Arab Gulf J. scient. Res. **2** (1), pp. 187-197 (1984)

Optimisation of a Central Receiver Type Solar Thermionic Power Plant

F.A. Abou-Elfotouh and M.A. Al-mass'ari

Physics Department, Faculty of Science, King Saud University, Riyadh, Saudi Arabia

ABSTRACT. In this work a solar thermionic power plant is proposed and analyzed. The geometric configuration of the system, which is based on the central thermal receiver tower concept, could be optimized to achieve an average concentration ratio more than 1800. In a laboratory model for the heat transfer ststem, the cathode of the thermionic diode is heated by a hot air flow supplied from the cavity. A silicon-carbide cavity with depth-to-width ratio 1.2 was found successful. By building a thermionic diode of 20 percent efficiency into a solar electric power system, the cost-per-unit-power output can be reduced by 3 to 5 percent.

Research and development on the conversion of solar radiation into electricity have been expanded tremendously. Various types of plants were discussed at various symposia and solar engineering conferences. The current trend of this research is to design a solar electric power plant (SEPP) which can provide minimal cost electric power. From thermodynamic point of view, a SEPP has to be operated at temperatures as high as possible to achieve the highest possible efficiency. High-temperature, large-scale solar energy conversion can be obtained in the central receiver tower concept (Easton *et al.* 1974 and Jarvinen 1975) giving rise to an overall cycle efficiency of 40 percent. By building a thermionic diode converter into the system, its performance can be improved by 15 percent at low cost. The proposed attainable efficiency of the thermionic generator is about 25 percent, although 35 percent is possible.

A development program leading to a commercial solar thermionic power plant is planned. In the present stage, laboratory investigations of the design features of the basic components are performed together with the design concept for a 10 MW thermal pilot plant, which will be constructed and tested in a next stage.

Experimental

A simple laboratory experimental thermionic diode in the form of two concentric tubes has been constructed in a bell jar vacuum unit to study its operation characteristics, and to investigate the conditions for increasing conversion efficiency. In this experiment, the cathode was heated by electron gun. In another model, the cathode was heated by a hot air supplied from a cavity heated by a parabolic mirror concentrator. The anode was also cooled by an air flow. Measurements of the cavity effective absorbtivity (emissivity) and its material (with and without coating) were also carried out to maximize the thermal efficiency of the cavity and the heat-transfer technique.

System Description

In this section, the design concept of the solar thermionic power plant (STEPP) will be described together with experimental data obtained for each particular unit or subsystem. Then we will be concerned with selection of the optimum scheme for the STEPP to obtain the high concentrating power of the concentrator-receiver system desired for efficient operation of the thermionic generator. The solar thermionic electric power plant consists of three major sub-systems:

1. Thermionic Diode Generator (TDG)

The practical application of a solar thermionic converter requires the solution of problems related to the converter, receiver, and coordination between them. Therefore, the objectives of this work are: a) production of long life materials for the emitter with high thermal emission, b) development of the converter design for higher efficiency, and c) reduction of energy loss due to thermal transport by radiation and conduction.

In order to maintain the cathode temperature at the level required (1600-2000°C) for efficient operation (20-25 percent), it had to receive a power density about 100 w/cm^2, to give a maximum output power density (25 w/cm^2) from the available material (Rouklov 1965). Therefore, the power density received from the sun (860 w/m^2 on the average in Riyadh) has to be concentrated at a ratio of about 1600 or more to allow the 100 w/cm^2 at the cathode after 35 percent optical and thermal loss at the receiver. To satisfy this condition, a central receiver tower concept is now considered. The cathode is a hollow cylinder, in which the outer surface is heated by a high thermal efficiency cavity receiver. The electron collector (anode) is in the form of a cylinder with extended surface area coaxial with the cathode. A schematic section of the TDG and its characteristics are shown in Fig. 1 and 2.

