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Manufacturing with the Sun

Lawrence M. Murphy
Steven G. Hauser
Richard J. Clyne

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National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
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MANUFACTURING WITH THE SUN

Lawrence M. Murphy
Steven G. Hauser
and
Richard J. Clyne

National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
1617 Cole Blvd.
Golden, CO 80401

ABSTRACT

Concentrated solar radiation is now a viable alternative energy source for many advanced manufacturing processes. Researchers at the National Renewable Energy Laboratory (NREL) have demonstrated the feasibility of processes such as solar-induced surface transformation of materials (SISTM), solar-based manufacturing, and solar-pumped lasers. Researchers are also using sunlight to decontaminate water and soils polluted with organic compounds; these techniques could provide manufactures with innovative alternatives to traditional methods of waste management. The solar technology that is now being integrated into today's manufacturing processes offers even greater potential for tomorrow, especially as applied to the radiation-abundant environment available in space and on the lunar surface.

INTRODUCTION

Researchers at the Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) are developing advanced manufacturing processes that are powered by the sun. These processes are offering industry viable alternatives for accomplishing many of today's manufacturing tasks, and they are likely to be a key ingredient in solving energy problems in tomorrow's advanced manufacturing environment. The advanced solar manufacturing research is managed through NREL's Mechanical and Industrial Technology Division, which is dedicated to bringing American industry practical renewable alternatives that reduce or replace fossil-fuel-based sources of energy.

Currently, the most promising results related to materials manufacturing have come from using concentrated solar radiation to modify the surface properties of materials used in advanced technology applications. Applications such as transformation hardening of steel, cladding, self-propagating high-temperature synthesis, thin-film deposition, and electronic materials processing have been successfully demonstrated and analyzed at NREL.

The advanced manufacturing research is centered around NREL's high-flux solar furnace, which can achieve solar intensities of up to 50,000 times normal ambient conditions. While using directed energy beams for advanced manufacturing has been understood and integrated in certain applications for more than a decade, researchers are now demonstrating that solar-energy-based processes are economically competitive with traditional methods of materials processing [1].

These processes are also environmentally benign, as all the energy driving them comes directly from the sun. High levels of energy efficiency are achieved because the energy conversion steps inherent in traditional processing—fossil fuel to heat, heat to electricity, electricity back to heat—are eliminated. Reflected, concentrated solar flux is applied directly to the materials being processed.

NREL researchers are also investigating solar-based methods to reclaim process water contaminated with organic compounds. This solar detoxification process uses sunlight in combination with a photocatalyst to destroy aqueous volatile organic contaminants. In the near future, as early as the middle of this decade, this process could be a viable waste management technique to cleanse water used in manufacturing processes and to reclaim polluted water.

NREL's HIGH-FLUX SOLAR FURNACE

New techniques for manufacturing advanced materials are being explored through the use of NREL's solar furnace. The solar furnace began operating in early 1990 and allows researchers to study the properties and applications of very high solar flux. The facility currently has the ability to produce solar flux densities of up to 50,000 suns (5000 W/cm^2). This upper limit rose dramatically recently with a new first-of-its-kind concentrator design. New research directions and applications for this promising technology are continually being discovered.

Figure 1 shows the physical configuration of the solar furnace. The heliostat tracks the sun and reflects incoming solar energy onto the stationary primary concentrator, which consists of 23 individual curved facets (see Figure 2). These facets collectively focus the solar flux at a point in the test facility, which is located just off the primary axis. The long focal length of the primary concentrator produces a 10-centimeter-diameter concentrated beam of approximately 2,500 suns at the center of the target area. When a secondary concentrator is placed at the beam's focus, the peak flux can be increased 10 to 20 times, the upper limit applying to dielectric-filled secondaries.

Three performance characteristics put the solar furnace at the cutting edge of solar industrial process research. The first is the system's ability to produce very high temperatures directly from the sun. (For example, we have melted through a 2-inch alumina fire brick, which has a melting point of 1800ºC, in less than 1 minute.) The second is the extremely high rate of heating made possible by very high solar flux. In certain applications this rate exceeds 1 million degrees Celsius per second. These heating rates produce thermal conditions attainable only through radiant heating processes. The third characteristic is the furnace's ability to deliver the entire solar spectrum (from 300 to 2500 nanometers); this allows researchers to study applications requiring either broad spectrum radiation or a particular frequency, ranging from the infrared to the near-ultraviolet.

