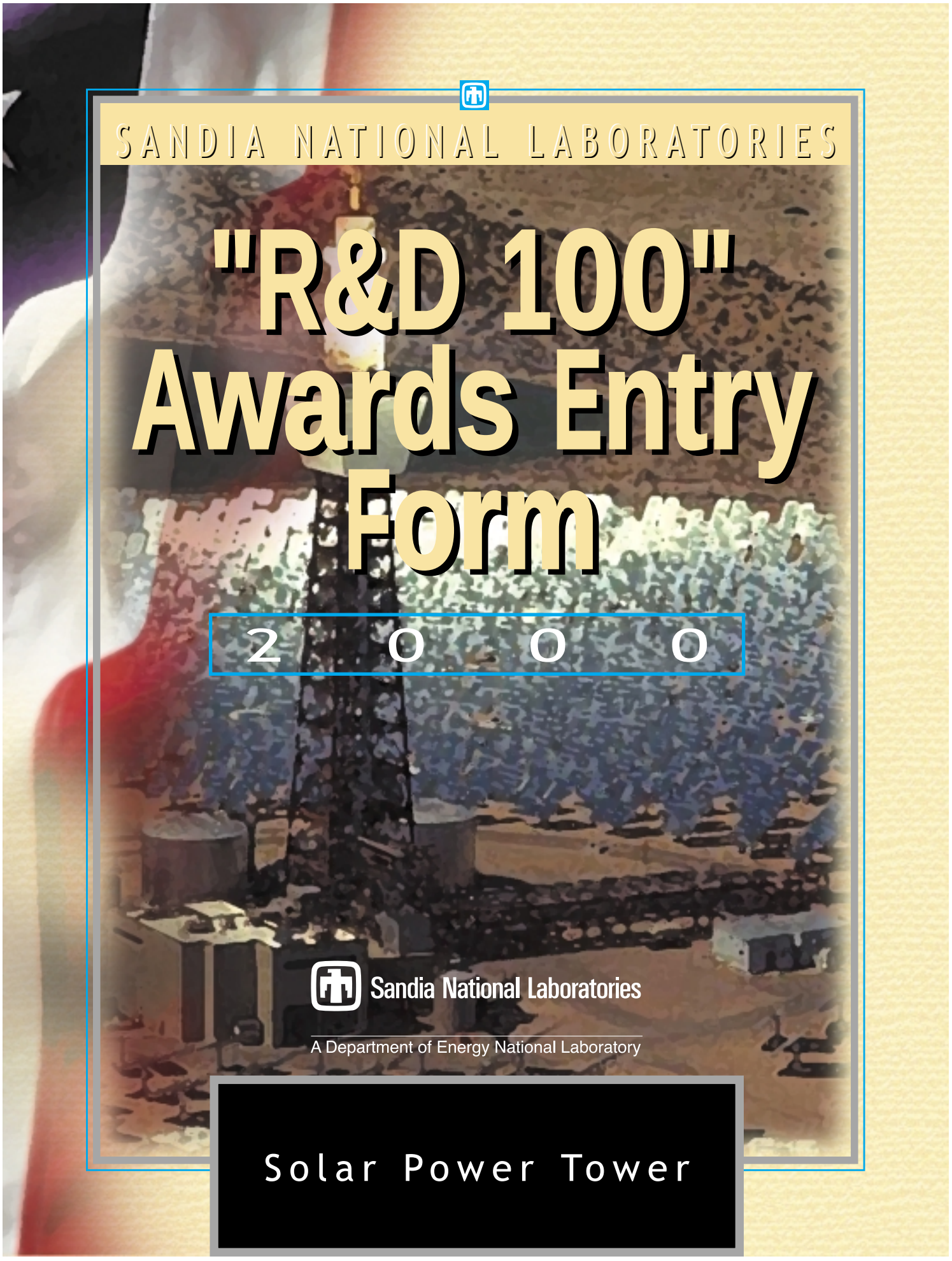
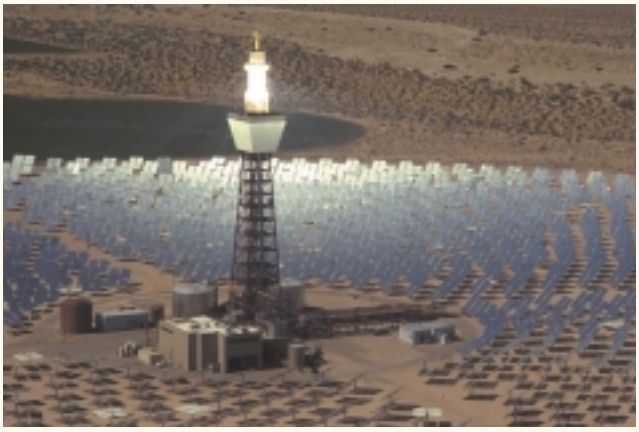

