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INTEGRATED PHOTOVOLTAIC-THERMAL SOLAR ENERGY CONVERSION SYSTEMS

George A. Samara

Sandia Laboratories, Albuquerque, New Mexico 87[illegible]5

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Principal Investigators: D. G. Schueler
R. P. Stromberg

Person in Charge: G. A. Samara

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ABSTRACT

One potential solution to the economic viability of solar energy is the application of total energy concepts to solar energy conversion systems. The total energy concept envisions providing a major fraction of the energy requirements of residential and light commercial buildings from solar energy. Specifically, electricity, air conditioning, space heating and hot water would be provided.

The overall objective of this Sandia program is (i) to demonstrate the feasibility of a combined photovoltaic-thermal solar total energy system, and (ii) to develop the hardware which can provide the proper ratio of electrical and thermal energy for residential and commercial applications at a cost competitive with alternate energy sources.

The approach adopted is based on solar concentration (initially 40-50 suns). Sunlight is concentrated on photovoltaic cells (currently single crystal silicon) which absorb the light and convert some of the solar energy into electricity. The remainder of the absorbed energy, which is converted into heat in the cell, is extracted as useful thermal energy by a circulating fluid. Since we find that the dollar values of the electrical and thermal energies produced by the combined system are nearly equivalent for the applications envisioned here, the cost-effectiveness of the combined collector system is essentially doubled compared to photovoltaic concentration systems which do not make use of the excess heat.

The program consists of four closely coordinated tasks: (1) Systems Analysis, (2) Silicon Cell Development for High Illumination, High Temperature Operation, (3) Development of the Combined Photovoltaic-Thermal Collector, and (4) Systems Demonstrations. Work on the first three tasks is well under way. The basic plan for the program is to build on existing broad technology bases and to concentrate on developing an overall technical and economic view of the combined total energy systems. In the early phases of this program we have emphasized modeling and computer simulation of both solar cell and overall system configuration and performance, in parallel efforts which seek to define critical or important design paramet s.

The successful utilization of solar energy depends on achieving the proper balance between (i) the solar input power, (ii) the power load to the system, (iii) the energy storage requirements, and (iv) the available conventional power sources. In addition, since both solar input powe and load power requirements are time varying functions, dynamic systems modeling techni[illegible] needed to determine the optimal system configuration and energy st[illegible] necessary to support load demands for all available time histo[illegible] wer and load

data for any application. Towards this end Sandia has developed a large solar energy systems computer analysis code (SOLSYS). We are employing this code to assess the technical and economic feasibility of the combined system relative to various utilization scenarios. Initial studies have dealt with configuring individual residences using Albuquerque solar and load data.

The Silicon Cell Development task has emphasized the redesign of the cell to yield high efficiency at the operating conditions of the combined system (40-50 suns and temperatures to ~ 100°C). A Sandia-developed numerical semiconductor device analysis code which yields one-dimensional numerical solutions of the carrier transport equations throughout the thickness of the cell is being used and has proved to be an indispensable aid towards achieving the desired goal. Analyses have been carried out on a number of cell designs at solar intensities ranging from 1 to 140 suns and temperatures from 27 to 200°C. A design has been selected and is being experimentally tested which yields 12% conversion efficiency at 50 suns and 100°C. The modifications needed, in comparison with the conventional cell, include lowering the substrate resistivity by an order of magnitude to ~ 0.3 Ω-cm, reducing the junction depth from 0.5 to 0.2 μm, decreasing the diffused surface layer concentration to $N_D \simeq 1 \times 10^{20} cm^{-3}$, and optimizing the top surface metallization. Experimental results on Sandia-built modified cells have thus far given excellent confirmation of the code results.

A combined photovoltaic-thermal collector has been built and is now being tested. Initial tests have concentrated on evaluating the thermal efficiency of the collector before and after the silicon cells are mounted. With likely improvements in bonding between cells and receiver and in the absorptivity of the cells, thermal efficiencies > 50% can be expected for the combined receiver operating at 100°C.

