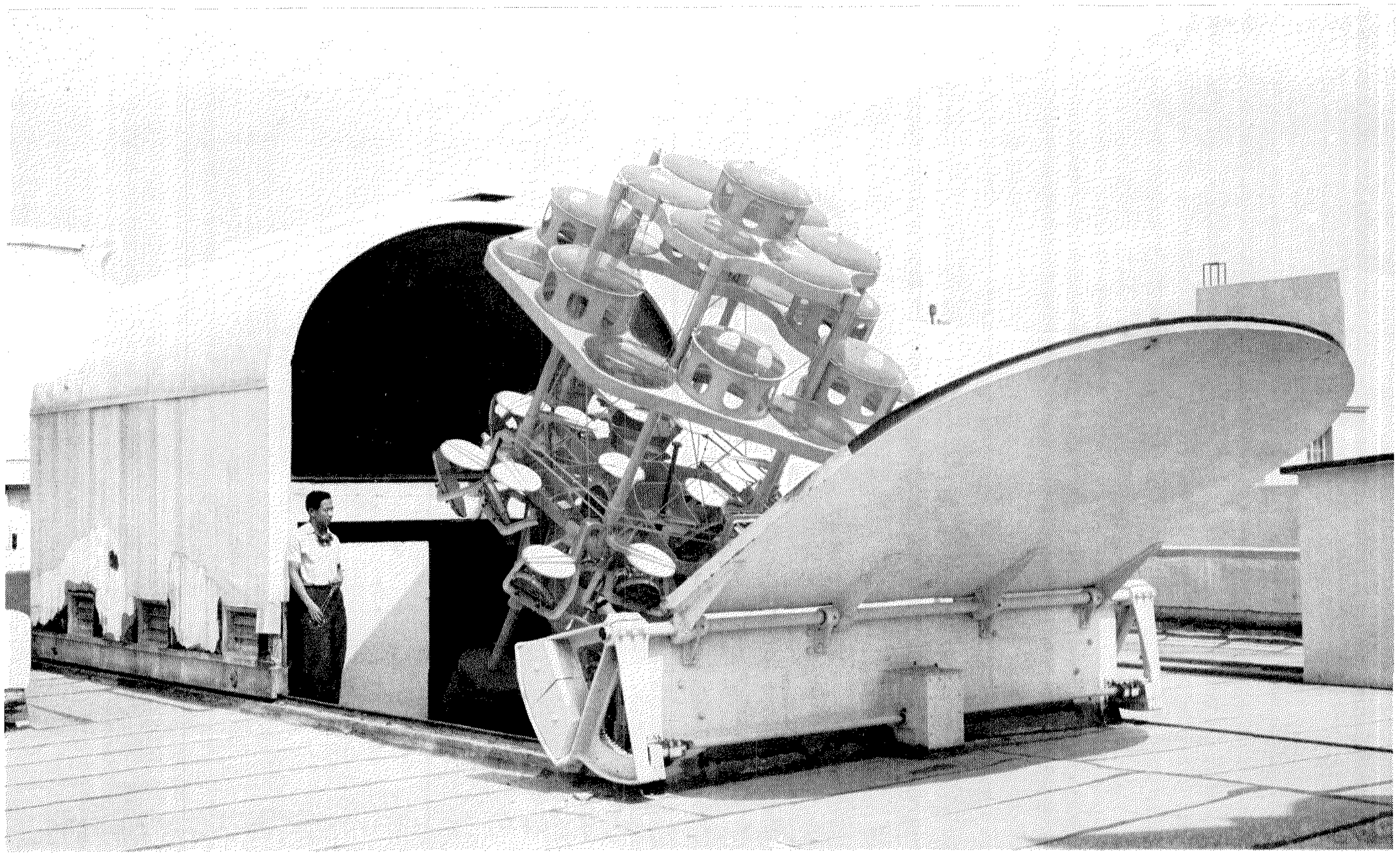


Caltech's solar furnace, built almost 25 years ago, is now being used for high temperature materials research.