SANDIA NATIONAL LABORATORIES
"R&D 100"
Awards Entry
Form
2000
Sandia National Laboratories
A Department of Energy National Laboratory
Solar Power Tower

2000 "R&D 100" AWARDS
ENTRY FORM



*Solar Two, the prototype power tower, used 1,926 mirrors to produce 10 million watts of electricity.*

1. SUBMITTING ORGANIZATION

Sandia National Laboratories
P.O. Box 5800, MS 0703
Albuquerque, NM 87185-0703

Submitter's Name:
Hugh E. Reilly,
Senior Member of Technical Staff
Solar Thermal Technology Department

Phone: (505) 845-9811
Fax: (505) 844-7786
Email: hereill@sandia.gov

AFFIRMATION
I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Signature: _____

2. JOINT ENTRY WITH…
This is a joint entry with the following four companies.

Bechtel Corporation
P.O. Box 193965
San Francisco, CA 94119-3965
Submitter: William R. Gould
Phone: (415) 768-2342
Fax: (415) 768-3580
Email: wrgould@bechtel.com

The Boeing Company
499 Boeing Blvd., MC JW-63
P.O. Box 24002
Huntsville, AL 35824-6402
Submitter: Walter E. Collier
Phone: (256) 461-2144
Fax: (256) 461-3045
Email: Walter.Collier@HSV.Boeing.com

The Solar Two Consortium, represented by
Southern California Edison Company
300 N. Lone Hill Avenue
San Dimas, CA 91773
Submitter: Larry D. Hamlin
Phone: (909) 394-8667
Fax: (909) 394-8966
Email: hamlinld@sce.com

The National Renewable Energy Laboratory
1617 Cole Blvd.
Branch 4710/105-03
Golden, CO 80401-3393
Submitter: Mary Jane Hale
Phone: (303) 384-7453
Fax: (303) 384-7495
Email: maryjane_hale@nrel.gov

*The solar central receiver at Solar Two.*

3. PRODUCT NAME
Solar Power Tower

4. BRIEF DESCRIPTION OF ENTRY
(25 words or less, e.g., balance, camera, nuclear assay, etc.)

A 10- to 400-megawatt power plant capable of producing clean electricity both night and day from solar energy.

5. WHEN WAS THIS PRODUCT FIRST MARKETED OR AVAILABLE FOR ORDER? Proof of actual sale or intent to sell must be submitted (i.e., invoice, marketing brochure, or a 1-page letter from a company using your product).

April 1999

As the prototype plant (Solar Two) completed operations on April 8, 1999 in Daggett, Calif., solar power towers were presented to a number of interested parties and project developers. Three of these parties since have agreed to pursue a power-tower project. Bechtel Corp., The Boeing Company, and Ghersa, a Spanish company, are planning a solar power tower plant in Spain. Their intentions are illustrated by reservation of the name of their partnership, as illustrated by the notice in the Appendix.