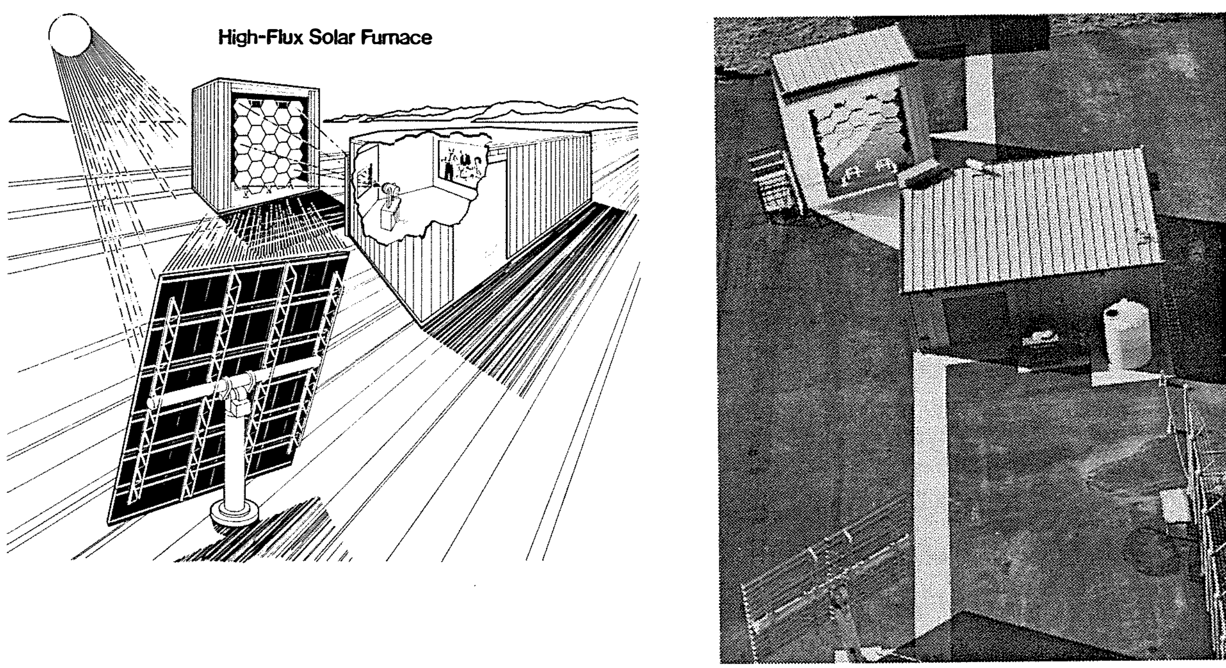


Figure 1. NREL's high-flux solar furnace.
Left: Schematic view of system operation.
Right: The actual facility located on South Table Mountain in Golden, Colorado.

MATERIALS PROCESSING APPLICATIONS

Materials processing is a major area of research at NREL's high-flux furnace facility. Specifically, research pertaining to the solar-induced surface transformation of materials (SISTM), which is ideally suited to the high-flux environment created by the solar furnace, is at the center of these studies. SISTM research uses the thermal energy (as opposed to the photochemical energy) produced from solar radiation. The key to SISTM is the rapid, controlled heating that alters the surface of a workpiece without affecting its base properties. The processes we are developing can be carried out without consuming fossil resources and without producing a host of environmental liabilities.

NREL researchers are refining ways to use solar energy to produce surface modifications that are critical to a number of materials technologies including hardening, cladding, chemical vapor deposition, and the manufacture of electronic components and circuitry. These are currently being fabricated using electron beams, arc lamps, lasers, and induction heating. Preliminary economic analyses indicate that concentrated solar flux, when used in large-scale production applications, could produce these materials at one-half to one-quarter of the cost of production associated with the conventional radiant methods in use today.