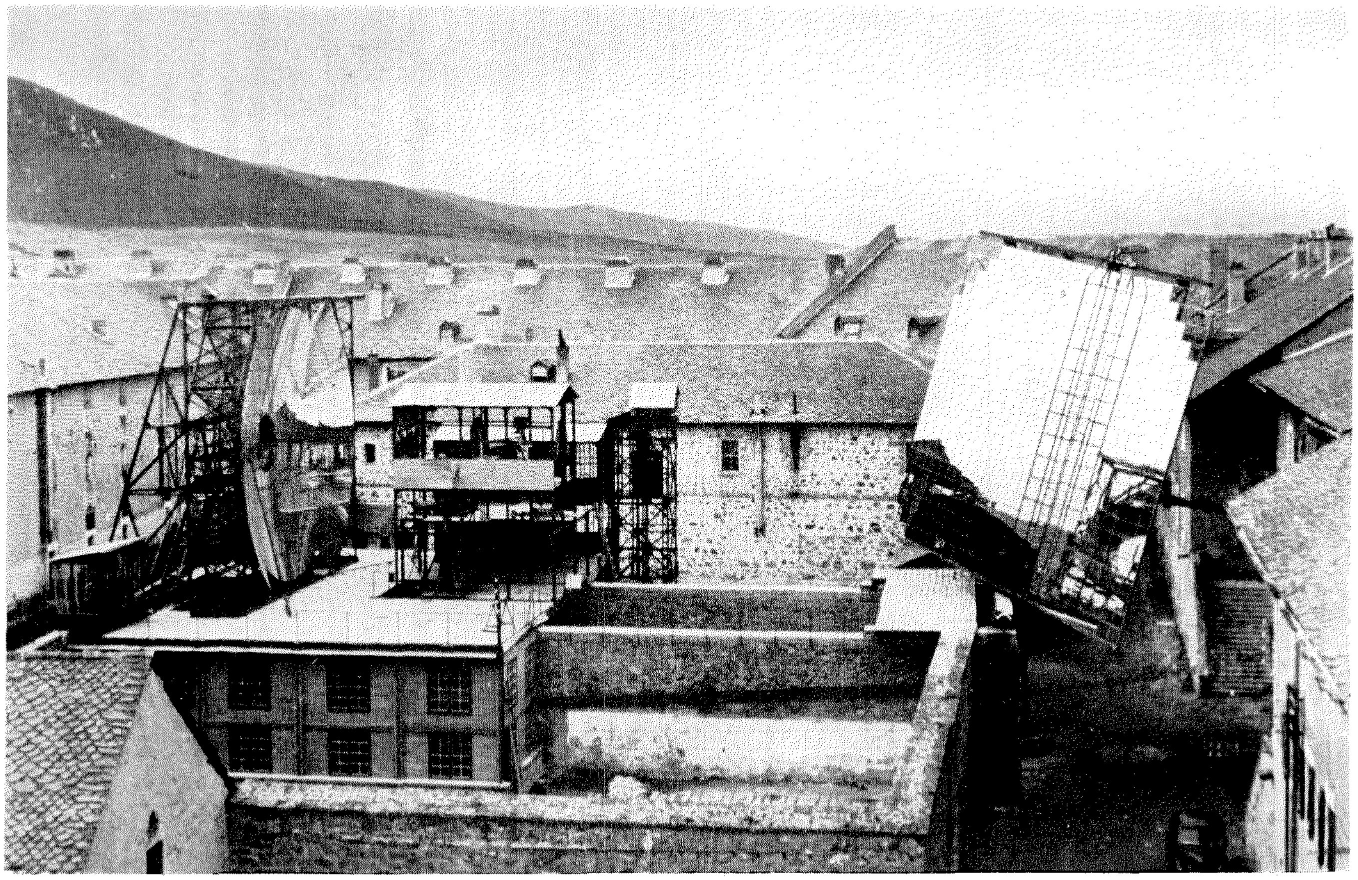
THE SOLAR FURNACE

It uses the sun's rays for high temperature research

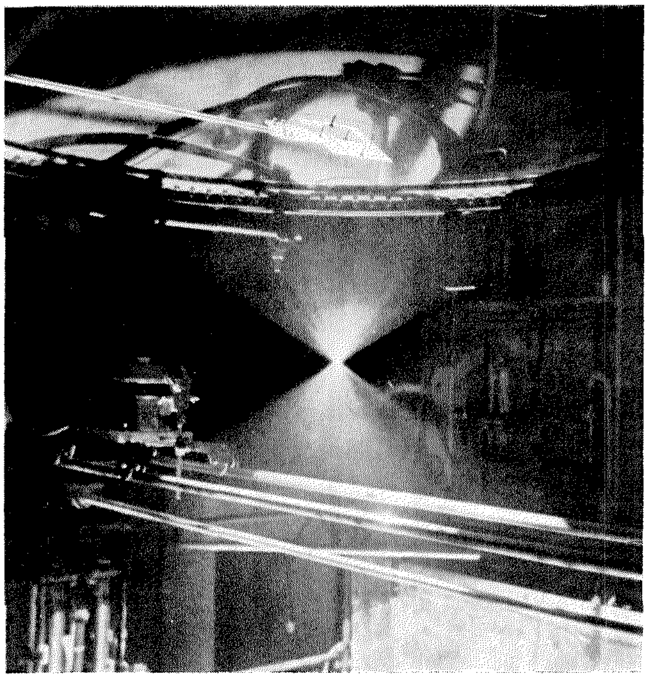
by POL DUWEZ

A SOLAR FURNACE is not exactly a furnace, but an optical system in which the solar radiation received by a collector is concentrated into a small area. If this highly concentrated radiant energy is received into a cavity, heat is generated and very high temperatures may be obtained. This cavity, which is really the furnace, is a minor part of the whole system, and solar furnaces should rather be called solar energy concentrators.

The idea of using solar energy to produce high temperatures is not new. In 212 B.C. Archimedes presumably set fire to the Roman fleet by concentrating the sun's rays on the ships by means of several hundred plane mirrors. In the 17th and 18th centuries both mirrors and lenses were used, and in 1772 Lavoisier built a furnace with a collecting lens having a diameter of about 5 feet, in which he almost reached the melting point of platinum (1773° C.) After La-



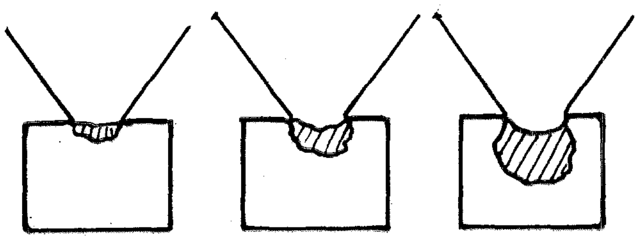
An overall view of the 35-foot solar furnace in Montlouis, France. The parabolic mirror at the left is fixed, while the plain mirror at the right reflects the sun's rays into the parabola and tracks the sun automatically. The sun's rays are concentrated in a cone on a furnace located in the structure shown between the two mirrors.



One of the six 7-foot parabolic reflectors at the laboratory for solar energy in Montlouis, France. This furnace, in which the concentrated cone of sun rays has a vertical axis, is most practical for metallurgical studies.

voisier, until the beginning of this century, solar furnaces were completely ignored. In 1921 Straubel and his collaborators at the Zeiss Co. in Germany constructed what may be considered as the first modern furnace of the reflecting type. With a glass parabolic mirror of about 6 feet in diameter and a focal length of 2 feet, they reached temperatures of the order of 3000° C. Since then parabolic mirrors of various sizes have been used. W. Conn, who collaborated with Straubel, built a 10-foot furnace and installed it at Rockhurst College in Kansas. This furnace, made of aluminum alloy sheet, is now in operation at Convair in San Diego and is used for studies in high temperature materials. Searchlight mirrors 5 feet in diameter are also relatively good concentrators and are in operation in various laboratories in the United States.