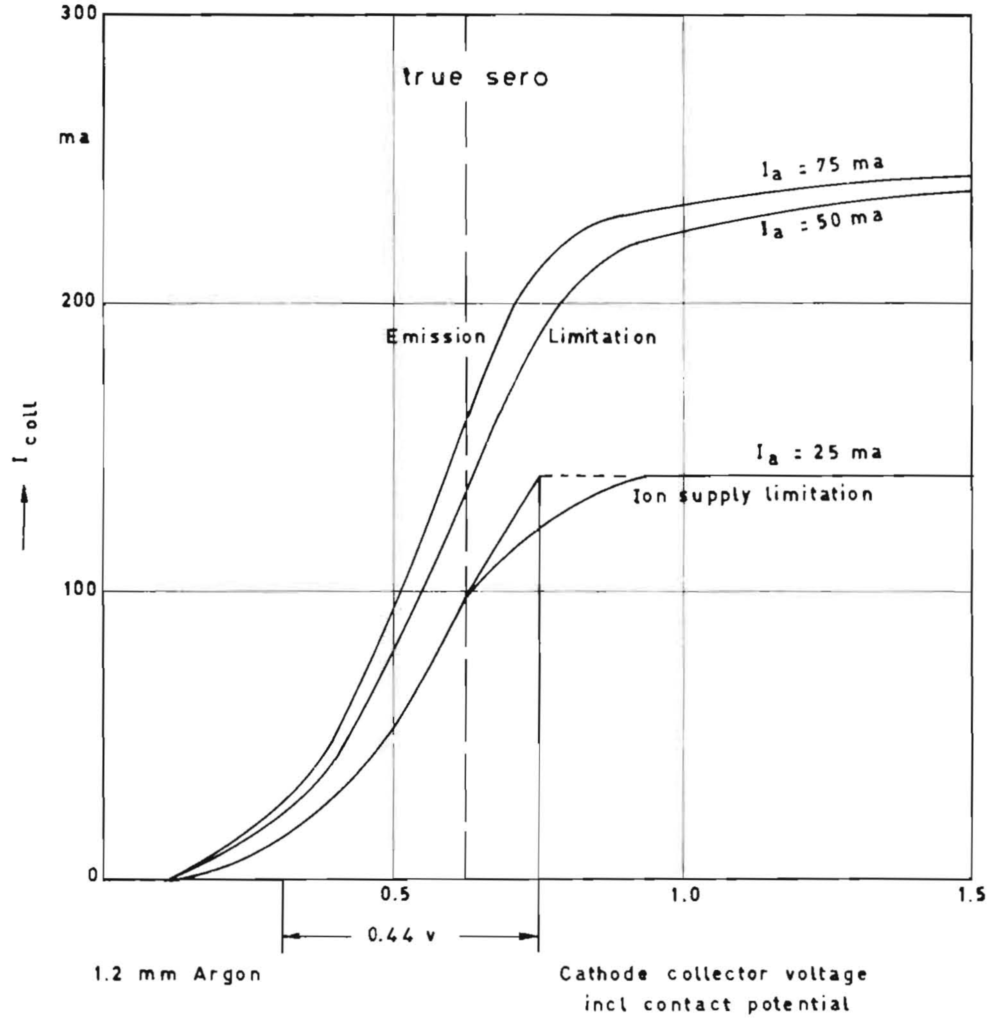

Fig. 1. Characteristics of the simple experimental tube shown in Fig. 2.

To increase the conversion efficiency of TDG, and auxiliary pulsed current source is used to reduce the space charge. A solar pulse generator with silicon solar cells is proposed to make the system more independant.

2. The Central Thermal Receiver (CTR)

In this proposed system, the heat to be supplied to the cathode of the TDG is collected by a cylindrical central thermal receiver (CTR). This cylindrical CTR is

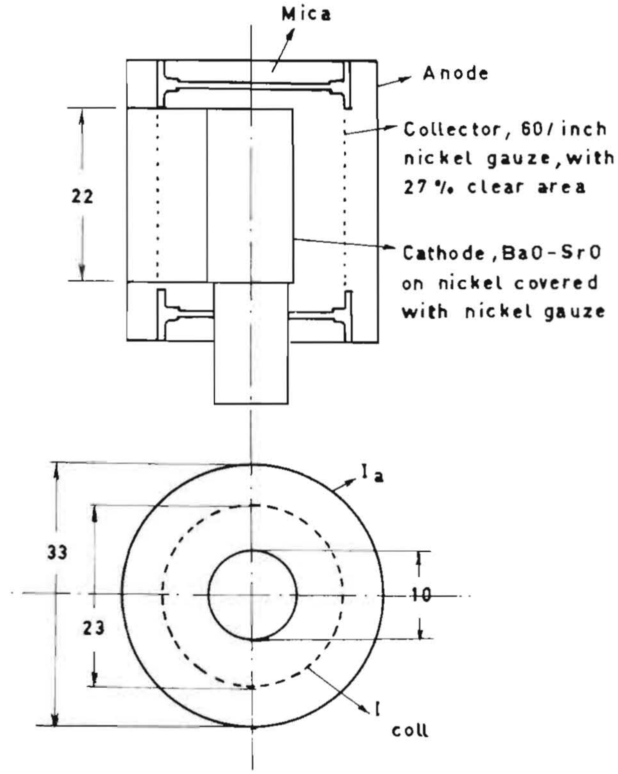

Fig. 2. Thermionic diode configuration.

