

*C.2

SERI/TP-641-782

SERI/TP-641-782
UC CATEGORY: UC-62

PROPERTY OF
U.S. GOVERNMENT

SOLAR ENERGY RESEARCH INSTITUTE
Solar Energy Information Center

OCT 21 1980

GOLDEN, COLORADO 80401

POTENTIAL APPLICATIONS
OF LIQUID METALS IN
SOLAR ENERGY

STEVEN L. POHLMAN

AUGUST 1980

PRESENTED AT THE SECOND INTERNATIONAL
CONFERENCE ON LIQUID METAL TECHNOLOGY
IN ENERGY PRODUCTION, 20-24 APRIL 1980,
RICHLAND, WASHINGTON

PREPARED UNDER TASK NO. 3141.00

Solar Energy Research Institute

A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:

Microfiche \$3.00
Printed Copy \$4.00

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

POTENTIAL APPLICATIONS OF LIQUID METALS IN SOLAR ENERGY

Steven L. Pohlman
Solar Energy Research Institute
Golden, Colorado 80401

ABSTRACT

The employment of liquid metal as a primary heat transfer fluid in solar thermal energy conversion systems has been identified by the Department of Energy as a potential alternative to the use of water/steam. Designs for central receiver power generation plants employing liquid sodium have been developed. Material concerns associated with the use of liquid metal and enhanced by the cyclic thermal nature of solar energy systems have been identified and include: creep/fatigue behavior, general corrosion and mass transport behavior, and thermal fatigue behavior of container materials; alloy development and code qualification of receiver materials; caustic cracking of steam generator tubes; and a number of secondary concerns.

I. INTRODUCTION

In 1974 the Solar Energy Research Development and Demonstration Act was signed into law, and immediately a program was initiated with the goal to provide the nation with solar energy options for meeting future energy requirements. Solar energy activities are under the jurisdiction of the Office of the Assistant Secretary for Conservation and Solar Energy.¹

On June 20, 1979 President Carter committed the nation to establish a solar energy program that would be capable of producing 20 percent of the projected yearly U.S. energy consumption by the year 2000. This would mean that approximately 18.5 quads (1 quad = 10^{15} Btu) of fossil fuel energy would be replaced by solar energy by the

target date. The goal of the solar thermal program is to produce 5 quads/year by the year 2000.² It is estimated that 2 quads/year will be produced by nonconcentrating heating and cooling systems, 1 quad/year by line-concentrating systems, and 2 quads/year by point-concentrating systems with one-half of that total produced by distributed systems and the other half by central systems.

The DOE Solar Thermal Power Systems Program is focusing its effort on concentrating systems and is divided into three sub-element areas¹:

- Central Receiver Engineering Development
 - Systems and Application
 - Subsystems and Components
- Distributed Receiver Engineering Development
 - Line-Focusing Systems
 - Point-Focusing Systems
- Advanced Technology
 - Material Technology
 - Advanced Subsystems
 - Advanced System/Applications
 - Supporting Programs

II. CENTRAL RECEIVER DEVELOPMENT

The central receiver program is directed towards achieving commercialization of large solar

thermal plants by the mid 1980s using central receiver technology. The central receiver program is geared towards providing energy needs for industrial process heat (IPH), total energy/cogeneration, utilities, and fuels and chemicals processing. As outlined by DOE in their 1980 Solar Thermal Plan, the key elements of their program are based on the achievement of the following goals:²

- To identify temperature and performance requirements for markets (including large and small central receiver applications) with significant potential for reduction in fossil fuel use via solar-generated heat.
- To develop cost goals for systems to serve these markets, carry the cost goals to the component level, and use them as criteria in selecting research and development activities and in measuring progress toward these goals.
- To develop and test a first-generation water/steam pilot plant to establish the technical readiness of the concept and assemble a cost data base with integrated teams composed of users (potential purchasers), industry representatives, and state regulatory officials.
- To develop second-generation, more cost-effective components and subsystems and test them at the Central Receiver Test Facility in order to reach the cost readiness stage.
- To establish a base for a viable heliostat and central receiver manufacturing industry using repowering and industrial retrofit initiatives, allowing for inclusion of second-generation technology.
- To verify the cost readiness of central receiver systems by utilizing third-generation technology.