Addendum: This product was previously judged in 1996 under the title, "Molten Salt Solar Central Receiver Power Plant," when the prototype plant (Solar Two) first began operation. At that time, the key customers of this product were regulated utilities in the southwestern United States seeking renewable technologies that could shift power generation to meet peak load demands—which is a key feature of this product. In the late 1990s, the movement to deregulate utilities prompted these utilities to sell their generation capacity. Therefore, they no longer were interested in any new generation (conventional or renewable power). In fact, most U.S. utilities are selling their power generation, often to independent power producers.

At the same time, interest greatly increased regarding global greenhouse-gas emissions. Several countries signed onto the Kyoto Protocol to reduce $CO_2$ emission to 1990 levels. For example, on Jan. 1, 1999, King Juan Carlos of Spain signed a Royal Decree (enacted by the Spanish government) stipulating that utilities in Spain must pay a premium for solar-generated electricity—equal to $0.25 per kilowatt-hour. His goal was for renewable energy to meet 12 percent of Spain's power needs. During the same period, the World Bank began providing grants in several countries (such as Mexico, Morocco, Egypt, and India) to field new solar technologies (like power towers) to reduce $CO_2$ emissions and meet their power demands. In most of these countries, the power demand peaks after sunset and into the night. In the United States, several states are considering renewable-energy portfolios, which also require higher prices to be paid for electricity generated from renewable sources.

The successful completion of the Solar Two project in 1999 has reduced the financial risk of commercial power-tower projects. In addition, changing market conditions have dramatically increased the value of solar power towers. Instead of the electricity value from these solar

plants being based solely on their ability to meet peak demands, there is real value placed on being able to positively reduce greenhouse-gas emissions.

Other solar technologies cannot store solar energy as efficiently or cost-effectively and dispatch electricity on demand. Solar power towers can supply clean electricity on demand with no emissions, and are uniquely able to efficiently store solar energy. Other solar technologies (like photovoltaics) do not have cost-effective energy storage and, thus, only produce electricity during daytime periods. Solar Two demonstrates that the technology is practical on a large scale. For these reasons, and more, the partnership mentioned above (a non-utility partnership) decided in 1999 to aggressively pursue construction of a solar power-tower plant.

## 6. INVENTOR OR PRINCIPAL DEVELOPER

The development team consisted of:

- Bechtel Corp.,
- The Boeing Co.,
- the Solar Two Consortium, and
- Sandia National Laboratories, with support from the National Renewable Energy Laboratory.

## 7. PRODUCT PRICE

Electricity for sale at $0.15/kW hour (1st unit)
Electricity for sale at $0.05/kW hour (5th unit, similar to a coal power plant's price)

Price is proprietary: Yes

## 8. DO YOU HOLD ANY PATENTS OR PATENTS PENDING ON THIS PRODUCT?

Yes

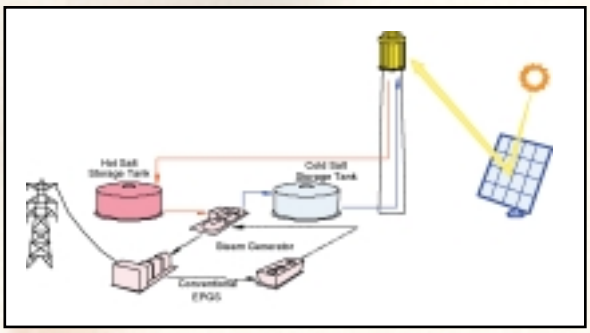
The Boeing Corporation holds two patents regarding the receiver technology.

*Heliostats tracking the sun at Solar Two.*

## 9. PRODUCT'S PRIMARY FUNCTION

The primary function of a solar power tower is to produce clean electricity for the world's electricity grids. Solar power towers:

- Dispatch electricity to the grid when needed—even at night or around-the-clock,
- Are unique among solar electric technologies in their ability to efficiently store solar energy,
- Are non-polluting and do not release greenhouse gases, and
- Will be the lowest-cost solar electricity.