Since we are still in the early stages of this program it is expected that the analytical and experimental work under the various tasks will continue for the near future. The systems analysis will be expanded to include other cities and other loads; the modified cell work will emphasize optimizing the top-surface metallization; and the combined collector work will concentrate on optimizing both electrical and thermal efficiencies and gaining operational experience under field conditions. Plans for a complete integrated system development model will be formulated.

The attached figures elaborate on and further illustrate certain aspects and accomplishments of the program.

OVERALL OBJECTIVES:

- To Demonstrate the Feasibility of Combined Photovoltaic-Thermal Solar Energy Systems
- To Develop the Hardware Which can Provide the Proper Ratio of Electrical and Thermal Energy for Pertinent Applications at a Cost Competitive with Alternate Energy Sources

PROGRAM TASKS:

1. Systems Analysis
   a. Computer Simulation
   b. System Configurations
2. Silicon Cell Development for Solar Concentration
   a. Code Simulation and Analysis
   b. Cell Fabrication
   c. Performance Testing
3. Combined Collector Development
   a. Modeling
   b. Fabrication and Testing
4. Systems Demonstrations
   a. Development Models
   b. Full-Scale Demonstrations

SOLAR ENERGY SYSTEMS COMPARISON

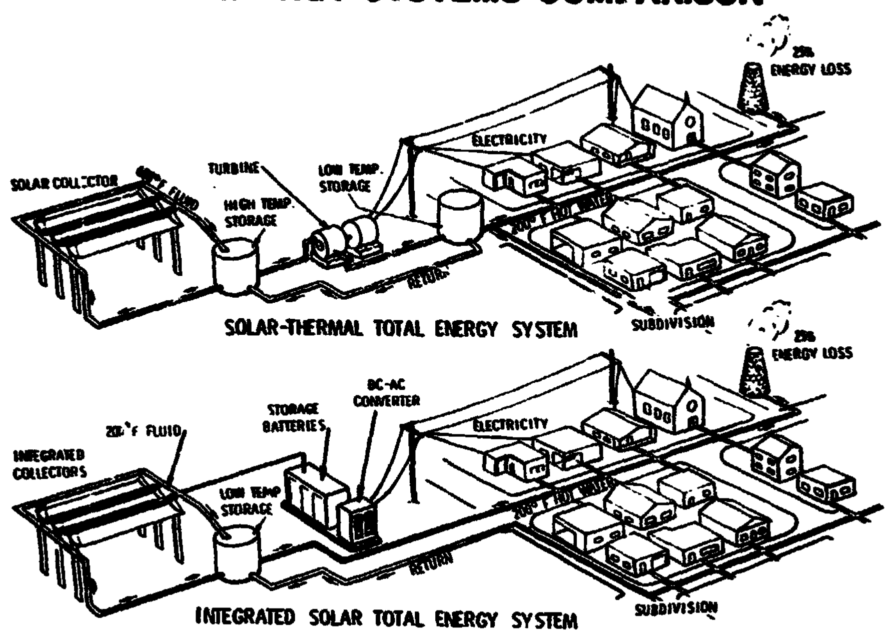

FIGURE 1 (top) A solar energy system using solar-thermal conversion and thermal cascading.

(bottom) A solar energy system using combined photovoltaic and thermal conversion.

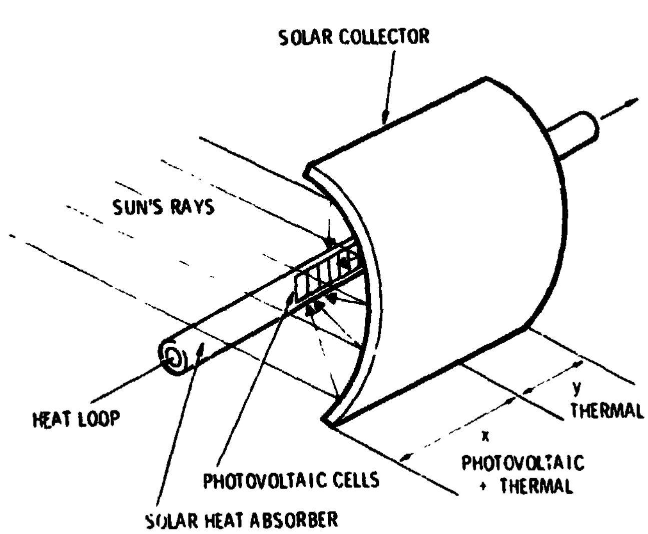

FIGURE 2. An integrated photovoltaic-thermal solar concentrating collector.