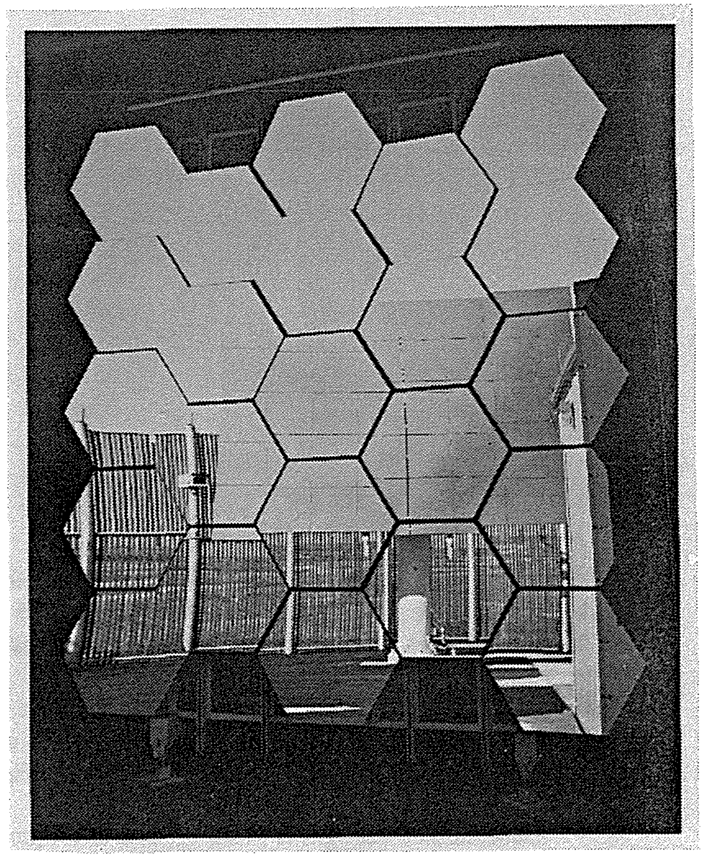


Figure 2. The primary concentrator of NREL's solar furnace. The 23 enhanced-aluminum front-surface mirrors focus the reflected solar flux to a 10-cm-diameter beam inside the test building (not shown). The reflection of the heliostat, which tracks the sun and directs its energy to the concentrator, is shown.

The transformation hardening of steel is typically accomplished using lasers and is being applied most noticeably in the automotive industry for hardening drive-train components. Researchers at NREL have demonstrated that steel can be hardened using solar energy, and have shown that the process is competitive with laser-based techniques [2]. Hardened steel consists of a hard, wear-resistant layer surrounding a softer, steel core. Figure 3 shows a hardened steel sample produced in the high-flux furnace.

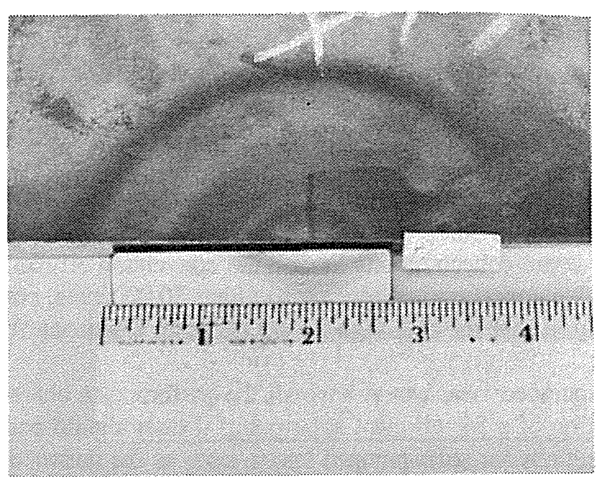
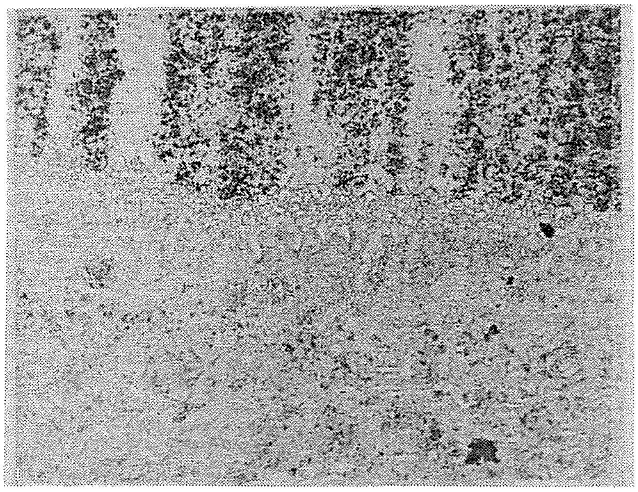