The largest installation of solar furnaces of various sizes is located in Montlouis in the French Pyrenees. Professor Felix Trombe, head of the laboratory for the study of solar energy, now has in operation 6 furnaces made with German parabolic searchlight mirrors 6.5 feet in diameter, and one large furnace 35 feet in diameter. This large-size reflector is made of 3500 small plane mirrors which are attached to a steel frame of parabolic shape. In order to achieve the best possible



The concentrated effect of the sun's rays melting a block of solid material from the inside out.

focusing, each mirror is mechanically bent to a curvature approaching that of the ideal parabola. A still larger furnace, more than 100 ft. in diameter, has been designed and components of the reflector have been tested. The power of this large installation will be about 1000 kw. W. Conn's design was adopted by Professor Guillemonat who built a furnace 27 ft. in diameter in Algiers. The parabola is made of 144 panels of electropolished aluminum formed to the desired curvature. In Soviet Russia, a large solar energy research laboratory has been established near Tachkent, but there is no report so far about the existence of solar furnaces designed specially to obtain very high temperatures.

Lavoisier's furnace was not the last one ever built with lenses as a means of concentrating the sun's energy. Between 1930 and 1932 a lens furnace was erected at Caltech by George Ellery Hale and his collaborators, with the objective of achieving a high-temperature source for spectroscopic studies. The furnace, located on the roof of the astrophysics building, is now being used for high temperature materials research.

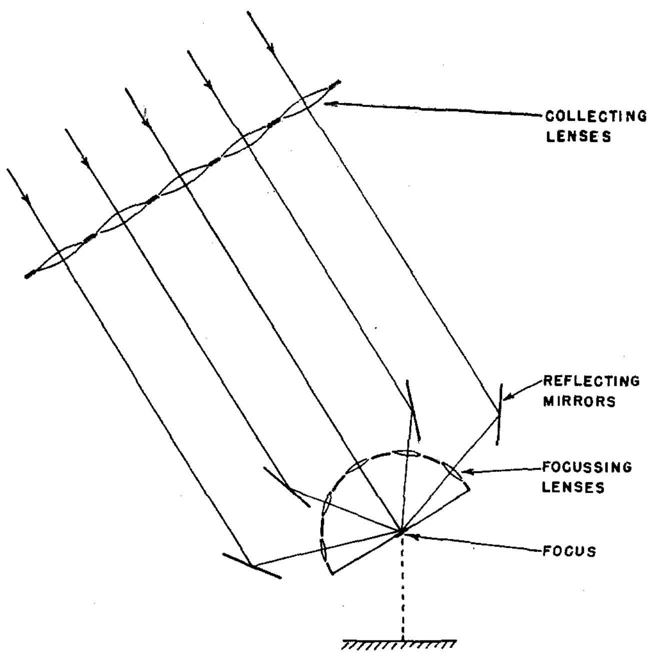
Advantages of the solar furnace

To anyone familiar with the field of very high temperatures, the performances of existing solar furnaces will not appear very spectacular. Temperatures of the order of 3000° C. may be obtained through many different techniques: flames, electrical resistance heating (using graphite or tungsten elements), induction heating, arc melting in neutral atmosphere or levitation melting. All these techniques, however, have limitations—mostly because they require a certain type of atmosphere around the specimen under study. The flame heat source is always highly chemically reactive; the use of tungsten or graphite as an electrical heater, or as a susceptor in induction heating, requires a neutral or reducing atmosphere; arc melting and levitation are limited to electrical conductors. In a solar furnace, the heat source, in the form of a cone of radiation energy, may be called 'pure heat,' and does not impose any restriction to the kind of atmosphere which surrounds the specimen. It is indeed possible to place the object to be heated in a transparent vessel (made of glass or fused silica) and fill this vessel with any suitable gas. Operating under high vacuum is also a rather easy experimental technique.