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TABLE I

Calculated Performances of Conventional and Optimized Solar Cells at T = 100° C

	Conventional			Optimized		
	1 sun	40 suns	100 suns	1 sun	40 suns	100 suns
V_{oc} [V]	0.379	0.481	0.499	0.447	0.568	0.597
J_{sc} [mA/cm^2]	41.9	1757.	4476.	43.6	1749.	4395.
(per sun)	(41.9)	(43.9)	(44.8)	(43.6)	(43.7)	(43.9)
FF	0.720	0.629	0.486	0.743	0.769	0.754
η^* [%]	7.0	8.2	6.7	8.9	11.8	12.2

$^*\gamma = 0.96$

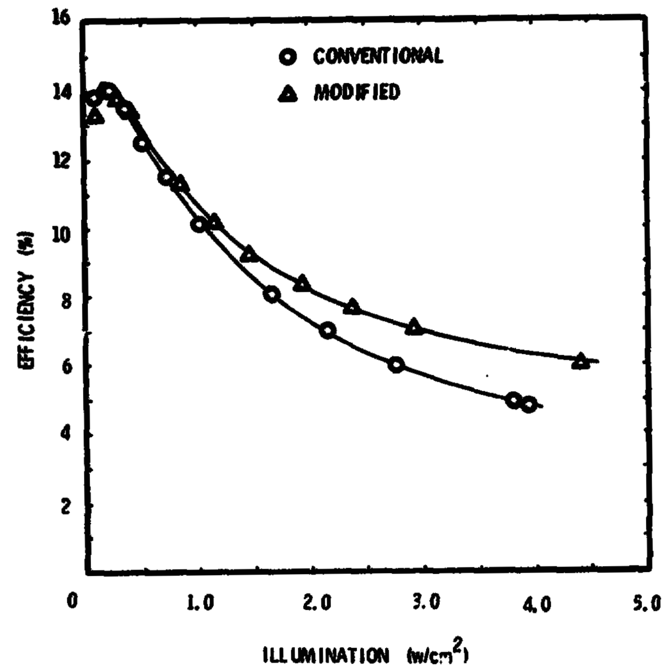


Fig. 3

Efficiency versus illumination intensity for a conventional silicon cell and our modified silicon cell at 26°C. Front surface electrode pattern is not optimized.

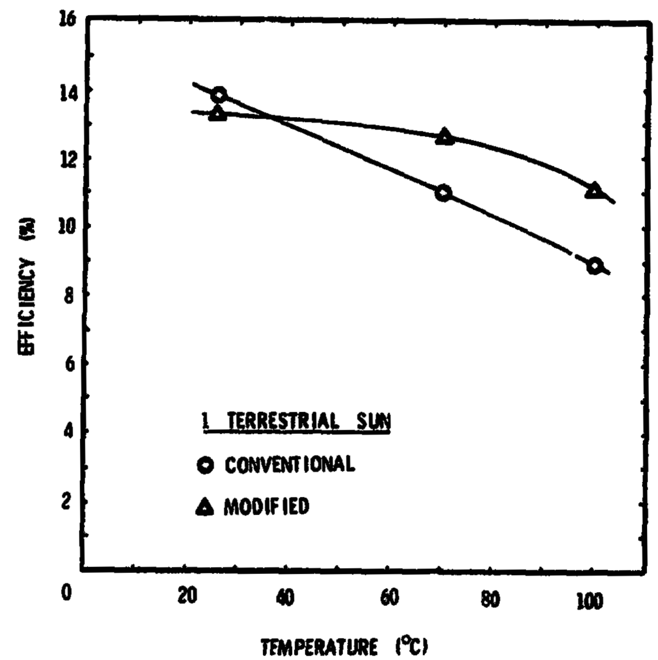


Fig. 4

Efficiency versus temperature for a conventional silicon cell and our modified silicon cell at 1 terrestrial sun (0.1 W/cm^2). Front surface electrode pattern is not optimized.

