Solar Energy Handbook

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Eyes, though not ours, shall see
Sky high a signal flame,
The sun returned to power above
A world, but not the same
C. D. *Lewis*

PREFACE

The *Solar Energy Handbook* collects into one volume all the archival data and procedures available for solar system assessment and design, current as of its preparation date. The Handbook differs from a textbook in that it emphasizes applications, not theories, and provides information of a permanent nature which is not expected to change during the life of the book. For this reason proposed solar technologies for which there is no significant field experience are excluded. Nearly two-thirds of the authors, all of whom are preeminent experts, are from the private sector, i.e., excluding academia or government service.

The many forms of solar energy conversion are the principal topic of this Handbook. Sufficient data for the most mature technologies are presented to permit technical and economic analysis and synthesis through the final system design stage. Less detailed design information is given for less mature technologies. Large-scale electric power production by land- or sea-based systems represent the least mature of all technologies covered in this book. Since solar energy has impacts beyond purely technical areas, chapters on macroeconomics, microeconomics, and the law are also included.

The Handbook is separated into six major divisions, each made up of several chapters. The first, Perspective and Basic Principles, treats both the history of solar energy use and basic matters common to all solar systems including solar radiation and optics, heat transfer and thermodynamics, and solar component materials and storage. The second division, Solar-Thermal Collection and Conversion Methods, treats the many methods of producing heat from solar radiation. As such it treats only collectors, not systems, which become the subject of later divisions. Concentrating and nonconcentrating collectors are thoroughly treated in three chapters, and solar ponds are the subject of a fourth chapter.

The third division of the book, Low-Temperature Solar Conversion Systems, describes systems which operate below 100°C. These include the mature technologies of space and water heating using both gas and liquid working fluids as well as the less widely practiced applications of solar cooling and passive heating. System modeling and performance prediction are the subjects of two chapters followed by a chapter on agricultural applications. Finally, ocean temperature gradient power systems are examined.

High-temperature solar systems are treated in the fourth division along with industrial process heat systems. Heat engines and solar-thermal electric power are the subjects of the first two chapters of this division. The fifth division covers Advanced and Indirect Solar Conversion Systems, including wind and biomass energies. Biomass energy conversion is undergoing vigorous development and major new developments are expected in the 1980s. Photovoltaic conversion of sunlight to electricity is included in this division as well.

The final division, Architecture, Economics, the Law, and Solar Energy, treats matters not directly associated with the technical design of solar systems. However, these subjects—microeconomics and macroeconomics, the law, and energy conservation in buildings—are tantamount to the more technical subjects of preceding divisions. These are areas which might not be treated in a handbook devoted strictly to energy, but they are important in the Solar Handbook owing to the far-reaching effects of this energy source.

This Handbook uses hundreds of diverse sources for its material. As many of these as are known have been acknowledged formally in the text. Both the U.S. Customary System and the Système International d'Unites are used bilingually to communicate with the largest possible group of users. Conversion factors and a uniform nomenclature section for the book are contained in the Appendices.

A special acknowledgment is reserved for the small group of solar practitioners, some of whom are contributors to this volume, who persisted in their advancement of the state of the art for decades in the face of nearly universal disinterest. The technologies which are mature today owe their level of refinement in some respects to these persons. The editor-in-chief expresses his appreciation for the support offered by Dottie Lang through the long course of Handbook production. Jeremy Robinson suggested the idea for this Handbook and has been most supportive and helpful throughout.

A final note to the user. The information in this Handbook is current as of its production date. However, solar energy technology is in a state of continuing evolution and some subjects treated are undergoing development and refinement, the details of which can only be followed by review of the current literature. In the course of preparing hundreds of tables and figures and hundreds of thousands of words of text, it is inevitable that a few errors remain. The reader can provide a service to the solar community by reporting errors to the editor for correction of future printings.

Jan F. Kreider
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Chapter 1

The History of Terrestrial Uses of Solar Energy*

KEN BUTTI
and
JOHN PERLIN

EARLY UTILIZATION OF SOLAR ENERGY

Solar Architecture in Ancient Greece, Fifth Century B.C. to Third Century B.C.

Space heating and cooling The first written account of solar energy use comes from ancient Greece. The Greeks did not have any mechanism for cooling their homes in the extreme heat of summer, nor did they have an adequate heating system for the cold winter. They frequently used kitchen stoves fueled by wood and portable braziers fueled by charcoal for heat.