Another outstanding feature of solar furnaces is the very concentration of heat obtainable within the focal area (the sun's image). Because of this high heat flux, heat is provided over a relatively small portion of a solid sample and, as shown in the diagram at the left, melting of the inside of a solid sample may be achieved so that the material under study serves as its own crucible. This possibility of heating a body from the inside out, which is unique to the solar furnace, is extremely useful in melting refractory substances which react very rapidly with any known crucible material at high temperature.

The research project which is now being carried out with the Caltech furnace makes full use of these two outstanding features of solar heating, namely, pure heat and absence of crucible. The first project is an investigation of highly refractory thorium oxide and zirconium oxide (melting points 3200° C. and 2750° C., respectively). These compositions can be melted in air at the focus of the furnace, thus assuring an oxidizing atmosphere around the melt, which is impossible to achieve in any known laboratory furnace at these temperatures. The second project is concerned with the structure of ceramic bodies based on mixtures of titanium and zirconium dioxides, in which, however, the oxygen content is less than it should normally be These complex sub-oxides are extremely reactive and must be melted in an atmosphere of inert gas. The absence of crucible and the possibility of operating in a glass vessel filled with helium make the solar furnace an ideal tool for such investigation.

The principle of construction of the Caltech solar furnace is shown below. Nineteen lenses, each two feet in diameter and pointed toward the sun, are arranged in a hexagonal close-packed array. Since all the images are to be superimposed, secondary lenses 7.5 in.



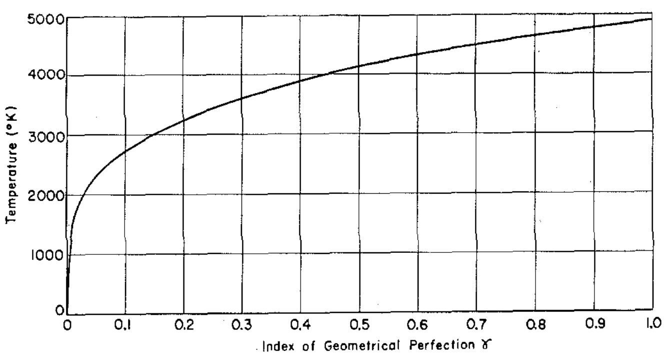
The basic elements of Caltech's lens furnace.

in diameter are arranged on a hemisphere centered at the focal point. For all lenses, with the exception of the center one, it is necessary to deflect the rays before they reach the secondary lenses, and that is done by a series of 18 plane mirrors. The sun's image, at the focus, is one half inch in diameter.