The concept is simple: A few thousand heliostats (mirrors that continuously track the sun) concentrate sunlight onto a central receiver (a high-tech heat exchanger) that sits atop a tower. The central receiver heats molten salt at 290°C, pumped from a "cold" storage tank, to 565°C, where it flows to a "hot" tank for storage. When the grid load dispatcher decides electricity is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a turbine/generator. The salt then is returned to the cold tank, where it is stored and eventually reheated in the receiver to complete the cycle.

The salt storage medium is a common fertilizer, a mixture of 60% sodium nitrate and 40% potassium nitrate. It melts at 220°C and is always molten in the "cold" storage tank. Molten salt is used because it is inexpensive and provides for efficient storage (99%); it is liquid at atmospheric pressure and its "hot" operating temperature perfectly matches the needs of today's high-pressure and high-temperature steam turbines. The molten salt is safe since it is nonflammable and nontoxic.

The collector field, salt storage capacity, and the receiver are optimally sized for the needs of the utility. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum rate of energy consumption by the turbine. Storage tanks can be designed with enough capacity to power a turbine at nearly full output for 24 hours per day and up to 70% of the total hours in a year—as compared to 24% if electricity were only generated when the sun shines.

The readiness of power tower technology is illustrated by the successful completion of the Solar Two project in 1999 (see Appendix for Aug. 30, 1999 press release). Solar Two was a partnership between government and private parties to complete the development of solar power towers. Solar Two was the world's largest power tower, producing 10 MW of electricity with enough thermal storage to operate the turbine for three hours at full capacity.

Solar Two has mitigated the risk associated with the first commercial power tower plants now being offered for sale in four countries by proving that the technology is practical on a large scale. Solar power towers in the 10–400 MWe range can now be built—and indeed, design of the first plant in Spain is now underway.

## 10A. PRODUCT'S COMPETITORS
(by manufacturer, brand name, and model number)

The nearest solar competitor to solar power towers is solar trough technology [e.g., Solel (Israel) and Pilkington Solar (Germany)]. However, troughs do not have cost-effective thermal storage. Other grid-connected renewable energy competitors are photovoltaics, wind, hydro-electric, and biomass. We also compete with all conventional, intermediate load, and grid-connected electricity generating technologies including coal, gas, and nuclear. However, unlike our competitors, power towers do not emit pollution.

## 10B. PRODUCT'S AND COMPETITORS' KEY FEATURES MATRIX
[include both numerical (data) and descriptive (written) comparisons]

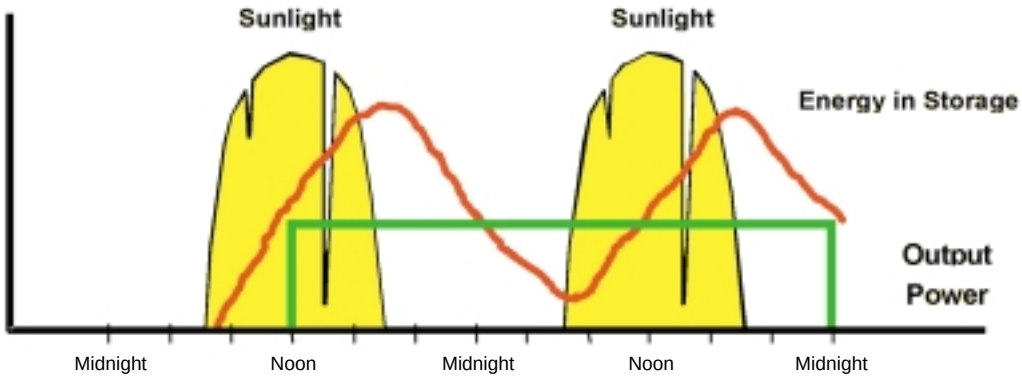
The following table compares cost and performance for currently available grid-connectable solar energy alternatives.