By the fifth century B.C., wood and charcoal had become very scarce. The Greeks, having consumed most of their domestic supply, depended more and more on costly imports from (1) Macedonia and Thrace, (2) the Black Sea region, chiefly Bithynia, (3) the eastern Mediterranean (the coast of Asia Minor, Phoenicia, and Cyprus), and (4) southern Italy.

During this time (the Hellenic period), it became popular to utilize the sun's energy for both heating and cooling buildings. The Greeks developed basic principles of solar architectural design. Aeschylus, Aristole, and Xenophon outlined principles of using the sun's heat in winter. They pointed out that the main rooms of a house should face south and the north side of the building should be sheltered from the cold winds. To minimize solar heat gain in summer, eaves on the south side should provide shade to keep out the hot sun.

Example of solar architecture: the Olynthian house The most extensively excavated city of ancient Greece, Olynthus, illustrates how solar architectural theory was translated into practice. Other excavations at Colophon, Delos, and Priene suggest that similar techniques prevailed throughout most of the country.

The typical Olynthian home was rectangular in shape (Fig. 1.1). The north wall had few window openings (windows during Greek times were not covered with glass, for transparent glass had not yet been invented), and the main rooms occupied the north wing. They faced an area on the south side of the building called the "pastas." The pastas extended east-west across

*This chapter is abridged from *The Golden Thread* by the authors, Van Nostrand-Reinhold Co., 1980. For their contributions the authors would like to thank Jon Billigmeier, Ph.D., for his French and German translations; Borimir Jordan, Ph.D., Associate Professor of Classics, University of California at Santa Barbara, for his translations and advice on the Greek and Roman sections; and Gloria J. Leitner for editing the entire manuscript.

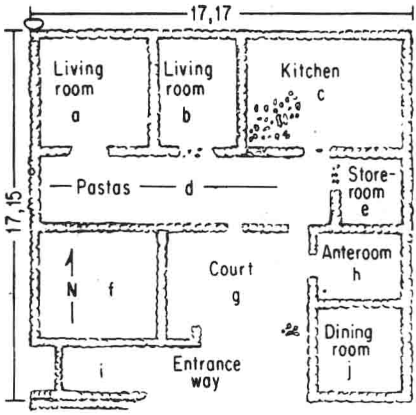

Fig. 1.1 Olynthian house plan. (*From David M. Robinson and J. Walter Graham, "Excavations at Olynthus," Johns-Hopkins, Baltimore, 1938.*)

the entire width of the building and the center section consisted of a colonnade which led into an open-air courtyard.

According to D. Robinson and J. W. Graham, the principal excavators of Olynthus,[12]

> The width of the openings of the pastas on the court . . . varies considerably, as for example [house] BVI and AVii6-width between 9.2 m and 3.8 m (30.16 ft and 12.5 ft) respectively. The breadth of the pastas varies from 3 to 4 meters (9.83 ft to 13.1 ft).

Distances between the pillars of the pastas usually varied from 2.75 to 2.2 m (9.02 to 7.2 ft). The court ranged in size from 48 to 14.5 m^2 (516.1 to 155.1 ft^2), or 19.8 to 5.4 percent of the total area of the dwelling.

Olynthus lies at about 40° north latitude. With the noon elevation of the sun at the winter solstice about 26°30′, sunlight streamed through the courtyard and the pastas and into the main living rooms. To help retain the solar heat, the floors of the main rooms generally were made of earth. The walls were usually adobe, a poor conductor of heat and therefore a good insulator. Almost all of the walls of the houses at Olynthus measured 0.4 to 0.5 m (1.31 to 1.64 ft) thick.

In summer—with the noon elevation of the sun at the solstice at about 73°30′—eaves shaded the pastas, and the main rooms did not receive the direct rays of the sun. In addition, the adobe walls helped exclude the heat.

Olynthus' orthogonal plan, with avenues running east-west, guaranteed maximum solar exposure for every house, as the excavator observed:[12]

> The house plan and the city plan exercised a strong influence upon one another, for the regular rectangular shape [of the houses was] . . . facilitated by the regular city plan.

Other examples of solar architecture in Greece The Greeks used other types of solar design as well. At Delos, for example, the ground floor of the Maison du Trident and the Maison des Masques was built higher on the north side than on the south side of the building. In this way the south-facing window openings of the main rooms of the house in the north wing could face the sun in winter without obstruction.

In another equally successful technique, the north wing was built two stories high and the south wing only one story high. Thus the upper floor of the north wing was elevated above the south wing and received the winter sunlight.