heated by multiple reflected images of the sun with heliostats. The thermal collection efficiency that is determined by optical and thermal features of the system design (including reflectors) must be at least 65 percent at a concentration ratio of 1800. The mean radiation density, E, on the receiver surface is controlled by the optical losses, where E is given by Teplyakov and Aproisi (1975):

$$E = \frac{\emptyset}{A_c} = \frac{SRA_rF}{A_c}$$

where $\emptyset$ = flux of radiation reflected by the mirrors.
S = density of direct solar radiation.
R = mirror reflection coefficient.
A_r = total reflecting area.
F = concentrator utilization factor.

A_c is the radiation receiving area for a cylindrical receiver, where

$$A_c = \frac{ab}{\mathrm{Sin\,u\,Cos^2\,u}} XY$$

The mean concentration factor $K = \frac{1}{(B/H)^2} \frac{\mathrm{Sin^2\,u}\,F}{XY}$

$$X = \mathrm{Cos(u)} + \frac{2\theta}{(a/H)}, \qquad Y = \mathrm{Cos(u)} + \frac{2\theta}{(b/H)}$$

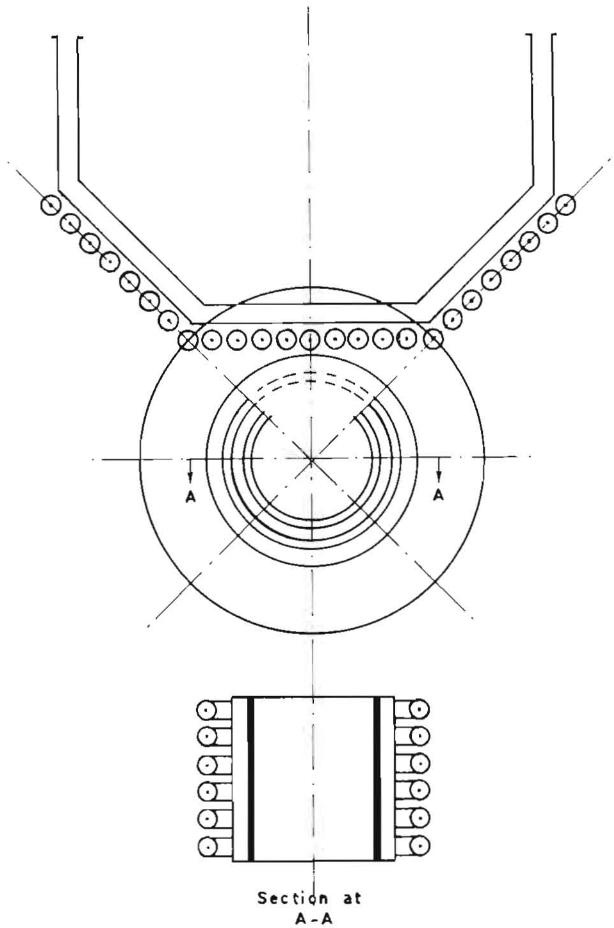

Fig. 3. Cavity heated air central receiver.

u = concentrator aperture

θ = angular divergence of image

The optical losses of the system due to F, reflectivity, *2nd* optical accuracy can be optimised to be no greater than 25%. This means that thermal losses must not exceed 10% of thermal energy received at the CTR if the total loss is to be 35%. Heated air cavity receivers with efficiency near 90% is now easily achieved (Jarvinen 1977). The heat is transferred to the cathode of the TDG using a compressed air flow ducted to the back sides of the cavity walls. In Fig. 3, a laboratory model for the heat transfer system is shown. In this experimental model, the cavity inside walls were heated by a parabolic mirror to a temperature of about 1600°C. The residual heat carried out from the cavity side walls, the cathode, and heat dissipated from the collectors are utilized in the form of an air jets directed to a power turbine. A block diagram illustrating heat transfer in the CTR is shown in Fig. 4. Homogeneous heating of the cavity walls was obtained for this cavity at depth (D) to width (W) ratio = 1.2.