The major effort for 1980 in the central receiver technology area is the continued construction of the Barstow 10-MW_e pilot plant.¹ Due to the direct impact that developments in liquid metal technology may have on central receiver technology, the Barstow pilot plant will be discussed in detail in Section V.

III. DISTRIBUTED RECEIVER PROGRAM

The Distributed Receiver Program is directed towards achieving widespread commercial use of Solar Thermal Systems incorporating a distributed receiver concept. Two separate receiver concepts, line-focusing and point-focusing, are being developed. The basic strategy of the distributed receiver program is to achieve the following goals:¹

- To improve the efficiency of collectors,
- To increase durability and reliability of collectors,
- To reduce weight of collectors in order to achieve low manufacturing costs,
- To improve system design and reduce costs,
- To accumulate user operating experience through system experiments, and
- To develop a sound solar thermal industrial base by encouraging mass production of distributed collector systems through cost-shared engineering experiments.

The Distributed Receiver Program is directed towards providing energy for midtemperature (under 550° C) industrial heat application; electricity for small communities, irrigation, and remote application; and total energy systems requiring both electric and thermal energy and in case of point-focussing systems achieve higher tempera-

tures to drive chemical reaction up to 1650°C. Even though the technology is presently available for implementation of these systems, long-term reliability and durability must be proven before widespread acceptance by the users can be achieved.

A. Parabolic Trough Receivers

The greatest near-term potential for parabolic trough systems as described by DOE² is in the midtemperature process heat market. A major portion of this energy is currently supplied through direct combustion of natural gas and fuel oil. Initial studies have also shown that the application of line-focusing collector systems to irrigation needs has a high market potential.

Parabolic troughs/line-focusing systems are commercially available but need improvements, e.g.,

- The thermal efficiency of existing systems is below (about 40-50 percent) the calculated potential (about 60-70 percent).
- The durability of existing systems is not fully known but is less than the lifetime required by the marketplace (about 20-30 years).
- Existing technology uses conservative estimates for design load data resulting in some reduction of structure weight.
- Existing technology may not be suited to fabrication using current mass-production materials and techniques, a condition which will be required to meet established cost goals.

B. Point-Focusing Receivers

Another goal of the distributed receiver program is to develop solar thermal power systems to

generate electricity for small community and remote installations and to provide sufficiently high temperatures to drive chemical reactions for fuel and chemical production. Point-focusing receiver technology (parabolic dishes) is the approach intended for this market. The point-focusing units are attractive because of their modularization capability, allowing individual communities to specify size and need. The high-temperature capability of these systems (400°C to 1400°C) allows the use of Brayton and Stirling Cycle heat engines and also calls for some sophisticated material research and development programs.

The technology for low-cost point-focusing collectors is being developed. Receiver and concentrators operating under 800°C are being developed under this program.

IV. Advanced Technology Program

Technology development under the Central and Distributed Receiver Program is directed towards commercial viability of systems by the mid 1980s. Anticipating that these first-generation systems will only be marginally competitive with conventional systems, the Advanced Technology Program was established to initiate research and development activities to improve subsystems, components, and materials that will help increase efficiency or decrease costs of the solar thermal systems. The Advanced Technology Program was also established to support generic research common to all the solar thermal technologies. The primary functions are divided among the following program subelements:²

- Materials
- Advanced Systems and subsystems
- Exploratory Components
- Technology Assessment.

The goals of the Advanced Technology Program are:²

- To identify candidate components, subsystems, systems, processes, and applications for solar thermal;
- To conduct exploratory development and testing of materials, components, and subsystems;
- To test the most attractive systems and processes to establish technical feasibility; and
- To make these systems available to the concentrator programs for engineering experiments.