Solar-Heated Homes, Baths, and Greenhouses in Rome, First Century A.D. to Fifth Century A.D.

Fuel problems Like Greece, Rome also depleted fuel resources at a voracious pace. For example, at a short distance from Rome, Monte Cimino was a densely forested region up to the Third Century B.C. but by the First Century B.C., Rome had to import pine and other types of wood from as far east as Caucasia. Fuel consumption continued to rise with the standard of living. By the First Century A.D., many of the wealthier citizens enjoyed central heating. Tests done on a reconstructed furnace of the time showed that it would have had to consume

130 kg (287 lb) of wood per hour to heat a large villa adequately, or 16 m^3 (565 ft^3) every two days.

Public baths required even greater amounts of fuel. Whole tree trunks blazed inside their furnaces, and furnace temperatures reached up to 800°C (1472°F). Such baths could be found throughout Italy. By the Third Century A.D., 800 baths were located in Rome alone. The largest could hold nearly 2000 visitors at a time.

The steady depletion of indigenous supplies of fuel had a natural consequence—a steep rise in the price of wood and charcoal. Energy conservation techniques, including the use of solar energy, became important.

Solar architecture modeled after Greek designs The three most influential Roman architects—Vitruvius, Palladius, and Faventinus—emphasized proper solar orientation of private villas and public baths. They wrote that rooms primarily used in winter, as well as bathing areas, should face south or southwest. Architectural evidence demonstrates that builders followed these recommendations wherever possible. The most detailed account of the construction and use of villas during the Second Century A.D., *The Letters of Pliny the Younger*, described how all the winter rooms in Pliny's villas faced the winter sun.

The Romans also went beyond techniques of passive solar building design—i.e., simply optimizing the solar energy exposure of a structure. They developed more sophisticated methods of exploiting solar energy including use of glass as a solar heat trap and use of several kinds of solar heat storage.

Use of window glass: the greenhouse effect The Romans invented window glass in the First Century A.D., but only conjectures about its degree of transmittance have been made. Seneca referred to its transparency and Pliny the Elder differentiated it from opaque glass, stating that window glass allowed the visible spectrum to enter a structure. Other writers of the period remarked that window glass lets in "pure, unfiltered sunlight," that it "admits a clear light." Such comments were, of course, entirely relative since they were based on a comparison with opaque and translucent materials. Glass panes of good quality have been discovered. The largest panes found intact measured 0.33 × 0.55 m (1.08 × 1.8 ft).

We can surmise that the Romans knew about the greenhouse effect. A passage from Palladius indicates that they recognized that clear glass is opaque to low-temperature radiation.

Additional evidence of glass use can be found among the ruins of public baths (Fig. 1.2) built during or after the Imperial period (First Century A.D.). Most of the baths had their south-facing windows glazed. The window frames of the central baths at Pompeii, for example,

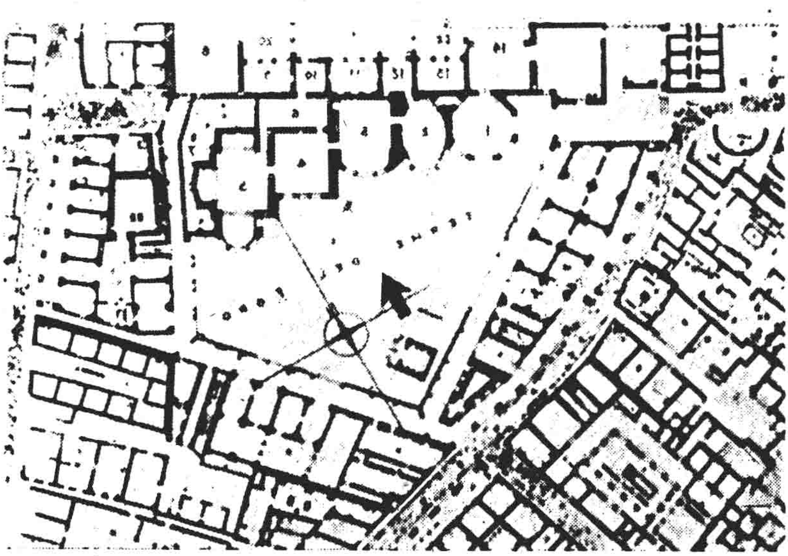

Fig. 1.2 Central baths at Ostia. Arrow points north to the five chambers of the baths. (*From X. Thatcher, "Ostia."*)

measured 1 × 3 m (6.56 × 9.84 ft). The accumulation of solar heat inside such baths because of glazing, Seneca noted, allowed the bathers "to broil."