Figure 3. Cross section of solar-hardened steel. The fully hardened region is 1 to 2 mm deep and about 20 mm in diameter.

Using solar radiation to clad preapplied powders to steel substrates has generated a considerable amount of industrial interest. Solar cladding produces excellent



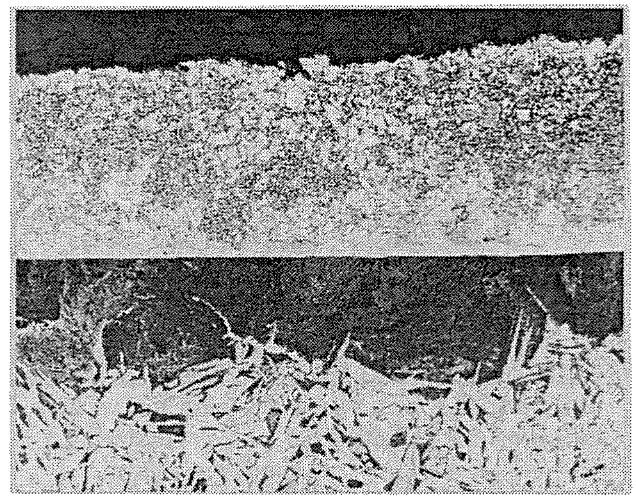


Figure 4. Photomicrographs of alloy coatings formed by solar melting of preapplied powders on steel substrates. Note the high density of the coatings and the good metallurgical bonds between the coatings and their substrates. The images show an area measuring approximately 600 μm by 400 μm.

metallurgical bonds between the melted powder and the substrate. The desirable properties of an expensive material such as a superalloy can be economically obtained by cladding relatively small amounts of this material to a less expensive substrate base such as mild steel. Figure 4 shows micrographs of solar-clad materials.

Concentrated sunlight is being applied to a number of chemical vapor deposition processes. Chemical vapor deposition consists of generating sufficient levels of heat on or near the surface of a given workpiece in the presence of selected gaseous reactants. The heat causes the reactants to form solid products on the surface. Solar furnace technology is well suited to this process because the surface heating can be closely controlled, eliminating the formation of solid product on surfaces other than the specific material of interest. NREL is investigating the chemical vapor deposition process for the production of TiN, TiB_2, SiC, and hard carbon films.

Rapid thermal annealing (RTA), a process that uses radiative heat to accomplish diffusion processes or to remove defects from delicate electronic components such as semiconductors, has traditionally relied on tungsten-halogen lamps as the source of energy. The high level of control required for RTA is easily obtained using concentrated solar radiation; the solar furnace meets the precise requirements of this process. Depending on the materials being annealed, the solar furnace rapidly heats a workpiece to operating temperature and provides the required thermal treatment. RTA studies conducted at NREL's solar furnace include producing high-temperature superconductor films on substrates such as $SrTiO_3$, ZrO_2, and MgO.

SOLAR-PUMPED LASER APPLICATIONS

Recent advances in secondary concentrator systems are causing researchers to reevaluate using concentrated solar flux to pump lasers. The concept of solar-pumped lasers has been studied for more than two decades, but low beam concentrations limited the conversion efficiencies to approximately 1%. With the upper bounds of attainable concentration now approaching 50,000 suns, conversion efficiencies are approaching 5%, which offers the potential for both high power and high efficiency for several types of lasers [3].

A solar-pumped laser would have all the performance characteristics of traditionally powered devices, and a demonstration of a 5%-efficient solar-pumped laser should occur in mid-1992. Researchers are developing innovative applications for solar-pumped lasers, such as the destruction of toxic compounds (polychlorinated biphenyls, PCBs) and the manufacture of inorganic high-value substances (ceramic carbides and borides) [3].