| | COST EFFECTIVENESS | | | PERFORMANCE | | |
|---|---|---|---|---|---|---|
| | Electricity cost of 200 MW plant | Installed cost of energy storage for 200 MW plant | Lifetime of storage system (years) | Annual roundtrip storage efficiency | Maximum capacity factor of optimized system | Annual solar to electric efficiency |
| POWER TOWER | $0.06/kWhr | $23/kWhr$_e$ | 30 | 99 percent | 70 percent | 17 percent |
| SYNTHETIC OIL PARABOLIC TROUGH | $0.12/kWhr | $200/kWhr$_e$ (appx.) | 30 | 95 percent | 24 percent** | 13 percent |
| PHOTOVOLTAICS WITH BATTERY STORAGE | $0.25/kWhr | $650/kWhr$_e$* | 7.5 | 76 percent | 24 percent** | 10 percent |

* This investment would be required four times to match lifetimes of the other storage options.

** Because of the high storage cost, economically optimized trough and photovoltaic systems do not have storage.

Power tower technology is the only solar energy alternative that cost-effectively includes storage, a prerequisite to the long-term viability of utility-scale solar electricity. With thermal energy storage, solar power-tower plants can be designed with up to 70% capacity factors. The other solar technologies without storage are limited to 24%. Higher capacity factors mean larger contributions to the electricity grid from solar and a solar electricity source that is economically attractive.




By integrating 13 hours of thermal storage into the design, a power tower can operate around the clock. Other solar technologies (like photovoltaics) do not have cost-effective energy storage and, thus, only produce electricity during daytime periods.

## 10C. DESCRIPTION OF PRODUCT'S IMPROVEMENT OVER COMPETITORS

(BE SPECIFIC! Include such items as how much faster, how much less cost, etc.)

Power tower technology improves upon existing solar electric technology in its ability to store energy efficiently and dispatch electricity when needed, at night or during cloudy weather. Other solar technologies cannot store energy economically; when storage is added to other solar technologies, electricity cost increases; in a power tower, electricity cost decreases for storage sizes up to 13 hours. Consequently, the solar power tower is the most inexpensive technology for generating utility electricity from solar energy. Furthermore, decoupling solar energy collection from electricity generation allows the turbine/generator to operate more efficiently by improving instantaneous steam quality and eliminating cloud-induced turbine trips that occur in systems that generate steam directly in the receiver.

Because of storage, power towers can be designed with annual capacity factors up to 70%. This means that a power tower can operate at full capacity for 70% of the year without using fossil fuel as a backup. Thus, power towers can deliver power to meet nearly base-load power demands. No other solar technology can even come close to making this claim.

A solar power tower has no emissions; the most significant environmental impact is the land required for the collector field, about 10 acres per megawatt, which is significantly less than a hydroelectric project, and about the same as a coal power station, when mining operations are taken into account.

*The thermal storage system at Solar Two. Pictured are the 230,000-gallon hot (left) and cold (right) salt storage tanks. The steam generator is in the center. These high-temperature tanks are the largest of their kind in the world.*

## 11A. PRODUCT'S PRINCIPAL APPLICATIONS

The principal application for this technology is solar-only, grid-connected, clean electricity production.

The technology is now entering the commercial sector and costs will be competitive with many of the alternatives. The dispatchable feature of power towers makes them far more valuable to electric utilities than other solar technologies that produce intermittent power. As a renewable energy technology, a power tower produces $CO_2$-free electricity and slows the greenhouse effect.

Now that Solar Two has successfully demonstrated power tower technology, the first commercial plants now for sale in Spain, Egypt, Morocco, and Mexico will be approximately three times larger than Solar Two. These countries are targeted for market entry because financial incentives exist in each of these countries to reduce $CO_2$ emissions.