The Romans also seem to have used window glass in their houses. Only if the south-facing windows were glazed could Pliny the Younger have boasted that his favorite winter room not only collected solar heat but increased its intensity. Excavations at Pompeii and Herculaneum, as well as other sites, have verified that by the Imperial period the windows of at least the wealthier homes were made of glass.

The Romans also used glass for greenhouses in which vegetables were grown in winter and exotic plants thrived during inclement weather. Furthermore, they installed glass on the south walls of their winter olive-pressing rooms. Solar heat accumulated inside and prevented congealing of the oil stored in the rooms.

Solar heat storage Methods of solar heat storage were used by the Romans. For instance, southwesterly facing winter dining rooms had specially made floors that absorbed and stored solar energy. The storage floors were constructed by (1) digging a cavity 0.610 m (2 ft) deep and pounding down the earth inside it; (2) putting rubble or shards of broken earthenware into the hole; (3) gathering cinders and trampling them into a thick mass inside the pit; (4) applying a layer of dark sand mixed with ashes and lime, to a thickness of 15.24 cm (6 in), so that the surface of the floor was black; (5) leveling the floor with a square.

Sun rights Roman law took into account the sun rights of its citizens. By the Second Century A.D., it had become a civil offense for anyone to place an object in such a way that it obstructed the solar exposure of a structure which required access to the sun's energy. Solar heating must have become a common practice to provoke the enactment of such a law.

Experiments with Solar Hot-Boxes, 1767–1881

Horace de Saussure, 1767 In 1767 Horace de Saussure, a Swiss naturalist, began to test the effectiveness of glass as a solar heat trap. He built five glass boxes, each a cube cut in half parallel to its base. The sides of the first box measured 30.48 cm wide × 15.24 cm high (12 × 6 in), the second box measured 25.4 cm wide × 12.70 cm high (10 × 5 in), and so forth, to the fifth and smallest box which had sides 10.16 × 5.08 cm (4 × 2 in). The bases were cut out so the boxes could be stacked one inside the other. They were attached to a table made of black pearwood.

De Saussure exposed the set of glass boxes to the sun. He found that the temperature of the largest box rose the least, and in each succeeding box the temperature increased. The smallest box reached 87.5°C (189.5°F). Observing that the boxes tended to lose heat by convection, he improved their insulation. The second device he constructed was a box made out of pine 1.27 cm (½ in) thick. It measured 30.48 cm wide × 22.86 cm high (12 × 9 in) per side. The interior was lined with black cork 2.54 cm (1 in) thick. Three glass covers were placed 3.81 cm (1.5 in) apart. When de Saussure exposed the device to the sun, he obtained a temperature of 109°C (228.2°F), or 9°C above the boiling point of water. He called it a hot-box, and thus the prototype of the flat-plate solar collector was born (Fig. 1.3).

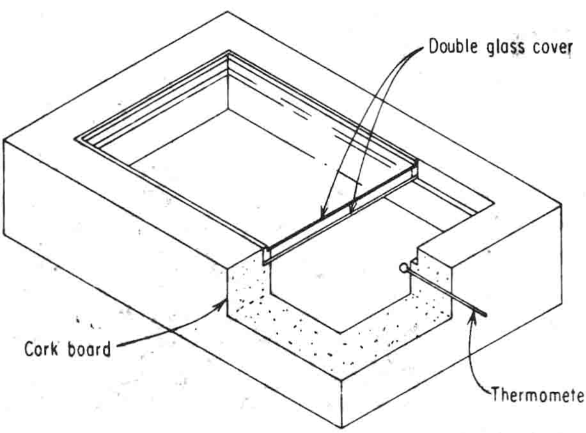

Fig. 1.3 Hot-box.

Despite its superior design, the hot-box lost some heat. To correct this, de Saussure placed the hot-box in a larger container filled with cotton wool as insulation. The container had an open top. Upon exposure to the sun, the temperature inside the hot-box rose to 110°C (230°F), even though the weather was not as favorable as during prior experiments.

As a third measure to eliminate heat loss, he put the hot-box into a glass-covered tin box. As the sun heated the hot-box, de Saussure heated the tin box by conventional means. He was careful always to keep the outer box slightly cooler than the inner one. Using this method, he recorded a temperature of 160°C (320°F) inside the hot-box.