A. Solar Materials Program

The goal of this program is to achieve improvements in the reliability and the cost to performance ratio of materials which will result in the accelerated implementation and broadened applications of solar thermal systems. The program has been divided into five functional areas: absorber materials, reflector materials, transmitting materials, structural materials, and heat transfer/containment materials.³ During FY80, research projects are being carried out with a goal of: (1) identifying a low-cost, durable, Ag/glass mirror material; (2) developing low-cost stable polymeric materials for reflective and transmitting materials; (3) establishing the high temperature stability of black chrome and black cobalt selective absorber coatings; (4) evaluating optical measurement techniques, (5) evaluating ceramics for high-temperature receivers; (6) developing appropriate measurement techniques and formulating a detailed solar materials property data base; (7) developing optical reflectance standards and (8) initiating work for gaining an understanding of degradation mechanisms in reflectors, transmitters,

absorbers and containers.

Longer-term R&D is planned for: (1) detailed understanding of degradation mechanisms leading to accurate life-time prediction, (2) composite structural materials, (3) intermediate-temperature selective absorbers 600°C, and (4) compatible fluid/alloy containment combinations operating at elevated temperatures. This follows the proposed DOE plans.¹

B. Advanced Systems and Subsystems Program

The advanced systems and applications program supports all major solar thermal technologies. The major areas of application are advanced electric systems, fuels and chemical conversion schemes, and industrial process heat systems (over 550°C).

C. Exploratory Components Program

The advanced components development is designed to provide durable, high-performance, and low-cost components to the various solar thermal programs. Activities include the development of advanced receiver, high-efficiency heat engines and suitable energy storage and transport systems.

V. CENTRAL RECEIVERS

The central receiver collector concept consists of a field of suntracking mirrors, which redirect the sun's radiant energy onto a receiver mounted atop a centrally located tower. The absorbed heat is then transferred to a working fluid circulating through the receiver and is used directly as process heat or to produce steam or hot gas for powering a turbine. The heat transfer fluids being investigated for central receivers include water/steam, molten salts, liquid metals, and hot gases. Each of these fluids possess different advantages, and therefore a variety of proven

transfer fluids is required to ensure the widespread deployment of central receiver systems.

A. Barstow Pilot Plant⁴

Currently, DOE is working with Southern California Edison Company, the Los Angeles Department of Water and Power, the State of California, and several private contractors to construct a 10-megawatt-electric (MW_e) central receiver pilot plant at Barstow, California that will convert solar thermal energy into electrical energy, which will be added to an operating grid system.

The 10- MW_e Solar Central Receiver Pilot Plant is designed to provide development, fabrication, and operating data necessary to demonstrate the technical feasibility of the solar central receiver concept. The Pilot Plant consists of approximately 1900 reflecting heliostats that redirect solar insolation to a central receiver mounted atop a 90-meter tower. The energy collected by the receiver is used to produce superheated steam, which is then used to generate electricity and/or charge storage. Performance of the plant will be studied during five-year test period scheduled to begin December 1981. The plant is being designed for a thirty-year life.

The receiver subsystem is an external single-pass boiler/superheater design that will be mounted atop the central tower. The peak power density at the receiver will be 300 kW/m^2 , with an average influx of 160 kW/m^2 . There are 24 panels of 70 tubes each in the receiver; each tube is 0.50-inch O.D. 0.27-inch I.D. and the exposed portion is 45-feet long. The tubes are to be fabricated from Incoloy 800 and coated with a vitreous refractory metal oxide paint. The tubes are to be welded together longitudinally and continuously along the back side. The welding is designed to improve heat transfer between adjacent tubes, to

reduce shine-through losses, and to distribute the heat load should one of the tubes become plugged. The superheated steam achieves maximum temperatures and pressures of 515°C and 10 megapascals. The maximum metal temperature at the crown is to be below 620°C .

The mechanical response of the receiver tubing will be determined by peak operational stress plus complications due to the daily (diurnal) thermal cycling of the receiver, departure from nucleate boiling (DNB), and the effects of time-dependent plasticity coupled with cyclic deformation.