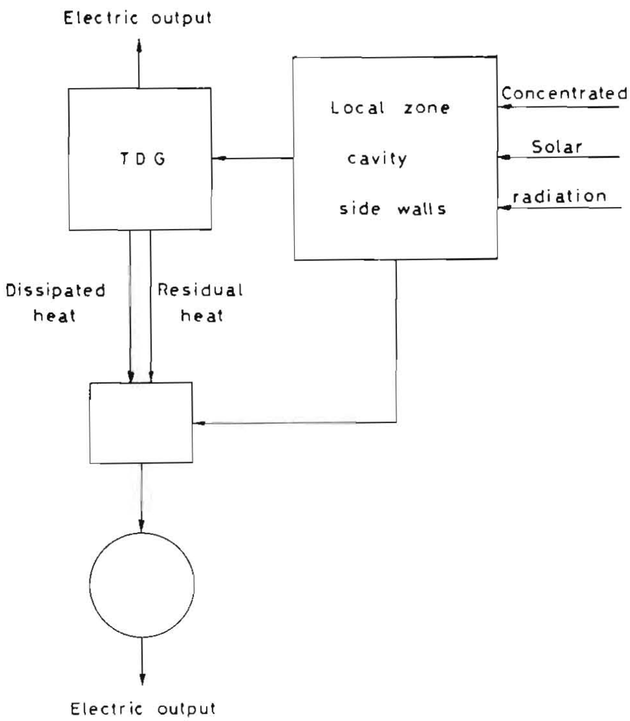

Fig. 4. Block diagram illustrating heat transfer in the CTR.

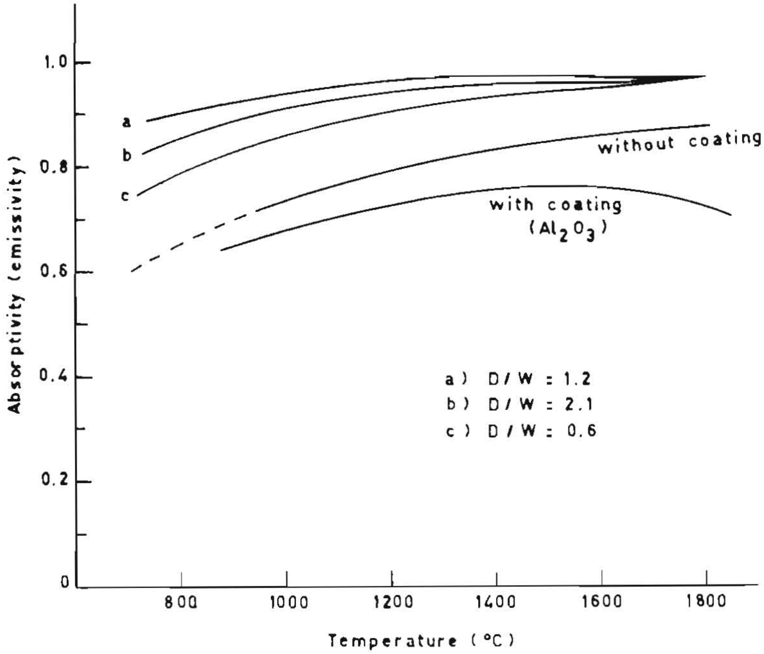

Fig. 5. Absorptivity of silicon carbide in the region of 0.5 μm (maximum of solar radiation).

The material used for cavity construction was silicon carbide. It is found suitable not only as a good absorber of the solar radiation, but also as a cathode material for the TDG when coated with zirconium oxide as an emitting surface. The absorptivity (emissivity) of silicon carbide with and without coating is shown in Fig. 5, which also shows the absorptivity of a silicon carbide cavity related to the bulk material for different D/W ratios.

3. Solar Collectors (Reflectors)

The geometric configurations of the proposed system which was exemplified by the design concept of the university of Houston in collaboration with McDonald-Douglas in the United States are shown in Table 1. The sun's energy will be collected by four similar reflector fields located around the CTR.