De Saussure did not try to improve the seal on the hot-box by adding more glass covers. He realized that what heat he might have conserved would have been offset by increased absorption, reflection, and dispersion of incoming sunlight by extra layers of glass.

Sir John Herschel, 1837 Several prominent 19th Century scientists substantiated the results of de Saussure's hot-box experiments. Among them was Sir John Herschel, a noted British astronomer. Herschel reported that during an expedition to Cape Town, South Africa, he built a small hot-box out of mahogany with a blackened interior and a single sheet of glass on top. Exposing the box perpendicular to the sun, he observed that a thermometer inside rose to 65°C (149°F). When he improved the insulation of the box by heaping sand around the sides, he found that the temperature reached 80.6°C (177°F).

Herschel also placed the simple hot-box inside a larger container with a glass cover. He piled sand around its outer sides, and the thermometer in the hot-box rose to 115.8°C (240.5°F).

Samuel Pierpoint Langley, 1881 Samuel Pierpoint Langley, an American astrophysicist, also tested the effectiveness of the hot-box. He conducted his experiments in 1881 near Mt. Whitney, California. Langley constructed a copper box with a glass top, measuring 16.5 cm in diameter and 4 cm deep (6.5 × 1.58 in). He placed it in a wooden box which in turn rested inside a larger copper box with a glass cover, 32 cm in diameter and 8 cm deep (12.6 × 3.15 in). Loose cotton packing filled the space between the sides of this copper box and the walls of the wooden box. An outer shell of wood enclosed the walls of the entire apparatus.

On September 9, 1881, Langley recorded that the innermost copper box was 113.3°C (235.9°F)—98.5°C (209.3°F) hotter than the outside shade temperature (Table 1.1). These experiments proved that temperatures exceeding the boiling point of water could be obtained without the use of mirrors or other solar-focusing devices; however, no useful heat was removed from these devices.

History of Solar-Focusing Reflectors, Fourth Century B.C. to 1750s

Antiquity The ancient Greeks discovered the principle of solar-focusing reflectors. They knew that if a large number of people held plane mirrors in the proper position so that the mirrors focused to the same point, a target at that point could be set on fire. Theophrastus, writing in the Fourth Century B.C., reported that such mirrors were made of polished silver or copper.

Soon the Greeks realized that concave spherical reflectors could produce fire in a similar manner, dispensing with the bulk and large number of people required by the former method. By the Third Century B.C. they were building parabolic mirrors, which were still more efficient. Diocles, a Greek mathematician of the Second Century B.C., gave the first formal geometric proof of the different focal properties of spherical and parabolic concave mirrors (Figs. 1.4 and 1.5). He wrote in his treatise *On Burning Mirrors*,[7]

> [The] property of [the parabolic mirror is] that all rays are reflected to a single point, namely the point whose distance from the surface is equal to one-quarter of the line which [constitutes] the ordinates. . . . The intensity of the burning mirror in this case is greater than that generated from a spherical surface, for from a spherical surface the rays are reflected to a straight line, not to a point.

In antiquity, concave mirrors principally served as a method of kindling fires. Plutarch, for example, noted that the Vestal Virgins used "concave vessels of brass" to reignite their sacred flames. The story of Archimedes burning the fleet at Syracuse by using solar reflectors is mere conjecture and appears to be a legend concocted many years after the supposed event.

Late antiquity and the Middle Ages Several works of late antiquity and the early Middle Ages discussed, as did Diocles' treatise much earlier, differences in the focal properties and methods of construction of spherical and parabolic concave mirrors. Such tracts included *On the Burning Mirror* by Anthemius of Tralles (500 A.D.) and two works—*A Discourse on the Concave Spherical Mirror* and *A Discourse on the Parabolic Mirror*—by Alhazan of Cairo