The operational stresses arise from (1) internal steam pressure, which leads to an approximately constant tensile hoop stress, and (2) differential (single-sided) heating, which leads to large temperature gradients, an axial moment, and compressive axial stresses on the hot-side tube crown. The compressive axial stress is "strain controlled," because its amplitude is dictated by the front-to-back temperature differential in the tubes.

Both the diurnal and DNB stresses are non-steady with time. Cooling due to diurnal cycling plus cloud cover and maintenance shutdowns will produce about 10^5 cycles in a 30-year lifetime. The DNB stresses occur over a short length of the receiver tube, in which the transition from saturated water to saturated steam takes place. DNB flow is an inherent operating condition in once-through boiler designs. In this region of flow instability, liquid and vapor pockets alternately traverse the tube in different flow patterns, leading to rapid local temperature changes in the metal because of the difference in heat transfer coefficient between liquid and vapor. A model developed at Sandia Livermore Laboratory⁴ predicts the

change in temperature to be 150°C in from 3 to 8 seconds.

Candidate alloys for service in the pilot plant boiler/superheater include stainless steels 304L and 316L, and Incoloy 800/800H. Analysis of the low cycle fatigue problem led to the conclusion that the stainless steels probably would not last the 30-year lifetime required in the design. Based primarily upon the low cycle fatigue life, and its superior strength properties at operating temperature, Incoloy 800/800H was chosen as the boiler/superheater tube material.

The storage subsystem for the pilot plant is designed to contain sufficient sensible heat to permit generation of 7 MW_e for 4 hours without sunlight. The system employs a dual medium thermocline concept, using oil, rock, and sand. The rock and sand reduce the oil volume and provide some heat storage. "Thermocline" refers to the use of one tank to contain both hot and cold liquids, with a sharp stable interface developing between the two. The interface moves up or down with hot liquid addition, and cool withdraw. In this way the tank size and thermal losses are reduced. A petroleum distillate fraction has been proposed for use with local granite rocks and sand in the pilot plant. The temperature cycle ranges from 300° to 218°C with a column change of 9%; a nitrogen cover gas is employed to prevent oxidation of the oil.

B. Liquid Metal Receivers

Several conceptual design studies of advanced solar central receiver power plants in which liquid sodium serves as the receiver coolant and heat transfer medium have been conducted. This concept offers promise for improved plant performance and reduced capital cost with respect to the first generation systems.⁵

The power plant designs are based upon a steam cycle that receives thermal energy from a liquid sodium-cooled receiver. There are several advantages to the sodium-cooled system. One of these is that the heat transport fluid remains in the liquid state at all times; therefore, the control of the system is simpler, and there is not a large density change between receiver inlet and outlet. A second advantage is that liquid sodium is a very good heat transfer material; consequently, the receiver can be made smaller and the heat flux can be substantially higher. A third advantage is that the heat transport fluid can also serve as the heat storage material, and operation from storage can be accomplished under the same thermodynamic conditions as would exist when operating directly from the receiver. In addition, the receiver, which is subject to varying heat input, can be totally decoupled from the power cycle. Also, the sodium system is capable of providing steam to a turbine at temperatures and pressures commensurate with or exceeding modern steam plant requirements. Finally, the use of liquid sodium as the heat transfer medium also permits the design of a more efficient reheat steam cycle because the steam generators can be located at the base of the tower. A reheat cycle would not be practical in a system employing a water/steam-cooled receiver because steam would have to be piped from the high-pressure turbine exhaust to the receiver to be reheated. These advantages are offset, to some extent, by the need for some additional pieces of equipment not necessarily required by a water/steam system.⁷ The disadvantages are mainly materials problems as outlined in Section VI.

The conceptual designs also include a liquid metal thermal storage subsystem that will permit steam to be generated at full throttle inlet conditions during the entire storage discharge cycle. Consequently, the steam turbine need not be derated during operation from storage as is the case

with systems employing a water/steam-cooled receiver, but will continue to produce full power during this mode of operation.