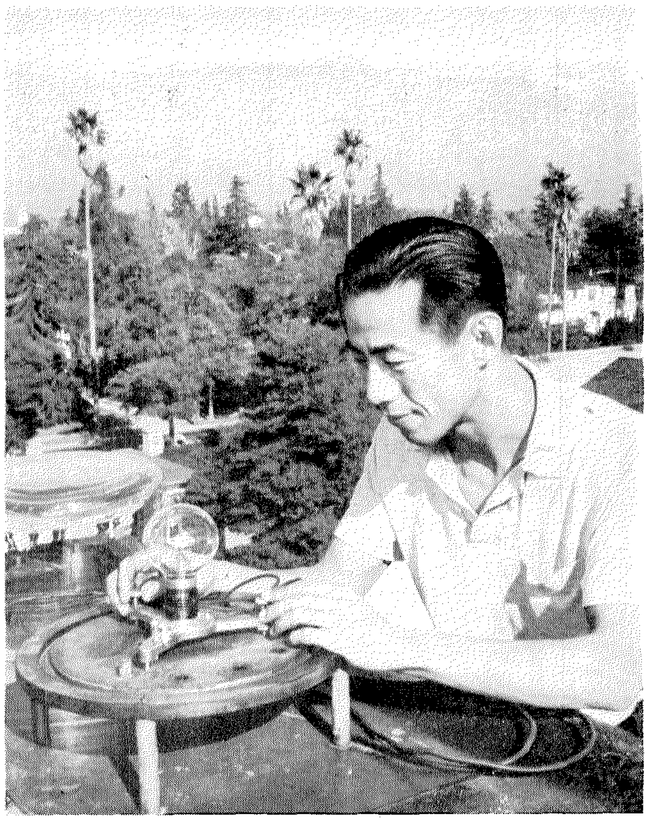
The entire optical system is mounted like a telescope on an equatorial axis and has a synchronous drive so that the furnace stays pointed on the sun. The lenses are permanently attached to the frame but the plane mirrors can be adjusted for best focusing conditions. This is done most conveniently by making use of the full moon. The negligible heat flux in this case permits observing the moon's image on a ground glass and adjusting each plane mirror by centering every one of the 19 images around the focus.

An analysis of the performances of the Caltech furnace was made and it has been established that, as far as maximum attainable temperature is concerned, this lens furnace is equivalent to a parabolic reflector furnace with a ratio of focal length to diameter equal to 0.7. A maximum theoretical temperature can be computed if a perfectly insulated black body cavity with a solar constant of 2 cal/min/cm^2 (2 calories per minute and per square centimeter) is used, thus eliminating atmospheric absorption. Assuming that there are no losses through the optical system, this maximum temperature is approximately 4200° C. A realistic figure may be arrived at by taking 1.6 cal/min/cm^2 for solar radiation (this figure was reached only three or four times in Pasadena during the last three months) and by estimating the absorption and reflectivity coefficients of the lenses and mirrors to be 0.85. Under these conditions, the maximum temperature would be around 3400° C. Although no accurate measurements have been made so far, temperatures of the order of 3100 to 3200 have been reached—as evidenced by the fact that thorium oxide, whose melting point is 3200° C. + 100, has been melted in the furnace. Realizing that the furnace was designed by astronomers, it is not surprising to find that its performances actually meet the design criteria.

The temperature obtained with the Caltech furnace is probably close to the maximum capability of a lens



The effect of the optical equality of a parabolic reflector on the maximum attainable temperature.



Dr. Eugene Loh checks the pyroheliometer on Caltech's solar furnace, which gives a continuous record of the intensity of solar radiation.

type solar furnace. The parabolic reflector furnace is capable of higher temperatures, at least in theory. With a parabolic reflector having a focal length to diameter ratio of 0.45, it should be possible to reach a temperature of 4500°C. This figure was obtained by taking a solar constant equal to 1.6 cal/cm^2/min (which is not unusual in many parts of the United States) and a reflectivity co-efficient of 0.85 for the mirror surface. In this analysis, however, the parabolic reflector was assumed to be optically perfect, and that is the most difficult condition to satisfy in practice. The degree of perfection of a parabolic reflector used in a solar furnace may be defined as the ratio of the actual heat flux received through the sun's image at the focus to the heat flux that should be received if the reflector were perfect. This index of quality has a very large effect on the maximum temperature attainable.

As shown in the diagram at the left, a relatively poorly built reflector with an index of quality of only 0.2 is capable of temperature of the order of 3000°C. Most of the existing parabolic furnaces are in the range of 3000°C., and therefore their index is about 0.2. To achieve temperatures from about 3500 up to 4500° C. it would be necessary to construct a parabolic reflector in which more than 80 percent of the radiation collected by the mirror would be concentrated within the sun's image area. It is believed that there is no physical limitation in building these high performance parabolic mirrors, but their cost might be very high.