This configuration is based on very small, flat, square mirrors 1.32 m^2 area, and is capable of collecting 10 MW thermal energy on 10 m^2 cathode of the TDG element. The CTR is divided into four cavity segments, and each cavity is facing one reflector field. Only the north facing field is considered in this calculation, with a reflector field in the form of south facing slope to reduce the mutual shading effect of such small B/H ratio. The reflecting area is 1.7 $\times$ 10^4 m^2 using 1.3 $\times$ 10^4

Table 1. Geometric configuration of the reflectors.

Parameter	**Houston University Concept**	**Proposed STEPP Pilot Plant**	**Commerical STEPP**
Reflector dimension (a, b)	4.6 m	1.15 m	3.32 m
Reflector spacing (B)	7.3 m	1.5 m	4.5 m
Tower height (H)	450.0 m	70.0 m	220.0 m
Mean Concentrator aperture (U)	63 deg	75 deg	75 deg
Reflector geometric error plus sun – tracking error	7.2×10^{-3} rad	5.5×10^{-3} rad	5.5×10^{-3} rad
Reflector surface utilization factor (F)	0.7	0.74	0.74
Reflection coefficient (R)		0.92	0.9

mirrors. Table 2 shows different alternatives computed for the different design parameters to obtain a concentration ratio higher than 1600. Figure 6 shows the cavity shape and field of view from the receiver focal zone. The disadvantage of this configuration is that the large number of reflectors present complicate the problems concerning the adjustment and maintenance of such a multiple system. However, this design is suitable for the components test, where manufacturing of good quality mirrors and the TDG element is only possible at these sizes with the available facilities. In the design of a commercial STEPP the 1.32 m^2 mirrors are replaced with a 11 m^2 one and a CTR of 300 m^2 area on the top of a 220 m high tower.

Table 2. Alternative values computed for different design parameter of the STEPP giving k 1600.

	a = b = 1.1 m		**S = 800 m^{-2}**		**h = 60 m,**	**R = 0.8**
k	**1680**	**1740**	**2119**	**2200**	**2600**	**2700**
E (cm^{-2})	107.5	111.4	135.7	145.5	166.5	172.5
F	0.7	0.72	0.7	0.725	0.7	0.725
Ø (10^3)	4.5	4.5	3.0	3.0	3.0	3.0

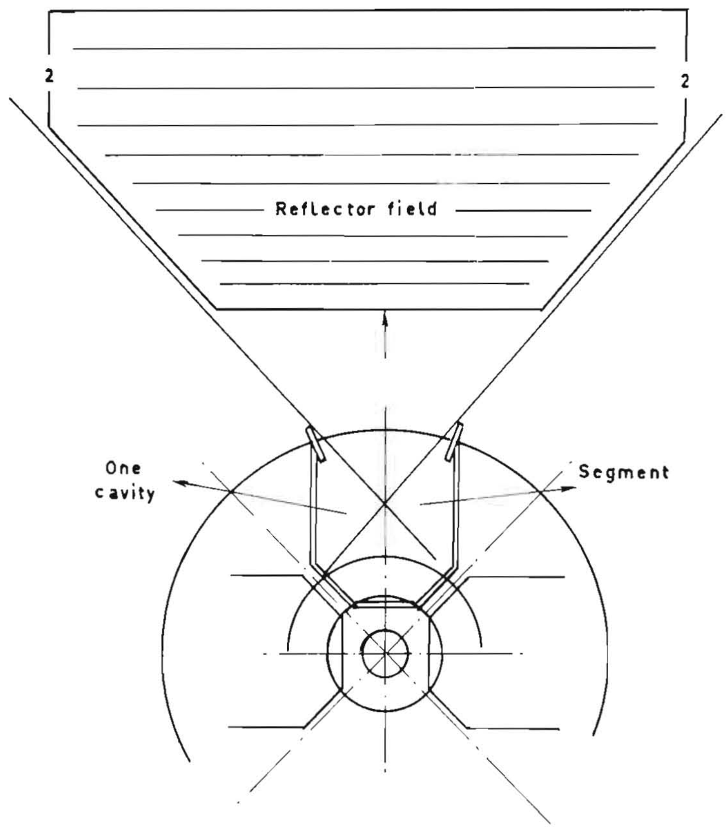

Fig. 6. Cavity shape and field of view of the receiver focal zone.