DESTROYING CHEMICAL WASTES

NREL researchers are studying two distinct solar-based methods to destroy hazardous environmental waste. The first process—the solar detoxification of water—uses low solar concentrations to breakdown organic compounds in contaminated process water and groundwater. The second method—known as gas-phase detoxification—uses the concentrated solar flux produced in the solar furnace to destroy hazardous compounds that have been desorbed from solids and exist in the gas phase.

The first process destroys unwanted organic compounds found in waste water or polluted groundwater. The process works as follows: polluted water is brought into contact with a semiconducting photocatalyst, such as titanium dioxide, which in the presence of sunlight creates highly reactive hydroxyl radicals. These radicals react with the organic compounds and convert them into water, carbon dioxide, and easily neutralized mineral acids such as hydrochloric acid. Because the process requires low solar flux concentrations, the reaction can be initiated using either flat-plate solar panels (one-sun concentrations) or a transparent tube mounted at the focus of a parabolic reflecting trough (up to 30-sun concentrations). This latter design is shown in Figure 5. This process is currently being field tested at a Superfund site and could be available to industry as a waste management tool soon.

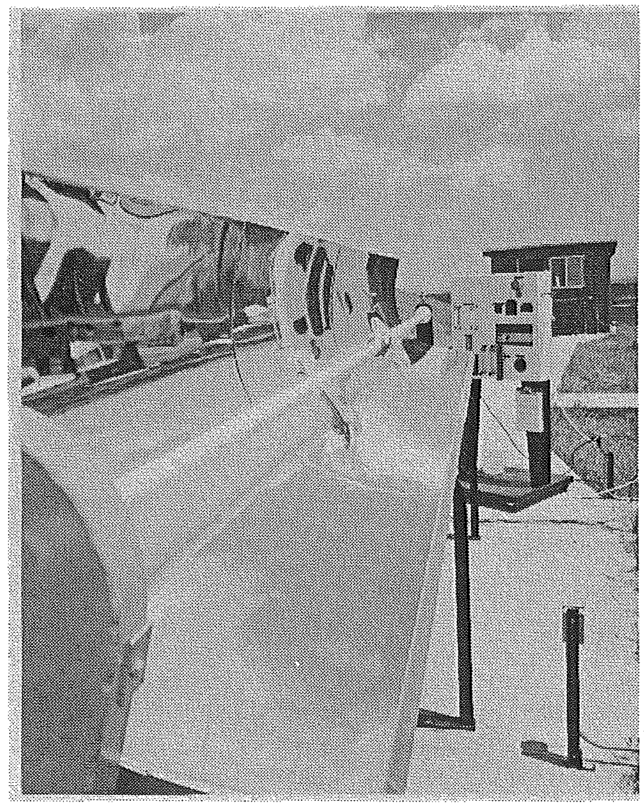


Figure 5. Experimental solar decontamination trough.

Gas-phase detoxification is a hazardous waste destruction method being applied to contaminated solids, such as soils. This process, which is being studied at NREL's high-flux solar furnace, can use energy from throughout the solar spectrum. Typically, a concentration of greater than 300 suns is required to drive the reaction. During the process the contaminants are desorbed from the solid using either vacuum extraction or heat (heat produced by the infrared portion of the solar spectrum can be used for this purpose). After being desorbed, the contaminants are introduced into a reactor (shown in Figure 6) that is mounted at the focus of a solar concentrator system. The near-ultraviolet portion (high-energy photons) of the flux then converts the contaminants to end products such as CO_2, H_2O, and HCl. Catalysts are being studied that can greatly improve the effectiveness of the process.

Both of these methods are remarkably efficient in destroying hazardous organic compounds (exceeding the EPA's 99.9999% requirement), and neither produce the detrimental by-products associated with many of the conventional waste remediation techniques [4]. By the latter part of this decade these methods could become standard tools for decontaminating process waste water, soils, and other contaminated media.