For example, the country of Spain has signed the Kyoto Climate-Change-Convention Protocol and plans to obtain 12% of its primary energy needs from renewables. On Jan. 1, 1999, Spain passed the Royal Decree which stipulates that above-market rates will be paid for solar-generated electricity. U.S.-based Bechtel, Boeing, and Sandia have joined forces with Spain's Ghersa Co. and began planning the first commercial power tower plant in Spain. Several other orders are expected following this commercial plant. As other countries become committed to the Kyoto Protocol, the market for $CO_2$-free electricity sources will skyrocket. The Electric Power Research Institute has estimated that total possible market penetration by solar photovoltaics (without storage) will be limited to only 10% of total grid capacity. Total market penetration will be much larger for power towers than for an intermittent solar technology (like photovoltaics) without storage. This is due to the combination of high annual-capacity factor (the fraction of the year that the plant produces power at its full capacity) and the fact that energy storage will allow power to be brought onto the grid in a controlled manner. In other words, the inclusion of storage reduces electrical transients and results in a more stable overall utility grid.

Because solar power towers can lead to much greater than 10% of a grid's capacity, they are capable of providing a very substantial contribution to worldwide $CO_2$ reduction efforts. Of all the renewable technologies available for large-scale power production today and for the next few decades, a solar power tower (because it uses conventional technology and is easy to scale-up) is one of few with the potential to make major contributions of $CO_2$-free electricity, at a reasonable price.

Furthermore, the majority of the plant-unique hardware (heliostats, receiver, storage tanks) can be built in the target countries with in-country labor. Solar photovoltaics cannot make these claims because this technology suffers from high cell costs and high energy storage costs, and because special-purpose facilities must be built to manufacture the solar cells.

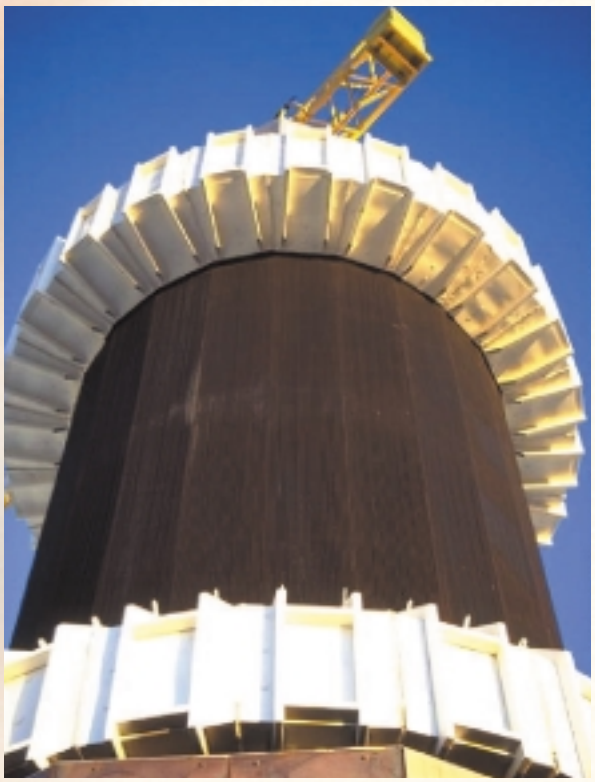
## 11B. THE PRODUCT'S OTHER POSSIBLE CURRENT APPLICATIONS

In addition to the solar-only configuration, other possible applications are solar/coal and solar/natural gas hybrid systems.

## 11C. POTENTIAL APPLICATIONS AND WHY NOT CURRENTLY FEASIBLE FOR PRODUCT

Other applications for solar power-tower technology are

- Solar hydrogen production, and
- Storage and transport of heat for large industrial processes.



Solar hydrogen could be produced from electricity (in which case the technology is ready) or directly using solar heat. The latter application would require the development and demonstration of the associated chemical processes. Storage and transport of thermal energy could be accomplished through the use of a reversible chemical reaction that is endothermic at the solar end and exothermic where the heat is required. This concept has been under development for a number of years, but still requires large-scale demonstration to become technically viable.

*Close-up of the Solar Two receiver, designed to absorb solar concentrations over 800 times natural sunlight.*

12. SUMMARY OF PRODUCT'S IMPORTANCE AND BENEFITS
(in layman's terms why you feel your product should receive an R&D 100 Award. Why it's important to have this product? What benefits will it provide?)