TABLE 1.1 Temperature Readings by Langley with Hot-Box, September 9, 1881

	Time		Hot-box temperature °C	°F	Temperature in shade °C	°F	Difference, °C
(A.M.)	11h	30m	88.44	191.2			
	11	35	91.22	196.2			
	11	40	94.06	201.3			
	11	45	96.72	206.1			
	11	50	98.88	210.9			
(Noon)	11	55	101.05	213.9			
(P.M.)	12	00	102.61	216.7	15.78	60.4	86.81
	12	05	103.89	219.0	15.78	60.4	88.11
	12	10	105.00	221.0	15.94	60.7	89.06
	12	15	105.94	222.7	16.61	61.9	89.33
	12	20	107.17	224.9	15.67	60.2	91.40
	12	25	108.00	226.4	15.56	60.0	92.44
	12	30	108.94	228.1	15.39	59.7	93.55
	12	35	109.55	229.2	15.39	59.7	94.16
	12	40	110.11	230.2	15.94	60.7	94.17
	12	45	110.67	231.2	17.06	62.7	93.61
	12	50	111.17	232.1	16.78	62.2	94.39
	12	55	111.55	232.8	16.17	61.1	95.38
	1	00	111.83	233.3	15.44	59.8	96.39
	1	05	109.55	229.2	15.56	60.0	93.99
	1	10	111.28	232.3	15.56	59.9	95.78
	1	15	111.83	233.3	16.11	61.0	95.72
	1	20	112.50	234.5	15.94	60.7	96.56
	1	25	112.89	235.2			
	1	30	113.17	235.7			
	1	35	113.33	236.0	16.00	60.8	97.33
	1	40	113.33	236.0	14.83	58.7	98.50
	1	45	112.89	235.2	14.44	58.0	98.45
	1	50	112.11	233.8	14.39	57.9	97.72

SOURCE: S. P. Langley, *Researches in Solar Heat*, U.S. Gov't Printing Office, 1884.

(965–1039 A.D.). Arab contemporaries of Alhazan used spherical concave mirrors made of Damascus steel for distillation purposes.

Europeans had translated Alhazan's works on mirrors into Latin by the late Twelfth or early Thirteenth Century, and they were commonly used as textbooks for several centuries thereafter, stimulating the imagination of early European scientists such as Witelo and Roger Bacon (both of whom lived during the Thirteenth Century). Bacon and Witelo wrote works on mirrors which became standard references. (Bacon dreamed of giant mirrors being used as weapons of war to burn armies and cities.)

The 17th and 18th Centuries More than 300 years passed before the first experiments with concave mirrors were reported in Europe. One of the first to write about his experiments was Maginus, an Italian astronomer. He constructed a spherical concave mirror in 1619, which had a diameter of 0.509 m (1.67 ft) and could melt lead. Villete, a 17th Century French optician from Lyons, surpassed Maginus' feat by building even larger spherical concave mirrors. The largest of the five he built measured 1.16 m (3.8 ft) in diameter. All were made of an alloy of copper, tin, and tin glass. One of the reflectors, built in 1662, measured 0.763 m (2.5 ft) in diameter and weighed more than 50 kg (110 lb). Its focal line of 1.76 cm (0.66 in) was located at a distance of 0.97 m (3.19 ft) from the center of the mirror. The reflector could be moved to track the sun, and the reflected rays had the ability to pierce through a silver 15-pence piece in 24 s and to melt a small piece of pot iron in 40 s, an iron nail in 30 s, and a steel watch spring in 9 s.

In 1718, two independent researchers, J. Harris and J. T. Desaguliers, tested one of Villete's solar reflectors. Between 9 A.M. and noon on a June morning, they placed various objects at the mirror's focal line and observed that:

1. Copper ore vitrified in 8 s.
2. Iron ore melted in 24 s.

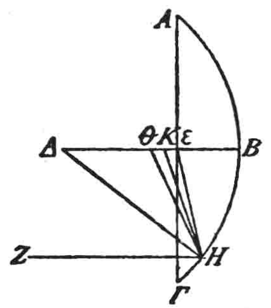

Fig. 1.4 Line focus of spherical mirror. (*From Huxley, "Anthemius de Tralles."*)

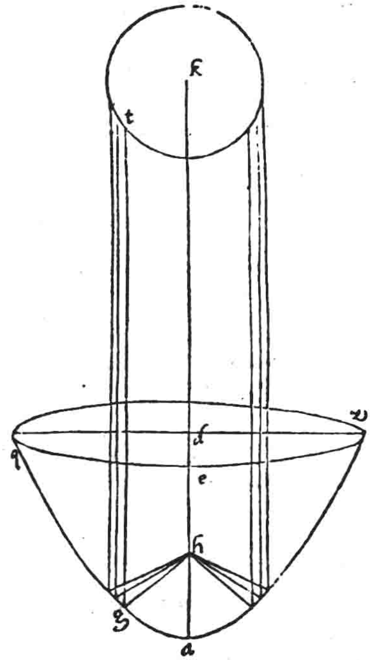

Fig. 1.5 Point focus of parabolic mirror. (*From Vitello, "Perspective."*)

3. A silver sixpence melted in 7.5 s.
4. Cast iron melted in 16 s.
5. Tin melted in 3 s.
6. Slate melted in 3 s and was pierced through in 6 s.
7. An emerald melted into a substance resembling turquoise.
8. A diamond weighing 25.92×10^{-5} kg (4 gr) lost 87 percent of its weight.