SOLAR MANUFACTURING PROCESSES IN SPACE

The concentrated solar radiation applications that are now being proven and integrated into manufacturing processes here on earth hold even greater potential for use in space. As we strive for a permanent presence in space, the practical issues of energy logistics and efficiency will be crucial to the success of the endeavor. Solar technology is remarkably well suited to supply a large portion of the energy needed in a working space environment.

Concentrated solar radiation technology would produce greater efficiencies in space than attainable in the terrestrial environment. Available solar radiation increases by 70% outside the earth's atmosphere [5], and the ultraviolet portion of the spectrum expands down to 200 nm, providing more energy for photolytic interactions. Also, the direct use of solar radiation would employ a much smaller solar-collecting system because of the high efficiencies inherent in the technology. For example, to attain the same levels of usable power as a direct solar beam system, a photovoltaic-driven arc lamp, which experiences high energy losses converting solar radiation to electricity, would require 10 times the amount of collector surface area; a photovoltaic CO_2 laser system operating at the same level would require a collector 25 times larger than that used for a direct solar beam system. Additionally, the space environment would introduce complications in dissipating the excess heat produced by these conventional technologies [6].

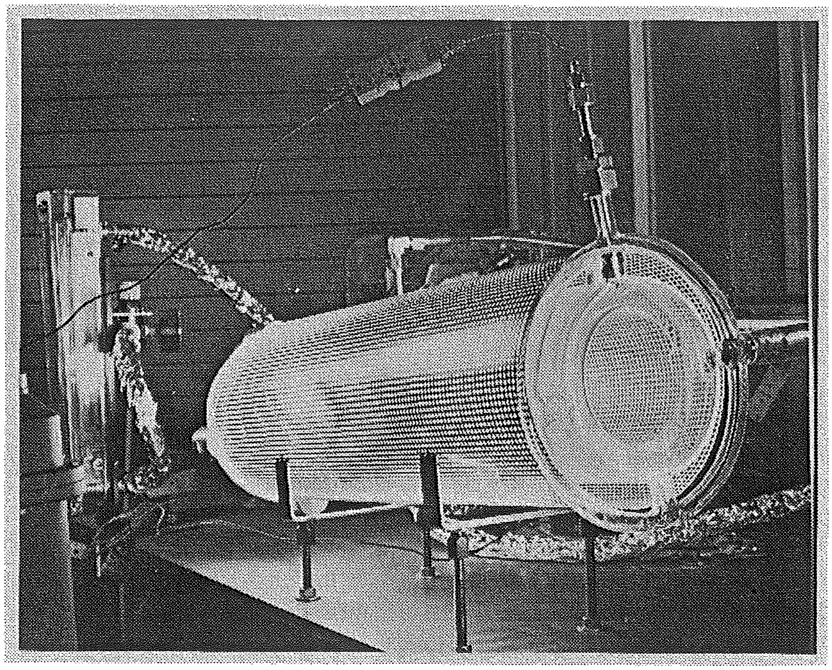


Figure 6. Solar gas-phase detoxification reactor.

In addition to the surface modification applications discussed previously in the Materials Processing section of this paper, a number of other applications are readily identified for using concentrated solar radiation in a space environment. High solar flux could be applied to materials joining, welding, fabricating, repairing, and surface cleaning operations. The technology could also be integrated in lunar mining operations to provide bulk heating for extracting certain products from mined bulk materials. An artist's conception of a lunar-based solar furnace is shown in Figure 7.

Water would be available in limited quantities in any space environment, and solar radiation could be applied to extract water from human waste and reclaim water used in operating processes.

RESEARCH COLLABORATION AND TECHNOLOGY TRANSFER

The long-term success of NREL's research and development projects is tied to working closely with industry and other outside research organizations.

NREL works with industrial partners through a variety of arrangements, including cost-shared demonstrations, joint research, and Cooperative Research and Development Agreements (CRADAs). NREL technology transfer is fostered through written material, presentations, workshops, training programs, and traveling exhibits. Our participation in industry projects, and exchanges between our researchers and their industry counterparts, also play an important role in disseminating technology advances.

Only through close cooperation and information exchange among researchers, manufacturers, and operators will solar-based manufacturing processes continue to make inroads into U.S. industry.