VI. MATERIAL PROBLEMS

The anticipated material problems associated with the use of sodium as the primary heat transfer fluid in a central receiver solar energy system were formulated at a materials workshop sponsored by SERI.⁷ The material concerns in order of importance are given below:

A. Creep/Fatigue Behavior of Container

Materials in Molten Sodium

Material behavior under creep-fatigue conditions is extremely important in determining the lifetime performance of solar receiver tubes. The absorber tubes will be subjected to daily cyclic loads from shut-down and start-up operations, with additional cycles imposed upon the system from intermittent cloud cover and focusing and defocusing cycles. Thus, the absorber tubes will be expected to undergo hundreds of thousands of strain cycles over a 30-year service life.

B. Sodium Corrosion and Mass Transport

Behavior of Container Materials

Present solar system designs specify the use of austenitic steels and nickel-rich alloys in the receiver, austenitic and ferritic steels in the piping, ferritic steels in the steam generators, and carbon steel in the low-temperature storage tanks. Metallic mass transfer and carbon transfer, which will occur during operation and be complicated by the presence of the various metals and cyclic temperatures, may be enhanced by the potentially higher oxygen content of the sodium employed for solar use. Future high-temperature designs will probably require specifying new receiver

materials with unknown sodium corrosion/carbon transport behavior. Therefore, corrosion and transport studies under simulated or actual environments are required.

C. High Strength Ferritic Alloy Development

Alternative structural materials to the 316L and 304L austenitic stainless steels and Incoloy 800 are needed for use in sodium-heated steam generators. These materials are prone to chloride and caustic stress corrosion cracking and are sensitized at 500°-600°C in weld heat affected zones. They have high expansion coefficients and lower thermal conductivity than ferritic steels, and in proposed systems require transition weld joints. The austenitic stainless steels are already ASME code approved, and it would be advantageous to develop and obtain ASME code acceptance of high-strength ferritic steel that could withstand temperatures up to 650°C.

D. Thermal Striping and Thermal Fatigue Behavior of Container Materials

Material evaluation under thermal cycling conditions of the proposed sodium central receiver system is extremely important. In addition to diurnal and intermittent thermal cycling, thermal striping, a rapid thermal cycling phenomenon seen in the nuclear steam generators, caused by flowing fluids of varying temperatures, will occur in the receiver and piping. Both of these thermal cycling phenomena can cause failure due to a thermal fatigue mechanism and should be investigated.

E. Development and/or Qualification of Coolant Containment Alloys for Receiver Operation of 700°C for Third-Generation Plant Designs

Present design strategies for both sodium-cooled and molten salt-cooled solar thermal

conversion systems are based on present steam generator temperatures and technology. This is the proper technology base for the short term, but both the problems and opportunities in the solar thermal technology are different from those in nuclear technology and, over the long term, many benefits may result from using higher receiver operating temperatures.

F. Caustic Cracking of Steam Generator Tubes

The possibility exists of caustic attack or stress corrosion cracking the water/steam circuit (steam generator) of a sodium-cooled central receiver. Changes in coolant chemistry may happen as a result of unplanned intrusion of sodium or sodium hydroxide. These intrusions result from ineffective control of chemical constituents in the feed water as well as from leaks between the sodium and water/steam circuits. The resistance of container materials exposed to typical solar environments and to caustic cracking needs to be explored.

G. Secondary Concerns

The following problems are not considered to be as significant as those previously discussed but do warrant consideration: degradation of external containment surfaces by oxidation, pitting, and sensitization; control of the chemical constituents in the sodium coolant; control of sodium fires; improved nondestructive testing of flaws or cracking; wear and galling of parts due to clean up by sodium; on-line monitoring of the coolant; heat flux and asymmetric thermal stress effects on corrosion and oxide scale spalling in the liquid sodium; establishment of the fracture mechanics of receiver materials in a sodium environment; corrosion and degradation of internal (storage tank) insulation materials in sodium; and development or modification of material standards and codes.