In 1687 the Baron of Tchirnhausen built the largest and most powerful mirror that had yet been made using a single piece of material. Measuring 1.7 m (5.57 ft) in diameter, the mirror was constructed of plate copper less than twice as thick as an ordinary knife blade. The reflector weighed much less than the ones built by Maginus or Villete, which were made of an alloy. As a result the Baron's reflector was much easier to operate, requiring only one person to move it.

A contemporary of Tchirnhausen, from Dresden, simplified the technique of mirror construction. He made a concave shape out of wood, applied pitch mixed with wax to the inner surface of the concavity, and covered it with gold leaf.

Despite such attempts at improving the construction of mirrors, metallic reflectors built from 1619 to 1755 remained relatively small. This was because alloy mirrors were made by melting the alloy in a concave mold, removing the hardened form, and polishing it—a relatively costly process which put constraints on size. The bulk and weight of alloy reflectors also made them difficult to operate. Mirrors of gilded wood had the advantage of being lighter, but they did not reflect as well as those made of alloy, and they deteriorated rapidly. Hand-built mirrors of plate copper were limited by problems of size and cost. Consequently, during this period scientists used solar-focusing reflectors for spectacular demonstrations rather than practical purposes.

P. Hoesen of Dresden invented a technique that overcame the difficulties of early mirror-building methods. He conducted his work during the late 1750s, although the results were not widely reported until 1769. Hoesen used a concave parabolic shape made out of segments of hardwood and lined the cavity with thin plates of highly polished brass. By adjusting the plates with great precision, he minimized the size of the junctures between the sections so they could hardly be seen. This method allowed him to build comparatively inexpensive, lightweight mirrors with sufficient focal length and relatively large dimensions. For example, one of his devices had a diameter of 3.08 m (10.1 ft) with a focal line of less than 0.013 m (0.043 ft).

The power of Hoesen's mirrors can be attested by the following experiment with one of his smaller devices, 1.55 m (5.08 ft) in diameter:

1. A piece of silver in green talc rock melted in 1 s without any trace of smoke. At the end of a minute, the stone melted.
2. Copper ore melted in 1 s.
3. Tin ore melted in the first second. After a minute of fusion, many grains of tin escaped and the stone changed into a dark glassy substance.
4. Lead melted at the blink of an eye. At the end of 3 s, it flowed in the liquid state.
5. A piece of black striated hematite began to melt after 4 s, without smoke. In 10 min several globules of perfect iron were found adhering to the stone.
6. Asbestos changed into a yellowish-green glass at the end of 3 s.
7. Slate became a black glassy material after 12 s.
8. A half-crown from Saxony began to melt immediately. A hole was pierced through it in 3 s.
9. An iron wheel melted in 3 s and began to flow in 5 s. Large droplets, looking like big peas, fell from the mass, reunited, and appeared to form a green-colored glass.

Unfortunately, although Hoesen's solar reflectors were effective and used by other experimenters, no practical purpose was found for them during this period.

SOLAR-POWERED ENGINES

The First Solar Engines, 1860–1904

August Mouchot, 1860 In 1860, French professor of mathematics August Mouchot began the first scientific investigation of the practical applications of solar power. At this time France was experiencing phenomenal industrial growth but had to import nearly 70 percent of its coal from Belgium and England. With coal prices increasing at nearly 10 percent per year, Mouchot saw vast potential for solar power in France as well as in its colonies.

Drawing from the work of de Saussure, Mouchot conducted his initial experiments with a hot-box. The results disappointed him, and he decided to design his own solar receiver. It consisted of a blackened copper cauldron placed under a glass bell jar mounted on a wooden insulating block. Mouchot placed a number of silvered metal reflectors around the circumference of the apparatus, creating the first primitive solar boiler. It could raise the temperature of 4×10^{-3} m³ (1.05 gal) of water from 10°C (50°F) to 100°C (212°F) in less than an hour. He later connected a small steam engine to the boiler and demonstrated the first solar-powered engine.