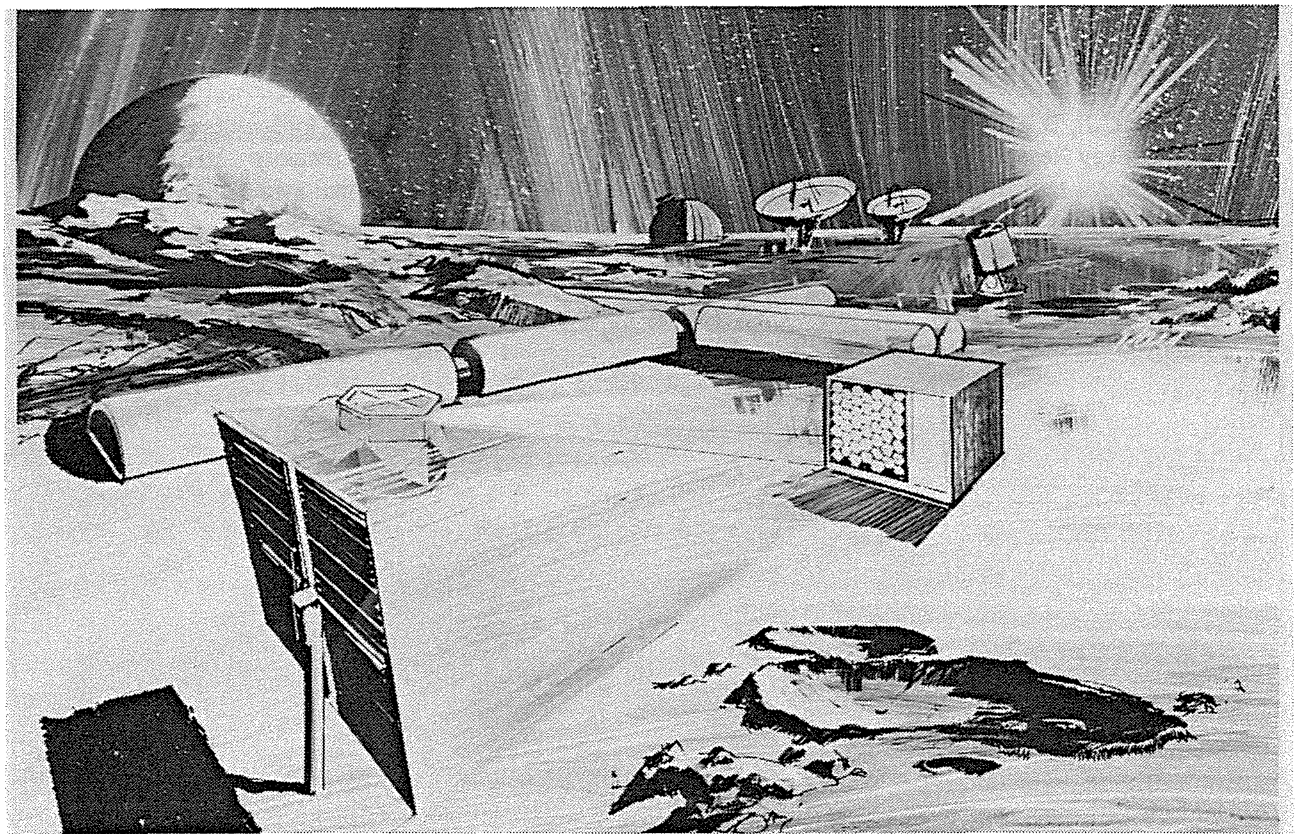


Figure 7. Artist's conception of lunar-based solar furnace.

CONCLUSION

The solar-based manufacturing processes developed at NREL have advanced to the point where they can be considered competitive energy alternatives for many conventional manufacturing applications. One of the most attractive features of solar manufacturing systems is their immunity to fluctuations in the price of fuel; operation and maintenance costs remain extremely stable over the life of a facility.

As this technology gains a foothold in the marketplace, other solar processes currently in the developmental stage will mature. Certainly these advances will play a crucial role in the next generation of advanced manufacturing technology, both on earth and in space.

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