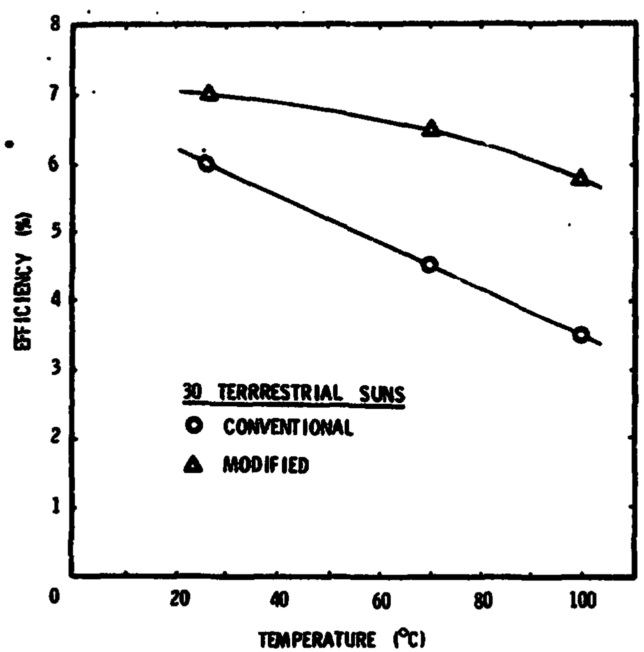


Fig. 5 Efficiency versus temperature for a conventional silicon cell and our modified silicon cell at 1 terrestrial sun (0.1 W/cm^2). Front surface electrode pattern is not optimized.

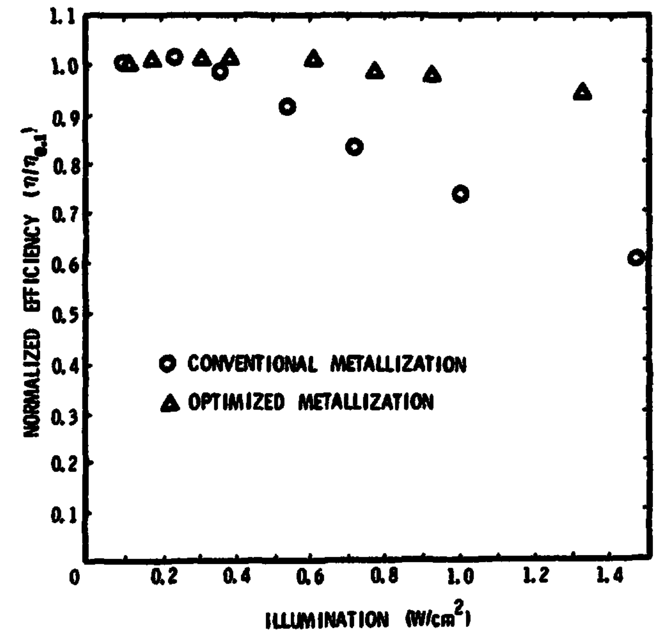


Fig. 6 Normalized efficiency versus illumination for conventional silicon cells with conventional and optimized front surface electrode patterns.