The success of these experiments persuaded the fuel-short French government to sponsor Mouchot's research. Working in Tours, in 1872 he constructed an even larger solar-powered engine (Fig. 1.6). The solar concentrator was a silver-plated copper mirror in the shape of a truncated cone—2.6 m (8.5 ft) in diameter at the aperture and 1 m (3.28 ft) at the base. The boiler was situated in the center of the mirror along its vertical axis. Similar to the first solar boiler Mouchot had made, it consisted of a blackened cauldron set inside a glass bell jar. The mirror focused the direct rays of the sun onto the entire length of the boiler which was 0.79 m (2.6 ft) long. The whole device was mounted equatorially, and rotated at 15°/h to track the sun. The solar-powered boiler could produce 0.14 m³ (37 gal) of steam per minute at a pressure of 101 kPa (1 atm). A reciprocating engine adapted to the boiler produced 373 W. Later Mouchot used an engine to pump water.

Continuing his research in 1878, Mouchot built a solar engine for the Universal Exposition in Paris (Fig. 1.7). The mirror was nearly 5 times larger than the one he had constructed 6 years earlier, measuring 5.04 m (16.4 ft) in diameter at its widest point and 1 m (3.28 ft) at the narrowest. The reflector was so well balanced that it required a force of only 22 N (5 lb) to rotate it. The boiler had a different design than the first model. It consisted of a series of vertical tubes which were encased under glass and located along the linear focus of the mirror. Under a clear sky the machine could boil 0.07 m³ (18.5 gal) of water in 30 min, generating a pressure of 608 kPa (6 atm). Mouchot won a gold medal for the device from the Paris exposition.

The following year the French government sent Mouchot to Algeria to study the industrial feasibility of solar engines. He performed a number of experiments there in chemical distillation and irrigation using solar power. At the same time, the government also commissioned two

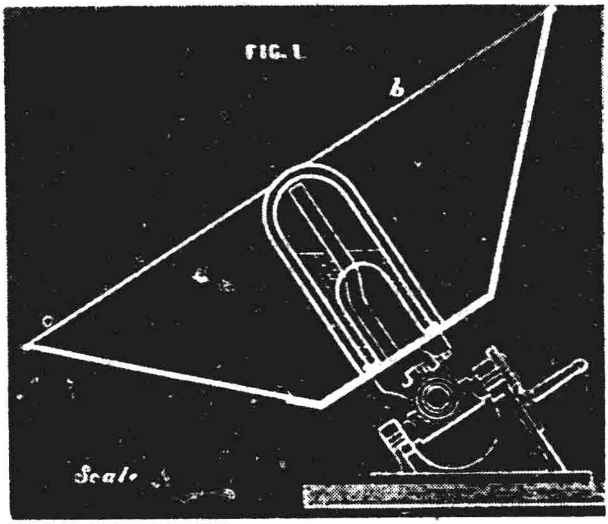

Fig. 1.6 Mouchot's first major sun machine. (*From A. B. Mouchot, "Solar Heat and Its Industrial Applications."*)

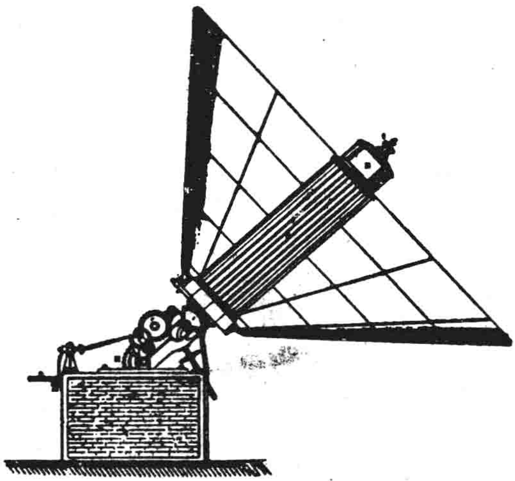

Fig. 1.7 Mouchot's sun motor for the Universal Exposition, 1878. (*From A. B. Mouchot, "Solar Heat and Its Industrial Applications."*)

independent engineers to run a year-long study of Mouchot's invention. After reviewing Mouchot's and the engineers' test results, the government concluded that the cost of constructing and maintaining the silver reflectors was excessive and therefore such solar motors could not meet the demands of commerce. The government withdrew its financial support and Mouchot ended his research.

John Ericsson, 1870 John Ericsson, a prominent American engineer most noted for his design of the Civil War battleship *Monitor*, began solar experiments at about the same time as Mouchot. In the late 1860s he wrote that the potential of solar motors was far beyond calculation, and declared he would dedicate the rest of his life to solving the problems of solar energy application.