Cost-Performance Analysis

A cost-performance analysis for the STEPP was made in a similar way to that given by Duff *et al.* (1975). The baseline items in the calculation include solar energy concentration by heliostats, the CTR and TDG with 25 percent conversion efficiency using silicon solar panels as an auxiliary power supply. In this analysis, the daily, seasonal and annual output power from the STEPP were computed in terms of the configuration and characteristics of the systems – including the overall geometry of the system, determined by the relative positions of the reflectors with respect to the tower, and the reflectors distributions and orientations. The variation in the reflector utilization factor, F, for each mirror was calculated in the course of the day different heights of the sun (*i.e.*, air mass conditions). It was also computed for four different typical days representing the four seasons. Details of this calculation will be published elsewhere (Abou-Elfotouh and Al-mass'ari 1983). These lines of reflector utilization factor, F, were used as a guideline for mirror distribution and for power output calculations. It was found that the total costs of construction and money investment on a STEPP is about 8 to 10 percent higher than that for a SEPP using the same power turbine. However, the total electricity production of the STEPP is 12-15 percent more than the SEPP electric output. This means that a 3-5 percent reduction in the cost per unit power is obtained by building the thermionic converter into the system.

Eight to ten percent reduction in the cost per unit power would be possible if a thermionic generator with 35 percent conversion efficiency could be developed.

Conclusion

Building a thermionic converter in a SEPP is a technically feasible undertaking. The cost per unit power output of the plant can be reduced by 5-10 percent according to the thermionic diode efficiency. Further research and testing scheme is essential to develop a large size, long life, thermionic generator with enhanced efficiency. Therefore long-life, high emission cathode material is required. Also, development of durable efficient concentrators is essential. The scheme must include improvement of heat transfer techniques, especially when applied to the commercial system.

References

Abou-Elfotouh, F.A. and **Al-mass'ari, M.A.** (1983) *International Symposium Energy 83, The International Association of Science and Technology for Development, San Francisco, May 16-18.*

Duff, W.S., **Lameiro, G.P.** and **Löf, G.O.G.** (1975) Parametric performance and cost for solar concentrators, *Sol. Energy* **17**: 47-58.

Easton, C.R., **Hallet, R.W.** and **Gronich, S.** (1974) Evaluation of Central solar tower power plant, *9th Intersociety EnergyConversion and Engineering Conference, San Francisco, Ca.*, pp. 264-268.

Jarvinen, P.O. (1975) Solar-heated-air turbine generating systems, *10th Intersociety Energy Conversion and Engineering Conference, University of Delaware, Newark, Delaware.*

Jarvinen, P.O. (1977) Solar-heated-air receivers, *Sol. Energy* **19**: 139-147.

Rouklov, P. (1965) *Proceedings of the International Conference on Thermionic Emission, London*, pp. 131-136.

Teplyakov, D.I. and **Aproisi, R.R.** (1975) Concentrating power of reflecting systems in solar energy stations; the influence of geometric factors, *Geliotekhnika, Appl. Sol. Energy* **11** (6): 46-58.

(Received 08/03/1983; in revised form 14/05/1983)

التحـديـد المثالي لمحطة قوى أيونية - حرارية باستخدام الطاقة الشمسية بواسطة مستقبل مركزى

فؤاد أبو الفتوح و محمد عبد الله المسعرى

قسم الفيزياء - كلية العلوم - جامعة الملك سعود الرياض - المملكة العربية السعودية

نقـترح فى عملنـا هذا محطـة قوى ثرميـونيـة تعمـل بالطـاقـة الشمسيـة. ولقـد أمكن تحديـد الـتركيب الهندسى للنظام، الـذى بنى على فكـرة برج الاستقبال المركزى، تحديداً مثالياً للحصـــول على نسبــة تركيـز متـوسطـة تزيـد على ١٨٠٠ ضعف. وفى نمـــوذج معملى لنظـــام النقـــل الحـرارى، تم تسخين المهبط (الكاثود) لثنائية القطب الثرميونية بواسطة تيار من الهـواء الحـار آتٍ من التجـويف. ويتكون هذا التجويف من كربيـــد السيليكـــون. كما وجـــدنـا أن نسبـة العمق إلى العـــرض تؤدى الغـرض إذا كانت ٢ , ١ . لذلـك نعتقـد أن إدخـال ثنـائيـة قطب ثرميـونية كفاءتها ٢٠٪ على نظام توليد الكهـربـاء بواسطة الطاقة الشمسية سوف يؤدى إلى إنقاص كلفة وحدة الطاقة بمقدار ٣ إلى ٥٪ .