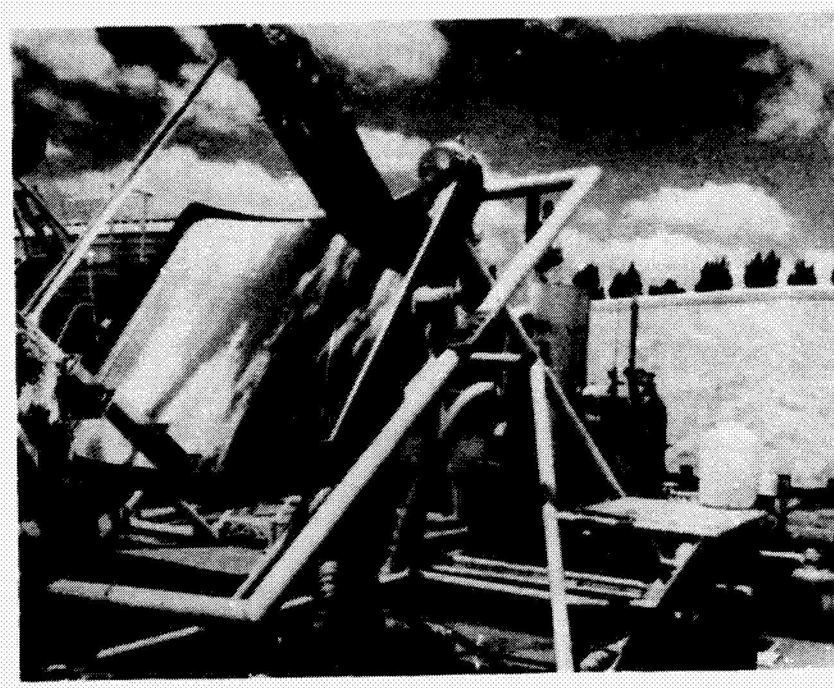
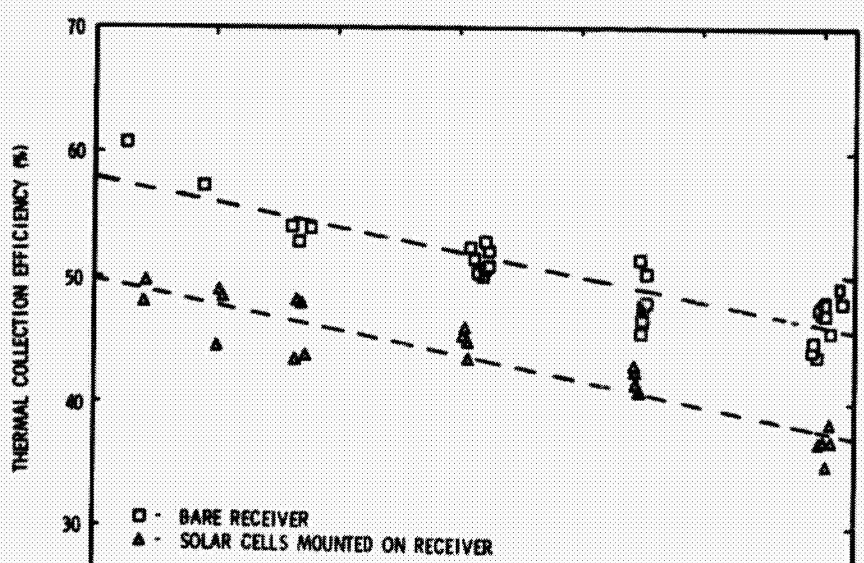


Fig. 7 Reflector and integrated receiver pipe under test.



THERMAL EFFICIENCY MEASUREMENTS AS FUNCTION OF COOLANT FLUID TEMPERATURE.

Fig. 8

SUMMARY

- Sandia's Solar Energy Systems Computer Analysis Code (SOLSYS) is Being Utilized to Assess the Technical and Economic Feasibility of Combined Photovoltaic Systems Relative to Various Utilization Scenarios.

- Combined Systems Using Concentrators and High Efficiency (≥ 10%) Silicon Cells can Provide Residences (or Communities) with a Reasonable Balance of Electrical and Thermal Ene rgy.

- The Device Analysis Code has been Used to Redesign the Silicon Cell for High Temperature, High Illumination Operation.

- A Design Yielding 12% Efficiency at 50 Suns and 100°C has been Selected.

- Modified Cells have been Fabricated and Tested. Results have Confirmed Code Predictions.

- A Combined Collector has been Built and is being Tested. Thermal Efficiencies > 50% at 50 Suns and 100°C can be expected.