Several other papers have also been written that outline the materials problems anticipated in the development of liquid metal solar thermal systems.⁸⁻¹⁷

VII. CONCLUSION

The use of liquid metals in central receiver solar thermal energy production and storage is a possible alternative to the present designs. It is important that the liquid metal materials community provide designers with information to assist them in materials to be employed in the construction of these second-generation systems. Also in light of the importance that DOE has placed on the development of dispersed solar energy, it would be to the best interest of the liquid metal community to examine potential applications of liquid metal to noncentralized solar energy and thermal storage systems.

REFERENCES

1. "A Guide to the Solar Energy Thermal Program—FY1980," U.S. Department of Energy, Solar Thermal Branch, EG-77-C-01-4024, 1980.
2. "Solar Thermal Power Systems—Program Summary," U.S. Department of Energy, Assistant Secretary for Conservation and Solar Energy, DOE/CS-0145, Dec. 1979.
3. B. L. Butler, Semi-Annual Report, Materials Branch Staff (Jan.-June, 1978), SERI/TR-31-042, Nov. 1978 and 1979.
4. J. C. Swearingen and S. L. Robinson, "Materials Performance in Solar Central Receiver Pilot Plant," SAND 79-8259, Oct. 1979.
5. R. M. Salemme, "Conceptual Design of Advanced Central Receiver Power Systems," in Reliability of Materials for Solar Energy—Workshop Proceedings, SERI/TP-31-243. R. Staehle and S. Pohlman, eds., Vol. II Part I, pp. 187-202, Oct. 1979.

6. T. Springer, "Advanced Sodium Cooled Central Receiver Power Plant," in Reliability of Materials for Solar Energy—Workshop Proceeding, SERI/TP-31-248, R. Staehle and S. Pohlman, eds., Vol. II Part I, pp. 221-234, Oct. 1979.
7. R. Staehle and S. Pohlman, eds., Reliability of Materials for Solar Energy—Workshop Proceedings, Vols. I & II, SERI/TP-31-248, Oct. 1979.
8. S. L. Pohlman, "Corrosion Science and its Applications to Solar Thermal Energy Material Problems," Solar Materials Science, Academic Press, New York, 1980 (in Press).
9. J. Swearingen and S. Pohlman, eds., "Containment Materials for Solar Thermal Energy Transport Systems: an Overview of Research and Development Needs," SERI/MR-334-247, March 1980.
10. S. L. Pohlman, "Overview of Materials and Corrosion in Solar Energy Systems," Materials and Corrosion Problems in Energy Systems, Chapter 10, NACE, New Orleans, 1980.
11. C. Bagnall et al., "Materials Performance in Sodium Heat Transport Solar Energy Systems," Westinghouse Electric Corporation, Advanced Reactors Division, SERI-WARD/TR-101, April 1979.
12. O. K. Chopra et al., "Review of Sodium Effects on Candidate Materials for Central Receiver Solar-Thermal Power Systems," Argonne National Laboratory, ANL-79-36, July 1979.
13. W. F. Brehm, "Materials Compatibility in Liquid Sodium," Hanford Engineering Development Laboratory, HEDL-SA-1559, Aug. 1978.
14. L. N. Tallerico, "A Description and Assessment of Large Solar Power Systems Technology," Sandia Laboratory, SAND 79-8015, Aug. 1979.
15. C. Spalaris, "Liquid Metal Heated Steam Generators Effects of Corrosion on Performance," in Reliability of Materials for Solar Energy—Workshop Proceedings, SERI/TP-31-248. Vol. II, Part I, pp. 321-344, Oct. 1979.
16. G. Whitlow, "Materials Considerations in the Design of Sodium Cooled Central Receiver Solar Thermal Power Plant," in Reliability of Materials for Solar Energy—Workshop Proceedings, SERI/TP-31-248. Vol. II, Part I, pp. 391-399, Oct. 1979.
17. S. L. Pohlman, "Corrosion of Solar Energy Systems: An Overview," NACE Publication No. 198, March 1979.



National Renewable
Energy Laboratory



02LIB119258