Solar power tower technology deserves an R&D 100 Award for two important reasons: 1) technical excellence, and 2) it helps solve global energy and environment problems.

Technical Excellence

Though simple in concept, many challenging engineering problems were overcome to make power tower technology a commercial product. For example, the receiver is similar to the tubes in a fossil-fired boiler, but it is "fired" by radiant sunlight that very rapidly changes input intensity on a frequent basis. The engineering of a resilient receiver capable of withstanding this harsh operating environment required several advanced design features at Solar Two:

- Laser welding,
- Hi-tech materials capable of absorbing a solar concentration of 1,000 suns,
- A sophisticated tube expansion and contraction system, and
- Receiver control via non-contact solar-flux measurement devices.

Another engineering challenge was the practical use of the heat-transfer fluid. Molten salt can be tricky to handle; it freezes at 220°C, has low viscosity, and wets metal surfaces extremely well. An important element in the successful implementation of this technology was the identification of pumps, valves, valve packing, gasket materials, and heat tracing that work with molten salt.

Solar Two achieved the following major breakthroughs in utility-scale solar power technology. It:

- Routinely produced electricity during cloudy weather and at night,
- Delivered power to the utility grid 24 hours/day for 7 straight days, and
- Demonstrated a 97% energy-storage efficiency.

The development of solar power-tower technology (and its successful implementation at Solar Two) culminates years of effort. It brings utility-scale solar electricity from an idealistic concept to commercial reality. In designing a power tower, the size of the turbine, the fraction of the day it is in operation, and the period when it operates all are completely flexible. The plant's efficient thermal storage system provides dispatchability, and by adjusting the size of the solar field and the size of the storage tanks, the capacity factor can be tailored to meet the specific needs of the utility. No other solar energy technology can claim this degree of versatility.

Helping to Solve Global Energy and Environmental Problems

Initial commercial power-tower projects are planned for Spain, Egypt, Mexico, and Morocco. A consortium of U.S. and Spanish companies is currently developing the *Solar Tres* power plant for Spain to help meet its commitment to the Kyoto Protocol. As more countries get serious about global warming and $CO_2$ reduction, a huge market will develop for solar power towers.

Solar power towers will be the preferred solar electricity source because they are the only solar technology with a low cost and highly efficient energy storage system that makes it economically feasible to operate 24 hours per day and 70% of the hours in a year. Electricity from power towers will be priced competitively and should be affordable by the nations of the world. Initial deployments are planned in sunny countries, but as the efficiency of power transmission improves, it will be possible to provide solar power to most of the world's
population centers.

Polls have proven that solar is the "dream" power source that most people would prefer if economics and practical barriers, like nighttime operation, were not standing in the way. Through the successful operation of the Solar Two power tower, solar power's Berlin Wall has begun to fall.

ORGANIZATION DATA

13. ORGANIZATION LEADER

C. Paul Robinson,
President
Sandia National Laboratories
P.O. Box 5800, MS 0101
Albuquerque, NM 87185-0101
Phone: (505) 844-7261
Fax: (505) 844-1120
Email: cprobin@sandia.gov

14. CONTACT PERSON FOR ARRANGEMENTS
(on exhibits, banquet, and publicity)

Patricia M. Keane,
Office Administrative Assistant
Solar Thermal Technology Department
Sandia National Laboratories
P.O. Box 5800, MS 0703
Albuquerque, NM 87185-0703
Phone: (505) 844-0686
Fax: (505) 844-7786
Email: pmkeane@sandia.gov

15. CONTACT PERSON FOR READER INQUIRIES

Hugh E. Reilly
Senior Member of Technical Staff
Solar Thermal Technology Department
Sandia National Laboratories
P.O. Box 5800, MS 0703
Albuquerque, NM 87185-0703
Phone: (505) 845-9811
Fax: (505) 844-7786
Email: hereill@sandia.gov

# *APPENDIX*